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# Environmental impacts and emissions reduction potential of floating wind and marine energy in future energy scenarios of Great Britain

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*Doctor of Philosophy*

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# Lay Summary

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Human activities are impacting the natural cycles of planet Earth in many ways. Climate change is a contemporary crisis that affects people and the environment disproportionately around the globe. Governments have agreed to try to limit further climate change, and recognise that replacing energy from greenhouse gas emitting energy fossil fuels with low emission renewable energy is a crucial step. One way to measure the effectiveness of a renewable energy system in limiting climate change is an assessment of ‘carbon payback’, the time required for a renewable energy system to offset the carbon dioxide emitted during its lifetime through avoided fossil fuel use in operation. However, as more renewable energy is built, electrical power is getting less carbon intensive, and it is unclear if renewable energy systems will achieve carbon payback during their lifetimes.

This thesis will focus on arrays of newer types of offshore renewable energy technologies: floating wind turbines, wave energy converters, and tidal stream turbines. These technologies usually have higher climate impacts (or ‘carbon footprints’) than onshore wind, solar and fixed-bottom offshore wind, although estimates do vary. This thesis looks at the life cycle environmental impacts of these technologies and how these apparently higher life cycle carbon emissions are affected when these technologies are integrated into national power systems in the future, using the island of Great Britain as an example.

This thesis reviews scientific literature to provide a broad context for the life cycle assessments of arrays of wave energy converters and floating wind turbines. A suitable method to determine the operational impact of these generators is then described, and data developed for a new power system modelling tool and open-source dataset (PyPSA-GB). Finally, the net

emissions impact of these technologies in future scenarios is determined in an example, showing that carbon payback of these technologies is now unlikely in most scenarios and that climate change mitigation performance is not strongly associated with the complementarity of these sources, but dominated by to installed capacity and rapid deployment.

# Abstract

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Humans are unequally causing environmental harm through consumption of natural materials and energy beyond sustainable limits. Amongst the most severe and cross-cutting human induced pressures on Earth is climate change. This is driven by higher average temperature from increased retention of solar energy via increased atmospheric concentrations of greenhouse gases released by human activities; primarily carbon dioxide (CO<sub>2</sub>) from combustion of fossil fuels: oil, gas and coal. This thesis considers the environmental impacts and climate change impacts of novel forms of offshore renewable energy, and assesses how effectively they can obviate emissions from fossil fuel power generation, using the electricity system of Great Britain as a case study.

The United Kingdom and its devolved nations have enshrined in law a target to achieve net zero greenhouse gas emissions by 2050 or earlier. Simultaneously, the UK's oceanic climate and island geography are well placed to host significant installed capacities of offshore wind which will form the backbone of the power system in almost all Net Zero scenarios, and – although to a lesser extent – marine energy (wave and tidal stream). These renewable energies obviously forgo fossil fuels as a primary consumable, but do include non-zero environmental impacts via their construction, operation and disposal.

Wave energy remains an untapped source of renewable electricity, with ongoing technological development beginning in the 1970's. Studies of the life cycle environmental impacts of arrays of new wave energy converter (WEC) devices are uncommon, and a life cycle assessment (LCA) of a novel device – the Blue Horizon – is presented here, deployed in four utility-scale arrays including a substation, highly detailed vessel representation and site-

specific energy production, finding a global warming impact of 68.3 to 94.9 gCO<sub>2</sub>eq/kWh across the arrays and carbon payback beyond the lifetime of the array when future scenarios of carbon intensity are used.

Conversely, UK floating wind deployment is growing. Here, arrays of the International Energy Agency (IEA) 15 MW Reference Wind Turbine (RWT), on floating platforms arranged in commercial-scale arrays at multiple locations are assessed and compared to the wave energy results, finding a climate impact of 17.4 to 26.3 gCO<sub>2</sub>eq/kWh, and a payback time of three to twelve years depending on future scenario. Site-specific energy production and vessel operations are provided by a dedicated offshore wind farm operations and maintenance (O&M) model, COMPASS, allowing service operation vessel (SOV) O&M impacts to be assessed with increased confidence.

The next aspect of the thesis considers ways of modelling the integration of these life cycle impact assessments with the wider energy system. To permit this, projections for wave and tidal stream installed capacities are developed with discrete geospatial coordinates of potential deployment sites to create three scenarios (low, mid and high) of future deployment around GB. These scenarios are then used with a new power system modelling tool, PyPSA-GB, and Future Energy Scenarios (FES) from National Grid, to consider the emissions reduction potential of marine renewable generation in the future, and how this relates to the static attributional impacts from preceding LCA studies. Accounting for the fleets of generation within the FES finds that carbon payback is almost never achieved for the cases considered, and that complementarity has a limited effect on the technology's climate change mitigation efficacy, which is simply dominated by the installed capacities in the future scenarios.

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# Abbreviations

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AEP	Annual energy production	CLV	Cable lay vessel
AESA	Absolute environmental sustainability assessment	COMPASS	Combined Operations and Maintenance, People, Assets and Systems Simulation
AGR	Advanced gas reactor (UK civil nuclear reactor design)	CPT	Carbon payback time
AHTS	Anchor handling tug supply (vessel)	CT	'Consumer transformation' (FES)
AOD	Aerosol Optical Depth	D&R	Decommissioning & removal (also, DR)
BAU	Business as usual	DALY	Disability life adjusted years
BB	Building block (FES)	DNO	Distribution Network Operator
BECCS	Biomass energy with carbon capture and storage	DP	Dynamic positioning
BFOW	Bottom fixed offshore wind	E/MSY	Extinctions per million species-years
BRICS	Brazil, Russia, India, China and South Africa	EE-MRIO	Environmental input-output model
CAP	Carbon abatement potential	EEIO	Environmentally extended multiregional input-output
CBA	Cost benefit analysis	EIA	Environmental impact assessment
CCC	Climate Change Committee	EMM	Electricity market model
CCGT	Combined cycle gas turbine	EPD	Environmental product declaration
CCS	Carbon capture and storage	EPT	Energy payback time
CDR	Carbon Dioxide removal	ERP	Emissions Reduction Potential
CE	Circular economy	EROI	Energy return on investment
CED	Cumulative energy demand	ESB	Earth System Boundary
CfD	Contract for Difference	ESM	Energy System Model
CFC	Chlorofluorocarbon	ESO	Energy system operator

ESOM	Energy system optimisation model	HANPP	Human appropriation of net primary production
ESPM	Energy system planning model	HCT	Human carcinogenic toxicity
ESSM	Energy system simulation model	HNCT	Human non-carcinogenic toxicity
FBOW	Fixed-bottom offshore wind	HVAC	High voltage alternating current
FE	Freshwater eutrophication	HVDC	High voltage direct current
FESA	Future energy scenario analysis (model)	IAM	Integrated Assessment Model
FEX	Freshwater ecotoxicity	IEA	International Energy Agency
FES	Future energy scenarios	IEC	International Electrotechnical Commission
FHN	Fulfilment of human needs	IMF	International Monetary Fund
FOW	Floating offshore wind	IPAT	Impact Population Affluence Technology
FPMF	Fine particulate matter formation	IPCC	Intergovernmental Panel on Climate Change
FRS	Fossil resource scarcity	IR	Ionising radiation
FS	'Falling short' (FES)	IRP	Ionising radiation potential
FWTU	Floating wind turbine unit (towable, fully assembled turbine and platform)	L&R	Landfill & recycling (also, LR)
GB	Great Britain (the island of)	LCA	Life cycle assessment
GDP	Gross Domestic Product	LCI	Life cycle inventory
GFRP	Glass fibre reinforced plastic	LCIA	Life cycle impact assessment
GHG	Greenhouse gas	LCOE	Levelised cost of energy
GMST	Global mean surface temperature	LCP	Lifetime CO <sub>2</sub> eq production
GRP	Glass reinforced plastic	LEP	Lifetime energy production
GSP	Grid Supply Point	LOPF	Linear optimal power flow
GW	Global warming	LP	Linear programming
GWP	Global warming potential	LU	Land use
		LULUCF	Land use, land use change and forestry

LW	'Leading the way' (FES)	OECD	Organisation for Economic Co-operation and Development
M&M	Materials & manufacturing (also, MM)	OFHH	Ozone formation, human health
MDF	Marginal displacement factor	OFTE	Ozone formation, terrestrial ecosystems
ME	Marine eutrophication	OPEX	Operational expense
MEX	Marine ecotoxicity	ORE	Offshore renewable energy
MILP	Mixed integer linear programming	OSCV	Offshore subsea construction vessel
MMT	Modern Monetary Theory	OSP	Offshore substation platform
MRS	Mineral resource scarcity	OTEC	Ocean thermal energy conversion
NDC	Nationally determined contribution	OTM	Offshore transformer module
NET	Negative Emissions Technologies	PB	Planetary Boundary
NG	National grid	PDZ	Pembrokeshire demonstration zone
NGET	National Grid Electricity Transmission (TNO in England and Wales)	PFAS	Per- polyfluoroalkyl substances ("forever chemicals")
NMVOC	Non-Methane Volatile Organic Compounds	pLCA	Prospective life cycle assessment
NREL	National Renewable Energy Laboratory	PSA	Power system analysis (model/tool)
NLP	Non-linear programming	PSM	Power system model
NPgY	Northern Power Grid Yorkshire (DNO in Northern England)	PSV	Platform supply vessel
NPP	Net Primary Production	PTO	Power take off
NZE	Net Zero Emissions	PWR	Pressurised water reactor (nuclear reactor design)
O&M	Operation and maintenance (also, OM)	PyPSA	Python for power system analysis
OCGT	Open cycle gas turbine	RCP	Representative concentration pathway
ODP	Ozone depleting potential	ROV	Remotely operated vehicle
ODS	Ozone Depleting Substance	RWT	Reference wind turbine

S/A	Sub-assembly	TEX	Terrestrial ecotoxicity
SEPD	Southern Electric Power Distribution plc (DNO in Southern England)	TNO	Transmission Network Operator
SET	Strategic Energy Technology (Plan)	UK	United Kingdom
SOD	Stratospheric ozone depletion	UKMED	UK Marine Energy Database
SOP	Surplus ore potential	USA	United States of America
SPI	Social progress index	UUID	Universally unique identifier
SPTL	ScottishPower Transmission Ltd (TNO in Southern Scotland)	UV	Ultraviolet radiation
SSHLB	Semi-submersible Heavy Lift Barge	UVB	Ultraviolet radiation B
SSP	Shared socio-economic pathway	V2G	Vehicle-to-grid (grid flexibility)
ST	'System transformation' (FES)	VOC	Volatile organic compounds
STEPS	Stated targets emissions scenario	VRE	Variable renewable energy
SWL	Still water line	WC	Water consumption
T&I	Transport & installation (also, TI)	WEC	Wave energy converter
TA	Terrestrial acidification	WES	Wave Energy Scotland
		XLPE	Cross-linked polyethylene

# Symbols

Symbol	Description	Unit
$d_l$	Design life	[years]
$\varepsilon$	Carbon intensity	[gCO <sub>2</sub> /kWh]
E	Gross GHG emissions	[tCO <sub>2</sub> eq]
G	Installed capacity	[GW]
$H_s$	Significant wave height	[m]
$T_p$	Peak wave period	[s]
$\rho$	Density	[kg/m <sup>3</sup> ]
g	Gravitational constant	[N/kg]

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# Chapter 1:

# Introduction

---

Humans are changing the state of the Earth in multiple ways [1], [2], [3]. Increasing global average temperature, predominantly caused by fossil fuel use, is now an especially acute environmental impact, with significant and unequally distributed harms to people and biomes due to climate change [1], [4], [5]. Globally, national governments have agreed to pursue efforts to mitigate increasing global temperatures, and renewable energy generating technologies for replacing fossil fuels, are recognised as crucial to achieving this [6], [7].

However, renewable energy generation technologies also have measurable environmental impacts [8]. ‘Carbon payback’ (the time taken for a renewable generator to ‘pay back’ its embodied lifetime contribution to climate change, often simply carbon dioxide emissions, through obviation of fossil fuel or carbon intensive electricity) has been considered as a metric of merit for renewable power systems [9]. However, with expectations for significantly increased installed capacities of renewable energy and decreasing carbon intensity of power, it is not certain that carbon payback will be achieved within the lifetime of the generation technologies, and whether that is concerning.

This thesis will focus on three novel offshore renewable energy technologies: floating wind, wave power and tidal stream. These devices tend to be massive (floating wind) or subject to highly demanding load regimes (wave power and tidal stream), and are currently less well developed and optimised for performance, structural efficiency, installation and removal, operations and maintenance, disposal and energy capture relative to more established

technologies such as solar energy, onshore wind, and fixed-bottom offshore wind. Furthermore, these early-stage technologies tend to have higher carbon footprints than other renewable energies, although estimates can be highly variable, as described in Chapters 4 and 5 of this thesis.

To improve our understanding of the significance of these variations, this thesis investigates the methodology of life cycle assessment as applied to these technologies and – crucially – considers the associated changes in energy emissions and system performance when these novel technologies are integrated into an energy system, tying static ‘carbon footprinting’ to the concept of avoided emissions through the lifetime of the generation technology.

## 1.1. Research objectives and scope

Preliminary research prior to this PhD observed that in future scenarios, floating wind, wave energy, and tidal stream generation were likely to inject power to the British national grid in different locations, in varied amounts, and with (potentially complementary) phase differences between their temporal profiles of generation. When measured against a baseline case, increased installed capacity of novel renewable energy reduces fossil-fuelled power generation – hence reducing bulk operational emissions from the power system as a whole. The research objectives for this PhD developed from these findings, but with the goal of expanding the treatment to a sophisticated energy system model and in representative future scenarios, and to develop a method to integrating the avoided emissions with the conventional static, attributional life cycle assessment (LCA). Accordingly, this research has several objectives:

1. Provide an overview of the life cycle climate change (and other environmental impacts) of floating wind & marine energy systems.

2. Develop a methodology to account for the carbon reduction potential of different interacting technologies.
3. Identify the carbon reduction potential of floating wind and marine energy operating on the British grid.
4. Provide a tool to considering the holistic consequential impact on carbon emissions of floating wind & marine energy systems.

## 1.2. Thesis and Contribution to knowledge

Overall, this thesis will test the hypothesis that:

*In future energy scenarios, floating wind, wave, and tidal stream technologies do provide a net emissions reduction when their life cycle emissions are considered, despite their conventionally calculated higher life cycle impacts.*

While several attempts have been made to integrate the findings of LCA into a broader schema using energy systems or power system modelling (Chapter 6), this work quantifies the emissions reductions explicitly. Furthermore, the life cycle assessments for new technologies in new locations presented here are comprehensive and can be compared both between different sites within the same analysis and – due to the intentional consistency in practitioner assumptions – between two technologies (wave energy and floating wind).

The main contributions to knowledge from this work are:

1. LCA of a new type of wave energy converter (Blue Horizon) in four utility-scale arrays at multiple sites allowing detailed comparison of the impact of site-specific characteristics.
2. LCA of a very large reference wind turbine on floating platforms at four arrays in the ScotWind leasing round, coupled with inputs from a dedicated O&M model, allowing similarly detailed comparison.
3. The development of data for the novel power system modelling tool PyPSA-GB:
  - a. Presentation of representative sites, and time-series of capacity factors thereof, for wave energy, tidal stream and tidal lagoon generation.

- b. Low, mid and high scenarios of installed capacity for wave energy and tidal stream attributed across same sites.
  - c. Operational emissions according to the literature for different technologies in the PyPSA-GB model.
  - d. PyPSA-GB functionality to determine hourly emissions and average emissions of generation at network buses for a given period (python based Jupyter notebook).
4. Quantifying:
- a. The emissions reduction potential of nation-wide fleets of floating wind, wave energy and tidal stream using an arithmetic method (“AEP-CI”) with the National Grid Future Energy Scenarios, along with an expression for the necessary carbon footprint to achieve carbon payback in those scenarios.
  - b. The avoided emissions of nationwide fleets of wave energy and tidal stream using PyPSA-GB, compared to AEP-CI method and demonstrating the functionality of PyPSA-GB to model the carbon intensity of generation across the network for a single case study year (2045).

This work may be relevant to anyone with an interest in environmental and carbon footprinting of renewable energy technologies, such as: policy makers, project developers and technology developers. This work should help to improve confidence in our understanding of life cycle assessment of these technologies and in their efficacy at climate change mitigation, relative to their other associated harms, and other renewable energy technologies in general terms.

### 1.3. Thesis outline

This thesis consists of nine chapters. It is broadly structured into three parts (Figure 1.1). The first part (Chapters 2 to 5) concentrates on life cycle assessment of offshore renewable energy technologies. The second part (Chapters 6 to 7) identifies methods and develops the data necessary to perform the life cycle and emissions reduction potential of these technologies when integrated into a case study of the British energy system, which is described in the final part, Chapter 8.

- **Chapter 2, “Setting in context”:** Introduces important theory and contextual terms for life cycle assessment and the wider system of planet Earth. The overall narrative of the thesis and how it is underpinned by the research described in each chapter is also introduced.
- **Chapter 3, “Literature review of floating wind & marine energy life cycle impacts”:** Provides a detailed review of the life cycle assessment literature for floating wind and wave, related technologies of fixed-bottom offshore wind and tidal stream and discusses emerging techniques in the wider sustainability assessment literature. A review of energy system models which integrate assessments of environmental impacts is also performed to identify modelling requirements for later chapters.
- **Chapter 4, “Life cycle assessment of the Blue Horizon wave energy converter in four arrays around Scotland”:** details a full, static, attributional life cycle assessment of four arrays of a novel wave energy converter, Blue Horizon, in hypothetical commercial scale arrays around the North of Scotland, with the intent of expanding the literature reviewed in Chapter 3, providing a concrete example of an execution of the LCA

process and simultaneously setting a foundation for comparison and use in Chapter 5 and Chapter 8.

- **Chapter 5, “Life cycle assessment of four floating wind farms around Scotland”:** Building on the work from Chapter 4, details a full, static, attributional life cycle assessment of four arrays of the International Energy Agency’s (IEA) 15 MW Reference Wind Turbine, 240-15-IEA-RWT, located in arrays representing four extreme sites in the ScotWind leasing round. This is compared with results from Chapter 4 and subsequently used in Chapter 8.
- **Chapter 6, “Methodology and model selection for assessing operational emissions displacement impact of renewables”:** The power system model used in Chapter 8 of this thesis, PyPSA-GB, is introduced.
- **Chapter 7, “Power generation from wave, tidal stream, floating wind and tidal lagoons in future scenarios around GB”:** as identified in Chapter 6, necessary inputs for PyPSA-GB are developed in detail: interpretation of National Grid’s Future Energy Scenarios (FES); development of future scenarios of installed capacity *and* hourly power time series for wave, tidal stream, tidal lagoon and floating wind are described.
- **Chapter 8, “Emissions reduction potential of floating wind, wave and tidal stream in future energy scenarios around GB”:** the final chapter of analysis, describes the PyPSA-GB cases considered to satisfy the research objectives, their results, the scale of attributable CO<sub>2</sub> emissions reductions and how these interact with the results from Chapter 4 and 5 for wave and floating wind. The limitations and opportunities for future research are also explained.

- **Chapter 9, "Conclusions"**: Summarises the findings of this research, new insights garnered, limitations and future research opportunities.

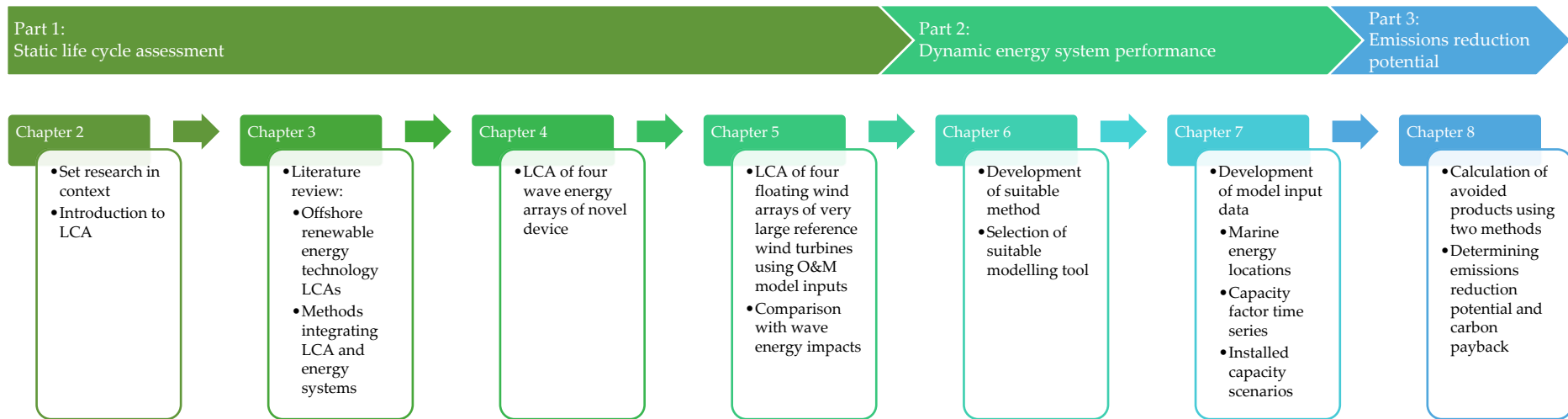


Figure 1.1. Overview of the flow through the chapters of this thesis and high level contents, excluding Chapter 1 (Introduction) and Chapter 9 (Conclusion).

## 1.4. Publications from this Thesis

### 1.4.1. Oral presentations

Struthers, I. A., and R. C. Thomson. 'Carbon Reduction Potential of Novel Offshore Renewable Energy Technologies'. Presented at *Energy Technology Partnership 9<sup>th</sup> Annual Conference (ETPAC19), Dundee, UK, 14<sup>th</sup> November, 2019.*

Struthers, I. A., G. P. Harrison, and R. C. Thomson. 'Life Cycle Assessment of Four Potential Blue Horizon Wave Energy Converter Arrays Around Scotland'. Presentation at *Energy Technology Partnership 9<sup>th</sup> Annual Conference (ETPAC20), online, 2<sup>nd</sup> November, 2020.*

Struthers, I. A., G. P. Harrison, and R. C. Thomson. 'Life cycle assessment of four floating wind farms in the ScotWind leasing round'. Presentation at *futureWind&Marine 2023 (FWM23), Glasgow, UK, 17<sup>th</sup> February, 2023.*

Struthers, I. A., G. P. Harrison, D. Coles, A. Angeloudis, and R. C. Thomson. 'Developing datasets of tidal and wave energy generation from renewable resource models'. Presented at *The 7<sup>th</sup> International Conference Energy & Meteorology (ICEM23), "Towards climate-resilient energy systems", Padua, Italy, 27<sup>th</sup> – 29<sup>th</sup> June, 2023* (Presented by R. C. Thomson).

### 1.4.2. Posters

Struthers, I. A., G. P. Harrison, and R. C. Thomson. 'Carbon Reduction Potential of Novel Offshore Renewable Energy Technologies'. Poster at *Wave Energy Scotland Annual Conference 2019 (WESAC19), Edinburgh, UK, 5<sup>th</sup> December, 2019.*

Struthers, I. A., G. P. Harrison, and R. C. Thomson. 'Getting to Net Zero: Lifetime and Avoided Emissions of Floating Wind & Marine Energy Systems'. Poster at *futureWind&Marine 2020 (FWM20), Glasgow, UK, 5<sup>th</sup> March, 2020*.

### 1.4.3. Conference papers

Struthers, I. A., G. P. Harrison, D. Coles, A. Angeloudis, and R. C. Thomson. 'Future Scenarios and Power Generation of Marine Energy Deployment around Great Britain'. Conference Paper and Presentation at *The 11th International Conference on Renewable Power Generation - Meeting Net Zero Carbon (RPG 2022), 2022:223–27, 2022*.  
<https://doi.org/10.1049/icp.2022.1831>. [10]

Struthers, I. A., A. Lyden, W. Sun, and R. C. Thomson. 'Achieving zero carbon communities by co-location of marine renewable energy'. Conference Paper and Presentation at *The 8th International ICARB Conference 2023, Edinburgh, UK, 25th - 26th September, 2023* [11].

### 1.4.4. Journal papers

Struthers, I.A.; Avanessova, N.; Gray, A.; Noonan, M.; Thomson, R.C.; Harrison, G.P. Life Cycle Assessment of Four Floating Wind Farms around Scotland Using a Site-Specific Operation and Maintenance Model with SOVs. *Energies* 2023, 16, 7739.  
<https://doi.org/10.3390/en16237739>. [12]

Lyden, A., Sun, W., Struthers, I.A., Franken, L., Hudson, S., Wang, Y. and Friedrich, D. PyPSA-GB: An open-source model of Great Britain's power system for simulating future energy scenarios. *Energy Strategy Reviews* 2024, 53, 101375. [13]

### 1.4.5. Associated Research

During the course of this PhD, the author completed a six-month position at the University of Edinburgh as a research assistant in life cycle assessment on the NEWEST-CCUS project. The project considered the life cycle impacts of waste-to-energy with carbon capture and storage with significant practical overlap with the LCA techniques used in the thesis, in particular consideration of avoided impacts, uncertainty assessment and sensitivity studies. The following conference papers were delivered from that project:

Herraiz, L., D. Su, H. Muslemani, I. Struthers, R. C. Thomson, H. Chalmers, and M. Lucquiaud. 'A Preliminary Assessment of Negative CO<sub>2</sub> Emissions in the European Waste Sector', 2nd International Conference on Negative CO<sub>2</sub> Emissions, June 14-17, 2022, Göteborg, Sweden ,32, 2022 [14].

Struthers, I. A., L. Herraiz, H. Muslemani, D. Su, R. C. Thomson, and M. Lucquiaud. 'Assessing the Negative Carbon Emissions Potential from the Waste-to-Energy Sector in Europe'. At GHG16, Lyon, France, 2022 [15].

# Chapter 2:

## Setting in context

---

This chapter summarises contemporary scientific understanding of the human induced climate and biodiversity crises, as background to this research. Potential dimensions for mitigating environmental pressures are presented at a high level, followed by a detailed description of the principles of life cycle assessment. The novel offshore renewable energy technologies considered in this thesis (floating wind, wave energy and tidal stream) are introduced.

## 2.1. Introduction

Human activities interact with Earth system processes across multiple domains, phases of matter and spatial and temporal scales. The flow of this chapter moves from a planetary to product-system scale, with vignettes from Earth science, economics, industrial ecology, biology, politics, history and (even) engineering.

- **Section 2.2 – Terminology and conceptual frameworks for planetary sustainability:** introduces basic terminology, planetary domains and relevant geological timeframes to set the scope of the thesis in a planetary context.
- **Section 2.3 – Anthropogenic environmental pressures:** describes macro-scale anthropogenic environmental pressures: socioeconomic metabolism, technological and material intensity (and relating it to life cycle assessment, LCA, itself described in Section 2.4), climate change, nature loss, material consumption, and the contemporary energy system. Potential dimensions commensurate with the global challenge of mitigating environmental pressures are set out.
- **Section 2.4 – Life cycle assessment:** introduces the process of life cycle assessment and core terminology with reference to preceding sections. Emerging life cycle assessment techniques which could be explored in further work are laid out.
- **Section 2.5 – Technologies under consideration in this thesis:** introduces the wave energy, floating wind and tidal stream technologies with reference to their principle of operation, technological deployment status and potential resources.
- **Section 2.6 – Conclusion:** distils the narrative of the chapter into relevant considerations for the following chapters.

## 2.2. Terminology and conceptual frameworks

This section introduces terms and concepts that are used to contextualise the environmental impact findings of later chapters by providing a simplified but holistic schema of the Earth system, with reference to historical trends.

### 2.2.1. Earth System components

The planet, or 'Earth System', can be defined as the integrated biophysical and socioeconomic processes and cycles between *planetary component spheres* [16]. These can be combined with the concepts of the *ecosphere* and *technosphere* [17] for high-level but comprehensive framework for discussing global environmental impacts (Figure 2.1).

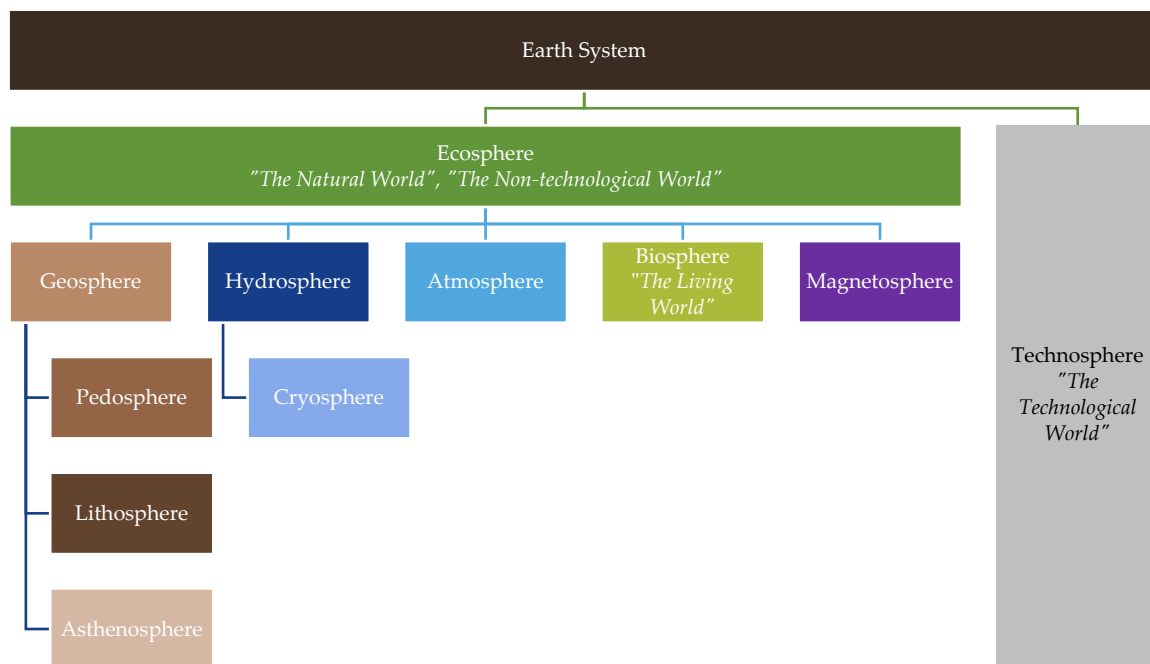


Figure 2.1. Schematic of relevant planetary component spheres, combining industrial ecology and physical geography terms.

#### 2.2.1.1. Ecosphere

The ecosphere is all *living* (biotic) and *non-living* (abiotic) planetary component spheres, also described as the Natural or "*Non-technological*" world, comprising:

- **Geosphere:** primarily the *pedosphere* (soil) and *lithosphere* (rock fragments, bedrock and the crust). Importantly, the pedosphere *interfaces* with many other spheres, interacting with human activities, pollutants and biogeochemical cycles (Section 2.2.2).
- **Hydrosphere:** the total amount of water on Earth, including the *cryosphere* (ice and permafrost), freshwater, saltwater, rivers, seas, clouds and groundwater [18].
- **Atmosphere:** the layer of gas and vapour around the Earth. The atmosphere interacts with solar radiation, and partly shields the surface, cultivating benign conditions for life. Gases, vapours and particulates are relevant pollutants to the atmosphere.
- **Biosphere:** All living organisms on Earth, sometimes called “the Living World”. The biosphere is deeply connected to many planetary component spheres and is a major influence on the overall planetary state [16].
- **Magnetosphere:** the magnetic field around the Earth which deflects solar and cosmic charged particles away from Earth’s surface (stated for completeness).

#### 2.2.1.2. Technosphere

In contrast to the non-technological, natural ecosphere, the technosphere is the “*the interlinked set of communication, transportation, bureaucratic and other systems that act to metabolise fossil fuels and other energy resources*” [19]. Philosophically, the technosphere could be considered a *subset* of the biosphere, a memetic product no more remarkable than a beaver’s dam [20]. However, the technosphere is a foundational concept to the procedure of life cycle assessment, which *defines* the environmental impacts of a product or system’s life cycle by inventorying and characterising energy and materials which flow across the *boundary* between the ecosphere and technosphere, termed *elementary flows*.

The technosphere is closely related to the *anthroposphere*, a suggested planetary component sphere comprising “*anything and everything that is connected with or created by human civilization*” [21]. Also related is the human *socioeconomic metabolism*, a key concept in industrial ecology which describes the material and energy throughput of human societies, or the consumption of the ecosphere *into* the technosphere, its conversion and final excretion (Section 2.3.1).

### 2.2.2. Biogeochemical cycles

The *state* of the Earth system thus defined, is highly dynamic and regulated by spatially and temporally complex flows of energy and material between different planetary component spheres. These flows are termed *biogeochemical cycles*. Four major biogeochemical cycles are introduced below, given their relevance to the impacts considered in this thesis:

1. **Carbon cycle:** the basis of all life forms on Earth, the element carbon cycles around the planetary system on two main timescales:
  - **Slow (geological):** over millions of years, carbon flows between the geosphere (lithosphere, pedosphere), biosphere, hydrosphere and atmosphere. Fossil fuels are *formed* in the slow carbon cycle [17].
  - **Fast (biological):** in the span of years, carbon flows between the atmosphere, biosphere and hydrosphere. Human activities have dramatically altered the *fast* carbon cycle by the transportation of carbon-rich fossil fuels from the lithosphere and combustion in the technosphere [3]. The combustion products are emitted to the atmosphere, leading to the global warming via increased retention of solar energy (Section 2.3.4). Simultaneously, human-caused

deforestation and land use change have weakened and destabilised natural biosphere carbon sinks, further accelerating global warming [2].

2. **Nitrogen:** influences the rate of ecosystem processes such as primary production and decomposition. The nitrogen cycle involves the atmosphere, pedosphere, biosphere and hydrosphere and many biotic and abiotic processes. Human activities have dramatically altered the nitrogen cycle via by-products of fossil fuel combustion and artificial nitrogen fertilisers, leading to global warming, toxicity, acidification, human health and eutrophication impacts [17].
3. **Phosphorus:** is also an important nutrient for ecosystem processes. Human activities have significantly affected the phosphorus cycle via extraction of phosphorus from the lithosphere and subsequent artificial phosphorus fertilisation and transportation [2]. The phosphorus cycle traverses the lithosphere, hydrosphere, and biosphere.
4. **Water:** essential to life on Earth, the water cycle spans the atmosphere, pedosphere, lithosphere and biosphere as liquid, ice or vapour. Through consumption and physical intervention, human activities have driven detectable changes in the global water cycle since the mid 20<sup>th</sup> century [22].

### 2.2.3. Historical context of the Earth's state

With these terms of reference in place, the contemporary trends and state of the Earth can now be assessed within historical context.

The Earth is around 4.5 billion years old, and has experienced profound differences in global average temperature in its history (Figure 2.2). Anatomically modern humans evolved in Africa around 300,000 years ago in the late Pleistocene, and by around 12,000 years ago – the

beginning of the Holocene, a notably long and warm epoch – had colonised most of the globe not covered in ice [23]. The remarkably stable Holocene is therefore the only condition of the Earth system that *agricultural and industrial human civilizations* have known [2], [24]. However, human activities are driving conditions beyond those of the Holocene [18] (Section 2.2.4), potentially heralding the beginning of the *Anthropocene*.

The proposed Anthropocene epoch could be demarcated by significant and lasting impacts of human activities on Earth's geology and ecosystems, such as anthropogenic climate change, and geologically marked by non-naturally occurring entities (such as plastics, radiological materials and 'forever chemicals') [2]. From this perspective, the *anthroposphere* (Section 2.2.1.2) has become *a new geological force*, capable of stalling an Ice Age [2], [25]. Within the biosphere, the global rate of species extinction is tens to hundreds of times higher than the average in the last 10 million years [1] and the multi-faceted ecological crisis caused by human activities is "quite probably" the start of the Earth's Sixth Mass Extinction [26].

Within the Anthropocene– indeed within some peoples' lifetimes – lies *The Great Acceleration*. Since the mid 20<sup>th</sup> century, multiple socio-economic and environmental indicators have rocketed [27]. In this extremely short timeframe, human industrialisation, urbanisation, and technological advancement have fuelled unprecedented resource extraction, greenhouse gas (GHG) emissions, and land-use changes, rampantly increasing the extent of technosphere and its impact on the planet, detailed in Section 2.3.

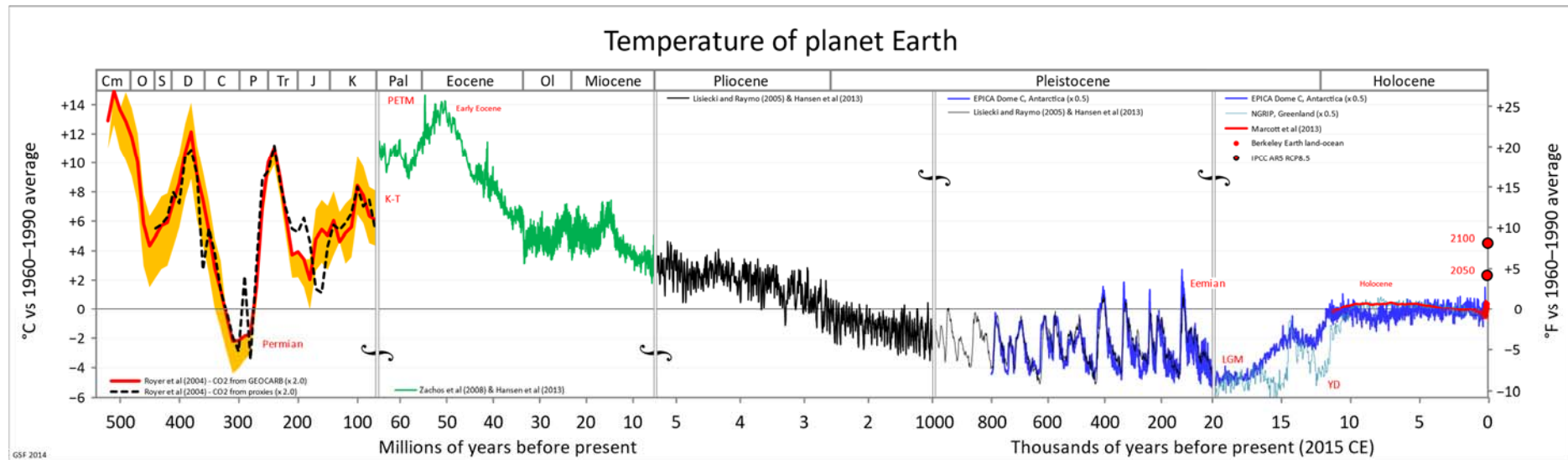


Figure 2.2. Global average temperature estimates over the last 540 million years [28]. Holocene temperatures are indicated on right-most part of the chart, with possible warming from IPCC representative concentration pathway (RCP) 8.5 – where emissions continue to rise throughout the century – indicated via red circles with black outlines.

## Earth system trends

## Socio-economic trends

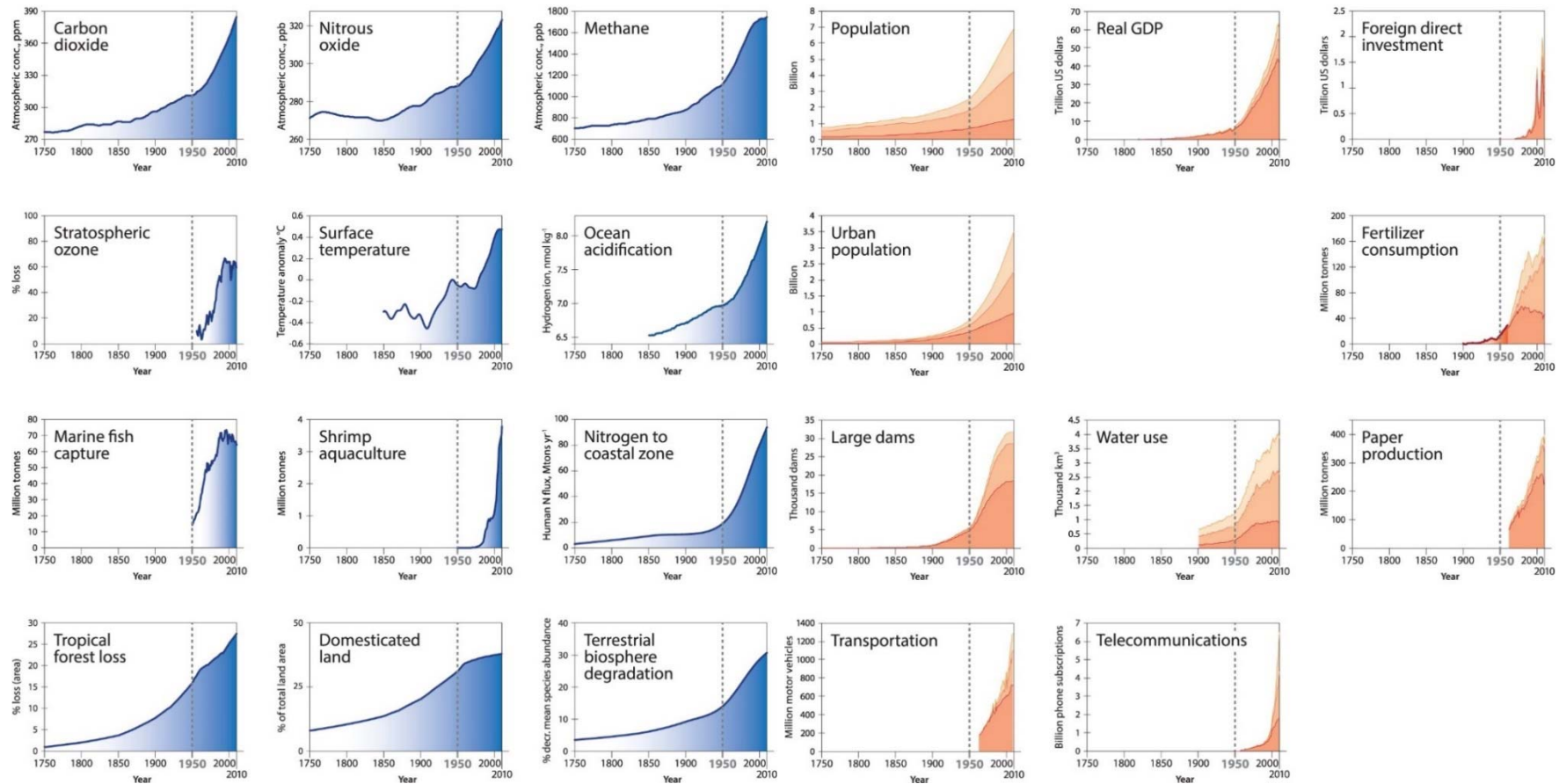



Figure 2.3. Trends from 1750 to 2010 in indicators for the structure and functioning of the Earth System (left) and globally aggregated indicators for socio-economic development with three splits for: the OECD (Organisation for Economic Co-operation and Development) countries, the so-called BRICS (Brazil, Russia, India, China and South Africa) countries, and the rest of the world (right) [27].

### 2.2.4. Planetary boundaries

This section introduces the *planetary boundaries framework* [29], continuing the arc of the chapter from planetary-scale to life cycle ‘product system’ scale. The planetary boundaries (PBs) framework was first published in 2009 [16] (last updated in 2023 [2]), and provides a simple definition of the limits to maintaining a Holocene-like state (empirically, compatible with civilisations founded on human agriculture). The nine PBs span the planetary component spheres of the Earth system (atmosphere, hydrosphere, geosphere, biosphere and cryosphere<sup>1</sup>). Each boundary is described by ‘control variables’ assuming that maintaining the control variables within Holocene historical precedents defines a ‘safe operating space for humanity’. The latest revision [2] finds that the state of six of the nine boundaries are currently unprecedented in the Holocene epoch (or, “transgressed”, Figure 2.4). The nine boundaries are [2]:

- **Climate change:** considers the average atmospheric CO<sub>2</sub> concentration and radiative forcing, which are both transgressed relative to Holocene precedents [2].
- **Novel entities:** considers synthetic substances from the anthroposphere, such as microplastics [30], nuclear materials and genetically modified organisms. Clearly without a Holocene precedent the precautionary PB is exceeded.
- **Stratospheric Ozone Depletion:** occurs when manufactured gases (primarily halocarbons, chlorofluorocarbons and hydrochlorofluorocarbons) react with ozone in the high atmosphere (stratosphere), decreasing naturally occurring ozone

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<sup>1</sup> This has been expanded to incorporate justice (the Earth System Boundaries, ESBs) [1].

concentrations which absorb most solar ultraviolet radiation (UV). In the PB framework, a safe range is set at less than 5% deviation from the preindustrial era. The control variable is currently assessed (using 2020 data) as within the safe range.

- **Atmospheric aerosol loading:** assesses both anthropogenic (particulate from industry, land-use and fossil fuel combustion) and natural (wildfire soot, dust) aerosol sources. This PB is assessed (with high uncertainty) as within a safe range globally, but likely transgressed in monsoon regions where high aerosol loading leads to lower rainfall.
- **Ocean acidification:** occurs in the fast carbon cycle, where increased concentrations of atmospheric CO<sub>2</sub> are absorbed by the surface seawater, producing carbonic acid which dissociates into a bicarbonate ion and free Hydrogen (H<sup>+</sup>). The PB is set at 80% of the preindustrial average carbonate ion concentration, which is marginally exceeded at 81%, but will continue to worsen with anthropogenic CO<sub>2</sub> emissions.
- **Biogeochemical flows:** considers the changes in nutrient flows and element ratios of Nitrogen and Phosphorus introduced in Section 2.2.2. The boundary for Nitrogen is exceeded globally, while Phosphorus is exceeded globally and regionally.
- **Freshwater change:** includes *blue water* (surface and groundwater) regulating rivers and aquatic ecosystems, and *green water* (root-zone soil moisture, or plant-available water) accounting for terrestrial ecosystems, climate, and biogeochemical processes. The framework assumes that conditions from a preindustrial period (1661 to 1860) are representative of a Holocene-like state, and suggests the blue and green water boundaries were crossed a century ago, in 1905 and 1929, respectively [2]. Relevantly, electricity from fossil gas and nuclear power stations require large amounts of water.

- **Land-system change:** considers tropical, temperate, and boreal forests globally. The boundary is set at retaining 85% of boreal forests, 50% of temperate forests, and 85% of tropical forests relative to their coverage in the Holocene, which is assessed as exceeded and worsening. In a relevant example of the interconnectedness of the PBs, planetary component spheres, and biogeochemical cycles, severe land-use change has led to the Amazon tropical forest flipping from a carbon sink to a carbon source [31].
- **Biosphere integrity:** is assessed in two ways: 'functional' and 'genetic'. Functional biosphere integrity is assessed using net primary production (NPP)<sup>2</sup>, and the human appropriation thereof (HANPP). NPP is relevant to energy from biomass and BECCS (biomass energy with carbon capture and storage), which increase HANPP [12]. The threshold for the zone of increasing risk is set as a HANPP equal to 20% of average NPP during the Holocene period (transgressed, currently 30%). Secondly, the genetic PB is the maximum extinction rate that can still support the ecological complexity of the biosphere. This is transgressed significantly and increasingly, by a factor of around 100.

The PB framework provides a quantifiable, multi-dimensional approach for assessing the global impact of the human technosphere on the natural ecosphere, and the breadth and depth of changes required to maintain it within Holocene precedents.

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<sup>2</sup> NPP is a measure of the energy available for use by local ecosystems and is crucial for both ecosystems and human societies as it supports their maintenance, growth, differentiation, networking, and overall functioning in the Earth system [5].

The next section will describe the drivers of anthropogenic pressures on the environment in more detail.

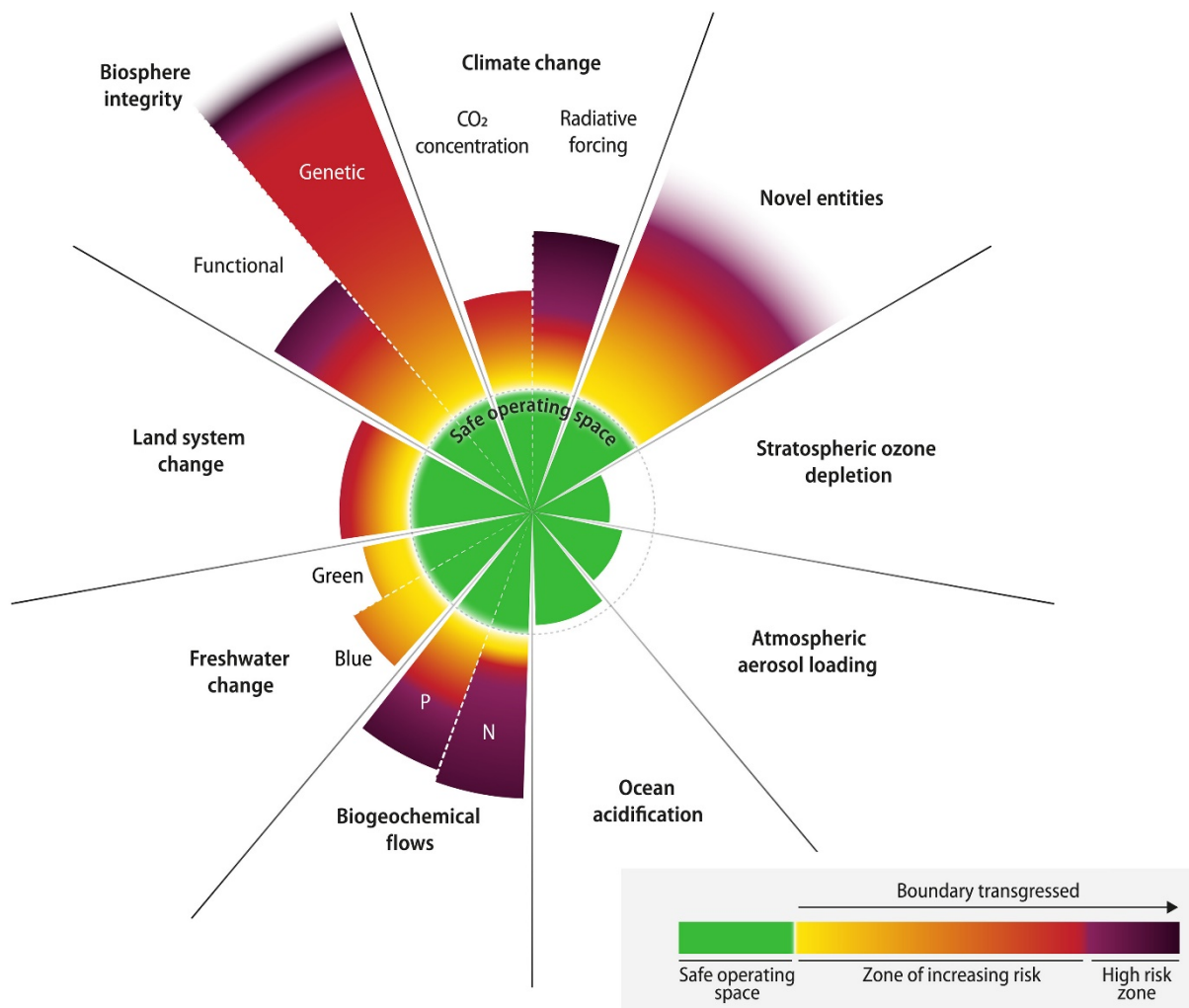


Figure 2.4. Current state of the control variables for all nine planetary boundaries [2].

## 2.3. Anthropogenic environmental pressures

The previous section has introduced important Earth system components and asserted that human activities are driving the Earth system away from a Holocene state, the only state known for certain to support agricultural and industrialised civilisations [27]. This section will explore the specific human activities that are driving the observed changes, towards a comprehensive understanding of the relevance of LCA in Section 2.4.

### 2.3.1. Socioeconomic metabolism

There is an intuitive image of aggregate human activities as some uber-animus; ingesting, metabolising and emitting material according to its practices. More than a metaphor, *socioeconomic metabolism* is a useful paradigm that describes the flow of materials and energy from the ecosphere to the anthroposphere, and back again (Figure 2.5). These flows provide energy, fuel, and maintain the physical structures of society, like buildings and infrastructure, or other artefacts in the technosphere and wider anthroposphere. However, The Great Acceleration and the Planetary Boundaries suggest that radical innovation in socioeconomic metabolisms is required to rebalance the Earth system within a Holocene-like state.

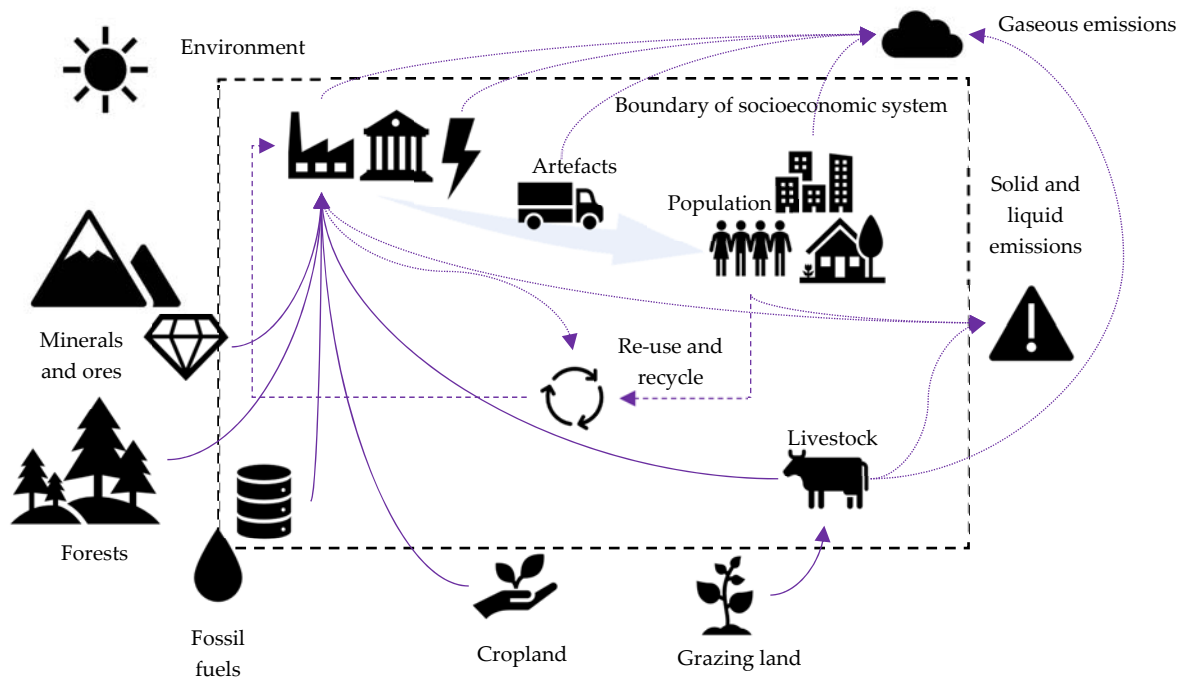


Figure 2.5. Major biophysical stocks and flows considered in socioeconomic metabolism assessments, adapted from [32].

### 2.3.2. Technological environmental intensity

Human technology influences the capabilities, demands and wastefulness of socioeconomic metabolisms. A simple method for ideating the environmental impacts of any human artefact or technology is the 'IPAT equation', which describes that the environmental impact (I) of a system is equal to the product of the human population (P), the per unit (or per capita) material affluence (A), and the system's environmental intensity (T), (Equation 1):

$$I = f(P, A, T)$$

Equation 1: The IPAT equation: a generalised impact (I) is defined as a product of population (P), material affluence (A) and technological environmental intensity (T).

Within the Great Acceleration, the global population (P) has almost tripled (Figure 2.3). This was the strongest driver of material extraction to feed the global socioeconomic metabolism in the years 1970 to 2000, but between 2000 to 2016, *affluence* (A) became the dominant driver

[33], [34]. Thus, population and gross domestic product<sup>3</sup> (GDP) are typically seen as the two most important drivers of the socioeconomic metabolism's natural resource use [33]. Global increases in affluence have increased consumerism and consumption, increasing resource use and waste emissions far more rapidly than innovations which reduce environmental intensity (T) [35]. Since the 1970s, and within the Great Acceleration, global population doubled and global GDP quadrupled, creating a surge in demand for materials, land and water [33]. Total material extraction of the global socioeconomic metabolism increased by eight times in the 105 years between 1900 to 2005 [36], with a concomitant rise of excreted wastes and emissions [37].

The most affluent citizens of the world are thus responsible for most environmental impacts through their consumptive practices, and displace these impacts to the less affluent [35]. This is deeply challenging for today's rich demographics as the dominant contemporary economic imperative of neoliberal globalisation *incentivises* non-mindful indulgence and overconsumption, hindering meaningful change [35]. Reducing total affluence – while noting some people are not affluent enough to have their human needs met – implies a reduction in the affluence of those most well off. Population reduction is considered only slightly more problematic than such consumptive redistribution.

This uncomfortable situation leaves a potentially impossible burden on improving technological environmental intensity, at the pace and scale necessary to arrest the trajectories

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<sup>3</sup> The monetary value of goods and services within a territory over some period. GDP is a metric of affluence, socioeconomic metabolism and shorthand for human quality of life.

of the Great Acceleration. The quantification of technological environmental intensity is one such application of the process of life cycle assessment.

### 2.3.3. Material, land and water consumption

Although the link between aggregate material use and environmental deterioration is complex, bulk material use clearly indicates environmental pressures from human activities [36] and are a credible proxy for environmental damage [38]. Specifically, material, land and water appropriation from the ecosphere is a major driver of global environmental change (particularly climate change, biodiversity loss, and air pollution [33]) and directly or indirectly related to many of the dimensions in the Great Acceleration (Section 2.2.3) [39]. While the planetary boundaries framework currently excludes direct material use, a sustainable boundary for global material use has been estimated at around 25 to 50 billion tonnes per year – which would have been exceeded in 1970 or 1997 respectively [40]. Contemporary models of global and regional business as usual (BAU) show that human material use will grow beyond what can be considered a sustainable level [34], with subsequent implications for the ecosphere, and biosphere especially unless radically different forms of production – or socioeconomic metabolism – can be developed, echoing the adamant logic of the IPAT equation.

### 2.3.4. Climate change

Anthropogenic climate change is caused by increasing the solar energy retained by the Earth system, due to the increased concentrations of atmospheric GHGs emitted by human activities. Short-wave solar radiation is naturally absorbed by both the Earth's atmosphere and surface, and reflected from the Earth's surface, with the warmed surface of the Earth re-radiating the energy as longer-wave infrared radiation. Atmospheric GHGs capture the

infrared radiation and re-emit it omnidirectionally, some of which reaches the surface, warming it further and causing global average temperature to rise.

GHGs enter the atmosphere primarily from fossil fuel combustion and processing (via fugitive methane) and land-use change (Figure 2.6)<sup>4</sup>. The largest contribution to climate change is from carbon dioxide (with a radiant forcing contribution of 2.16 W/m<sup>2</sup>), methane (0.54 W/m<sup>2</sup>) and nitrogen dioxide (0.21 W/m<sup>2</sup>), although other halogenated gases also contribute (0.41 W/m<sup>2</sup>) [22]. Concentrations of carbon dioxide (CO<sub>2</sub>), methane (CH<sub>4</sub>), and nitrous oxide (N<sub>2</sub>O) have increased to levels unprecedented in at least 800,000 years, and there is high confidence that current CO<sub>2</sub> concentrations have not been experienced for at least 2 million years [22]. Following a reduction in annual emissions during the global economic slowdown of the Covid-19 pandemic, annual emissions have returned to growth (Figure 2.6).

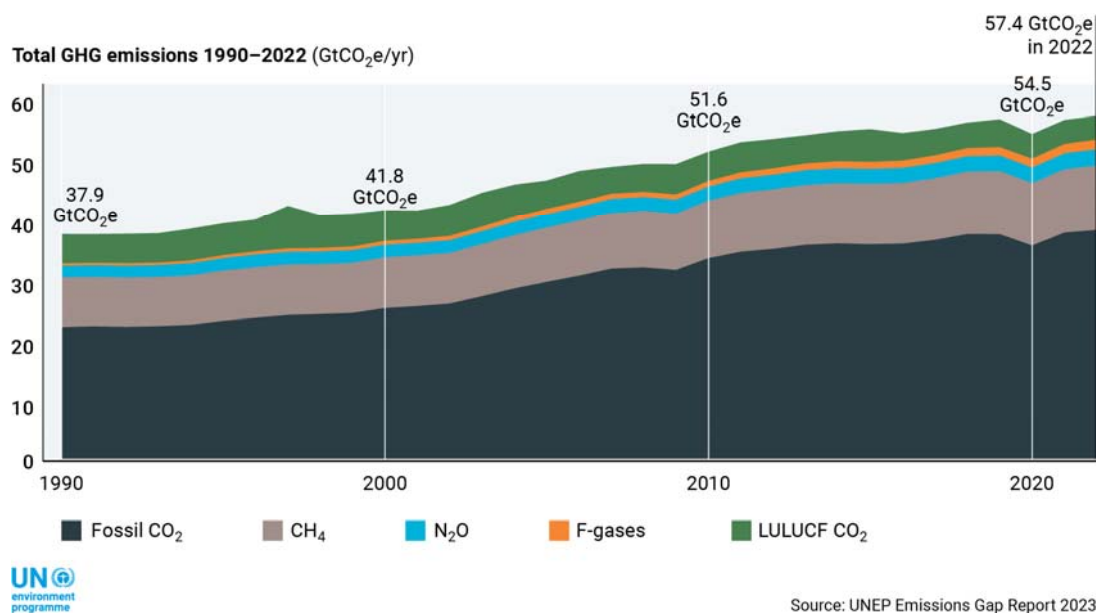


Figure 2.6. Total net anthropogenic GHG emissions, 1990–2022 (GWP100) [7].

<sup>4</sup> LULUCF, land use, land use change and forestry

From a physical science perspective, limiting anthropogenic global warming to a specific temperature requires atmospheric GHG concentrations to remain steady. This implies limiting additional cumulative GHG emissions, reaching “net zero” GHG emissions (a balance between GHG sources and sinks). This would *stop* additional warming, but not reduce the previously accrued increase above pre-industrial levels. Carbon dioxide removal (CDR) – which could be natural (afforestation, moving Carbon from the atmosphere to the biosphere) or artificial (such as CCS, moving Carbon from the atmosphere to the lithosphere) will be necessary to achieve net negative CO<sub>2</sub> emissions [3]<sup>5</sup>.

Figure 2.7 demonstrates the sectoral breakdown for global GHG emissions (in 2016), with the majority attributable to the energy sector (73.2%). 5.8% of this is simply from leaks from energy production (fugitive methane). After the energy sector, nearly one fifth of emissions were attributed to land-use, forestry and agriculture, illustrating the important systemic link between the planetary boundaries of climate change and biosphere integrity [2].

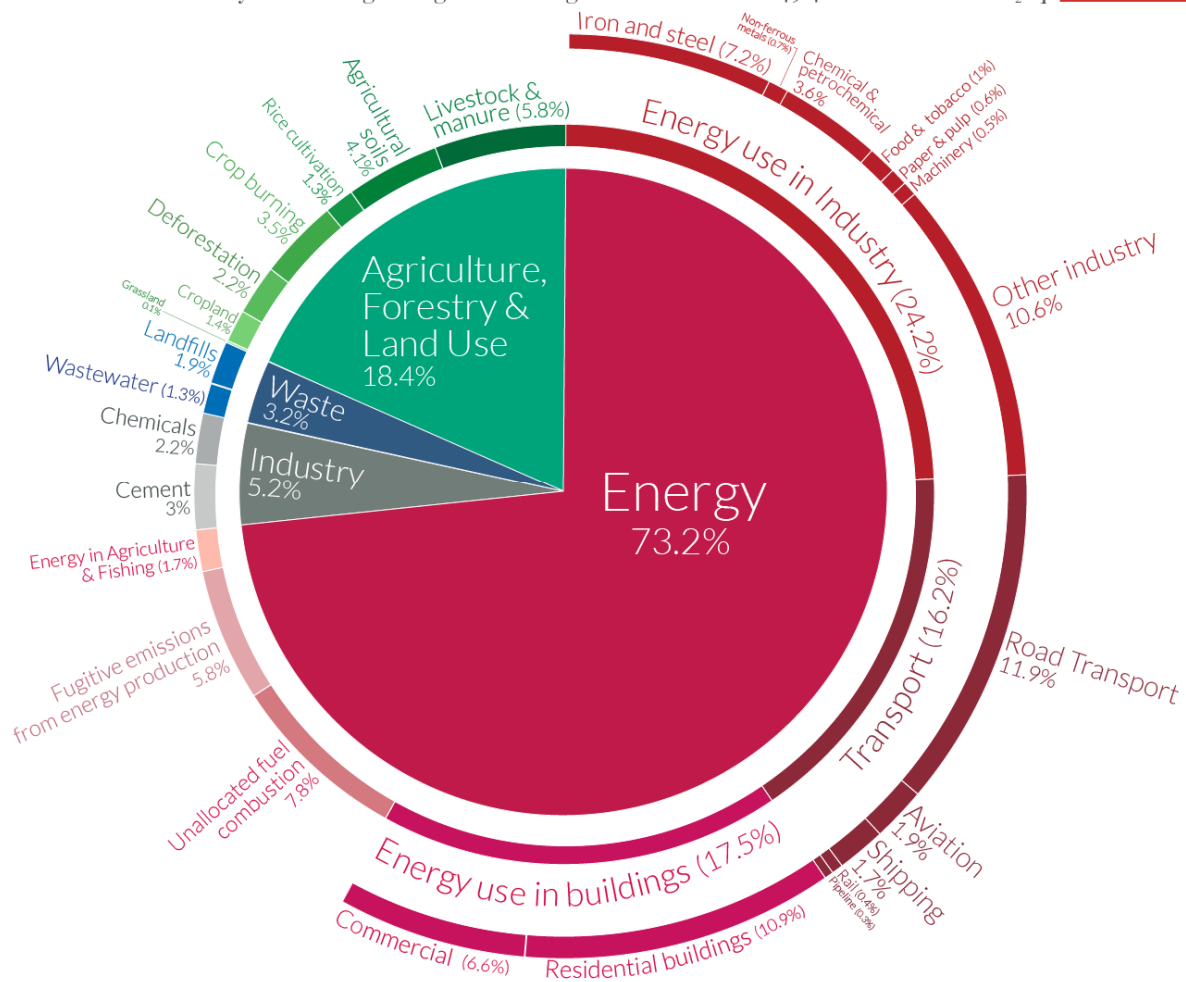
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<sup>5</sup> Some organisations promote futures that are compatible with no increase in atmospheric CO<sub>2</sub> without CCS: “absolute zero” [26].

# Global greenhouse gas emissions by sector

Our World  
in Data

This is shown for the year 2016 – global greenhouse gas emissions were 49.4 billion tonnes CO<sub>2</sub>eq.



OurWorldinData.org – Research and data to make progress against the world's largest problems.

Source: Climate Watch, the World Resources Institute (2020).

Licensed under CC-BY by the author Hannah Ritchie (2020).

Figure 2.7. Breakdown of CO<sub>2</sub>eq (expected to be GWP100) emissions by sector [41].

Accordingly, the characteristics all “Paris Compliant” pathways<sup>6</sup> involve rapid, deep and, in most cases, *immediate* GHG emissions reductions in all sectors [3]. Further warming from CO<sub>2</sub>

<sup>6</sup> The Paris Agreement is an international treaty on climate change, the goal of which is to hold the increase in the global average temperature to well below 2°C above pre-industrial levels and pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels by the

in these pathways is halted by achieving global net zero CO<sub>2</sub> emissions in the early 2050s and around the early 2070s, respectively, from which arises the concept of “Net Zero by 2050”, and the idea of remaining ‘carbon budgets’. The global GHG emissions reductions required to achieve emission levels in 2030 that are consistent with a 1.5°C pathway, are now 8.7% per year on average from 2024 [7]. For comparison, this is almost twice as large as the reduction in total global GHG emissions due to the COVID-19 pandemic in the years 2019 to 2020, which was 4.7% [7].

### 2.3.5. Nature loss

Previous sections have outlined that the biosphere (‘The Living World’, or ‘Nature’) is a functionally influential component of the dynamic planetary state which contributes to maintaining a safe operating space for humanity. In a more immediate sense, the biosphere provides and regulates many of the ecosphere’s planetary ‘life support systems’ (air and water quality regulation, nutrition, medicine, regulation of extreme events) in ways which cannot be fully replicated by engineered systems [1]. However, coinciding with The Great Acceleration, human activities have substantially changed the biosphere in many parts of the world. As of 2019, most metrics for ecosystem health and biodiversity<sup>7</sup> are rapidly declining [1]. The human activities which directly drive nature loss are: land and sea use change (conversion of habitats to farming or urban areas) [42]; direct exploitation (harvesting, logging, hunting and fishing); climate change (via extreme weather, changes to droughts and

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year 2100. It was adopted in 2015. Pathways represent possible emissions and temperature trajectories depending on societal choices.

<sup>7</sup> Biodiversity: the diversity within species, between species and of ecosystems [1].

floods, increasing temperatures, ocean acidity and sea-levels); pollution (release of nuclear, toxic, eutrophying, or “forever chemicals”<sup>8</sup>, and macro- and micro-plastic pollution) [43]; and species introductions or spreading (causing decline in endemic species and ecosystem functions) [1].

The five direct drivers of nature loss themselves stem from *indirect* drivers, circling back to societal values and behaviours such in the IPAT equation but also governance and economic systems. The encroachment of the technosphere into the ecosphere now seems clearly related to growing consumption which correlates to GDP. Indeed, sustainable ‘glide paths’<sup>9</sup> for nature have been assessed as requiring an intentional shift away from “*the current, limited paradigm*” of increasing GDP [1].

### 2.3.6. Human economic activity

Each of the dimensions described in the preceding subsections is inescapably underpinned to some degree by the tenets of human economies<sup>10</sup>. However, increasing evidence shows that increasing GDP (canonical shorthand for economic growth) directly contributes to greater resource consumption and higher GHG emissions [44]. In an extractivist ‘take-make-waste’

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<sup>8</sup> Persistent organic pollutants, typically perfluoroalkyl and polyfluoroalkyl substances (PFAS), used in a variety of common consumer products including waterproof materials, food packaging, non-stick culinary coatings.

<sup>9</sup> Author’s terminological choice. “Pathways” is an alternative.

<sup>10</sup> Economy: derived from the Ancient Greek “house” and “to manage”; very apt for the crew of Spaceship Earth.

*linear* economy, extracted materials are metabolised into products that become waste, expediently maximising GDP without necessarily meeting human needs. Indeed, empirical evidence shows that human needs satisfaction declines rapidly with increasing levels of consumption beyond a certain point [35].

Through the Great Acceleration, global GDP has skyrocketed, fuelling a similar increase in demand for biotic and abiotic materials [33]. While *relative* decoupling<sup>11</sup> of GDP and material extraction has been observed, GHG emissions and material consumption have not decreased in absolute terms [33], and empirical studies demonstrate that ‘green growth’ is, at best, highly unlikely [45]. A recent review of *absolute* decoupling rates in high-income countries found they fell far short of meeting the climate and equity commitments of the Paris Agreement<sup>12</sup>, where decoupling rates would on average need to increase by a factor of 10 by 2025 [46]. If humankind seeks now to arrest the environmentally damaging trends of the Great Acceleration, it seems likely that radical economic transformations are required (Section 2.3.8.4) [39].

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<sup>11</sup> Reducing the rate of resource use per unit of economic output, typically GDP or energy. Absolute decoupling (rather than relative decoupling) is required to compensate for the effect of increasing GDP and achieve absolute reductions in resource use or environmental harm.

<sup>12</sup> A legally binding 2015 international treaty to limit global surface temperature to well below 2°C above pre-industrial limits, and to pursue efforts towards 1.5°C.

### 2.3.7. Global energy system

Within the socioeconomic metabolism, interwoven with the global human economy, is the global energy system, providing the superhuman power for the socioeconomic metabolism to consume the ecosphere at a geological scale and rate far beyond human physiology. The majority of humankind's energy is provided by fossil fuels: coal (37%), oil (29%) and gas (20%) respectively: 86% of all CO<sub>2</sub> emissions in 2022 [7], with large inequalities in energy use according to affluence – as with material consumption [47]. The provision of primary energy and industrial processes is the largest contribution to anthropogenic climate change [48] and contributes to environmental pollution, human health impacts and biodiversity loss [33]. Despite encouraging progress in the roll-out of renewable energy, the incumbent fossil fuel energy system is tenacious, and installing low carbon generation (as set out in all Paris-compliant modelled pathways) does not guarantee displacement in practice [3].

Common features of the energy system in all 1.5°C pathways are: demand reduction; low carbon intensity of electricity; electrification of industry, buildings and transport (“end-use sectors”); and reduction in the carbon intensity of any residual fossil fuels (primarily by CCS). Said pathways include wind, solar, biomass and nuclear fission as the main power generation technologies, and significant deployment of CDR (which is always required in 1.5°C pathways). Relatedly, GDP growth is a baseline assumption in nearly all scenarios, but scenarios which assume *decreasing GDP* require *lower rates of decoupling and deployment of renewable energy and CDR* [35].

Regarding the use of fossil fuels, any expansion of the fossil fuel industry is now incompatible with the temperature limits of the Paris Agreement [49]. Existing fossil-fuel infrastructure's committed emissions were shown to jeopardise the remaining carbon budget for the Paris

Agreements 1.5°C climate target, echoing the IEA findings that little or no new fossil fuel ‘assets’ can be commissioned and – moreover – that existing infrastructure may need to be retired early (or be retrofitted with CCS) [50]. Further, nearly 60% of oil and gas, and 90% of coal reserves must remain unextracted to keep within the 1.5 °C budget [51], supporting calls to “keep it in the ground”.

However, despite the November 2021 Glasgow Climate Pact calling on countries to “*phase-out ... inefficient fossil fuel subsidies*”, 2022 global fossil fuel subsidies soared to the largest annual value ever recorded, over \$1 trillion USD, [52]. This was corroborated by the International Monetary Fund, IMF, finding that explicit subsidies of \$1.3 trillion in 2022, were almost treble that in 2020 [53]. Like the tobacco, lead and chemical industries before them, the fossil fuel industry has funded biased analyses to support of their business interests [54], which synergises neatly with the deeply institutionalised memetic hegemony of the GDP growth imperative. This is clearly good value for fossil fuel companies which spend hundreds of millions of dollars yearly lobbying politicians across the globe [55]. This ‘*regulatory capture*<sup>13</sup>’ emulates global historical patterns of colonialism, and chimes with the anti-abolitionist stances of the British magnates during the abolition of the Atlantic Slave Trade [56]. In the same way, there are those who call for reparations from oil, gas, and coal producers, and compensation for the appropriation of the atmosphere as part of the global commons [57],

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<sup>13</sup> A form of political or regulatory corruption when an organ or individual in a position of public authority is co-opted to serve the financial, commercial or political interests of a minority group such as a profession, industry or ideology.

[58]. Despite this, the fossil fuel industry maintains – wittingly or not – that they “don’t want to be the bad guys” [59].

*Box 2.1: Compensation for ‘The Interest’*

On 28<sup>th</sup> August 1833, the Slavery Abolition Act received Royal Assent in the United Kingdom. Ultimately, British slave owners were paid £20 million compensation for the ‘loss’ of their ‘assets’, around which £10 million remained in Great Britain [60]. These payments went directly to the magnates responsible for the unjust exploitation who had likely accumulated significant wealth by it. This sum was around 40% of government annual expenditure. For comparison, in FYE 2022, UK tax spending was £1040.9 billion [61], 40% of which would be a lump-sum compensation of £416 billion. By contrast, a single supermajor, BP’s *annual* revenue in 2022 was \$248.9 billion [62]. Arguably, the same dynamics are playing out in real-time with the *brinkmanship* of the (apparently penniless) supermajors beseeching global governments for financial assistance to fund emissions reduction, with their caps outstretched gently, gripped in mailed fists.

Taking stock, it appears that the biggest obstacles to reducing anthropogenic environmental pressures are not technical but ideological, economic and socio-political. Indeed, the “*dogmatic political-economic hegemony and influential vested interests*” along with “*narrow techno-economic mindsets and ideologies of control*” have been assessed as a major factor in the failure to bend the emissions curve [63], not to mention the other exceeded planetary boundaries.

Clearly, a rapid decline in fossil fuels is required, but any future energy provisioning systems must also provide equitable access to energy services while remaining within the planetary

boundaries of the Holocene [64], [65]. The relative environmental performance of different energy system technologies are discussed in Section 2.5.7.

### 2.3.8. Potential mitigation dimensions

In response to the previous section, some potentially unorthodox mitigation opportunities arise.

#### 2.3.8.1. Reducing inequality

In 2019, the most affluent 1%<sup>14</sup> were responsible for 16% of global CO<sub>2</sub> emissions; the same amount as the poorest 66% (some 5 billion people) [4]. So far, climate policies have often disproportionately impacted low and middle-income groups, while leaving the consumption habits of the wealthiest – simultaneously most culpable, powerful and politic [4] – unchanged [5]. This is doubly unjust because the poorest half of the globe live overwhelmingly in the countries most vulnerable to climate change [66]. Moreover, the exchange between developing and undeveloped nations is extremely unequal with significant material, energy and labour extracted from the Global South (often former colonies) to the Global North (often former colonial powers) [67]. However, radically reducing inequality by increasing global consumption would clearly exacerbate the issues described above. The challenge then follows; what kind of life is compatible with the limits of planetary boundaries? What artefacts and practices are necessary to live well and how can these be provided in the most ecologically efficient and humanly pleasing manner?

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<sup>14</sup> For context, on average, an individual from the top 10% of the global income distribution earns approximately €87,200, \$122,100 or £75,000 per year (at time of writing) [55].

### 2.3.8.2. Satisfying human needs

Human needs theory argues that there are a finite number of basic needs that are universal, satiable and non-substitutable [65], [68]. These can be considered as a *social foundation*<sup>15</sup> (beneath an *ecological ceiling*) in much the same way as the thresholds of the planetary boundaries framework [70].

Unfortunately, for data from 2011, no country met the basic needs for its citizens at a globally sustainable level of resource use [65] (by a factor of two to six times), and – in a subsequent study – the trajectories for the years range 1992 to 2015 were either “*dangerously unsustainable for the biosphere or strikingly insufficient for human well-being – or both*” [71]. In another empirical study, factors such as public service quality, income equality, democracy, and electricity access were associated with high human need satisfaction and low energy requirements, while extractivism and GDP growth beyond moderate levels of affluence were associated with greater energy requirements and lower need satisfaction [72]. This suggests human needs *can* be satisfied at lower, ecologically sustainable levels, defying the prevailing political and

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<sup>15</sup> For example *need satisfiers* (nutrition, sanitation, income, access to energy, education, social support, equality, democratic quality and employment) and *well-being measures* (self-reported life satisfaction and healthy life expectancy) [65]. For example, increases in the life expectancy have been empirically found to be only weakly coupled to increases in primary energy use and carbon emissions, and strongly coupled to critical need satisfiers (such as food and household electricity). This suggests that rapid emissions reductions do not imply a reduction in life expectancy (via the aphorism “going back to the caves”), so long as critical need satisfiers are prioritised [69].

economic dogma. Nevertheless, “massive gaps” exist between average per capita footprints and targets for lifestyles compatible with 1.5 °C warming by the year 2100 [73].

Moreover, empirical data demonstrates that high human wellbeing (as measured by the SPI, social progress index) is closely correlated to a country’s *cumulative* material inputs, with an SPI of over 80 having a cumulative material input of 1100t (over the period 1950 to 2010) per head in 2010 [74]. This challenges the notion that high human well-being is possible without significant material (and hence ecological) footprints. Regardless, societal provisioning systems in both affluent and less-affluent jurisdictions are likely to require fundamental restructuring to enable basic human needs to be met a far lower levels of resource use to be compatible with planetary limits [65], [72].

#### 2.3.8.3. Energy and material demand reduction

Intuitively, highly materially and energy efficient ‘provisioning systems’ (such as transportation, infrastructure, government) are likely to be necessary for humanity to achieve social thresholds within planetary boundaries [65]. Unfortunately, the transition away from fossil fuels to a low carbon energy system is very likely to require increased material use for the fleets wind, solar and energy storage [75], with the future supply of the critical minerals sector far from assured [76]. The rapid deployment of renewable energy is “set to supercharge demand for critical minerals” [77], with total mineral demand rising up to four times by 2040 in IEA’s “Sustainable Development Scenario”, likely leading to concomitant increases in direct emissions and other environmental impacts from mining activities. Recycling will be necessary to ensure the long-term supply of critical metals and may “peak-shave” the environmental impacts compared to the use of virgin materials, but overall the energy sector is expected to emerge as a major force in future mineral markets [77]. However, many

electrification techniques are likely to ultimately reduce primary energy demand, potentially paving the way to the satisfaction of human needs at lower energy use [72].

Overall, the global socioeconomic metabolism is expected to grow, both in extraction and waste generation, through the transition to net zero pathways, placing increasing importance on recycling and circular principles, and the other factors in the IPAT equation.

#### 2.3.8.4. Alternative economic approaches

Completing the circle on mitigation dimensions is the relationship between increasing GDP (“economic growth”), material consumption, human wellbeing and anthropogenic environmental harms; where global GDP, material footprint and CO<sub>2</sub> emissions from fossil fuel combustion and industrial processes rise in lockstep [35].

The 2010 world economy was far from even *relative* decoupling and actually on a path *rematerialisation* [34]. While things improved in the period 2013 and 2019, an empirical study found that the relative decoupling rates achieved in high-income countries were all grossly inadequate for meeting the climate and equity commitments of the Paris Agreement [46]. At a global scale, there is no evidence of absolute decoupling between GDP and material use [39]. Therefore, to achieve Paris-compliant emission reductions, high-income countries would require implementation of “*post-growth demand-reduction strategies*”, redirecting their economies towards satisfying human wellbeing alone while simultaneously accelerating technological rollout and efficiency gains [46]; a challenging political manifesto.

Finally, implicit in the prose above has been the concept of planned, managed decline of certain environmentally harmful sectors, such as the fossil fuel industry. At an economic scale, this is termed ‘degrowth’, for economic activities that do not contribute to human well-

being. Recently, degrowth and Modern Monetary Theory<sup>16</sup> (MMT) have been used to develop monetary and fiscal policies suitable for a stable degrowth transition: in the whimsically titled “how to pay for saving the world” [78].

## 2.4. Life cycle assessment

With these environmental pressures outlined, we turn now to the technique utilised in the first part of this thesis: life cycle assessment (LCA), which can be used to quantify the environmental impacts (or benefits) of a human construct within the technosphere, and elucidate these harms in terms of the anthropogenic environmental pressures on the Earth system described in preceding sections.

LCA is process of an evaluation of the potential environmental impacts of a product, service or system throughout its life cycle; from raw material extraction, through production, use, end-of-life treatment, recycling and final disposal [79], [80]. This is similar to the paradigm of socioeconomic metabolism but on an individual product or system level, rather than a societal scale. The basic process of performing an LCA is to:

- Collate a material and process inventory of the product life cycle;
- Populate the inventory using data from an appropriate database;
- Aggregate the flows of material and energy across the boundary between the ecosphere and the technosphere (manually or automatically);

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<sup>16</sup> A macroeconomic theory which asserts that sovereign currency states can create money to pay for activities that the state has the physical infrastructure to actually produce.

- Characterise the flows according to environmental harm of the selected impacts;
- Report the environmental impacts using pre-defined LCA algorithms (methods).

To model a life cycle, the practitioner gathers details of materials and processes at every life cycle stage (termed the *foreground* data). This is linked to a Life Cycle Inventory (LCI) database of standard processes, products, and waste flows (the *background* data) which has comprehensive details of the associated resource consumption and pollutant emissions. All flows of matter between the natural ecosphere (or non-technological world) and the artificial technosphere (or technological world) are designated as *elementary flows*. Each flow must have a characterisation factor attributed to it, relative to some environmental impact category, and summing the product of the flows and characterisation factors will, by definition, yield the environmental impacts according to pre-defined Life Cycle Impact Assessment (LCIA) characterisation methods. This whole procedure can be performed efficiently using specialised LCA software, as in this thesis.

LCA is a relatively young discipline with its beginnings around 1970 in the United States [81]. Subsequent efforts emerged across Europe, undergoing a surge in interest in the late 1980s, codification in the early 1990s, and international standardisation of the scientific method in the late 1990s [17]. Today, the methodology and applications continue to innovate and mature, with increasing numbers of publications annually in the last two decades [82]. Accordingly, LCA is now widely recognised and increasingly applied in diverse fields including industry, academia, and policy development [83].

### 2.4.1. Methodology

The basic process of an LCA is to collate a material and process inventory of the product life cycle; represent the inventory using data selected from an appropriate environmental impact database; aggregate the flows of material and energy to and from the environment manually or automatically; and report the environmental impacts using pre-defined life cycle impact assessment (LCIA) algorithms (“Methods”). Specifically, however, the basic structure of a LCA according to internationally standardised LCA principles and framework (ISO 14040), and general requirements and guidelines (ISO 14044) [84], [85], comprises four phases [17]:

- 1. Goal and scope definition:** sets out the context and purpose of the study in detail. The scope determines the specific technical terms, limits, and characteristics of the analysis to be executed.
- 2. Inventory analysis:** constructs a system model (or ‘life cycle model’) according to the requirements of the goal and scope definition [86]. This is the central phase of an LCA, the core activity of which is the development and collation of data on the physical (material and energy) flows which make up the life cycle model of the system in question [17]. An assessment of uncertainty can be performed in this phase [17] (for example, via Weidema [87], as in Chapter 4 and 5). The output of this phase is the system Life Cycle Inventory (LCI) which is often housed within specialised LCA software using dedicated LCI databases, which contain the “building blocks” of the life cycle model that the LCA practitioner can use to “build” their model.
- 3. Impact assessment:** transforms the LCI data of physical flows and inventories of the product system into environmental impacts via impact models and pathways (LCIA “Methods”), developed by environmental science [17]. The selected impact categories

are specified in the study scope, which classifies and assigns a characterisation factor to each physical flow, enabling aggregation of all contributing harms from diverse chemical species into a single score for a given impact category.

- 4. Interpretation:** In the final phase, the practitioner interprets the results of the assessment in accordance with the goal and scope. An iterative approach is usually required to judge the robustness of the conclusions, and may include uncertainty or sensitivity assessments to fully evaluate the findings [86].

Developing a life cycle model of an artefact requires a sound understanding of the life cycle processes, as well as a significant effort to obtain representative inventory data. This is particularly challenging for future technologies, where engineering judgement must be applied throughout the assessment, to determine the modelled level of detail and appropriateness of available data. This challenge can be mitigated by the appropriate use of uncertainty assessment and sensitivity studies as set out in the international standards [84], [85].

#### 2.4.2. LCA software

SimaPro was selected as the LCA software package for this thesis on the basis of in-house expertise and support at the University of Edinburgh. Other suitable packages are Gabi, openLCA and Activity Browser.

#### 2.4.3. Life cycle inventory modelling approach

For the LCA studies in this thesis, an *attributorial* LCI modelling approach was chosen (as opposed to a *consequential* approach) on the basis of the research intent, which was to determine the emissions reduction potential attributable to a particular technology.

Nevertheless, the subsequent analysis skirts the domain of consequential LCI modelling approach by explicitly quantifying (effectively) the marginal generation in Chapter 8. A fuller discussion of the merits and disbenefits of each LCI modelling approach can be found in [17].

#### 2.4.4. Life Cycle Impact Assessment methods

The assessment of life cycle impact, known as Life Cycle Impact Assessment (LCIA), converts the life cycle inventory's information on the elementary flows (emissions and resource extractions) into a set of finite environmental impact scores.

The LCA practitioner must select the LCIA method by considering multiple factors, such as: the study goal and scope and the suitability of the method's breadth of impact categories; geographical and temporal coverage; and external factors such as related studies or client specifications. After the practitioner selects the LCIA method, the LCI results are *classified* according to their known potential effects, and *characterised* (by characterisation *factors* derived from characterisation *models* of potential harms) to determine the contribution of the flow to said impact – often automatically by dedicated software. A detailed treatment is available in [17].

##### 2.4.4.1. ReCiPe (2016)

ReCiPe (2016) was selected for this thesis because it is relatively up-to-date, wide ranging, with precedent in related studies, being temporally and spatially appropriate and originally developed in cooperation with the software developers, Pré Consultants [88]. Using a multi-indicator method permits insight to any 'burden shifting' arising when comparing to systems. The Hierarchist cultural perspective was selected, as this is based on scientific consensus of plausible impact mechanisms on a balanced time horizon of 100 years [17], [88]. Global normalisation was used for simplicity, although region-specific characterisation factors are

available [89]. Midpoint indicators were chosen to permit a more detailed assessment of potential impacts compared to aggregated Endpoint indicators [17]. The cause-and-effect chain and units of each impact category in ReCiPe (2016) are described in the following sections for reference in later chapters.

*Box 2.2: Indicators of economic health*

The world is undergoing a recession – not of GDP – but of social progress [90]. If the Social Progress Index (SPI) were to be used as an indicator of economic health instead of GDP, the global ranking of top performing territories would be upended. This is an interesting parallel between the approach of using a single indicator (GDP) and multi-indicator approach in LCA. In a sense, GDP is like a single impact category (for example, like climate change), while what should really be considered is multiple impacts, for example social progress, job creation or other social values. Perhaps then, an LCA method could be developed for assessing the socioeconomic metabolism or economies of territories, instead of an over-simplified crutch and faith in a single metric. Arguably, this could be considered the overlapping domain of ecological economics<sup>17</sup> and Social-LCA (S-LCA)<sup>18</sup>.

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<sup>17</sup> The study of human economies within natural ecosystems and biophysical limits, which rejects that human-made capital can replace natural processes.

<sup>18</sup> Social life cycle assessment quantifies the social or human well-being impacts of a product's life cycle [17].

#### 2.4.4.2. Linking ReCiPe (2016) and Planetary Boundaries LCIA Methods

Clearly, there must also exist some link between the planetary boundaries and the impact of a product system. This linkage is at the leading edge of contemporary knowledge, but a brief description is included below, to enable contextualisation of the results in following chapters. Note that planetary boundary LCIA methods have been developed [91], which references ReCiPe (2008) amongst other methods. A linkage to ReCiPe (2016) was illustrated in a recent paper [92]: the links here are presented in a qualitative fashion only for reference (Figure 2.8).

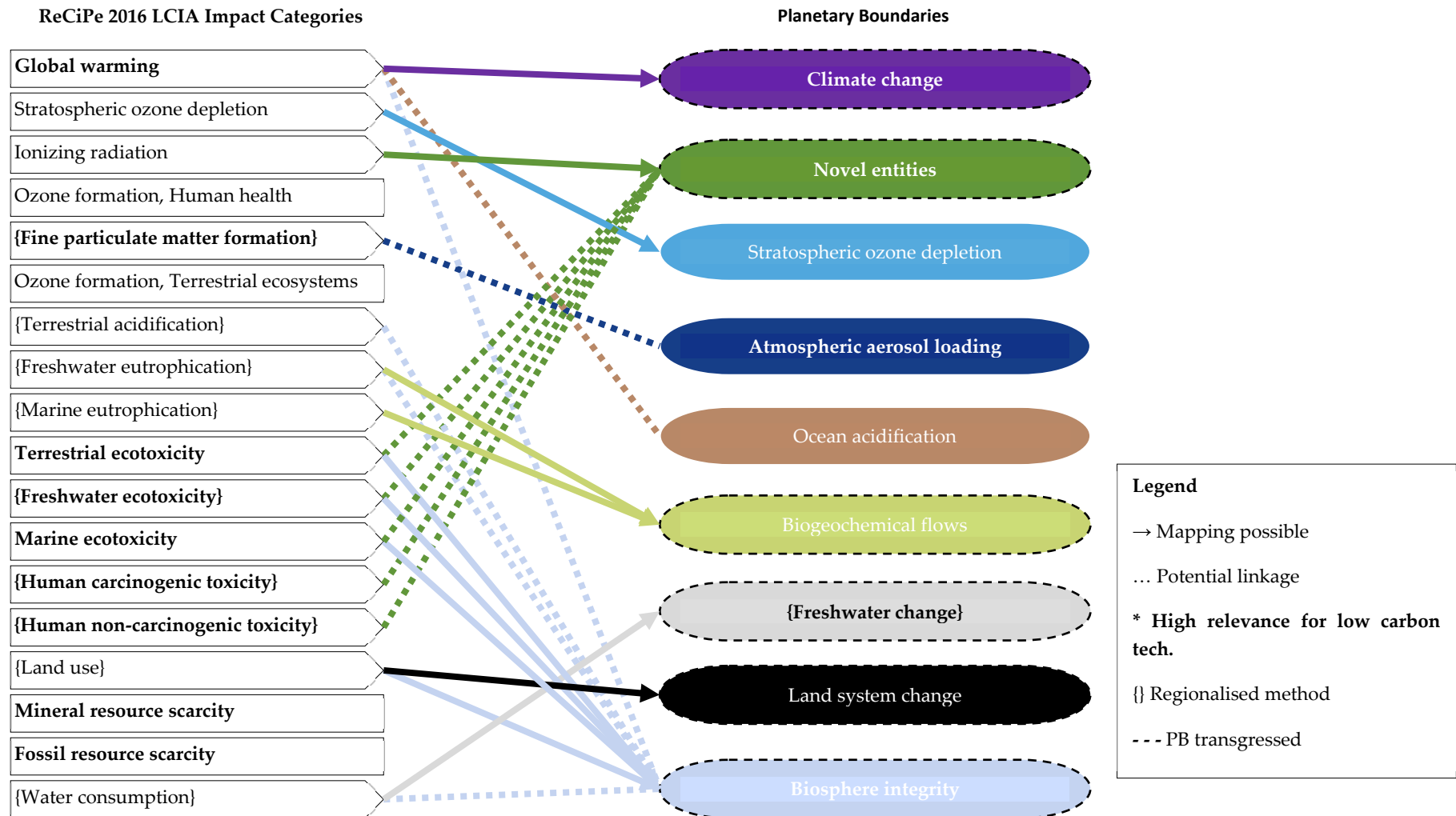


Figure 2.8. Connection between the ReCiPe (2016) LCIA (Life Cycle Impact Assessment) method impact categories [89] and latest Planetary boundaries [2]. The arrow presents the reporting of a possible mapping onto the PB Framework. The dashed line represents the potential linkage between LCIA category and PB. Adapted from [92].

### 2.4.4.3. Details of ReCiPe2016

A description of each of the impact categories of ReCiPe2016 is included below as reference for subsequent chapters.

#### 2.4.4.3.1. *Global warming*

The impact category of global warming considers the climate change impacts due to GHG emissions (Figure 2.9). The midpoint characterisation factor for global warming is Global Warming Potential (GWP), which expresses the potential radiative forcing from GHGs with widely different atmospheric persistence times (and degradation pathways), by considering the 1000 year warming potential of each GHG and comparing it to the warming potential of CO<sub>2</sub> (a very long-lived GHG) [88]. Typically, a time perspective of 100 or 20 years (denoted GWP<sub>100</sub> or GWP<sub>20</sub>) is used. GWP<sub>100</sub> tends to ‘de-emphasise’ the warming potential of short-lived GHGs (like methane at 28 kgCO<sub>2</sub>eq/kgCH<sub>4</sub>, compared to 84 kgCO<sub>2</sub>eq/kgCH<sub>4</sub> using GWP<sub>20</sub>). This impact category is clearly linked to the climate change planetary boundary, which is transgressed, making this a central impact category.

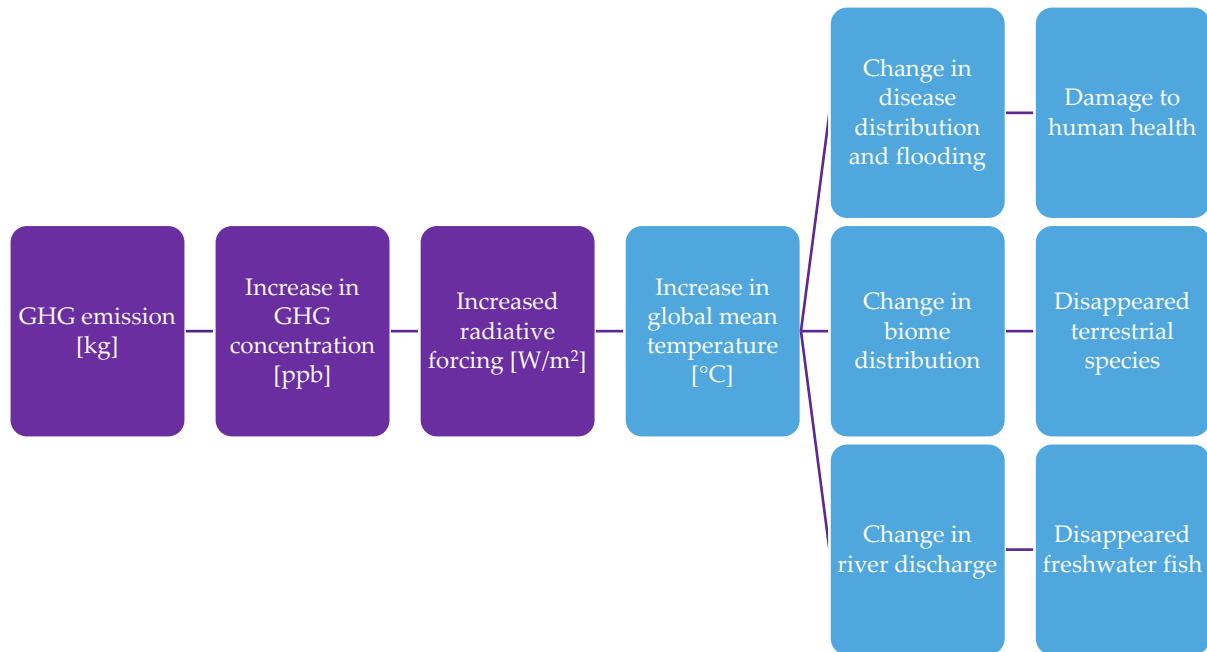


Figure 2.9. Cause-and-effect chain from greenhouse gas emissions to human health damage and relative loss of species in terrestrial and freshwater ecosystems. Midpoint relevant impacts shown in purple, Endpoint in blue. Adapted from [88].

#### 2.4.4.3.2. Stratospheric Ozone Depletion

Ozone Depleting Substances (ODS) typically originate in the troposphere<sup>19</sup> and rise to the stratosphere, reducing atmospheric ozone and allowing more solar UVB radiation to reach the Earth's surface. This can lead to human health impacts (Figure 2.10). Like GWP, ozone depleting potential (ODP) is expressed in kgCFC-11 equivalents; the amount of ozone a substance can deplete relative to CFC-11 for a specific time horizon. This is linked to the planetary boundary of stratospheric ozone depletion, which is not currently transgressed.

<sup>19</sup> The lowest and densest layer of Earth's atmosphere where most weather occurs, in which human inhabit.

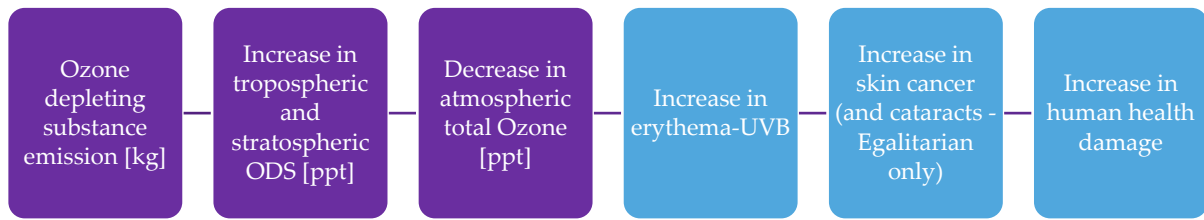


Figure 2.10. Cause-and-effect chain for emissions of ODS resulting in damage to human health. Midpoint relevant impacts shown in purple, Endpoint in blue [88].

#### 2.4.4.3.3. Ionising Radiation

Anthropogenic releases of radiological materials occur from mining, processing and disposal of nuclear material, as well as coal combustion and phosphate rock extraction. The midpoint characterisation factor is the ionising radiation potential (IRP), again relative to a reference substance: Cobalt-60 (Co-60eq) emitted to air. This is a fairly complex impact category with challenging uncertainties (detailed in [88], Figure 2.11). This impact category is now related to the planetary boundary of novel entities, which is exceeded, making this a central impact category [2].

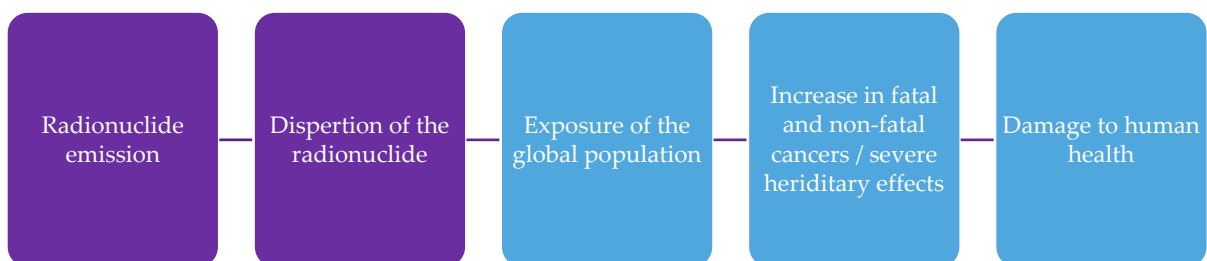


Figure 2.11. Cause-and-effect chain from an airborne or waterborne emission of a radionuclide to damage to human health [88].

#### 2.4.4.3.4. Ozone Formation (Human Health, Terrestrial Ecosystems)

Ozone forms through solar photochemical reactions involving NO<sub>x</sub> and Non-Methane Volatile Organic Compounds (NMVOCs), creating smog. Tropospheric ozone poses health risks to humans by inflaming airways and damaging lungs. It also negatively affects plant

life (especially photosynthetic organs). Most anthropogenic VOCs derive from fossil fuelled road traffic [17]. ReCiPe (2016) distinguishes between the Ozone formation impact on Human Health and Terrestrial Ecosystems as two separate impact categories, both with units ( $\text{NO}_x\text{eq/kg}$ ), Figure 2.12. Disability Adjusted Life Years (DALY) are used to express the life years affected by respiratory health damage due to ozone exposure, and species.yr is used to express the damage to terrestrial species due to ozone exposure. This impact category is not currently linked to a planetary boundary.

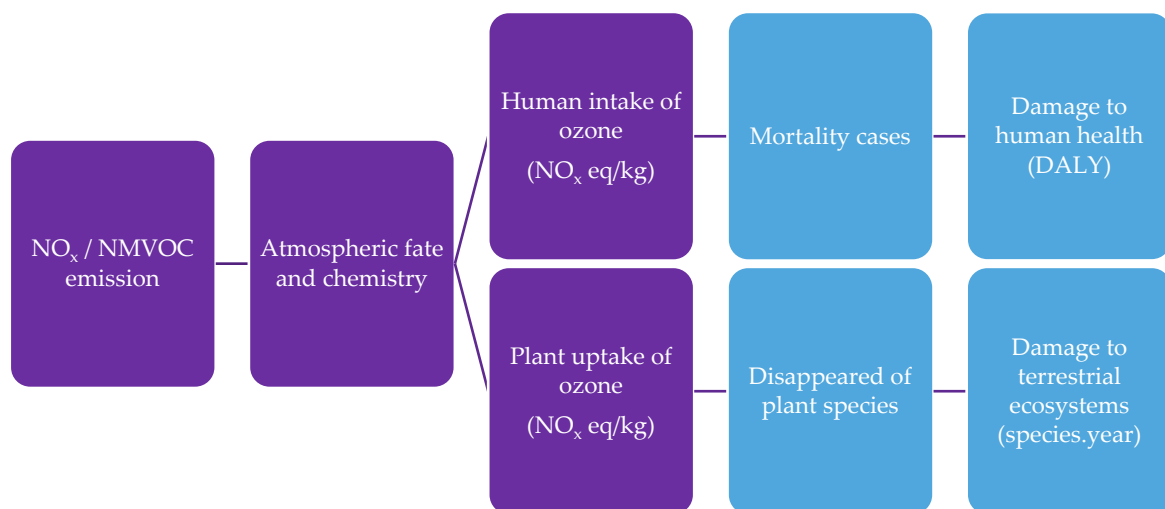


Figure 2.12. Cause-and-effect chain from greenhouse gas emissions to human health damage and relative loss of species in terrestrial and freshwater ecosystems [88].

#### 2.4.4.3.5. Fine particulate matter formation

Air pollution, which produces primary and secondary aerosols in the atmosphere, can significantly harm human health, causing respiratory symptoms (Figure 2.13). The main sources are fossil fuelled road traffic (although tyre dust also contributes, regardless of the vehicle's propulsive medium), domestic solid fuel consumption and fossil fuelled power stations, with over 5 million deaths per year directly attributable to air fossil fuel induced air pollution [93]. Disability Adjusted Life Years (DALY) are used to express the life years

affected by respiratory health damage due to exposure to PM<sub>2.5</sub>. This impact category is potentially linked to the planetary boundary of atmospheric aerosol loading which is not currently transgressed.

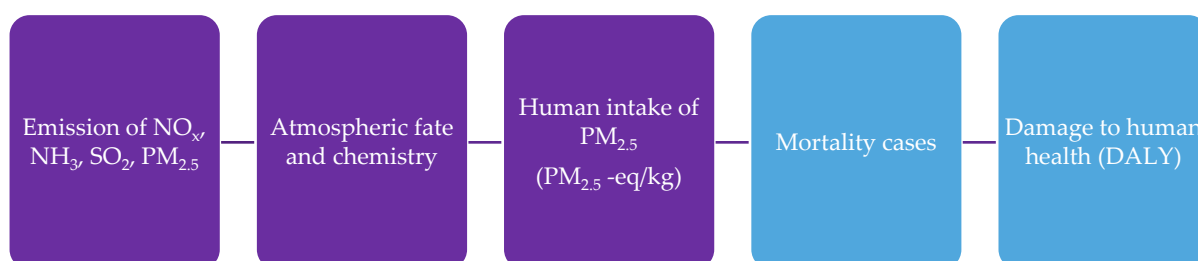


Figure 2.13. Cause-and-effect chain from fine dust forming emissions to damage to human health [88].

#### 2.4.4.3.6. Terrestrial acidification

Sulphates, nitrates, and phosphates from the atmosphere can acidify the soil. NO<sub>x</sub>, SO<sub>2</sub>, are major contributors and commonly arise from most combustion processes (fossil fuel power plants and vehicles, waste incineration), Figure 2.14. Ammonia is also commonly released by animal agriculture processes (particularly animal urine and faeces). Acidification potential is measured in 'sulphur dioxide equivalents' (kg SO<sub>2</sub>e/kg). This is potentially linked to the PB of biosphere integrity, which is transgressed, making this a central impact category.

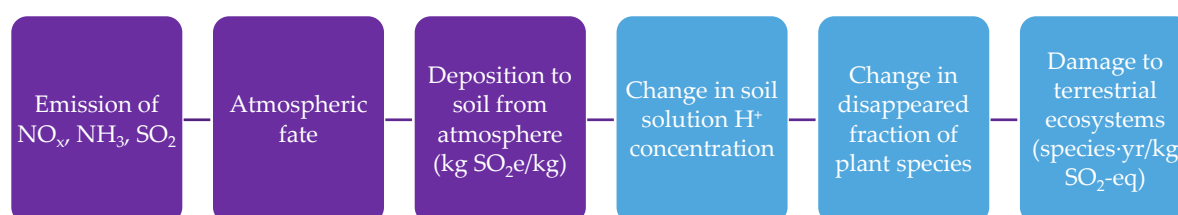


Figure 2.14. Cause-and-effect chain from acidifying emissions to relative species loss in terrestrial ecosystems [88].

#### 2.4.4.3.7. Eutrophication (Freshwater and Marine)

Freshwater eutrophication occurs when nutrients, particularly phosphorus and nitrogen, are discharged into soil or freshwater bodies (Figure 2.15). This increases microorganism growth,

depleting oxygen levels and suffocating other species. Marine eutrophication occurs in a similar manner for saltwater bodies (Figure 2.17). In ReCiPe (2016) the impacts on freshwater are assessed based on the transfer of phosphorus from soil to freshwater bodies. These impact categories are linked to the planetary boundary of biogeochemical flows which is transgressed, making this a central impact category.

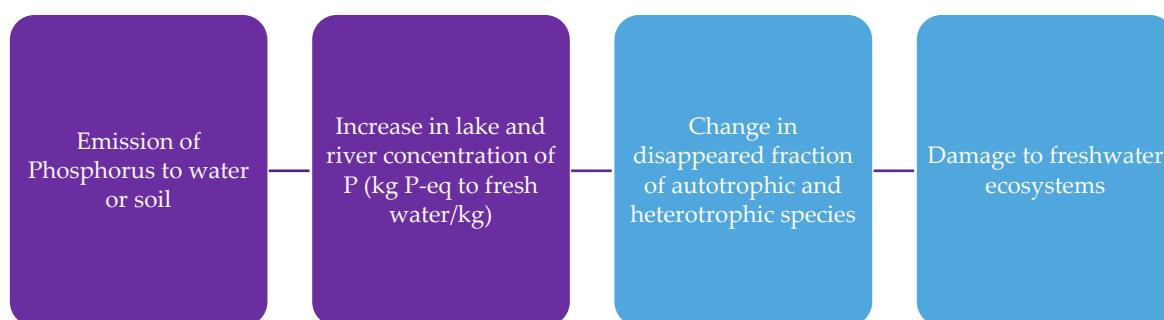


Figure 2.15. Cause-and-effect chain from Phosphorus emissions to damage of freshwater ecosystems [88].

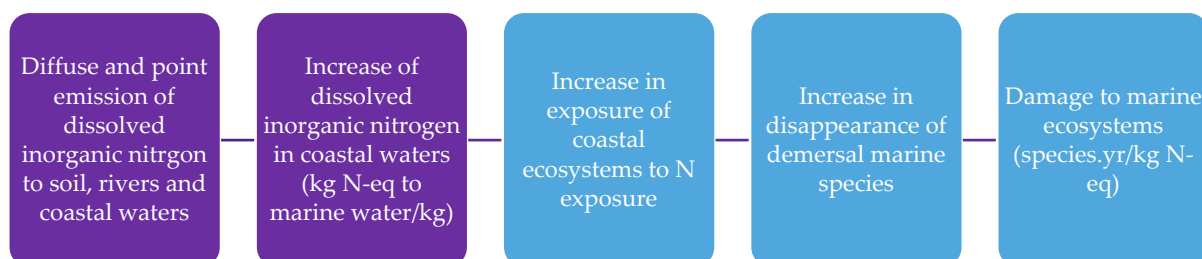


Figure 2.16. Cause-and-effect chain for dissolved inorganic Nitrogen from diffuse and point emissions causing loss of marine biodiversity. Adapted from [88].

#### 2.4.4.3.8. Toxicity

Toxicity includes five separate impact categories in ReCiPe (2016): terrestrial, freshwater, marine, human carcinogenic and human non-carcinogenic. Each impact category considers the environmental fate, exposure and toxicity effect of each substance, leading to the potential for significant methodological uncertainty (Figure 2.17). These impact categories are linked

to the transgressed PB of biosphere integrity and novel entities which are both transgressed, making these important impact categories.

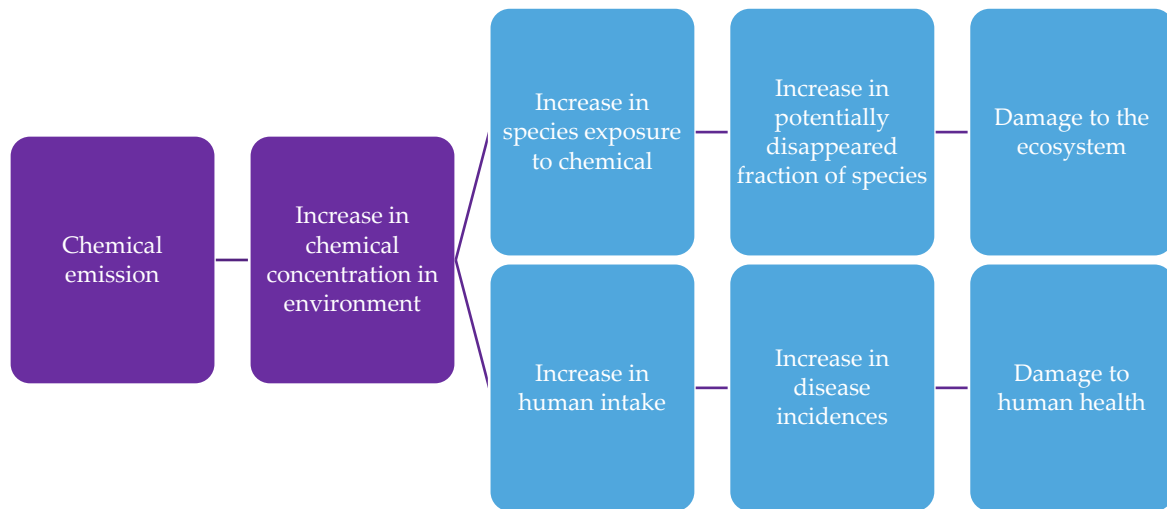


Figure 2.17. Cause-and-effect chain from chemical emissions to damage to the ecosystem and human health. Adapted from [88].

#### 2.4.4.3.9. Land use

This impact category considers natural land transformation, land occupation, and land relaxation but not a switch from one anthropogenic use to another, nor the species loss due to land use induced climate change (Figure 2.18). Land use is linked to the transgressed PBs of land system change and biosphere integrity which are both transgressed, making this a central impact category.

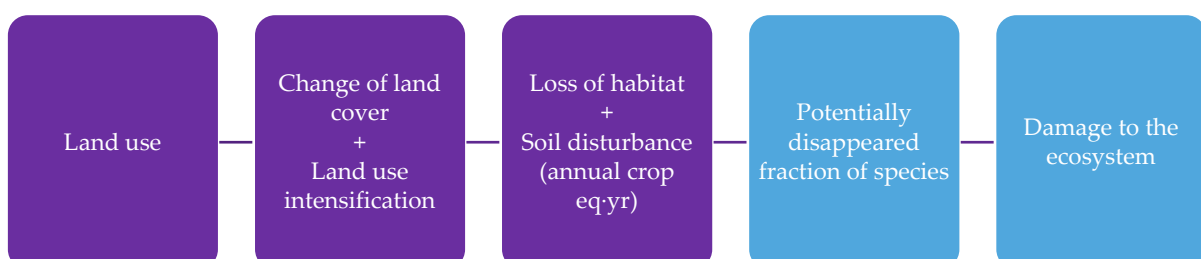


Figure 2.18. Cause-and-effect chain of land use, leading to relative species loss in terrestrial ecosystems. Adapted from [88].

#### 2.4.4.3.10. Mineral resource scarcity

Practically, any extraction of a mineral resource reduces the concentration of that resource in ores<sup>20</sup> worldwide, that is, reduces the global *ore grade*. This reduction in concentration leads to an increase in volume of ore mined hence, environmental disruption and cost per kilogram of mineral resource. This can be said to increase the average surplus ore potential (SOP), which serves as the midpoint indicator for this impact category (Figure 2.19). While this indicator is clearly related to the concept of material use as discussed in previous sections of this chapter, it excludes any biomass and fossil resources. This impact category is not linked to the current PB framework, but should be noted as a good indicator for environmental impact generally [38], and that other proposed sustainable boundaries for global material use have already been assessed as exceeded [40] (Section 2.3.3).

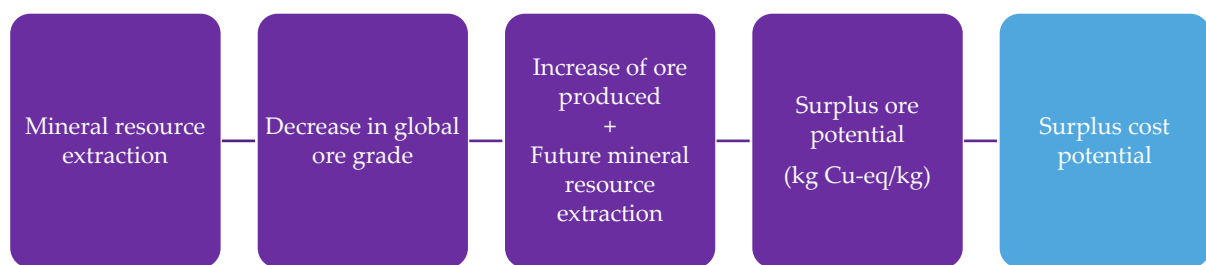


Figure 2.19. Cause-and-effect chain from mineral resource extraction to natural resource scarcity. Adapted from [88].

#### 2.4.4.3.11. Fossil resource scarcity

Similarly, it is assumed that increased extraction of fossil fuel will lead to rising costs, either due to a shift in production techniques or obtaining fossil fuels from more expensive locations. The 'surplus cost potential' serves as the endpoint indicator while damage related to natural

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<sup>20</sup> Consolidated or unconsolidated rocks or sediment which contain higher than average levels of valuable minerals.

resource scarcity is the midpoint indicator (Figure 2.20). This is not currently linked to a planetary boundary.

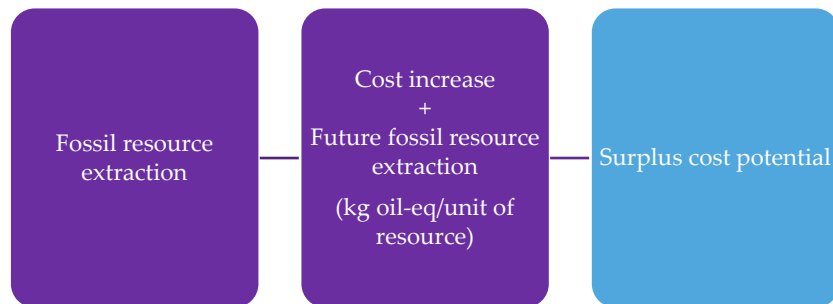


Figure 2.20. Cause-and-effect chain from fossil resource extraction to fossil resource scarcity. Adapted from [88].

#### 2.4.4.3.12. Water consumption

Human activities and production systems can both remove freshwater from and release freshwater to the hydrosphere. This can lead to endpoint harms to human health, terrestrial species and fish (Figure 2.21). Water consumption is linked to the transgressed planetary boundary of freshwater change and potentially linked to the transgressed PB of biosphere integrity, making this a central impact category.

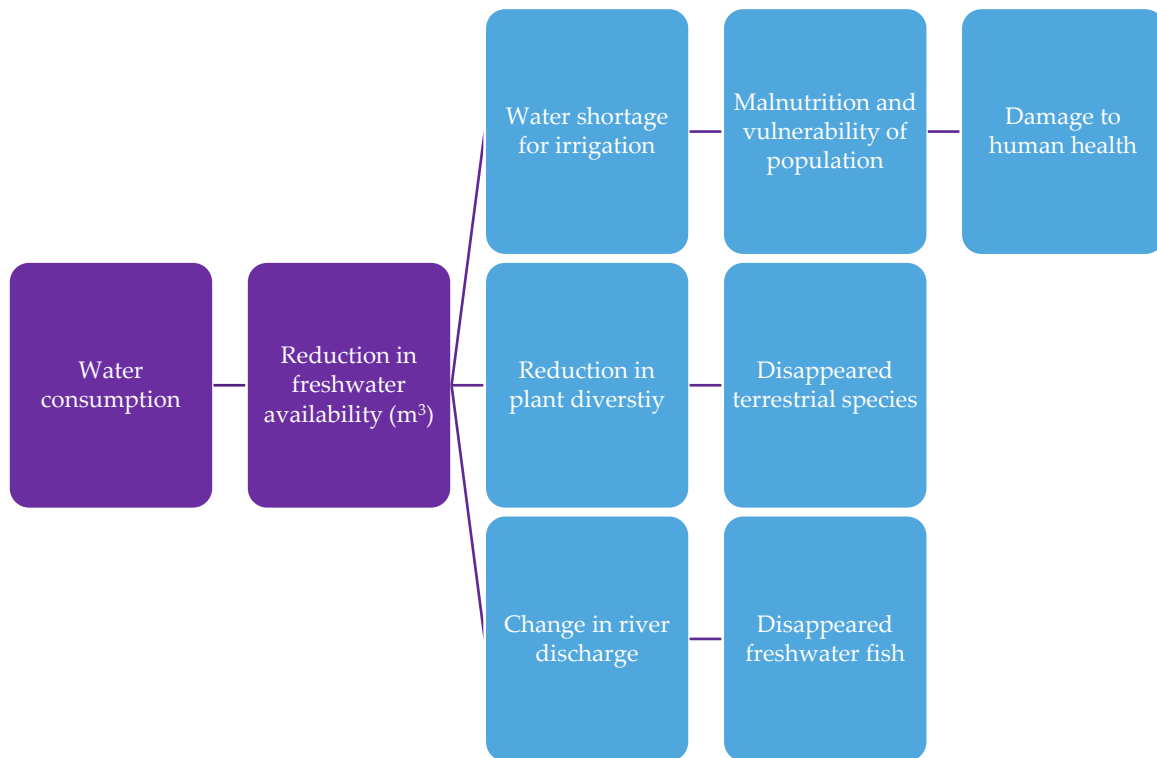


Figure 2.21. Cause-and-effect chain of water consumption. Adapted from [88].

#### 2.4.4.4. Cumulative Energy Demand

Cumulative energy demand (CED) is not part of ReCiPe (2016) and represents the direct and indirect energy use of a product, including the energy consumed during the extraction, manufacturing and disposal of the raw and auxiliary materials. The total CED is composed of the fossil CED (i.e., from hard coal, lignite, peat, natural gas, and crude oil) and the CED of nuclear, biomass, water, wind, and solar power in the life cycle [94]. It is not linked to a planetary boundary, but is of interest to more economically minded enquiries, which may consider using CED in energy return on investment (EROI) or energy payback time (EPT) calculations, and so is included in later chapters.

#### 2.4.5. Emerging life cycle assessment techniques

This section will briefly introduce some advanced life cycle techniques that have emerged in recent years as reference for further work.

#### 2.4.5.1. Absolute environmental sustainability assessment

Absolute environmental sustainability assessment (AESA) is a methodological approach aimed at evaluating the environmental impact of human activities without relativistic comparisons, which was introduced around 2016 [95]. AESA uses the planetary boundary framework to allocate a proportion of the PB control variable levels to an actor, be it a continent, nation, region or corporation. Inescapably, this technique requires judgment to select a suitable *downscaling principle*. This methodologically significant and can affect the results in major ways, as this inevitably involves normative choices of sharing allocation principles – this is neatly discussed in [96]. AESA downscaling methods could be built in to SimaPro functionality, akin to how LCIA methods are automatically included in SimaPro [91].

#### 2.4.5.2. Relating LCA and circularity indicators

The circular economy (CE) is a concept of production and consumption that posits that the Great Acceleration can be arrested by the conversion of extractive linear economies (socioeconomic metabolisms) into regenerative circular ones. However, indicators of the “circularity” of a product only provide a partial view of its environmental performance [97]; and circular economy product-level indicators and LCA results have been shown to not necessarily align [98]. Further, given the rampancy of the Great Acceleration, the implementation of circular principles faces significant headwinds if it is to become an environmentally restorative practice commensurate with the scale of the challenge, and with the blessings of the financial beneficiaries of the incumbent linear system: an empirical sociometabolic study on circularity in the years 1900 to 2015 (encompassing the Great

Acceleration) found non-circular inputs<sup>21</sup> increased by a factor of 16 and noncircular outputs<sup>22</sup> by a factor of 10 [99], indicating the challenge facing implementation. Explicitly, a recent review notes that while CE could facilitate PB thinking, its compatibility with growth based linear economic systems appears challenging, and recommends socio-institutional change towards a postgrowth economy [100].

#### 2.4.5.3. Dynamic LCA

Conventional LCA studies provide a stationary picture of environmental impacts associated with a product or process given static foreground and background data. Dynamic LCA extends conventional LCA methods by incorporating a dimension of time. While relevant to this work, Dynamic LCA is listed here only for reference and was outside of the scope of study – although it would be ideally suited to the future-looking nature of this thesis. Relevant examples would be:

- Dynamic background data (Prospective LCA) [101];
- Dynamic product system data (for example, for vessel propulsion in offshore renewable energy LCAs);
- Dynamic LCIA methods (such as biogenic CO<sub>2</sub> for power system modelling).

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<sup>21</sup> Fossil fuels, non-renewable biomass, non-recycled metals, all fossil fuel based materials and other mineral materials.

<sup>22</sup> All waste and emissions released to the environment including landfill excluding renewable biomass.

#### 2.4.5.4. Other

LCA of future technologies and multiple-region input/output (or hybrids thereof) are not covered in within the scope of this thesis.

#### 2.4.6. Summary

LCA is an established, extremely comprehensive and multi-disciplinary technique for assessing the environmental harms of a product or service, which complements other decision support methods such as environmental impact assessments (EIA), cost benefit analyses (CBA) and levelised cost of energy (LCOE) calculations [102]. LCA can inform policy and strategic-level decisions, and has become an increasingly popular technique in the fields of climate science and low carbon energy engineering.

For this thesis, if the planetary boundaries framework is considered, the eleven midpoint impact categories of most import are:

- Global warming (Climate change)
- Ionising radiation (Novel entities)
- Terrestrial acidification (Biosphere integrity)
- Freshwater and marine eutrophication (Biogeochemical flows)
- Terrestrial, freshwater, marine, human carcinogenic and human non-carcinogenic toxicity (Biosphere integrity and Novel entities)
- Land use (Biosphere integrity).

## 2.5. Technologies under consideration in this thesis

By virtue of the participation of the author the in Centre for Doctoral Training in Wind & Marine Energy Systems, the energy generation technologies that will be considered in detail in this thesis are novel offshore technologies: floating offshore wind, wave energy and tidal stream. Tidal range is also included by necessity in Chapter 7 as shall be explained; and for a description of this technology the reader is referred to [103].

### 2.5.1. Available energy

All energy sources accessible to the Earth's ecosphere are ultimately cosmic in origin: solar radiation; tidal forces from the interaction of celestial bodies' gravitational fields, and fissile elements formed in merging neutron stars. Both nuclear and solar energy contribute to the dynamics of the component spheres discussed in Section 2.2: nuclear fission still warms the Earth's core, influencing the asthenosphere and magnetosphere; solar energy is converted by photosynthesis and made accessible to the biosphere (whence living organisms and ancient fossil fuels derive); winds and waves arise from differential solar heating cells across the planet; and tidal forces play a key role in the hydrosphere and global coastal biomes.

Dividing further, between finite and effectively infinite (to human scale) sources, reserves of fossil or nuclear fuels are finite (with their rate of consumption far higher than their rate of replenishment<sup>23</sup>) while solar and tidal force driven processes are essentially infinite, or renewable. In this sense, all types of renewable energy generation (along with biomass and

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<sup>23</sup> With certain fuel routes and breeder technologies, nuclear fuel reserves could be extended significantly.

fossil fuels) are ultimately a form of solar power (apart from tidal energy), and nuclear a form of cosmic power (and all elements comprising the machine's construction being cosmic in origin). The energy density of these sources varies markedly however, with 3.5% enriched uranium having around 40,000 to 80,000 times more energy by mass than gas and coal [104]. Similarly, nuclear is the most spatially dense source of non-fossil fuel, with offshore wind, wave and tidal being 197, 96 and 268 times less energy dense per unit area (TWh/km<sup>2</sup>).

The total *technical potential*<sup>24</sup> (and even *economic potential*<sup>25</sup>) for utility-scale renewable technologies, if considered additive, has been shown to be orders of magnitude larger than the 2050 global *electricity* demand in the IEA's Net Zero Emissions scenario (62.2 PWh/year) [105] – while noting that the global *feasible potential*<sup>26</sup> would be lower due to inevitable societal and environmental constraints<sup>27</sup>, and that electrification is 52% of final energy consumption in other IEA scenarios [107].

The same study concludes >100, >1 and >1 PWh/year for offshore wind (including floating), wave and tidal stream. This is similar to a contemporary, high-resolution review which

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<sup>24</sup> The amount of electricity that can be produced in available and suitable areas using current technologies.

<sup>25</sup> The amount of the technical potential that can be produced below a certain LCOE.

<sup>26</sup> A subset of economic potential considering social and environmental factors that affect deployment.

<sup>27</sup> For context, in 2019, global final energy consumption was 116 PWh (418 EJ), of which only 22.9 PWh (82.3 EJ or 20%) was electricity [106].

suggests optimistic global resources of 55, 1 and 0.18 PWh/year for offshore wind (including floating), wave and tidal stream [108].

### 2.5.2. Wave energy

Wave energy could contribute in to global climate change mitigation efforts in the long term [109], contingent on technological development and deployment. In 2020, the combined capacity of *all* ocean energy technologies amounted to 0.53 GW, producing 0.001 PWh/year. The IEA STEPS scenario has a global ocean energy capacity of 37 GW, forecasting production of 0.10 PWh/year in 2050 [105].

#### 2.5.2.1. Principle of operation

Ocean surface waves are driven by the wind, which is itself driven by pressure differences arising from differential heating of the atmosphere, from solar radiation. The prime mover design of wave energy devices is highly varied and dependent on their mode of energy extraction. The motion of the surface wave impels the prime mover to translate or rotate around some reacting body, and the relative motion can be used to generate electricity through unique generator topologies.

#### 2.5.2.2. Technological development status

Wave energy faces a number of challenges to becoming a widespread alternative to fossil fuel energy globally, including a high levelised cost of energy, low technology readiness and measurable environmental impacts [110], [111]. Nevertheless, energy systems models have indicated that wave energy can perform a valuable function when integrated into American [112], European [113], [114] and UK energy systems [110], [115], [116], and a number of WECs are currently under commercial development, the largest of which is around 1 MW rated power.

### 2.5.2.3. Resource

2023 research on wave power literature found a global technical potential of 534 to 17500 TWh/year across the literature, with a median of 4040 TWh/year (mean of 4480 TWh/year), noting that “the lack of original estimates precludes a clear understanding of the sources of differences” [105]. This contrasts with a contemporary finding of 1000 TWh/year [108]. The UK (in particular Scotland) attracts a significant proportion of the global resource and is historically a hotbed of international research in this area, with one ambitious target of 22 GW installed capacity by 2050 [117].

## 2.5.3. Floating wind

### 2.5.3.1. Principle of operation

Solar energy creates differential pressures in the atmosphere, creating air flow currents. Wind turbines harness the kinetic energy in the incident wind to generate aerodynamic lift, and hence torque, over their rotor blades. The rotor spins a generator in the turbine nacelle to generate electricity.

### 2.5.3.2. Technological development status

The first (fixed-bottom) offshore wind turbines (450 kW) started operating in 1991 (at Vindeby in Denmark), and took 16 years before the first floating wind turbine (80 kW) was operational in 2007 at Apulia, Italy. Offshore wind turbines are now heading to rated powers upwards of 20 MW.

### 2.5.3.3. Resource

Estimates for global offshore wind technical potential between 2008 and 2021 span two orders of magnitude, from 4170 to 626,000 TWh/year, with median 19,300 and average 18,200 TWh/year [105], however, the majority of this is expected to be fixed-bottom offshore wind.

Electricity generation from floating offshore wind (FOW) turbines is expected to make a major contribution to the electricity sector from around 2030 [49]. However, bottom-fixed offshore wind (BFOW) technologies currently make up 99.7% of all offshore wind installed capacity: in 2022, the global installed capacity of offshore wind was 64.3 GW, of which only 188 MW was floating [118].

In 2022, the UK was the second largest operator of offshore wind globally, with nearly a quarter of all operating capacity, after China with 46%. The UK offshore wind installed capacity of 13.7 GW delivered 45 TWh, or around 14% of all UK electricity generation in 2022 [119]. Of this, only 78 MW, or 0.6%, of the UK's total offshore wind capacity is floating. While nascent, this is around 41% of all floating wind generation globally, making the UK the single largest operator of floating wind in 2022 [118].

All of these installed capacities are expected to grow significantly to achieve the UK's climate targets: in 2022, the UK government stated its ambition to deploy up to 50 GW of offshore wind by 2030 [120]. For the UK, FOW is expected to be located primarily in the Celtic Sea and Scottish waters, at around 4.5 GW [121] and 7 GW, respectively. The ScotWind seabed leasing round is expected to achieve 10 GW of offshore wind around 2030, of which more than 70% (7 GW) may use FOW technologies [122], subject to ongoing commercial development.

In the UK, the Climate Change Committee (CCC) has identified that FOW could cut costs and improve the diversity of the UK's energy mix by 2050, and so play a greater role in the power sector decarbonisation [123]. FOW can be constructed in water depths that are cost-prohibitive for BFOW, increasing the spatial distribution of wind generation across the grid, and potentially reducing the variability of aggregate wind power generation. Furthermore, additional wind power is likely to further reduce the carbon intensity of power generation

operating on the British grid [124], which stood at 182 gCO<sub>2</sub>/kWh in 2022 [125]. However, to avoid unintended burden shifting from climate change to other environmental impacts, the significant expansion of FOW installed capacity should merit a proportional interest in not just the operational emissions impacts, but the wider life cycle environmental impacts of these emerging technologies, as in Chapter 5.

## 2.5.4. Tidal stream

### 2.5.4.1. Principle of operation

Like floating wind, the prime mover for a tidal turbine is a rotor, which is impelled to move by hydrodynamic lift generated by tidal current flowing over the blades. Electricity is generated within the turbine via generator.

Tidal range (considered later in the thesis by necessity) is completely different technology requiring large impoundments and acting more like a hydroelectric dam, exploiting current induced by the potential difference between two reservoirs.

### 2.5.4.2. Technological development status

Again, the UK has led the way in tidal stream development. There are currently 2 MW devices under development.

### 2.5.4.3. Resource

Tidal energy technical potential estimates span two orders of magnitude, from 10 to 1000 TWh/year (this seems to refer to tidal stream, but the difference is not emphasised) [105]. Alternatively, a value of 180 TWh/year was proposed in the same year [108].

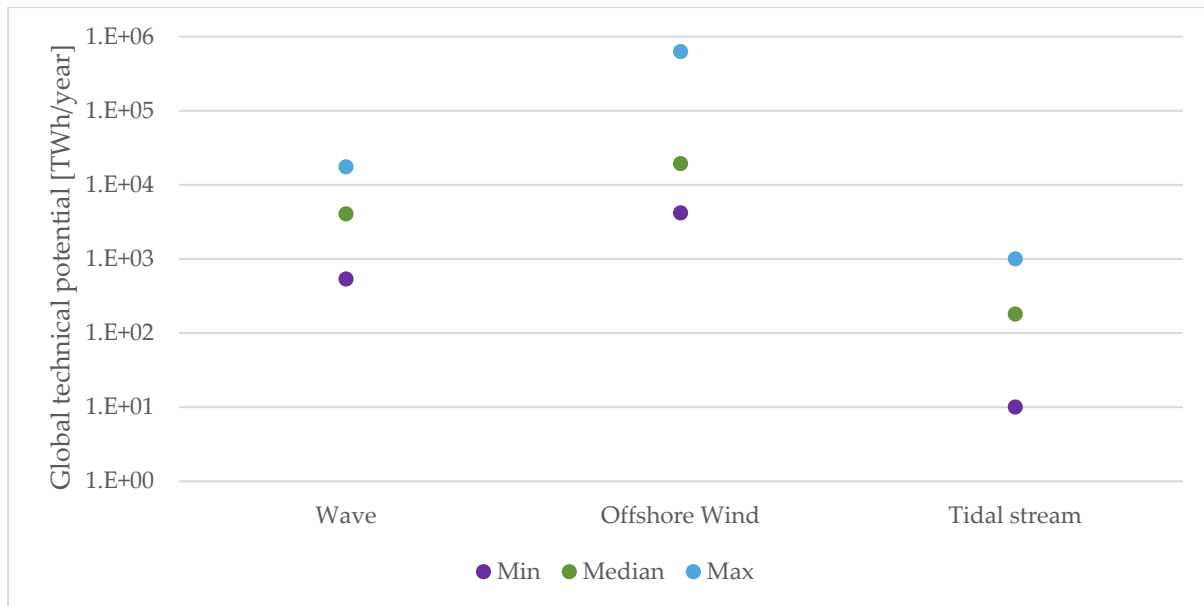


Figure 2.22. Comparison of global technical potential resource from the three main technologies in this thesis (note the logarithmic scale).

### 2.5.5. Current technological status in the British Isles

The UK is – currently – a leading nation in floating wind and marine energy technology development, research and deployment [116], with 78 MW of floating wind installed in 2022 [118] and 8.5 MW of tidal stream installed in 2023 [126]. Remarkably, all floating wind and tidal stream arrays are located in Scotland, but with firm intentions to develop sites in Wales and England. Wave energy is less well developed, with no permanent presence today. Given these relatively small installed capacities, none of these technologies make an appreciable contribution to the contemporary electricity (or energy) mix of the UK. For example, in 2023, demand ranged between 14 and 44 GW [127].

Nevertheless, floating wind is expected to make a significant contribution to the UK's electricity mix in the 2030s, with 4.5 GW and 7 GW expected to be deployed in the Celtic Sea and around Scotland. These sites are on the cusp of commercial development, in contrast to marine energy, which operates under a different technological and commercial paradigm.

Estimates of *potential* UK marine energy resource (rather than leasing areas) are around 11.5 GW installed capacity for tidal stream and 24 GW for wave energy [126]. Relatedly, the European Commission has set Europe-wide deployment targets for marine energy of 1GW by 2030 and 40 GW by 2050 [116].

### 2.5.6. Future global deployment

Future deployment of these technologies in line with the scope of the thesis will be considered in detail in Chapter 7. A key characteristic of most global net zero scenarios is the transition to high proportions of renewable energy generation and storage, primarily solar and wind with hydro, nuclear, hydrogen and CCS technologies, along with rapid phase out of fossil fuels. The UK energy system is likely to feature similar characteristics of net zero pathways, but with specific differences due to historical technological choices, available energy resources, perceived political feasibility and legislated commitments. Overall, ocean energy (including wave and tidal) sees limited deployment in IEA, or IPCC scenarios. .

### 2.5.7. Comparison of different technologies

LCAs can be applied to understand the environmental impacts of electricity generation technologies and energy systems. LCAs are available for all of the specific technologies of interest for this PhD but LCA studies which compare technologies directly are fairly limited (one good example is Gibon, [128]). No power generation systems are without environmental impacts, and each has its own characteristics across the wide variety of impact categories [17]. While renewable energy systems do have some consumables, in general this is not significant compared to the fuel cycles of thermal plant. Despite this, renewable energy technologies generally have a higher abiotic material intensity than fossil fuels, driven by the lower energy density of the energy resource (chemical energy compared to converted forms of solar energy

or tidal forces). In general, moving from fossil fuel to renewable energy technologies achieves a 1 to 2 orders of magnitude reduction in climate change impact for the same electricity output [17], as well as reductions in acidification and particulate matter impacts. However, toxicity related impacts and material resource depletion may be comparable or increase.

## 2.6. Conclusion

*“The challenge of space exploration has joined with the depletion and degradation of the earth’s environment ... to entice or compel individuals and governments to think in terms of our common destiny: to counter humanity as a single gifted but greedy species, sharing a common, finite and endangered speck of the universe.”*

*Thomas Franck, 1995*

Since the industrial revolution, high consumption of rich individuals and nations has caused the degradation of Earth’s key planetary cycles and global biodiversity loss. In particular, fossil fuel combustion for the provision of primary energy and industrial processes is the largest contribution to anthropogenic climate change [48], while fossil fuel extraction, processing and distribution also contribute to environmental pollution, human health and impacts and mortality and biodiversity loss [33].

Limiting further climate change is dependent on stabilising atmospheric concentrations of greenhouse gases as rapidly as practicable, with adherence to the terms of the Paris Agreement likely requiring ‘net zero’ greenhouse gas emissions by 2050. Analysis suggests any new fossil fuel infrastructure incompatible with the temperature limits of the Paris Agreement, and a managed, rapid degrowth of the fossil fuel sector is likely required. In its place, any future energy provisioning systems (comprising efficiencies, renewable, nuclear and storage technologies for power and end-use sectors) must also provide equitable access to energy and other basic human need provisioning services while remaining within Earth’s planetary boundaries, to avoid further planetary destabilisation [64], [65]. The Anthropocene,

marked by the Great Acceleration, underscores the urgency of addressing sustainability challenges and mitigating the adverse impacts of human activities on the planet.

Affluent, high consuming demographics have become a dominant global influence on life on earth, and have caused natural terrestrial, freshwater and marine ecosystems to decline with dire consequences for nature and benefit incumbent, historical patterns of extraction. Six of the nine planetary boundaries which define a Holocene precedent for humanity are now exceeded, risking abrupt transitions into a new epoch.

Given the urgency, multi-dimensional coverage and scale of the situation, there is an equivalently pressing need to quantify the environmental impacts of future decisions. One way to minimise environmental harm, is for decision-makers to consider the holistic environmental implications of products, goods and services; their use, supply-chain and waste management. One such tool is LCA.

The UK has major ambitions and heritage in floating wind and marine energy systems. The following chapter will review the life cycle impacts of these technologies.

# Chapter 3:

## Literature review of floating wind & marine energy life cycle impacts

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This chapter reviews the life cycle assessment literature for wave energy, floating wind technologies and compares it to tidal stream and fixed-bottom offshore wind. The literature for each technology is described and critically appraised, and opportunities for future research are identified to inform the life cycle assessments executed in Chapters 4 and 5. This chapter also considers the literature where LCA is combined with other models and techniques to determine the emissions reduction potential of specific power generation technologies.

### 3.1. Introduction

The literature review presented here primarily focusses on climate change impact categories associated with wave energy and floating wind technologies, in alignment with the emissions reduction objective of this thesis, although other impact categories and technologies are discussed, without providing an exhaustive assessment of the environmental impacts of every design. Only academic publications were reviewed: journal papers, conference papers and theses.

Features and gaps in the literature are identified to influence the goal and scope of Chapters 4 and 5 which execute two novel LCAs for wave and floating wind arrays.

### 3.2. Wave energy life cycle assessments

To date, there exists no commercially conventional design of a wave energy converter (WEC) beyond the common components of: prime mover, foundation, power take-off system (PTO) and electrical export system (usually a high power electrical cable). Devices differ in rated power, physical size, materials, deployment location (near-shore, deep water or breakwater), design wave climate, operation and maintenance (O&M) approach, power generation response (power matrix), annual energy production (AEP) and stage of technological development. A total of nineteen attributional LCA studies on wave energy devices published between 2006 and 2022 were identified and reviewed (Table 3.1).

Overall, device properties (especially design life and AEP) and practitioner methodological choices (particularly vessel modelling approach and O&M assumptions) cause WEC life cycle inventories and consequent environmental impacts to vary – in some cases significantly – across the literature. Pertinently to this thesis, there is significant variation in the Global

Warming (GW) or Global Warming Potential (GWP) results from existing studies – not only across different device types, but also within them – ranging from **13 to 126 gCO<sub>2</sub>eq/kWh** with a mean of 50.5 and median of **41.9 gCO<sub>2</sub>eq/kWh** (Table 3.1). There is great variety in the coverage with each paper (single design, multiple designs, comparison with tidal technologies) with newer studies focussing on the most recent devices in development.

Table 3.1. Characteristics of the wave energy attributional LCA literature. Values marked \* were back-calculated from values in the original publication.

Study Authors	Device Name	WEC Type	Location	Installed Capacity	AEP [GWh/year]; Capacity Factor	Scale (No. WECs)	Scope	Software, database	LCIA Method (No. Impact Categories)	Life [years]	gCO <sub>2</sub> eq /kWh	Carbon payback / intensity [years; gCO <sub>2</sub> /kWh]	O&M Assumptions	Spare Parts	Uncertainty
Sorensen et al (2006) [129]	Wave Dragon	Over-topping	Denmark	7 MW	Neither stated	Device	Cradle-to-grave	Not described	EDIP (15)	50	13 (via [111])	2.42; not quantified (2001 Danish power grid mix)	Not included	N	N
Parker et al. (2007) [130]	Pelamis P1	Attenuator	UK	750 kW	2.97; n/a	Device	Cradle-to-grave	Inventory analysis	Energy use and CO <sub>2</sub> intensities (2)	20	22.8	1.08; 430	2 un/re-latching, 6 inspections (ROVs) /year	N	N
Dahlsten (2009) [131]	Seabased	Point Absorber	Norway Sweden	20 MW	Neither stated	Array (50)	Cradle-to-grave	SimaPro; multiple	EPD (8)	20	39 126	Energy payback only	2 hours/year	1 wire rope replacement per lifetime	Background
Thomson et al. (2011) [132]	Pelamis P1	Attenuator	UK	750 kW	2.97; n/a	Device	Cradle-to-grave	SimaPro 7.2 PhD; ecoinvent v2.2	EDIP (19)	20	30	1.17; 499	Not described	N	N

Study Authors	Device Name	WEC Type	Location	Installed Capacity	AEP [GWh/year]; Capacity Factor	Scale (No. WECs)	Scope	Software, database	LCIA Method (No. Impact Categories)	Life [years]	gCO <sub>2</sub> eq /kWh	Carbon payback / intensity [years; gCO <sub>2</sub> /kWh]	O&M Assumptions	Spare Parts	Uncertainty
Walker & Howell (2011) [133]	Oyster 1	Oscillating Wave Surge Converter	UK	315 kW	1.41; 55%*	Device	Cradle-to-grave	Inventory analysis	Energy use and CO <sub>2</sub> intensities (2)	15	25	0.67; 592	3 visits per year, car, ferry	N	N
Banerjee et al. (2013) [134]	Pelamis P1; Wave Dragon	Attenuator; Overtopping Device	Various	750 kW; 7 MW	2.5; n/a 20; n/a	Device	Cradle-to-grave	Not described	Energy use and CO <sub>2</sub> intensities (2)	20; 50	19.68; 28.25	n/a	Not described	N	N
Dalton et al. (2013) [135]	Wavestar	Hinged Arm	Ireland	1 MW	1.93; n/a	Device	Cradle-to-grave	GEMIS	Energy use and CO <sub>2</sub> intensities (2)	20	47	1.67; 559	Not described	Not described	N
Douziech et al. (2016) [136]	Oyster 800	Oscillating Wave Surge Converter	UK	800 kW	2.8; 40%	Device	Cradle-to-grave	ARDA;ecoinvent v2.2	ReCiPe 2008 (5)	20	65.5	1.74; 752*	Every 5 years, + "semi-annual" inspection	N	N

Study Authors	Device Name	WEC Type	Location	Installed Capacity	AEP [GWh/year]; Capacity Factor	Scale (No. WECs)	Scope	Software, database	LCIA Method (No. Impact Categories)	Life [years]	gCO <sub>2</sub> eq /kWh	Carbon payback / intensity [years; gCO <sub>2</sub> /kWh]	O&M Assumptions	Spare Parts	Uncertainty
Uihlein (2016) [137]	Various	Attenuator; Point Absorber; Oscillating Wave Surge; Oscillating Water Column; Overtopping Device; Submerged Pressure Differential; Rotating Mass; Other	Europe	Not stated	Not stated; 20%	Device	Cradle-to-grave	GaBi v6.4; Thinkstep / ecoinvent v2.2	ILCD (13)	20	43.7; 104.5; 64; ~48; ~15; ~40; ~105; ~75;	n/a	If no information was available, average values of 100 h maintenance per year, 70% using a vessel, 30% using a barge were used.	N	N
Zepeda, 2017 [138] (MSc)	Wave Activated Body (WAB)	Point Absorber	North Sea	20 MW	Not stated; 50%	Array	Cradle-to-grave	SimaPro7; not stated	CO <sub>2</sub> emissions (1)	5	40	n/a	Not included	N	N

Study Authors	Device Name	WEC Type	Location	Installed Capacity	AEP [GWh/year]; Capacity Factor	Scale (No. WECs)	Scope	Software, database	LCIA Method (No. Impact Categories)	Life [years]	gCO <sub>2</sub> eq /kWh	Carbon payback / intensity [years; gCO <sub>2</sub> /kWh]	O&M Assumptions	Spare Parts	Uncertainty
Elginoz & Bas (2017) [139]	Floating multi-use offshore platform (MUP)	Multi-functional Platform	Spain	265.5 MW (231 WECs)	110 (0.476 per WEC); 5%	Array	Cradle-to-grave	GaBi; ecoinvent v2.2	CML 2001 (9)	25	18.1	n/a	Barge, 10/year; Helicopter 1/year (for the array)	N	N
Curto et al. (2018) [140]	DIEM I, DIEM II	Point Absorber	Mediterranean	30 kW	n/a	Component	Cradle-to-grave	ThinkStep	ADPe, APDi, FAETP, GWP, HTP, MAETP, TETP <sup>28</sup> (7)	Not stated	67.05; 143.32	n/a	Not included	N	N
Zhai et al. (2018/21) [141], [142]	Buoy-rope-drum (BRD) WEC	Point Absorber	China	10 kW	0.01* - 0.04*; 20% - 50%	Device	Cradle-to-grave	SimaPro v 8.3.0.0; ecoinvent v3	ReCiPe Midpoint (I) V1.13 / World (18) / IMPACT 2002+ (15)	20	89	1.92; 929*	Annual inspection, workboat	N	Background (2021)

<sup>28</sup> Abiotic depletion (fossil), abiotic depletion (elements), freshwater aquatic ecotoxicity, global warming potential, human toxicity potential, marine aquatic ecotoxicity potential, terrestrial ecotoxicity potential.

Study Authors	Device Name	WEC Type	Location	Installed Capacity	AEP [GWh/year]; Capacity Factor	Scale (No. WECs)	Scope	Software, database	LCIA Method (No. Impact Categories)	Life [years]	gCO <sub>2</sub> eq /kWh	Carbon payback / intensity [years; gCO <sub>2</sub> /kWh]	O&M Assumptions	Spare Parts	Uncertainty
Patrizi et al. (2019) [143]	Overtopping Breakwater for Energy Conversion (OBREC) WEC	Breakwater	Italy	3 kW	0.0126; n/a	Device	Cradle-to-grave	SimaPro 8.4.0; ecoinvent v3.3	CO <sub>2</sub> emissions (1)	60	37	2.08; 540*	12 trips per year to the plant (average 30 km each), car	60 years for the concrete structure; 10 years for the turbine; 20 years for PVC pipes; 50 years for terrestrial cables; 25 years for marine cables	N

Study Authors	Device Name	WEC Type	Location	Installed Capacity	AEP [GWh/year] ; Capacity Factor	Scale (No. WECs)	Scope	Software, database	LCIA Method (No. Impact Categories)	Life [years]	gCO <sub>2</sub> eq /kWh	Carbon payback / intensity [years; gCO <sub>2</sub> /kWh]	O&M Assumptions	Spare Parts	Uncertainty
Karan et al. (2019) [144]	Oyster 1 Oyster 800	Oscillating Wave Surge Converter	UK	315 kW 800 kW	1.52; 55% 3.86; 55%	Device	Cradle-to-grave	SimaPro 8	EDIP2003, CED (20)	15 20	79; 57	2.58; 462 2.50; 462	Multi-cat/5 years @ 20 days (8hrs), Dive boat 3/year @ 20 days (4hrs) Multi-cat/5 years @ 20 days (8hrs), Dive boat 2/year @ 10 days (4hrs)	N	N
Thomson et al. (2019) [145]	Pelamis P1	Attenuator	UK	750 kW	2.97; 45%	Device	Cradle-to-grave	SimaPro v8.3 PhD, ecoinvent 3.3	ReCiPe 2016, Midpoint, Hierarchist, European normalisation & CED (19)	20	35	1.5; 473 2; 352	Tug/year @ 4 days, Inspection vessel @ 1.3 days	N	Foreground & background

Study Authors	Device Name	WEC Type	Location	Installed Capacity	AEP [GWh/year]; Capacity Factor	Scale (No. WECs)	Scope	Software, database	LCIA Method (No. Impact Categories)	Life [years]	gCO <sub>2</sub> eq /kWh	Carbon payback / intensity [years; gCO <sub>2</sub> /kWh]	O&M Assumptions	Spare Parts	Uncertainty
Apolonia & Simas (2021) [146]	MegaRoller	Oscillating Wave Surge Converter	Portugal	1 MW	2.1 – 3.2; 25%	Device	Cradle-to-grave	SimaPro v8.5.2, Ecoinvent 3.4	ReCiPe 2016 Midpoint & CED (19)	20	33.8	2.3; 295*	1.3 days of sea vessel operations per year and a fuel consumption of 500 l/day, major maintenance is assumed every 5 years, 3 days of operations, including tow to shore and redeployment, over the device's lifetime.	N	N

Study Authors	Device Name	WEC Type	Location	Installed Capacity	AEP [GWh/year] ; Capacity Factor	Scale (No. WECs)	Scope	Software, database	LCIA Method (No. Impact Categories)	Life [years]	gCO <sub>2</sub> eq /kWh	Carbon payback / intensity [years; gCO <sub>2</sub> /kWh]	O&M Assumptions	Spare Parts	Uncertainty
Pennock et al. (2022) [147]	CorPower Ocean WEC	Point Absorber	Portugal	10MW	33; 38%	Array	Cradle-to-grave	SimaPro v9.1PhD, ecoinvent 3.6	ReCiPe 2016, Midpoint, Heirarchist, European normalisati on & CED (19)	20	25.1 to 46.0 over 95% confidence interval	n/a	Various – three scenarios for frequency of unplanned maintenance. All operations using Multicat	N	Background

Table 3.2. Review of global warming environmental impact from wave energy LCAs by device type, device design and rated power. The ratios  $s_{min}$  and  $s_{max}$  indicate the difference between the extrema and the mean, divided by the standard deviation (SD). For example, the overall variation between the minimum and mean global warming environmental impacts is less than one standard deviation (0.90), while the maximum is almost three (2.93) standard deviations above the mean, giving an indication of the distribution within the range of results.

Device type	Study	Device design	Rated power	Global warming [gCO <sub>2</sub> eq/kWh]	Min.	Mean	Median	Max.	SD	$s_{min}$	$s_{max}$
Attenuator	Parker et al. (2007) [130]	Pelamis P1	750 kW	22.8	19.68	30.2	30.0	43.7	9.6	1.07	1.42
	Thomson et al. (2011) [132]	Pelamis P1	750 kW	30							
	Banerjee et al. (2013) [134]	Pelamis P1	750 kW	19.68							
	Uihlein (2016) [137]	Various	Various	43.7							
	Thomson et al. (2019) [145]	Pelamis P1	750 kW	35							
Hinged Arm	Dalton et al. (2013) [135]	Wave Star	1000 kW	47	-	-	-	-	-	-	-
Multi-functional Platform	Elginos & Bas (2017) [139]	OWC (Array)	1150 kW	18.1*	-	-	-	-	-	-	-
Over-topping Device	Sørensen et al (2006), via [111]	Wave Dragon	7 MW	13	13	23.3	21.6	37	11.4	0.76	1.35

Device type	Study	Device design	Rated power	Global warming [gCO <sub>2</sub> eq/kWh]	Min.	Mean	Median	Max.	SD	S <sub>min</sub>	S <sub>max</sub>
	Banerjee et al. (2013) [134]	Wave Dragon	7 MW	28.25							
	Uihlein (2016) [137]	Various	Various	15							
	Patrizi et al. (2019) [143]	Overtopping Breakwater for Energy Conversion (OBREC)	3 kW	37							
Other	Uihlein (2016) [137]	Various	Various	75	-	-	-	-	-	-	-
Oscillating Wave Surge Converter	Walker & Howell (2011) [133]	Oyster 1	315 kW	25	25	54.1	60.5	79	20.6	1.73	0.90
	Douziech et al. (2016) [136]	Oyster 800	800 kW	65.5							
	Uihlein (2016) [137]	Various	Various	64							
	Karan et al. (2019) [144]	Oyster 1	315 kW	79							
	Karan et al. (2019) [144]	Oyster 800	800 kW	57							
	Apolonia & Simas (2021) [146]	MegaRoller	1000 kW	33.8							

Device type	Study	Device design	Rated power	Global warming [gCO <sub>2</sub> eq/kWh]	Min.	Mean	Median	Max.	SD	S <sub>min</sub>	S <sub>max</sub>
Oscillating Water Column (OWC)	Uihlein (2016) [137]	Various	Various	48	-	-	-	-	-	-	-
Point Absorber	Dahlsten (2009) [131]	Seabased WEC (Array)	20 kW	39	25.1	71.6	67.5	126	40.6	1.05	1.44
	Dahlsten (2009) [131]	Seabased WEC (Array)	20 kW	126							
	Uihlein (2016) [137]	Various	Various	104.5							
	Zhai et al. (2018/21) [141], [142]	Buoy-rope-drum (BRD)	10 kW	89							
	Pennock et al. (2022) [147]	CorPower Heaving Buoy (Array)	357	25.1							
	Pennock et al. (2022) [147]	CorPower Heaving Buoy (Array)	357	46							
Submerged Pressure Differential	Uihlein (2016) [137]	Various	Various	40	-	-	-	-	-	-	-

Device type	Study	Device design	Rated power	Global warming [gCO <sub>2</sub> eq/kWh]	Min.	Mean	Median	Max.	SD	S <sub>min</sub>	S <sub>max</sub>
Rotating Mass	Uihlein (2016) [137]	Various	Various	105	-	-	-	-	-	-	-
Overall	-	-	-	-	13	50.5	41.9	126	31.0	0.93	2.71

\* Includes energy generation from integrated 5 MW wind turbine which produces around seven times more energy per year than the three WECs (777.25 GWh/year to 110 GWh/year), reducing the global warming potential of the WEC technology in isolation.

### 3.2.1. Scope, detail and cut-off criteria

Given the subject matter, each study's scope is similar, but with significant diversity in inventory details. Life cycle models vary from device to array-scale and cover a range of water depths (45 m to 95 m [138], [147]), distances to port (3 km and 320 km [139], [145]) and device attributes. Most studies include the major components of device, the moorings, and export cable, as well as vessel operations for transportation, installation, operation, decommissioning and removal. Only two peer-reviewed studies consider arrays of devices [139], [147], of these one study includes an array large enough to require a substation, assessing an array of hybrid floating wind and wave energy platforms [139]. Indeed, in this study, the treatment of the fixed-bottom offshore substation and subsea cables is particularly detailed (based on Birkeland [148]), where the materials for the export cable and substation are shown to account for approximately 5-6% of the global warming impact (although the impact of O&M of these particular subsystems is negligible). The other studies typically do not break down the results to this level. Overall, with so few studies that consider arrays, no clear implications can be discerned on the impact differences between array and device-level studies, a recommendation from Uihlein [137] for future studies to consider.

Foreground data used to compile to life cycle inventories (LCI) includes publicly available information to commercially confidential data from device developers. Background data is typically provided by the ecoinvent database (with some exceptions) and SimaPro is a popular software, also featuring ThinkStep and GaBi. The functional unit is exclusively 1 kWh of power delivered to the grid, however, some semantics are omitted by this simplification, according to the definition in [149]. Location is almost exclusively limited to European geographies, with only

two beyond this, in China, by the same author for the same device [141], [142]. As with the scope or “coverage”, the foreground data detail, or “granularity” also varies for the major components above. Cut-off criteria are explicit in only two examples: 1% by mass in Dahlsten [131], emulated by Apolonia and Simas [146].

Earlier studies tend to use a different *system model* whereby credits are assigned to the environmental performance as a result of recycling (such as Parker, [130]) but this becomes less common in more recent studies which generally use the ‘allocation, recycled content’ (or ‘*cut-off*’) system model, which excludes (cuts-off) the impacts from recycling materials from the product under consideration and so nullifies and ‘credits’ for recycling to the product thus avoiding economic allocation for said impacts [149].

### 3.2.2. Life cycle impact assessment methods

In general, the depth of LCA treatment and number of impact categories included has tended to increase with publication date, from CO<sub>2</sub> and energy audits to multiple LCIA methods within a single study. Most studies use standard LCIA methods such as EDIP, ReCiPe, Cumulative Energy Demand (CED) and IMPACT 2002+. Others forgo a dedicated LCA software tool or do not give details, and tend to be less recent [129], [130], [133], [134]. Using standard methods improves confidence in the method, and typically provides a wider range of impact categories for discussion. Generally, the literature breaks down impacts by: life cycle stage; assemblies or components, and most impactful processes.

### 3.2.3. Life cycle stages

The life cycle stages are generally similar across the literature, aiding intercomparison: materials and manufacturing; assembly, transportation and installation; operation and maintenance; decommissioning and removal; disposal and recycling. Materials and manufacturing are consistently the most impactful stage of the WEC life cycle varying from 40% to over 90% in some categories, but especially climate change, ionising radiation freshwater eutrophication, toxicity metrics, land use and (clearly) material consumption.

This is generally followed by vessel operations – typically dominated by the operations and maintenance (O&M) stage – which are most impactful in impact categories such as ozone formation, particulate formation, stratospheric ozone depletion. This aligns with the high level review of ocean energy technologies LCAs (tidal stream, tidal range and ocean thermal energy conversion, OTEC) [111]. O&M impact varies markedly, however, with the widely cited Uihlein [137] having a near negligible impact – possibly due to selection of background data process, whereby vessel movements are represented using a process of a ‘bulk commodity carrier’ and ‘barge’, the former likely being far more efficient than marine vessels used for O&M (see Chapter 4).

In the studies that use a default allocation system model (not a ‘recycled content’ one), disposal credits the impact quite significantly [130], [146] making comparison with the remaining life cycle stages challenging.

### 3.2.4. Major components

Across the literature, the most massive components are typically the most environmentally harmful across most impact categories. For example, Uihlein [137] finds mooring and foundations are the largest single global warming contribution, followed by PTO components, electrical cabling, or structural components such as the prime mover.

### 3.2.5. Impactful processes

Steel is almost always the most impactful material (and usually the largest by mass), across multiple impact categories: climate change, freshwater eutrophication, most toxicity metrics, land use, water consumption and mineral resource use. Beyond the materiality, manufacturing processes themselves (such as cutting, welding or sand-blasting) are occasionally represented but are found to have nominal impacts [145], [147].

Impacts from fossil fuel combustion during vessel operation can vary from negligible (Uihlein, [137]) to dominant in the majority of impact categories considered (Pennock, [147]). These contribute to many impact categories including: global warming, ozone depletion, photochemical oxidant formation, fine particulate matter formation, terrestrial acidification, land use and ozone depletion [111].

Analysing the vessel activities during offshore renewable energy array O&M is a specialist discipline, so most wave energy LCA studies provide only basic assumptions for O&M, often with input data direct from the device developer. However, some studies include O&M activities, but offer no description [134], [135], and some do not account for O&M at all [129], [140]. Importantly, with recent improvements in the sophistication of O&M representation (both

development of unit processes judged to be more representative, by Thomson [145], Karan [144] and Pennock [147]) and by use of exogenous O&M modelling as foreground data (Pennock, [147]), the impacts from O&M have increased relative to earlier studies, suggesting this is an important aspect for consideration. Fuel consumption between the different vessel types and operational modes is remains a key research gap.

Only three studies ([131], [135], [143]) account for spare parts consumed during maintenance. Dalton [135] does not, unfortunately, provide details, but this aspect does not appear to be significant to the results. In some studies road transportation and office operation are included in the inventory, (such as [133], [143]) however the impacts are not significant.

### 3.2.6. Sensitivity and uncertainty

ISO 14044 states that sensitivity and uncertainty analyses shall be conducted for any comparative and publicly released studies [150]. Sensitivity studies in the literature are widespread and consider: AEP or capacity factor [130], [136], [137], [142], [144], [145], [147]; design life [129], [136], [137], [144], [145], [146]; recycling rates [130], [131], [136], [139], [146]; transportation distances [131], [132], [136], [145], [147]; material quantities [131], [136], [141]; material variation [130], [137], [146]; manufacturing processes [130], [131], [136]; maintenance burden [131], [147]; all foreground data [144]; electricity mix [136] and LCIA methods [141]. Considering these in turn:

- Any variation in the lifetime energy production (i.e. AEP or capacity factor) will, by definition, have an inverse effect on the environmental impacts per unit of energy produced, and this is reported across multiple studies. Design life has a similar effect, but the annual impacts from the O&M life cycle stage.

- The sensitivity to recycling rates varies across studies with Douzief [136] finding increases of 2% to 9% across all impacts from a 10% reduction in metal recycling rates; Elginos [139] finding significant increases in abiotic depletion (2.5 times) and freshwater aquatic toxicity (4.5 times) with reductions in metal recycling rate from 90% to 25%; and Apolonia and Simas [146] report a 24% increase in GWP from a reduction in *steel* recycling rate from 85% to 50%, making recycling rate an important consideration.
- Multiple studies show life cycle impacts are relatively insensitive to transportation distances: varying the installation distance from 600 km by  $\pm 250$  km leads to a maximum variation of  $\pm 4\%$  (in eutrophication) and only  $\pm 1\%$  in GWP [131]; a 10% variation in installation distance results in a maximum of 0.84% change in particulate matter formation (only 0.61% in climate change) [136]; up to a maximum of 6% (in terrestrial acidification) and a negligible increase in other categories is reported by Thomson [145] from a 10% increase in distance from site to shore and between the site and fabrication yard; and only a  $\pm 1\%$  change in the most impacted categories of GWP and terrestrial ecotoxicity from a  $\pm 20\%$  change in transportation distances [147].
- Increasing material quantities increases environmental impacts, usually the main constituent is steel with associated impact categories as listed previously. Uihlein notes that the weight has “a great influence” on the results, indicating the criticality of accurate foreground data. Regarding alternative materials, use of glass reinforced plastic (GRP) or concrete instead of steel are both shown to reduce embodied energy and carbon dioxide by Parker et al [130] but without assessment of other impact categories. Replacing

stainless steel with “finished cold-rolled coil steel” affects impact categories by 47 to 99 % although a detailed breakdown is not provided, and it is not clear if this is an appropriate material selection [137]. Regardless, a stainless steel WEC structure is unlikely in practice on the grounds of cost, and this practitioner assumption implies reported values may be elevated relative to a more likely carbon steel. Replacing reinforced concrete steel rebar with “glass fibre” is shown to improve the GWP of the MegaRoller device by 24%, although – again – other impact categories are not considered rendering an assessment of burden shifting impossible [146]. In the same study, replacing stainless steel with low carbon steel reduced GWP by 28%. Manufacturing processes are generally minor, for example,  $\pm 50\%$  change in cold rolling and cutting affecting GWP by  $\pm 3\%$ , water use by  $\pm 8\%$  and ozone depleting potential by 5% [131]; and increasing the material input to the processes of steel and metal product manufacturing by 10% yielded an average increase in impact categories of 2% [136].

- The sensitivity of the results to WEC maintenance burden is rarely assessed but with the two studies showing the results are sensitive to this aspect: an increase on-station maintenance from 2 hours to 4 hours resulting in an increase of 9%, 8% and 3% in ozone depleting potential, eutrophication and GWP (the largest change in the five sensitivity cases considered) [131]; and  $\pm 20\%$  increase in fuel consumed during O&M resulting in a  $\pm 8\%$  change to GWP [147].

Only four of the 19 studies include an uncertainty assessment, [131], [141], [145], [147], and Thomson [145] appears to assess both foreground *and* background uncertainty Overall, a lack of

uncertainty assessment fails to evaluate the confidence interval in the results, and omitting an assessment of uncertainty in the foreground data implies that practitioner input uncertainty are similarly excluded. Effectively, studies which lack these two aspects of uncertainty quantification could be perceived to have lower assurance in their respective results.

### 3.2.7. Emerging life cycle assessment techniques

No examples of consequential or prospective LCA or absolute environmental sustainability assessment (AESA) studies were identified. One master thesis from August 2022 did however explore the effect of decarbonising energy systems on a 10 MW wave energy array of 'UMACK' devices [151]. The background data was manually adjusted (a dynamic background system) according to the 2050 energy mixes in the National Grid's 2021 future energy scenarios (FES2021). The study found a (very low) GWP of 16.7 gCO<sub>2</sub>eq/kWh assessed in the year 2016 fell to 13.9 gCO<sub>2</sub>eq/kWh in 2050 using this method. Burden shifting was observed to other impact categories, notably ionising radiation (due to increased nuclear power in FES2021 in 2050) and land use (presumably due to wider coverage of wind turbines and solar power). Methodological issues remain with this approach, as the materials remain a significant impact unaffected by the change in electricity mix, but it is a welcome addition to the wave energy LCA literature.

### 3.2.8. Summary

There is a great deal of variation in almost every aspect of the wave energy LCA literature, apart from the functional unit, the background databases (generally) and LCIA methods. Nevertheless, materials were seen to consistently dominate environmental impacts, across a wide range of impact categories, with vessel use often the next most polluting aspect.

Wave energy LCA studies typically consider a single device or a small demonstration array rather than a utility-scale wave farm including a substation. Site-specific energy production or operations are generally omitted and vessel operations are modelled in simple terms, with limited vessel types, operational modes, and consideration of frequency of operations and duration on-site. In the sensitivity studies reviewed, the results showed significant sensitivity to lifetime energy production via AEP or capacity factor, the selection and volumes of materials and the method of vessel representation, and assumptions of O&M activities. Lastly, uncertainty is quantified in only a handful of studies.

Gaps in the literature include the modelling of utility-scale arrays with substations, newly developed WEC designs and vessel representation (especially during O&M); a wide range of environmental impact categories with a recognised LCIA method; and including sensitivity and uncertainty assessments which assess both foreground and background uncertainty.

### 3.3. Floating wind life cycle assessments

The number of LCA studies for floating wind is not large. A 2018 literature review [152] collated 148 wind energy LCA studies, of which 32 were for offshore wind farms, and only two floating wind – perhaps reflecting the relative maturity of these technologies. This chapter reviews ten floating wind LCA studies, published between 2009 and 2023, nine journal papers and one Master’s Thesis, [153], making attributional life cycle assessments for floating wind turbines actually less numerous than wave energy machines.

In general, it appears that life cycle models of floating wind systems have tended to increase incrementally in representation and sophistication, particularly around different array

configurations and floating substructure designs. The rated power of the turbine assessed is also increasing (broadly), as is the popularity of semi-submersible substructure designs, somewhat mirroring real-world technological trends. The capacity factor varies significantly from 23 to 54% across the studies, and this is the predominant method of energy calculation, with [154] and [155] augmenting this process using site-specific metocean data and, in the latter, linking this to a dedicated operations and maintenance (O&M) model to determine turbine availability. Across the literature GWP ranges from **11.5 to 45.2 gCO<sub>2</sub>eq/kWh**, with a mean of 28.0 and **median of 30.2 gCO<sub>2</sub>eq/kWh**, almost half of the mean GWP reported across the wave energy literature, and more than a quarter less than the median. The comparatively higher ranges of GW of wave energy technologies may reflect the early stage of the technologies involved, and the materiality required to withstand design extreme and fatigue load cases.

Key gaps in floating wind LCA remain around the representation of O&M, which has tended to be represented by simple assumptions – perhaps due to the modelling complexity and expertise required – apart from one recent exception [155], and studies which include multiple arrays of very large turbines.

Table 3.3. Selected characteristics of floating wind farm LCA. \* the Supporting Information of Tsai references the floating foundation in [156] which is a Sway design.

Abbreviations include: Tension Leg Buoy (TLB); Semi-submersible (Semi-Sub); Tension Leg Platform (TLP); Megavolt-amp (MVA); High Voltage Alternating Current (HVAC);

High Voltage Direct Current (HVDC); Service Operation Vessel (SOV); Cumulative Energy Demand (CED); Global Warming Potential (GWP).

	Weinzettel [156]	Raadal [157]	Tsai [158]	Elginoz [139]	Bang et al. [153]	Poujol [154]	Yildiz [159]	Garcia- Teruel [155]	Yuan [160]	Brussa [161]
<b>Year</b>	2009	2014	2016	2017	2019	2020	2021	2022	2023	2023
<b>Publication type</b>	Journal paper	Journal paper	Journal paper	Journal paper	Master's Thesis	Journal paper	Journal paper	Journal paper	Journal paper	Journal paper
<b>Turbine rated power (MW)</b>	5	5	3	5	8	6	2	6; 9.5	6.7	15
<b>No. turbines</b>	40	100	100	77	75	4	1	5; 5	100	190
<b>Array scale (MW)</b>	200	500	300	385 (wind), 265.5 (wave)	600	24	Single turbine	30; 47.5	670	2800

	Weinzettal [156]	Raadal [157]	Tsai [158]	Elginoz [139]	Bang et al. [153]	Poujol [154]	Yildiz [159]	Garcia- Teruel [155]	Yuan [160]	Brussa [161]
<b>Substructure design</b>	Sway	Spar; TLB; Sway; Semi-sub; TLP	Sway *	Multi-use offshore platform (integrated wave power)	Spar	Semi-sub	Barge-type	Spar; Semi-sub	Semi-sub (Wind Float, Gen 3)	Semi-sub
<b>Location</b>	Dogger Bank area, England	Not stated	Great Lakes, US	Cantabria, Spain	California, US	Leucate, France	FLOATGEN, France	Hywind; Kincardine, North East Scotland	China	West of Sicily, Italy
<b>Water depth (m)</b>	Concept suitable for 100–300 (not stated)	200	60–140	Not stated (est. 100)	450	Not stated	Not stated	95–129; 60–80	60–80	200

	Weinzettel [156]	Raadal [157]	Tsai [158]	Elginoz [139]	Bang et al. [153]	Poujol [154]	Yildiz [159]	Garcia- Teruel [155]	Yuan [160]	Brussa [161]
<b>Distance to shore (km)</b>	50	200	5–30	3–13	35	16	Not stated	25; 15	12–20	230
<b>Design life (years)</b>	20	20	20	25	25	20	20	25	25	30
<b>Site status</b>	Hypothetical	Hypothetical	Hypothetical	Hypothetical	Hypothetical	Pre- construction	Constructed	Constructed	Hypothetical	Pre- construction
<b>Energy calculation</b>	Capacity Factor	Capacity Factor	Site-specific	Capacity Factor	Capacity Factor	Site-specific	Capacity Factor	Site-specific, O&M model	Capacity Factor	Site-specific
<b>Capacity factor (%)</b>	53	46	28–35	23 (wind)	50	34	Not stated	50.2 (tow), 49.4; 40.5 (tow), 39.7	53.8	34.35
<b>Array voltage (kV)</b>	Not stated	30–36	33	33	Not stated	Not stated	Not stated	33	33	66

	Weinzettel [156]	Raadal [157]	Tsai [158]	Elginoz [139]	Bang et al. [153]	Poujol [154]	Yildiz [159]	Garcia- Teruel [155]	Yuan [160]	Brussa [161]
<b>Export voltage (kV)</b>	170	145	132	132	Not stated	Not stated	Not stated	33	132 (HVDC)	500 (HVDC)
<b>Substation (substructure)</b>	250 MVA (Floating)	500 MVA (Not stated)	Yes (Floating)	Yes (Jacket)	1000 MVA (Floating)	No	No	No	Yes (Jacket)	Yes (Floating)
<b>Reference flow</b>	Up to the end of the subsea export cable	Up to the end of the subsea export cable	Up to the end of the subsea export cable	Up to the end of the subsea export cable	Up to the end of the subsea export cable	Up to the end of the subsea export cable	Floating unit only: no export cable	Up to the end of the subsea export cable	Up to the end of the subsea export cable	Includes onshore HVDC cable
<b>Array designs assessed</b>	1	6	20	1	1	1	n/a	2	1	1

	Weinzettal [156]	Raadal [157]	Tsai [158]	Elginoz [139]	Bang et al. [153]	Poujol [154]	Yildiz [159]	Garcia- Teruel [155]	Yuan [160]	Brussa [161]
<b>Life cycle stages</b>	Materials, Manufacturing, transport, O&M, dismantling, end-of-life credits	Production of raw materials, transport, installation, decommissioning, disposal	Manufacturing and assembly, installation, O&M, and decommissioning	Manufacturing and processing, transportation, installation; O&M; end-of-life	Manufacturing, transportation, installation, operation, decommissioning, and end-of-life treatment (credits)	Materials, manufacture, transport, offshore installation, grid connection, maintenance, end-of-life	Manufacture, transportation, erection, O&M, disposal, and recycling	Materials, manufacturing, installation (including transport), O&M, decommissioning, disposal	Components manufacturing and transport, wind farm construction, O&M, decommissioning, disposal	Raw materials supply, manufacturing and transport of components, assembly and offshore installation, O&M, dismantling, end-of-life including transportation

	Weinzettal [156]	Raadal [157]	Tsai [158]	Elginoz [139]	Bang et al. [153]	Poujol [154]	Yildiz [159]	Garcia- Teruel [155]	Yuan [160]	Brussa [161]
<b>Manufacturing processes</b>	Yes	No	Yes (excludes capital goods)	Yes	No	Yes	No	Yes	No	No
<b>Component transportation and installation</b>	Trucks, vessels	Vessels only	Trucks, vessels	Trucks, vessels	Trucks, vessels	Trucks, vessels	Trucks, vessels	Trucks, multiple vessel types	Lorry, barge	Lorry, ship, vessels
<b>Vessel representation</b>	t.km process (barge)	Fuel consumption	Fuel consumption data for shipping	t.km process (barge)	t.km process (transoceanic shipping)	Diesel (market for)	t.km process (not stated)	t.km process (ferry), scaled to vessel fuel consumption	t.km/direct fuel use	t.km/fuel consumption

	Weinzettal [156]	Raadal [157]	Tsai [158]	Elginoz [139]	Bang et al. [153]	Poujol [154]	Yildiz [159]	Garcia- Teruel [155]	Yuan [160]	Brussa [161]
<b>Maintenance vehicles</b>	Helicopter, towing boat	Not stated	Vessel, jack-up, crane	Barge, helicopter	Small boat, helicopter, specialized vessel, crane vessel	Not stated	Multiple vessel types	Multiple vessel types, road vehicles	Not stated	Excluded
<b>Maintenance frequency</b>	Assumed	Assumed	Assumed	Assumed	Assumed	Assumed	Assumed	Modelled	Assumed	Excluded
<b>LCA software</b>	SimaPro 7.1	SimaPro (version not stated)	SimaPro 7.3.2	GaBi	No (Excel)	SimaPro 8.4	Gemis 5	SimaPro 9.1	eFootprint	SimaPro 9.3
<b>LCI database</b>	ecoinvent v1.3	ecoinvent (version not stated)	ecoinvent v2.0	GaBi	ecoinvent v3	ecoinvent v3.3	Europa	ecoinvent v3.6	Chinese core life cycle database (CLCD)/ecoinvent v3.5	ecoinvent v3.7.1

	Weinzettal [156]	Raadal [157]	Tsai [158]	Elginoz [139]	Bang et al. [153]	Poujol [154]	Yildiz [159]	Garcia- Teruel [155]	Yuan [160]	Brussa [161]
<b>LCIA method/Impact category</b>	CML 2 baseline 2000 V2.03	CED	TRACI;  CED	CML 2001	GWP	ILCD 2011, AWARE, ReCiPe 2016 Midpoint (H), CED	GWP, AP, ADPF, EPT	ReCiPe Midpoint (H) 2016;  CED	CML 2002	EPD; CED
<b>Uncertainty assessment</b>	No	No	No	No	Monte Carlo (input data)	Background	No	Background	Foreground and background	No
<b>GWP [gCO<sub>2</sub>eq/kWh]</b>	11.5	25.3;  18.0;  20.9;  31.4;  19.2;  18.9	38.1;  32.9;  33.0;  33.8;  35.5;  33.1;	18.1	22.3	15.4	18.6	32.4–45.2 (tow),  30.2–32.7;  27.7–39.4 (tow),  25.6–27.6	25.8 (tow)	31.3

	Weinzettal [156]	Raadal [157]	Tsai [158]	Elginoz [139]	Bang et al. [153]	Poujol [154]	Yildiz [159]	Garcia- Teruel [155]	Yuan [160]	Brussa [161]
			33.9;  35.5							

### 3.3.1. Scope, detail and cut-off criteria

Life cycle models vary from a single turbine [159] to an array of 190 turbines [34], but generally, array-scale models are more common than in wave energy LCA studies. Water depths vary from 60 to 450 m in near-shore to distant offshore sites (3 to 200 km). The studies consider a mix of hypothetical, planned, pre-constructed and constructed sites, mostly in Europe, but include North America and, most recently, China [160]. Cut-off criteria are only explicit in Bang, [153]: 5% of product mass and 1% of input mass. Nearly all are HVAC export systems with only two recent studies including HVDC [160], [161]. Most models include the hardware up to the end of the export cable, but manufacturing processes and vessel operations during O&M are not consistent. No strong trends appear from these site characteristics across the overall research landscape, although within a single study (Tsai, [158]), water depth, distance from shore and distance to grid are shown to be the site characteristics which affect environmental impacts most significantly.

### 3.3.2. Life cycle impact assessment methods

Generally, the impact assessment methods are more wide-ranging than the wave energy literature and include multiple impact categories.

### 3.3.3. Life cycle stages

As with wave energy, the definition of life cycle stages is typically similar across the literature. The materiality of floating offshore wind farms is typically the most impactful stage across most impact categories, with O&M following. Installation, dismantling and disposal are typically less impactful. Component transportation (trucks and vessels) and manufacturing processes (for example, sand-blasting, welding and paint application) are variously present

and modelled in different ways and levels of detail. Overall, however, this typically has very little effect on the final results relative to the impact from the materials.

Only one study uses a dedicated O&M model to represent the O&M life cycle stage, and this study (Garcia-Teruel, [155]) finds median GWP to be amongst the highest in the literature, suggesting the importance of including this level of detailed modelling to accurately capture the impacts correctly. Overall, the O&M fuel use impacts are modelled diversely: vessels (and helicopters) are represented by different processes, for example: per tonne-kilometre (t.km) transportation of various vessel types; direct fuel consumption; or by scaling existing transportation processes to represent appropriate vessels. Poujol, [154], appears to use 'Diesel {Europe without Switzerland}| market for | Cut-off, U' (as stated in the papers Supplementary Material, Table S2-1), which – on inspection – represents the 'inventory for the distribution of petroleum product to the final consumer (household, car, power plant, etc.) including all necessary transports' [162], not the combustion of the diesel itself, implying the impacts could actually be higher than reported.

#### 3.3.4. Major components

A variety of floating substructure (platform) designs are considered, generally semi-submersible being the most common, commensurate with emerging technological consensus on the advantages of this design. For large arrays where substations are necessary, they are included, with examples of both floating and bottom-fixed jacket substructures: all studies but three include a substation of some kind [154], [155], [159], but this is appropriate for the small number of turbines in the respective life cycle models. As with wave energy studies, the most massive components are generally most impactful, typically the platforms themselves. Copper cables also start to appear as impactful components in multiple studies, notably [160],

[161], and for diverse impact categories (typically abiotic depletion of elements or mineral resource scarcity, acidification, eutrophication, toxicity potentials and ozone creation), due to their generally higher power transmission export cable (which drives the copper conductors cross-sectional area), and the distance to grid-connection point, which drives the cable length.

### 3.3.5. Impactful processes

Once again, reflecting the wave energy LCA literature, floating wind LCAs find steel and fossil fuel impacts to be significant throughout. Notably, the glass fibre reinforced plastic (GFRP) composition of the wind turbine blades create different impacts than the primarily steel WECs: comprising over a quarter (27%) of GWP [157]; along with steel being the highest two contributions to ODP and GWP [139]; 9% of GWP [155] but only up to around a maximum of 10%, and in water scarcity [161]. Conversely other studies find limited impacts, particularly [153], [154], [159].

### 3.3.6. Sensitivity and uncertainty

Sensitivity studies appear to be actually more limited than the wave energy literature, with [155], [157], [158] exploring multiple cases within a specific study instead. Energy production and capture factor are explored in [153], [154], [155], [157], [160], [161] with similar results to wave energy. Bang [153], provides a little riff on this by describing the essentially equivalent effect on the functional unit that would arise from wind turbine *curtailment* caused by grid operational constraints. Raadal [157] and Yuan [160] find similar results from increasing steel mass: a 1% increase resulting in changes in GHG emissions of between 0.12% and 0.5%, and a 20% increase leading to a 3% to 15% increase in the indicator scores of multiple impact categories. Perhaps reflecting the method of vessel representation, Raadal [157] finds that a 25% increase in fuel has comparatively little (5% to 8% impact) in GWP, which contrasts

against the more sophisticated treatment in Garcia-Teruel [28], which finds that more efficient 'offshore' (as opposed to 'towing') O&M strategies achieve reductions in GWP of 7% to 28% (for a Spar design) and 8% to 30% (for a semi-submersible design). This likely arises from the difference in the treatment of O&M between the studies, with Garcia-Teruel [28] using the findings from a dedicated O&M model compared to more simple assumptions in Raadal [157]. Poujol offers a sophisticated sensitivity study for a wide range of parameters finding (for a 20% variation in):

- Steel mass affects climate change impacts by around 7%
- Zinc, Aluminium and Lead mass cause a ~4%, ~2% and ~1% change in resource depletion
- Aluminium, steel, Copper mass and construction waste cause a ~2%, ~4%, ~5% and ~4% change in marine ecotoxicity
- Steel mass and fuel consumption each cause a ~4% change in CED.

Yuan [160] also demonstrates the dominance of steel mass across GWP, primary energy demand, acidification potential, particulate matter; while diesel affected ODP most, and copper affected eutrophication potential. Most recently, the sensitivity studies in Brussa [161] found limited impact from alternative blade end of life scenarios and either geared or direct-drive designs. It is challenging to summarise this variety, but clearly steel, fuel use and copper generally emerge as the most significant processes within the life cycle models, alongside lifetime energy production.

In terms of uncertainty quantification, the state of the art is approximately similar to wave energy LCA, with only [154], [155], [160] considering background uncertainty and Yuan approximating an assessment of foreground data uncertainty with a sensitivity study.

### 3.3.7. Emerging life cycle assessment techniques

Obviously, renewable energy in general is not environmentally-impact-free – indeed this is one of the latest rallying calls of the climate delayers – but, arguably, a mature and clear eyed assessment of the planetary state is necessary in order to avoid ‘energy transition’ iatrogenesis. Let us now take a short foray to the shores of other research which hints at a wider system view of ‘sustainable development’.

Two studies from 2022 describe the bulk *material* requirements of offshore wind on a global scale from 2020 to 2040 [163] and a prospective life cycle assessment of the aggregate environmental impacts thereof [164]. These studies find dramatic increases (by factors of around 5 to 15 times for certain rare earth elements and around 50 times for steel and concrete relative to current demand); that circularity can mitigate demand only to a minor degree; but that climate change, marine ecotoxicity, marine eutrophication, and metal depletion are reduced by approximately 20% per unit energy over the same period, finding that global offshore wind deployment between 2020 and 2040 emits 2.6 to 3.6 GtCO<sub>2</sub>eq.

### 3.3.8. Summary

Transparently condensing and communicating the high level of detail, assumptions and references required to generate a life cycle model inventory is not trivial, and this can be further exacerbated by the proprietary nature (or technology readiness) of the turbine, cable, substation and substructure technologies themselves, to say nothing of the commercially sensitive data such as maintenance burdens. Accordingly, it can be challenging to fully

interrogate the assumptions behind some of the literature. This, along with the differences in each practitioner’s style, life cycle model coverage and granularity, and the choice of life cycle impact assessment method, combine to make inter-study comparison difficult and, at worst, potentially misleading. To combat this, considering multiple arrays within a single study can be insightful. Other key gaps in floating wind LCA remain around the representation of O&M, which has tended to be represented by simple assumptions, and assessing very large turbines.

### 3.4. Climate change impacts of offshore renewable technologies

#### 3.4.1. Carbon payback time

Carbon payback time (CPT) or carbon payback is a metric investigated in around half of the wave energy LCA studies identified [129], [130], [132], [133], [135], [136], [142], [143], [144], [145], [146]. It is the ratio of the lifetime emissions of the life cycle model considered, divided by the displaced emissions, assumed as equal to the product of the system AEP and the average emissions intensity of the grid (Equation 2):

$$\text{Carbon Payback Time [years]} = \frac{\text{Lifetime emissions [kgCO}_2\text{eq]}}{\text{AEP } \left[ \frac{\text{kWh}}{\text{year}} \right] * \text{Emissions intensity of displaced electricity } \left[ \frac{\text{kgCO}_2\text{eq}}{\text{kWh}} \right]}$$

Equation 2. Expression for calculating carbon payback time.

Reducing coal generation on the GB national power system and increasing volumes of renewable energy have led to a reduction in the average emissions intensity of power from the grid (usually, carbon dioxide only, hence *carbon intensity*). This increases CPT, which can be an unflattering technical parameter when assessing new technologies in light of the climate

crisis, and may possibly explain why CPT is omitted in recent wave energy LCA papers such as Pennock, [147]. By contrast, CPT is not present in floating wind LCA.

CPT as a standalone 'nameplate' figure could be argued to be misleading as it is composed of three critical parameters: system AEP, carbon intensity of connecting power grid (typically nationwide annual average), and lifetime embodied carbon (determined from by LCA). As shown in Table 3.1, the carbon intensity used to determine CPT varies widely, and makes the CPT highly localised given the local variation in carbon intensity of power grids in *space*, and in *time*, as the carbon intensity of power tends to reduce with increasing penetrations of renewable energy (Figure 3.1).

### 3.4.2. Comparing global warming potential for offshore renewable energies

LCA studies of tidal stream and fixed-bottom offshore wind (FBOW, as opposed to floating wind) usually share many similarities in terms of scope, methodology and modelling approach to array infrastructure and vessel operation assumptions to the wave energy and floating wind literature reviewed in previous sections. The tidal stream LCA literature is even sparser than wave [136], [137], [165], [166], [167], [168], and yields a range across different technologies of 10.7 to 34.2 gCO<sub>2</sub>eq/kWh (via [111]). The offshore wind LCA literature is more developed, with climate impacts 5.2 to 32.0 gCO<sub>2</sub>eq/kWh for offshore wind [169]. Like wave energy and floating wind, materials and manufacturing account for the majority (for example 86% in Douglas, [166] and more in Uihlein [137]).

Figure 3.2 shows the variation across these four technologies. Wave energy stands out with the highest median GWP followed by floating wind, tidal stream and offshore wind. The variety in WEC designs leads to a significant spread in the wave energy GWP data. The two

technologies with the highest GWP (wave energy and floating wind) will be analysed in detail using gaps from the literature in Chapters 4 and 5.

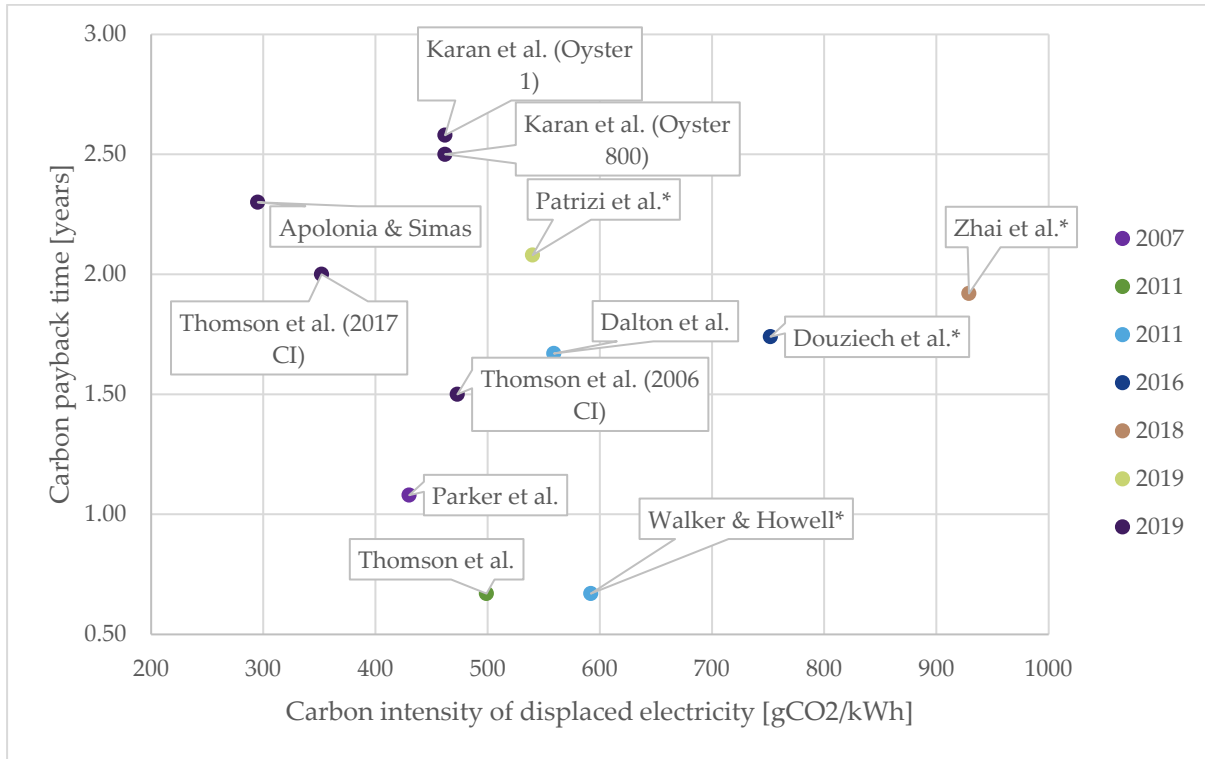


Figure 3.1. Variation in carbon payback time and carbon intensity of displaced power. The legend indicates the year of publication. The year in braces in the call-out indicates the carbon intensity assumed in the carbon payback calculation. The \* indicates that the CPT is back-calculated from values in the study (Zhai CPT = 23 months; Patrizi CPT = 25 months).

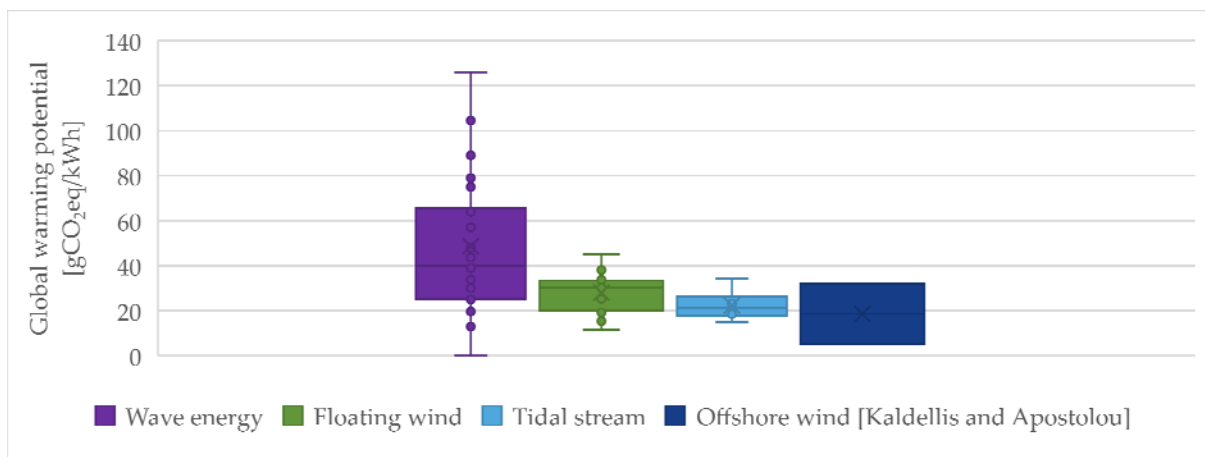


Figure 3.2. Overview of GWP for different offshore renewable energy technologies.

## 3.5. Quantifying the environmental impacts of renewable energy technologies in future energy systems

### 3.5.1. Background

This section considers the literature where environmental impacts of power generation technologies are considered when integrated into a wider energy system, beyond a static attributional LCA. Two main branches emerge, which have been termed here:

1. **“System-wide Accounting”**: where the impacts of each technology in the future energy system are considered.
2. **“Avoided Accounting”**: where the avoided impacts attributable to the generation technologies are considered.

Avoided accounting is the most likely to be used in this Thesis, but the System-wide approach is review for context.

#### 3.5.1.1. Energy System relative to Power System

Like Chapter 2, let us begin with definitions of the energy and power systems for this Thesis.

- **Energy system**: is the sequence necessary to meet the energy demand for a given society or economy beginning with the extraction of primary energy and ending with use of final energy, [170]. This includes the *resources* (renewable energy, fossil fuels, fissile material, biomass), *infrastructure* (generation, storage, transmission, transportation) and *demand* (industrial, commercial, domestic, agricultural, transportation) within a specific region or system over time, across multiple *vectors* (typically electricity in the power system, methane, oil, coal and perhaps novel vectors

such as hydrogen or ammonia). The energy system can be represented to varying degrees by some or all of these aspects.

- **Power system:** the interconnected components to generate, transmit, and distribute *electrical energy* to end users. In essence, the power system is effectively only a part of the wider energy system. With increasing electrification desirable for emissions reduction, the power system will encompass the heating and transport sectors which are today largely non-electrified.

### 3.5.1.2. Model Groups

“Energy system models” use axioms (primarily mathematical) to create a functioning apparatus which represents some characteristics of the energy system. The models are extremely numerous and can be differentiated along several dimensions (Figure 3.3).

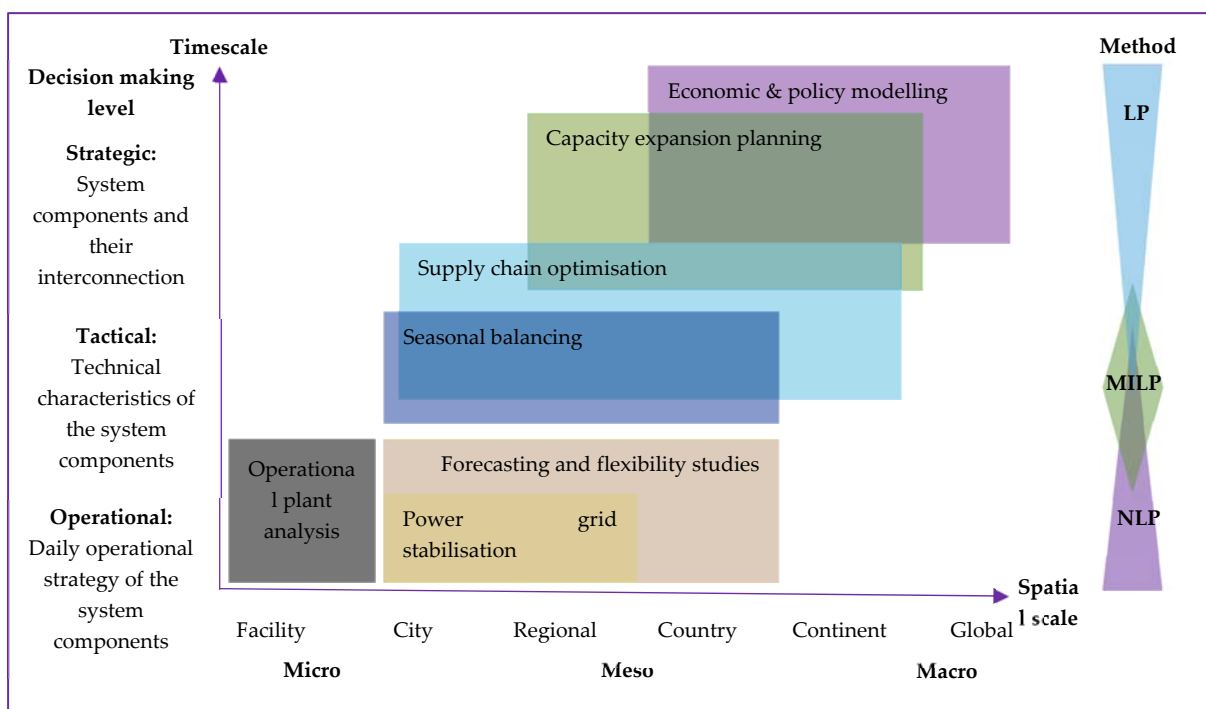


Figure 3.3. Multi-scale modelling for energy systems. Adapted from [171]. LP = linear programming, MILP = mixed integer linear programming, NLP = non-linear programming.

At a high level energy system models can be delineated in general terms by [170]: calculation *method* and intended *purpose*; focus on *planning* (forward looking or strategic) or *operations* (immediate-term); and temporal window – *snapshots* or *pathways*.

**1. Method and purpose:**

- a. **Optimisation method, for the purpose of outputting scenarios** outputs an *optimal system design* according to specified ‘norms’ (making the models ‘normative’) to minimise or maximise an *objective function* within defined constraints, for example minimising total system cost, or achieving targeted GHG emissions while meeting specified demand [170]. The optimisation method may be achieved through use of linear programming (LP), mixed integer linear programming (MILP) or non-linear programming (NLP) [172].
- b. **Simulation method, to produce forecasts (‘Predictive’):** predicts the *performance* of a known system design in response to given initial conditions and according to physical or economic behaviours.

**2. Planning or operational models:**

- a. **Planning:** typically low spatial resolution, used to optimise national-scale future scenarios over the long-term (also known as capacity expansion models). Some recent power system models have also developed this functionality [173].
- b. **Operational:** usually national-scale or finer, these models determine how energy (often electrical energy in the power system) is dispatched per timestep to meet demand.

**3. Snapshot or pathway models:**

- a. **Snapshot:** outputs information at a single point or end-state of a system.
- b. **Pathway:** shows how the system will evolve to reach that state.

In more prosaic terms, energy system models can be divided into four main groups (Table 3.4), or by detailed functional capabilities, as detailed by Hall and Buckley [174]. The imprecision of the descriptions above reflects the variety of extant models, which are challenging to categorise succinctly.

Table 3.4. Four energy and power system model groups [170].

	Model group	Primary Focus	Examples
1.	Energy system optimisation models (ESOMs)	Normative scenarios	MARKAL, TIMES, MESSAGE, OSeMOSYS
2.	Energy system simulation models (ESSM)	Forecasts, predictions	LEAP, NEMS, PRIMES
3.	Power system models, Electricity market models (PSM, EMM)	Operational decisions, business planning	WASP, PLEXOS, ELMOD, EMCAD
4.	Qualitative and mixed-methods scenarios	Narrative scenarios	DECC 2050 pathways

#### 3.5.1.2.1. Energy system optimisation models

Energy System Optimisation (or Planning) Models (ESOMs/ESPMs) output future energy system scenarios according to *objective functions* and specified constraints via linear optimisation, usually to minimise total system cost or GHG emissions. ESOMs are usually ‘bottom-up’, having detailed representation of technical hardware (): primarily the electricity network, gas network and fuels for industry or transport. ESOMs typically cover a national or regional spatial scale with temporal coverage over many years at annual or sub-annual (seasonal) resolution. However, given the breadth of their coverage, ESOMs usually make

significant simplifications to remain tractable. Characteristically, ESOMs tend to use “time-slices” (Summer/Winter, Morning/Day/Evening/Night etc) as temporal resolution, and limit the representation of power plants, typically excluding techno-economic or operational constraints (such as ramp rates) which can have a significant impact on the results [175]. These simplifications are sufficient for modelling traditional energy systems dominated by dispatchable fossil fuel, biomass or nuclear power, but are not ideal for systems with significant penetration of VREs [170]. This type of model does have precedence of use with LCA (Section 3.5.2.1).

*Box 3.1. Top-down, Bottom-up and Hybrid energy system models*

*Top-down energy system models* use historical data to represent economy-wide responses to changes in the energy system [174]; the energy system itself is usually represented in a simplified manner. Top-down models are typically used to assess the effects of energy and climate interventions on other socio-economic sectors, such as employment [176]. Using historical data for future changes (given the radical futures ahead) could be viewed as potentially misleading.

By contrast, *Bottom-up energy system models* are technologically explicit and analyse the components and interconnections between the different energy sectors in detail [174]. However, to be tractable, connections between the energy system and other sectors are simplified or absent [176].

*Hybrid models* were developed in the 1990s and can be soft-linked (MESSAGE-MACRO) or hard-linked (MARKAL-MACRO), but these have not supplanted established bottom-up models.

#### 3.5.1.2.2. *Energy systems simulation models*

Energy system simulation models (ESSMs) also represent the entire energy system at a national or regional scale. However, these are primarily used to provide *forecasts* of how the system will perform based on an initial conditions and simulation modules, rather than *optimising* the system design in response to an objective function [170]. This type of model is relatively uncommon in combination with LCA (Section 3.5.1.2.2).

#### 3.5.1.2.3. *Power systems models*

Power system models (PSMs) usually have more detail and capability to model temporal variation (with resolution of at least one hour or less) given the key requirement of a power system to continuously balance supply and demand to ensure specified power quality. Power system models *usually require scenarios as inputs* but some examples can also be run in an optimisation mode. Some PSMs may include energy vectors such as hydrogen.

#### 3.5.1.2.4. *Electricity market models*

EMMs consider electricity markets rather than the physical characteristics of the power system. These can be used to explore possible electricity market regulation or inform investment choices [170] and are relatively ill-suited to quantifying avoided emissions from a particular technology. Power systems models are more common than EMMs in combination with LCA (Section 3.5.1.2.3 and 3.5.1.2.4).

#### 3.5.1.2.5. *Qualitative scenarios*

Engineering judgement, expert elicitation or stakeholder engagement can also be used to develop qualitative energy system scenarios. Potentially, these avoid the obscurity of quantitative models described above, by depending on subject matter experts [177].

#### 3.5.1.2.6. *Integrated Assessment Models*

Integrated assessment models (IAMs), combine interdisciplinary mathematical representations of the socioeconomic metabolism of the technosphere (for example population, GDP, agricultural practices, economic markets, energy systems, carbon taxes, infrastructure), and the planetary domains of the ecosphere (such as the carbon cycle, water cycle, and land use) to assess the likelihood of achieving specific societal goals, such as global warming temperature targets. These are not truly considered in this thesis, but indicated for completeness and context.

### 3.5.2. System-wide life cycle impact accounting

The combination of LCA and future looking energy system models is becoming more widely practised [178]. Most energy system models of any of the groups described tend to have a relatively limited environmental impact assessment (usually only operational CO<sub>2</sub> or GHG emissions), and so neglect a more comprehensive assessment of the total life cycle impacts, potentially leading to burden shifting or the inability to identify potential co-benefits from future energy systems features. On the other hand, unlike most LCA studies, most energy system models include economic dimensions, which are usually fundamental to policymaking. Some models (ESOMs, IAMs) also explicitly output future changes in production systems, which is a major advantage, given this is a limitation of static LCA background data. Combining these types of models has the potential then to improve the temporal and technological representativeness, completeness and precision of inventories [179].

Figure 3.4 shows the difference in system boundaries for energy system models and LCA. This subsection describes the literature of these combined models to identify gaps for the research questions of this thesis.

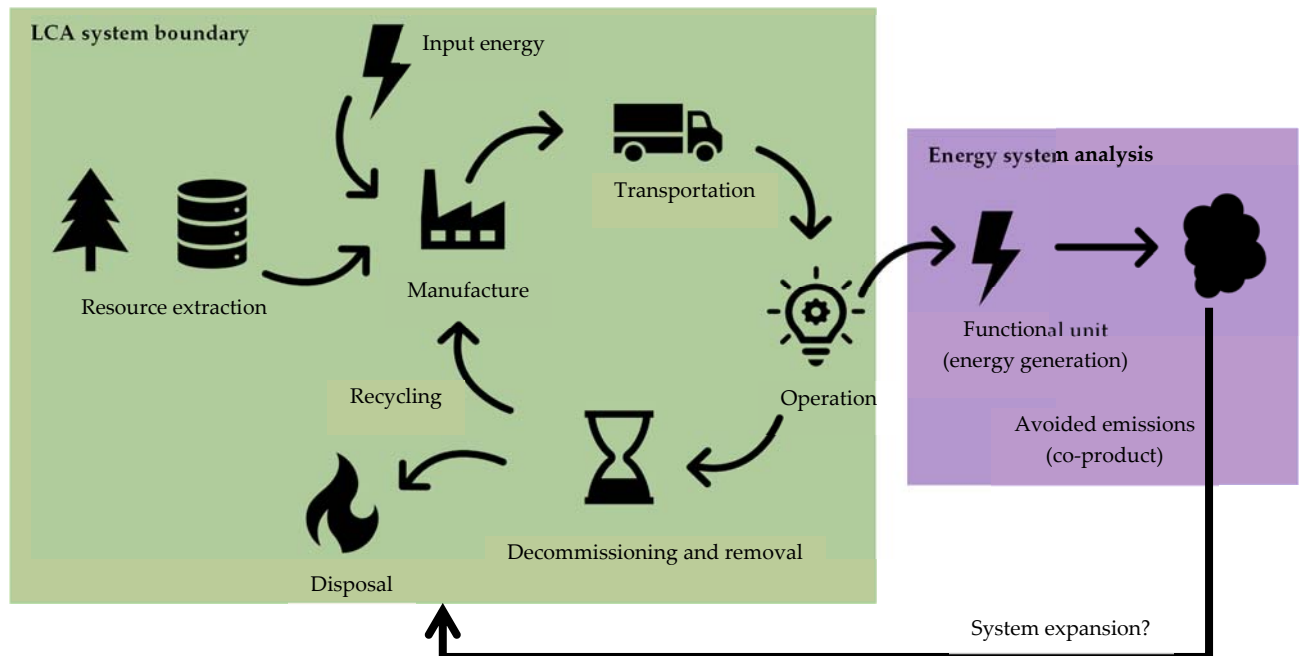


Figure 3.4. Graphical representation of the difference in the system boundaries for LCA and energy system modelling. LCA includes the environmental impacts from the whole life cycle, while energy system modelling focuses on direct emissions from the use phase of, in this case an energy technology (energy inputs to other life cycle phases might be included depending on the production location) [180].

### 3.5.2.1. LCA + ESOM

Two main approaches are available for combining LCA and ESOM: the 'ex-post' assessment of the results from an ESOM versus the optimisation of environmental impacts as a variable *within* the ESOM itself.

Ex-post analyses include the energy systems of the UK [181], Europe [182], [183], [184], Brazil [185], Quebec [186] and USA [187], with timeframes from 2030 [187] to 2050 [185] being most common, in line with the time horizons of Paris compliant pathways (Chapter 2). As with the

generation technologies themselves, highly renewable energy systems reduce life cycle climate change impacts compared to fossil fuel systems [182] along with reduced ozone layer depletion; terrestrial, marine and freshwater eutrophication; photochemical ozone creation, but with larger (sometimes significantly) non-fossil mineral resource depletion, ecotoxicity and human health impacts [188]: in one study Paris Agreement 2°C compliant systems resulted in burden-shifting in up to eight environmental impacts [187].

Accordingly, the literature is not conclusive on least harmful (or Paris or planetary boundary compliant) energy system design: on one hand, mitigating climate change by replacing fossil fuels with non-fossil power reduces the impact on human health and ecosystem quality via reduced fossil fuel and water use [186]; alternatively (for the European energy system) indirect CO<sub>2</sub> emissions can be as large as direct emissions in highly decarbonised energy systems, and toxicity impacts can become a third to twice as high [184]. Another study has shown that additional warming can arise when life cycle emissions are considered in an ESOM, via methane releases from increased use of hydropower [185]. Subsequently then, the marginal abatement *cost* of mitigating *life cycle* emissions (as opposed to direct emissions, which is the metric frequently used in common discourse) could be higher than direct emissions; by one example, by a factor of two in the UK in 2050 [181].

Recent years have seen significant innovation in this space with open-source developments linking ESOMs and LCA via python open-source software, wurst and Brightway 2 [186]; FRITS (FRamework for the assessment of environmental Impacts of Transformation Scenarios) [189]; SecMOD (Sector-coupled energy system model) [190] which is augmented by dynamic LCA [188]. The integration of dynamic LCA (adjustment of the background database, as introduced here [191]) reduced 9 out of 17 impact categories, which 5 not

significantly influenced, indicating that static LCA remains sufficient for identifying general trends in energy system optimisation and assessment (at least for Germany until 2050), which informs the approach taken in this thesis. Lastly, the range of technologies that is included in the literature varies, but all studies exclude floating wind and only a handful include marine (wave power only in 2016 [192] and 2018 [193], and tidal stream and wave energy in 2021 [188]).

Studies which combine the life cycle impacts (usually GHG emissions only) *into* the energy system optimisation are much rarer and typically more recent. Including GHG emissions into the optimisation obviously affects the optimal system design [183], with higher GWP technologies (solar) being crowded out by lower ones (wind); which would clearly affect the higher GWP wave energy as considered in this thesis. Burden shifting between fossil fuels and renewable energy is confirmed by this approach too, with climate impacts migrating from direct to indirect emissions, and with poor environmental performance of lowest cost systems, echoing the findings of increased abatement costs from other studies [194] and [195].

*Box 3.2. Energy systems Modelling and Absolute Environmental Sustainability Assessment (Future work)*

The planetary boundaries framework can be applied in energy systems modelling to assess the absolute environmental sustainability of a given energy system design in a specific region [171]. For example, at a territorial scale, Taiwan's nationally determined contribution (NDC) targets have been assessed as "not ambitious" relative to climate change and ocean acidification planetary boundaries, and with very high risks in territorial biogeochemical flows [196]. Similarly, over the period 1995 to 2009, the economies of Canada and Spain (and two sub-regions thereof), all failed to consume resources with their shares of four planetary boundaries (climate change, biogeochemical flows, freshwater use and land-system change)

[197]. It follows then that global energy provision may breach bio- and geophysical planetary boundaries [171]; a claim that is supported by regional studies for the US and Europe. Using an American energy systems model, the least cost 2°C Paris compliant energy mix would still transgress five of eight PBs [198], however *doubling* the energy system cost relative to the least cost solution (using offshore wind, CCS gas and BECCS) achieved transgression of only one PB. In practice though, this extra cost was equivalent to only 1.3% of the USA GDP in 2017. More concerningly, a European case study used two sharing principles to demonstrate that no power system scenario (of three) was PB compliant [199]. These findings [198], [199] lie parallel to the discourse from Chapter 2 regarding living within planetary boundaries.

Overall, the AESA concept asserts that engineers must change the current focus on only eco-efficiency (the inverse of the environmental intensity of a technology, Chapter 2) to a search for “solutions that are effective in terms of operating within the share of the total pollution space that they can claim” [200]. Philosophically, some authors assert that AESA is inescapably relative through the choice of sharing principles [201], perhaps prompting the development of the “Fulfilment of Human Needs” (FHN) principle that operationalises *sufficientarianism* (making sure everyone gets enough) [202]. Certainly, the sharing principles for AESA of energy systems should be assessed carefully to account for historical, colonial, and intergenerational dimensions: underlined by the rolling debate about how to actually translate the Paris Agreement into globally equitable Carbon Budgets [203].

#### 3.5.2.2. LCA + ESSM

LCA and energy system simulation models are far less common in the literature than LCA + ESOM combinations. An early example from 2008 uses the EnergyPLAN simulation model [204] to develop hourly computer simulations for future scenarios (2030, 2050) for Denmark

using exogenous scenario assumptions. Perhaps given their age, this includes an optimistic 1 GW wave power [205]. Environmental impacts were then calculated for the Danish energy system in 2030 using ecoinvent and SimaPro [206], yet again confirming burden shifting from a reduction in GHG to increased depletion of abiotic resources [207].

### 3.5.2.3. LCA + PSM

LCA and power system models can contribute to a more accurate understanding of the temporal performance of a technology when integrated in a wider power system. Generally, the PSM uses exogenous definitions of a power system “portfolio” as inputs to the analysis. For example, detailed hourly resolution unit commitment and economic dispatch assessments were performed on scenarios of the Irish power system in 2025, finding that cycling emissions of thermal power plant increased with the installed wind capacity (decreased with the addition of storage), but were overall less than 7% of the life cycle emissions of the total system portfolios [208]. Cycling emissions are recommended to be considered, but the bulk emissions are not related to the attributional GWP. Relevantly for marine energy, a 2023 study [126] emulates the proposed method of this PhD, for the year 2030 using the CorPower point absorber wave energy converter (WEC) and a simple tidal stream turbine. Like this thesis, this study uses the Future Energy Scenario ‘Leading the Way’ as a case study, and a scenario with adjustment as a counterfactual. The study finds that increased wave power and tidal stream installed capacities consistently reduced emissions (and system costs) relative to scenarios without, and that marine energy – at 0.5% of total installed capacity in 2030 – reduced total dispatch costs by up to 1.1% and operational emissions up to 3.3%, but does not attribute the multifunctionality of this emission reduction as co-product of the WEC or tidal turbine on a life cycle basis.

#### 3.5.2.4. LCA + EMM

Only one relevant study of LCA and electricity market model could be found: a chapter which finds increased land use, metal and ozone depletion for increased penetrations of solar in European renewable energy scenarios [209].

#### 3.5.2.5. LCA + Scenarios

Examples of life cycle assessments of UK, [210] (uniquely, to 2070 [211]) or global future energy scenarios [212], generally find greatly increased demand for materials. Marine rarely features; one notable exception considers the projected (direct + indirect) impacts from the UK Electricity Supply Industry (apparently in terms of total energy delivered) in three exogenous scenarios over 1990–2050 using SimaPro and ReCiPe 2008 [213]. Another [211] includes the Wave Dragon WEC, and finds scenarios of up to ‘16 GW of biomass and marine’ combined. Ocean and tidal is included in [214], and by now the risk of burden shifting from climate change to other environmental impacts to decarbonise the energy system is abundantly clear [215]. In a very high level (global) study, the scale of cumulative attributable emissions from the new energy system hardware is found to be small with respect to remaining carbon budgets [217]. Further, a global low-carbon electricity scenario showed strong human health benefits but (concerningly) a significant trade-off for ecosystem quality arising from bioenergy [218]. As mentioned in Box 3.2, a 2023 study combines three existing scenarios with the AESA framework [199], for the European energy system finding that none were within Europe’s Share of the Safe Operating Space by either of the two sharing principles considered. Lastly, at a UK level, three pathways for generation technologies (including tidal and wave) were assessed on a ‘cradle-to-gate’ basis [219], with an alternative treatment in [177] showed improved impacts in almost all impact categories relate to 2008 generation mix.

### 3.5.2.6. LCA + IAMs

Multiple examples of life cycle assessment and integrated assessment modelling exist, but will not be discussed at length given the scope of this thesis. For IAMs, life cycle impacts tend to reduce through time for different technologies [220] and life cycle emissions have only minor effects on the results of cost-optimal mitigation scenarios [217] (replicating findings from a smaller European-scale ESOM study [183]). IAMs have been used to model global metallic and non-metallic mineral use for the construction of hydro, solar, and wind generation [221], and this developed in a subsequent study which includes moderate electricity production from marine energy having a “relatively large material footprint” [222], which aligns with the findings from chapter 4.

#### *Box 3.3. Using Prospective Life Cycle Inventories in Future Looking Energy Systems analysis*

Conventional LCAs are static in time and use historical data to inform potential environmental impacts. However, in the future, production systems are anticipated to change radically, creating uncertainty in future-orientated LCAs. Alternatively, a new technique has emerged in recent years: Prospective LCA [101]. Prospective LCA needs to deal with the large epistemological uncertainty about the future to support robust future environmental impact assessments [191]. One approach is to systematically amend the background processes based on scenarios of an the IAM; Luderer et al comprehensively explored decarbonization pathways using five structurally different IAMs [223]. In that study, all decarbonization pathways yield major environmental co-benefits, but the scale of co-benefits and negative side-effects are strongly dependent on technology choice: scenarios focusing on wind and solar power are more effective in reducing human health impacts compared to those with low renewable energy, but induce a more pronounced shift away from fossil and toward mineral

resource depletion. Conversely, non-climate ecosystem damages are highly uncertain but tend to increase, chiefly due to land requirements for bioenergy. The study does not include marine energy.

An example for future research is Futura; open-source software which creates novel background databases for LCI representing arbitrary scenarios [224].

The approach for such a future-oriented LCAs still divides the research community, and formal guidance is currently missing: LCA's ISO standard does not offer explicit guidance on modelling future and long-term solutions. LCA of products and systems that do-not-yet-exist inescapably involves practical challenges, which is well described in a recent comprehensive review [225].

### 3.5.3. Avoided life cycle impact accounting

This section will consider the literature of extant examples of accounting for additional impacts by integration with the energy system. It is important to note that in each example a *counterfactual* is required for avoided impacts of any kind to be quantified, inherently introducing some level of uncertainty.

- The potential for avoided GHG emissions from solar PV in the United States for the year 2009 is calculated by assuming 10% of total generation is replaced by solar, using the hourly energy system simulation model EnergyPLAN [226]. The avoided emissions ranged from 0.67 to 1.5 MtCO<sub>2</sub>/GW in this year, and were not related to an LCA.
- Avoided emissions of 1.0 to 2.0 MtCO<sub>2</sub>/GW in the year 2030 are calculated for wind generation in Brazil, excluding a life cycle perspective [227].

- A 2020 study [228] considers a 49.5 MW onshore wind farm (33 turbines at 1.54 MW). The study asserts a farm AEP of 11.8 GWh/year, which back-calculates to a concerning low capacity factor of around 3%. Further, the lifetime carbon reduction potential is given as 179.5 MtCO<sub>2</sub> with a carbon intensity of the Chinese grid stated as 866.3 gCO<sub>2</sub>/kWh. This implies a lifetime generation of 207,238 GWh, or an AEP of 10362 GWh/year, suggesting an error in the reported figures. This makes it difficult to fully understand the calculation, but the ideation is similar to that presented later in this thesis, setting a precedent for this style of calculation.
- The “climate change mitigation potential” of nuclear power is calculated to be around 2–3% of the yearly global GHG emissions in the years 2020–2040 (stated as 1.1 to 17.6 Gt). A life cycle perspective is included to find the net reductions (that is, the avoided emissions minus the life cycle emissions) [229]. While the methodology is not terribly clear, this does set a small precedent for the analysis in chapter 8.
- In 2022, [230] a TIMES model was used to determine the diverse GHG emissions savings of wind and solar in the United States at an hourly resolution. The study found that the emissions savings, when converted into social costs of carbon, did not outweigh the required system integration costs, but beyond the emissions savings quantification, no LCA techniques were used.
- Alternatively, in 2023, the regionally distributed carbon abatement potential (CAP) of wind power in China in the years 2030 and 2060 – through obviation of coal generation – is quantified, accounting for changes in wind resource due to climate change, under specific shared socio-economic pathways (SSPs), without considering life cycle emissions [231].

### 3.5.4. Summary

This section has reviewed the scientific literature which assesses the life cycle impacts of future energy mixes in a ‘system-wide’ and an ‘avoided accounting’ approach, where the ‘system-wide’ approach typically covers many technologies and impact categories without considering consequential changes, and ‘avoided accounting’ approach typically considers only GHG emissions (usually just carbon dioxide) for a particular technology, between some scenario and a counterfactual.

Overall, there are multiple methods to assess the life cycle impacts of future energy systems, and the roles of specific technologies within them. Most LCA and energy system combinations are ESOMs, with burgeoning open-source development in this area. These are limited in their temporal resolution which is an issue for VREs, but can output novel scenarios based on multi-objective optimisation, including minimising environmental harms, although ex-post analyses using ESOM optimal scenarios are most common. A few examples of LCA combined with “hour-by-hour” dispatch models do exist [177], [205], [206], [207], but are based on non-GB energy systems, or could be updated to focus specifically on emerging technologies and avoided emissions.

Repeatedly, the literature finds that energy systems comprising wind and solar (and occasionally nuclear) offer multiple environmental co-benefits compared to contemporary energy systems, but come with an increase select environmental impacts, such as mineral depletion, ionising radiation, toxicity, and ozone depletion.

Numerous examples of amending the life cycle inventory databases to represent future energy scenarios also exist. This is almost exclusively achieved by amending the regional electricity mixes, but in some cases the material processes themselves [214]. These seem to stem from

the THEMIS and EXIOBASE projects and applications. There is a prolific literature from Gibon, Turconi, Arvesen, Astudillo and related research institutions using these applications, in a variety of geographical and technological coverage. However, these techniques appear to have recently been superseded by prospective LCAs [191], which instantiates open-source modifications to the ecoinvent database for a given scenario. This direction currently culminates in enticing python-base open-source code [224].

In general, there are only a scattering of papers which include marine energy, or differentiate it to wave and tidal stream, and even then, with very low deployment relative to wind and solar. Only one pre-print considers floating wind explicitly [232]. The emissions reduction potential is occasionally discussed, rarely taking centre-stage, and is never really combined as multifunctional co-product in combination with LCA. A few examples of carbon reduction potential exist, but are far less sophisticated and are often a secondary analysis strand to the study's main gist, and possibly susceptible to higher degrees of uncertainty due to their requirement for a counterfactual scenario.

#### 3.5.4.1. Proposed method to quantify the environmental impacts of renewable energy technologies in future energy systems

In light of the findings above, the proposed method to quantify the environmental impact of select renewable energy technologies in future energy systems for this thesis is to:

1. Take the life cycle impacts of the arrays in isolation, as determined by the static, attributional life cycle assessments in Chapter 4 and 5;
2. Identify an approach whereby the potential *change* from the installation of novel renewable energy *relative to some baseline* can be measured (considered an 'avoided impacts approach');

3. Specify requirements for a model and dataset suitable for this approach;
4. Review the literature and identify a suitable networked energy system model;
5. Model possible futures and determine the emissions output over a specified year of operation, then use augmented scenarios with increased levels of installed capacity of specific technologies as counterfactuals and determine the emissions output for the same years (developed in Chapter 7);
6. Combine these with the life cycle emissions to provide new insight to the carbon payback of these technologies (explored in Chapter 8).

#### 3.5.4.2. Modelling requirements as determined by this section

The model requirements to achieve the proposed method are therefore:

- Future looking (out to 2050), with ease of use to developing power system input data;
- Ideally open-source and tractable on laptop computer;
- Able to model multiple technologies, but especially with capability to include variable renewable energies as well as flexibility, and energy storage;
- Able to account for hydrogen, transportation, and heating;
- Accessible technical support;
- Spatial scale: national (GB, not global);
- Temporal scale: likely to be hourly, depending on subsequent exploration of complementarity, Section 3.6 (eliminating most ESOMs, driving towards PSA tools);
- Able to model (at least) CO<sub>2</sub> emissions;
- Adaptable to suit needs of life cycle emissions reduction potential calculation;
- Able to disaggregate emissions spatially and temporally within GB.

The next section will discuss the concept of complementarity with reference to the above to complete the energy system model requirements, before the model is selected in Section 6.3.

## 3.6. Renewable resource complementarity and modelling methods

This section introduces the concept of complementarity and discusses renewable resource modelling, with a view to describing the potentially beneficial complementary properties of floating wind and marine energy compared to other forms of generation, and specifying an appropriate spatial and temporal scale for the energy system analysis.

### 3.6.1. Definition

Complementarity is the capability of discrete systems to work in a complementary way; which can be observed in time, space and jointly in both domains [233]. Complementarity can improve the overall reliability of an energy system to deliver power, especially for diverse types (and spatially distributed) VRE generation. This creates the opportunity to increase the carbon reduction potential of a technology if this also complements local demand, avoiding emissions from thermal stations which could be a key benefit of diversity of generation types.

Three types of complementarity can be considered:

- **Spatial complementarity:** occurs when scarcity of one VRE in a region is complemented by its availability in another region at the same time, subject to suitable transmission or distribution of power. For example, the smoothing effect of spatially distributed wind generation due to large spatial scale differences in wind resource.

- **Temporal complementarity:** occurs when VREs have complementary availability in the time domain. For example, wind is abundant in the winter months, while solar is abundant in the summer months (despite being potentially co-located).
- **Spatio-temporal complementarity:** is a combination of the two. For example, the solar generation in the south of Europe is highest in the summer, while the wind generation in the north of Europe is most productive in the winter.

Complementarity is an important factor for secure, reliable and affordable power systems with high installed capacities of VRE [234], and enables higher deployment and energy export with lower volumes of energy flexibility (such as storage and curtailment) [235], maximising the energy export of existing network capacity [236], [237].

### 3.6.2. Complementarity characteristics of technologies under consideration

The following section provides an overview of the complementary characteristics of floating wind and marine energy around the UK, to inform the modelling requirements and method for this thesis.

- **Floating wind:** is rarely explicitly defined in energy system modelling studies. However, in one clear example, the increased spatial diversification (access to water depths of 70 to 1000 m) offered by floating wind compared to fixed-bottom offshore wind enabled a reduction in the installed capacity of backup generation. This study considered the GB power system in 2050 using the power system optimisation model highRES, and employed wind resource data at a spatial resolution of 0.5° latitude and longitude with the coverage of one year, a transmission network model of 20 zones and output results at an hourly temporal resolution.

- **Marine (combined assessment of wave power and tidal stream):** is usually only a significant contribution to national capacity of ESOMs when other generation technologies are proscribed (no new nuclear or carbon capture and storage) [238] or CCS alone [239]. Similarly, using an ESOM (UK TIMES) and power system model (PSM) highRES, found that only under very favourable economic conditions would marine energy have a significant contribution to the UK's energy system decarbonisation [110]. The complementarity of marine energy does offer system benefits when considered in PSMs [116], [126] but it tends to appear only in small volumes in UK pathways to Net Zero due to its high relative cost of energy [240].
- **Wave power:** is highly persistent at high energy sites in the UK [116]. Across Europe, remote generated waves driven by Atlantic swell (rather than fetch) have the most beneficial complementarity with wind, which tends to be driven by more local weather conditions [241]. Nevertheless, even for continental Europe scale (echoing the marine studies above), wave energy requires high carbon prices and efficiency improvements to achieve even moderate installed capacities using ESOM (JRC-EU-TIMES), although the temporal resolution is very coarse, potentially masking the system benefits [113].
- **Tidal stream and tidal lagoon:** by contrast, tidal power oscillates rigidly from maximum to zero power output four times per day, repeating over a 14-day cycle. Tide times vary around the coast of GB, so distal tidal sites have the same variability but with some phase lag depending on location [242]. Tidal lagoon sites could be large (around 1 GW scale) and have similar variability if built [103]. Tidal power availability has different cycle to consumer demand patterns, but has been empirically shown to be highly predictable [243], which is advantageous for power system operation. Tidal stream has been shown to complement the GB 2050 whole energy system by displacing

some capacity of thermal plant and lowering system integration costs, especially in high electrification (rather than hydrogen) pathways [244]. Interestingly, tidal stream in England and Wales is demonstrated to have 2.5 to 4% higher system value than in Scotland due to the requirement for transmission investment to alleviate network congestion. Understandably, the value of tidal stream also falls when interconnection capacity is increased.

In essence then, all studies reviewed find system benefits of renewable resource complementarity: lower back up generation requirements; lower storage requirements; reduced overall variability in net load; reduced extreme values in net load; reduced ramping requirements; more renewable generation can be installed (hosted) and total energy export can be increased.

### 3.6.3. Modelling requirements as determined by this section

In addition to the modelling requirements defined in Section 3.5.4.2, the following requirements are confirmed:

- Spatial scale: national (GB, not global)
- Temporal scale: hourly

The temporal resolution drives the model selection towards PSM, eliminating ESOM from consideration. The next section will discuss the availability of input data for such a model.

While smart grids techniques such as active network management further boost the value of resource diversity, these will not be modelled explicitly and the basis of the project scope. Similarly, while climate change has been shown to be impactful on renewable resource to varying degrees in multiple studies [245], [246], [247], incorporating the impacts of climate

change on the diverse resources under consideration was omitted and described as further work. The specifics of resource and device interaction are described in Chapter 7

### 3.7. Conclusion

This chapter has reviewed the literature for wave energy and floating wind LCA, contextualised the climate impacts relative to fixed-bottom offshore wind and tidal stream, and reviewed the scientific literature which assesses the life cycle impacts of future energy mixes in a 'system-wide' and an 'avoided accounting' approach (where the 'system-wide' approach typically covers many technologies and impact categories without considering consequential changes, and 'avoided accounting' approach typically considers only GHG emissions for a particular technology, between some scenario and a counterfactual). In conclusion:

- The wave energy LCA literature includes significant variety primarily in device types and results, but with commonalities in functional units, background databases and LCIA methods. Wave energy studies typically consider a single device or a small demonstration array rather than a utility-scale wave farm including a substation. Floating wind LCA literature appears to exhibit more commonality (given the technological consensus on horizontal-axis commercial machines) but still includes a variety of floating platform concepts, locations, site characteristics and turbine sizes.
- For both technologies, materials were seen to consistently dominate environmental impacts across a wide range of impact categories, with vessel use usually the next most polluting aspect: for wave energy this is only significant in some studies, but it tends to be more important in floating wind. Given the material impacts on climate change, decarbonising vessel operations is arguably lower priority than addressing the impact

of materiality, however burden shifting is important to consider. Copper and GFRP are important considerations for floating wind, but steel is almost always the most impactful material.

- Assumptions on transport, operation and maintenance (O&M) are rarely detailed in the wave energy LCA literature, but are generally more advanced in the floating wind LCA literature using different vessel types and even modes of operation. Vessel operations are modelled in simple terms, with limited vessel types, operational modes, and consideration of frequency of operations and duration on-site, creating the possibility that significantly different results could be reported depending on methodology for example: fuel use assumptions, distance to shore, O&M strategy, site conditions, frequency of interventions and generation availability. An opportunity remains to investigate this in greater detail, as has been attempted in at least one study in floating wind LCA.
- In the sensitivity studies reviewed, the results always showed significant sensitivity to lifetime energy production via AEP or capacity factor (given the functional unit), the selection and volumes of materials and the method of vessel representation, and assumptions of O&M activities. Lastly, uncertainty is quantified in only a handful of studies, and usually most comprehensively in floating wind LCA.
- Gaps in the wave energy literature include: modelling of utility-scale arrays with substations, newly developed WEC designs and vessel representation (especially during O&M and using different modes of operation); using a wide range of environmental impact categories with a recognised LCIA method; and including

sensitivity and uncertainty assessments which assess both foreground and background uncertainty.

- Gaps in the floating wind LCA literature include: modelling very large turbines (over 10 MW), with HVDC architecture in arrays far from the grid-connection; using site-specific wind resource data to assess AEP; incorporating dedicated O&M model outputs to determine the impacts of this important life cycle stage most accurately, and to consider development representative sites where possible.

Although introduced in this review, subsequent work in this thesis will not utilise a dynamic LCA approach or planetary boundaries framework, on the basis of achieving a tractable thesis within the available funding. This thesis will consider the British (GB) energy system only, to focus on how these technologies impact the UK response to the climate and ecological crises. Future work could expand the following treatment to a sectoral or global scale.

The literature reviewed for the energy system modelling aspect of this PhD presents a broad existing landscape of accounting methods which consider the environmental impacts of energy generation technologies when integrated into an energy system. While combinations of LCA and energy system models do exist, there are specific gaps around: floating wind and marine generation; addressing multifunctionality of the 'co-product' of emissions reduction by considering the 'avoided emissions' in combination with a life cycle assessment study of climate change impacts; the accuracy of the approach when related to annual average values or an operational power system model.

The principle of renewable resource complementarity and how this has been investigated using power system models to investigate potential complementary benefits of floating wind

and marine systems have also been outlined as the main benefit of diverse renewable co-generation.

# Chapter 4: Life cycle assessment of the Blue Horizon wave energy converter in four arrays around Scotland

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This chapter presents the first life cycle assessment (LCA) of the Blue Horizon wave energy converter (WEC) arrayed in four near-future wave farms around Scotland. The assessment includes site-specific resource, detailed representation of vessel operations, an uncertainty assessment and sensitivity analyses. There is a particular focus on WEC operation and maintenance (O&M), with foreground data estimated from LCA and levelised cost of energy (LCOE) literature of adjacent technologies. Using uncertainty assessment, the median Global Warming (GW) impact of electricity from across the four sites ranged from 68.3 to 94.9 gCO<sub>2</sub>eq/kWh, or around four to five times less than from a contemporary British Combined Cycle Gas Turbine (CCGT) power plant. The materials and manufacturing (M&M) life cycle stage was generally the most impactful across all environmental impact categories, followed by operation and maintenance (O&M) and landfill and recycling (L&R). Array infrastructure (array cables, floating substation and export cables) has a non-trivial impact on the GW impact (approximately 10 to 16%). Diesel combustion and steel use are the most GW impactful processes, while at a subassembly level, the WEC structure, mooring and generator are largest contributions. WEC retrieval/reinstatement during O&M, subsea maintenance of moorings and array cables and WEC mooring installation/decommissioning are the most GW impactful

vessel operations. Carbon payback is not achieved within the 20 year design life when decarbonising annual average emissions intensities are considered; excluding any account for future vessel decarbonisation. All impact categories are inversely proportional to annual energy production (AEP), given the functional unit, and are especially sensitive to design life and device mass, while relatively insensitive to water depth and distance to O&M port. To address future arrays' environmental impacts, sustainable material production and decarbonising vessel propulsion should be a priority for project developers. Validated vessel operation data, dynamic process inventory (prospective LCA) and dynamic systems inventory are identified as key areas for future wave energy LCA research. The results of this chapter are used in chapter 8 to investigate the emissions reduction potential of this type of technology in GB future energy scenarios.

## 4.1. Introduction

This chapter presents the first life cycle assessment (LCA) of the Blue Horizon wave energy converter (WEC), developed by Mocean Energy. This chapter addresses the gaps identified in Chapter 3 through a site-specific LCA of four utility-scale arrays of the Blue Horizon WEC around Scotland. Foreground data was provided by Mocean Energy, with additional information obtained from peer-reviewed literature and publicly available industry data, and background data from the ecoinvent 3.6 database 'allocation, recycled content' or 'cut-off' system model [162]. Special attention was given to the development of representative vessel data. In addition, a review of LCA and levelised cost of energy literature was used to synthesise generic figures for vessel operations during the operation and maintenance (O&M) phase. Monte Carlo simulation was used to quantify uncertainty along with sensitivity

analyses of significant array design parameters. The following sections describe the study methodology with reference to ISO 14040 and 14044 [79], [80].

#### 4.1.1. Blue Horizon WEC

Blue Horizon is a utility-scale, floating, hinged raft WEC, with a rated power of 1 MW (Figure 4.1). The machine comprises two cylindrical hulls (fore and aft), connected by a single degree of rotation hinge with an integrated, co-axially mounted, geared, electrical generator. The hulls terminate in wide, sloped 'wave channels' which impel relative rotation of the hulls and enhance survivability in energetic sea-states. The device is compliantly moored to the seabed and electrically inter-connected into arrays by dynamic power cables (Figure 4.2) [248], [249]. The device is currently undergoing design development, and the specifications of the machine used in this analysis are subject to change.



*Figure 4.1. Illustration of an array of eight Blue Horizon 1 MW-scale WECs, from Mocean Energy.*

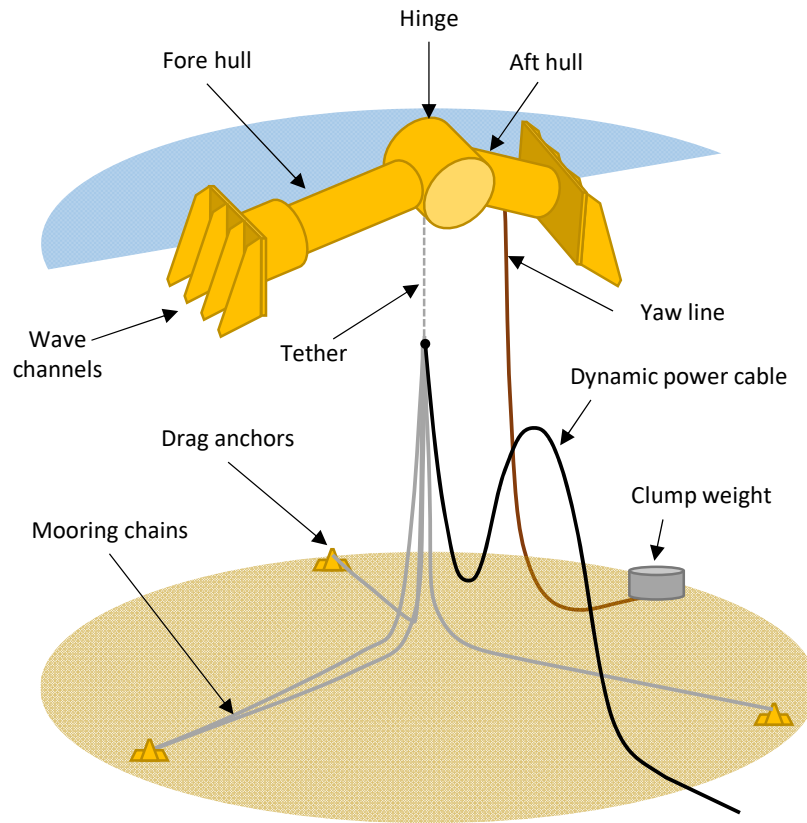


Figure 4.2. Schematic diagram of the Blue Horizon WEC as installed in isolation.

## 4.2. Material and methods

### 4.2.1. Goal

The intended application of this chapter was to quantify the environmental performance of the Blue Horizon device by comparing the impacts of four arrays representative of likely future wave farms around Scotland and identifying environmental impact “hot spots”. The analysis includes the impact of site renewable resource on annual energy production (AEP); location (on vessel journey times); array size and array electrical infrastructure and uses regionally appropriate background data. This improves representativeness but limits the findings for application in other regions. The temporal scope is near-future (assumed operation in 2025) but is limited by necessary use of static, empirical background data and re-analysis resource data. The study is intended to present the environmental impacts of a variety of possible future arrays, and is targeted towards an audience of WEC technology developers and policy-makers in an accounting decision context (Situation C) [149]. The treatment is compared directly to the results from Chapter 5, and was commissioned as a piece of original academic research.

### 4.2.2. Scope

The scope of an LCA determines what product systems are to be assessed and how the assessment should take place. An overview of the scope is shown in Figure 4.3, described in detail in the following sections. The analysis was executed in SimaPro v9.1.0 software, using ecoinvent v3.6 for background data.

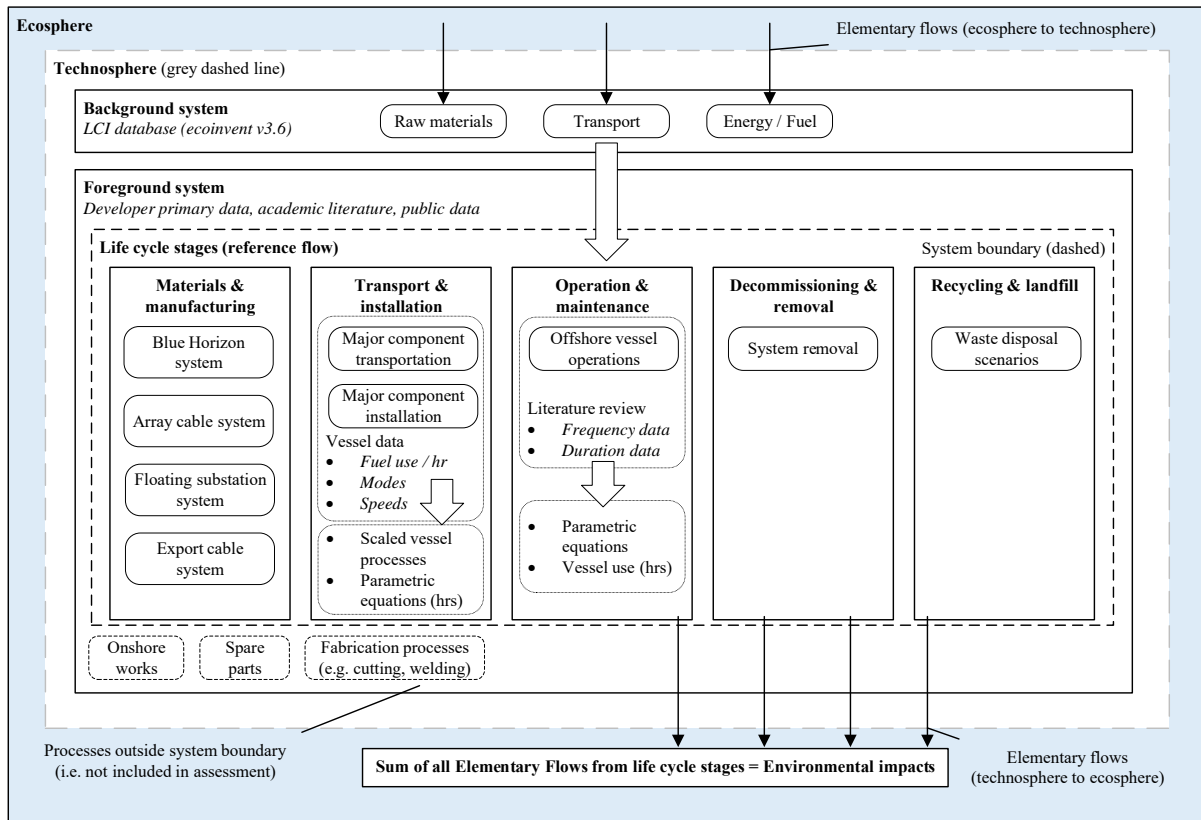


Figure 4.3. Overview of LCA system boundary, reference flow, foreground/background data, life cycle stages, sources and methods used in this chapter.

#### 4.2.2.1. Reference flow and functional unit

The reference flow of the study was a wave farm comprising multiple identical WECs, moorings, array cable system, floating offshore substation system and export cable up to the onshore cable joint (Figure 4.4). The selected functional unit was the output of 1 kilowatt hour (kWh) of electrical power, supplied at the export cable to the grid, assuming zero cabling losses and appropriate power quality, over a 20 year design life, subject to the incident variable renewable resource. The lifetime generation of energy was calculated from site-specific metocean data as described in Section 4.2.3.3.

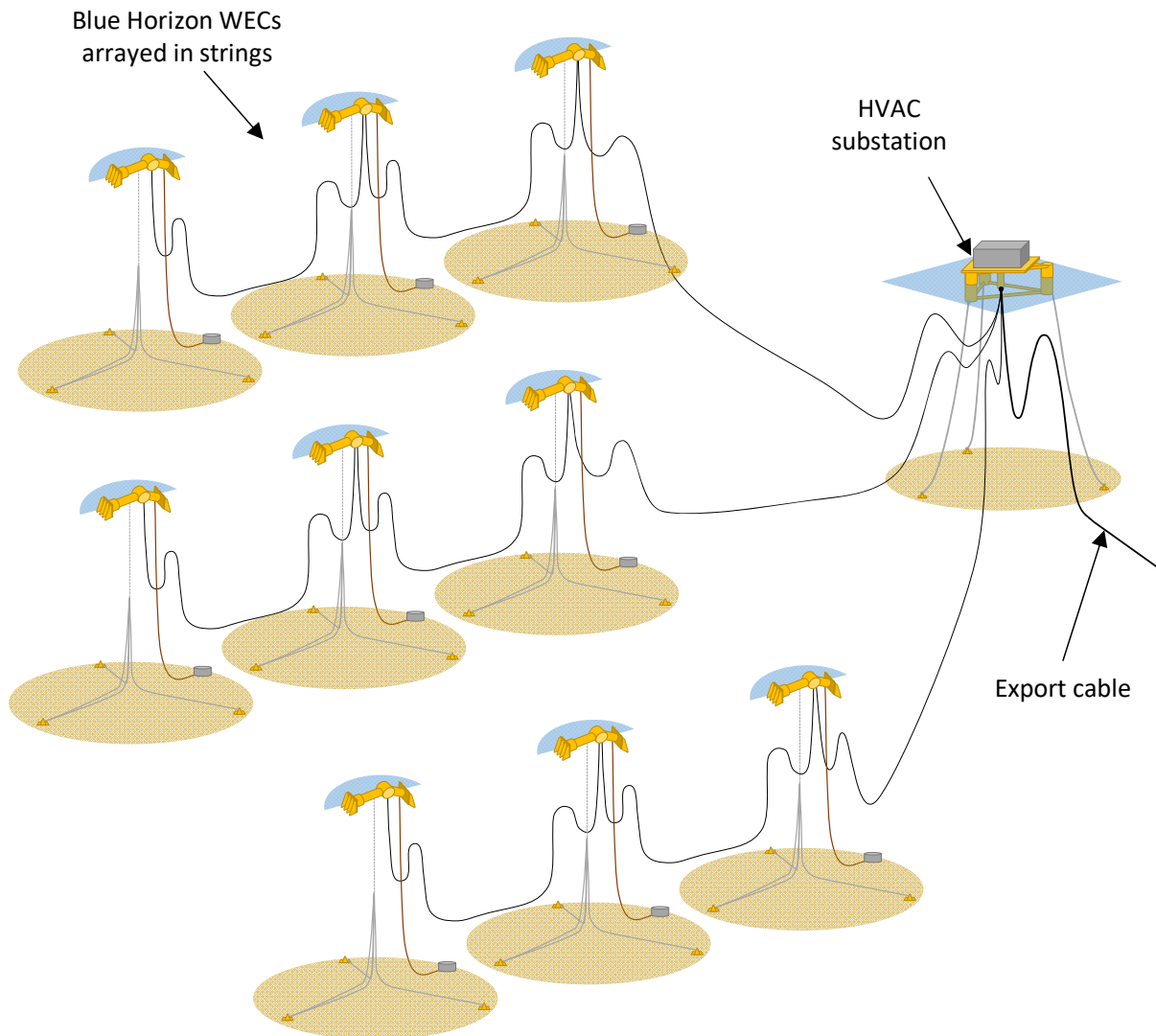


Figure 4.4. Schematic of the components included in each array modelled.

#### 4.2.2.2. LCI modelling framework and handling of multifunctional processes

The LCI modelling framework was attributional using average background processes, given the decision context [149]. The Recycled Content (or Cut-off) approach was used to allocate the impact of multifunctional processes, such as waste recycling. This is the recommended system model approach in the European Product Environmental Footprint guideline [149], where recycling of waste material is outside the system boundary and recycling impacts are only included for input materials.

#### 4.2.2.3. System boundaries and completeness requirements

Onshore works were not considered within the system boundary, as per [145]. Replacement of spare parts was not modelled following the example of the majority of the literature reviewed. This implies a consistent 20 year design life span for all subsystems and materials within the system boundary. Transportation processes were restricted to vessel operations only: all transportation by road was assumed to be accounted for by the product specific transport distance estimations within the LCI background data. No cutting, welding, sand-blasting, painting, or handling processes were included explicitly based on the negligible impacts noted in [131], [145]. Energy and heating processes used in manufacturing, and minor components (such as gaskets, fasteners, wiring) were also excluded. Grid reinforcement necessary to integrate the array with the national power system was not considered, as with other studies [137]. The sites were all located around Scotland, hence European variants of unit processes were preferred, and temporally the most recent background data was used.

#### 4.2.2.4. Representativeness of LCI data

At the time of writing, the Blue Horizon WEC design is under development. The life cycle inventory was based on primary design data provided to the authors by Mocean Energy, as well as engineering assumptions necessary to develop representative wave farm arrays. These assumptions were supported by academic and industrial literature as described in Section 4.2.3. An assessment of the uncertainty of all the foreground data (as well as practitioner modifications to the background data) is published in the Inventory Data

(SimaPro Input Parameters)<sup>29</sup>, according to the basic and additional uncertainty approach in [87].

#### 4.2.2.5. Impact assessment method

The LCIA method 'ReCiPe 2016 v1.1, midpoint method, Hierarchist version with Global normalisation' was used. This has a comprehensive range of impact categories (including global warming) and is extensively used in the literature according to a 2020 review [251]. Hierarchist is one of three cultural perspectives in ReCiPe, and that most widely employed because it is based on scientific consensus with regards to the time frame (typically 100 years) and plausibility of impact mechanisms [89]. In addition, as has become convention in some wave energy LCAs, Cumulative Energy Demand CED (V1.11) was also assessed to evaluate the embodied energy of the system. It should be noted that using CED to assess this has been disputed, but alternative standardised methods do not yet exist [252].

#### 4.2.2.6. System comparisons

The study is not directly comparative between two technologies, but rather considers four separate arrays using a consistent scope and equivalent methodological considerations. The uncertainty of the results is evaluated and communicated considering both the foreground and background data, and sensitivity to key parameters is explored for a single array only. The LCIA provides a wide range of impact categories, enabling an assessment of burden shifting between arrays.

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<sup>29</sup> All life cycle model data is available via the University of Edinburgh DataShare portal: <https://datashare.ed.ac.uk/handle/10283/8557> [250].

### 4.2.3. Inventory analysis

#### 4.2.3.1. Systematic breakdown structure

The array was broken down into four primary systems to assist development of the life cycle inventory: the Blue Horizon system (including moorings); the array cable system; the floating substation system, and; the export cable system. Each system was then broken down into assemblies, sub-assemblies and parts with corresponding hierarchical numbering (Figure 4.5). Further, four life cycle stages were modelled: materials and manufacturing (M&M); transport and installation (T&I); operation and maintenance (O&M), and; decommissioning and removal (D&R). Environmental impacts from disposal (recycling and landfill, L&R) were automatically output from SimaPro as a fifth life cycle stage. Full details of the array breakdown structure are available [250].

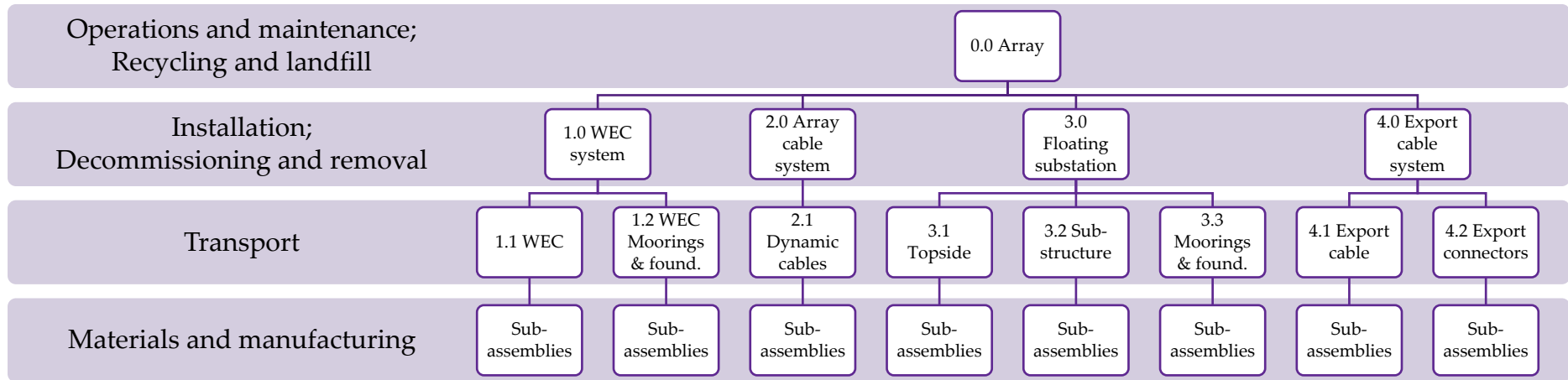


Figure 4.5. System breakdown structure, cut-off at third level for brevity. Relevant life cycle stages are shown on left of diagram.

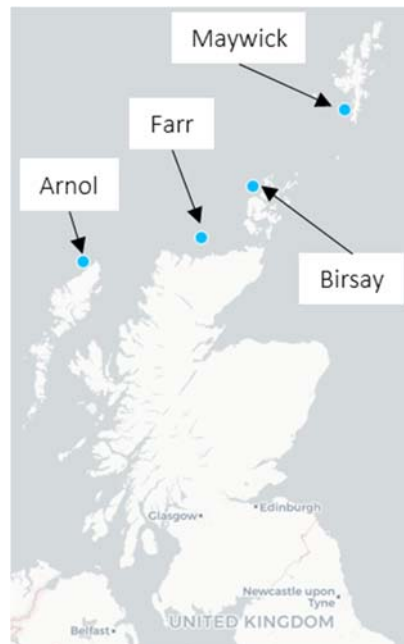


Figure 4.6. Four array locations considered in this chapter. Array properties are based on previously consented utility-scale wave farms.

#### 4.2.3.2. Site parameters

Four representative utility-scale sites were developed from previously consented or planned wave energy sites in Scottish waters (Costa Head, Armadale, Siadar and Aegir) [253], [254], [255], [256] to simulate the utility-scale deployment of Blue Horizon arrays. The sites have been renamed in this chapter to Birsay, Farr, Arnol and Maywick respectively to differentiate them from their antecedents due to the different WEC technology and other differences (for example, micro-siting the Siadar site to deeper water to be more suitable for a non-near-shore WEC) (Figure 4.6, Table 4.1). Likely O&M ports were selected by assessing the properties of local port facilities and scale of the adjacent array.

Table 4.1. Details of site modelled.

Site name	Birsay	Farr	Arnol	Maywick
Planned site name	Costa Head	Armadale	Siadar	Aegir
Planned technology	AWS-III	Pelamis P2	Oyster 801	Pelamis P2
Planned technology type	Multi-absorber [257]	Attenuator	OWSC	Attenuator
Planned site centroid (Latitude, Longitude)	59.2148, -3.277	58.65, -4.25	58.5, -6.65	59.9992, -1.464
Metocean data (Latitude, Longitude)	59.25, -3.25	58.75, -4.25	58.5, -6.5	60, -1.5
Distance from centroid to metocean coordinates [km]	4	11	9	2
Array rating [MW]	200	50	40	100
Number of WECs	200	50	40	100
Number of substations	1	1	1	1
Assumed water depth [m]	75	80	65	110
O&M base	Kirkwall	Scrabster	Arnish	Scalloway
Distance to O&M base [km]	35	45	80	20
Distance to export cable landfall [km]	20	30	20	20
Array cable voltage [kV]	33	33	33	33
Export cable voltage [kV]	150	36	36	66
Design life [years]	20	20	20	20

#### 4.2.3.3. Site specific wave energy resource

The effect of site location and resource on the AEP was assessed by using wave climate reanalysis data from the open-access ESOX Map [258]: 30 years' (1990 to 2019 inclusive) of

significant wave height ( $H_s$ ) and peak wave period ( $T_p$ ) data from the nearest marine-bound quarter-degree of latitude and longitude, at hourly resolution. Using the Blue Horizon power matrix<sup>30</sup> provided by Mocean Energy (confidential) the power output for each hour over those 30 years was determined. The hourly data was averaged to determine a 30 year average AEP at each site (Figure 4.7). The highest 30-year mean AEP is at Farr (3.76 GWh/year), followed by Birsay (3.38), Arnol (3.29) and Maywick (2.37).

The spatial resolution of this data was 0.25 degrees latitude/longitude (around 28 km), meaning that compromises were required to represent each of the sites. Accordingly, the distances from the site centre to the grid data point were (to the nearest kilometre): Birsay (4 km), Farr (11 km), Arnol (9 km) and Maywick (2 km). Moreover, any array-wide resource variation or blockage effects were neglected at this resolution. Further, reanalysis data is obviously based on empirical data and contains no information on how future renewable resource will evolve. This evolution of renewable wave energy resource, especially in light of climate change, involves significant downscaling of detailed climate forecast data, which is outside the scope of this LCA, but would introduce additional uncertainty to the results. In general, climatic conditions are expected to become more energetic in time, but local effects cannot be discounted. No obvious increasing trend is shown for the four sites over the 30 years considered (Figure 4.7). Relatedly, no allowance was made for the degradation of the device power-train, assuming that all components continue to function at a constant level of

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<sup>30</sup> Analogous to a two-dimensional wind turbine power curve (with independent variable of wind speed, and dependent variable of turbine power output), a WEC power matrix is a numerical array which specifies the device power output in a given sea state: which is generally defined by two variables, wave height and wave period. In simple terms, this is a lookup table, as opposed to a lookup curve for wind turbines.

efficiency. Any degradation in efficiency would have a knock-on impact on the results as discussed in Section 4.3.4.1.

To model the array availability, contemporary empirical data on the availability for select UK offshore wind farms at similar distances to shore was used (95.36%), representing a future scenario where these arrays are operating as an established technology [259].

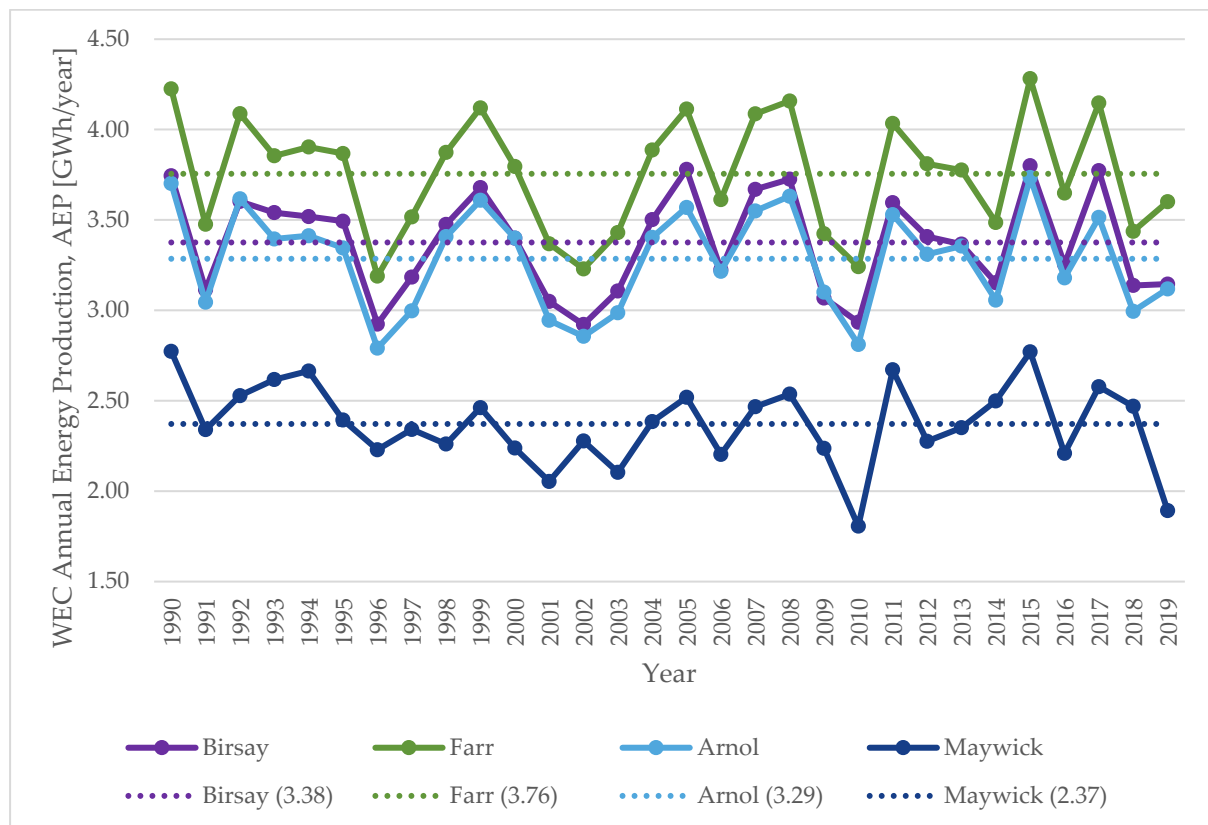


Figure 4.7. Variation in single WEC AEP across the four sites for the time period 1990 to 2019. Average WEC AEP shown in brackets is based on hourly reanalysis data and (confidential) device power matrix.

#### 4.2.3.4. Vessel characteristics

All vessel operations were modelled using simple, parameterised equations in SimaPro. In order to specifically model the necessary installation operations for each vessel, it was recognised that data on different modes of operation would be required: economic speed (design transit speed with low fuel consumption); towing (transit speed under tow); dynamic

positioning (use of propulsion for precise, active position keeping); and standby (idling, but no propulsion). However, ecoinvent database v3.6 does not contain processes representing these vessels, nor in different operational modes. Accordingly, an appropriate process within ecoinvent v3.6 was identified which could represent the resource consumption and pollutant emissions of the required vessel operations. The process *'Diesel, burned in fishing vessel \{GLO\' [MJ]* was selected. This process: includes the combustion of diesel in marine engines using Tier 1 emission factors for fishing vessels using marine diesel oil/marine gas oil; starts with the provision and consumption of diesel, and ends with the diesel consumption and emissions from fuels combusted for inland, coastal and deep-sea fishing; and excludes infrastructure (marine engine, vessels and port facilities) and maintenance. This was judged to be the most appropriate contemporary process as the location, fuel types and engine sizes are most similar to the required vessel specifications and use cases in the Blue Horizon life cycle.

The next step was to convert the units of the selected process to represent the necessary fleet of vessels. This was achieved by reviewing publicly available literature and vessel specifications to identify fuel consumption rates associated with each mode. By interrogating the diesel consumption in the process [kg/MJ] and scaling according to fuel consumption from the literature [l/hr] and fuel density [kg/m<sup>3</sup>], it was possible to develop scaling factors [MJ/hr] [250]. These were then be used to create new processes which represented total hours of vessel operations, input directly or calculated from simple parameterised equations of distance and speed. This chapter includes the following types of vessels for installation, operation and decommissioning: Multicat; Crew Transfer Vessel (CTV); Tug; Anchor Handling Tug Supply (AHTS); Offshore Subsea Construction Vessel (OSCV); Cable Lay Vessel (CLV) and Platform

Supply Vessel (PSV). This method builds on similar approaches published in [144], [145], [147], [260].

#### 4.2.3.5. Wave energy O&M foreground data development

The O&M burden required for future wave arrays is still relatively uncertain, with assumptions and models unable to be verified until sufficient deployment experience has been achieved [147]. Scheduled maintenance estimates for Blue Horizon were provided by Mocean Energy, however, device specific failure rates (which are necessary to assess unscheduled maintenance requirements) were unavailable at the time of writing. In lieu of this, a representation of the combined scheduled and unscheduled maintenance O&M burden was developed from a review of relevant literature [250].

These representative figures were referred to two main parameters to represent transit time and time in-field. These parameters were: the number of vessel mobilisations per year and duration (in hours) at site per year. The operations were further sub-referenced in terms of array 'units' (that is; per WEC, per offshore substation platform, per km of export cable and per array). This definition of the O&M burden allows the size of array and the distance between the site and relevant operation ports to be modelled explicitly by simple equations, using variables for transit distance and vessel speed to calculate the vessels duration in specific modes of operation. In this way, the figures are useful for application at any wave farm employing a tow-to-shore maintenance approach and can be considered *partially* site-specific, based on distances travelled. However, approach is limited because the effect of site-specific metocean conditions cannot be resolved from the source material, and (crucially) the figures are not device specific. In this way, the representative figures can be considered generic, despite the caveat that such generalisation has the potential to be inaccurate.

Clearly, some level of interpretation of the literature was required to develop representative figures from such diverse sources; for example, ensuring applicability for a tow-to-shore maintenance approach. After aggregation, it was assumed that all retrievals are completed by a single tug, unspecified light maintenance is completed by a multicat, and dedicated subsea inspections or unspecified heavy maintenance is completed by an offshore subsea construction vessel. Helicopters and barges were omitted due to their low occurrence within the data and relevance for the Blue Horizon device.

The final O&M requirements are given in Table 4.3. Note that the export cable inspection is broadly consistent with Chapter 5's reference for floating wind cable inspection [153]; which assumes 0.5 times per year (i.e. every 2 years) at 1 km/h (where  $1.43 \text{ hrs/km}_{\text{cable}}$  is equal to 0.7 km/h).

#### 4.2.3.6. Materials and manufacturing (M&M)

The following sections introduce and describe the assumptions behind the inventory development. Full inventory data of all array assemblies is available [250].

##### 4.2.3.6.1. WEC design

The preliminary WEC design by Mocean Energy is commercially confidential. Table 4.2 describes the major design features comprising 100% of the materiality of the WEC at this stage of design development.

*Table 4.2. Properties of Blue Horizon main components.*

Property	Quantity
WEC Length	Approx. 60 m
WEC Breadth	Approx. 20 m
WEC Structure and ballast mass	526 t
Gearbox mass	86 t
Generator mass	32 t

The WEC construction is almost all steel. It was assumed that the generator is 26% copper, 58% steel, 16% permanent magnets by mass, based on prototype Mocean Energy designs. Chromium steel was assumed for the gearbox, to represent steel with a high wear resistance. All other WEC components were assumed to be hot-rolled steel. 0.2 t of electronic components and 0.8 t of aluminium anodes were included, based on previous Mocean Energy concepts. The WEC was modelled in detail, however to protect the intellectual property of the device developer, this is aggregated (Table 4.4). Environmental product declarations (EPDs) were used to represent electrical equipment in the array (Table 4.5).

Table 4.3. O&M frequency and duration parameters for a generic wave energy array using a tow-to-shore maintenance strategy, developed from LCA, LCOE and industrial literature

Description	Vessel	Frequency [mobilisations / unit / year]	Unit	Vessel mode of operation	Duration in-field [hrs / year / unit]	Unit	Vessel mode of operation
Device retrieval / reattachment	Tug	0.86	WEC	Economic, Towing	1.84	WEC	DP
Inspection, unspecified WEC maintenance	Multicat	0.87	WEC	Economic	11.6	WEC	Standby
OSP maintenance	CTV	8	OSP	Economic	50	OSP	Standby
Moorings/cable inspection (ROV), unspecified heavy maintenance	OSCV	0.52	Array	Economic	12.5	WEC	DP
Export cable inspection	OSCV	0.52	Array	Economic	1.43	kmexport	DP

Table 4.4. Aggregate WEC materials and associated processes fromecoinvent [162].

Uncertainty Indicators	Selected Inventory Process	Mass [te]
<b>Structural steel</b>	Steel, low-alloyed, hot rolled {GLO}   market for   Cut-off, U	544.6
<b>Chromium steel</b>	Steel, chromium steel 18/8 {GLO}   market for   Cut-off, U	86
<b>Copper</b>	Copper {GLO}   market for   Cut-off, U	8.3
<b>Magnets</b>	Permanent magnet, for electric motor {GLO}   market for permanent magnet, electric passenger car motor   Cut-off, U	5.1
<b>Electronic components</b>	Electronic component, active, unspecified {GLO}   market for   Cut-off, U	0.2
<b>Anodes</b>	Aluminium, cast alloy {GLO}   market for   Cut-off, U	0.8

Table 4.5. Electrical equipment references.

Component	Reference
<b>Device Transformer (315 kVA, 11 kV)</b>	ABB (2007) Environmental Product Declaration - Distribution transformer - 315kVA, 11kV, 3 phase, ONAN. BA Distribution Transformers, <a href="https://search.abb.com/library/Download.aspx?DocumentID=AUEPD_001&amp;LanguageCode=en&amp;DocumentPartId=&amp;Action=Launch">https://search.abb.com/library/Download.aspx?DocumentID=AUEPD_001&amp;LanguageCode=en&amp;DocumentPartId=&amp;Action=Launch</a>
<b>Device / Array Switchgear (24 kV)</b>	ABB (2001) Environmental Product Declaration - HD4. ABB T and D SpA - SACE T.M.S, <a href="https://search.abb.com/library/Download.aspx?DocumentID=ITEPD008&amp;LanguageCode=en&amp;DocumentPartId=&amp;Action=Launch">https://search.abb.com/library/Download.aspx?DocumentID=ITEPD008&amp;LanguageCode=en&amp;DocumentPartId=&amp;Action=Launch</a>
<b>Export Transformer (250 MVA)</b>	ABB (2003) Environmental Product Declaration – Power Transformer 250 MVA, <a href="https://search.abb.com/library/Download.aspx?DocumentID=ITEPD054&amp;LanguageCode=en&amp;DocumentPartID=&amp;Action=Launch">https://search.abb.com/library/Download.aspx?DocumentID=ITEPD054&amp;LanguageCode=en&amp;DocumentPartID=&amp;Action=Launch</a>
<b>Export Transformer (63 MVA)</b>	ABB (2003) Environmental Product Declaration – Power transformer TrafoStar 63 MVA, <a href="https://search.abb.com/library/Download.aspx?DocumentID=SEEPD_TPT_TrafoStar_0001&amp;LanguageCode=en&amp;DocumentPartId=&amp;Action=Launch">https://search.abb.com/library/Download.aspx?DocumentID=SEEPD_TPT_TrafoStar_0001&amp;LanguageCode=en&amp;DocumentPartId=&amp;Action=Launch</a>
<b>Export Switchgear (300 kV GIS)</b>	ABB (2007) Life Cycle Assessment of ELK-14 for 300 kV, 1HC0030603, Version AB, 2007, <a href="https://search.abb.com/library/Download.aspx?DocumentID=EPD-HV-05&amp;LanguageCode=en&amp;DocumentPartId=&amp;Action=Launch">https://search.abb.com/library/Download.aspx?DocumentID=EPD-HV-05&amp;LanguageCode=en&amp;DocumentPartId=&amp;Action=Launch</a>
<b>36 kV Export Cable</b>	Nexans (2008), 2XS(FL)2YRAA 18/30(36) kV, 'Nexans Submarine Power Cables'.
<b>66 kV Export Cable</b>	ABB (2010), XLPE Submarine Cable Systems, Attachment to XLPE Land Cable Systems – User’s Guide, <a href="https://new.abb.com/docs/default-source/ewea-doc/xlpe-submarine-cable-systems-2gm5007.pdf">https://new.abb.com/docs/default-source/ewea-doc/xlpe-submarine-cable-systems-2gm5007.pdf</a>
<b>150 kV Export Cable</b>	Westermost Rough Ltd (2013), Construction Method Statement.

#### 4.2.3.6.2. *WEC mooring design*

At the time of writing, a detailed Blue Horizon mooring design was not available. In personal communication with Mocean Energy, it was agreed that, for the purposes of this assessment, the final mooring design could be well represented by another floating WEC mooring: the Pelamis P2 [261]. In this design, only the tether line scales with water depth, making it well suited to sizing for a range of water depths. The moorings are primarily steel chain, anchors or clump weights by mass. The tethers are 125 mm diameter Gama98 polyester rope, and 100 m long for 130 m water depth (or 0.75 m per metre of water depth).

#### 4.2.3.6.3. *Array cable design*

The array cables connect a string of six WECs in series, emulating utility-scale offshore wind farm radial array cable designs (as per the schematic representation in Figure 4.4. Schematic of the components included in each array modelled.). Each string is pulled-in to the floating substation. The riser section of the cables are assumed to be installed in a dynamic lazy-wave configuration, with a riser length 2.6 times the water depth (based on the Hywind floating wind farm array cable design and Pelamis P2 design [261], [262], plus a static section with length dependent on the device separation (assumed at 400 m in accordance with Mocean Energy's expectations). Buoyancy modules and clump weights are also modelled. Depending on water depth this created a total cable length between WECs of 390 to 626 m.

The array cables were assumed to be rated at 33 kV as per contemporary floating wind pilot parks, Hywind and Kincardine [260]. The average proportion of material per metre of cable between these two designs was taken with the proportion of materials in the cable assumed as 23.2% copper cores, 13% cross-linked polyethylene (XLPE) insulation, 58% steel armour

wire and 5.9% high density polyethylene sheath, with a total mass per unit length of 55.5 kg/m.

The total number of array cables was set equal to the number of WECs plus a downfeeder to the export cable, to allow for the correct number of dynamic array cables plus a dynamic section for the export cable.

#### *4.2.3.6.4. Floating substation design*

Currently, there are no examples of substation designs for wave farms. Fixed-bottom, subsea or floating designs were considered for this analysis, with a floating design selected on the basis of water depth and expected technological development trends. No designs of this type exist for wave energy, so representative model inputs were developed from similar designs for wind energy, specifically the floating platform design for the National Renewable Energy Laboratory 5 MW reference wind turbine, with an allowable payload equivalent to 546.5 t [263]. The hydrodynamic suitability of this platform for this application was not assessed, as this would require significant detailed analysis and design work that is outside of the scope of this project. The impact of this assumption on the results should be examined in future work as the design of wave farms develop.

The basic complement of electrical gear included: an export transformer, export switchgear, and array switchgear, as well as the topside's structural steel. EPDs were used to develop inventories for these items [264]. The export transformer data was scaled according to the array apparent power, and two types were used for different sites: a scaled 250 MVA transformer (Birsay, Maywick) and scaled 63 MVA transformer (Farr, Arnol). The export switchgear (300 kV) and array switchgear were not scaled as per kV data was not provided.

The Lightweight Offshore Substation design used for Beatrice offshore wind farm (also known as the Siemens Offshore Transformer Module, OTM) was used to develop a mass of topside structural steel [265] and the total payload mass was checked to be below that of the 5 MW reference turbine to ensure consistency with the platform design. The offshore transformer is rated at 320 MVA (above the array apparent power in every case), so only a single substation platform was required for each array.

#### *4.2.3.6.5. Export cable design*

A single three-core copper AC export cable per hub was assumed with the rated voltage varying by farm. The export cable route was assumed to run subsea around headlands but without detailed consideration of bathymetry; instead, the total length was assumed to be 20% in excess of the straight line distance. The point of landfall was assumed either from previous site consent documentation or inspection of local distribution networks. The proportion of materials within the cable was based on offshore wind farm cable specifications [250]. Different cable voltage ratings were utilised according to the differences in array power (Table 4.6).

Table 4.6. Properties of assumed export cable designs.

Site	Birsay	Farr, Arnol	Maywick
Export voltage rating	150	36	66
Mass per unit length [kg/m]	98	48.9	60.1
Copper by mass [%]	35.0	45.6	47.7
Polyethylene by mass [%]	3.9	5.2	4.9
Polypropylene by mass [%]	10.9	8.9	9.3
Steel by mass [%]	43.3	39.8	37.5
Unaccounted mass [%]	6.9	0.5	0.6

#### 4.2.3.7. Transport and installation (T&I)

Vessel operations were modelled parametrically within SimaPro, accounting for distance travelled and time spent engaged in specific operations. Various ports and assembly yards were selected for each of the four sites considered on the basis of proximity and capability [266]. For the floating platform, however, the assembly yard was selected as Aalborg, Denmark for all sites, based on the significant the experience of this site in the offshore wind sector. Aberdeen was selected as the 'regional port' where larger vessels originate given its important role in the Scottish offshore energy industry. The distance from the site centre to each port was measured using online mapping software to the nearest 5 km (Table 4.7).

Table 4.7. Transportation, installation and O&M locations (distance to farm given in km).

Location	Birsay	Farr	Arnol	Maywick	Definition
<b>WEC Assembly Yard (km)</b>	Nigg (220)	Nigg (210)	Arnish (80)	Nigg (310)	Where the WEC is fabricated and assembled. Prior transportation is accounted for by average distances in the ecoinvent processes
<b>Regional Port (km)</b>	Aberdeen (275)	Aberdeen (270)	Aberdeen (425)	Aberdeen (340)	Mobilisation port for large vessels (AHTS, OSCV and PSV) during installation and O&M
<b>Array Cable Load-out (km)</b>	Hartlepool (555)	Hartlepool (545)	Hartlepool (685)	Hartlepool (600)	Cable manufacturing and load-out facility
<b>Floating Platform Assembly Yard (km)</b>	Aalborg (1000)	Aalborg (1000)	Aalborg (1145)	Aalborg (870)	Fabrication and assembly site for substation platform and topsides
<b>Export Cable Load-out (km)</b>	Hartlepool (555)	Hartlepool (545)	Hartlepool (685)	Hartlepool (600)	Cable manufacturing and load-out facility
<b>Local Port (km)</b>	Kirkwall (35)	Scrabster (45)	Arnish (80)	Lerwick (60)	Mobilisation port for support multcats during WEC installation by tug
<b>O&amp;M Port (km)</b>	Kirkwall (35)	Scrabster (45)	Arnish (80)	Scalloway (20)	Mobilisation port for smaller O&M vessels (CTV, multcats, tugs)

#### 4.2.3.8. Operation and maintenance (O&M)

As per the T&I stage and study scope, only vessel operations were modelled in the O&M phase. The generic figures synthesised in Table 4.3 were used.

#### 4.2.3.9. Decommissioning and removal from site (D&R)

The decommissioning of the WEC arrays was assumed to be identical to the installation, except export cable laying/trenching operations are omitted.

#### 4.2.3.10. Landfill and recycling (L&R)

Reflecting other papers in the literature, a recycling rate of 90% was assumed for four key materials: steel, copper, polyethylene and polypropylene [144], [145], [147].

#### 4.2.3.11. Data quality

Although not a major piece of comparative work, the data quality of the study is described below in accordance with ISO 14044 [80]:

- Time-related coverage: the majority of the foreground data is contemporary, almost exclusively within 10 years of difference to the time period of the dataset. The background data is historical with time periods specific to each process (see Supplementary Material – Inventory Data for full LCI and ecoinvent v3.6 for specific time periods). Temporally, the scenario was for a device manufactured and installed in 2025 with a lifetime of 20 years. All foreground data was gathered between 2020 and 2023 the end date for the ecoinvent v3.6 background data is the end of 2019, so the mismatch in temporal coverage of the foreground and background data sets does introduce some uncertainty into the results. This will be increased if the installation date of the arrays is delayed.

- Geographical coverage: site specific foreground data has been used where practical. Background data is localised where possible but typically global, reflecting the globalised material and fuel markets economy. The foreground data describes four arrays of Blue Horizon devices built and installed in Scotland, with the cables and substations originating in England and Denmark respectively. Background data fromecoinvent generally uses average materials data from the global market.
- Technology coverage: technology specific foreground data has been used where possible, else following the data quality pedigree of the ‘technological correlation’ indicator from [87, p. 76]. Due to the novelty of this technology, examples of export cables, dynamic cables and substations were used from the offshore wind sector, and the moorings were based on those for the Pelamis P2 WEC. Some uncertainty will be introduced by these assumptions, but the technologies and application are similar. The representativeness of the site-specific metocean data varies due to mismatches between the site and the grid spacing of the metocean dataset.
- Precision: primary data sourced directly from the device developer is assumed to be precise, as is much of the data from academic and industrial literature, subject to design changes and refinement with time, and technological correlation.
- Completeness: primary data provided by Mocean Energy comprised: a mass inventory for a preliminary design, device power matrix and commentary on vessel operations. The transportation of raw materials is not considered: each scenario assumes that the generic global market data for materials provided by ecoinvent already includes this (Section 4.2.2). Paints, sand-blasting and other processes were omitted. Large electrical components were modelled by considering the mass only.

- Representativeness: the degree to which the data set reflects the true population of interest (i.e., time-related coverage, geographical coverage, and technology coverage) is qualitatively assessed as suitable.
- Consistency: the study methodology is qualitatively assessed at a commensurate and appropriate degree relative to the significance of the various components of the analysis. All background data was sourced from the single ecoinvent system model (Cut-off, Unit processes) or scaled using foreground data (vessel operation processes). Full details of the vessel process scaling method are provided in the Supplementary Material – Inventory Data, Vessel characteristics.
- Reproducibility: Every attempt has been made to provide the inventory data necessary to reproduce the results reported in the study, subject to confidentiality agreements, notably the device mass inventory and power matrix.
- Data sources: are provided in the study references and supplementary material. The remainder of the data sources were from published literature or publicly available sources - some from single vessel operators or equipment manufacturers.
- Uncertainty of the information: the uncertainty was assessed using the method described in [87], and is detailed in the Supplementary Material - Inventory Data.

All input data, assumptions and probability distributions for the uncertainty assessment are detailed in Supplementary Material - Inventory Data.

#### 4.2.4. Impact Assessment

As discussed in the study Scope (Section 4.2.2.5) the 'ReCiPe 2016 v1.1, midpoint method, Hierarchist version with Global normalisation' and CED methods were used for a total of 19

impact categories. Uncertainty was assessed using the default values for basic uncertainty applied to both foreground and background data in accordance with ecoinvent data quality guidelines, and a Monte Carlo analysis with 1000 steps and a stop factor of 0.005 [87].

#### 4.2.5. Interpretation

Results are presented for all four sites and by life cycle stage. Results are not directly compared with other studies however ranges are discussed in relation to the literature review of wave energy and other generation technology. “Hot spots” or materials and process associated with a significant contribution to life cycle impacts are presented, with recommendations to reduce impacts. Carbon and energy payback times are explored and sensitivity analyses of lifetime energy production and key design parameters are presented.

### 4.3. Results and discussion

#### 4.3.1. Basic results without uncertainty

The basic LCIA results (with no assessment of uncertainty) using the ReCiPe and CED impact methods are shown in Table 4.8. The penalty on environmental impact due to site-specific AEP can be observed by reciprocating the ratio of AEP to the highest AEP (Farr). The GW impacts are **63.1**, **63.2**, **80.3** and **89.6** gCO<sub>2</sub>eq/kWh for Birsay, Farr, Arnol and Maywick.

Figure 4.8 shows the relative contribution of each life cycle stage in each impact category. Materials and manufacturing contribute the largest proportion of the impact in 14 of the 19 impact categories. The next most impactful life cycle stage is O&M; largest in 3 of 19 impact categories: ozone formation affecting human health and terrestrial ecosystems, and terrestrial acidification. Disposal (landfill and recycling) is largest in 2 of the 19 categories (freshwater and marine ecotoxicity) but transportation and installation (and decommissioning) are always

minor. Materials comprise between 55 and 65% of the climate change impact across the four sites; transport and installation at 6 to 8%, O&M is 17 to 33%, decommissioning and removal 5 to 8% and landfill and recycling 2%.

### 4.3.2. Results using default uncertainty factors

Epistemic uncertainty (that which can be reduced by improved data) was assessed by applying lognormal standard deviations to each foreground parameter after assessing its data quality [267]; ecoinvent includes distributions for the background data. For the foreground data, basic uncertainty (from use of non-specific data) and additional uncertainty (from use of estimates or extrapolation) were determined by this procedure [87]. Basic uncertainty variances follow from the unit processes used, while additional uncertainty variances are determined by data quality 'indicator scores' from a pedigree matrix of: reliability; completeness; temporal correlation; geographical correlation, and; technological correlation [87]. The resulting indicator scores are then converted to uncertainty variances yielding a final variance distribution of basic and additional uncertainty for each parameter, which are input to SimaPro. Monte Carlo random sampling is then used to perform multiple simulations with these distributions, with the results collated and statistically reported. Monte Carlo is the most common sampling method for uncertainty propagation in the field of LCA [267], with use in wave energy LCA literature [131], [141], [145], [147], and is innately supported by SimaPro and ecoinvent. All basic and additional uncertainty variances for every foreground parameter in this study, are available [250].

The life cycle environmental impacts using default uncertainty factors according to ecoinvent data quality guidelines [87], are shown in Table 4.9. Using this methodology, the median GW

impacts are increased to **68.3**, **69.3**, **87.1** and **94.9** gCO<sub>2</sub>eq/kWh for Birsay, Farr, Arnol and Maywick.

Generally, the highest AEP sites have lowest impact (due to the functional unit definition) but the scale of the array (number of WECs) relative to the array infrastructure (substation, export cable) is also relevant. Birsay tends to have the lowest impacts, due to its short vessel transit distances, relatively high AEP, high utilisation of substation infrastructure relative to the size of the array, shortest distance to landfall and second-shallowest water depth. Farr performs well – despite the low utilisation of substation infrastructure of a small array – by having the highest AEP. Arnol generally has the second highest impacts, and Maywick performs least well due to the lowest AEP, relatively low utilisation of substation infrastructure and transportation distances: the favourable distance to the O&M port is not sufficient to counteract these aspects. The effect of site design in isolation is explored in more detail in Section 4.3.3.

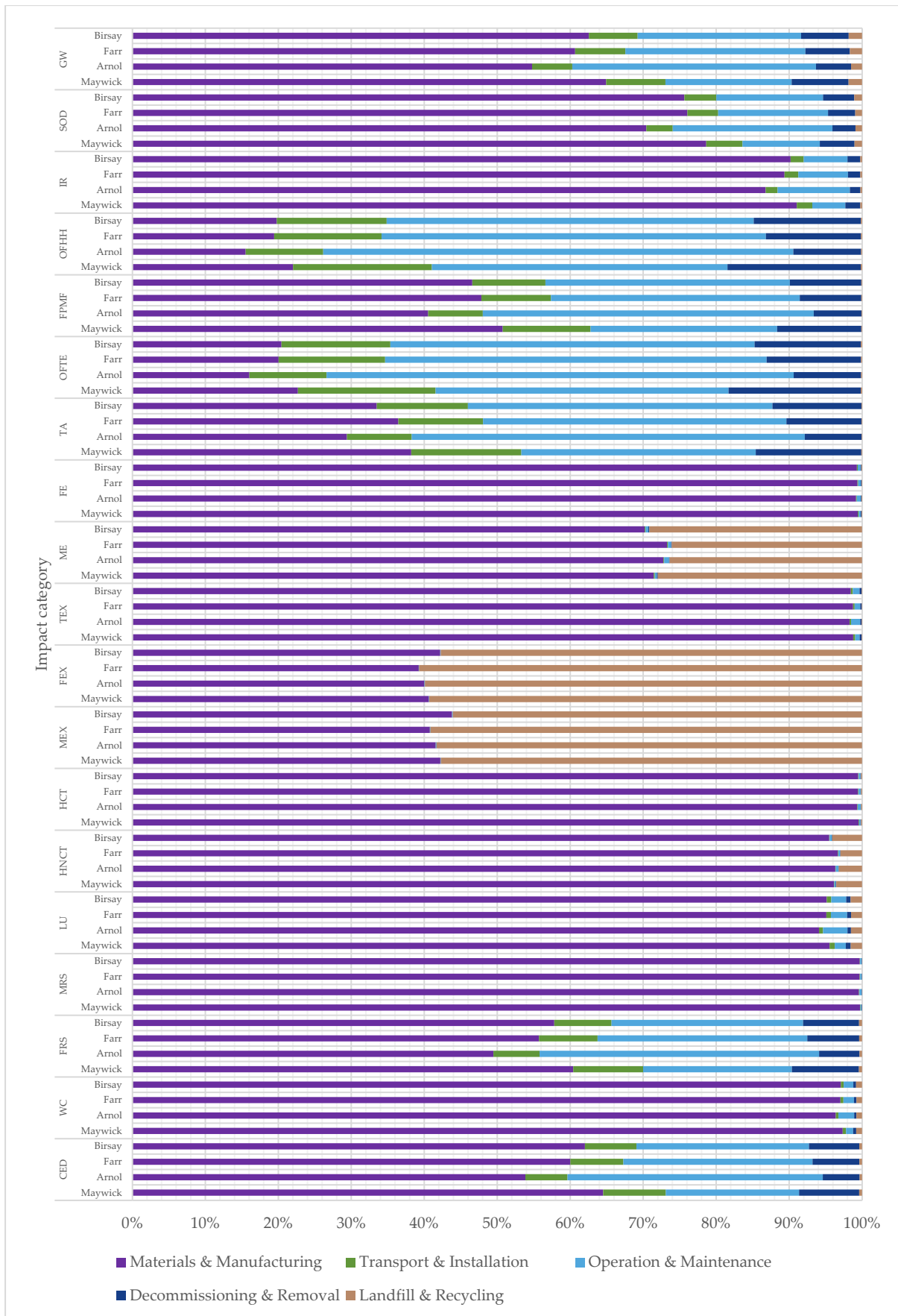


Figure 4.8. Relative contribution of life cycle stages to environmental impact categories for all sites.

Table 4.8. Top level results from for all four arrays using ReCiPe and CED impact methods, with no assessment of uncertainty.

	<b>Birsay</b>	<b>Farr</b>	<b>Arnol</b>	<b>Maywick</b>	<b>Unit</b>
<b>Lifetime array energy production</b>	12.88	3.58	2.51	4.52	TWh
<b>WEC AEP (including availability)</b>	3.22	3.58	3.13	2.26	GWh/yr
<b>Penalty solely due to WEC AEP</b>	-	-	-	-	-
<b>WECs</b>	200	50	40	100	-
<b>Global warming</b>	<b>63.1</b>	<b>63.2</b>	<b>80.3</b>	<b>89.6</b>	<b>g CO<sub>2</sub>eq / kWh</b>
<b>Stratospheric ozone depletion</b>	24.2	25.9	30.7	36.6	µg CFC11 eq / kWh
<b>Ionizing radiation</b>	2.1	2.1	2.4	3.1	Bq Co-60 eq / kWh
<b>Ozone formation, Human health</b>	0.6	0.7	0.9	0.8	g NOx eq / kWh
<b>Fine particulate matter formation</b>	0.3	0.3	0.4	0.4	g PM2.5 eq / kWh
<b>Ozone formation, Terrestrial ecosystems</b>	0.6	0.7	0.9	0.9	g NOx eq / kWh
<b>Terrestrial acidification</b>	0.8	0.8	1.1	1.1	g SO <sub>2</sub> eq / kWh
<b>Freshwater eutrophication</b>	43.5	51.9	55.9	70.3	mg P eq / kWh

	<b>Birsay</b>	<b>Farr</b>	<b>Arnol</b>	<b>Maywick</b>	<b>Unit</b>
<b>Marine eutrophication</b>	3.4	3.4	3.8	5.0	mg N eq / kWh
<b>Terrestrial ecotoxicity</b>	1.3	1.7	1.8	2.2	kg 1,4-DCB / kWh
<b>Freshwater ecotoxicity</b>	56.3	80.4	82.3	99.7	g 1,4-DCB / kWh
<b>Marine ecotoxicity</b>	69.2	98.5	100.8	122.3	g 1,4-DCB / kWh
<b>Human carcinogenic toxicity</b>	24.9	24.4	28.1	36.8	g 1,4-DCB / kWh
<b>Human non-carcinogenic toxicity</b>	0.3	0.4	0.4	0.5	kg 1,4-DCB / kWh
<b>Land use</b>	11.2	11.4	13.0	16.7	cm <sup>2</sup> a crop eq / kWh
<b>Mineral resource scarcity</b>	2.4	2.4	2.7	3.6	kg Cu eq / kWh
<b>Fossil resource scarcity</b>	17.1	17.3	22.3	24.2	kg oil eq/kWh
<b>Water consumption</b>	0.3	0.3	0.4	0.5	l / kWh
<b>Cumulative energy demand</b>	875	880	1122	1241	kJ / kWh

Table 4.9. LCIA results with median values and confidence limits within 95%, using default uncertainty factors for foreground and background data. Array attributes are also shown.

Attribute / Impact Category	Abbreviation	Birsay			Farr			Arnol			Maywick			Units
		2.5%	Median	97.5%	2.5%	Median	97.5%	2.5%	Median	97.5%	2.5%	Median	97.5%	
Global warming	GW	32.6	<b>68.3</b>	153.0	33.6	<b>69.3</b>	151.5	38.4	<b>87.1</b>	197.7	47.1	<b>94.9</b>	190.2	gCO <sub>2</sub> eq/kWh
Stratospheric ozone depletion	SOD	12.4	<b>25.7</b>	57.3	13.2	<b>28.0</b>	60.1	13.9	<b>32.3</b>	75.4	17.3	<b>39.0</b>	82.4	µgCFC <sub>11</sub> eq/kWh
Ionizing radiation	IR	0.3	<b>1.4</b>	10.9	0.3	<b>1.4</b>	9.9	0.4	<b>1.7</b>	10.8	0.5	<b>2.0</b>	16.3	BqCo-60eq/kWh
Ozone formation, Human health	OFHH	0.3	<b>0.7</b>	1.7	0.3	<b>0.7</b>	1.9	0.4	<b>1.0</b>	2.7	0.4	<b>0.9</b>	1.9	gNO <sub>x</sub> eq/kWh
Fine particulate matter formation	FPMF	0.2	<b>0.3</b>	0.7	0.2	<b>0.4</b>	0.8	0.2	<b>0.4</b>	1.1	0.2	<b>0.5</b>	0.9	gPM <sub>2.5</sub> eq/kWh
Ozone formation, Terrestrial ecosystems	OFTE	0.3	<b>0.7</b>	1.7	0.3	<b>0.7</b>	1.9	0.4	<b>1.0</b>	2.7	0.4	<b>0.9</b>	2.0	gNO <sub>x</sub> eq/kWh
Terrestrial acidification	TA	0.4	<b>0.8</b>	2.0	0.4	<b>0.9</b>	2.2	0.5	<b>1.2</b>	3.0	0.6	<b>1.1</b>	2.4	gSO <sub>2</sub> eq/kWh
Freshwater eutrophication	FE	20.4	<b>45.1</b>	112.8	21.3	<b>52.9</b>	134.6	22.9	<b>55.7</b>	140.7	31.3	<b>73.4</b>	166.3	mgP <sub>eq</sub> /kWh
Marine eutrophication	ME	1.7	<b>3.5</b>	8.0	1.6	<b>3.6</b>	8.5	1.9	<b>3.9</b>	9.0	2.3	<b>5.3</b>	11.1	mgN <sub>eq</sub> /kWh
Terrestrial ecotoxicity	TEX	0.5	<b>1.3</b>	3.8	0.6	<b>1.6</b>	5.0	0.6	<b>1.7</b>	5.6	0.8	<b>2.2</b>	6.5	kg1,4-DCB/kWh
Freshwater ecotoxicity	FEX	28.0	<b>59.9</b>	130.6	34.7	<b>79.6</b>	209.6	35.6	<b>80.0</b>	213.4	44.9	<b>101.6</b>	221.3	kg1,4-DCB/kWh

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Attribute / Impact Category	Abbreviation	Birsay			Farr			Arnol			Maywick			Units
		2.5%	Median	97.5%	2.5%	Median	97.5%	2.5%	Median	97.5%	2.5%	Median	97.5%	
Marine ecotoxicity	MEX	34.5	<b>73.6</b>	160.0	42.8	<b>97.6</b>	254.9	43.7	<b>98.3</b>	262.1	55.5	<b>124.8</b>	270.5	kg1,4-DCB/kWh
Human carcinogenic toxicity	HCT	9.6	<b>24.1</b>	65.4	9.6	<b>24.1</b>	69.5	10.7	<b>28.1</b>	80.8	13.5	<b>34.8</b>	98.5	kg1,4-DCB/kWh
Human non-carcinogenic toxicity	HNCT	0.2	<b>0.3</b>	0.8	0.2	<b>0.4</b>	1.0	0.2	<b>0.4</b>	1.1	0.2	<b>0.5</b>	1.2	kg1,4-DCB/kWh
Land use	LU	5.7	<b>11.9</b>	25.9	5.6	<b>12.0</b>	25.8	6.6	<b>13.7</b>	29.2	8.2	<b>17.6</b>	36.9	cm <sup>2</sup> acrop <sub>eq</sub> /kWh
Mineral resource scarcity	MRS	1.2	<b>2.5</b>	5.5	1.2	<b>2.5</b>	5.3	1.3	<b>2.9</b>	6.3	1.7	<b>3.7</b>	7.7	kgC <sub>ueq</sub> /kWh
Fossil resource scarcity	FRS	9.0	<b>18.6</b>	41.9	9.2	<b>18.9</b>	41.3	10.3	<b>24.0</b>	55.3	12.7	<b>25.4</b>	52.2	kgoileq/kWh
Water consumption	WC	-199.5	<b>7.2</b>	135.2	-183.9	<b>5.4</b>	129.6	-201.2	<b>6.0</b>	162.5	-250.5	<b>8.1</b>	201.6	l/kWh
Cumulative energy demand	CED	455	<b>957</b>	1957	442	<b>933</b>	2057	538	<b>1202</b>	2735	649	<b>1332</b>	2786	kJ/kWh
WECs	-	200			50			40			100			-
WEC AEP (including availability)	-	3.22			3.58			3.13			2.26			GWh/yr
Lifetime array energy production (20 years)	-	12.88			3.58			2.51			4.52			TWh

### 4.3.3. Comparing default and empirical uncertainty factors

ISO 14044 requires that whenever feasible, uncertainty analysis should be performed to better explain and support the LCI conclusions [80]. This is relatively infrequent in the literature: three studies consider background data uncertainty [131], [141], [147], only one considers foreground and background, Thomson [145]. Accordingly, this section expands on the previously presented analyses to determine the effect of different approaches to assessing uncertainty based on the methodologies in [87], [268].

The Birsay site was used as a base case; first of all, without any assessment of uncertainty ("Basic", Table 4.10). Re-analysing the Birsay site considering the uncertainty of the background data only as per [147] generally did not change the median impacts, except for a few impact categories (particularly Ionising Radiation and Water Consumption). However, by extending the uncertainty assessment to the foreground data according to the default values for basic and additional uncertainty (via the pedigree matrix used to assess the quality of data sources) generally shows an increase in the median value for most impact categories. Specifically, the median value for global warming is increased by 8%. This implies that assessments with zero (or background only) assessment of uncertainty will under-report the impacts relative to this thesis, perhaps explaining another contributing factor to the higher than literature results presented here.

This study also assesses the impact of using default and empirically based uncertainty factors to model uncertainty in the foreground and background data [268]. The general method is the same, regardless of the set of uncertainty factors used: the practitioner assesses the quality of the foreground data using two pedigree matrices for *basic* and *additional* uncertainty, using data quality indicators [87]. The use of empirically based uncertainty factors significantly

increases the uncertainty (Figure 4.9, Table 4.10). This suggests that the default uncertainty factors, which, to date, have been used exclusively in the wave energy LCA literature (if uncertainty is modelled at all) are not conservative.

However, relative to global warming, the median value using empirical factors for uncertainty (145 gCO<sub>2</sub>eq/kWh) remains less than the basic value for 'Electricity, high voltage {GB}| electricity production, natural gas, combined cycle power plant | Cut-off, U' process fromecoinvent (353 gCO<sub>2</sub>eq/kWh). Further work is required to assess the implications of this increase in uncertainty, relative to the literature for all generation types.

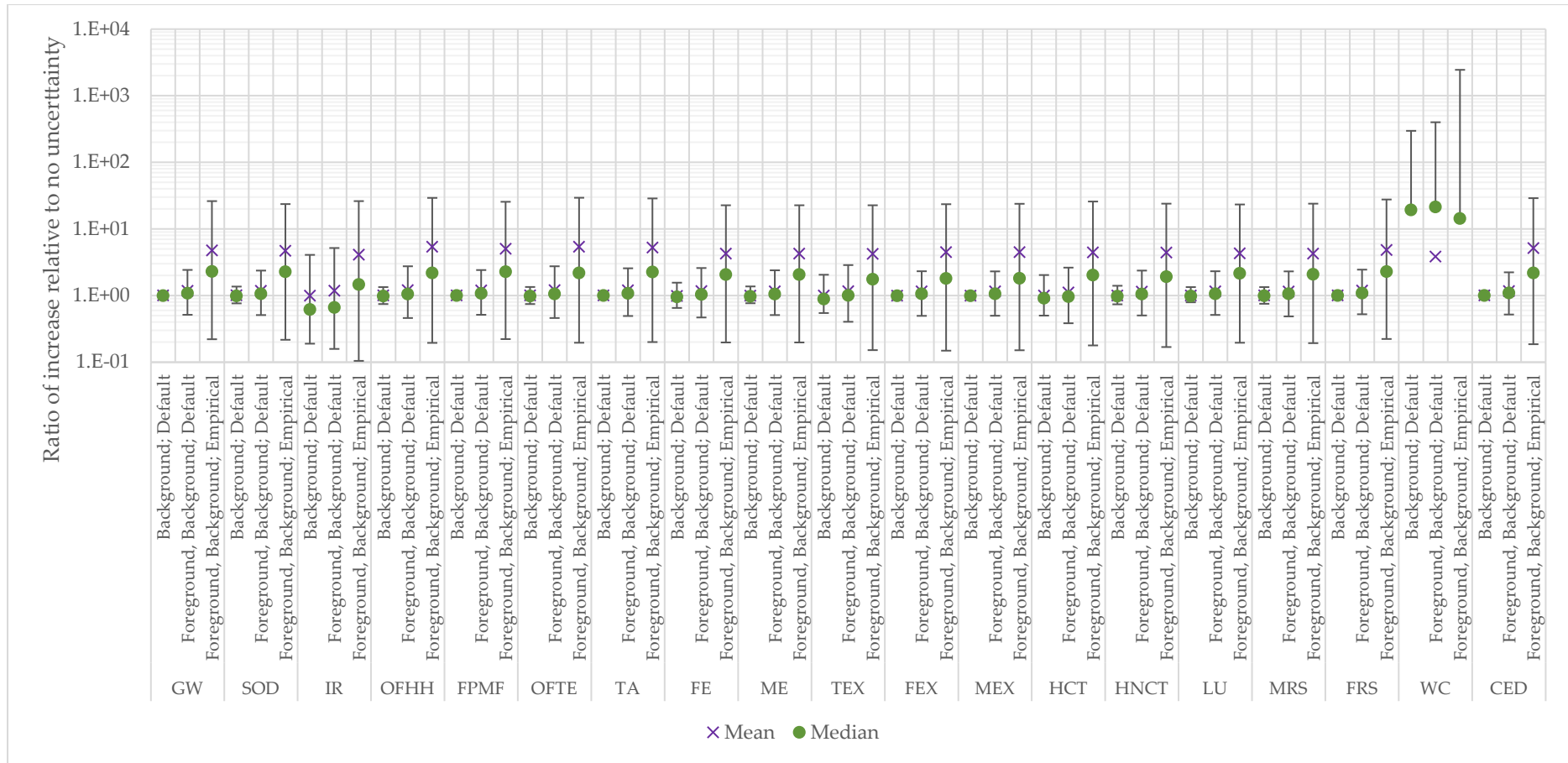


Figure 4.9. Comparison of different uncertainty approaches on the impacts of the Birsay site, relative to an approach with no uncertainty (unity). 'Background' and 'Foreground' refer to the life cycle inventory data. 'Default' and 'Empirical' refer to the default and empirically based uncertainty factors [87], [268].

Table 4.10. Comparison of different uncertainty approaches on the impacts of the Birsay site, relative to an approach with no uncertainty (unity). 'Background' and 'Foreground' refer to the life cycle inventory data. 'Default' and 'Empirical' refer to the default and empirically based uncertainty factors. For example, 1.08 indicates an increase of 8% relative to the Basic value, 0.95 indicates a decrease of 5%.

	Basic	Background; Default				Foreground, Background; Default				Foreground, Background; Empirical			
		2.5%	Mean	Median	97.5%	2.5%	Mean	Median	97.5%	2.5%	Mean	Median	97.5%
<b>GW</b>	<b>1.00</b>	0.88	1.00	<b>1.00</b>	1.16	0.52	1.18	<b>1.08</b>	2.42	0.22	4.77	<b>2.29</b>	26.21
<b>SOD</b>	<b>1.00</b>	0.76	1.01	<b>0.99</b>	1.37	0.51	1.18	<b>1.06</b>	2.37	0.22	4.69	<b>2.28</b>	23.59
<b>IR</b>	<b>1.00</b>	0.19	0.99	<b>0.62</b>	4.08	0.16	1.18	<b>0.66</b>	5.17	0.10	4.11	<b>1.46</b>	26.16
<b>OFHH</b>	<b>1.00</b>	0.75	1.01	<b>0.98</b>	1.34	0.46	1.21	<b>1.06</b>	2.76	0.20	5.41	<b>2.18</b>	29.34
<b>FPMF</b>	<b>1.00</b>	0.90	1.00	<b>1.00</b>	1.14	0.51	1.19	<b>1.08</b>	2.42	0.22	5.05	<b>2.27</b>	25.55
<b>OFTE</b>	<b>1.00</b>	0.75	1.01	<b>0.98</b>	1.35	0.46	1.21	<b>1.06</b>	2.75	0.20	5.40	<b>2.19</b>	29.37
<b>TA</b>	<b>1.00</b>	0.91	1.00	<b>1.00</b>	1.13	0.49	1.20	<b>1.08</b>	2.56	0.20	5.25	<b>2.25</b>	28.76
<b>FE</b>	<b>1.00</b>	0.65	0.99	<b>0.95</b>	1.56	0.47	1.17	<b>1.04</b>	2.59	0.18	4.41	<b>1.97</b>	23.76
<b>ME</b>	<b>1.00</b>	0.77	1.00	<b>0.97</b>	1.37	0.51	1.16	<b>1.05</b>	2.39	0.20	4.26	<b>2.06</b>	22.64
<b>TEX</b>	<b>1.00</b>	0.55	1.00	<b>0.89</b>	2.05	0.40	1.16	<b>1.00</b>	2.87	0.15	4.23	<b>1.75</b>	22.68

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		Background; Default				Foreground, Background; Default				Foreground, Background; Empirical			
	Basic	2.5%	Mean	Median	97.5%	2.5%	Mean	Median	97.5%	2.5%	Mean	Median	97.5%
FEX	1.00	0.89	1.00	0.99	1.14	0.50	1.16	1.06	2.32	0.15	4.48	1.80	23.59
MEX	1.00	0.89	1.00	0.99	1.14	0.50	1.16	1.06	2.31	0.15	4.48	1.81	23.84
HCT	1.00	0.50	1.00	0.91	2.04	0.38	1.11	0.97	2.63	0.18	4.44	2.03	25.80
HNCT	1.00	0.74	1.00	0.98	1.41	0.50	1.15	1.05	2.37	0.17	4.42	1.91	23.94
LU	1.00	0.79	1.00	0.98	1.34	0.51	1.16	1.06	2.32	0.20	4.31	2.15	23.30
MRS	1.00	0.75	1.01	0.99	1.34	0.49	1.15	1.06	2.31	0.19	4.27	2.09	24.02
FRS	1.00	0.88	1.01	1.00	1.17	0.52	1.19	1.09	2.45	0.22	4.82	2.29	27.67
WC	1.00	-463.78	-2.85	19.25	296.90	-591.44	3.84	21.31	400.66	-2211.29	-26.80	14.33	2452.36
CED	1.00	0.88	1.01	1.00	1.17	0.52	1.17	1.09	2.24	0.19	5.15	2.18	29.05
Median				0.99				1.06				2.15	

#### 4.3.4. Sensitivity analyses

##### 4.3.4.1. Lifetime energy production

Clearly, the environmental impacts are inversely proportional to the lifetime energy production, by the definition of the functional unit (kWh). The results are therefore inversely proportional to the site-specific WEC AEP (or capacity factor) and array availability (which is assumed as a constant in this treatment). Any reduction in the capability of the machine to generate power, for example through component or system degradation is not accounted for here.

##### 4.3.4.2. Device and array design parameters

In addition to array design life, important device and array properties were identified by inspecting the process network flow for the Birsay site: device mass; operations base and local port distances to site; and water depth. These variables were increased by 10% to assess the sensitivity of the results (Figure 4.10 – a 10% decrease simply reverses the change by the same magnitude). Given the role of lifetime energy production stated above, design life is consistently the most influential, apart from in impact categories where vessel operations (primarily from O&M) dominate – as O&M impacts are obviously increased for every additional year of operation. Effectively, increasing the design life makes the impacts from every stage except O&M lower per functional unit.

Device mass follows in most categories; with distance to operations base typically the next most influential. For global warming, the sensitivity to 10% increase in the distance to operations base was low; only 1.3%. The results generally have low sensitivity to water depth. As stated previously, only one component in the WEC mooring inventory (the tether) scales with water depth (based on the Pelamis P2 mooring design), however the substation platform

chains and all array cables both scale with water depth. The corresponding increase in global warming from the 10% increase in water depth is low (0.2%) but terrestrial, freshwater and marine ecotoxicity impacts are increased categories by around 2% primarily due to the landfill and recycling of the increased length of copper conductors in the array cables.

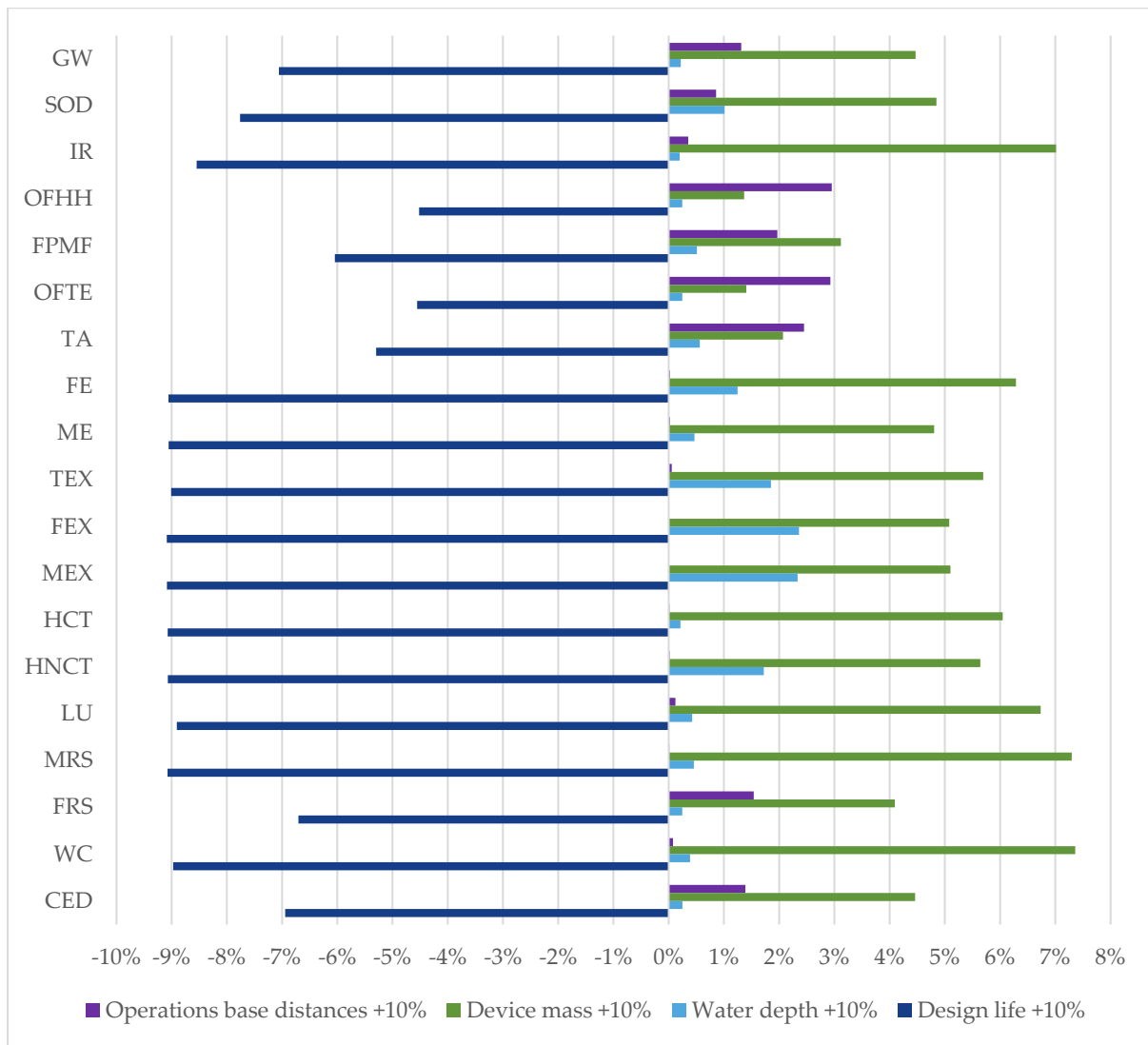


Figure 4.10. Change in environmental impacts with select device and array properties for the Birsay site.

#### 4.3.5. Comparability with other wave energy LCA global warming results

The basic and median global warming impacts are higher than the literature median (41.9 gCO<sub>2</sub>eq/kWh) but within the literature range 13 to 126 gCO<sub>2</sub>eq/kWh. Compared to most

studies, this chapter considers: life cycle of array infrastructure (especially substations, strings of array cables and export cables); and models vessel operations in increased detail.

#### 4.3.5.1. Effect of array infrastructure

Only Dahlsten [131] and Elginos [139] consider substations in their system boundary, with other array-scale studies considering individual devices without array cables (Zepeda [138]); or strings of devices apparently arrayed together and transmitting power via a few export cables (Pennock [147], although there is no description of the export cables in the results; only array cables).

In this analysis, the climate change impacts of the array infrastructure across all life cycle stages were 6.6, 10.2, 12.6 and 12.1 gCO<sub>2</sub>eq/kWh, Figure 4.11, or between 10.5, 16.1, 15.7 and 13.5%. This is higher than both Dahlsten [131] (which appears to be less than 6%) and Elginos [139] (approximately 5% for M&M and O&M). As with the results from previous sections, the materials and manufacture and the O&M were the two largest life cycle stage contributions, and the floating substation materiality and the array cable O&M were particularly significant (up to 3.3% and 3.9% respectively, Figure 4.11). The two smaller sites (Farr and Arnol), with lower utilisation of essentially the same substation and export cable inventory per WEC, have accordingly higher impacts from these array-level systems, although it is possible that real world smaller arrays would optimise the substation and export cable designs allowed for here. The impact of water depth can also be discerned, whereby Maywick (by some margin the deepest site at 110 m) demonstrates significant additional M&M impact from array cables (due to longer length) and O&M impact from OSCV operation (due to the longest travel distance from Aberdeen – 340 km – and extended time on station for a large number of WECs – 100 – at relatively low AEP).

Overall, while arranging WECs in arrays is a more efficient use of materials than using individual export cables, it appears that omitting the life cycles of the substation, array-cable strings and export cable risks excluding non-trivial sources of environmental impact; especially the substation materials and array cable O&M.

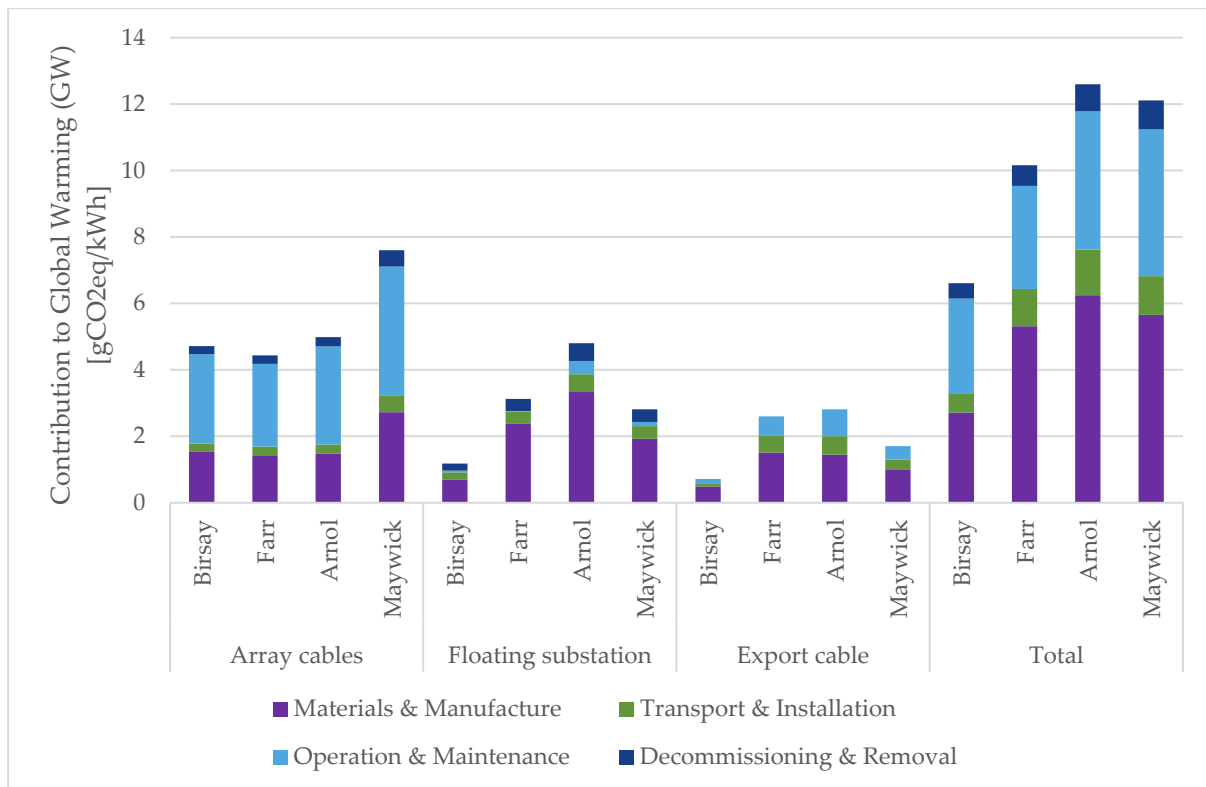


Figure 4.11. Array infrastructure life cycle stage contributions to global warming (GW) impact for all four sites.

#### 4.3.5.2. Effect of array scale compared to single device

The previous section showed that array infrastructure – especially the substation materials and array cable maintenance– is significant to the life cycle climate change impact of wave farms. However, the impact is obviously dependent on the array design optimisation, and the relative ‘utilisation’ of the substation and export cable relative to the number of WECs, and lifetime energy production. Conceivably, additional substations could also be required as a result of specific site bathymetry, geotechnical conditions, array topology or grid connection points.

In contrast, modelling only single device at the Birsay site (one WEC, and one export cable – no floating substation or array cables) results in a global warming impact of **120 gCO<sub>2</sub>/kWh**, approximately twice as high as results in previous sections. Figure 4.12 shows the sensitivity of the full suite of impact categories to this change in reference flow.

The sensitivity to the relative impact of the floating substation can be seen across all impact categories and life cycle stages. Omitting a substation *reduces* M&M and L&R impacts in all categories. However, the T&I impacts are increased around five-fold, around by a factor of around 2.6 in O&M. Nevertheless, reductions in total impact are observed in: freshwater and marine eutrophication; marine, terrestrial and freshwater ecotoxicity; human health (cancerous/non-cancerous); and material resource scarcity – primarily from the reductions in the materiality and disposal stages.

Arguably then, this change is less to do with the substation itself, but rather with the export cable's inclusion – and not its *materiality*, but its installation and O&M life cycle stages – which now dominates the array design. Instead of its impacts being shared between 200 WECs, its impacts are associated with the energy produced from only one. Another criticism of a single-device approach is that the array availability would likely be impacted by the significantly reduced redundancy of a single device relative to an array. However, quantifying this impact would require direct coupling to an O&M model, and Section 4.3.4.1 has already described the reciprocal effect on the environmental impacts that any change to availability would have.

This sensitivity study shows that curtailing the reference flow to a single device could lead to distortions in the reported results, especially when assumptions for installation and O&M are modelled in detail as will be discussed in the following section.

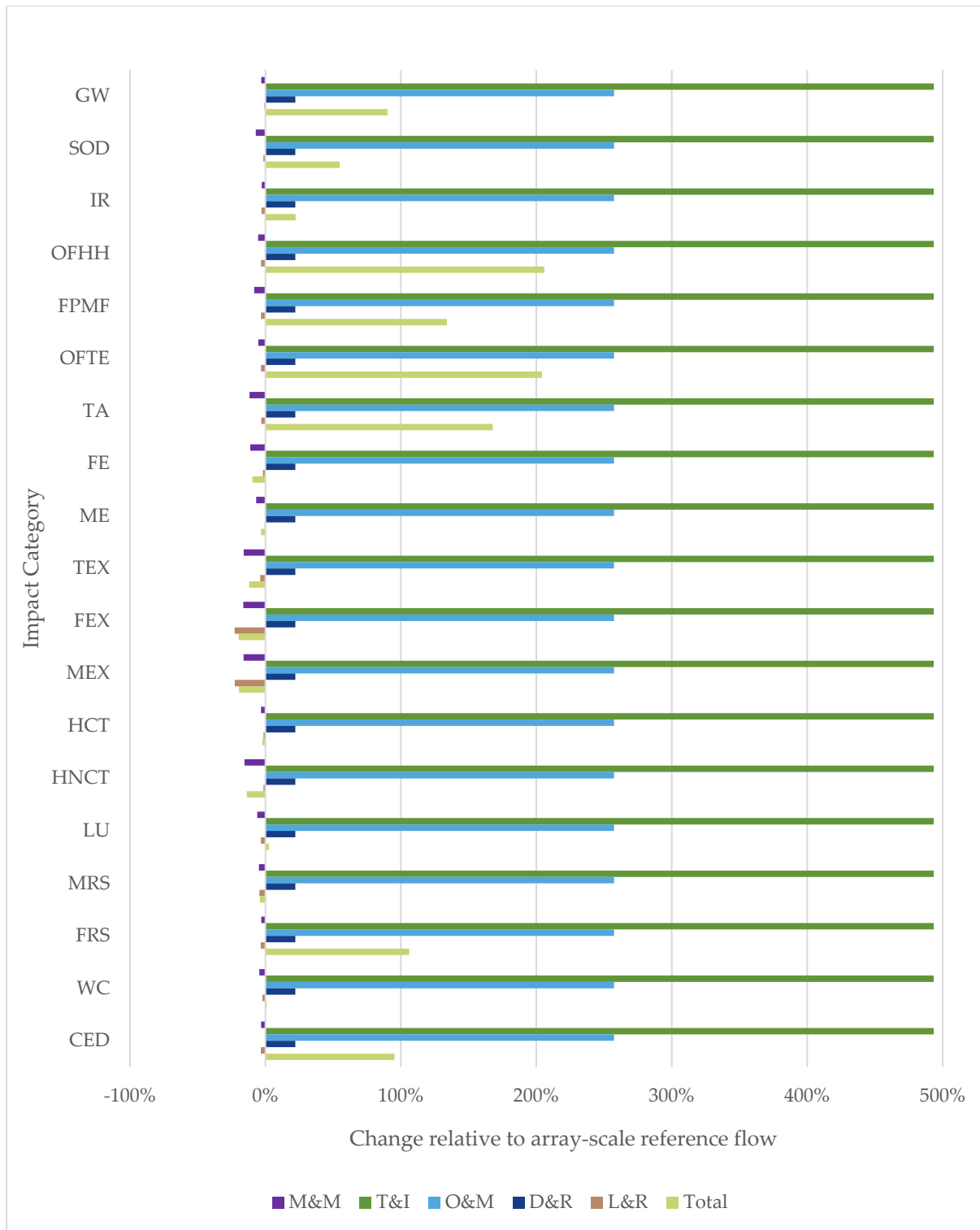


Figure 4.12. Sensitivity of Birsay results to change in reference flow from array of WECs to single WEC. All life cycle stage impacts of array cables and floating substation have been removed (M&M, T&I, O&M, D&R, L&R) but a single export cable remains within then system boundary.

#### 4.3.5.3. Effect of vessel representation

Vessel representation in offshore renewable energy varies significantly between studies. Uihlein [137] reports vessel operations in hours, but does not provide clarity on how this is converted from the Thinkstep default vessel process units<sup>31</sup>. Thomson [145] represents sea-going vessels by scaling a process of tonne.kilometres of transoceanic ships using vessel fuel consumption to find days of operation, while Karan [144] scales tonne.kilometres of river-going barges. Pennock [147] scales tonne.km of fuel consumed in a sea-going ferry using Heavy Fuel Oil (HFO), the background data of which includes averages for modes of operation and port infrastructure.

Relative to the literature then, vessel operations are modelled here using different vessel types and using different background data processes. In addition, this chapter assumes a wider (array-scale) O&M burden (including moorings, array cables and export cables), relative to most other studies, being based on a wide-ranging literature review (Section 4.2.3.5). Device design and maintenance philosophy will also affect the specific mobilisations and durations in-field, but this is harder to discern. As previously mentioned, modes of operations are rarely modelled.

Each of these methodological differences will have an effect on the environmental impacts associated with O&M, making comparison with this chapter challenging. The O&M contribution to GW varies between 17 and 33% across the four sites, which is comparable with contemporary studies using developer primary data [145], [147]. Figure 4.13 shows that here

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<sup>31</sup> 'GLO: bulk commodity carrier' and 'EU-27: barge incl. fuel' are interpreted as Bulk commodity carrier [kg] (UUID 579b25df-31b4-4361-87be-f67689ce6704) and Barge incl. fuel [kg.km] (UUID 09aa1e7b-1d7d-4a7c-8dde-ec6d40022fa1). Uihlein was not able to provide this conversion in personal communication with the author.

this is primarily driven by the WEC retrieval operations, and hence by distance to O&M base (assuming consistent vessel specification and performance and sea-state during transit). This is clearly shown by the Arnol site which has the further distance to O&M port. Conversely, Maywick with the assumed shorter distance to O&M base, has the subsea maintenance (of WEC moorings and array cables) as the most impactful O&M vessel operation. Generally, the O&M impact on GW of the substation and export cable is minor.

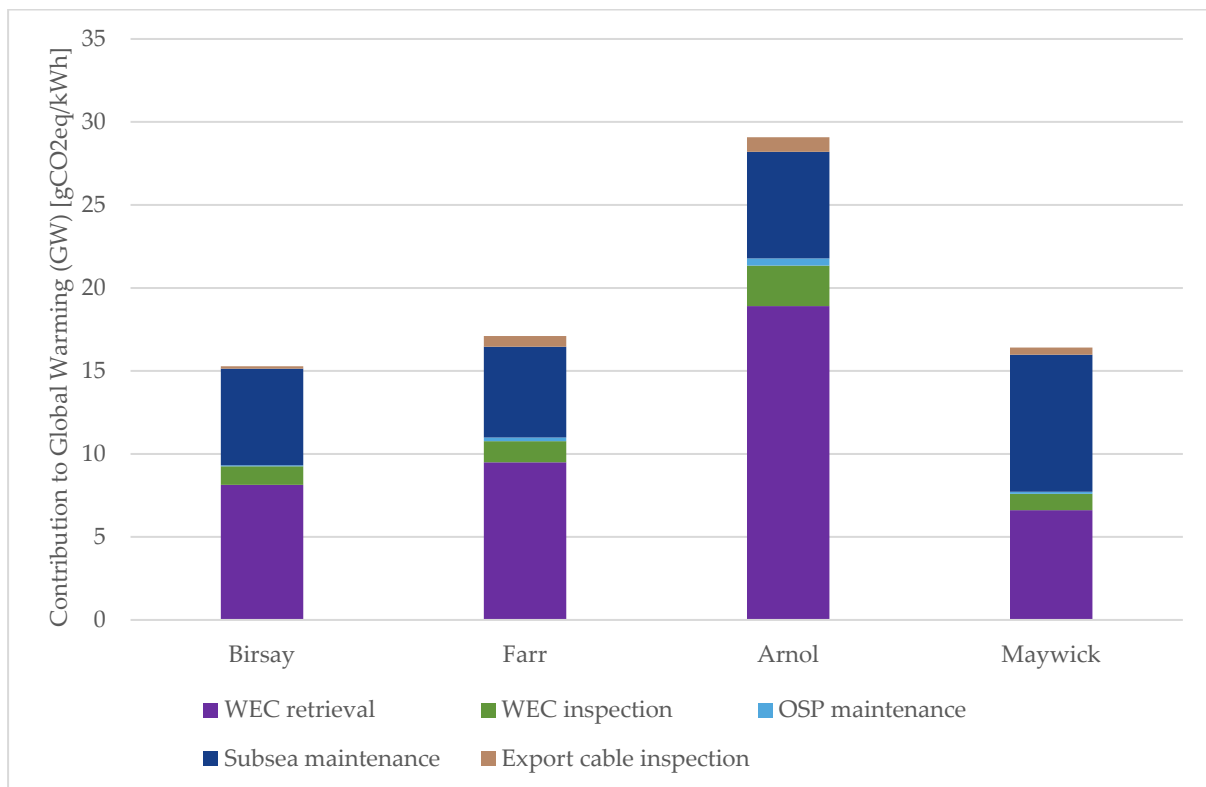


Figure 4.13. Contribution to global warming (GW) impact category from vessel operations during O&M across the four sites.

As described previously, the novelty of the vessel operation modelling in this study precludes direct comparison with comprehensive studies such as Uihlein [137]. However, isolating the differences between the studies can be one way to explore a comparison.

In this flagship paper, the vessel movements are modelled using the processes: 'GLO: bulk commodity carrier' and 'EU-27: barge incl. fuel' from the Thinkstep (now Sphera) Gabi database, with an average of 26 hours for installation and 100 hours of maintenance per year per device [137]. No environmental impacts were assumed for the disassembly process. Unfortunately, a description of how the vessel hours are transformed from these processes is not available, so, in a first approximation to quantify this difference, the Birsay model was rerun, assuming that hours were input directly as tonne.km.

To do this, the total hours of vessel operations from T&I and O&M for the Birsay case were aggregated (Table 4.11, Table 4.12). 70% of these were input to the model as theecoinvent process 'Transport, freight, sea, container ship {GLO}| transport, freight, sea, container ship | Cut-off, U', and 30% 'Transport, freight, inland waterways, barge {RoW}| processing | Cut-off, U' - the processes most analogous processes to the Sphera processes above. Decommissioning was omitted as per the approach in [137]. All transport and installation time (including array system installations) totalled 121 hours per Blue Horizon WEC, much larger than compared to 26 hours [137]. All maintenance operations (including array system maintenance) totalled 45 hours per WEC per year, much less than compared to 100 hours [137] above.

The net effect of this re-analysis was to make all vessel impacts effectively negligible as a percentage of the total impact (Figure 4.14). This echoes the findings from [137], (especially their Fig. 8 and Fig. 9), where 'impacts from assembly, installation and use are insignificant for all device types'. Here, the basic global warming result (without considering uncertainty) for Birsay falls to **40.6 gCO<sub>2</sub>eq/kWh**; below the median in the literature of 41.9 gCO<sub>2</sub>eq/kWh.



Figure 4.14. Base case Birsay results showing significant impact from vessel operations (left) versus the inferred method from Uihlein [137] (right). Note the effective removal of impact from vessel operations (right).

Table 4.11. Calculation of installation hours per WEC for the Birsay site

System	Process	Parametric Equation	Total [hrs/life]	Hours / WEC
<b>1.1 TI Blue Horizon WEC Subsystem</b>	Tug, towing	$d_{wec} / v_{tug\_tow}$	3.93E+01	59.8
	Tug, Dynamic Positioning	$t_{wec\_install}$	4.00E+00	
	Tug, economical speed	$d_{wec} / v_{tug\_econ}$	9.91E+00	
	Tug, standby	$t_{wec\_load}$	2.00E+00	
	Multi-cat, economical speed	$(d_{local} / v_{multicat\_econ}) / n_{tug\_team}$	5.95E-01	
	Multi-cat, Dynamic Positioning	$t_{wec\_install}$	4.00E+00	
<b>1.2 TI Blue Horizon Mooring Subsystem</b>	AHTS, economical speed	$(n_{wec} / n_{mooring\_AHTS}) * (d_{reg} / v_{AHTS\_econ}) * 2$	1.19E+03	42.0
	AHTS, Dynamic Positioning	$n_{wec} * n_{wec\_anchors} * t_{anchor\_install}$	7.20E+03	
<b>2.0 TI Array Cable System</b>	CLV, economical speed	$n_{array\_legs} * (d_{array} / v_{CLV\_econ}) * 2$	1.26E+02	11.2
	CLV, Dynamic Positioning	$n_{wec} * (1211/1000) / v_{array\_lay}$	2.11E+03	
	AHTS, economical speed	$d_{reg} / v_{AHTS\_econ} * 2$	2.97E+01	3.5
	AHTS, Dynamic Positioning	$t_{hub\_pull\_in} * n_{strings\_hub} * n_{hub}$	5.44E+02	

System	Process	Parametric Equation	Total [hrs/life]	Hours / WEC
3.2 TI Platform  (Topside + Substructure)	SSHLB, economical speed	$d_{platform} / v_{SSHLB\_econ} * 2 * n_{hub}$	8.30E+01	
	3.3 TI Mooring Subsystem	AHTS, Dynamic Positioning	$3 * t_{anchor\_install} * n_{hub}$	
4.0 TI Export Cable System	CLV, economical speed	$n_{hub} * (d_{export} / v_{CLV\_econ}) * 2$	6.31E+01	4.2
	CLV, Dynamic Positioning	$n_{hub} * l_{41} / v_{export\_lay}$	1.85E+02	
	OSCV, economical speed	$n_{hub} * (d_{reg} / v_{OSCV\_econ}) * 2$	2.48E+01	
	OSCV, Dynamic Positioning	$n_{hub} * l_{41} / v_{cable\_trench}$	2.76E+02	
	PSV, economical speed	$n_{hub} * (d_{reg} / v_{PSV\_econ}) * 2$	2.48E+01	
	PSV, Dynamic Positioning	$n_{hub} * l_{41} / v_{cable\_trench}$	2.76E+02	
<b>Total</b>	-	-	-	121

Table 4.12. Calculation of maintenance hours per year per WEC for the Birsay site

System	Subsystem	Process	Parametric Equation	Total [hrs/lifetime]	Hours / WEC / year
0.0 OM Novel Floating Wave Farm	OM1	Blue Horizon, Tug, economical speed [hours]	$OM1\_retrieval\_freq * (d\_ops / v\_tug\_econ) * (n\_wec * design\_life) * 2$	1.08E+04	45
		Blue Horizon, Tug, Dynamic Positioning [hours]	$OM1\_retrieval\_hr * (n\_wec * design\_life) * 2$	1.47E+04	
		Blue Horizon, Tug, towing [hours]	$OM1\_retrieval\_freq * (d\_ops / v\_tug\_tow) * (n\_wec * design\_life) * 2$	4.30E+04	
	OM2	Blue Horizon, Multi-cat, economical speed [hours]	$OM2\_inspection\_freq * (d\_ops / v\_multicat\_econ) * (n\_wec * design\_life) * 2$	1.24E+04	
		Blue Horizon, Multi-cat, standby [hours]	$OM2\_inspection\_hr * (n\_wec * design\_life)$	4.64E+04	
	OM3	Blue Horizon, Multi-cat, economical speed [hours]	$OM3\_OSP\_maint\_freq * (d\_ops / v\_CTV\_econ) * (n\_hub * design\_life) * 2$	2.63E+02	
		Blue Horizon, Multi-cat, standby [hours]	$OM3\_OSP\_maint\_hr * (n\_hub * design\_life)$	1.00E+03	

System	Subsystem	Process	Parametric Equation	Total [hrs/lifetime]	Hours / WEC / year
	OM4	Blue Horizon, OSCV, economical speed [hours]	$OM4\_subsea\_freq * (d\_reg / v\_OSCV\_econ) * (design\_life) * 2$	2.58E+02	
		Blue Horizon, OSCV, Dynamic Positioning [hours]	$OM4\_subsea\_hr * (n\_wec * design\_life)$	5.00E+04	
	OM5	Blue Horizon, OSCV, economical speed [hours]	$OM5\_export\_freq * (d\_reg / v\_OSCV\_econ) * (design\_life) * 2$	2.58E+02	
		Blue Horizon, OSCV, Dynamic Positioning [hours]	$OM5\_export\_hr * 141 * design\_life$	6.86E+02	

#### 4.3.5.4. Use of O&M model outputs in LCA to account for site specific conditions

Wave Energy Scotland (WES) provide an open Excel-based tool for simulating the O&M of wave energy arrays [269], including reliability data for the Pelamis P2 machine and default weather data for Farr Point. Farr Point is effectively an identical location to the Farr site defined earlier in this chapter, and were assessed a possible resource to carry out a coarse validation of the generic figures developed in this thesis. Accordingly, it was assumed that the reliability of the Blue Horizon could be represented as a first approximation by removing all failure data for the P2 oil hydraulic power take off (PTO) components, but retaining the default failure rates and weather data to model a Blue Horizon array at the Farr site (no failure rates for the Blue Horizon PTO were applied due to lack of data). A fleet of four tugs was exogenously assumed, using the same towing and steaming speeds as the life cycle model. This resulted in significant changes to the O&M burden: a four-fold increase in Tug transit, a 2.5 times increase in towing and a decrease in array availability (Table 4.13).

The fuel consumption between different modes of operation is not modelled explicitly in the WES O&M Simulation Tool, however, it is possible to estimate the durations of specific modes by back-calculating the model outputs. Interrogating the fuel costs, and comparing this with journey time can yield coarse indications of the durations in different modes. In addition, the Tool outputs an array availability, in this case 83.7%; lower than the empirical figure from established offshore wind data used in the main analysis (95.36%) [259], by a ratio of 0.88. As outlined in Section 4.3.4.1, impacts are inversely proportional to lifetime energy production (of which availability is a factor), so all environmental impacts of every life cycle stage increase by a factor of 1.14 ( $0.88^{-1}$ ) by this change in availability alone.

However, all environmental impacts from the O&M life cycle stage are increased by the additional O&M vessel movements. This increases the impact from the O&M life cycle stage by 2.16 times relative to the original Farr case (or 1.89 times when the effect of availability is removed, Table 4.14). When the influence of the change in availability is removed, this change to the O&M life cycle stage affects the overall life cycle environmental impacts by a ratio of 1.00 to 1.47 ( Figure 4.15, Table 4.14), depending on the significance of the O&M stage to the impact category. Alternatively, if the effect of availability *is* included, the life cycle environmental impacts are increased by a factor of 1.14 to 1.68. The impact categories that are most affected are ozone formation (human health and terrestrial ecosystems) due to the additional fuel combustion: other categories associated with O&M are terrestrial acidification, fine particulate matter formation, fossil resource scarcity, global warming, cumulative energy demand and stratospheric ozone depletion.

For global warming, the impact increases by a factor of 1.39 or 1.22 if adjusted for the effect of the change in availability. This increase emphasises the importance of accurate O&M foreground data (both calculated array availability and vessel operating time) to the total life cycle impacts. This is significant to the preceding sections in two ways. Firstly, it appears that the generic figures developed in Section 4.2.3.5 *underestimate* the maintenance burden for device retrieval and replacement relative to a dedicated O&M model (albeit one based on a single analysis with superficially similar device reliability data, and an arbitrary selection of maintenance fleet). Secondly, as indicated in Section 4.3.4.1, the array availability has an inversely proportional effect on the environmental impacts, and this alone may be a convincing reason to model array O&M in detail for any future wave energy LCAs.

This brief treatment has other limitations: the WES O&M Simulation Tool only includes towing as a maintenance intervention, and therefore has no impact on other maintenance categories such as OSCV cable inspection or on-station maintenance. Further, the metocean input data are not equivalent: the O&M Simulation Tool does include a power matrix, but this was left fallow for this work as it refers to lost earnings, not vessel movements. Conceivably though, this could be explored using the proprietary Blue Horizon power matrix with appropriate disclosure agreements in place, to investigate the renewable resource data on AEP. Alternatively, the same metocean data could be used in each model, as the ESIX data does not model vessel operability impacts on O&M burden (or availability). Lastly, only one array was studied here; it may be that the effect of these differences is amplified for sites further from operations base (such as Arnol).

Further work would be required to confirm the suitability of the reliability data and validity of the interpretation of the O&M Simulation Tool outputs, however where possible it seems that the use of O&M models to inform marine energy LCA would be a valuable research avenue, and is already being explored for floating wind [260].

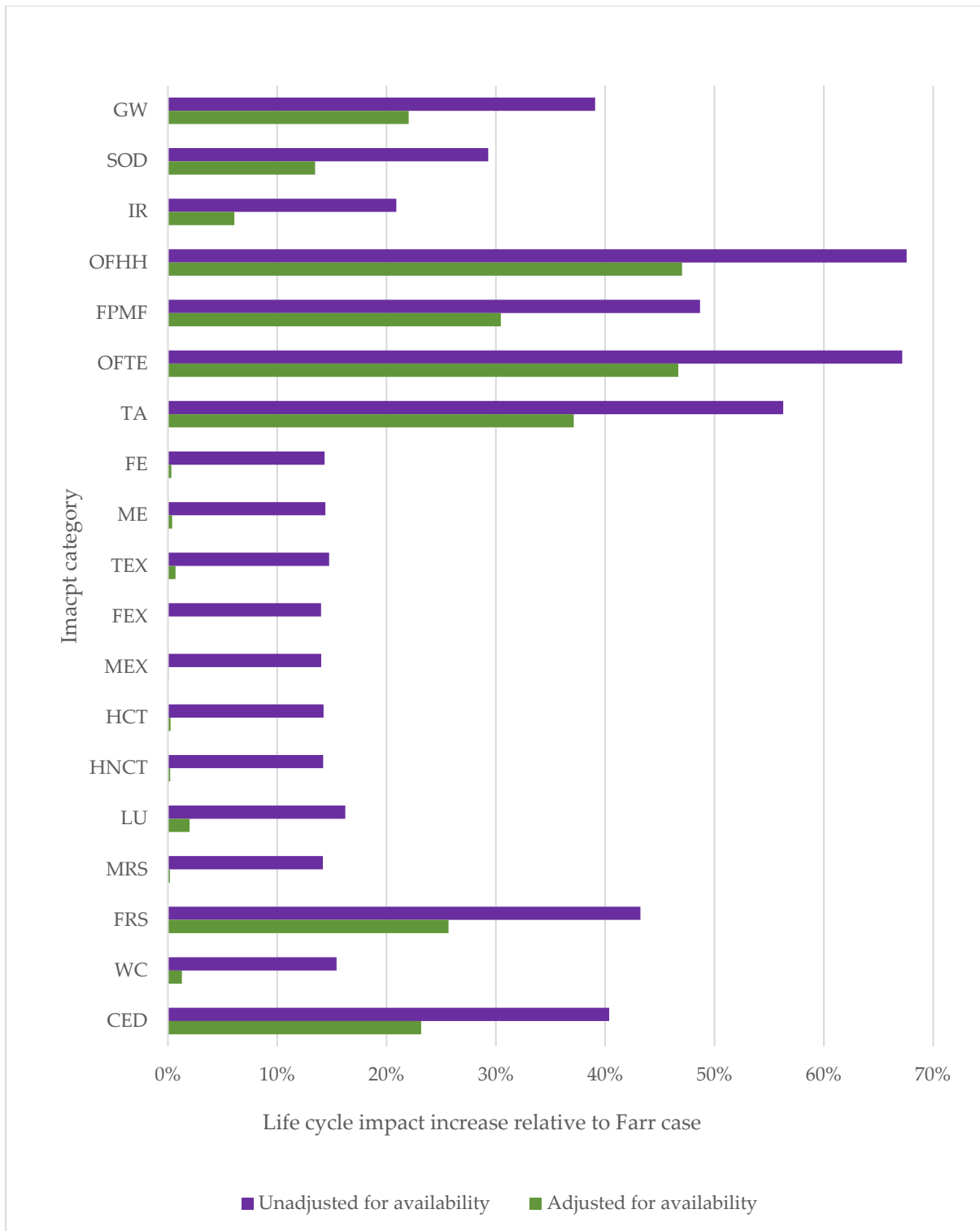


Figure 4.15. Relative increase in impact categories between base Farr case and using WES O&M Simulation Tool to retrieve/replace WEC.

Table 4.13. Differences between Farr base case O&M properties and outputs from WES O&M Simulation Tool.

Process / Parameter	Equation	Farr	WES	Ratio
Blue Horizon, Tug, economical speed [hours]	$OM1\_retrieval\_freq * (d\_ops / v\_tug\_econ) * (n\_wec * design\_life) * 2$	3490	13865	4.0
Blue Horizon, Tug, Dynamic Positioning [hours]	$OM1\_retrieval\_hr * (n\_wec * design\_life) * 2$	3680	7	0.002
Blue Horizon, Tug, towing [hours]	$OM1\_retrieval\_freq * (d\_ops / v\_tug\_tow) * (n\_wec * design\_life) * 2$	13400	33276	2.5
Array availability	-	0.954	0.837	0.88

Table 4.14. Percentage difference effects between Farr base case and using WES O&M Simulation Tool, unadjusted and adjusted for the change in availability

	Unadjusted for availability [%]						Adjusted for Availability [%]					
	M&M	T&I	O&M	D&R	L&R	Total	M&M	T&I	O&M	D&R	L&R	Total
<b>GW</b>	1.14	1.14	2.16	1.14	1.14	1.39	-	-	1.89	-	-	1.22
<b>SOD</b>	1.14	1.14	2.16	1.14	1.14	1.29	-	-	1.89	-	-	1.13
<b>IR</b>	1.14	1.14	2.16	1.14	1.14	1.21	-	-	1.89	-	-	1.06
<b>OFHH</b>	1.14	1.14	2.16	1.14	1.14	<b>1.68</b>	-	-	1.89	-	-	<b>1.47</b>
<b>FPMF</b>	1.14	1.14	2.16	1.14	1.14	1.49	-	-	1.89	-	-	1.30
<b>OFTE</b>	1.14	1.14	2.16	1.14	1.14	<b>1.67</b>	-	-	1.89	-	-	<b>1.47</b>
<b>TA</b>	1.14	1.14	2.16	1.14	1.14	1.56	-	-	1.89	-	-	1.37
<b>FE</b>	1.14	1.14	2.16	1.14	1.14	1.14	-	-	1.89	-	-	1.00
<b>ME</b>	1.14	1.14	2.16	1.14	1.14	1.14	-	-	1.89	-	-	1.00
<b>TEX</b>	1.14	1.14	2.16	1.14	1.14	1.15	-	-	1.89	-	-	1.01
<b>FEX</b>	1.14	1.14	2.16	1.14	1.14	1.14	-	-	1.89	-	-	1.00

	Unadjusted for availability [%]						Adjusted for Availability [%]					
	M&M	T&I	O&M	D&R	L&R	Total	M&M	T&I	O&M	D&R	L&R	Total
<b>MEX</b>	1.14	1.14	2.16	1.14	1.14	1.14	-	-	1.89	-	-	1.00
<b>HCT</b>	1.14	1.14	2.16	1.14	1.14	1.14	-	-	1.89	-	-	1.00
<b>HNCT</b>	1.14	1.14	2.16	1.14	1.14	1.14	-	-	1.89	-	-	1.00
<b>LU</b>	1.14	1.14	2.16	1.14	1.14	1.16	-	-	1.89	-	-	1.02
<b>MRS</b>	1.14	1.14	2.16	1.14	1.14	1.14	-	-	1.89	-	-	1.00
<b>FRS</b>	1.14	1.14	2.16	1.14	1.14	1.43	-	-	1.89	-	-	1.26
<b>WC</b>	1.14	1.14	2.16	1.14	1.14	1.15	-	-	1.89	-	-	1.01
<b>CED</b>	1.14	1.14	2.16	1.14	1.14	1.4	-	-	1.89	-	-	1.23

#### 4.3.5.5. Performance relative to other sources of electricity

As has been described, this chapter applies different approaches to most of the literature; and which, by definition, impairs comparison. As has been shown, maintenance assumptions are very diverse even within wave energy LCAs, and expanding investigations into other generation technologies reveals further discontinuities [147]: for example, theecoinvent v3.6 processes for onshore and offshore wind include no allowance for maintenance activities [162]. Subtracting array infrastructure or O&M impacts from the results presented above, may be a first approximation towards comparison with other studies. Nevertheless, these results are considered alongside those of floating wind and other technologies in Chapter 5.

#### 4.3.5.6. Carbon and energy payback times

The carbon payback time (CPT) is the length of time required for the lifetime carbon equivalent emissions of a system to be ‘paid back’ by displacing the next most likely means of delivering the functional unit. In wave energy LCAs the carbon payback time (CPT) is conventionally calculated by dividing the system lifetime carbon equivalent emissions, by the annual amount of electricity generated (assumed equal to the amount of grid electricity obviated or displaced) multiplied by the annual average carbon intensity of the spatially averaged (national) grid (Equation 3).

*Carbon Payback Time [years]*

$$= \frac{\text{Lifetime emissions [kgCO}_2\text{eq]}}{\text{AEP} \left[ \frac{\text{kWh}}{\text{year}} \right] * \text{Emissions intensity of displaced electricity} \left[ \frac{\text{kgCO}_2\text{eq}}{\text{kWh}} \right]}$$

*Equation 3. Expression for calculating carbon payback time.*

This assumption neglects any change in the yearly carbon intensity of power, and any network congestion issues, where power grid topology could impede transmission of low carbon

intensity power to areas typically supplied by high carbon intensity generation. In prior studies, power system carbon intensity is typically assumed to be constant (Chapter 3) however in recent years in GB where power system emissions intensity has fallen significantly (and is expected to fall further, Figure 4.16), this approach is likely to be less representative [270], [271].

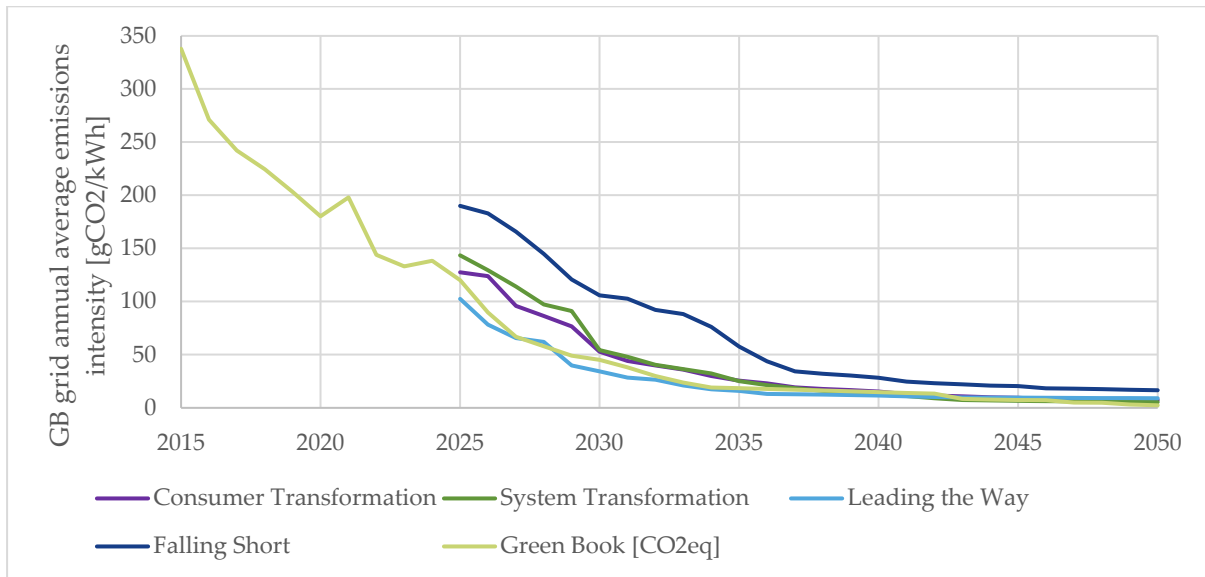


Figure 4.16. Examples of GB generation-based emissions intensity factors

Using Figure 4.16 and a constant generation-based emissions factor of 120 gCO<sub>2</sub>eq/kWh for the year 2025 [270] yields a payback time of 11 to 16 years across the four arrays (Table 4.15). However, calculating yearly displaced emissions by multiplying site AEP with factors from FES2022 'Leading the Way' and 'Green Book' series, and subtracting this yearly from the lifetime emissions yields payback times beyond the design life (20 years) of the arrays.

Table 4.15. Energy payback time, energy ratio and carbon payback time accounting for decarbonising power sector.

	Birsay	Farr	Arnol	Maywick
Array AEP (including Availability) [TWh/yr]	0.64	0.18	0.13	0.23
Lifetime energy production (LEP) [TWh]	12.88	3.58	2.51	4.52
Lifetime CO <sub>2</sub> eq production (LCP) [MtCO <sub>2</sub> eq]	0.88	0.25	0.22	0.43
Cumulative energy demand (CED) [TWh]	3.43	0.93	0.84	1.67
Energy Payback Time (CED/AEP) [years]	5.3	5.2	6.7	7.4
Energy Ratio (LEP/CED)	3.8	3.9	3.0	2.7
GHG emissions payback (2025 static) [years] [270]	11.4	11.6	14.5	15.8
GHG emissions payback (Green Book) [years] [270]	Beyond design life	Beyond design life	Beyond design life	Beyond design life
Carbon Payback (Leading the Way) [years]	Beyond design life	Beyond design life	Beyond design life	Beyond design life

Similarly, energy payback time is commonly defined as the time for the device to generate enough energy to offset the lifetime energy demand of its lifecycle, calculated using AEP and the CED impact category. The energy payback time was found to be approximately five to seven years; higher than, but comparable to Thomson, Karan and the upper range of Pennock (2.75, 3.75 and 5.2 years respectively) [144], [145], [147]. However, the energy ratio (2.7 to 3.9),

also known as Energy Return on Investment (EROI, the ratio of energy produced to energy demand) is lower than Thomson [145]. These differences likely arise from the treatment of vessels and site-specific AEP in this chapter. The long carbon payback time suggests that this may cease to be a meaningful parameter for low carbon generation in the face of increasing power sector decarbonisation. In the coming years, global warming impact calculated directly from LCA may become the more relevant metric, or alternatively, a change in the scale of analysis (for example, spatially or temporally) may be required. Perhaps energy payback time would become a more relevant parameter.

*Box 4.1. Changing the background data and carbon intensity of displaced energy with time*

As the background data of this LCA is static in time, the potential decarbonisation of material production or vessel propulsion is not included. Technological trends suggest the carbon intensity of these processes will decrease in time [272], [273], reducing the embodied carbon of the device but potentially shifting burdens to other parts of the life cycle.

Operational emissions are not "locked in" during the manufacturing stage in the same way as material emissions are: vessel emissions could conceivably be reduced by low carbon propulsive systems during design life of the array.

There could also be scope to consider the direct dispatch of wave power to displace fossil heating and transport which may yield shorter carbon payback times due to the typically higher emissions per unit heat energy from fossil fuels, and fossil fuel vehicles. This may be particularly relevant to Scottish highland and island communities where diesel generation and oil central heating are prevalent. Novel applications of this idea could be pursued in parallel with device development to maximise carbon reduction potential of these arrays, outside of traditional power markets.

### 4.3.6. Opportunities to mitigate global warming impact

This section describes the “hot spots” identified for global warming (GW) with only the Birsay site presented for brevity.

- The processes with the largest impact on global warming were: diesel burned in vessels; low alloyed, hot rolled steel; and chromium steel (Figure 4.17). It is important to note that the total exceeds 100% because some background data processes are used in multiple assemblies.
- The assemblies with highest impacts were: the WEC structural mass itself (fore and aft hulls, steel); the WEC mooring system (including clump weights and chain); the WEC generator components (electronic components, magnets, copper and steel), WEC gearbox (including chromium steel) and WEC ballast (steel).
- Tug transit (including towing) for WEC retrieval during O&M was the largest vessel operation impact, followed by offshore construction vessel Dynamic Positioning during mooring and array cable subsea inspections/maintenance. Interestingly, the next largest single component was AHTS DP during WEC mooring installation – the only time that T&I really appears significant.

The most significant opportunities to mitigate GW are therefore “greening” or obviating (or at least, optimising) steel and diesel use. This can be achieved in a number of ways, though each with its own practical challenges. The impact from vessel emissions can be addressed by reducing the need for maintenance. Designing for reliability and reducing the need for vessel intervention using condition monitoring or robotic intervention could further reduce this impact. Development and use of low carbon vessel propulsion technologies would

reduce the direct emissions further but is largely outside a WEC designer's control. Similarly, increasing structural efficiency (already challenging for WECs due to the need for survivability in infrequent extreme loads and onerous fatigue duties) and using fewer materials would reduce the impact, while the pursuit of decarbonised production and recycling of steel and other durable materials remains a systemic challenge. The distribution is similar across all four sites, although Arnol, with a longer distance to O&M base, does experience higher WEC retrieval and fuel use impacts.

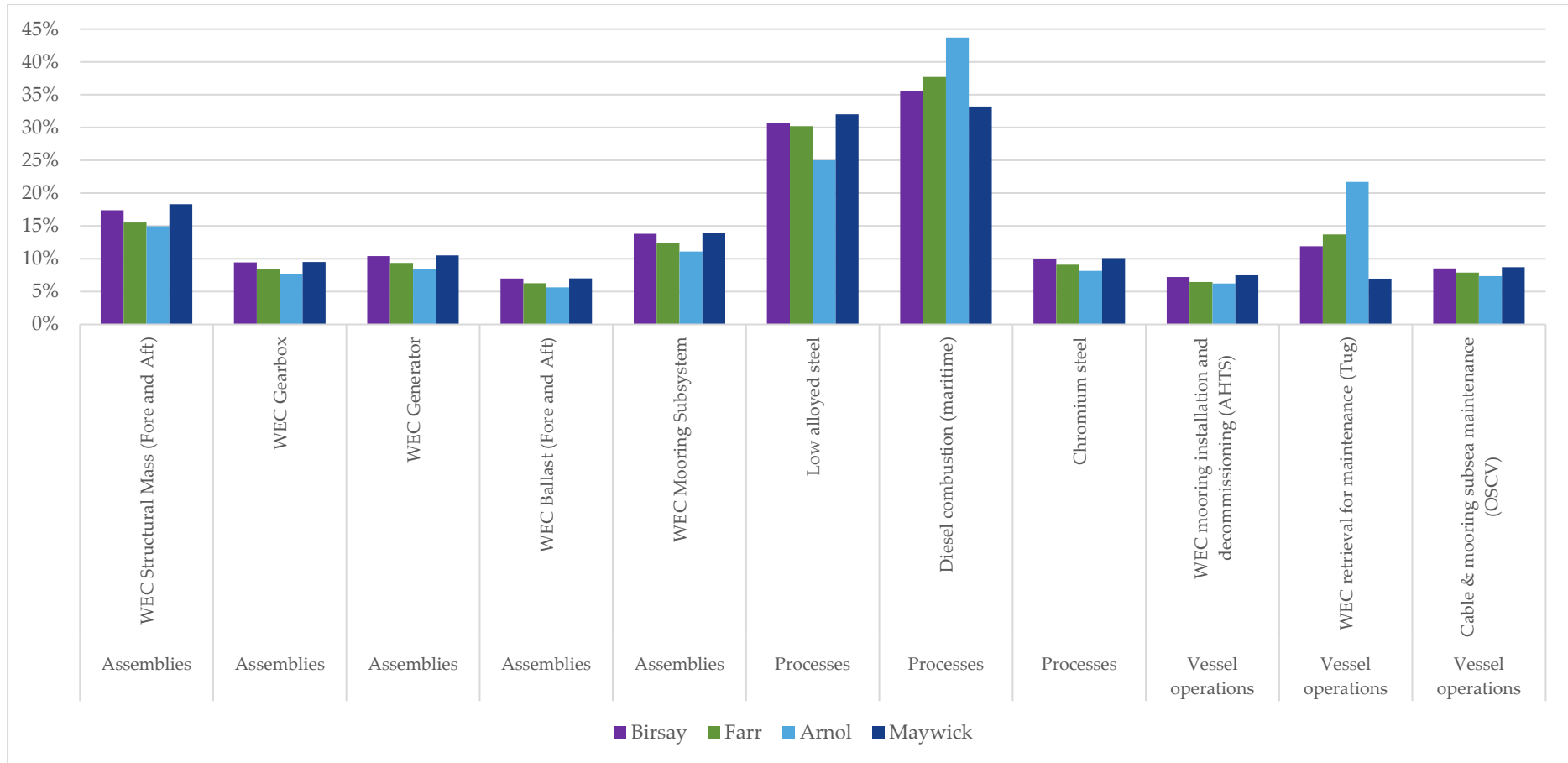


Figure 4.17. Summary of the largest contributions to global warming impact for all sites, split by 'Assemblies', 'Processes' and 'Vessel operations'. Totals are greater than 100% because

'Processes' appear within the impacts of 'Assemblies' and 'Vessel operations'.

#### 4.3.7. Limitations of the work and future research needs

It is important to present a discussion of the limitations of the study alongside any LCIA results. The system boundary of this chapter has already been well emphasised (Section 4.2), but could always be expanded in terms of coverage and completeness. Some discussion is provided below to set out the perceived limitations and possible avenues for future research.

- Any changes to the lifetime energy production will inversely affect the results. In particular, the WEC power performance and design life could change as the device design progresses. While site-specific, the AEP is based on macro-scale reanalysis data and neglects any allowance for device “shielding” due to array layout, or other large-scale hydrodynamic interactions which might affect device AEP. Similarly, any electrical losses arising from the array system design would directly affect the results (these are currently omitted). The effect of maintenance on array availability would also be significant.
- Spare parts are outside the system boundary of this chapter. This has been identified as an important aspect in some adjacent literature [274] and would act to increase the LCI and likely environmental impacts.
- Fundamentally, there remains a temporal difference in the empirical background data, and the future-looking reference flow. As has been discussed, systemic changes in steel production and vessel propulsion may be expected in coming years, limiting the applicability of historical background data. The ecoinvent database processes are relevant for a certain moment in time; ignoring the temporal inhomogeneity of life cycle inventory data is among the major recognised problems in LCA practices [141]. Using this database makes it impossible to account for technological progress such as

the decarbonisation of electricity, vessel propulsion and steel production. Specifically, the primary steel material used here is valid for the global market mix from 1/1/11 to 31/12/19, while the arrays studied here are assumed to be operational in 2025. Some novel approaches to remedy this have been pursued for other low carbon energy technologies (electric vehicles and heat pumps) by adjusting the LCA background data with inputs from integrated assessment models (IAMs) [275], [276] - *dynamic process inventory* [277]. Reducing environmental impacts of background materials and process will reduce the environmental pressures from these arrays. Challenges remain to model vessel propulsion technology development and any associated burden shifting to other impact categories (*dynamic systems*, [277]).

- Further, renewable resource data based on reanalysis contains no information on how future renewable resource will evolve. This evolution of renewable wave energy resource, especially in light of climate change, was considered to be outside of the scope of this LCA [278]. Metocean conditions from site could reveal different device power outputs at greater spatial fidelity, but at significantly more cost and measurement time for the site developer.
- It has been observed that 'there is no such thing as a realistic and generic O&M tool for WECs because of the lack of convergence on a single device design' [279]. By definition, the generic O&M figures developed here are based on literature review and cannot account for any operability impacts of site-specific metocean conditions, nor are they device or site optimised. The figures are presented for use by other WEC life cycle practitioners and remain an opportunity for further research. There is clearly more scope for soft-coupling of LCA and O&M models (as for floating wind in [260]),

or indeed a complete integration of life cycle cost, environmental impact and operation models. Some data are also uncertain due to limited available references and hence more subject to bias.

- Design optimisation in this analysis was limited (simply) to the substation topsides, while there was none for the substation platform, substation moorings, device moorings or dynamic cable designs. Indeed, the Blue Horizon device itself is in the preliminary design stage. Given the significance of these material contributions, there may be scope to improve the impacts calculated here.
- Installation times, while not a significant contribution to the environmental impacts, have not been optimised.
- The robustness of a number of material inventories could potentially be increased. The dynamic cable riser design is based on a simple scaling from a single source, and the mooring design is based on the Pelamis P2 design. The length of the export cable could not be accurately designed, and is represented by a simple factor of multiplication to account for bathymetric routing. A floating substation is potentially an unusual choice design, as floating wind farms are expected to be based with fixed-bottom substructures for substation designs (Chapter 5). Some of the O&M foreground data could also be based on a larger number of references.
- The selection of port locations was “normative”, not predictive or scenario based, however, the impacts are limited so this is not considered a significant limitation.
- Regarding LCIA, planetary boundaries were not explicitly assessed due to PhD scope, and arguably the results could benefit from more exploration of non-GHG impacts.

- The emissions payback time uses projections which - while temporally varying - are not spatially varying. In reality, the emissions intensity of displaced electricity will be regionally varying based on local generation and power flows. For example, the typically low carbon intensity of the distribution networks of Scotland would see a slower payback than renewable integration in higher carbon intensity regions of England or Wales. This could be expanded in further work using power system models. Average payback times would of course be affected by the emissions intensity of different national grids.

#### 4.4. Conclusions

This chapter presents a LCA of four potential arrays of the Blue Horizon WEC around Scotland in the year 2025. A process-based, attributional LCA was carried out on the 'cradle-to-grave' life cycle of the full wave energy arrays, comprising WECs, moorings, array cables, floating substation and export cable, using site-specific energy production.

The median global warming impact was found to be 68.3 to 94.9 gCO<sub>2</sub>eq/kWh across the arrays. The largest contribution to most impacts was typically materials, followed by vessel use during maintenance. This is higher than many existing studies of WECs, due to the system boundary (including array infrastructure), vessel representation and foreground and background uncertainty assessment. WEC O&M also had an important effect on the GW results, where WEC retrieval/replacement was generally most impactful.

The impacts are, by definition, inversely proportional to any change lifetime energy production given the functional unit, making array availability and annual energy production key design parameters. The design life, device mass, water depth and distance to operations base affected the results in varying degrees, with design life being most significant, followed

by device mass. Multiple parameters affect the lifetime energy production, including electrical losses (excluded here) and the effect of maintenance on array availability. Given the significance of vessel operations and array availability to the results, integrating O&M models with wave energy LCAs could be a fruitful avenue for future research. Similarly, modelling vessels in representative and detailed ways (vessel types and modes of operation) should be pursued due to the potential significance of their impact.

The GHG emissions payback was approximately 11 to 16 years for a generation-based emissions factor of 120 gCO<sub>2</sub>eq/kWh, and longer using emission intensity factors of a decarbonising GB grid, prompting discussion on the importance of this metric in low carbon power systems, where the array GW impact itself may be more relevant. Alternatively, the pathways of decarbonisation for materials and vessels may significantly modify these, where prospective LCA may be another avenue for further investigation. The energy payback time was also significant, approximately five to seven years, with an energy ratio of 2.7 to 3.9.

To reduce global warming impact from these arrays, device developers should maximise device AEP at each site and design life, and minimise structural mass, minimise maintenance requirements and utilise low carbon materials and vessels. System-wide efforts to decarbonise material production and sea vessel use should also be pursued.

The next chapter will use the LCA methodological learning from this chapter and apply it to floating wind technologies.

# Chapter 5:

## Life cycle assessment of four floating wind farms around Scotland

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This chapter presents a life cycle assessment (LCA) of the International Energy Agency (IEA) 15 MW Reference Wind Turbine (RWT), on floating platforms, deployed in commercial-scale arrays at multiple locations around Scotland in the ScotWind leasing round. The findings of this chapter were published in 2023 in the paper ‘Life cycle assessment of four floating wind farms around Scotland using a site-specific operation and maintenance model with SOVs’ [12].

In this analysis, site-specific energy production and vessel operations are provided by a dedicated offshore wind farm operations and maintenance (O&M) model, COMPASS, from one of the industrial partners of this project: ORE Catapult. This allows service operation vessel (SOV) O&M impacts to be assessed with increased confidence relative to the typical approach in the literature of exogenous O&M assumptions. For climate change, the median global warming impact varied from **17.4 to 26.3 gCO<sub>2</sub>eq/kWh** across the four sites within a 95% confidence interval, using an uncertainty assessment of both foreground and background data. As is common with other offshore renewable energy systems, materials and manufacture account for 71% to 79% of global warming impact, while O&M comprise between 9% and 16% of the global warming impacts. High-voltage direct current (HVDC) export cables, floating platforms, and composite blades are significant contributors to the

environmental impacts of these arrays (by mass and material choice), while the contributions from ballast, vessel transportation emissions, and power-train components are lower. The results suggest that material efficiencies, circularity, and decarbonising material supply inventories should be a priority for the Scottish floating wind sector, followed by minimising vessel operations and the decarbonisation of vessel propulsion, while avoiding burden shifting to other impact categories. This chapter also compares the floating wind LCA results with the wave energy LCA results from Chapter 4, and some unit processes of other electricity from other generation technologies from the ecoinvent life cycle inventory (LCI) database. The results of this chapter are used in Chapter 8 to investigate the emissions reduction potential of this type of technology in GB future energy scenarios.

## 5.1. Introduction

This chapter presents a life cycle assessment (LCA) of the International Energy Agency (IEA) 15 MW Reference Wind Turbine (RWT), on floating platforms, deployed in commercial-scale arrays at multiple locations around Scotland in the ScotWind leasing round. This chapter addresses the gaps identified in Chapter 3 through a site-specific LCA of four representative arrays of a very large floating wind turbine. Foreground data was provided by the IEA RWT documentation, with additional information obtained from ORE Catapult, and background data from the ecoinvent 3.6 database 'allocation, recycled content' or 'cut-off' system model [1]. Like Chapter 4, special attention was given to the development of representative vessel data. A dedicated O&M model (COMPASS) was used to develop availability and vessel movement data for the life cycle model. Monte Carlo simulation was used to quantify uncertainty along with sensitivity analyses of significant array design parameters. The following sections describe the study methodology with reference to ISO 14040 and 14044 [2], [3].

### 5.1.1. Floating wind turbine design (IEA-15-240-RWT)

The IEA-15-240-RWT is a mathematical model; a reference wind turbine of a variable speed, collective pitch, upwind, IEC Class IB direct-drive machine, with a rotor diameter of 240 m, and hub height 150 m above still water line (SWL) [280], [281] (Figure 5.1). It is typically used by researchers to provide a common platform for turbine controller design, structural, aerodynamic and hydrodynamic modelling. The LCI is detailed in Section 5.2.3.5.



Figure 5.1. IEA-15-240-RWT on VoltturnUS-S Reference Platform [282].

## 5.2. Material and methods

As with Chapter 4, this chapter also aims to address the gaps in the literature for floating wind life cycle assessments by presenting the first LCA of arrays of 15 MW floating wind turbines, around the coast of Scotland. The foreground inventory data is based on the IEA 15 MW reference wind turbine (IEA-15-240-RWT) and represents provisional ScotWind sites [283], using the turbine power curve and site-specific wind resource, as well as detailed inputs from a dedicated O&M model, COMPASS. As with Chapter 4, the LCA:

- Uses modified background processes, multiple vessels, four operational modes and parametric equations to model transport and installation vessel movement for each site, along with uncertainty assessment and sensitivity analyses on the main contributions to climate change.

- Is attributional, process-based, employing SimaPro 9.1 software with background data sourced from the ecoinvent database v3.6.
- Is aligned with internationally standardised LCA principles and framework (ISO 14040), and general requirements and guidelines (ISO 14044) [84], [85].

### 5.2.1. Goal

The intended application of this assessment was to quantify the environmental performance of the 15 MW reference wind turbine comparing the impacts of four unique ScotWind sites and identifying environmental impact “hot spots”. The goals of this study were to (i) address the opportunities identified in Chapter 3 and (ii) quantify the environmental impacts of multiple, real-world representative floating wind farms using site-specific metocean data, very large turbines, HVAC and HVDC architecture, and dedicated O&M modelling, including an assessment of foreground and background data uncertainty. The outputs of the study are intended for researchers, project developers, and policymakers.

As with Chapter 4, the analysis includes the impact of site resource on AEP; location (on vessel journey times); array size and array electrical infrastructure (including HVDC export systems) and uses regionally appropriate background data. However, the effect of O&M practices on AEP is provided by dedicated O&M modelling, unlike Chapter 4. These features all improve representativeness but consequently limit the findings for application in other regions. The temporal scope is near-future (assumed operation in 2025) but is again limited by necessary use of static, empirical background data and re-analysis resource data. The study is intended to present the environmental impacts of a variety of possible future arrays, and is intended for an audience of site, turbine or platform developers and policy-makers in an accounting

decision context (Situation C) [149]. The treatment is compared directly to the results from Chapter 4, and was commissioned as a piece of original academic research.

### 5.2.2. Scope

The scope of the study is a cradle to grave LCA of the 15 MW reference wind turbine and platform from IEA and University of Maine in four representative sites from the ScotWind leasing round: East 3, North East 1, North East 7, North 3 (E3, NE1, NE7 and N3, Figure 5.2). These sites were selected for their range of relevant characteristics: electrical export system design; distance to grid-connection point; distance to operating ports; water depth; number of turbines; and metocean conditions. Note that these sites represent general wind farm designs only, not the specific, commercial designs under development [284]. Five life cycle stages were defined as with Chapter 4: materials and manufacturing (M&M); transport and installation (T&I); operation and maintenance (O&M); decommissioning and removal (D&R); and landfill and recycling (L&R).

#### 5.2.2.1. Reference flow and functional unit

The reference flow of the study was an offshore wind farm comprising multiple identical floating wind turbine platforms with 15 MW turbines, moorings, array cables system, fixed-bottom HVAC collector and HVDC converter stations, and export cables, up to the onshore cable joint. Four sites were modelled, described in Section 5.2.3.2.

The functional unit for this study was 1 kilowatt hour (kWh) of electricity supplied to the grid, assuming zero cabling losses and appropriate power quality, over a 20 year design life, subject to the incident variable renewable resource. The energy production was determined using site specific data and the availability computed by the COMPASS O&M model (Figure 5.3).

### 5.2.2.2. LCI modelling framework and handling of multifunctional processes

Allocation by the 'Recycled Content' or 'Cut-off by classification' system model was used, as recommended in the European Product Environmental Footprint guideline [17] and per Chapter 4. Thus, recycling of waste material is outside the system boundary and recycling impacts are only included for input materials.

### 5.2.2.3. System boundary and completeness requirements

Figure 5.3 shows a schematic of the life cycle model. The system boundary was set as the landward end of the offshore transmission system, creating a reference flow of a single, complete floating wind farm: all floating wind turbine units, array cables, HVAC collector stations and HVDC converter stations, through its design life, decommissioning and recycling. Onshore works were not considered, nor spare parts (as with Chapter 4, implying a consistent 20 year design life for all subsystems and materials within the system boundary [285]), detailed manufacturing processes or minor components in accordance with Chapter 3 and 4. Throughout, the cut-off criteria were based on availability of representative data and acceptable granularity. The sites were all located around Scotland, hence European variants of unit processes were preferred, and temporally the most recent background data was used.

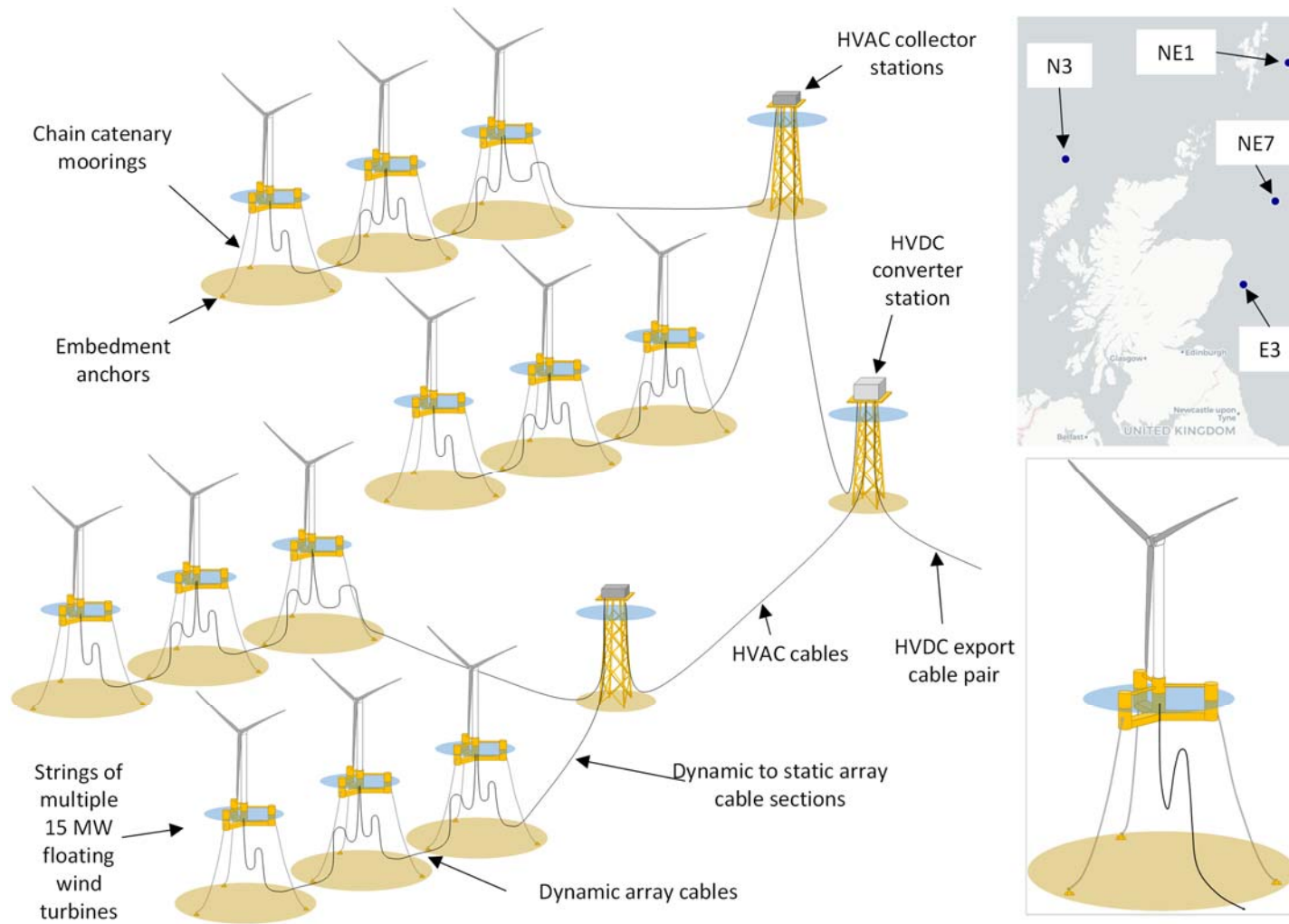


Figure 5.2. Overview of components included within the floating wind farms' reference flows; map of sites considered and general arrangement of the 15 MW reference wind turbine with platform.

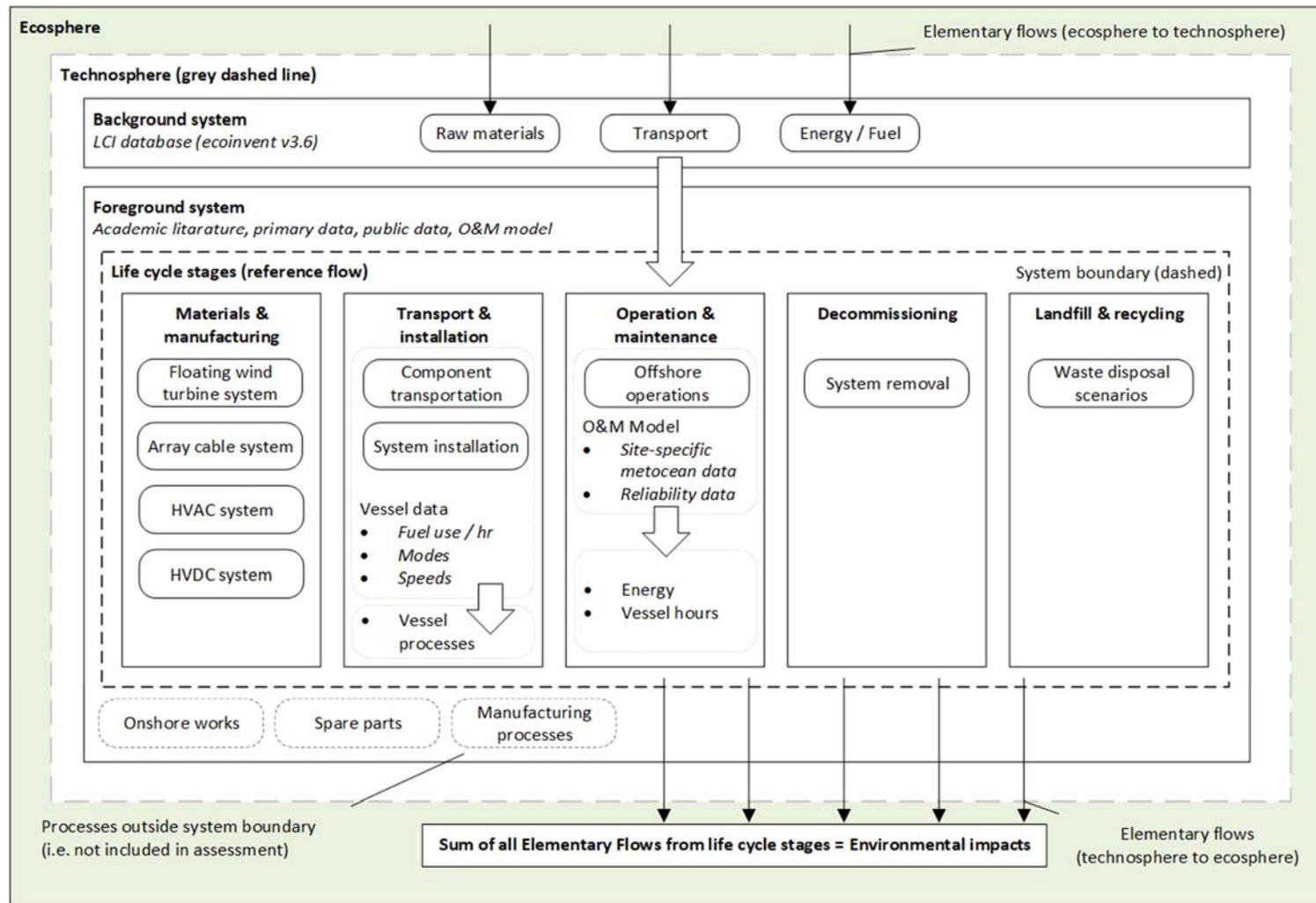


Figure 5.3. Schematic of the life cycle model, system boundary, life cycle stages, inventory assemblies, and processes, and the relationship with the COMPASS O&M model. White arrows indicate flows of data within the model, black arrows indicate elementary flows in the LCI.

#### 5.2.2.4. Representativeness of LCI data

The life cycle inventory was based on primary design data in the public domain [280], [281] as well as engineering assumptions necessary to develop representative arrays. These assumptions were supported by academic and industrial literature as described in Section 5.2.3. An assessment of the uncertainty of all the foreground data (as well as practitioner modifications to the background data) is published in the Inventory Data (SimaPro Input Parameters) in the supplementary material, according to the basic and additional uncertainty approach in [87].

#### 5.2.2.5. Impact assessment method

The LCIA method 'ReCiPe 2016 v1.1, midpoint method, Hierarchist version with Global normalisation' was used in accordance with Chapter 2 and Chapter 4.

#### 5.2.2.6. System comparisons

This work considers four separate arrays using a consistent scope and equivalent methodological considerations. The uncertainty of the results is evaluated and communicated considering both the foreground and background data, and sensitivity to key parameters is explored. The LCIA provides a wide range of impact categories, enabling an assessment of burden shifting between arrays. Given the similarities in practitioner decisions, comparison of the results from Chapter 4 is appropriate.

### 5.2.3. Inventory analysis

The inventory of foreground and background data as well as all results have been published in a journal paper in 2023. All data can be found in the associated supplementary material [12]. In the support of this work, ORE Catapult provided data to the life cycle model from two adjacent models:

- 1. Offshore wind farm cost model:** data from a proprietary, excel-based, cost model which replicated the site specifications of the LCA model. This provided water depth, number of days installation required per substructure, cable lengths and mooring lengths for example.
- 2. COMPASS (Combined Operations and Maintenance, People, Assets and Systems Simulation):** ORE Catapult's internal O&M simulation tool, a Python-based model primarily intended for estimating operational expense (OPEX) of offshore renewable energy farms. COMPASS takes the key characteristics of an offshore wind farm (such as number of turbines, site capacity, distance to O&M port, and maximum water depth) and populates a series of O&M activities against each wind turbine component. Maintenance activities are also assigned at a system level (such as export cables) or at a wind farm level (seabed surveys). Each maintenance activity can either be planned or unplanned and is assigned a rate of occurrence. In the time domain mode, at each time step the COMPASS tool checks whether maintenance is required and then checks for availability of personnel, vessels and suitable weather conditions (wave height and wind speed). At the end of the simulation, the COMPASS tool sums all the costs from all time steps associated with O&M activities and adds fixed costs (such as onshore base costs). In addition, the tool calculates array availability, total energy produced by the project and vessel operating hours [286]. The assumed maintenance pattern was maintenance offshore where possible using SOVs, with no routine towing to shore, given this was the lower of the two options in Garcia-Teruel et al. [155] and deemed more likely.

### 5.2.3.1. Systematic breakdown structure

Each floating wind farm reference flow was divided into four primary systems: the floating wind turbine unit (turbine, floating platform and moorings, FWTU); the array cable system (all dynamic and static sections); the HVAC collector station system and HVDC converter station system (both comprising station topside, jacket substructure, pile foundations and transmission cables, albeit with different properties).

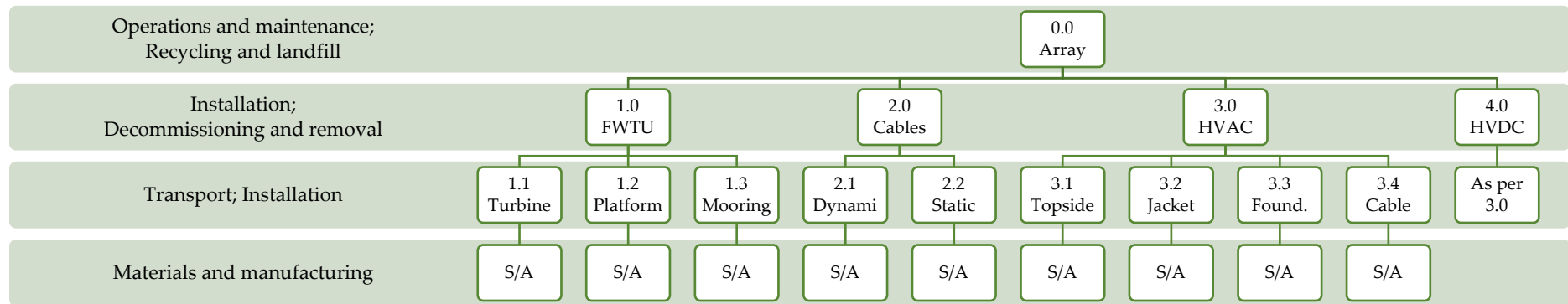


Figure 5.4. System breakdown structure, cut-off at third level for brevity. Relevant life cycle stages are shown on left of diagram. FWTU = floating wind turbine unit, HVAC = HVAC collector station, HVDC = HVDC converter station, Found. = foundation, S/A = Sub-assemblies.

### 5.2.3.2. Site parameters

Parameters were developed to represent the four floating wind farms [122] and cost modelling from ORE Catapult as well as publicly available data (Table 5.1). This data is aggregated from a number of sources and does not precisely represent the designs of the commercial project awards announced in January 2022 [284]. Full inventory data is provided [12].

- **E3:** is East of Montrose, and the shallowest site, with a 40 km export route, the lowest installed capacity (1.41 GW) and is the only site to use an HVAC export system.
- **NE1:** has a capacity of 2.31 GW located 48 km East of Lerwick in Shetland, in 130 m water depth, East of Shetland, with a HVDC export system.
- **NE7:** is north east of Peterhead, at 3 GW capacity in 110 m with an HVDC system.
- **N3:** is north of Lewis, the largest site considered (3.3 GW) and in the deepest water (150 m), with an HVDC system.

The number of HVAC and HVDC stations was provided by ORE Catapult's cost model. A single export cable is assumed for each HVDC station. For E3 a single export cable is assumed for each HVAC station.

Table 5.1. Main site parameters.

Site	E3	NE1	NE7	N3
Latitude	57.005	60.275	58.275	58.890
Longitude	-1.465	-0.200	-0.580	-6.500
Number of turbines	94	154	200	220
Installed capacity [MW]	1410	2310	3000	3300
Assumed water depth [m]	60	130	110	150

Site	E3	NE1	NE7	N3
Export system	HVAC	HVDC	HVDC	HVDC
Approximate export cable landfall route [km]	Aberdeen (40)	Sumburgh (72)	Montrose (207)	Dounreay (149)
HVAC Collector Stations	3	3	4	4
HVDC Converter Stations (and export cables)	0	2	2	4
O&M strategy	SOV (no towing)	SOV (no towing)	SOV (no towing)	SOV (no towing)
Number of SOVs	2	3	3	3
Lifetime [years]	20	20	20	20
FWTU Assembly Yard [km]	Methil, Scotland (145)	Nigg, Scotland (370)	Nigg, Scotland (220)	Nigg, Scotland (350)
Tower Origin [km]	Methil, Scotland (0)	Nigg, Scotland (0)	Nigg, Scotland (0)	Nigg, Scotland (0)
Nacelle Origin [km]	Esbjerg, Denmark (725)	Esbjerg, Denmark (820)	Esbjerg, Denmark (820)	Esbjerg, Denmark (820)
Blade Origin [km]	Hull, England (420)	Hull, England (670)	Hull, England (670)	Hull, England (670)
WT Platform Origin [km]	Methil, Scotland (0)	Nigg, Scotland (0)	Nigg, Scotland (0)	Nigg, Scotland (0)
Moorings Origin [km]	Bilbao, Spain (1910)	Bilbao, Spain (2170)	Bilbao, Spain (2170)	Bilbao, Spain (1815)
Mooring Load-out [km]	Methil, Scotland (145)	Nigg, Scotland (370)	Nigg, Scotland (220)	Arnish, Scotland (100)
Array Cable Origin [km]	Hartlepool, England (280)	Hartlepool, England (625)	Hartlepool, England (405)	Hartlepool, England (685)
HVAC Topsides Origin [km]	Aalborg, Denmark (870)	Aalborg, Denmark (835)	Aalborg, Denmark (790)	Aalborg, Denmark (1140)

Site	E3	NE1	NE7	N3
<b>HVAC Jacket Origin [km]</b>	Methil, Scotland (145)	Nigg, Scotland (370)	Nigg, Scotland (220)	Arnish, Scotland (350)
<b>HVAC Piles Origin [km]</b>	Methil, Scotland (0)	Methil, Scotland (0)	Methil, Scotland (0)	Arnish, Scotland (0)
<b>HVAC Piles Load-out [km]</b>	Methil, Scotland (145)	Methil, Scotland (510)	Methil, Scotland (295)	Arnish, Scotland (100)
<b>HVAC Cable Origin [km]</b>	Hartlepool, England (280)	Hartlepool, England (625)	Hartlepool, England (405)	Hartlepool, England (685)
<b>HVDC Topsides Origin [km]</b>	Aalborg, Denmark (870)	Aalborg, Denmark (835)	Aalborg, Denmark (790)	Aalborg, Denmark (1140)
<b>HVDC Jacket Origin [km]</b>	Methil, Scotland (145)	Methil, Scotland (510)	Methil, Scotland (295)	Arnish, Scotland (100)
<b>HVDC Piles Origin [km]</b>	Methil, Scotland (0)	Methil, Scotland (0)	Methil, Scotland (0)	Arnish, Scotland (0)
<b>HVDC Piles Load-out [km]</b>	Methil, Scotland (145)	Methil, Scotland (510)	Methil, Scotland (295)	Arnish, Scotland (100)
<b>HVDC Cable Origin [km]</b>	Hartlepool, England (280)	Hartlepool, England (625)	Hartlepool, England (405)	Hartlepool, England (685)
<b>O&amp;M Port [km]</b>	Aberdeen, Scotland (40)	Lerwick, Scotland (55)	Fraserburgh, Scotland (105)	Stornoway, Scotland (100)
<b>Major Repairs Port [km]</b>	Aberdeen, Scotland (40)	Lerwick, Scotland (55)	Aberdeen, Scotland (155)	Nigg, Scotland (350)

### 5.2.3.3. Site specific energy resource

Unlike Chapter 4, the site energy production in this LCA was informed by models from ORE Catapult, which also used the ERA5 reanalysis data (Table 5.2). As with Chapter 4, array losses and power train degradation were not assessed but would reduce total energy export as discussed in Section 5.3.6.1.

The spatial resolution of the reanalysis data was 0.25 degrees latitude/longitude (around 28 km, as with Chapter 4), meaning that compromises were required to represent each of the sites, with the site centroid is between 2 and 12 km from the reanalysis data point. As with Chapter 4, any array-wide resource variation was neglected. Further, reanalysis data is obviously based on empirical data and contains no information on how future renewable resource will evolve. Modelling the evolution of wind resource, especially in light of climate change, involves significant downscaling of detailed climate forecast data, which is outside the scope of this LCA. In general, climatic conditions are expected to become more energetic in time, but the possibility of local effects cannot be eliminated. The effect of changes to the lifetime energy generation are discussed in Section 5.3.6.1.

Table 5.2. Energy production and capacity factors for all sites.

Parameter	Dimension	E3	NE1	NE7	N3	RWT
Turbine rated power	MW	15	15	15	15	15
Number of turbines	#	94	154	200	220	-
Site capacity	GW	1410	2310	3000	3300	-
Turbine AEP (COMPASS)	GWh/year	68.7	70.8	71.5	68.9	77.4
Availability (annual average, time, COMPASS)	%	98.42%	97.57%	97.98%	91.92%	-
Availability (annual average, energy, COMPASS)	%	98.40%	97.19%	97.84%	91.16%	-
Capacity factor (COMPASS)	%	52.3%	53.9%	54.4%	52.5%	58.9%

#### 5.2.3.4. Vessel characteristics

Like Chapter 4, the transportation, installation, and decommissioning of each system, subsystem, assembly, or component by vessel were modelled explicitly in each life cycle stage, where required. Hours of vessel use were modelled in SimaPro using simple, parameterised equations which included vessel type, speed, operating mode, and site/port locations. The ecoinvent database does not contain processes representing the fleet required throughout the floating wind farm life cycle so an appropriate process within ecoinvent was modified to emulate representative vessels. Representative vessel types were informed by input from ORE Catapult and the COMPASS O&M model. By obtaining fuel consumption data for each vessel mode, the process 'Diesel, burned in fishing vessel GLO—diesel, burned in fishing vessel—Cut-off, U' (MJ) was scaled by inspection of diesel density ( $\text{kg/m}^3$ ), specific energy ( $\text{kg/MJ}$ ), and volumetric fuel consumption ( $\text{l/hr}$ ), converting the process to represent hours of vessel operation. In this way, the study included anchor handling tug supply (AHTS) vessels, tugs, high-speed heavy cargo vessels (HSHCVs), semi-submersible heavy cargo vessels (SSHCVs),

crane vessels, cable lay vessels (CLVs), offshore subsea construction vessels (OSCVs), and service operation vessels (SOVs).

#### 5.2.3.5. Materials and manufacturing (M&M)

The inventory for the FWTU was taken from primary data [280], [282], with mooring catenary chain and dynamic array cable length calculations performed by engineers at ORE Catapult.

The reference turbine is a direct-drive machine, with a rotor diameter of 240 m and a hub height of 150 m. The platform is a four-column, steel semi-submersible with three Ø12.5 m buoyant columns radially spaced with centres 51.75 m from the tower's vertical axis. The platform-tower interface is atop a fourth buoyant column located at the centre. This central column is connected to the outer columns via three 12.5 m wide x 7.0 m high rectangular bottom pontoons and three Ø0.9 m radial struts attached to the bottom and top of the buoyant columns, respectively.

The cable compositions, HVAC collector station and HVDC converter station properties were provided by ORE Catapult data and modelling. Electrical equipment was represented where appropriate using Environmental Product Declarations. The foreground and background data for the analysis are published [12] and aspects which required derivation or processing are detailed below.

##### 5.2.3.5.1. Generator design

The reference wind turbine uses a 15 MW direct-drive synchronous generator, with an air-gap radius of 5.08 m, core length of 2.17 m and mass of 372 t (227 t for the stator and 145 t for the rotor). The data in the definition report is quite comprehensive, however there are some discrepancies between the subtotal inventories for the stator and rotor (a difference of 34 t). Nevertheless, the *total* mass inventory is effectively consistent, so this difference is assumed

to be trivial (Table 5.3). There is also a discrepancy where it is stated “at least 50% of the mass stems from structural support”; in fact, this appears slightly lower at 42 %. Again, this is not assumed to be relevant to the LCI.

Table 5.3. IEA-15-240-RWT generator mass breakdown and derivations of mass by life cycle model assemblies. Parameters input to LCI are shown in bold.

Assembly	Material	Derived mass [t]	Specified mass [t]	Delta [t]
Stator	Steel	-	71.1	-
Stator	Iron	-	180.95	-
Stator	Copper	-	9.01	-
Rotor	Steel	-	86.2	-
Rotor	Magnet	-	24.2	-
Stator subtotal	-	261.06	226.63	34.431
Rotor subtotal	-	110.4	144.96	-34.563
Generator total	-	371.46	371.57	-0.11
Generator structural mass	Steel	157.3 (42 %)	-	-
Generator active mass	-	-	214.16 (58%)	-

The rotor magnets are specified as N40-grade sintered neodymium (NdFeB) magnets; this is consistent with the assumedecoinvent process of *'Permanent magnet, for electric motor {GLO}| market for permanent magnet, electric passenger car motor | Cut-off, U'*, which has input *'Neodymium oxide {GLO}| market for | Cut-off, U'*.

#### 5.2.3.5.2. Blade design

The IEA-15-240-RWT definition report does not include an accurate breakdown of blade mass by materials. To replicate realistic blade composition ORE Catapult provided scaling factors (Table 5.4).

Table 5.4. Turbine blade proportions by mass

Material	Ratio	Mass [t]
Carbon fibre reinforced plastic (CFRP)	0.150	9.78
Copper	0.001	0.10
Epoxy resin	0.235	15.33
Glass fibre reinforced plastic (GFRP)	0.542	35.36
Polyester resin	0.011	0.72
PVC foam	0.055	3.57
Low-alloy steel	0.006	0.40
Total	1.000	65.25

#### 5.2.3.5.3. Ballast design

The platform definition report specifies a ballast inventory of iron ore, concrete (fixed ballast) and seawater (active ballast). The seawater is not assumed to enter the LCA system boundary. In accordance with the scope of this assessment, the power required to actuate these pumps is not considered. The fixed ballast is specified as comprising equal parts by mass of iron-ore and concrete (1270 t each). The processes assumed are: *'Iron ore, crude ore, 63% Fe {GLO}| market for iron ore, crude ore, 63% Fe | Cut-off, U'* and *'Concrete, normal {GLO}| market group for concrete, normal | Cut-off, U'*. A nominal density of 2.3 t/m<sup>3</sup> was assumed for the concrete (whereby 1270 t is achieved by a volume of 552 m<sup>3</sup>).

#### 5.2.3.5.4. Mooring design

The mooring system consists of three chain catenary lines, spanning radially, spaced equally at 120 degrees. All lines use a studless R3 chain with a nominal bar diameter of 185 mm and mass per metre of 685 kg/m. The definition report includes an unstretched line length for a 200 m site only. ORE Catapult modelled the reference platform in OrcaFlex (a popular

software for dynamic analysis of offshore marine systems such as cables and mooring lines) to determine the mooring line mass per turbine at each of the four sites (Table 5.5).

Table 5.5. Platform mooring line mass ordered by site water depth.

Site	Water depth [m]	Mooring line mass [t]
E3	60	95
NE7	110	145
NE1	130	152
N3	150	419
IEA-15-240-RWT	200	582

The anchor design was assumed consistent across the four sites (with no accounting for geotechnical optimisation) at 35 te, akin to the Stevpris Mk 6; as per the (20 t) anchor used at Kincardine floating wind farm [155], [287].

#### 5.2.3.5.5. Cable designs

A number of different cable types were allowed for within the inventory of the floating offshore wind farm. For the array cables, two designs were included: static and dynamic cables, and HVAC collector station and HVDC export cables. For E3 with no HVDC, the HVAC cables were assumed as the export cables. The cable inventories were defined by two main parameters: the proportion of the material per metre by mass (Table 5.6) and the mass per unit length (Table 5.7). These parameters were necessarily collected from a number of different resources including ORE Catapult primary data, academic literature and industrial reports. Further, due to limited data, it was necessary to assume identical material proportions between the static and dynamic cables, even though in general, dynamic cables always feature additional armour layers to tolerate their design load cases. Design

appropriate mass per unit length parameters were however used to maintain as high a specificity as possible. HVDC cables are laid as pairs (one cable for each terminal, positive and negative). These were assumed to be installed concurrently, and mass breakdowns are provided for a pair and on a per cable basis.

Table 5.6. Material proportions for three floating wind farm cable types.

Component	Material	Array, 66 kV [kg/m]	HVAC, 220 kV [kg/m]	HVDC, 4000kV [kg/m]	Array	HVAC	HVDC
Conductor	Copper	6.2	14.2	108.6 (54.3 per cable)	0.143	0.141	0.708
Insulation	Polyethylene	10.7	16.4	24.8 (12.4 per cable)	0.246	0.163	0.162
Lead sheath	Lead	4.1	20.3	17.7 (8.9 per cable)	0.094	0.201	0.116
Fibre Optic Unit	Glass	0.7	1.5	0.0	0.016	0.015	0.000
Armouring	Steel wire	21.7	48.4	2.2 (1.1 per cable)	0.500	0.480	0.015
<b>Total</b>		43.5	100.8	153.3 (76.7 per cable)	1.000	1.000	1.000

Table 5.7. Mass per unit length for eight floating wind farm cable types.

Cable type	Copper conductor area (mm <sup>2</sup> )	Mass per unit length [kg/m]	Source
Dynamic	240	43.5	ORE Catapult
Dynamic	630	65.0	Average between Kincardine 500 mm <sup>2</sup> @ 57 kg/m [288] and CoreWind 800 mm <sup>2</sup> @ 72.3 kg/m [289]
Dynamic	800	72.3	[289]
Static	240	31.3	[290]
Static	630	52.0	[290]
Static	800	70.7	[290]
HVAC	Not stated	100.8	ORE Catapult
HVDC	Not stated	153.3 (76.7 per cable)	ORE Catapult

### 5.2.3.5.6. Fixed-bottom HVAC collector and HVDC converter stations

The materials inventory data for both the HVAC collector and HVDC converter stations were based on data from ORE Catapult's cost modelling, assuming fixed-bottom, jacket substructures with pile foundations.

Table 5.8. Inventory data for HVAC and HVDC stations

	E3	NE1	NE7	N3
Number of HVAC stations	3	3	4	4
Station capacity [MW]	500	700	700	700
Topside mass [t]	2725	3230	3230	3230
Primary steel mass [t]	3204	10879	8221	13938
Secondary Steel mass [t]	86	90	90	90
Piles mass [t]	769	10410	5169	20962
Number of HVDC stations	-	2	2	4
Station capacity [MW]	0	1200	1500	1200
Topside mass [t]	0	8900	10000	8900
Primary steel mass [t]	0	10879	8221	13938
Secondary Steel mass [t]	0	94	96	94
Piles mass [t]	0	10883	5404	21915

### 5.2.3.6. Transport & installation

The distances travelled by each vessel were developed using historical floating wind projects as examples, current and future supply chains, local content and site capabilities (Table 5.1). For every journey, an appropriate vessel was selected, using the scaled vessel processes created in Chapter 4.

#### 5.2.3.7. Operation and maintenance

O&M was identified as an important life cycle stage affecting environmental impacts of floating wind farms in Chapter 3. To this end, ORE Catapult modelled each site using their in-house COMPASS O&M model, yielding hours of use for SOVs, and overall array AEP, based on availability and site-specific wind resource and weather windows. In addition, 0.0205 maintenance interventions per turbine per year by crane vessel [291] and cable servicing at 1 km per hour, every 2 years using an OSCV [292] were assumed.

#### 5.2.3.8. Decommissioning

Decommissioning was modelled as the reverse of installation, but omitting the transportation of the disassembled subsystems, on the basis of the high uncertainty around disposal location. Cable laying and pile removal operations were omitted to represent cable abandonment and pile cutting at end of life.

#### 5.2.3.9. Landfill and recycling

The waste scenario was input identically to that in Chapter 4.

#### 5.2.3.10. Data Quality

As with Chapter 4, the data quality of the study is described below in accordance with ISO 14044 [80]:

- Time-related coverage: identical to Chapter 4.
- Geographical coverage: site specific foreground data has been used where practical.

Background data is localised where possible but typically global, reflecting the globalised material and fuel markets economy. The foreground data describes four arrays of 15 MW floating wind turbines built and installed in Scotland, with the cables

and substations originating in England and Denmark respectively, and other mooring components from Spain. Background data from ecoinvent generally uses average materials data from the global market.

- Technology coverage: technology specific foreground data has been used where possible, else following the data quality pedigree of the 'technological correlation' indicator from [87, p. 76]. Input data from ORE Catapult, the UK's innovation and research centre for offshore renewable energy, can likely be assumed to be credible, for example chain lengths, dynamic cable lengths, array cable lengths, export cable lengths, substation inventory and materials. The representativeness of the site-specific metocean data is assumed to be generally accurate, given the large geographical area of the sites (474 to 1106 km<sup>2</sup> [283]) in open water.
- Precision: primary data sourced directly from the RWT and platform definition literature is assumed to be precise, although the turbine is by definition a generic design, and thus not completely representative of a real-world, commercially designed machine. ORE Catapult data is assumed to be similarly precise.
- Completeness: primary data from the literature and ORE Catapult comprised a mass inventory for the reference turbine, power curve, mooring lengths, cable lengths and substation designs, as well as AEP and O&M vessel operations. The transportation of raw materials is not considered, (however transport of major components is). It was assumed that the generic global market data for materials provided by ecoinvent already includes suitable allowance for transportation. Paints, sand-blasting and other processes were omitted. Large electrical components were modelled by considering the mass only.

- Representativeness: the degree to which the data set reflects the true population of interest (i.e. time-related coverage, geographical coverage, and technology coverage) is qualitatively assessed as suitable.
- Consistency: the study methodology is qualitatively assessed at a commensurate and appropriate degree relative to the significance of the various components of the analysis. All background data was sourced from the single ecoinvent system model (Cut-off, Unit processes) or scaled using foreground data (vessel operation processes). Full details of the vessel process scaling method are provided in the Supplementary Material – Inventory Data, Vessel characteristics. The work in this chapter, was intentionally executed to have data quality consistent with Chapter 4 to enable comparison.
- Reproducibility: the inventory data necessary to reproduce the results reported in the study is published, subject to confidentiality agreements. However, the commercially sensitive intellectual property of the ORE Catapult calculations, data and models which generated certain foreground data (such as mooring lengths, cable lengths, cable composition, blade composition, substation design, SOV movements) are necessarily not divulged; only the foreground data itself [12].
- Data sources: are provided in the study references and supplementary material. The remainder of the data sources were from published literature or publicly available sources - some from single vessel operators or equipment manufacturers.
- Uncertainty of the information: the uncertainty was assessed using the method described in [87].

#### 5.2.4. Impact assessment

As with Chapter 4, two life cycle impact assessment (LCIA) methods were used: the multi-criteria ReCiPe 2016 v1.1, midpoint method, Hierarchist version with Global normalisation, and the single criteria Cumulative Energy Demand (CED) v1.11. Uncertainty was assessed using the default values for basic uncertainty applied to both foreground and background data, and a Monte Carlo analysis with 1000 steps and a stop factor of 0.005 [87].

#### 5.2.5. Interpretation

As with Chapter 4, LCIA results are presented for all four sites and by life cycle stage assuming (reasonably) that the methodological differences between the two life cycle assessments of this thesis are negligible. Results are not directly compared with other published studies however ranges are discussed in relation to the literature review of floating wind and other generation technology. “Hot spots” or materials and process associated with a significant contribution to life cycle impacts are presented, with recommendations to reduce impacts. Carbon and energy payback times are explored and sensitivity analyses of lifetime energy production and key design parameters are presented. In addition, the results are compared with Chapter 4, on the assumption that there is sufficient consistency between the two LCAs by intentionally similar demarcation of the system boundary and practitioner methodology. The sensitivity of the results to key site parameters is also assessed.

## 5.3. Results and discussions

### 5.3.1. Basic results without uncertainty

Table 5.9 shows the basic LCIA results (with no assessment of uncertainty) using the ReCiPe and CED impact methods. The penalty on environmental impact due to site-specific AEP can be observed by reciprocating the ratio of AEP to the highest AEP (NE7). For global warming, it is clear that AEP is not the only contributing factor, NE7 is the second-worst performing site (E3 is 15% less, NE1 is 3% less, despite 4% and 1% AEP penalties respectively). Finally, N3 has a penalty due to AEP difference of 4%, but has GW 29% higher. The reasons for these differences are explored in the subsequent sections.

As with other studies in the literature, life cycle impacts are dominated by the materials and manufacturing life cycle stage. For the four sites E3, NE1, NE7 and N3 materials and manufacturing accounts for 78%, 71%, 72%, 79% of the global warming impact respectively (Table 5.10). O&M is commonly the second most impactful across the impact categories, with L&R dominating in the freshwater and marine eco-toxicity metrics. Component-wise, the most massive typically have the highest impact, including wind turbine platforms and other massive steel components such as the nacelle housing and turbine tower (Section 5.3.5). The carbon-fibre-reinforced plastic (CFRP) of the turbine blades is also prominent due to its high primary energy requirement (heat and electricity). Relative to site N3, the environmental impacts of E3 are lower due to its proximity to the grid connection point and the HVAC export system design. For N3, the very long HVDC cables (connecting the farm in the east of Shetland to the GB grid at Dounreay) dominate these selected impacts. Each impact category is driven by different processes; for example, for GW, LU, MRS, and CED the most influential are steel, copper, lead, and polyethylene. O&M is significant for a number of impact

categories (OFHH, FPMF, OFTE, TA, FRS, CED, and GW). For GW, this ranges from 9% to 16% (with distant sites showing higher impacts); however, this is not as significant as in a recent study (25). This is possibly due to the optimisation of turbine availability (and hence, AEP) in COMPASS and the use of in-field SOVs for a broad range of interventions (dramatically reducing the number of vessel transit journeys to the site relative to port-based crew transfer vessels, CTVs), as well as the influence of array-scale components in this analysis. Waste disposal is as significant to climate change impacts as T&I, which is typical in the literature., as noted in Chapter 3. Table 5.10 details the relative importance of the life cycle stage for a given site. For example, the O&M life cycle stage contributes 16% of the GW impact for NE7, for N3 it is 10%.

Table 5.9. Basic results from life cycle impact assessment for all four arrays using ReCiPe and CED impact methods, with no assessment of uncertainty.

	Unit	E3	NE1	NE7	N3	E3	NE1	NE7	N3
Lifetime array energy production	TWh	129.2	218.1	285.8	303.3	-	-	-	-
Turbine AEP (including availability)	GWh/yr	68.7	70.8	71.5	68.9	0.96	0.99	1.00	0.96
Penalty solely due to WEC AEP	-	-	-	-	-	1.04	1.01	1.00	1.04
WECs	-	94	154	200	220	-	-	-	-
Global warming	g CO <sub>2</sub> eq / kWh	17.3	19.8	20.4	26.3	0.85	0.97	1.00	1.29
Stratospheric ozone depletion	µg CFC11 eq / kWh	7.8	8.2	9.4	14.1	0.84	0.88	1.00	1.51
Ionising radiation	Bq Co-60 eq / kWh	0.7	0.7	0.7	1.0	0.92	0.97	1.00	1.35
Ozone formation, Human health	g NO <sub>x</sub> eq / kWh	0.1	0.2	0.2	0.2	0.68	0.96	1.00	1.11
Fine particulate matter formation	g PM <sub>2.5</sub> eq / kWh	0.1	0.1	0.1	0.1	0.73	0.88	1.00	1.45
Ozone formation, Terrestrial ecosystems	g NO <sub>x</sub> eq / kWh	0.1	0.2	0.2	0.2	0.68	0.96	1.00	1.12
Terrestrial acidification	g SO <sub>2</sub> eq / kWh	0.2	0.2	0.2	0.3	0.68	0.86	1.00	1.44
Freshwater eutrophication	mg P eq / kWh	13.9	13.4	18.1	35.6	0.77	0.74	1.00	1.96
Marine eutrophication	mg N eq / kWh	1.6	1.6	1.7	2.4	0.93	0.92	1.00	1.41
Terrestrial ecotoxicity	kg 1,4-DCB / kWh	0.4	0.4	0.6	1.3	0.68	0.62	1.00	2.25
Freshwater ecotoxicity	g 1,4-DCB / kWh	18.7	16.5	28.4	66.2	0.66	0.58	1.00	2.33
Marine ecotoxicity	g 1,4-DCB / kWh	23.0	20.2	34.7	80.8	0.66	0.58	1.00	2.33
Human carcinogenic toxicity	g 1,4-DCB / kWh	7.8	8.3	8.5	12.3	0.92	0.98	1.00	1.45

	Unit	E3	NE1	NE7	N3	E3	NE1	NE7	N3
<b>Human non-carcinogenic toxicity</b>	kg 1,4-DCB / kWh	0.1	0.1	0.2	0.3	0.71	0.66	1.00	2.14
<b>Land use</b>	cm <sup>2</sup> a crop eq / kWh	3.5	3.6	3.9	6.0	0.89	0.90	1.00	1.54
<b>Mineral resource scarcity</b>	kg Cu eq / kWh	0.8	0.8	1.0	1.8	0.80	0.79	1.00	1.86
<b>Fossil resource scarcity</b>	kg oil eq/kWh	4.5	5.3	5.5	7.3	0.82	0.95	1.00	1.32
<b>Water consumption</b>	l / kWh	0.1	0.1	0.1	0.2	0.91	0.94	1.00	1.47
<b>Cumulative energy demand</b>	kJ / kWh	235	269	284	379	0.83	0.95	1.00	1.33

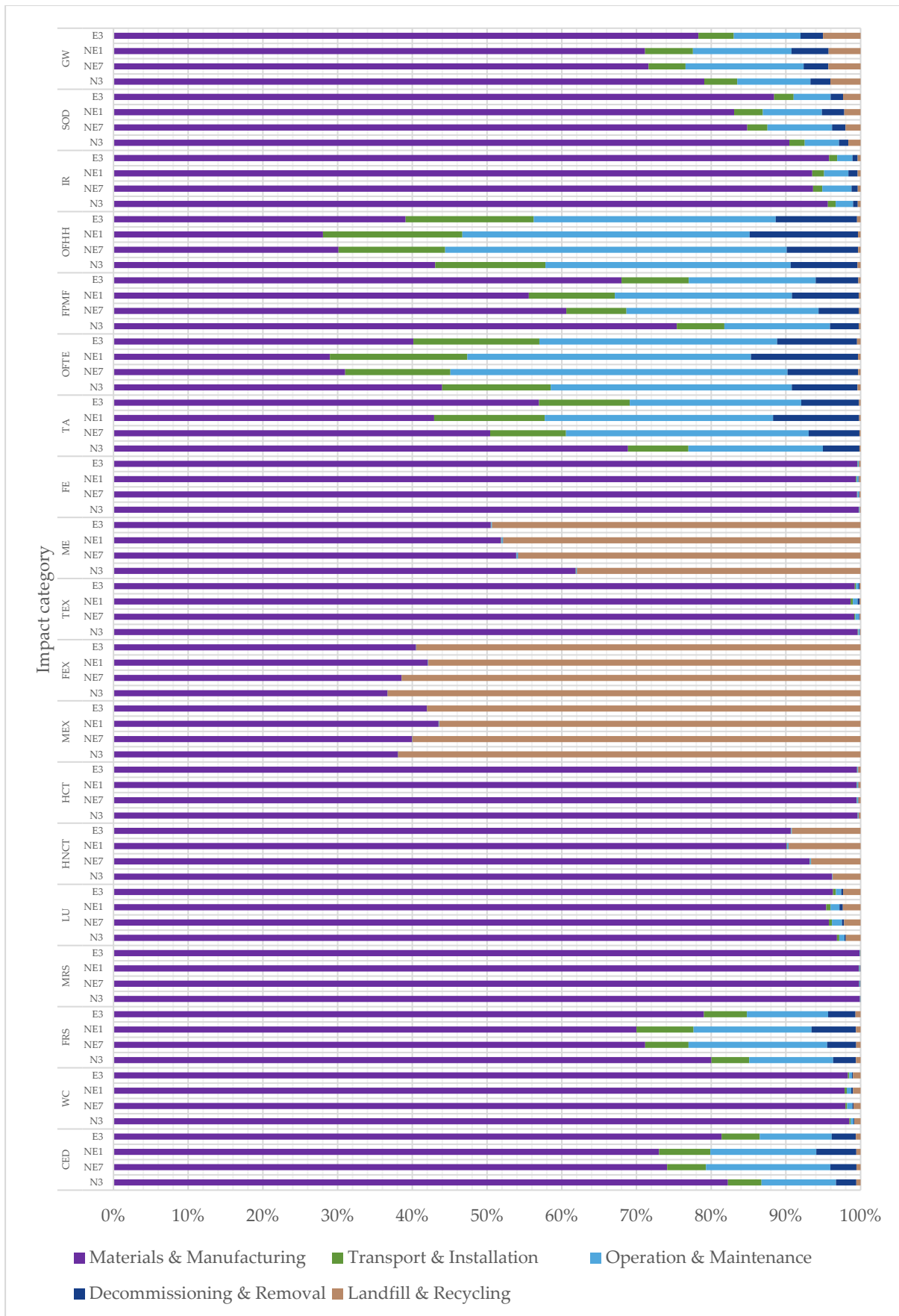


Figure 5.5. Relative contribution of life cycle stages to environmental impact categories.

Table 5.10. Percentage contributions of life cycle stages within each site to each impact category.

	E3					NE1					NE7					N3				
	M&M	T&I	O&M	D&R	L&R	M&M	T&I	O&M	D&R	L&R	M&M	T&I	O&M	D&R	L&R	M&M	T&I	O&M	D&R	L&R
GW	78	5	9	3	5	71	6	13	5	4	72	5	16	3	4	79	4	10	3	4
SOD	88	3	5	2	2	83	4	8	3	2	85	3	9	2	2	90	2	5	1	2
IR	96	1	2	1	0	94	2	3	1	0	94	1	4	1	0	96	1	2	1	0
OFHH	39	17	32	11	0	28	19	38	15	0	30	14	46	10	0	43	15	33	9	0
FPMF	68	9	17	6	0	56	11	24	9	0	61	8	26	5	0	75	6	14	4	0
OFTE	40	17	32	11	0	29	18	38	14	0	31	14	45	9	0	44	15	32	9	0
TA	57	12	23	8	0	43	15	31	12	0	50	10	32	7	0	69	8	18	5	0
FE	100	0	0	0	0	99	0	0	0	0	100	0	0	0	0	100	0	0	0	0
ME	51	0	0	0	49	52	0	0	0	48	54	0	0	0	46	62	0	0	0	38
TEX	99	0	0	0	0	99	0	1	0	0	99	0	0	0	0	100	0	0	0	0
FEX	40	0	0	0	59	42	0	0	0	58	39	0	0	0	61	37	0	0	0	63
MEX	42	0	0	0	58	44	0	0	0	56	40	0	0	0	60	38	0	0	0	62
HCT	100	0	0	0	0	99	0	0	0	0	99	0	0	0	0	100	0	0	0	0
HNCT	91	0	0	0	9	90	0	0	0	10	93	0	0	0	7	96	0	0	0	4
LU	96	0	1	0	2	95	1	1	0	2	96	0	1	0	2	97	0	1	0	2
MRS	100	0	0	0	0	100	0	0	0	0	100	0	0	0	0	100	0	0	0	0
FRS	79	6	11	4	1	70	8	16	6	1	71	6	19	4	1	80	5	11	3	1

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	E3					NE1					NE7					N3				
	M&M	T&I	O&M	D&R	L&R	M&M	T&I	O&M	D&R	L&R	M&M	T&I	O&M	D&R	L&R	M&M	T&I	O&M	D&R	L&R
<b>WC</b>	98	0	0	0	1	98	0	1	0	1	98	0	1	0	1	99	0	0	0	1
<b>CED</b>	81	5	10	3	1	73	7	14	5	1	74	5	17	3	1	82	4	10	3	1

### 5.3.2. Results using default uncertainty factors

An assessment of the basic and additional uncertainty was completed for all input parameters according to [293]. The median results show that E3 was typically the site with the lowest environmental impacts, *despite* having the lowest turbine AEP. The vessel travelling distances for E3, in almost every case, were the shortest of all the sites, and the site has no HVDC transmission equipment (reducing its material requirements relative to HVDC export systems). It also has the lowest total SOV usage time due to its proximity to O&M base. In contrast, site N3 has the highest impact in every category, driven by its remoteness to port facilities, HVDC system and relatively low turbine AEP (which itself likely driven by its extreme location and operability limitations).

The 95% confidence interval across the four sites is typically within an order of magnitude of the median result, but not for all categories; where Ionising Radiation (IR) and Water Consumption show the largest uncertainty (Table 5.11). WC is so uncertain as to vary from an environmental harm (positive) to environmental benefits (negative), as noted in other studies [294]. The median Global Warming (GW) impacts and 95% confidence interval for the E3, NE1, NE7 and N3 sites were 17.4 (13.0 – 23.6), 20.0 (14.9 – 27.8), 20.5 (15.4 – 28.2) and 26.3 (20.2 – 35.4) gCO<sub>2</sub>eq/kWh respectively.

Table 5.11. LCIA results with median values and confidence limits within 95%, using default uncertainty factors for foreground and background data. Array attributes are also shown.

Attribute / Impact Category	Abbreviation	E3			NE1			NE7			N3			Units
		2.5%	Median	97.5%	2.5%	Median	97.5%	2.5%	Median	97.5%	2.5%	Median	97.5%	
Global warming	GW	13.0	<b>17.4</b>	23.6	14.9	<b>20.0</b>	27.8	15.4	<b>20.5</b>	28.2	20.2	<b>26.3</b>	35.4	gCO <sub>2</sub> eq/kWh
Stratospheric ozone depletion	SOD	5.7	<b>7.7</b>	11.0	5.9	<b>8.2</b>	11.7	6.7	<b>9.3</b>	13.9	9.6	<b>13.8</b>	21.3	µgCFC11eq/kWh
Ionising radiation	IR	0.1	<b>0.4</b>	3.2	0.1	<b>0.4</b>	4.0	0.1	<b>0.4</b>	3.2	0.2	<b>0.6</b>	4.4	BqCo-60eq/kWh
Ozone formation, Human health	OFHH	0.1	<b>0.1</b>	0.2	0.1	<b>0.1</b>	0.3	0.1	<b>0.2</b>	0.3	0.1	<b>0.2</b>	0.3	gNO <sub>x</sub> eq/kWh
Fine particulate matter formation	FPMF	0.0	<b>0.1</b>	0.1	0.1	<b>0.1</b>	0.1	0.1	<b>0.1</b>	0.1	0.1	<b>0.1</b>	0.2	gPM2.5eq/kWh
Ozone formation, Terrestrial ecosystems	OFTE	0.1	<b>0.1</b>	0.2	0.1	<b>0.2</b>	0.3	0.1	<b>0.2</b>	0.3	0.1	<b>0.2</b>	0.3	gNO <sub>x</sub> eq/kWh
Terrestrial acidification	TA	0.1	<b>0.2</b>	0.2	0.1	<b>0.2</b>	0.3	0.2	<b>0.2</b>	0.3	0.2	<b>0.3</b>	0.5	gSO <sub>2</sub> eq/kWh
Freshwater eutrophication	FE	8.5	<b>13.5</b>	23.3	8.0	<b>13.1</b>	24.5	11.3	<b>17.6</b>	28.8	22.1	<b>34.7</b>	59.1	mgPeq/kWh
Marine eutrophication	ME	1.0	<b>1.6</b>	2.6	1.0	<b>1.6</b>	2.7	1.1	<b>1.7</b>	2.8	1.6	<b>2.3</b>	4.0	mgNeq/kWh
Terrestrial ecotoxicity	TEX	0.2	<b>0.4</b>	0.9	0.2	<b>0.3</b>	0.8	0.3	<b>0.5</b>	1.3	0.5	<b>1.1</b>	3.2	kg1,4-DCB/kWh
Freshwater ecotoxicity	FEX	14.0	<b>18.6</b>	25.6	12.6	<b>16.5</b>	22.4	21.5	<b>28.6</b>	38.2	49.4	<b>65.9</b>	90.1	kg1,4-DCB/kWh
Marine ecotoxicity	MEX	17.2	<b>22.8</b>	31.3	15.5	<b>20.2</b>	27.4	26.4	<b>35.0</b>	46.7	60.3	<b>80.4</b>	110.4	kg1,4-DCB/kWh
Human carcinogenic toxicity	HCT	3.5	<b>7.1</b>	17.6	3.8	<b>7.6</b>	18.0	3.8	<b>7.6</b>	18.4	5.9	<b>11.2</b>	25.3	kg1,4-DCB/kWh
Human non-carcinogenic toxicity	HNCT	0.1	<b>0.1</b>	0.2	0.1	<b>0.1</b>	0.2	0.1	<b>0.2</b>	0.2	0.2	<b>0.3</b>	0.5	kg1,4-DCB/kWh
Land use	LU	2.5	<b>3.5</b>	5.0	2.5	<b>3.5</b>	5.3	2.8	<b>3.9</b>	5.8	4.3	<b>5.9</b>	8.9	cm <sup>2</sup> acrop <sub>eq</sub> /kWh

Attribute / Impact Category	Abbrev- iation	E3			NE1			NE7			N3			Units
		2.5%	Median	97.5%	2.5%	Median	97.5%	2.5%	Median	97.5%	2.5%	Median	97.5%	
Mineral resource scarcity	MRS	0.5	<b>0.8</b>	1.2	0.5	<b>0.8</b>	1.2	0.7	<b>1.0</b>	1.4	1.3	<b>1.8</b>	2.5	kgCueq/kWh
Fossil resource scarcity	FRS	3.4	<b>4.6</b>	6.2	4.0	<b>5.3</b>	7.4	4.1	<b>5.6</b>	7.7	5.6	<b>7.3</b>	9.8	kgoleq/kWh
Water consumption	WC	-29.7	<b>0.3</b>	22.4	-29.9	<b>1.3</b>	24.6	-39.3	<b>1.9</b>	26.5	-61.1	<b>3.3</b>	47.7	l/kWh
Cumulative energy demand	CED	181	<b>237</b>	322	206	<b>273</b>	387	210	<b>286</b>	403	286	<b>382</b>	520	kJ/kWh
Turbines	-	94			154			200			220			-
Turbine AEP (including availability)	-	68.7			70.8			71.5			68.9			GWh/yr
Lifetime array energy production (20 years)	-	129.2			218.1			285.8			303.3			TWh

### 5.3.3. Comparability with other floating wind global warming results

The GW results are below the literature median of 30.2 gCO<sub>2</sub>eq/kWh (Chapter 3). This section explores the effect of array infrastructure and vessel representation on this impact category.

#### 5.3.3.1. Effect of array infrastructure

Array cables are a negligible contribution to the GW impact across all sites, and for sites with an HVDC export system, the HVAC collector station cables are also very small contributions (Figure 5.6). The HVAC and HVDC stations themselves are typically next largest as a system-level contribution, but the main impact stems from the HVAC (E3 only) and HVDC cables. NE7 actually has the longest distance to landfall (Table 5.1), but has only two converter stations, and hence two export pairs for a total of four cables. N3 has double the number of converter stations, for a total of eight cables over a distance only 28% less than NE7. Again, M&M is the largest contribution – almost all of the GW impact stems from this life cycle stage. Note that for NE1, the assumption of landfall in Sumburgh could be inaccurate (instead being exported by a much longer route to mainland GB), however no data to confirm or refute this was available at time of writing (Section 5.3.6.3).

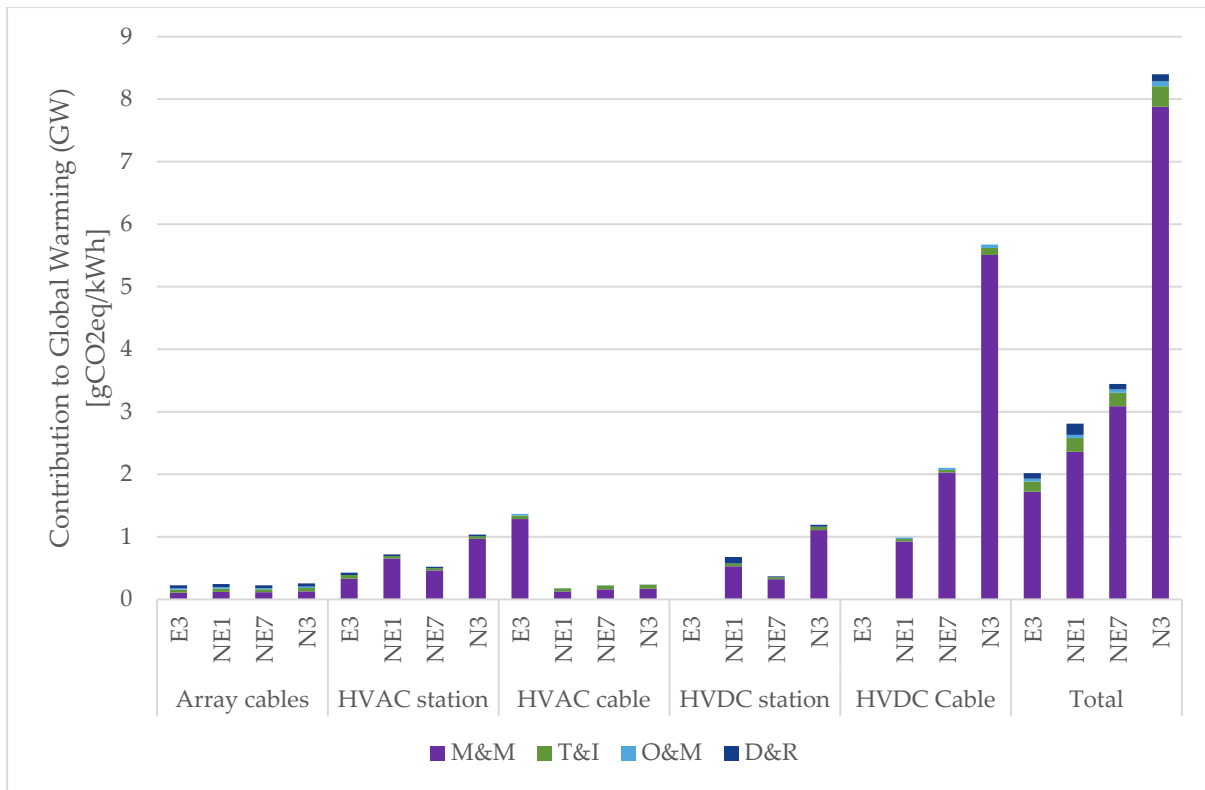


Figure 5.6. Array infrastructure life cycle stage contributions to global warming (GW) impact for all four sites.

### 5.3.3.2. Effect of vessels use during O&M

SOV transiting is the largest contribution to GW during the O&M phase (Figure 5.7). In general, though the O&M was a smaller contribution to GW than expected relative to the literature, possibly due to COMPASS' optimisation or inaccurate assumptions for modelling of heavier maintenance.

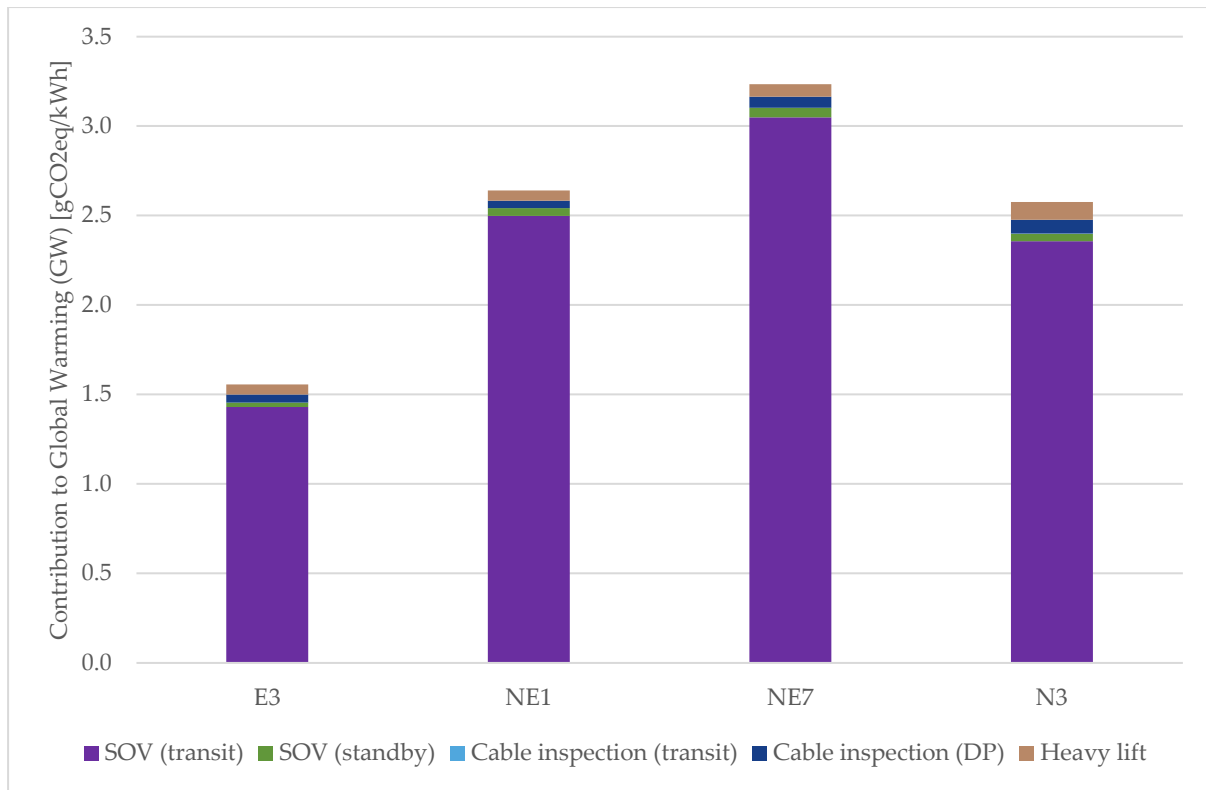


Figure 5.7. Contribution to global warming (GW) impact category from vessel operations during O&M across the four sites.

### 5.3.4. GHG emissions and energy payback times

Following the same method as set out in Chapter 4, the four sites achieve GHG payback in a maximum of 12 years, all within the 20 year design life for both of the decarbonisation pathways assumed (Figure 5.8, Table 5.12). While decarbonising steel would in theory reduce this payback time, because the emissions are “invested” during the construction of the wind farm, only decarbonising vessel propulsion and end-of-life disposal routes could actually accelerate these payback times (this concept is expanded in Chapter 8).

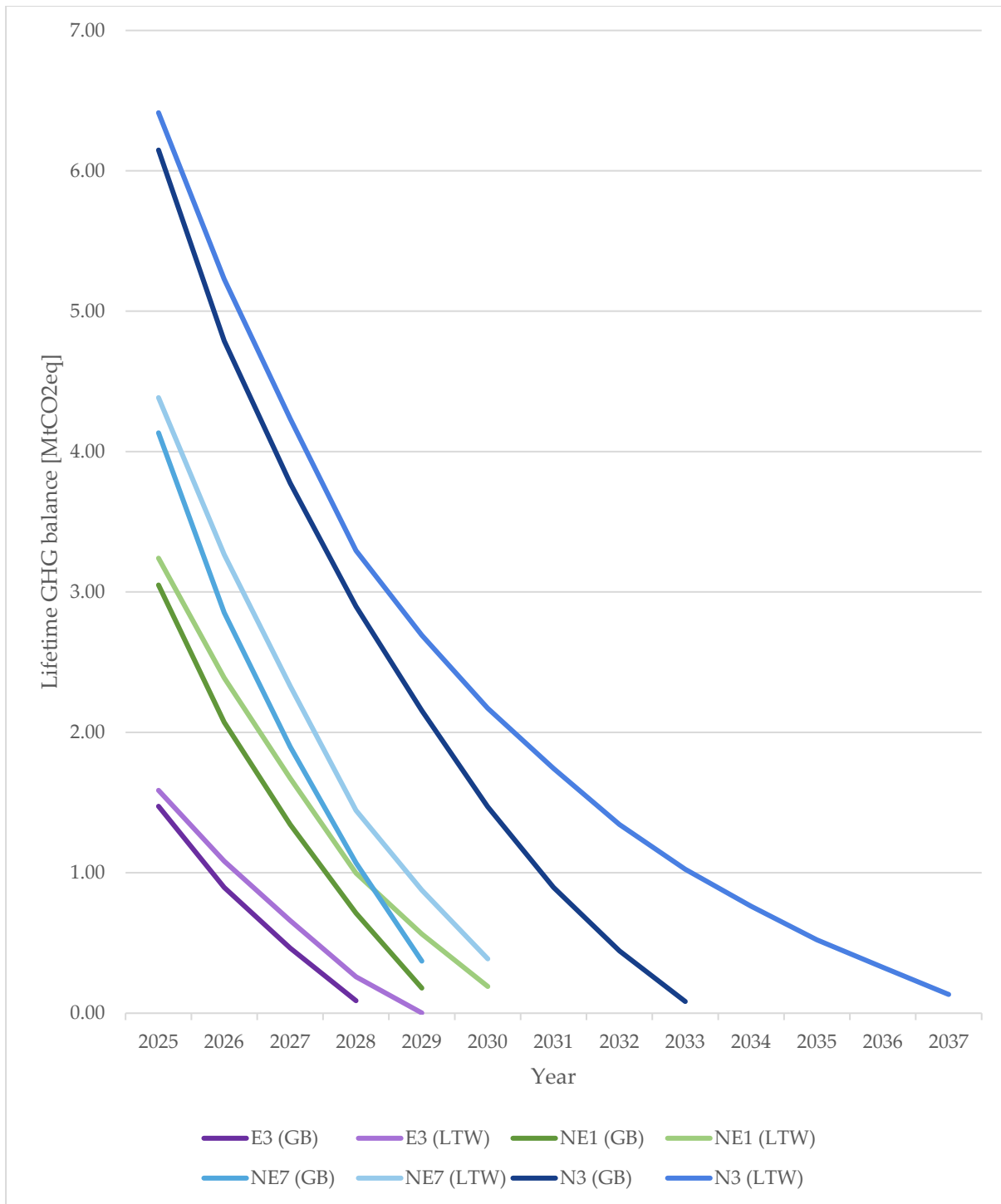


Figure 5.8. Payback time for Green Book projections (GB) and Leading the Way (LTW) scenario.

Table 5.12. Energy payback time, energy ratio and carbon payback time accounting for decarbonising power sector.

	E3	NE1	NE7	N3
Array AEP (including Availability) [TWh/yr]	6.46	10.91	14.29	15.16
Lifetime energy production (LEP) [TWh]	129.2	218.1	285.8	303.3
Lifetime CO <sub>2</sub> eq production (LCP) [MtCO <sub>2</sub> eq]	2.25	4.36	5.85	7.97
Cumulative energy demand (CED) [TWh]	8.50	16.54	22.72	32.17
Energy Payback Time (CED/AEP) [years]	1.3	1.5	1.6	2.1
Energy Ratio (LEP/CED)	15.2	13.2	12.6	9.4
GHG emissions payback (2025 static) [years] [270]	2.9	3.3	3.4	4.4
GHG emissions payback (Green Book) [years] [270]	3	4	4	8
GHG Payback (Leading the Way) [years]	4	5	5	12

### 5.3.5. Opportunities to mitigate global warming impact

Following on from the previous section, opportunities mitigate global warming impact were explored in more detail. Figure 5.9 shows the main contributions to GW for all four farms, split by assembly, process and vessel operation. The cut-off for this figure was around 5%, to include consistent ordinates for all arrays. As discussed, steel use is the single largest contribution to the GW impact for every farm. The turbine platform (all steel, excluding ballast) is the next most significant, which permits the opportunity for platform designers to significantly affect the climate impact of their products. Then, diesel combustion at around a fifth of the impact – also significant for contemporary efforts at vessel propulsion decarbonisation. For N3, export cables are also significant.

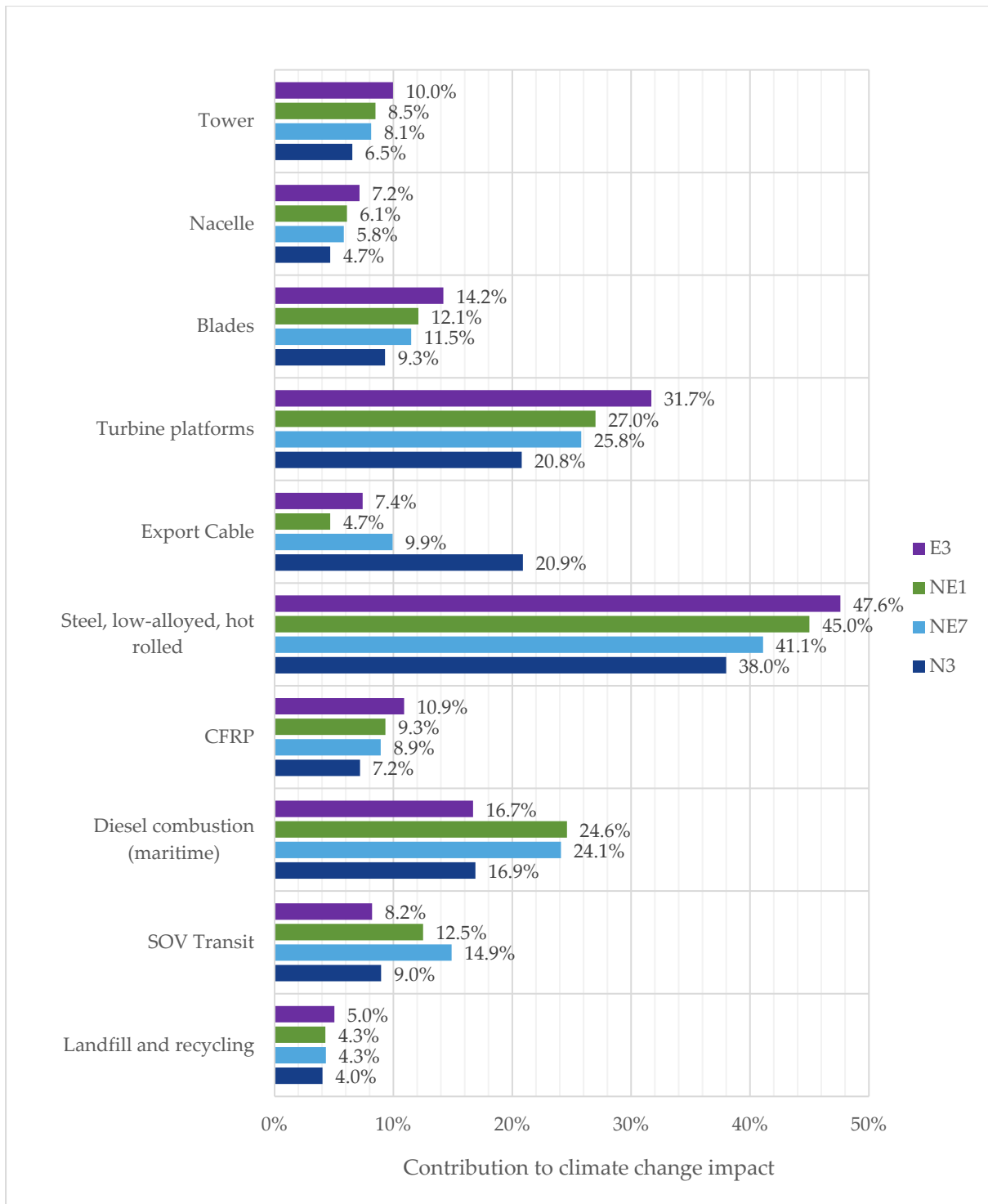


Figure 5.9. Main contributions to climate change impact (GW).

### 5.3.6. Sensitivity analyses

#### 5.3.6.1. Lifetime Energy Production

As described in Chapter 4, due to the functional unit, the environmental impacts will always scale in inverse proportion to the lifetime energy production (24), obviating the requirement to include this in a sensitivity study. Like wave energy, lifetime energy production is crucial to the levelised cost of energy from these arrays. Uniquely for wind turbines this can be affected by icing, erosion of blades and wakes from other wind farms, as well as the electrical losses and curtailment that wave energy is subject to.

#### 5.3.6.2. Turbine and array design parameters

The life cycle impact category results were reviewed for their sensitivity to site and engineering design parameters, which can be somewhat controlled during development. Five relevant parameters were identified: blade mass, wind turbine platform mass, export cable length (HVAC or HVDC), SOV use, and design life. The sensitivity of the life cycle impacts to these parameters was quantified by scaling the parameters by 10% and reviewing the change relative to the basic results without uncertainty, assuming no other changes to the life cycle model.

Firstly, the results for all sites were consistently improved by increasing design life, reflecting other sensitivity studies of this parameter (24). This reduction was -4.9% (OFHH) to -9.1% (multiple). Life extension improves every environmental impact almost linearly, bar the additional yearly requirement for O&M. Accordingly, ozone formation metrics show the least improvements due to these increased vessel emissions. This approach excludes additional impacts from increased structural materiality or O&M consumables necessary to maintain turbine life, which are expected to be relatively minor in most categories (25). This aligns with

typical cost reduction approaches, where extending design life aims to maximise developer return on investment, and – for this parameter – suggests synergy between project cost engineering and environmental impacts.

The results were relatively insensitive to 10% increased blade mass (0.02 to 2.6% across all categories) and platform mass (0.2 to 5.2% across all categories). However, the impact categories sensitivity to increased HVAC and HVDC export cable length was more pronounced, with some categories observing small differences (including global warming, GW at 0.5% to 2.2%) while others observed significant changes (up to 8.8% for terrestrial, freshwater, and marine ecotoxicity metrics: TEX, FEX, and MEX at N3). This pattern was found for all sites, but especially for N3 with the most HVDC converter stations (4) and the second longest export cable route (149 km) resulting in the longest total cable length of the sites considered.

Increases in SOV use (transit to site and station-keeping infield) saw the largest increases in categories associated with diesel combustion (up to 4.4% in OFHH at site NE7, which has the longest distance to O&M port, 105 km). However, multiple impact categories were insensitive to increased SOV use. Notably, the 10% increase in SOV use resulted in only a 0.8% to 1.5% increase in GW impacts, reflecting the dominance of other life cycle stages in climate change impacts.

These results show that the environmental impacts of these very large floating wind farms are primarily affected by design life, making life extension a crucial priority for the environmental impacts of these arrays. Material use – *not* vessel use – is, on balance, the next most significant contribution, suggesting that “greening” the supply of materials (via recycled materials, or alternative low-impact processes) should be the first priority for the industry, followed by

decarbonising vessel propulsion. However, there is already broad support for an accelerated transition to clean maritime operations in North Sea wind farm O&M.

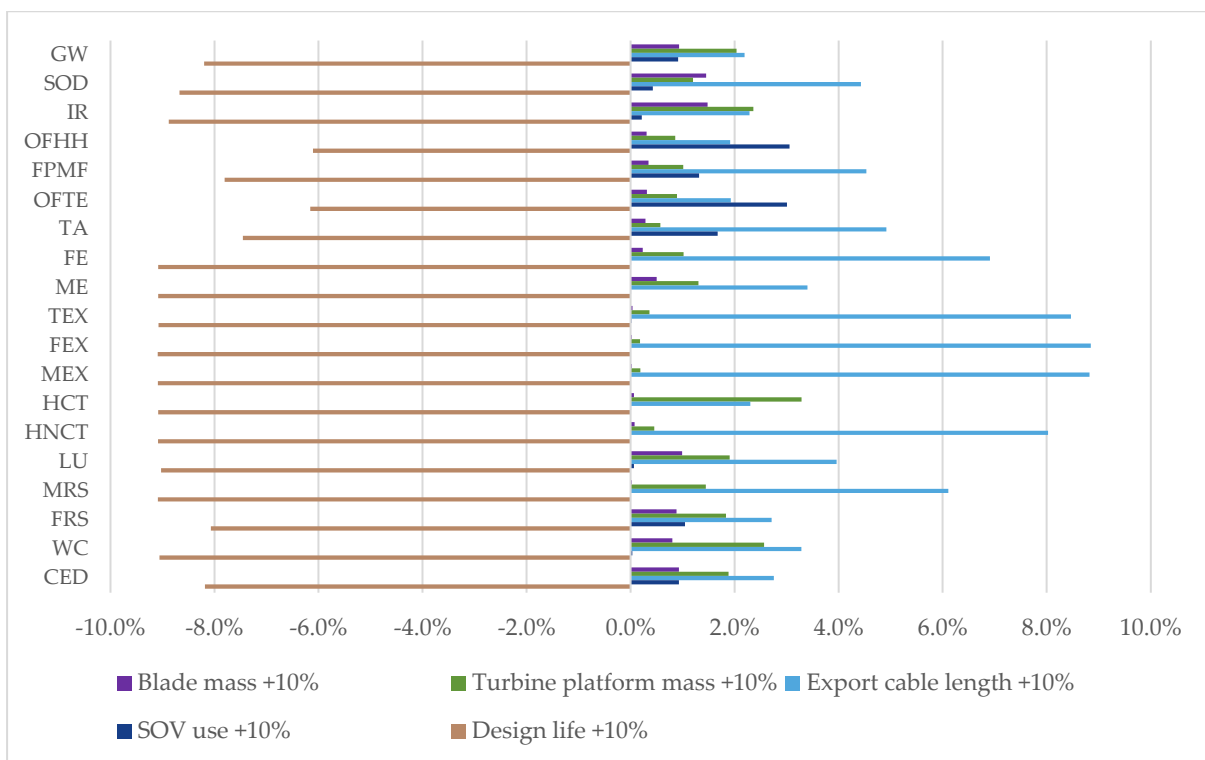
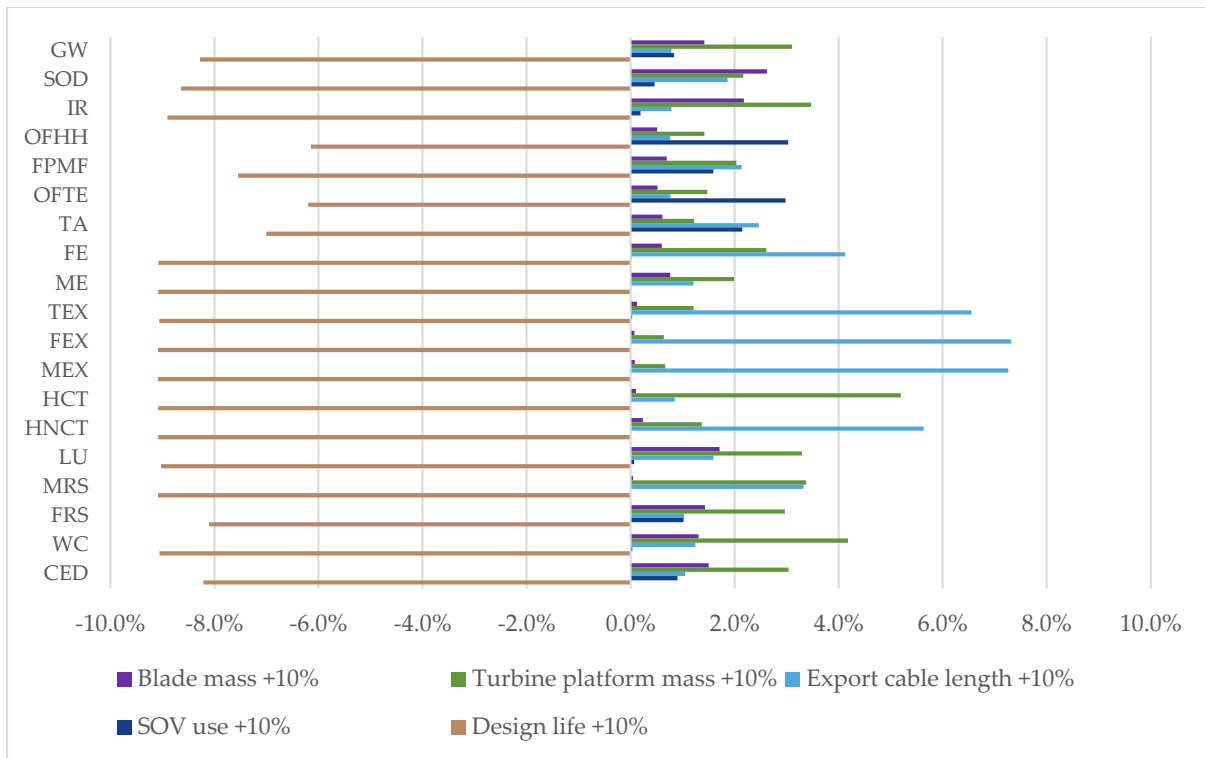


Figure 5.10. Sensitivity of impact categories to 10% increase in selected site and engineering design parameters for “corner case” sites E3 (top) and N3 (bottom).

### 5.3.6.3. Comparison with leased site designs

During the writing of this thesis, the leased ScotWind sites were announced some with significant differences to the representative sites modelled in previous sections. This short section explores some of the differences.

Data was scaled according to the ratio of installed capacity of the consented sites. This was simply multiplied to determine amended cable lengths, SOV hours and number of turbines. For HVAC stations a rating of 825 MW was assumed (same as for N3's original design), for HVDC 1500 MW (same as NE7's original design). The number of SOVs as determined by multiplying the ratio of the consented to pre-consented site installed capacity by the pre-consented number of SOVs from ORE Catapult and rounding up to an integer value (Table 5.13).

- E3 was consented as Site 6, named Cluaran Deas Ear ('South East Thistle' in Gaelic) by the developer Thistle Wind Partners. The site installed capacity was reduced to 72% of that of E3, but in a major change, the consented substructure design is a fixed-bottom jacket – not floating. It was not possible to manage this change in the LCA foreground data given the uncertainty around the selected jacket design.

Nevertheless, it can be noted that the inventory between the floating platform and E3 HVAC jacket are remarkably similar. The total turbine mass is 2280 te compared to the HVAC topside of 2725 te. The platform structural mass is 4014 te, with 2540 te of iron ore and concrete ballast, compared to the HVAC jacket at 3300 te with 769 te pile foundations. The differences then are the mass of ballast (shown in Section 5.3.5 to be at least less than 5 % impact on global warming) and the design material allowances required for the jacket and piles to resist significantly more wind loading

and slightly less payload than the HVAC topside jacket. A fixed-bottom jacket would also necessitate changes to the array cable cross-sectional mass balance (dynamic to static specification) and slight reductions in length due to the J-tube routing (as opposed to free-hanging dynamic arrangement). Leaving aside these differences, E3 is presented for reference, with these caveats in place.

- NE1 was consented as Site 19, 'Arven' (Norwegian for 'heritage or legacy') by Mainstream Renewable Power and Ocean Wind. The site installed capacity is reduced to 78% of that of NE1.
- NE7 was consented at the same installed capacity (3 GW), Site 11 'MarramWind' by ScottishPower Renewables and Shell. In this treatment, the foreground data for NE7 was not amended, and so was not reanalysed or included.
- N3 was consented as Site 15 'Talisk', an Anglicisation of Gaelic *Taileasg*, chess, in reference to the Lewis chessmen. It is under development by Magnora Offshore Wind. This site had the most significant change in installed capacity (only 15% of the pre-consented site).

To efficiently assess the difference a 'Compare' calculation was executed in SimaPro with the revised parameters in Table 5.13 – all other parameters were assumed identical, with no changes to vessel movements or ports, or (importantly) availability from the outputs of COMPASS.

Table 5.13. Select pre-consented site data and the consented site data.

Site designation	E3	NE1	NE7	N3	E3*	NE1*	NE7*	N3*
Consented site designation	-	-	-	-	Site 6	Site 19	Site 11	Site 15
Commercial site name	-	-	-	-	Cluaran Deas Ear	Arven	MarramWind	Talisk
Developer(s)	-	-	-	-	Thistle Wind Partners	Mainstream Renewable Power; Ocean Winds	ScottishPower Renewables; Shell	Magnora Offshore Wind
Site installed capacity [GW]	1.41	2.31	3	3.3	1.008	1.8	3	0.495
Ratio to pre-consented site	-	-	-	-	0.72	0.78	1.00	0.15
Number of turbines (15 MW)	94	154	200	220	68	120	200	33
HVAC stations (825 MW)	3	3	4	4	2	3	4	1
HVDC stations (1500 MW)	0	2	2	4	0	2	2	1
SOVs	2	3	3	3	2	3	3	1
Dynamic Array Cable (240 mm <sup>2</sup> ) [m]	5400	19500	21780	32400	3906	15195	21780	4860
Dynamic Array Cable (630 mm <sup>2</sup> ) [m]	4080	14040	14960	22800	2951	10940	14960	3420
Dynamic Array Cable (800 mm <sup>2</sup> ) [m]	1800	6500	7260	10800	1302	5065	7260	1620
Static Array Cable (240 mm <sup>2</sup> ) [m]	75600	126000	166320	181440	54689	98182	166320	27216
Static Array Cable (630 mm <sup>2</sup> ) [m]	57120	90720	114240	127680	41321	70691	114240	19152

Site designation	E3	NE1	NE7	N3	E3*	NE1*	NE7*	N3*
Static Array Cable (800 mm <sup>2</sup> ) [m]	33675	57875	75735	84060	24361	45097	75735	12609
HVAC collector station cable length [km]	240	40	50	55	160	27	50	14
Export cable length [km]	0	288	828	1188	0	288	828	297
Array install legs	6	4	5	6	2	3	5	1
HVAC station install legs	3	1	1	1	2	1	1	1
HVDC station install legs	0	5	13	19	0	5	13	5
Strings per station	6	9	9	10	6	7	9	6
SOV in-field [hrs/year/SOV]	214	417	675	554	155	325	675	83
SOV transit [hrs/year/SOV]	1478	2882	4670	3838	1069	2246	4670	576

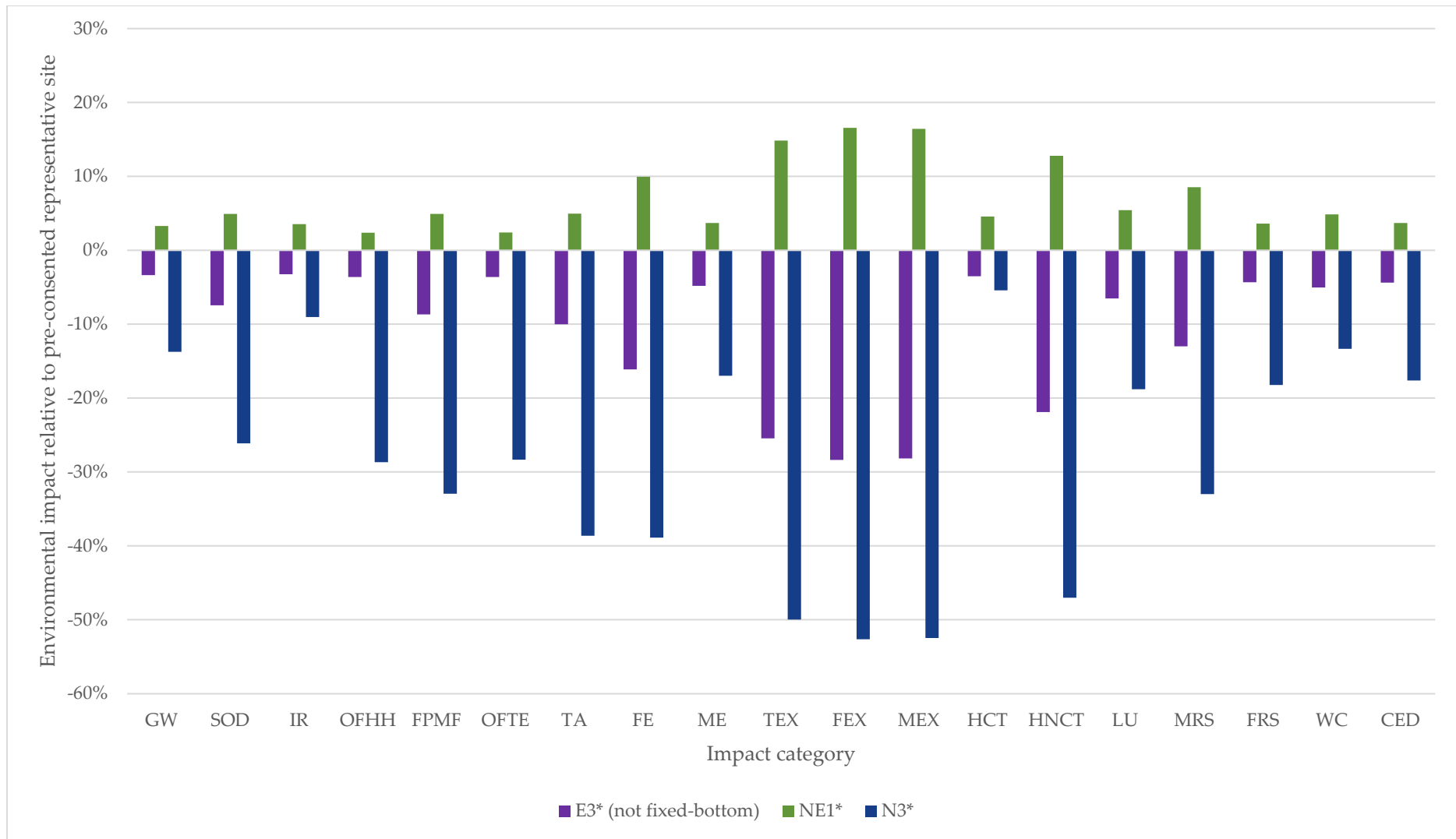


Figure 5.11. Change in environmental impact categories relative to the pre-consented sites modelled in previous sections.

Figure 5.11 shows the relative change in each impact category relative to the pre-consented site. In general, only NE1\*, shows an increase in impacts, with E3\* and N3\* showing reduced impacts – with the caveat that the actual consented site for Cluaran Deas Ear is a fixed-bottom design.

The first aspect of the results to remark on is the scaling of the foreground data by installed capacity. Scaling in this way will only create differences between the consented and pre-consented designs, where linear scaling does not apply. This is most obvious in the number of stations and SOVs, and indeed we see that for NE1\* where the stations are used least efficiently (the site has a requirement for 2.2 HVAC stations and 1.2 HVDC stations), the impacts are higher – not forgetting the additional export cables accompanying the stations.

The efficiency in cable utilisation in particular, drives the reductions in ecotoxicity impacts for E3\* and N3\*, due to the decreased burden of copper and lead disposal relative to the lifetime energy production.

Interestingly, global warming is one of the impact categories *least* affected by the changes, much more so for the categories relevant to the 'Biosphere Integrity' planetary boundary (PB) such as ecotoxicity and terrestrial acidification; up to 50% in the case of terrestrial, freshwater and marine ecotoxicity. The reduction in vessel emissions from cable inspections (via cable length) also imparts reductions in fine particulate matter formation, stratospheric ozone depletion and human health relevant ozone formation.

Overall, these results can give confidence to the pre-consented site results described in previous chapters, that a site's environmental impact is mainly driven by the lifetime energy production and the 'efficiency' of material utilisation. For changes in site design that reduce

this efficiency, increased harms are observed across a wide range of impact categories, and attention to burden shifting is necessary.

### 5.3.7. Comparison with wave energy LCA

A key advantage of this thesis is that the continuity of practitioner, cut-off criteria and LCA methodology, arguably enables a well-founded comparison between the results of Chapter 4 and Chapter 5. The least environmentally impactful wave energy site is Birsay (except in ionising radiation and human carcinogenic toxicity where Farr is lowest), while N3 is the most harmful floating wind array. N3 is lower than Birsay in every impact category except freshwater ecotoxicity, marine ecotoxicity and human non-carcinogenic toxicity (Figure 5.12), and generally there is a “gap” between the two technologies, where floating wind occupies the range of 20 to 30% of the most impactful wave energy site, while the less impactful wave sites occupy the range of 60 to 80%. Maywick is the most impactful site overall (due to low AEP) except for a few impact categories associated with vessel fuel use (ozone formation human health, ozone formation terrestrial ecosystems and terrestrial acidification) where Arnol (due to its distance to operations port) is most harmful.

Overall, this can likely be explained by the innate characteristics of the two technologies, their relative state of technological development and the differences in O&M foreground data.

- Arguably, wind energy has lower fatigue and extreme loading requirements per unit of energy than wave energy. This manifests as a reduced volume of load-resisting material for a given design life, and consequently a lower inventory per unit energy. Moreover, there is a fundamental difference in the resource; compare a wind turbine power curve with a WEC power matrix. Wave energy resource is more variable and WEC power output is more sensitively “tuned” to specific site resource than wind

power. This sensitivity negatively impacts AEP and hence worsens environmental impacts.

- Continuing in that vein, the large scale of wind turbines relative to WECs exacerbates the material efficiency of the machines. This large scale is achievable only after many years of technological development, as well as the fundamental difference in energetic media, where WEC size is more pressingly constrained by physical limits of free surface wave geometry, fluid properties and Earth's gravity.
- Lastly, while great effort has been made to maintain consistency between the two assessments, fundamentally, the O&M life cycle stage model was completely different. Given this is such an important part of the wave energy life cycle impacts, this makes an important caveat.

In summary, it seems fair that the floating wind farms of 15 MW turbines can be said to be lower impact per kWh than the wave energy arrays of 1 MW WECs. This does not account for any variation in the temporal or spatial delivery of this low carbon energy, of which wave has been shown to offer advantages over its nameplate rated power [116].

### 5.3.8. Compare with other forms of electricity fromecoinvent

Extending this comparison to other forms of electricity comes with the usual cautions. A credible way of comparing multiple sources is to use unit processes from the life cycle inventory database. However, the inventories of these processes are not iron-clad, especially the offshore wind process which notably does not include an allowance for O&M [162]. Figure 5.12 shows that the most impactful technology varies from category to category, with wave energy most harmful in 10 of the 19 categories – however this rank does not assess the relative perilousness of each impact category with respect to the transgressed planetary boundaries.

Nuclear power from pressurised water reactors (PWR) is next most frequent (4), then combined cycle natural gas (CCGT, 3), and utility-scale solar (2). These findings echo that of [128] where wind and solar are found to have more impactful freshwater eutrophication, metal depletion and land occupation impacts than natural gas, but lower climate change, freshwater ecotoxicity, human toxicity, particulate matter emissions, photochemical ozone formation and terrestrial acidification, lending credence to these results.

Clearly, climate change is one of the most publicly understood transgressed planetary boundaries, and here, gas is most impactful (353 gCO<sub>2</sub>eq/kWh), followed by solar (78 gCO<sub>2</sub>eq/kWh), slightly higher than the wave energy average calculated in Chapter 4 (74 gCO<sub>2</sub>eq/kWh) and well above the average from this Chapter (21 gCO<sub>2</sub>eq/kWh). Note also that the floating wind average is higher than that of theecoinvent data for smaller, fixed-bottom offshore turbines. This may arise from the different resolution between this LCA and theecoinvent process, and the larger inventory of materials of the floating platform, electrical stations and export cables.

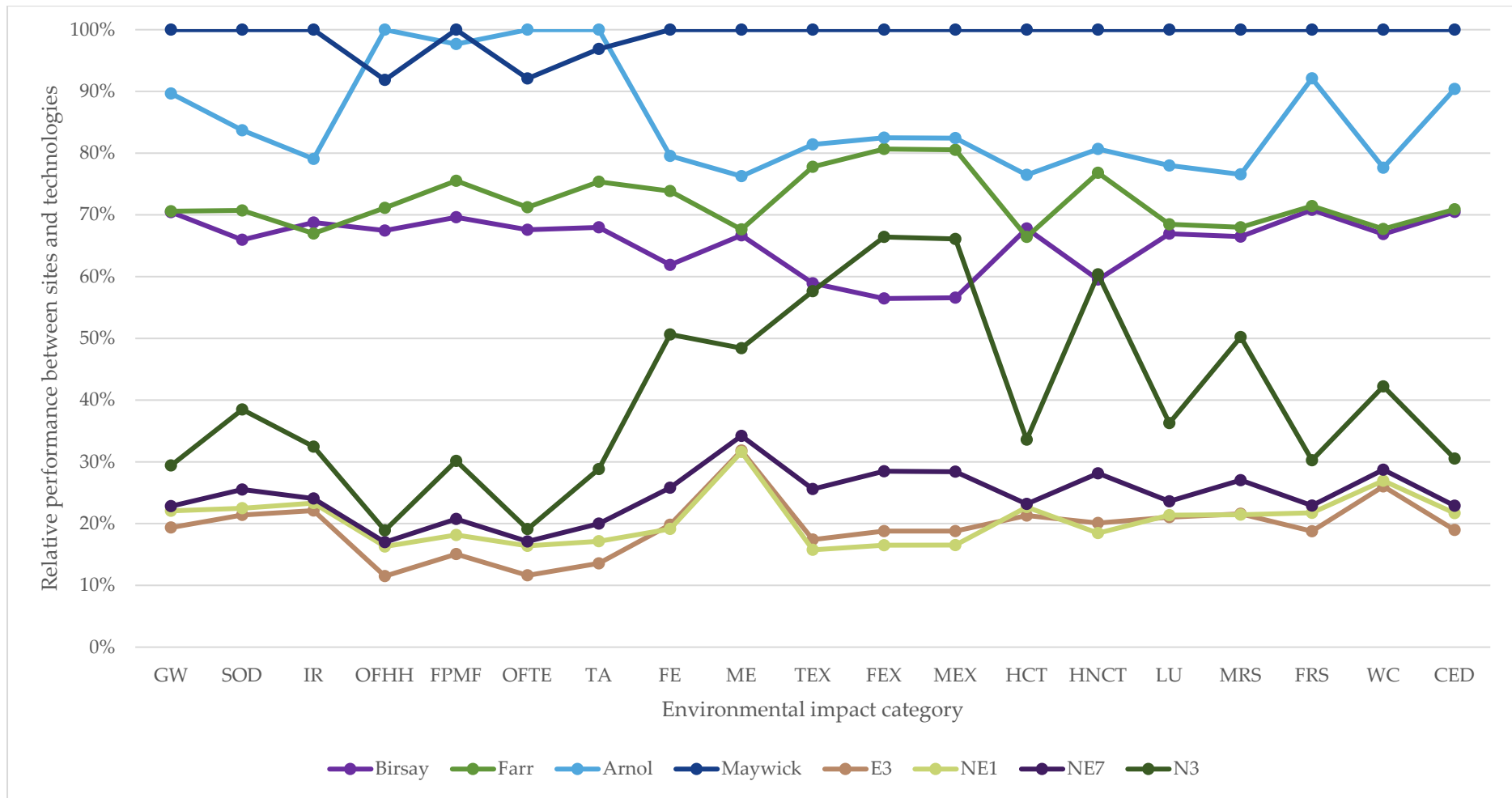


Figure 5.12. Comparing results without assessment of uncertainty between the four wave energy arrays in Chapter 4 and the four floating wind arrays from Chapter 5. The line graph facilitates the reader tracking the relative performance of the arrays.

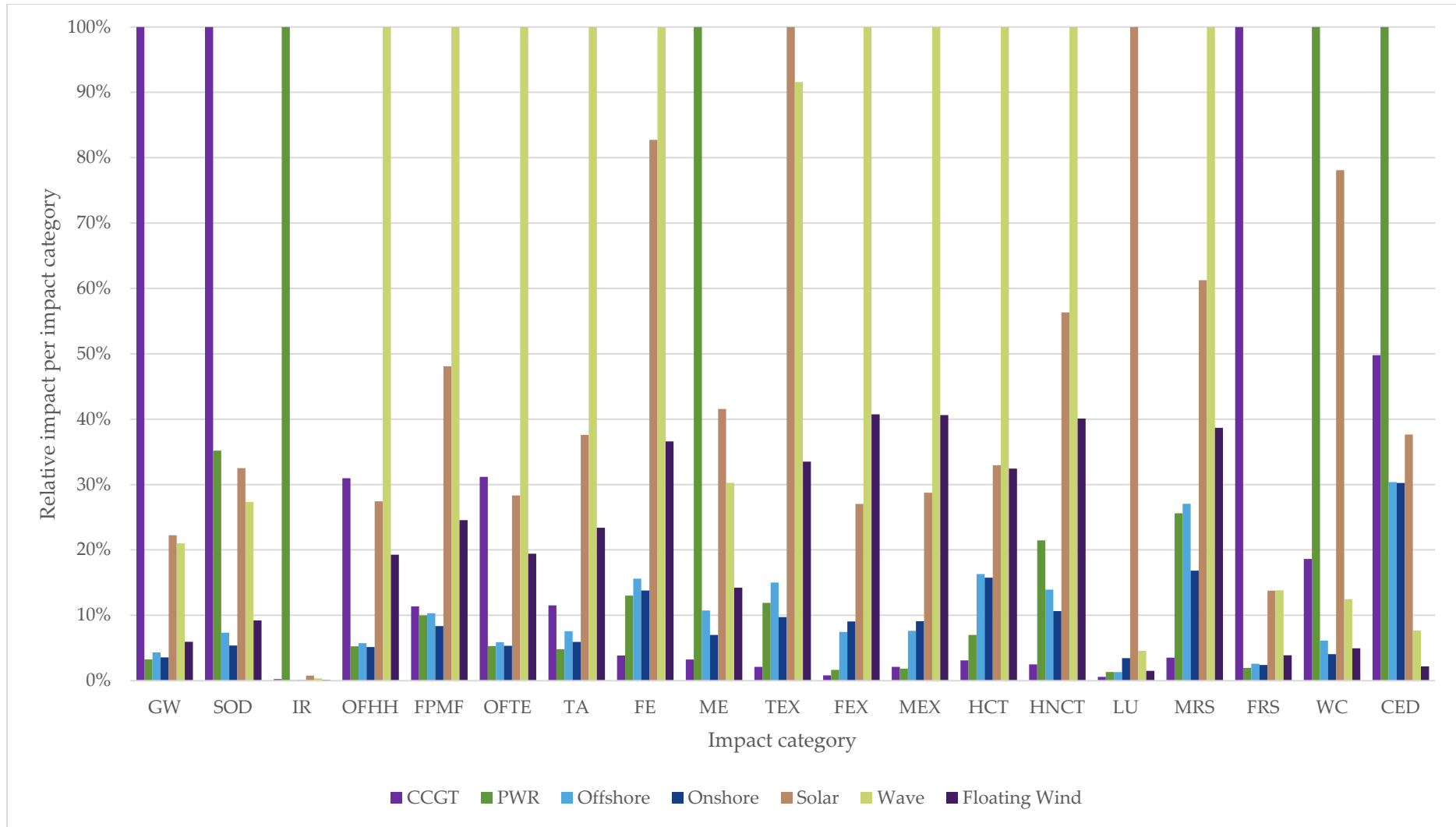


Figure 5.13. Comparing results between the average results from Chapter 4 and Chapter 5 with a range of electricity generation from ecoinvent.

## 5.4. Limitations of the work and future research needs

As with any model, it is impossible to replicate the complexity of the system under assessment, and approximations are essential for a tractable solution. Further, the more detailed a life cycle model, the more processes are included and typically the higher the impacts computed. This is observable in the literature where inclusion of manufacturing processes and detailed O&M modelling tends to be associated with higher climate change impacts (Chapter 3). Some obvious limitations include:

- No allowance for variation in seabed conditions, affecting foundation design and substructure selection. However, the platform anchors and station piles are below 5% of the impact of global warming (Figure 5.9), suggesting this would not have a significant contribution to GW results.
- No allowance for electricity required to power the pumps used for active ballast management. It is unlikely that this would have a material impact on turbine AEP (assuming the power is generated locally), but this is perhaps worth investigating for future designs that use this technique.
- In the context of a wider environmental footprint than just climate change, this assessment has not explored component contributions beyond a simple life cycle stages and selected sensitivities. In the spirit of a more comprehensive understanding of environmental impacts, exploring the component level contributions could be a future informative piece of work, especially using global sensitivity analysis [295].

- Absolute environmental sustainability and prospective life cycle assessment were beyond the scope of the analysis. Both would be a novel contribution to literature if executed.
- Only a nominal inclusion for cable inspection and major component replacement, with no allowance for other types of subsea inspection, such as moorings.
- Array losses have not been included in the lifetime energy production, which would have an inversely proportional effect on the environmental impacts.
- The turbine and platform model used are primarily intended as open benchmarks for new technologies or design methodologies and do not completely represent an extant floating wind turbine design.

Fundamentally, future use of low impact materials has the potential to significantly reduce the environmental impacts. Incremental benefits can also be achieved in the near term by technology maturation, such as optimising platform, turbine and transmission system designs to reduce mass and increase AEP.

## 5.5. Conclusions

This chapter has completed a life cycle assessment of the 15 MW reference wind turbine on floating platforms in sites representative of four floating wind farms in the ScotWind leasing round (E3, NE1, NE7 and N3) with a mixture of HVAC and HVDC transmission systems. The inventory data for this study has used inputs from ORE Catapult modelling for materials and O&M vessel usage, giving assurance on the accuracy and representativeness of the results. The median Global Warming (GW) impacts and 95% confidence interval for the E3, NE1, NE7 and N3 sites were 17.4 (13.0 – 23.6), 20.0 (14.9 – 27.8), 20.5 (15.4 – 28.2) and 26.3 (20.2 – 35.4) gCO<sub>2</sub>eq/kWh respectively, using default values for basic and additional uncertainty in the foreground data, and background data.

As is common with other papers of offshore renewable energy systems, life cycle impacts across most categories are dominated by the materials and manufacturing life cycle stage. For the four sites E3, NE1, NE7 and N3 materials and manufacturing accounts for 78%, 71%, 72%, 79% of the global warming impact respectively.

Although the O&M burden was smaller than other studies; O&M (mainly using SOVs) comprised 9 – 16% of global warming and 10 – 17% of cumulative energy demand impacts.

Sensitivity studies showed that environmental impacts of these very large floating wind farms are fundamentally affected by design life, making life extension a crucial priority for the sustainability of these arrays. Following that, material use – *not* vessel use – is the next most significant contribution on balance, suggesting “greening” the supply of materials (via recycled materials, or alternative low impact processes such as the use of hydrogen as a reducing agent in steel making) should be a research priority, with decarbonising vessel propulsion following. This echoes the results from Chapter 4.

Comparing the wave energy arrays from the previous chapter with the floating wind arrays, in almost every case the floating wind arrays were less environmentally impactful. Looking cursorily at the different technology processes within SimaPro yields a distribution of impact categories similar to those observed in other studies.

This chapter has presented a static life cycle assessment of representative future floating wind farms based on historical background data. The following chapters will adjust the 'lens' of this thesis significantly by stepping from the domain of life cycle assessment into power system modelling. Using power system modelling to represent the presence of these arrays when integrated into future GB power systems, will allow an assessment of the avoided emissions from local and national power systems with the ultimate aim of more fully understanding their climate change impact on a realistic dispatch order basis, at the conclusion of this thesis.

# Chapter 6: Methodology and model selection for assessing operational emissions displacement impact of renewables

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Building on the literature review, this section develops the methodology and model selection for the power system modelling in Chapter 8 of this thesis. The model and the data developed (PyPSA-GB), is introduced.

- **Section 6.1:** introduces the chapter and its aims.
- **Section 6.2:** describes the ideation of the method behind the thesis.
- **Section 6.3:** describes the data required and obtained for modelling the required future energy scenarios for GB. Introduces the power system modelling tool developed and used in this PhD, PyPSA-GB.
- **Section 6.4:** develops aims for subsequent chapters and lists omissions and further work.

## 6.1. Introduction

The previous chapters have assessed the life cycle impact of two novel arrangements of offshore renewable energy: wave energy and floating wind. However, these assessments are static in time, and do not consider the consequential effect arising from their delivery their functional unit: electrical energy to local power system.

The order in which types of power generation technologies are dispatched is usually determined by their cost, and renewable energies have typically lower (near-zero) marginal cost than other forms of power, as these re subject to higher operational costs from consumable fuels. For a given level of power demand then, increased installed capacity of renewable energy reduces the requirement for fossil-fuelled power generation, and hence reduces aggregate operational emissions from the power system. The magnitude of impact and how best this consequence should be accounted for in attributional life cycle assessment remains open, and a method to resolve this question is begun in this chapter.

## 6.2. Methodological development

### 6.2.1. Environmental impacts when integrated into an energy system

The main intent to installing variable renewable energy (VRE) into an energy system is to *avoid* the need for more harmful forms of generation; primarily fossil fuels given the urgency and severity of the anthropogenic climate change. However as described in Chapter 2, no power generation technology is without environmental harm.

Figure 6.1 illustrates the range of environmental harms from different generation technologies. It compares unit processes from the ecoinvent life cycle inventory database [162] with the mean of the findings from Chapter 4 and 5 using the same life cycle impact assessment (LCIA) method, ReCiPe 2016, at a midpoint level [89] (endpoint shown in Figure 6.2). Given the near absence of coal on the GB grid, methane used in unabated combined cycle gas turbines (CCGT) is the main fossil-fuelled power generation technology expected to be offset by increased penetrations of renewables. According to the data in Figure 6.1, this would nationally reduce global warming (GW), stratospheric ozone depletion (SOD), ozone formation hazardous to human health (OFHH), ozone formation hazardous to terrestrial ecosystems (OFTE) and fossil resource scarcity (FRS): in particular relevant to the transgressed planetary boundaries of climate change and stratospheric ozone depletion (Chapter 2). By contrast, nuclear power is particularly impactful in terms of ionising radiation (IR), marine eutrophication (ME), water consumption (WC) and cumulative energy demand (CED). All forms of VRE are more materially intense per unit of energy delivered, although – according to the ecoinvent database – onshore wind is the second best performing after nuclear.

Focussing on one example to illustrate this trade-off, offshore wind has higher impacts per kWh than CCGT in *nine* impact categories: freshwater eutrophication (FE), marine

eutrophication (ME), terrestrial ecotoxicity (TEX), freshwater ecotoxicity (FEX), marine ecotoxicity (MEX), human carcinogenic toxicity (HCT), human non-carcinogenic toxicity (HNCT), land use (LU) and (non-fossil) material resource scarcity (MRS). Alternatively, looking at an *endpoint* level shows that CCGT is the most harmful in all but one indicator: human health, in which wave energy performs least well (Figure 6.1). In this case then, a reduction in energy from CCGT would be expected to reduce the national impact on climate change and ozone depletion, while increasing other midpoint impact categories, but having an overall improvement at the endpoint level. However, the potential for this GHG emissions reduction or “climate change mitigation potential” is not captured in static, attributional LCAs. The next sub-section will lay out a method by which this could be considered.

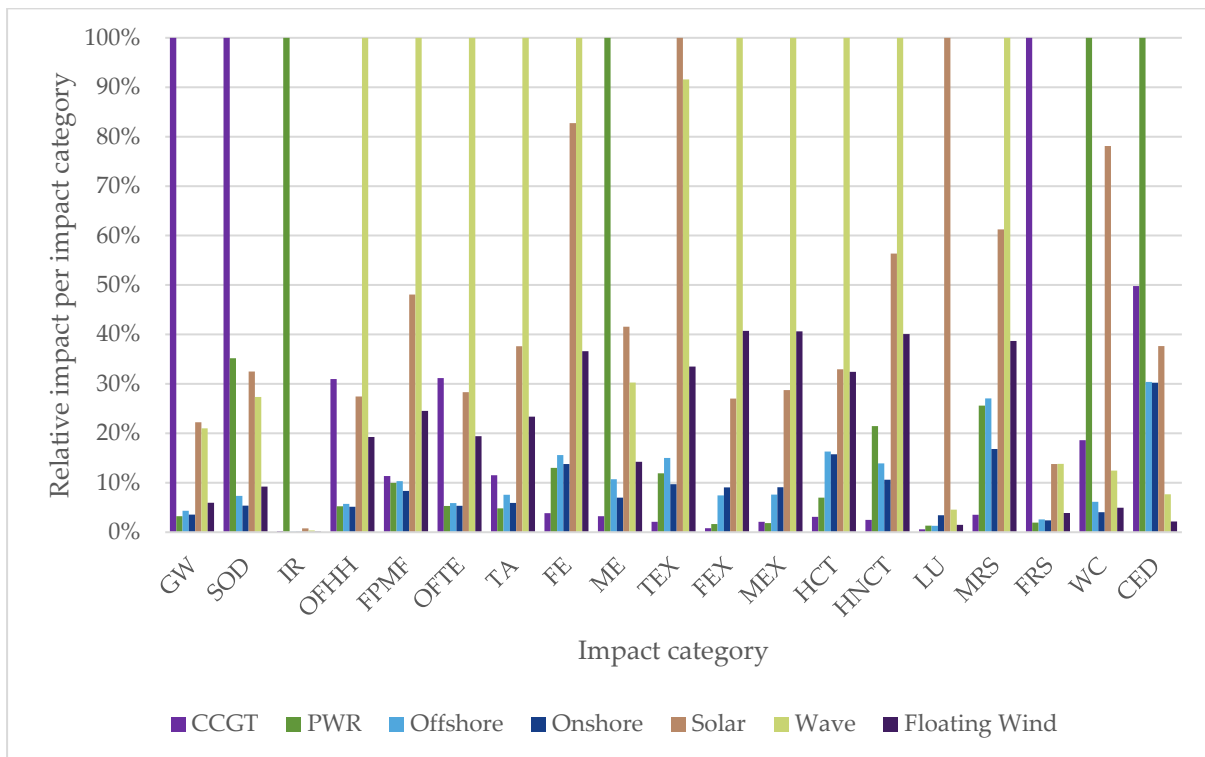
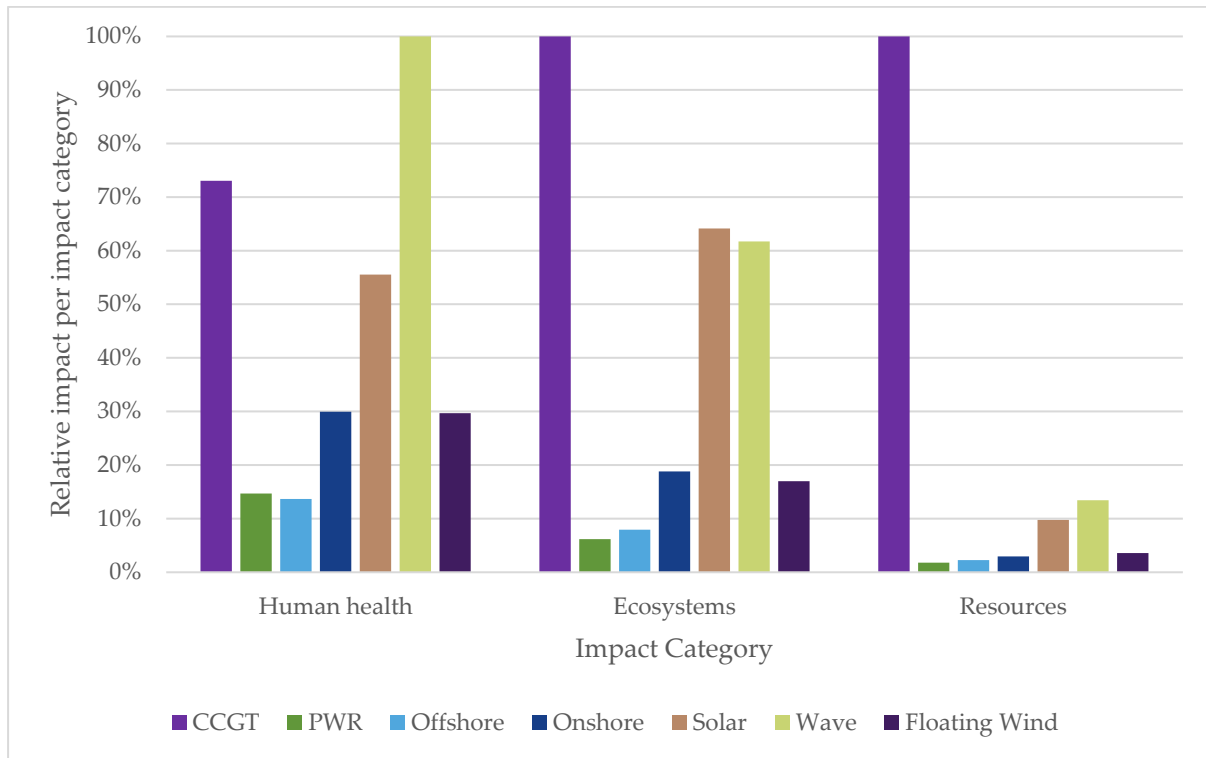


Figure 6.1. Relative impact of five electricity generation technologies from ecoinvent 3.6, per kWh, using ReCiPe 2016 Midpoint (Heirarchist) V1.04 / World (2010) where CCGT = natural gas, combined cycle power plant; PWR = nuclear,

*pressure water reactor, Offshore = 1-3MW offshore wind turbine; Onshore = >3MW onshore turbine; Solar = low voltage 570kWp open ground installation. Wave and Floating Wind are mean of the four sites considered in Chapters 4 and 5.*



*Figure 6.2. Relative impact of five electricity generation technologies from ecoinvent 3.6, per kWh, using ReCiPe 2016 Endpoint (Hierarchist) V1.04 / World (2010) where CCGT = natural gas, combined cycle power plant; PWR = nuclear, pressure water reactor, Offshore = 1-3MW offshore wind turbine; Onshore = >3MW onshore turbine; Solar = low voltage 570kWp open ground installation.*

### 6.2.2. Handling multifunctionality in life cycle assessment

LCA concerns itself with the elementary flows of materials and energy which traverse the boundary between the ecosphere and the technosphere. However, a system can provide multiple outputs (or *functions*) such as waste flows, which are valuable for other parts of the industrial ecosystem in addition to the functional unit: termed *co-products* [296]. Co-products are thus an example of *multifunctionality*, and the method of how they are accounted for can significantly effect LCA findings [296]. The question remains then: how should the emissions

reduction potential of VRE should be accounted for in LCA? Section 4.3.4.2 of ISO 14044 presents three approaches multifunctionality [150], ordered:

1. **Subdivision of unit process:** isolates the processes associated with the co-product(s) by inspection of their unit processes. This is usually challenging and potentially risks misrepresenting the life cycle (by cherry-picking unit processes for deletion).
2. **System expansion:** *subtracts* the impact of “the most likely alternative way of producing the co-product” from the impacts of the product system, or “crediting” the system with “avoided production” [296]. For example: waste incineration plants process residual waste, but can also deliver heat, electricity, and metal resources as co-products. The impacts that would have been incurred from the production of those products can be subtracted from the impacts of the waste disposal functional unit [15]. However, for this approach to work, the next most likely method of production must be known or assumed.
3. **Allocation:** attributes the elementary flows of the product system according to known relationships, such as economic value. This approach requires subjective judgements and the results are susceptible to changes expressions of economic value.

For this thesis, subdivision of a unit process is impossible (the emissions reduction from the wave or floating wind is not present in the life cycle model), and allocation of a price of emissions is complex and highly subjective – and would still require a quantification of the consequentially avoided emissions. System expansion, or *avoided production* is therefore judged as the most suitable approach.

Attributing multifunctionality of emissions reduction to the static attributional LCAs of power production from Chapter 4 and 5 via system expansion requires, then, a known (or most likely) alternative method of power generation to be subtracted. This means:

1. Determining a baseline energy scenario;
2. Quantifying the impact of the avoided emissions (which is the multifunctionality co-product) of some amended scenario;
3. *Subtracting* these avoided emissions from the environmental harms calculated in Chapter 4 and 5 to yield a fuller description of the life cycle impacts of these novel technologies.

### 6.2.3. Avoided emissions

‘Avoided emissions’ are a subset of avoided production, and hence a subset of all of the impact categories in the selected LCIA method (ReCiPe 2016). Figure 6.3 shows how avoided emissions can be calculated in a general manner [297]. It is clear from Figure 6.3 that a time span up to a *time horizon* is fundamental to the quantification of avoided emissions, and subjective selection of such will affect any results. For example, the lifetime of the technologies in question could be one choice of time horizon.

Therefore, it is clear from the definition of avoided emissions, that a ‘reference scenario’, or ‘counterfactual’, is essential to the quantification of avoided emissions (Figure 6.3). Thus, this thesis must also *identify suitable reference scenarios* by which to calculate the avoided emissions associated with floating wind or marine energy. This is explored in Section 6.3.

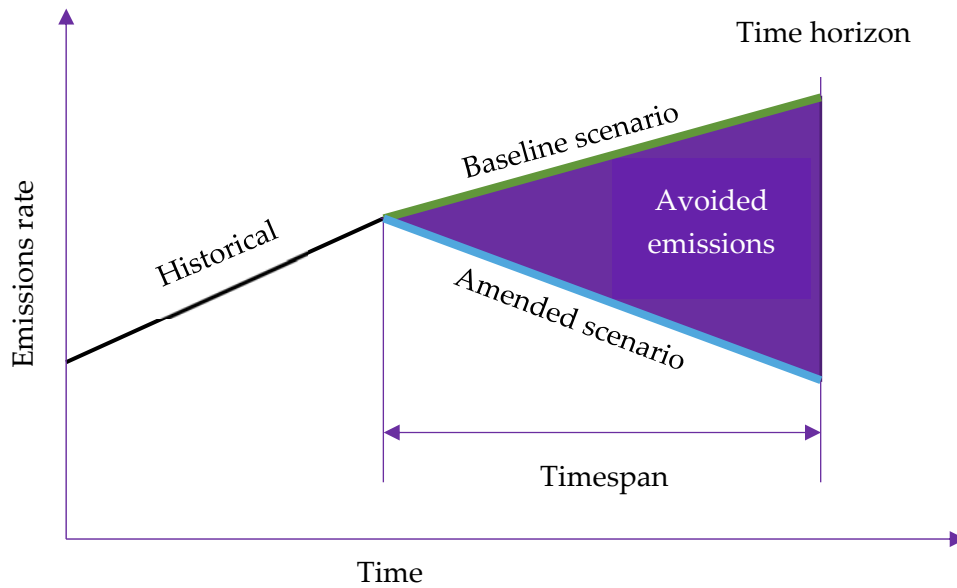


Figure 6.3. Calculation of the avoided emissions attributable to some amendment to a baseline scenario as the difference between the emissions associated with the amended scenario and baseline scenario [297].

From Section 6.2.1 it follows then that the energy generation by CCGT is the most likely avoided product for future scenarios, with associated change in environmental impacts, especially GHG emissions. However, the emissions (or carbon dioxide) intensity of avoided energy production cannot be assumed to be equal to CCGT alone due to the topology and operational characteristics of the GB power system: the *marginal* generation type will change dynamically on multiple time scales, changing the avoided emissions ‘on the margin’. One approach to determine the marginal emissions for some future GB power system is to consider the operation of the power system directly. This is reviewed in the next section.

## 6.3. Identifying suitable data and selecting a modelling tool

Two decisions remain: to identify suitable data for inputs to the model, and to identify a suitable PSM modelling tool.

### 6.3.1. Identifying suitable input data

For PSM tools, scenarios are a frequently used as inputs – and for the purposes of this study, the scenarios should:

- Include – or be modifiable to include – wave power, tidal stream and floating wind generation;
- Be scalable or cover the GB power system;
- Represent credible futures (at least from 2030 to 2050) in line with Net Zero ambitions;
- Include a wide array of power system components.

Three sources of scenarios were identified, each with various advantages and disadvantages:

1. Four exogenous future scenarios for Scotland's energy system (simulated in the EnergyPLAN ESSM): two each for 2030 and 2050 [298]. Each scenario includes small installed capacities of wave power and tidal stream, delivering 5.5 TWh and 1.1 TWh, or around 5% of total energy delivery, in the best case. These scenarios are highly detailed, include marine energy but do not differentiate to floating wind, and cover only the Scottish energy system, making them unsuitable.
2. By contrast, the International Energy Agency (IEA) provide the 2021 landmark report, on achieving a global net zero scenario [109]. This work includes 27, 77 and 132 TWh

of marine (wave and tidal combined) in 2030, 2040 and 2050 (0.19% contribution to a total electricity generation of 71,164 TWh in 2050), or 11, 32 and 55 GW respectively (0.16% against a total electricity installed capacity of 33,415 GW, in Annex Table A.3). Floating wind is not differentiated in the results but is asserted to make “major contributions” to electricity generation beginning around 2030. While a watershed report, the work is not useful due to its global scale.

3. Lastly, for the whole British system, the Energy System Operator (ESO), National Grid ESO, publish yearly the Future Energy Scenarios (FES) [299]. The scenarios represent different, credible ways to decarbonise the British Energy system towards the legislated 2050 Net Zero target [300]. The FES have been published annually since 2017 and are more modern than other scenarios or pathways such as [210], [211], [219], and have excellent data availability. The FES are a combination of outputs from whole system modelling using UK TIMES and power market dispatch model (BID3) to calculate power generation and operational emissions [300]. FES includes “Marine” technologies but these are aggregated (wave power, tidal stream and tidal lagoon).

From this overview, the FES are the most accessible scenarios with appropriate coverage and resolution. These are selected as suitable for the analysis and described in more detail in Chapter 7 and 8. In 2022, the four FES had the following characteristics, up to the year 2050:

- **Consumer Transformation (CT):** primarily electrified heating, consumer behavioural change, high energy efficiency and demand side flexibility;
- **System Transformation (ST):** primarily hydrogen for heating, low consumer behavioural change, lower energy efficiency, and supply side flexibility;

- **Leading the Way (LW):** rapid roll out of electrified *and* hydrogen heating, significant lifestyle changes, fastest decarbonisation;
- **Falling Short (FS):** slow decarbonisation of heat, minimal behaviour change, slowest decarbonisation.

*Box 6.1. Preliminary comparison of environmental impacts of power system FES2022: is a wrong map better than no map?*

Beyond the operational emissions impact of generation, FES2022 does not provide information on the life cycle environmental performance of each scenario. One way of providing an initial understanding of the life cycle environmental impact of the scenarios is to consider the environmental impact of electricity output from each generation technology, represented by a representative unit process from the ecoinvent database.

The FES2022 Data Workbook, sheet ES.E.07 [301] provides data on the annual electricity output by technology. Approximating these using ecoinvent unit processes over the period 2025 to 2050 produces Figure 6.4, where the performance of the electricity generation is shown relative to the least harmful scenario in each impact category. The planetary boundaries with potential mapped to each impact are also suggested.

This is a simple and coarse first approximation, and neglects many physical components of the energy system in each scenario, power exchange via interconnectors and energy use outside of the electricity system, such as fossil fuels for remaining non-electrified heat, transport and industry. Moreover, the static treatment assumes that the unit processes do not evolve over the 25 year period in the same way that a prospective LCA would, and – obviously – the correspondence between the unit processes and the generation technologies is unlikely to be complete. In particular, there are no representative unit processes for power generation from CCS Gas, BECCS or Hydrogen. Nevertheless, this treatment does improve the resolution

of insight relative to FES2022, which provides zero information on the life cycle impacts of each scenario.

These figures suggest that the electricity generation over the period for Falling Short (FS) is actually the least harmful (apart from four impact categories: Global Warming, Stratospheric Ozone Depletion, Ionising Radiation and Fossil Resource Scarcity). This may be explained in part by the lowest total generation, which aligns with the FES scenario description whereby natural gas and fossil fuels still play a significant role in the energy system, with low electrification of heating and transport – simply put, the environmental harms of power system are lower, because the environmental harms are shifted to the wider energy system and not accounted in this method. Leading the Way (LW) also has low total generation, but can be explained by the scenario's preference for energy efficiency. However, the preference for high electrification, as well as high generation from wind and solar, leads to high impacts in 13 of the 18 categories, especially Land Use (LU, from biomass and solar), Terrestrial, Freshwater and Marine Ecotoxicity (TEX, FEX, MEX), Human carcinogenic and non-carcinogenic toxicity (HCT and HNCT) both from solar panel production and copper mine operation, ozone formation and fine particulate matter (from silicon and pig iron production).

Overall, while enticing, this treatment would require careful consideration of the system boundary and prudent selection of suitable unit processes to yield definitive conclusions. It is clear that highly renewable power systems for GB are not an environmental panacea, despite their attractive performance in reducing climate change harms, relative to non-Paris compliant power system architectures.

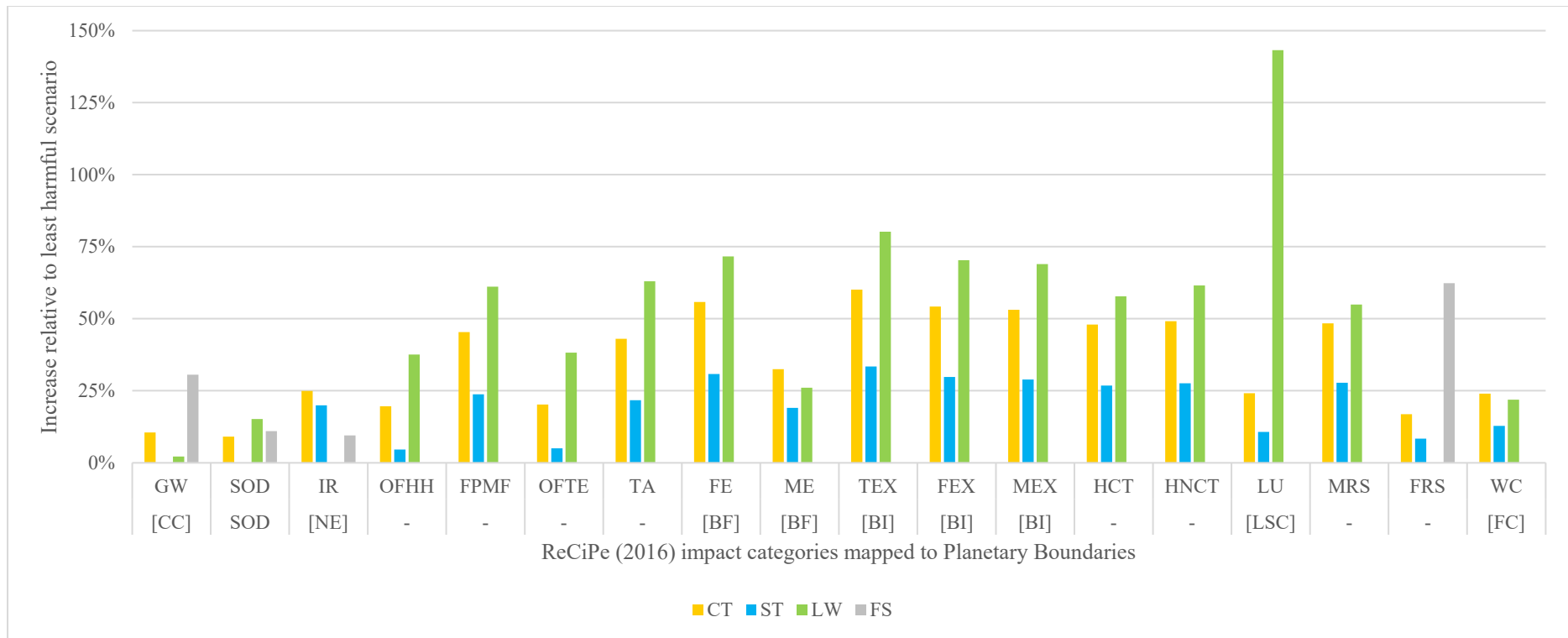


Figure 6.4. Relative environmental impact of electricity supply over the period 2025-2050 according to FES2022 (ES.E.07). ReCiPe (2016) impact category abbreviations as per Chapters 4 and 5, planetary boundaries indicated as per Chapter 2: Climate Change (CC), Stratospheric Ozone Depletion (SOD), Novel Entities (NE), Biogeochemical Flows (BF), Biosphere Integrity (BI), Land System Change (LSC) and Freshwater Consumption (FC). Square braces indicate the planetary boundary is transgressed.

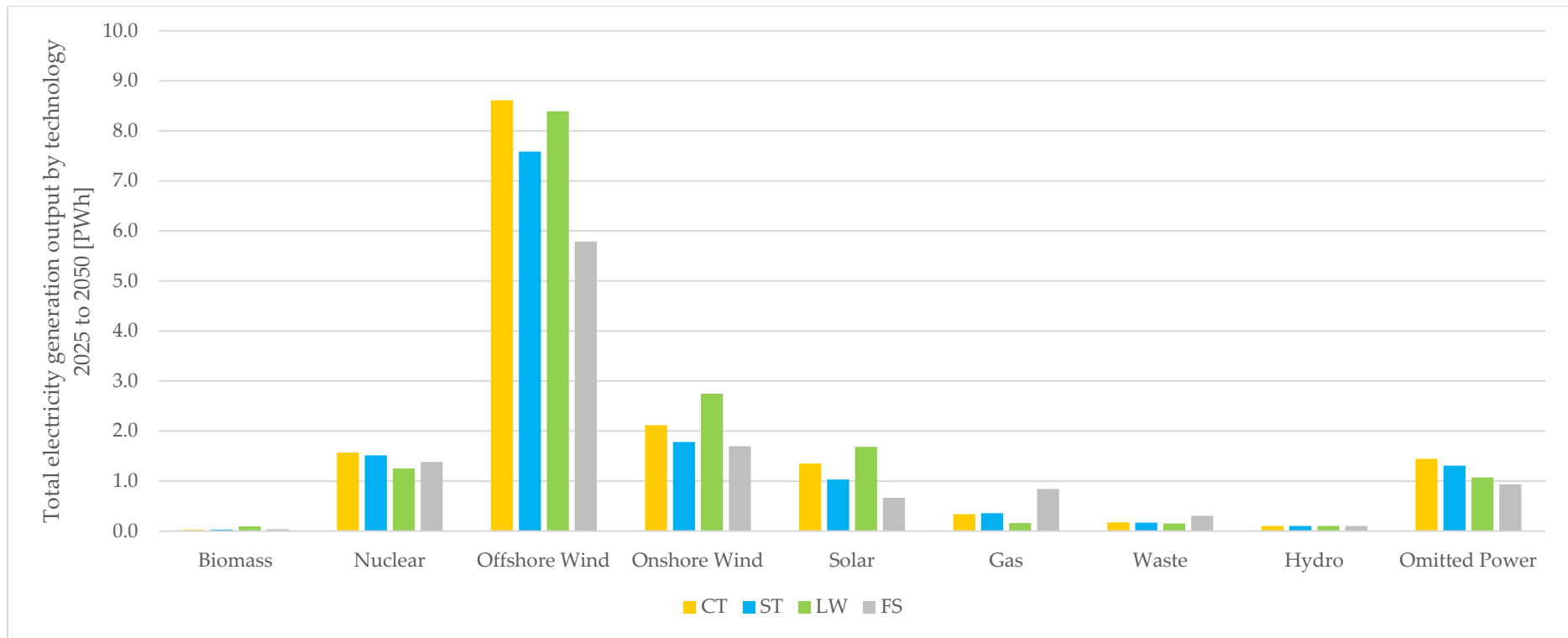


Figure 6.5. Total electricity generation output by technology in the period 2025 to 2050, excluding interconnectors according to FES2022 (ES.E.07). 'Omitted Power' includes BECCS, CCS Gas, Hydrogen and 'Other Renewables' (such as marine).

Table 6.1. Electricity output by technology in TWh in the years 2025 to 2050 (ES.E.07)

FES2022 Generation [PWh]	Unit process (ecoinvent) [162]	CT	ST	LW	FS
<b>Biomass</b>	Electricity, high voltage {GB}   heat and power co-generation, wood chips, 6667 kW, state-of-the-art 2014   Cut-off, U	0.02	0.03	0.09	0.04
<b>Nuclear</b>	Electricity, high voltage {GB}   electricity production, nuclear, pressure water reactor   Cut-off, U	1.57	1.51	1.25	1.38
<b>Offshore Wind</b>	Electricity, high voltage {GB}   electricity production, wind, 1-3MW turbine, offshore   Cut-off, U	8.61	7.58	8.39	5.79
<b>Onshore Wind</b>	Electricity, high voltage {GB}   electricity production, wind, 1-3MW turbine, onshore   Cut-off, U	2.12	1.78	2.74	1.70
<b>Solar</b>	Electricity, low voltage {GB}   electricity production, photovoltaic, 570kWp open ground installation, multi-Si   Cut-off, U	1.35	1.03	1.69	0.67
<b>Gas</b>	Electricity, high voltage {GB}   electricity production, natural gas, combined cycle power plant   Cut-off, U	0.34	0.36	0.16	0.84
<b>Waste</b>	Electricity, for reuse in municipal waste incineration only {GB}   market for   Cut-off, U	0.17	0.17	0.15	0.31
<b>Omitted Power</b>	-	0.10	0.10	0.10	0.10
<b>Total</b>	-	1.45	1.31	1.07	0.93

### 6.3.2. Selecting a suitable model

Lastly then, is to identify a suitable PSM. A review of modelling tools of energy and power systems specifically with large shares of variable renewable energy [204] was expanded on to consider the maturity of open-source energy system optimisation tools [302], finding: Switch, TEMOA, OSeMOSYS, and PyPSA as the top performing options.

- **Switch:** a ‘power system planning model’ which combines features of ESOMs (optimisation) and PSMs (generator unit commitment) [303]. It is primarily America and China focussed with an active research community.
- **Temoa:** an ESOM, designed to enable reproductions of third-party analyses and to handle uncertainty. It is primarily focussed on American territories, with interesting forays into offshore wind and marine energy [304].
- **OSeMOSYS:** an ESOM designed for wide applicability, primarily focussed on the Global South, but comparable to MESSAGE or TIMES [305]
- **Python for Power System Analysis (PyPSA):** also combines PSM and ESOM capability, written to handle variable renewables, storage, and sector-coupling in large networks over long time series [306].
  - **PyPSA-GB:** an open-source dataset and model which was under development at the University of Edinburgh by Dr Andrew Lyden at the same time as this research. PyPSA-GB can represent the GB power generation mix with a temporal resolution of one hour, in energy scenarios up to 2050, *directly* using data from the National Grid FES (without pre-processing).

The requirements from Sections 3.5.4.2 and 3.6.3 are assessed in Table 6.2. PyPSA-GB was selected as the most suitable tool.

Table 6.2. Energy system modelling tools assessed against requirements defined in Section 3.5.4.2 and 3.6.3 of this chapter. 0 = Negative, 1 = Neutral, 2 = Positive. Scores represent qualitative fulfilment of risk mitigation, or known quantities.

Requirement	Switch	TEMOA	OSeMOSYS	PyPSA	PyPSA-GB
Future looking (out to 2050), with ease of use to developing power system input data	0	0	0	1	2
Ideally open-source and tractable on laptop computer	1	1	1	1	1
Multiple technologies, but especially capability to include variable renewable energies, flexibility, and energy storage	1	1	1	1	2
Able to account for hydrogen, transportation, and heating	1	1	1	1	2
Accessible technical support	1	1	1	1	2
Spatial scale: national (GB, not global)	1	1	1	1	1
Temporal scale: hourly	1	0	0	2	2
Able to model (at least) CO <sub>2</sub> emissions	2	2	2	2	2
Adaptable to suit needs of life cycle emissions reduction potential calculations.	1	1	1	1	2
Able to disaggregate emissions spatially and temporally within GB.	1	1	1	1	2
<b>Total</b>	<b>10</b>	<b>9</b>	<b>9</b>	<b>12</b>	<b>18</b>

## 6.4. Conclusion

This chapter has summarised suitable and selected input data and models for assessing the operational impact of floating wind and marine technologies on credible future scenarios of the GB power system.

The next chapter reviews the modifications that would be required to the FES in order to create the 'amended scenarios' that can represent increased deployment of floating wind and marine, such that the attributable avoided emissions can be quantified using the selected model, PyPSA-GB, and the life cycle assessment climate change impact results from Chapter 4 and 5.

# Chapter 7:

## Power generation from wave, tidal stream, floating wind and tidal lagoons in future scenarios around GB

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The previous chapter identified a suitable methodology ('avoided emissions'), input data (FES2022) and modelling tool (PyPSA-GB) to assess this thesis' hypothesis and quantify the emissions reduction potential of floating wind and marine energy in future scenarios around GB. This chapter presents the development of two important datasets which were required to create the 'amended scenarios' which are compared to the FES baseline scenarios to calculate the attributable avoided emissions.

- Profiles of installed capacity for wave and tidal stream in the years 2025, 2030, 2035, 2040, 2045 and 2050 are mapped to discrete geospatial coordinates of potential deployment sites. Three amended scenarios (low, mid and high) are presented, with a simple approach to represent the chronological order of development of sites. This work was published in an associated conference paper [13]. Three scenarios for installed capacity for floating wind for the same period are also presented based on data provided by ORE Catapult (one of the PhD's industrial partners).

- Time series of capacity factor for FES2022 marine (wave power, tidal stream and tidal lagoon) at their respective sites are also presented. For wave energy, capacity factor time series were developed for two device power matrices (publicly available 750 kW Pelamis and confidential 1 MW Blue Horizon) using (historical) ERA5 reanalysis data. For tidal stream a single 2 MW device representative of the Orbital tidal turbine was developed, with tidal stream and tidal lagoon output predicted by the Thetis hydrodynamic model: tidal lagoon capacity factors were provided directly by supporting researchers. Floating wind capacity factors were modelled directly within PyPSA-GB, using the python package Atlite.

The combination of these data provides the detailed *spatial* and *temporal* variation in capacity factors from wave, tidal stream, floating wind and tidal lagoon, and enables linear optimal power flow analyses of FES2022 executed in PyPSA-GB for baseline and amended scenarios, in advance of the emissions computation in Chapter 8.

## 7.1. Introduction

This chapter presents the methodology and results for developing *installed capacity scenarios* and *time-series of capacity factor* for GB-wide wave energy, tidal stream, floating wind and tidal lagoon sites that were required inputs for the power system modelling, building upon the Future Energy Scenarios (FES2022) from National Grid ESO, and executed in PyPSA-GB. This chapter describes in detail the development of data necessary for the operation of PyPSA-GB with FES2022, as well as the data required to investigate the research questions of this thesis. The data gaps for this thesis and PyPSA-GB are introduced below to explain this chapter's structure.

Firstly, considering *installed capacity scenarios* for wave energy, tidal stream, floating wind and tidal lagoon sites across GB from 2025 to 2050: the data developed in this chapter is necessary to i) represent marine energy generation technologies (wave power, tidal stream, tidal lagoon) in the baseline scenarios of FES2022 and ii) execute the 'amended' scenarios to quantify the avoided emissions required to investigate the hypothesis of this work. This data is subdivided into:

1. Interpretations of the 'baseline' National Grid Future Energy Scenarios (FES2022) – for installed capacities of wave energy, tidal stream and tidal lagoon only – which are necessary to execute power flow analyses using FES2022 in PyPSA-GB. These are provided at a resolution of every year from 2025 to 2050.
2. The *amended scenarios* for wave energy, tidal stream, floating wind and tidal lagoon sites, developed using academic and industrial literature. These are provided every five years from 2025 to 2050, with linear interpolation between these years.

The *interpreted* baseline scenarios enable FES0222 and its complement of marine energy to be modelled in PyPSA-GB, while the *amended scenarios* permit quantification of the changes in grid generation attributable to increased installed capacities of these technologies on the GB power system.

Secondly, the methodologies for producing *time series of capacity factors* for the technologies at the respective sites is presented. Time series of capacity factors are required for running any kind of FES2022 hourly dispatch analyses in PyPSA-GB which includes these technologies.

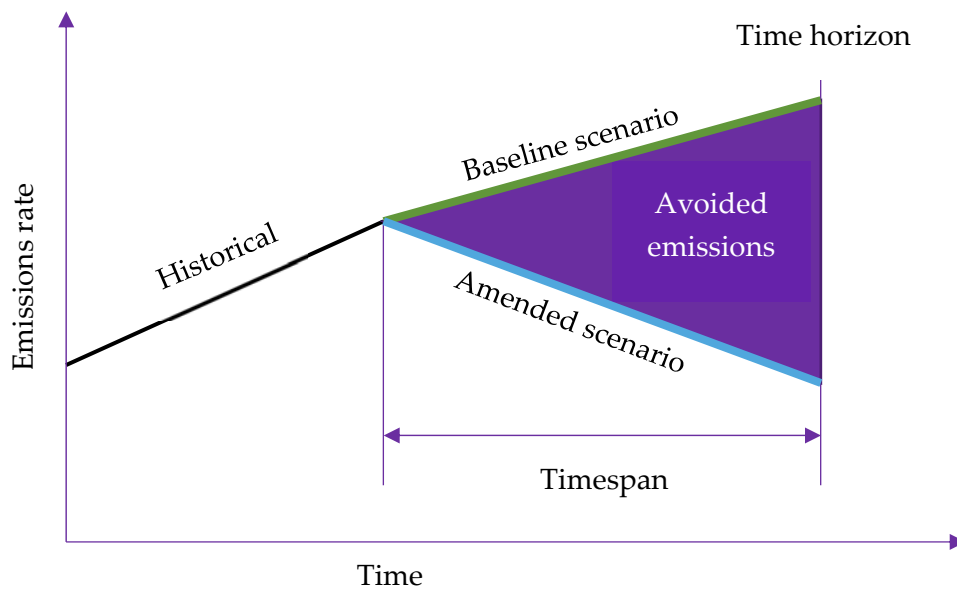


Figure 7.1. Calculation of the avoided emissions attributable to some amendment to a baseline scenario as the difference between the emissions associated with the amended scenario and baseline scenario [297].

### 7.1.1. Processing FES for input to PyPSA-GB

In essence, the development of PyPSA-GB itself was to automatically employ the National Grid Future Energy Scenarios as inputs for an open-source power system model for research at the University of Edinburgh. Elements of the model not described here were developed by the PyPSA-GB team, primarily Dr Andrew Lyden [13].

Some of the datasets described in this chapter were required simply to replicate the FES in PyPSA-GB (Section 7.1.2), but additional datasets were necessary to investigate the research questions of this thesis. The investigation of the research question was predicated on an operational build of PyPSA-GB, so the two tasks were synergistic.

### 7.1.2. Required data for PyPSA-GB

National Grid release the FES every year, however, only FES2022 is discussed here to demonstrate the methodology. The most relevant inputs from FES to PyPSA-GB are:

- The installed capacity of generation (in units MW) *per year per scenario*
- The spatial distribution of installed capacity (by Grid Supply Point, GSP) *per year per scenario*.

For each scenario then, these data therefore comprise *three* dimensions: installed capacity; geographic location and distribution in time (between 2021 and 2050). The subsequent sections describe the FES data in the context of the relevant technologies.

Table 7.1. Status of the four technologies at the time of PyPSA-GB development, within the context of the FES2022 building blocks (BB) and the requirements for data development in PyPSA-GB or for the purpose of this thesis. Scenarios were only interpreted for years 2025, 2030, 2035, 2040, 2045 and 2050. Text in bold indicates data gaps, “I” indicates interpretation required to execute FES2022 in PyPSA-GB, “N” indicates novel development required to answer thesis research objectives.

Considered technology	Relevant FES BB technology	FES BB ID No.	FES installed capacity?	FES spatial breakdown?	Installed capacity profile per year	Time series of capacity factor per site per year;	FES installed capacity per site per year	Thesis deployment scenario installed capacity per site per year	Injection network node per site (assumed constant per year)
Wave energy	“Marine”	Gen_BB017	Yes <b>(Aggregated)</b>	DNO License Area, GSP	<b>Required (I/N)</b>	<b>Required (I/N)</b>	<b>Required (I/N)</b>	<b>Required (I/N)</b>	<b>Required (I/N)</b>
Tidal stream	“Marine”	Gen_BB017	Yes <b>(Aggregated)</b>	DNO License Area, GSP	<b>Required (I/N)</b>	<b>Required (I/N)</b>	<b>Required (I/N)</b>	<b>Required (I/N)</b>	<b>Required (I/N)</b>
Tidal lagoon	“Marine”	Gen_BB017	Yes <b>(Aggregated)</b>	DNO License Area, GSP	<b>Required (I/N)</b>	<b>Required (I/N)</b>	<b>Required (I/N)</b>	<b>Required (I/N)</b>	<b>Required (I/N)</b>
Floating wind	“Offshore wind”	Gen_BB014	<b>Not present</b>	<b>Not present</b>	<b>Required (N)</b>	Computed in PyPSA-GB	<b>Required (N)</b>	<b>Required (N)</b>	<b>Required (N)</b>

### 7.1.3. Marine energy in FES2022

FES2022 includes an allowance for installed capacity of marine energy in units of MW, by GSP and per year (described by FES2022 building block Gen\_BB017). However, a major downside of this data (for the purposes of this thesis) is that the building block does not distinguish between the FES “Technology Detail” of “Tidal Stream, Wave Power and Tidal Lagoon”. It is therefore impossible to definitively determine what the specific dimensions (installed capacity and geographic distribution, each per year) of the discrete technologies of interest are without further information. Significantly, as already emphasised, development of this data is required for PyPSA-GB to represent these technologies accurately in FES2022 informed analyses. This interpretation is resolved in Section 7.2. However, the consequence of inaccuracy is arguably low, as the total installed capacities of Marine energy are always less than 5% of the total installed renewable energy capacity (Figure 7.2). System Transformation (ST) is the scenario with the most Marine energy in 2050, Leading the Way (LW) the least (8.27 GW to 1.10 GW).

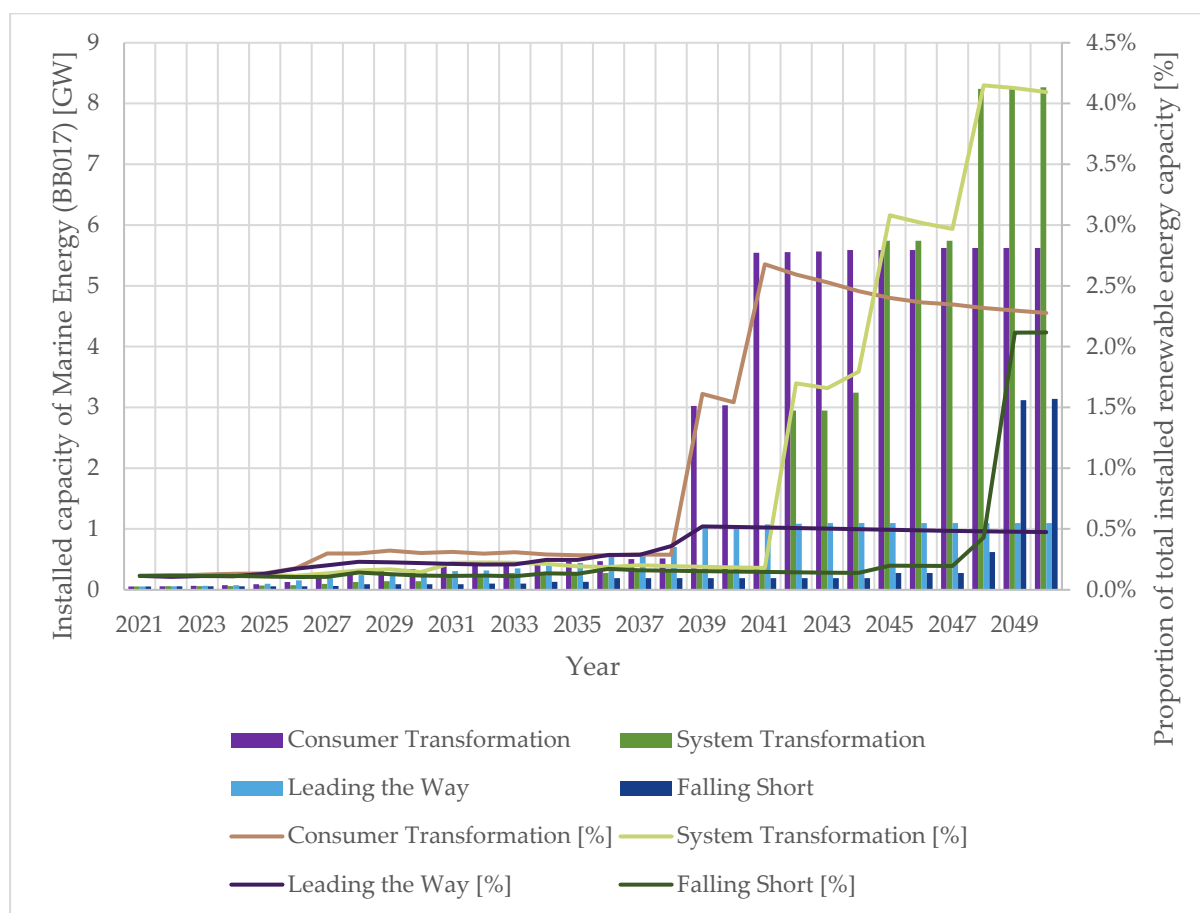


Figure 7.2. Aggregated installed capacity of Marine (Gen\_BB017) in FES2022 (ES.E.24) [301] which includes tidal stream, wave power and tidal lagoon, and proportion of total installed renewable energy capacity.

Table 7.2. Aggregated installed capacity of Marine (Gen\_BB017) in FES2022 [GW]

Total	2025	2030	2035	2040	2045	2050
Consumer Transformation	0.09	0.34	0.46	3.03	5.59	5.62
System Transformation	0.07	0.14	0.27	0.30	5.74	8.27
Leading the Way	0.10	0.29	0.44	1.07	1.10	1.10
Falling Short	0.06	0.09	0.13	0.19	0.28	3.14

#### 7.1.4. Floating wind in FES2022

Offshore wind energy comprises two building blocks within FES2022: Technology Detail “Offshore Wind” (Gen\_BB014) and Technology “Offshore-Wind (off-Grid)” (Gen\_BB024).

However, there is no explicit account of floating wind. Moreover, offshore wind as a proportion of total installed renewable energy capacity is significant; between 45% and 57% across the four FES. To investigate this technology within this thesis, amended scenarios were required to be developed and coded into a branch of PyPSA-GB (Chapter 8). This interpretation is resolved in Section 7.5.

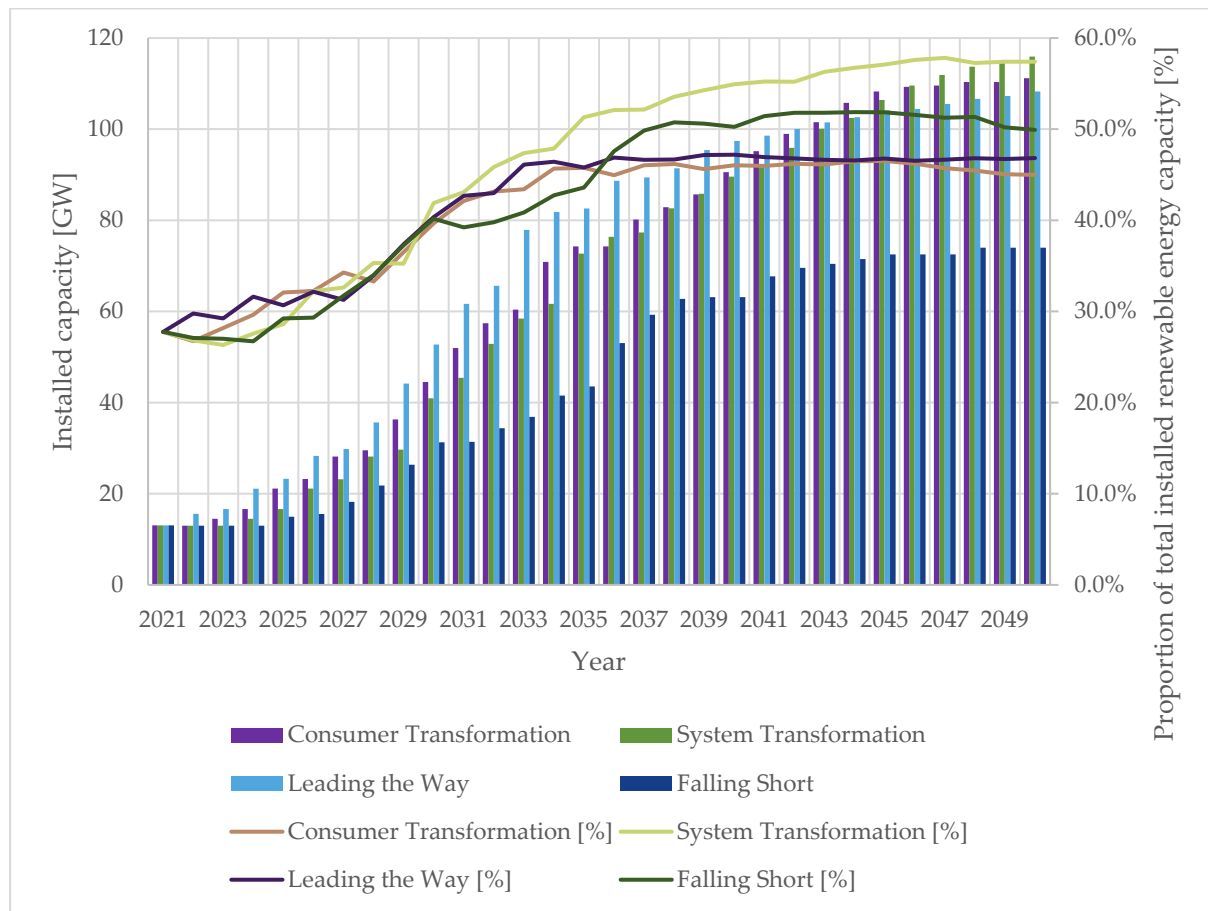


Figure 7.3. Aggregated installed capacity of “Offshore Wind” (Gen\_BB014) and “Offshore-Wind (off-Grid)” (Gen\_BB024) in FES2022 [301].

Table 7.3. Aggregated installed capacity of FES2022 “Offshore Wind” (Gen\_BB014) and “Offshore-Wind (off-Grid)”

(Gen\_BB024) [GW]

Total	2025	2030	2035	2040	2045	2050
Consumer Transformation	21.1	44.5	74.3	90.6	108.3	111.2
System Transformation	16.6	40.9	72.7	89.6	106.4	115.9
Leading the Way	23.3	52.8	82.6	97.4	104.1	108.3
Falling Short	14.9	31.3	43.5	63.1	72.5	74.0

## 7.2. Marine energy locations and capacity

The first step in resolving the installed capacities of marine energy from FES2022 into a suitable form for PyPSA-GB was to develop a consistent set of locations. These locations are introduced and developed in this section.

### 7.2.1. Wave and tidal stream

The scale of deployment of wave and tidal stream technologies in the UK is highly uncertain [123]. In general, potential wave power sites are distributed across the North and West of Scotland and around the South West coasts of Wales and England. Tidal stream sites are highly localised, and are concentrated around the Pentland Firth between mainland of Scotland and the Orkney Isles, as well as the North and West of Scotland, and some Channel Islands [116], [307]. These locations correlate poorly with the existing National Grid transmission system and current centres of load, presenting potential challenges to power system operators. The interaction of the spatial distributions, network capacity and demand centres, have the potential to suppress the utility of wave and tidal stream’s differing temporal profiles. Accordingly, it is important that power system models of future energy scenarios capture both the spatial distribution and temporal variability in power generation so that the

effectiveness of these technologies can be best understood. This section defines the locations of possible wave and tidal stream sites. Section 7.2 presents the interpretation of FES2022 to enable PyPSA-GB to include these technologies. Section 7.3 presents the method for developing capacity factor time series. Section 7.4 presents the future scenarios investigated for this thesis.

The locations and nominal generation capacity of the wave power sites were taken from the UK Marine Energy Database (UKMED) maintained by Renewable UK [308], previously consented sites and recent papers [116]. The spatial resolution was dictated by the renewable energy resource data. For wave energy, as with Chapter 4, the ERA5 data via the website ESOX Lautec was 0.25 degrees.

The tidal sites were similarly derived [307], [308], [309], however it was not possible to use the ERA5 data for current velocities as the spatial resolution was too low (this was previously investigated and assessed as inadequate for a short – unpublished – research project by the author). Dr Athanasios Angeloudis and Dr Daniel Coles agreed to provide velocity data for this work, as they were associated with an adjacent – now published – project [116]. The spatial resolution was not limited by their methods. Table 7.4 and Table 7.5 show the wave energy and tidal stream locations in alphabetical order. Sites with nominal capacity below 10 MW were omitted. For wave energy, Bernera and West of Lewis are same location; treated differently due to different nominal installed capacities that arise from the different sources.

Table 7.4. Wave energy locations.

Site name	Nominal installed capacity [GW]	Contribution to Total	Latitude	Longitude	Basis
Arnol	0.04	2%	58.50	-6.50	Chapter 4
Bernera	0.01	0%	58.50	-7.00	Bernera (58.31, -7.02) [308] – same resource as West of Lewis
Blackstones	0.2	10%	56.00	-7.00	Blackstones (56.05, 7.05) [116]
Brough Head / Birsay	0.2	10%	59.25	-3.25	Chapter 4
Farr Point	0.05	2%	58.75	-4.25	Chapter 4 / Farr Point (58.65, 4.20) [116]
Harris	0.1	5%	57.75	-7.25	EMEC Harris Demonstration Zone (57.87, -7.27) [308]
Maywick	0.1	5%	60.00	-1.50	Chapter 4
Pembrokeshire	0.2	10%	51.75	-5.50	Pembrokeshire (51.85, 5.50) [116]
Pembrokeshire Demonstration Zone	0.18	9%	51.50	-5.00	Wave Hub South Pembrokeshire Demonstration Zone (51.46, -5.13) [308]
Penzance	0.2	10%	50.25	-5.75	Penzance (50.31, -5.80) [116]
Scarweather	0.03	1%	51.50	-4.00	Scarweather (51.43, -3.92) [116]
St Mary's Point	0.2	10%	49.75	-6.50	St Mary's Point (49.82, 6.53) [116]
Tiree	0.1	5%	56.50	-7.25	Tiree (56.47, -7.13) [116]
Wave Hub	0.035	2%	50.25	-5.50	Wave Hub (50.32, -5.43) [308]
West of Hebrides	0.2	10%	57.25	-8.00	West of Hebrides (57.28, -7.90) [116]

Site name	Nominal installed capacity [GW]	Contribution to Total	Latitude	Longitude	Basis
West of Lewis	0.2	10%	58.50	-7.00	West of Lewis [116] – same resource as Bernera
West Orkney / Billia Croo	0.05	2%	59.00	-3.50	Billia Croo [116]
<b>Total</b>	2.095	100%			

Table 7.5. Tidal stream locations.

Site name	Nominal installed capacity [GW]	Contribution to Total	Latitude	Longitude	Basis
Alderney Race	1.4	43%	49.7077	-2.0809	Daniel Coles, personal communication 13/01/22, [309]
Anglesey Skerries	0.01	0%	53.4190	-4.5950	Daniel Coles, personal communication 13/01/22, [309]
Bardsey	0.003	0%	52.7754	-4.7715	Daniel Coles, personal communication 13/01/22, [309]
Brims	0.2	6%	58.7584	-3.2468	Daniel Coles, personal communication 13/01/22, [309]
Brough Ness	0.1	3%	58.7208	-2.9533	Daniel Coles, personal communication 13/01/22, [309]
Islay demo	0.1	3%	55.6741	-6.5701	Daniel Coles, personal communication 13/01/22, [309]
Isle of Man	0.21	6%	54.0400	-4.8469	Daniel Coles, personal communication 13/01/22, [309]
Isle of Wight	0.03	1%	50.5607	-1.3012	Daniel Coles, personal communication 13/01/22, [309]
Kyle Rhea	0.008	0%	57.2405	-5.6561	Daniel Coles, personal communication 13/01/22, [309]
Lashy Sound	0.03	1%	59.2141	-2.7215	Daniel Coles, personal communication 13/01/22, [309]
MeyGen	0.4	12%	58.6576	-3.1286	Daniel Coles, personal communication 13/01/22, [309]
Morlais	0.24	7%	53.3211	-4.7151	Daniel Coles, personal communication 13/01/22, [309]
Mull of Galloway	0.03	1%	54.6154	-4.8383	Daniel Coles, personal communication 13/01/22, [309]
Mull of Kintyre	0.03	1%	55.3002	-5.8449	Daniel Coles, personal communication 13/01/22, [309]
Ness of Duncansby	0.1	3%	58.6628	-3.0477	Daniel Coles, personal communication 13/01/22, [309]
Portland Bill	0.03	1%	50.4861	-2.4398	Daniel Coles, personal communication 13/01/22, [309]

Site name	Nominal installed capacity [GW]	Contribution to Total	Latitude	Longitude	Basis
Sound of Islay	0.01	0%	55.8425	-6.0990	Daniel Coles, personal communication 13/01/22, [309]
St David's head	0.01	0%	51.9021	-5.3289	Daniel Coles, personal communication 13/01/22, [309]
Stronsay Sound	0.1	3%	59.0890	-2.7640	Daniel Coles, personal communication 13/01/22, [309]
West Islay	0.03	1%	55.6557	-6.6082	Daniel Coles, personal communication 13/01/22, [309]
Westray South	0.2	6%	59.1330	-2.8000	Daniel Coles, personal communication 13/01/22, [309]
<b>Total</b>	3.271	100%			

The locations are shown in Figure 7.4 with circles to represent the nominal installed capacity.



Figure 7.4. Location of wave (blue) and tidal (yellow) arrays. The bubble size represents the capacity of in each profile (high, mid or low).

## 7.2.2. Tidal lagoon

Locations, installed capacities and order of construction are based on [103] and personal correspondence with study's author (Table 7.6).

Table 7.6. Tidal lagoon site locations (and order of construction).

Tidal Lagoon site	Maximum installed capacity [GW]	Latitude	Longitude	Order of construction
Cardiff	2.200	51.45	-3.15	1 <sup>st</sup>
Colwyn	1.940	53.33	-3.83	2 <sup>nd</sup>
Swansea	1.840	51.57	-3.98	3 <sup>rd</sup>
Liverpool	1.400	53.45	-3.02	4 <sup>th</sup>
Watchet	2.220	51.21	-3.13	5 <sup>th</sup>
Blackpool	1.960	54.03	-3.19	6 <sup>th</sup>
Solway	1.820	54.87	-4.4	7 <sup>th</sup>

As described in Table 7.1, interpretation is required to disaggregate the FES2022 Marine building blocks. National Grid were approached to disaggregate this data but could not reveal assumptions, stating [310]:

*“Tidal range and Wave are quite small capacities, with things such as Tidal lagoons being quite large capacities”*

To resolve this for PyPSA-GB, further locational data was required. In FES2022, installed capacities of each ‘building block’ are provided for each grid supply point (GSP). To disaggregate the technologies then, each GSP was inspected and a judgement made on the most likely proximal technology (Table 7.7). For every GSP then, a single technology was assumed, and the installed capacity for each technology could be determined across all GSPs.

Table 7.7. Interpreted locations of Marine energy from FES2022. Proximal locations are based on grid coordinates.

DNO License Area	GSP	Latitude	Longitude	Assumed location	Assumed network	Proximal location technology	Proximal site with largest capacity
NGET	Direct(NGET)	Not present	Not present	England/Wales	Transmission	Tidal lagoon	Tidal lagoons according to build order
SHETL	Direct(SHETL)	Not present	Not present	North Scotland	Transmission	Tidal stream	[10] (MeyGen)
SPTL	Direct(SPTL)	Not present	Not present	South Scotland	Transmission	Tidal lagoon	[103] (Solway)
SHEPD	Port Ann	56.026	-5.350	West coast Scotland	Distribution	Tidal stream	[10] (Sound of Islay)
South Western	Alverdiscott	51.006	-4.137	South west England	Distribution	Wave energy	[10] (Scarweather)
SEPD	Chickerell	50.624	-2.489	South England	Distribution	Tidal stream	[10] (Portland Bill)
NPgY	Elland	53.695	-1.823	Midlands	Distribution	Tidal lagoon	[103] (Liverpool)
SEPD	Fawley	50.821	-1.330	South England	Distribution	Tidal stream	[10] (Isle of Wight)
SHEPD	Lairg	58.008	-4.395	North Scotland	Distribution	Wave energy	[10] (Farr Point)
SEPD	Melksham	51.392	-2.150	South west England	Distribution	Tidal lagoon	[103] (Cardiff)
South Wales	Pembroke	51.682	-4.987	South Wales	Distribution	Wave energy	[10] (PDZ)
South Western	Taunton	51.017	-3.153	South west England	Distribution	Tidal lagoon	[103] (Watchet)
SHEPD	Thurso	58.572	-3.509	North coast Scotland	Distribution	Tidal stream	[10] (Brims)
SPM	Wylfa	53.414	-4.482	North Wales	Distribution	Tidal stream	[10] (Anglesey Skerries)

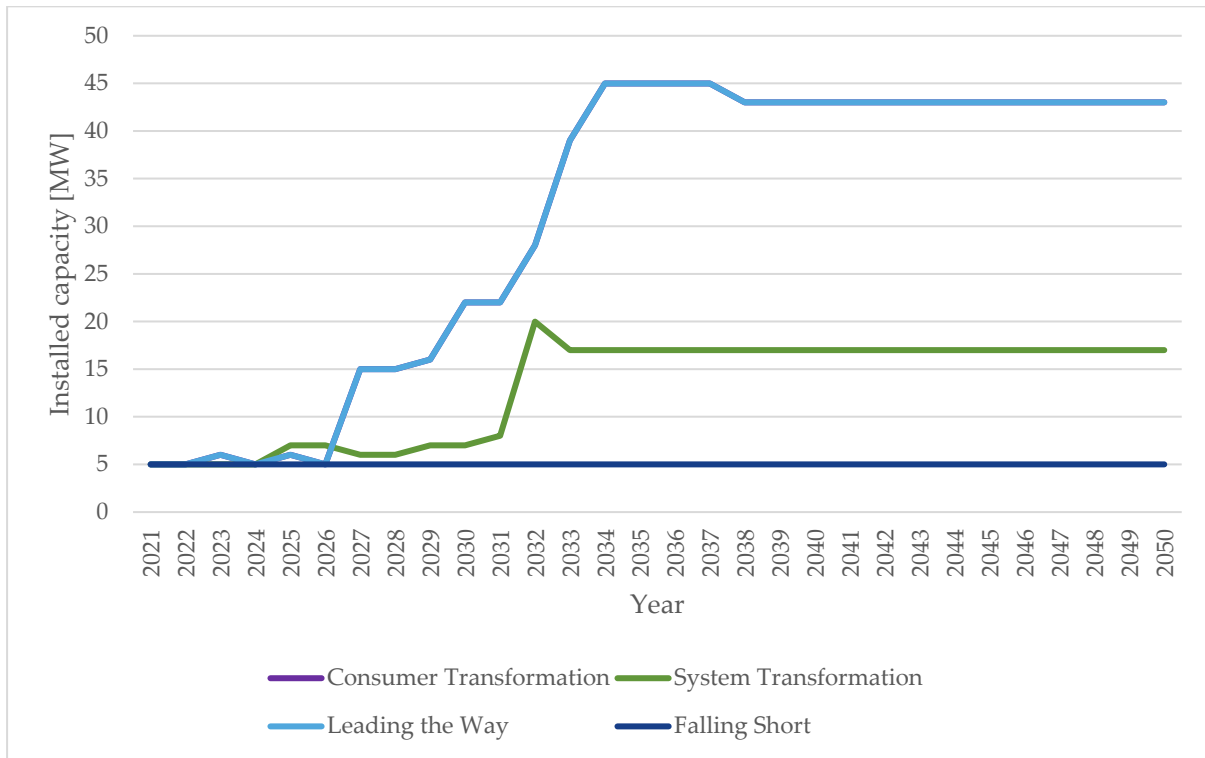


Figure 7.5. Variation in installed capacity between FES2022; wave energy.

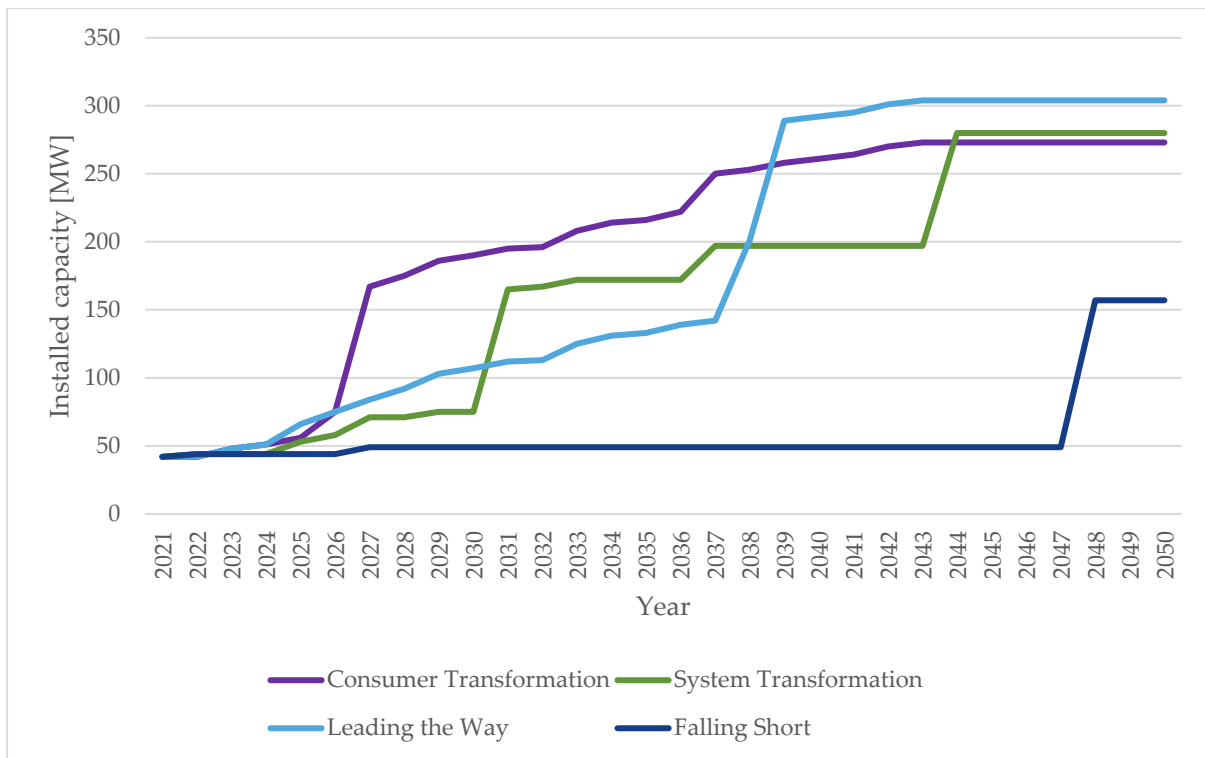


Figure 7.6. Variation in installed capacity between FES2022; tidal stream

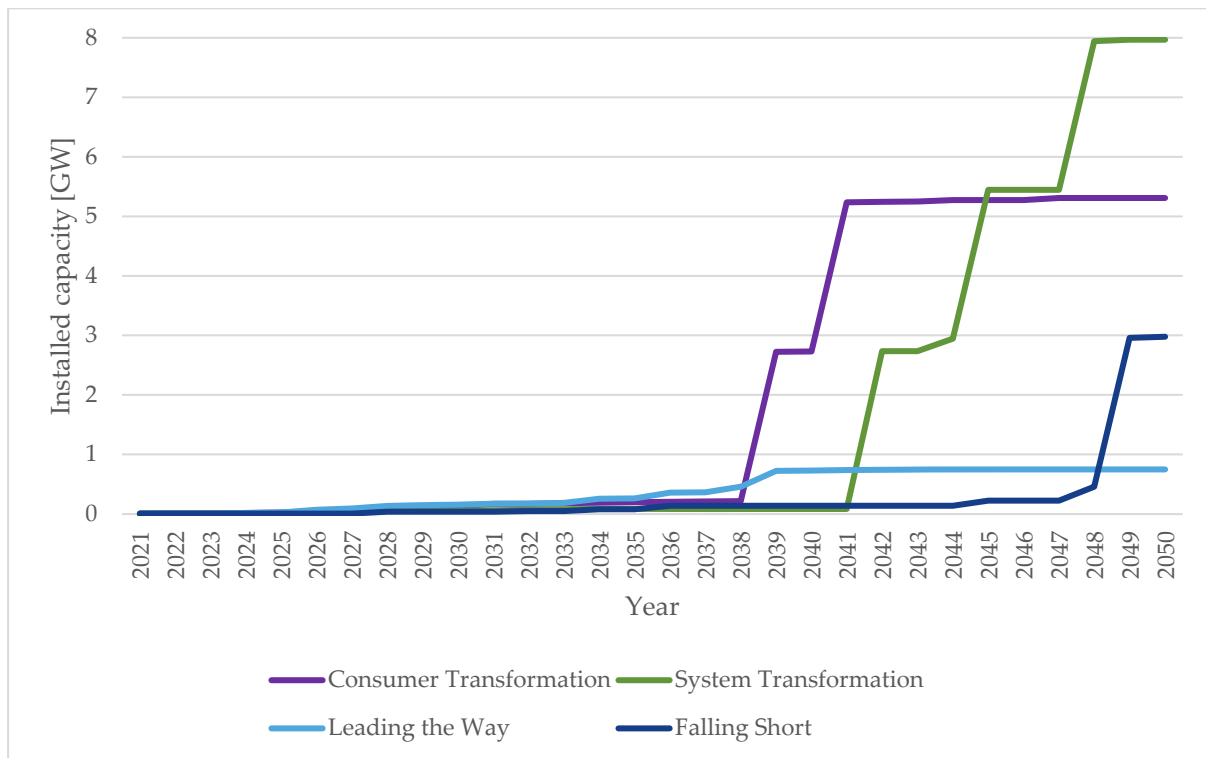


Figure 7.7. Variation in installed capacity between FES2022; tidal lagoon.

### 7.2.3. Interpreting locations by Grid Supply Point

For the total installed capacity to be applied to a spatially distributed network in PyPSA-GB, the installed capacity of the relevant technology at each GSP was assumed to be fulfilled by the nearest site. For example, all installed capacity at the ‘Port Ann’ GSP in each year was assumed to be fulfilled by the ‘Sound of Islay’ tidal stream site.

For tidal lagoon (with only one GSP identified) the build order was used to determine the site at which the installed capacity was located in each scenario; this was repeated until the maximum capacity of the site was reached, and then the next site in the build order was used. These interpretations of FES2022 allow the installed capacities of wave energy, tidal stream and tidal lagoon to be included as generators in a power system [13]. However, additional scenarios are required to fully explore the potential impact of wave and tidal stream: these are

developed in Section 7.4. The next section develops the capacity factor time series necessary for the power flow calculations in PyPSA-GB.

Figure 7.8. Installed capacity of wave energy per year in Consumer Transformation (CT) (and leading the Way, LW) in the years 2025 to 2050.

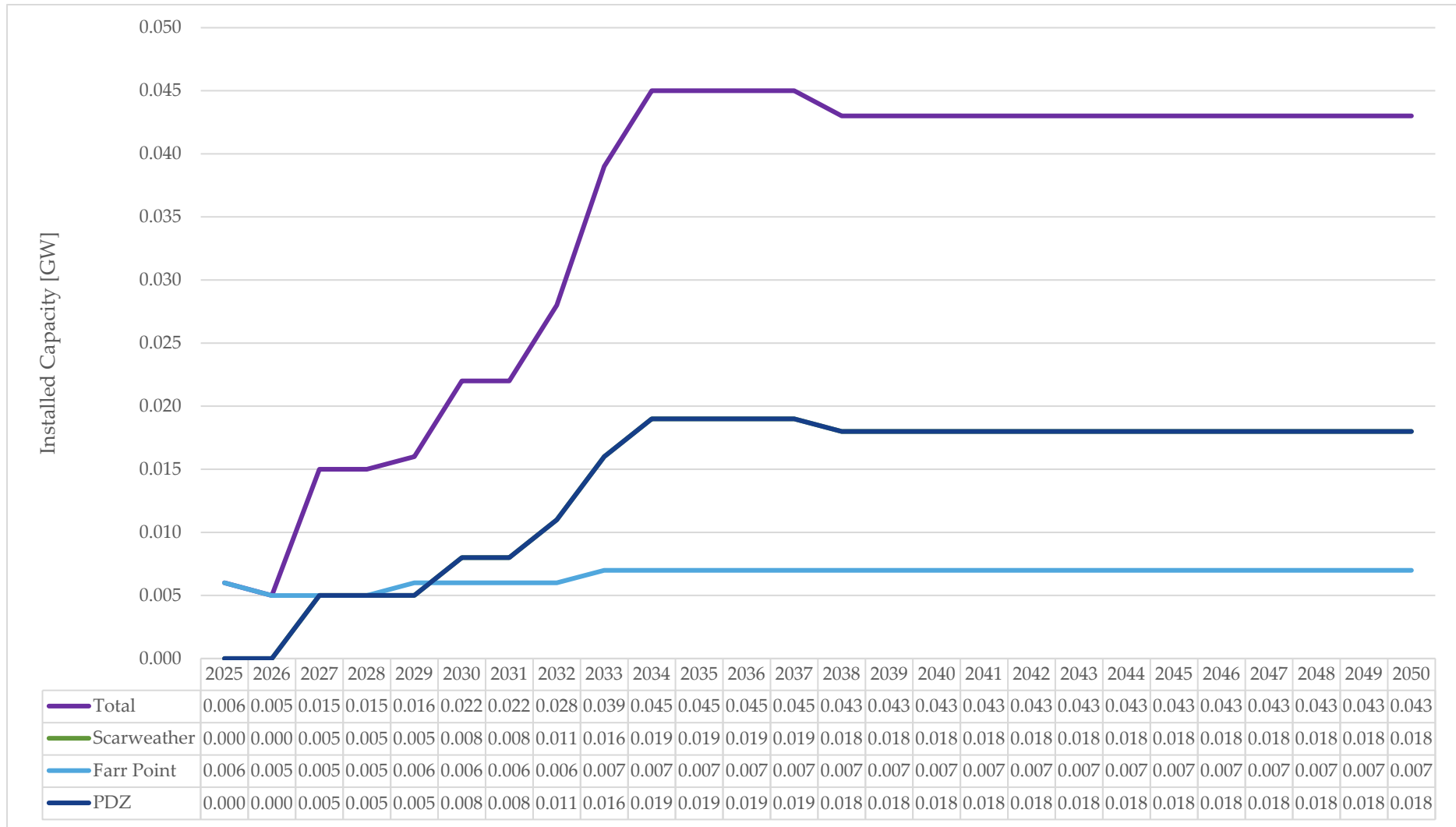


Figure 7.9. Installed capacity of wave energy per year in System Transformation (ST) in the years 2025 to 2050.

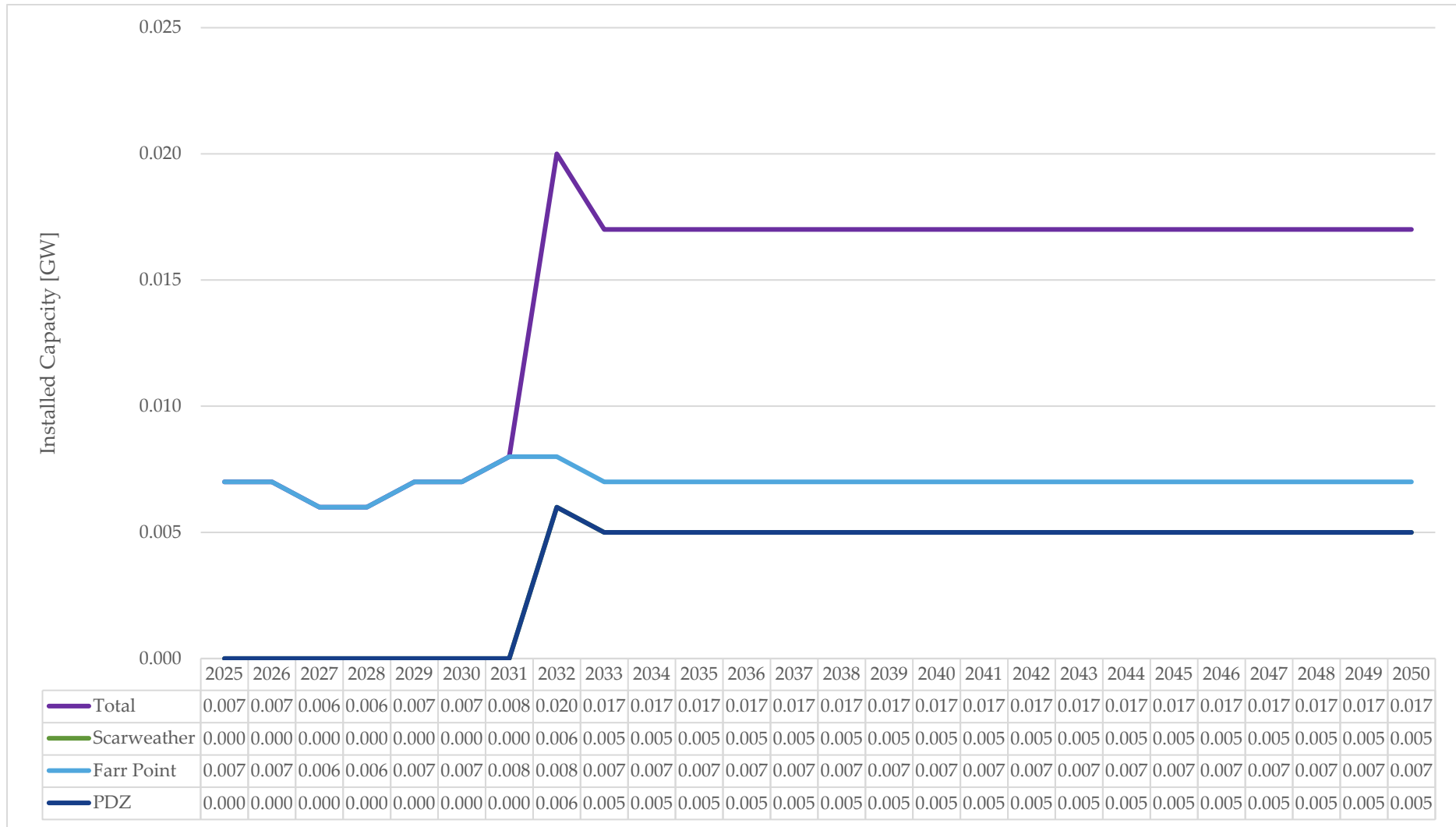


Figure 7.10. Installed capacity of wave energy per year in Falling Short (FS) in the years 2025 to 2050.

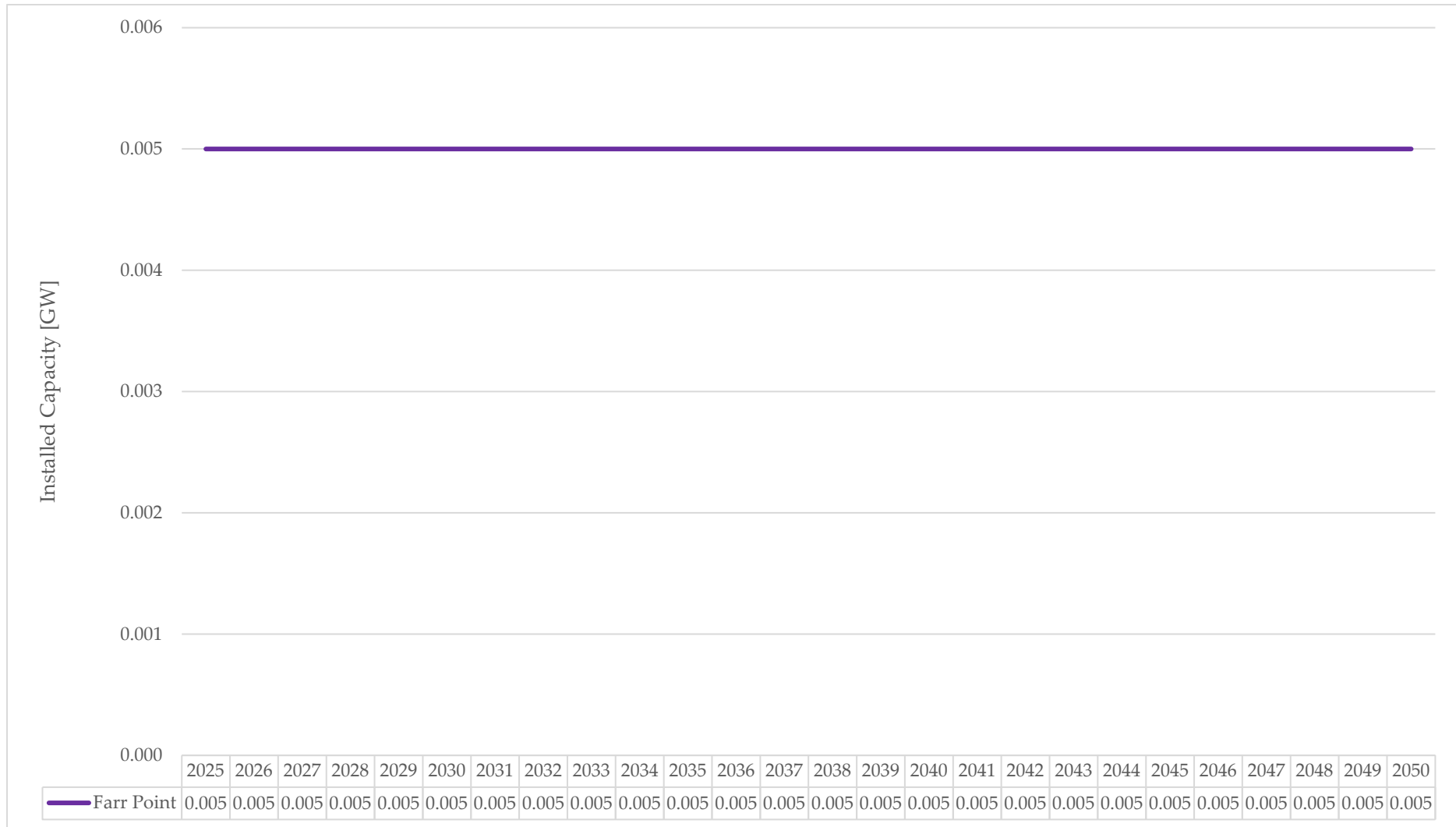


Figure 7.11. Installed capacity of tidal stream per year in Consumer Transformation (CT) in the years 2025 to 2050.

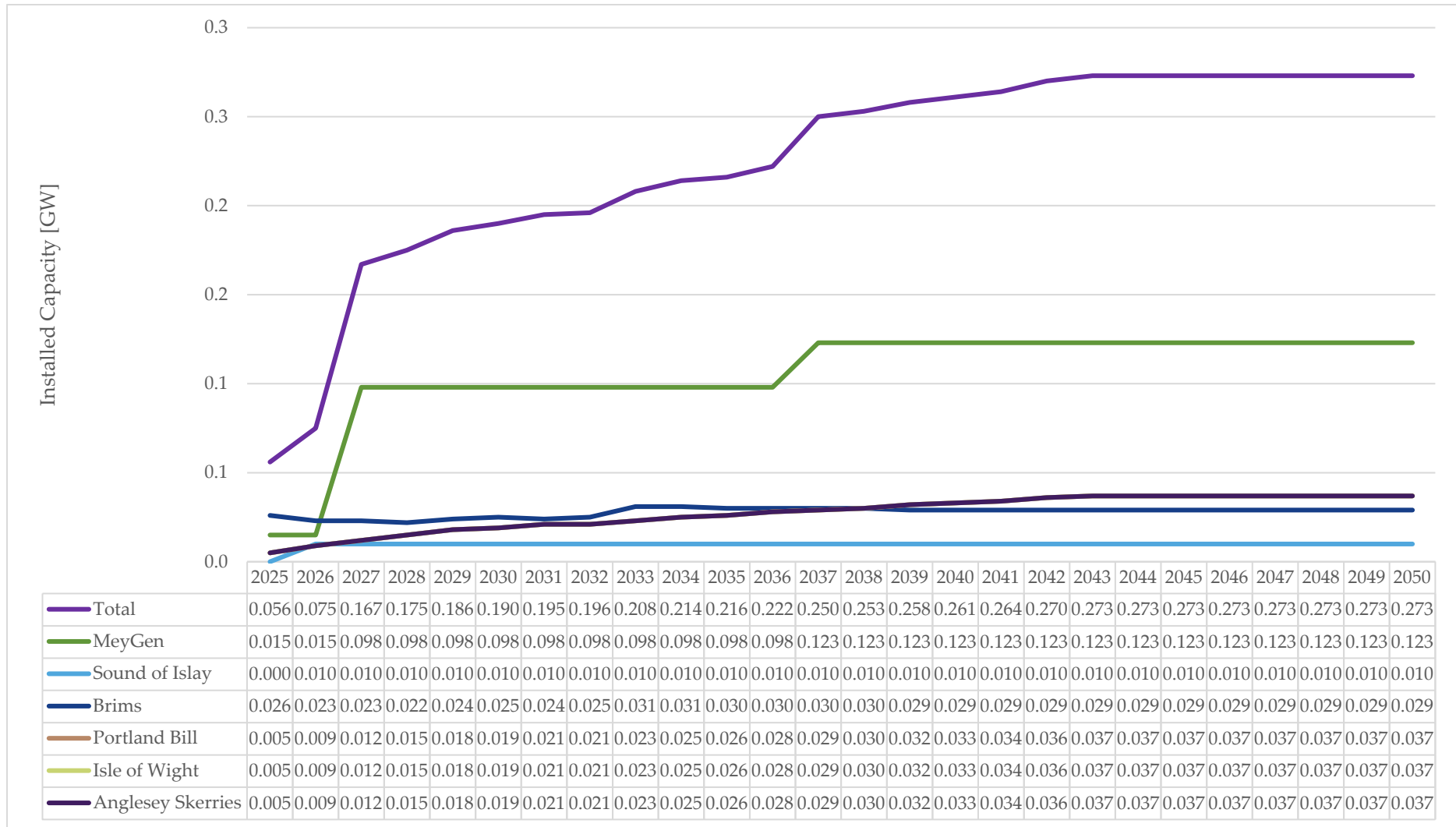


Figure 7.12. Installed capacity of tidal stream per year in System Transformation (ST) in the years 2025 to 2050.

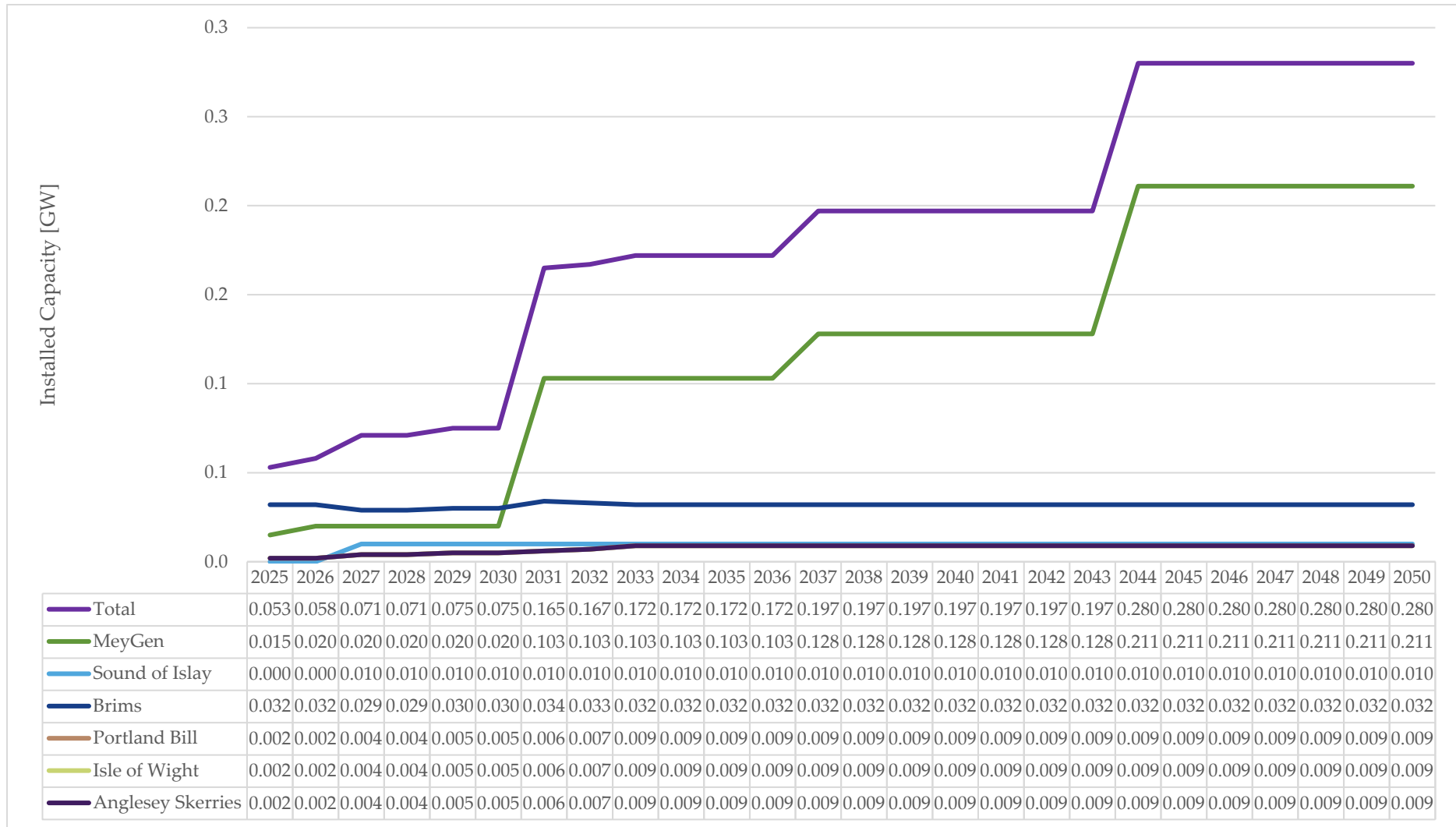


Figure 7.13. Installed capacity of tidal stream per year in Leading the Way (LW) in the years 2025 to 2050.

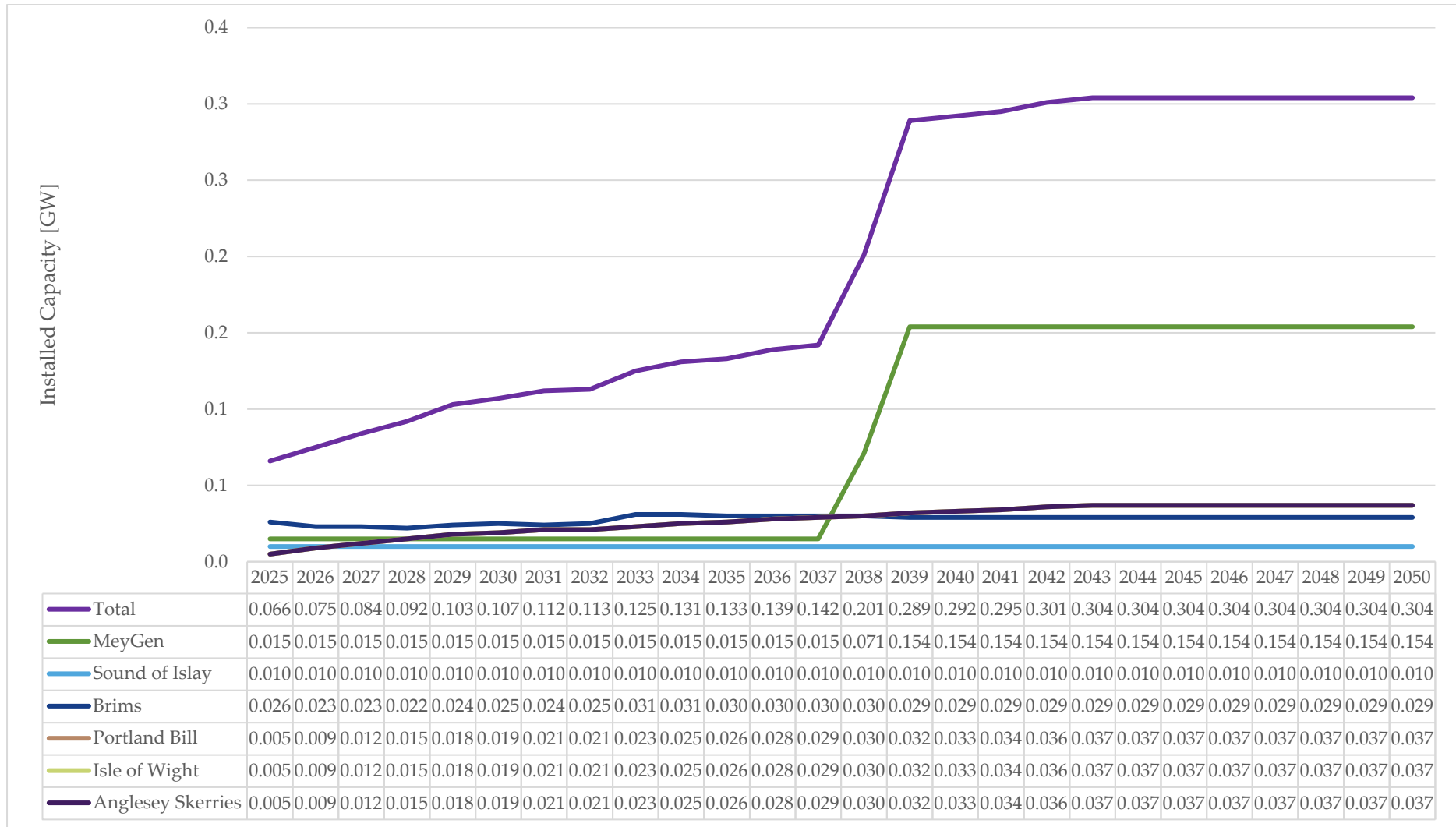


Figure 7.14. Installed capacity of tidal stream per year in Falling Short (FS) in the years 2025 to 2050.

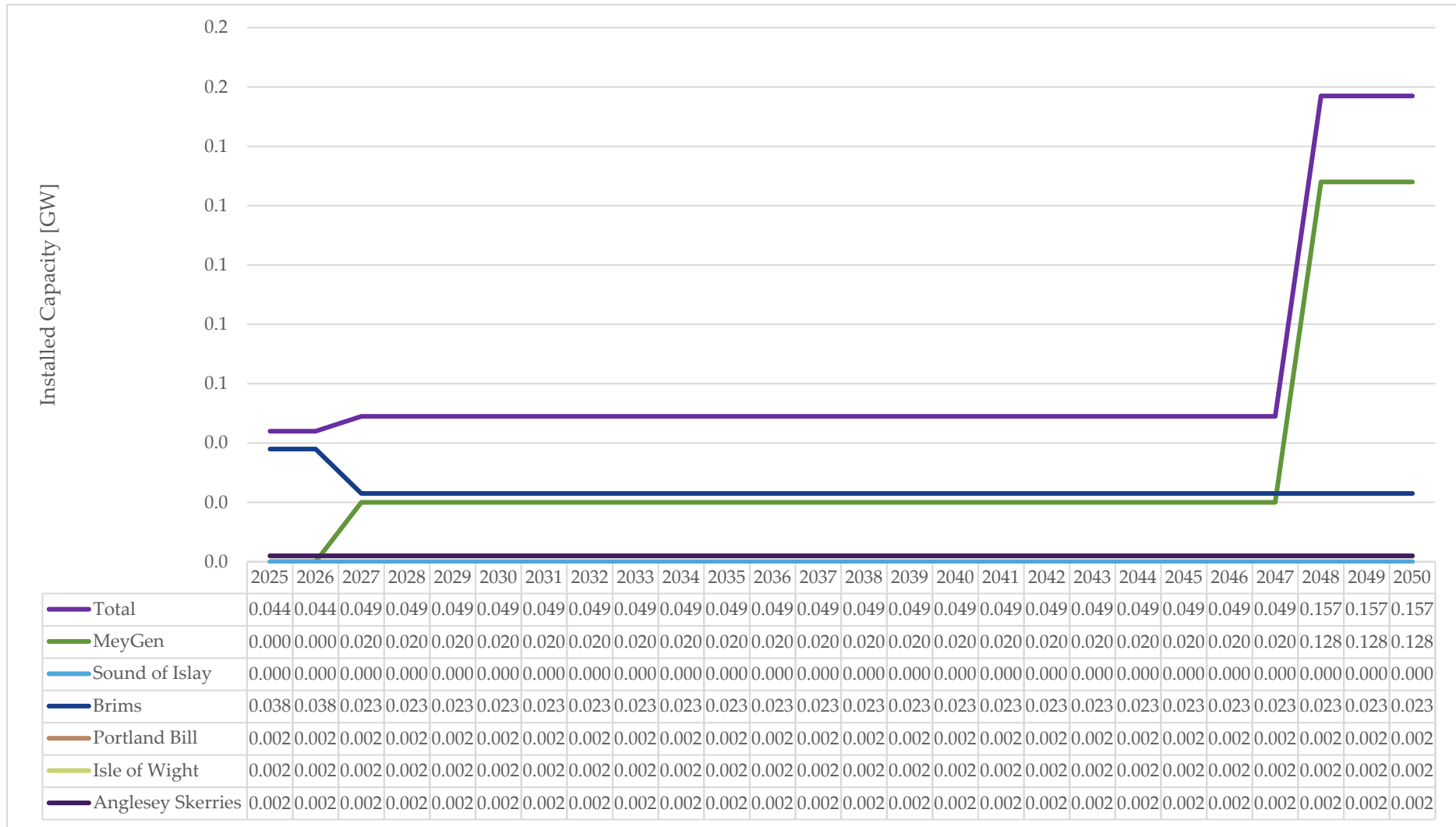


Figure 7.15. Installed capacity of tidal lagoon per year in Consumer Transformation (CT) in the years 2025 to 2050.

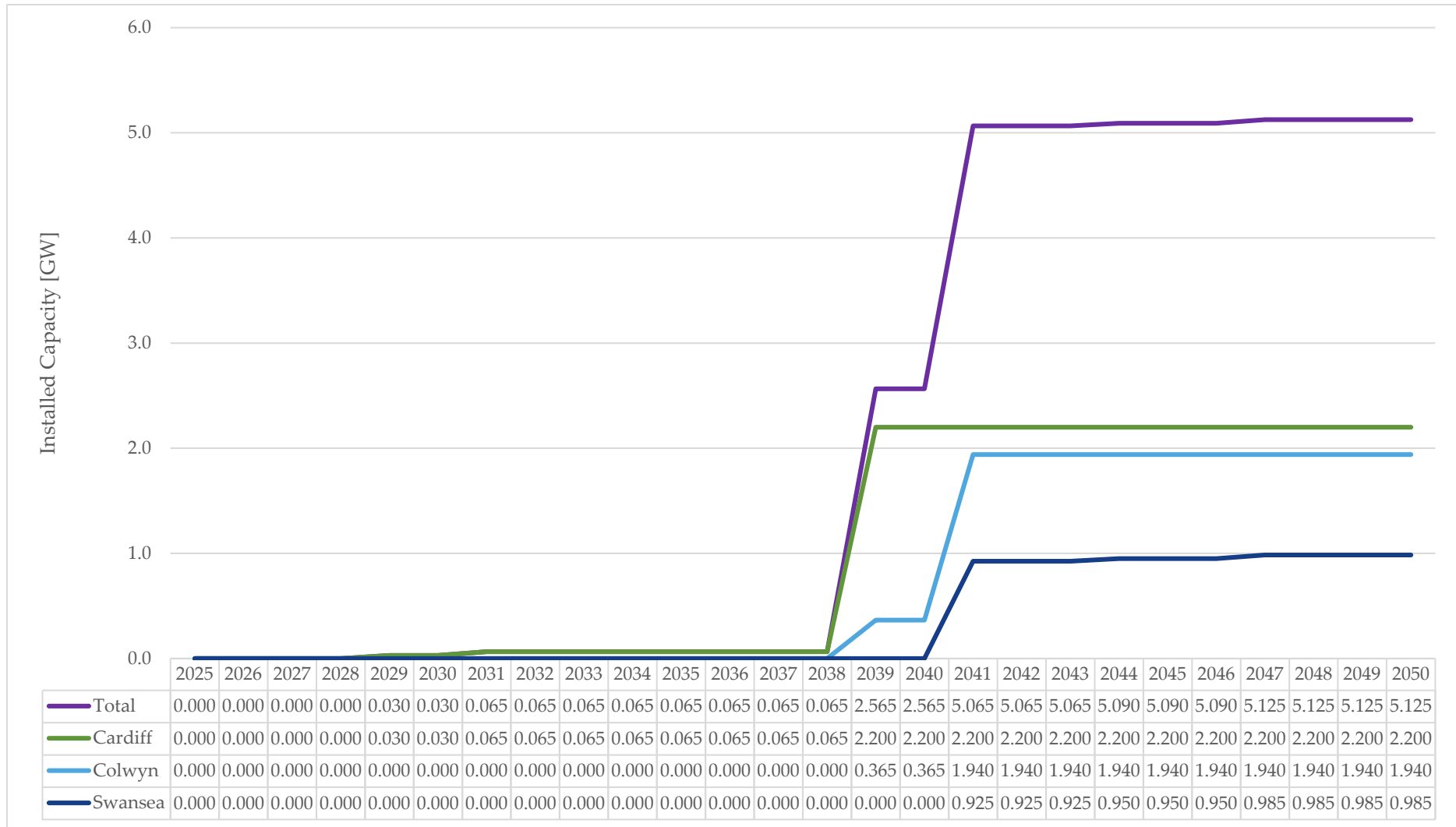


Figure 7.16. Installed capacity of tidal lagoon per year in System Transformation (ST) in the years 2025 to 2050.

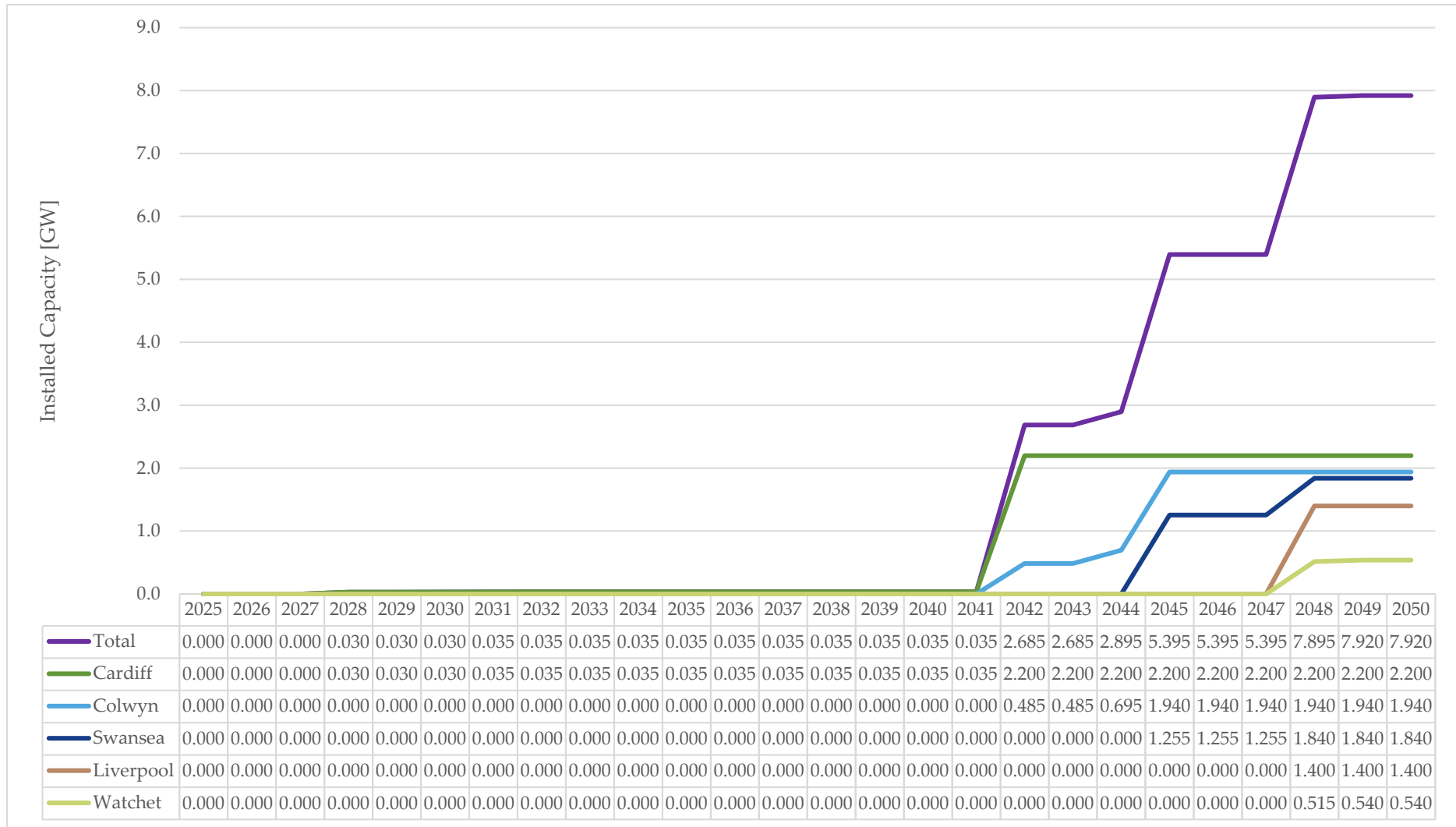


Figure 7.17. Installed capacity of tidal lagoon per year in Leading the Way (LW) in the years 2025 to 2050.

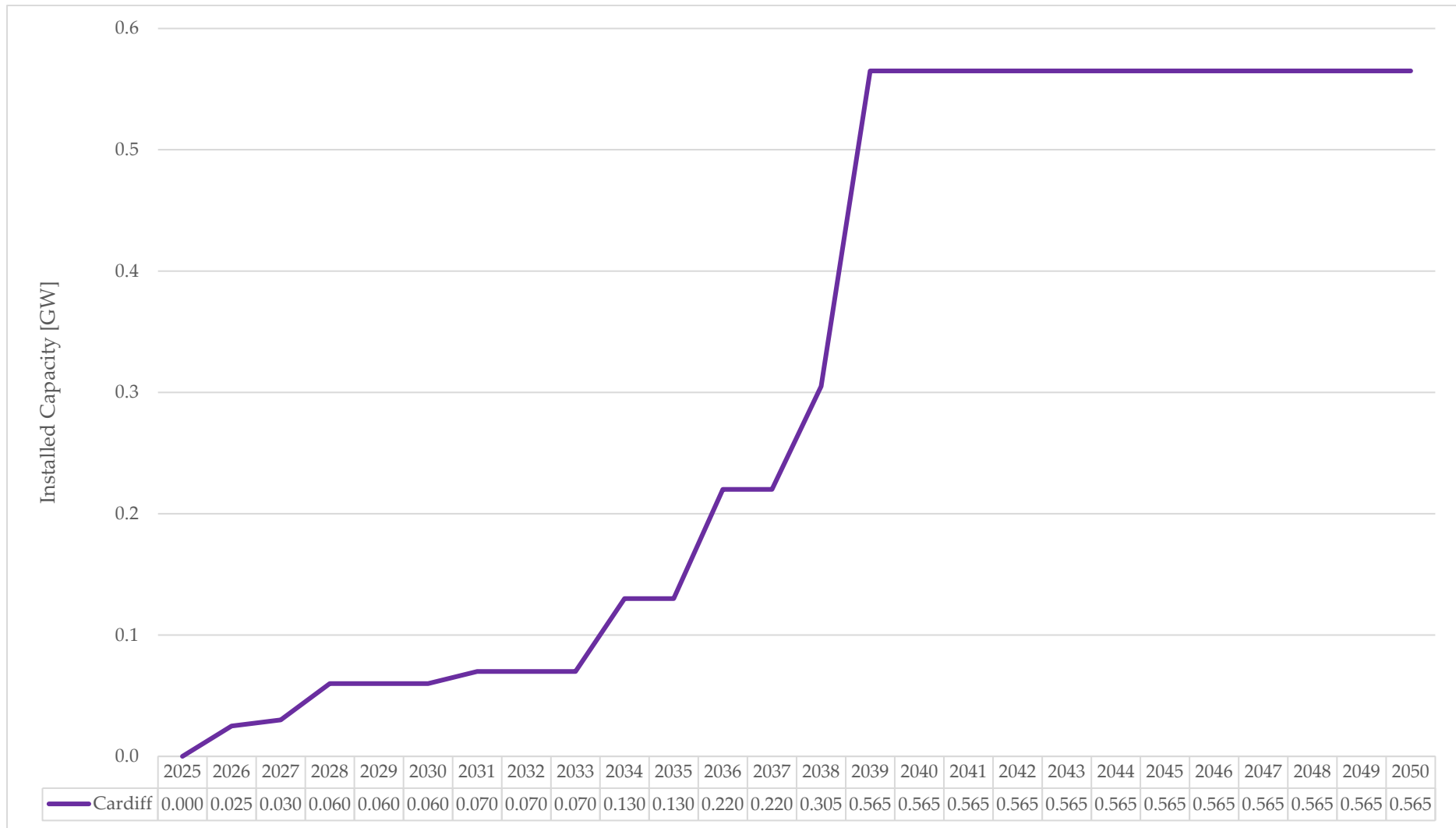
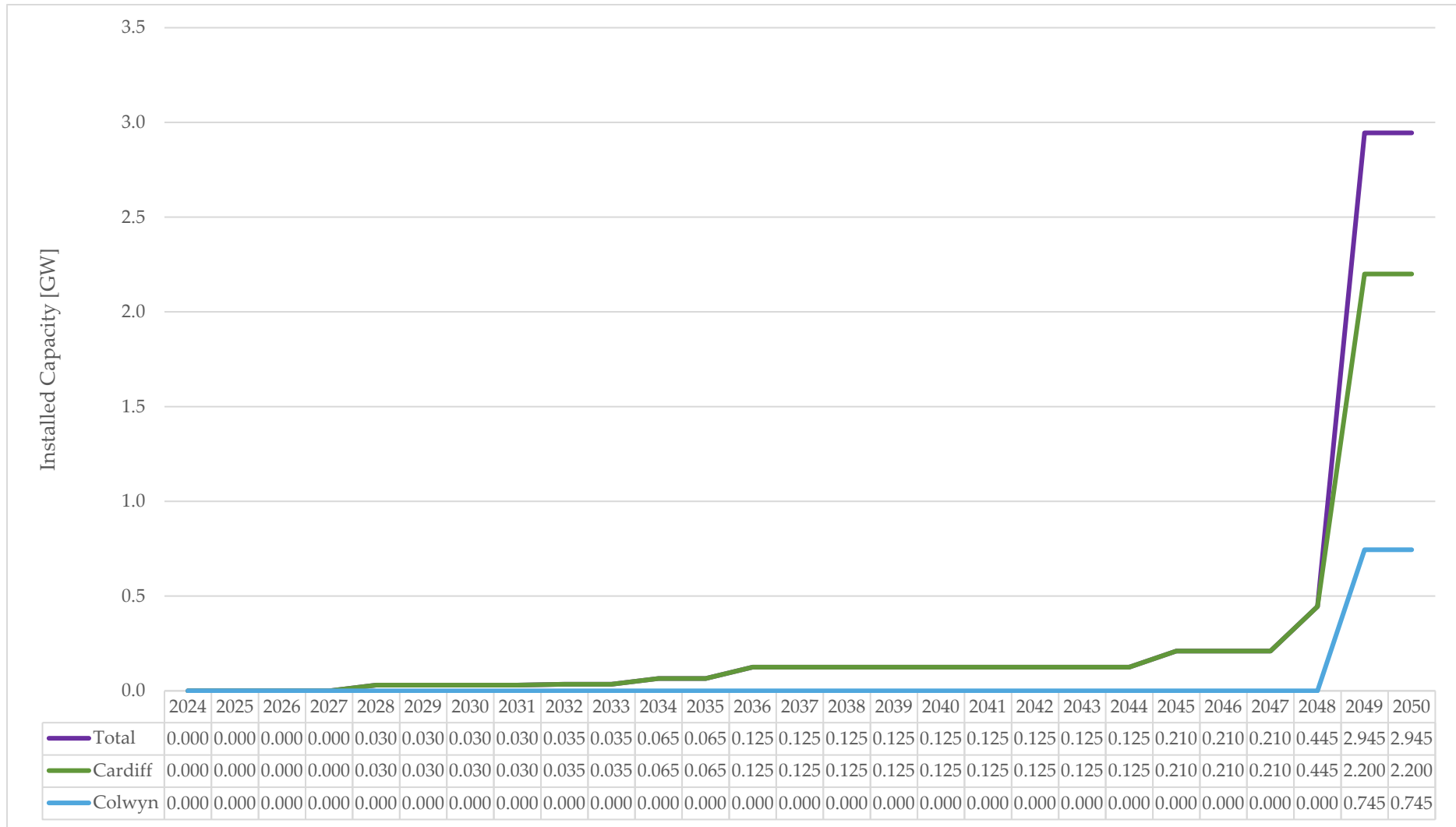


Figure 7.18. Installed capacity of tidal lagoon per year in Falling Short (FS) in the years 2025 to 2050.



### 7.3. Time series of capacity factor for each marine energy location

Now that the locations of the possible arrays have been defined, it was necessary to determine the capacity factor. Capacity factor is the ratio of the actual electrical energy generation over a known period of time to the theoretical maximum electrical energy generation over the same period. This is helpful because it allows the power delivery of a site to be determined, regardless of the installed capacity which (as shown by previous section) varies between scenarios. To determine the capacity factor of a technology at a particular site, renewable resource had to be transformed by the power characteristics (power matrix or power curve) of the technology at that site. For compatibility with PyPSA-GB, the renewable resource had to be hourly resolution, suitable spatial resolution and coverage of multiple years. This section describes this process for each technology.

#### 7.3.1. Wave energy

##### 7.3.1.1. Renewable resource data

Predicting wave climate at these time horizons is infeasible, so historical reanalysis data was used to determine the capacity factor. To be consistent with earlier chapters, ESOX Map [17], was used to quickly download the reanalysis data for the wave sites at hourly resolution, with a thirty year temporal coverage from 01/01/1990 to 31/12/2019.

##### 7.3.1.2. Site energy resource and order of construction

The order of construction was also necessary to approximate a realistic roll out of installed capacity. This was based on site average power, as a first approximate of LCOE, on the basis that cheaper (higher power sites) would be constructed first. The order of construction was

set equal to the ranking of peak power potential per unit width of wave front, averaged over the thirty years according to the equation [241]:

$$P = \frac{\rho g^2}{64\pi} H_s^2 T_e = 0.491 H_s^2 T_e \cong 0.5 H_s^2 T_e \quad \text{Equation 4}$$

While Bernera and West of Lewis are ostensibly the same location, this distinction was retained given the large difference in installed capacity, and the larger site (West of Lewis) was set to be constructed after Bernera on the basis of a “demo site” approach.

Table 7.8. Construction order of wave energy sites.

Site (Abbreviation)	Nominal installed capacity [MW]	Average power [kW/m]	Construction order
West of Hebrides (Wes-Heb)	200	63.9	1 <sup>st</sup>
Bernera (Ber)	10	48.2	2 <sup>nd</sup>
West of Lewis (Wes-Lew)	200	48.2	3 <sup>rd</sup>
Tiree (Tir)	100	47.8	4 <sup>th</sup>
Farr Point (Far-Poi)	50	46.9	5 <sup>th</sup>
Blackstones (Bla)	200	45.9	6 <sup>th</sup>
St Mary's Point (St-Mar)	200	42.5	7 <sup>th</sup>
Brough Head (Bro)	200	41.6	8 <sup>th</sup>
West Orkney / Billia Croo (Wes-Ork)	50	40.0	9 <sup>th</sup>
Arnol (Arn)	40	39.7	10 <sup>th</sup>
Penzance (Pen)	200	29.2	11 <sup>th</sup>
Maywick (May)	100	28.8	12 <sup>th</sup>
Harris (Har)	100	26.9	13 <sup>th</sup>
Wave Hub Wav-Hub)	35	26.3	14 <sup>th</sup>
Pembrokeshire Demonstration Zone (Pemb-Dem)	180	18.0	15 <sup>th</sup>
Pembrokeshire (Pem)	200	17.4	16 <sup>th</sup>
Scarweather (Sca)	30	8.4	17 <sup>th</sup>

7.3.1.3. Pelamis

The power matrix for the Pelamis 750 kW wave energy converter was used [241] showing production at different combinations of significant wave height ( $H_s$ ) and peak wave period ( $T_p$ ). The power matrix was transformed from terms of energy period ( $T_e$ ) to peak period ( $T_p$ ) using a ratio  $T_e/T_p = 0.884$ , calculated from a JONSWAP spectrum with a peak enhancement factor of 2, representative of a North Sea wave climate [311]. Table 7.9 shows the resulting power matrix. These were made available for PyPSA-GB use due to their public availability.

Table 7.9. Power matrix of the Pelamis WEC in terms of significant wave height ( $H_s$ , in m) and peak wave period ( $T_p$ , in s).

$H_s/T_p$	5.66	6.22	6.79	7.35	7.92	8.48	9.05	9.61	10.18	10.75	11.31	11.88	12.44	13.01	13.57	14.14	14.70
0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
1	0	22	29	34	37	38	38	37	35	32	29	26	23	21	0	0	0
1.5	32	50	65	76	83	86	86	83	78	72	65	59	53	21	42	37	33
2	57	88	115	136	148	153	152	147	138	127	116	104	93	47	74	66	59
2.5	89	198	180	212	231	238	238	230	216	199	181	163	146	83	116	103	92
3	129	270	260	305	332	340	332	315	292	266	240	219	210	130	167	149	132
3.5	0	0	354	415	438	440	424	404	377	362	326	292	260	188	215	202	180
4	0	0	462	502	540	546	530	499	475	429	384	366	339	230	267	237	213
4.5	0	0	544	635	642	648	628	590	562	528	473	432	382	301	338	300	266
5	0	0	0	739	726	731	707	687	670	607	557	521	472	356	369	348	328
5.5	0	0	0	750	750	750	750	750	667	667	658	586	530	417	446	395	355
6	0	0	0	0	750	750	750	750	750	750	711	633	619	496	512	470	415
6.5	0	0	0	0	750	750	750	750	750	750	750	743	658	558	579	512	481
7	0	0	0	0	0	750	750	750	750	750	750	750	750	621	613	584	525
7.5	0	0	0	0	0	0	750	750	750	750	750	750	750	676	686	622	593
8	0	0	0	0	0	0	0	750	750	750	750	750	750	750	750	690	625

#### 7.3.1.4. Blue Horizon

The power matrix for this device cannot be published in accordance with the non-disclosure agreement between the author, the University of Edinburgh and Mocean Energy. It was provided in terms of  $H_s$  and  $T_p$  so no modification was required.

#### 7.3.1.5. Results

Figure 7.19 to Figure 7.22 show the variation in annually averaged capacity factor for the wave energy sites using the modified Pelamis power matrix. Overall, the capacity factors were lower for Blue Horizon (with a sample time series comparing both machines in Figure 7.23), suggesting that the current power matrix is not optimised for maximum energy generation in the incident sea states. However, the larger device rated power means that fewer machines will be deployed for a given installed capacity, and on average will generate more energy than the Pelamis per MW installed. At a high level, over the period 1990 to 2019 there are no obvious climate change trends to be discerned, and variability is not notably different between sites; although North Western Scottish sites (Western Hebrides, Farr Point, West of Lewis and Bernera) stand out as high energy sites, and Scarborough as a far lower energy site when capacity factor is considered.

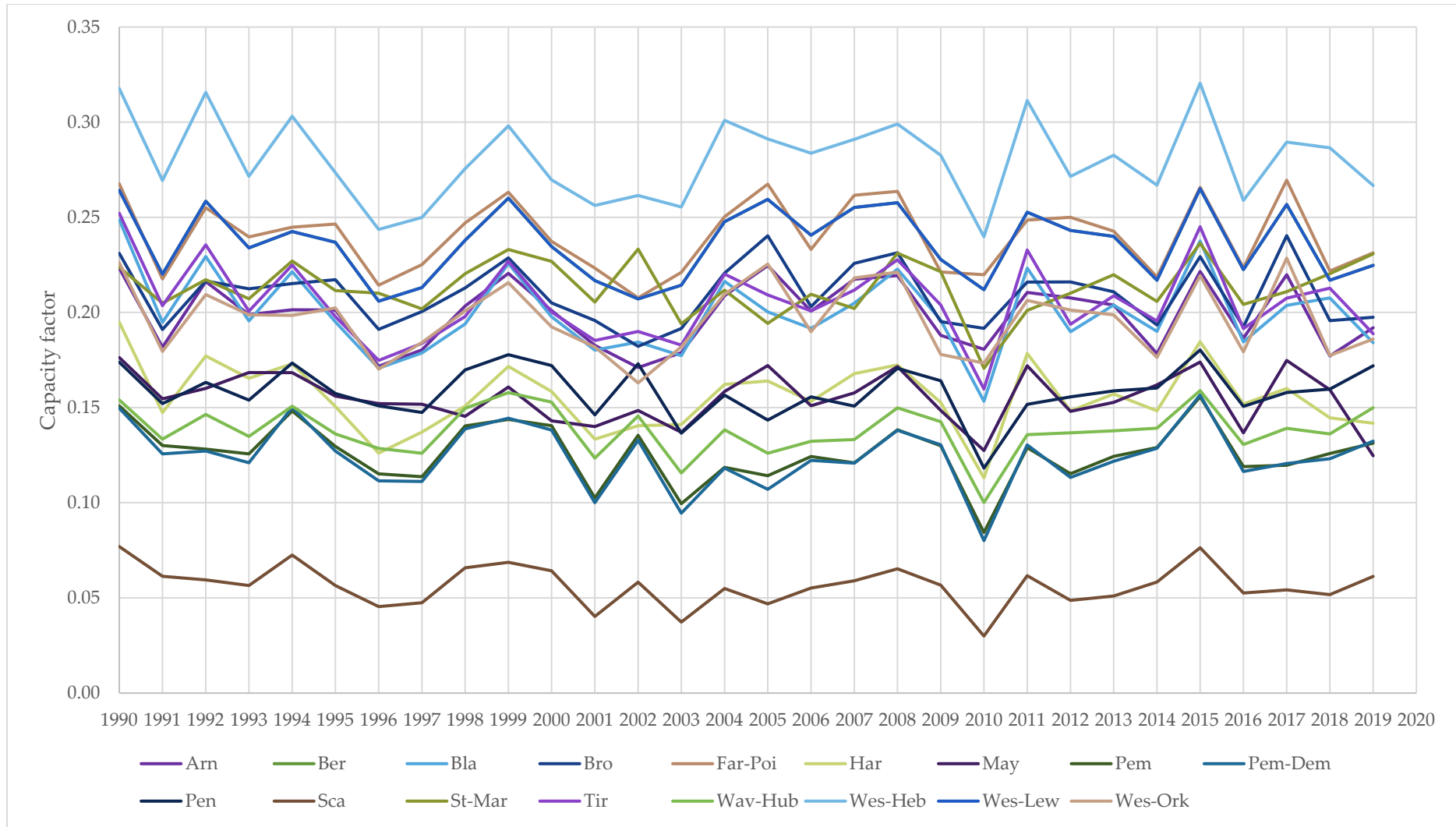


Figure 7.19. Variation in annual average capacity factor for each wave energy site, using modified Pelamis power matrix.

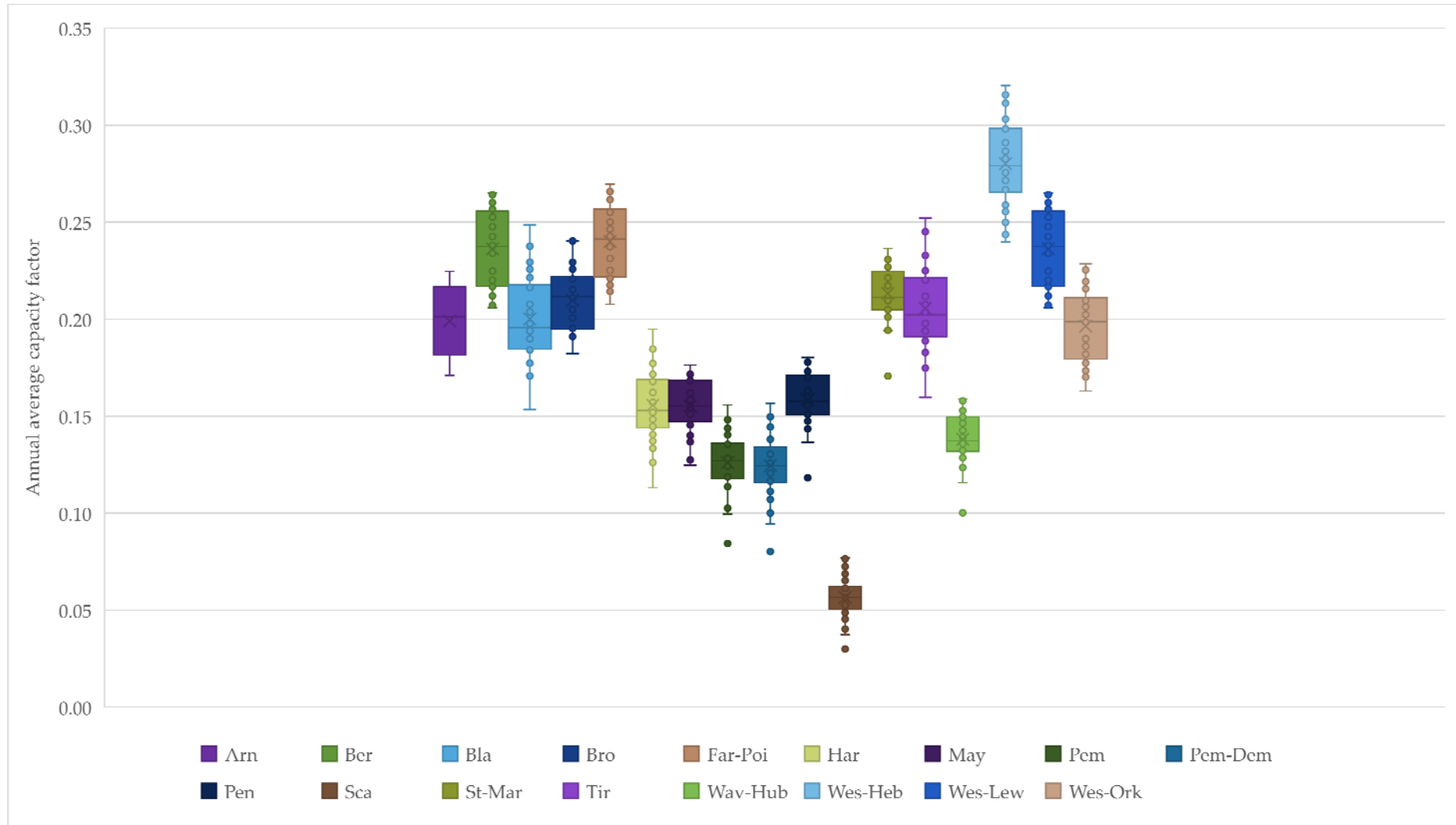


Figure 7.20. Box and whisker plot of variation in annual average capacity factor for 1990 to 2019 for each wave energy site, using modified Pelamis power matrix.

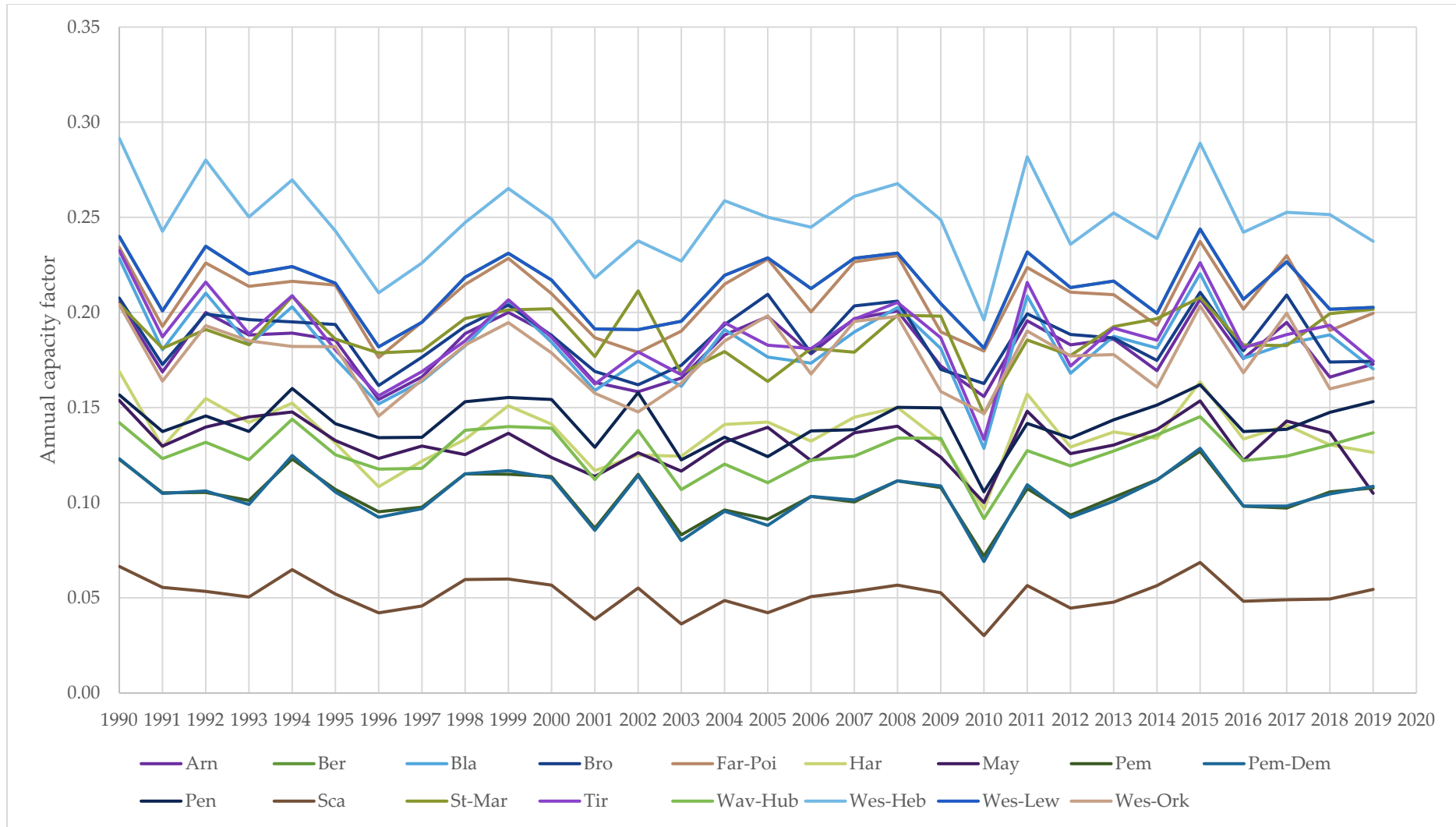


Figure 7.21. Variation in annual average capacity factor for each wave energy site, using Blue Horizon power matrix.

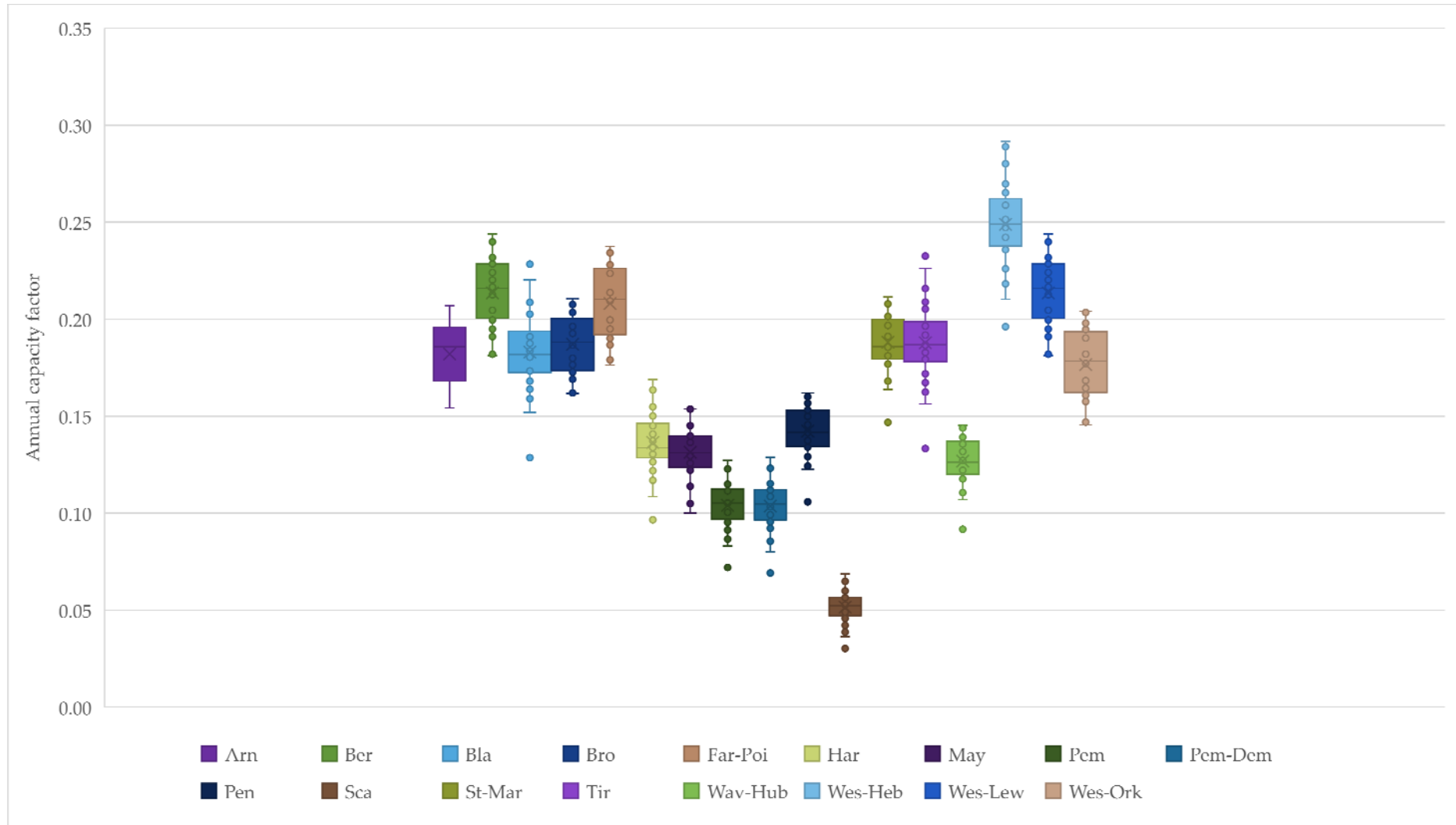


Figure 7.22. Box and whisker plot of variation in annual average capacity factor for 1990 to 2019 for each wave energy site, using Blue Horizon power matrix.

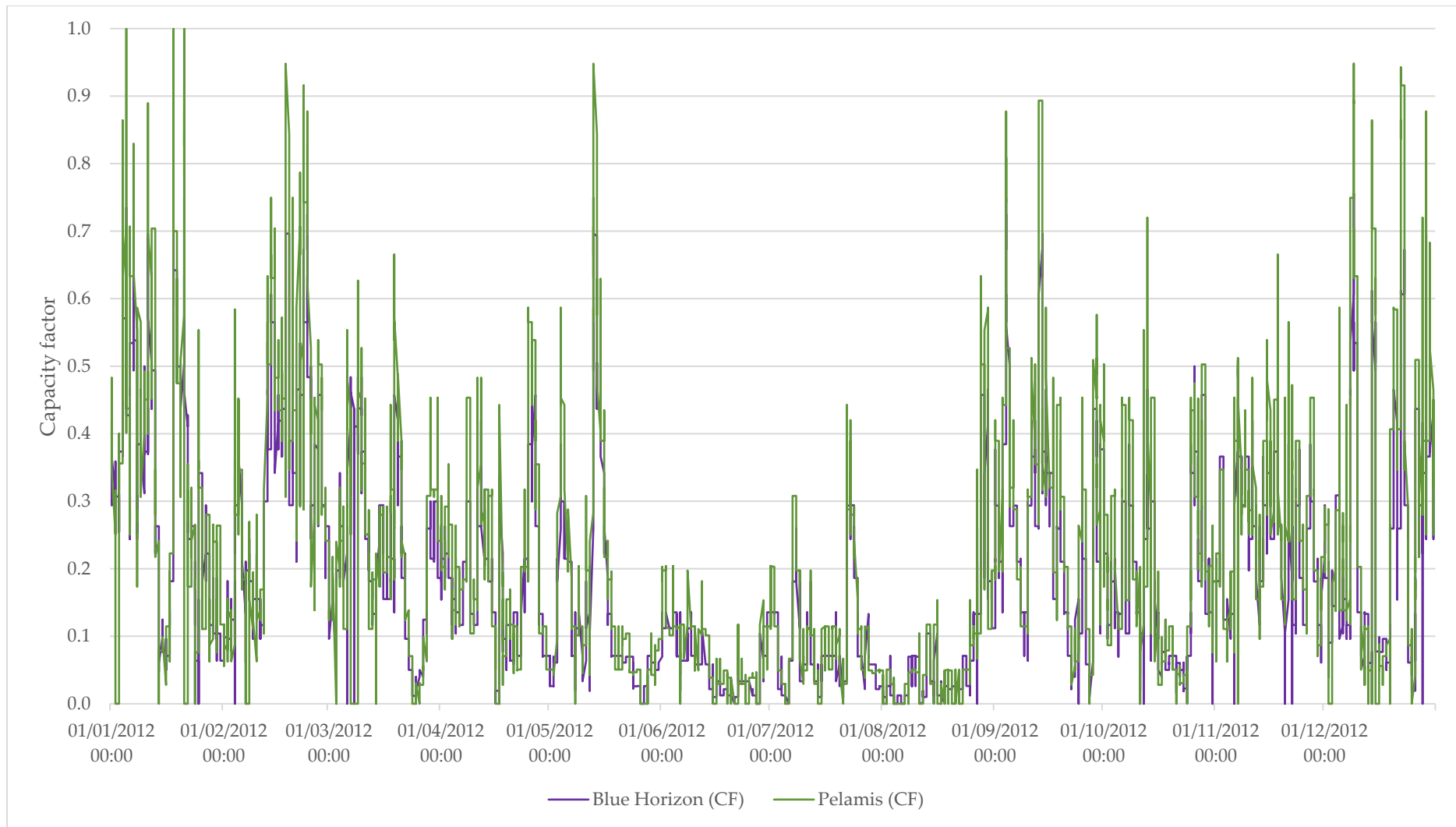


Figure 7.23. Sample capacity factor time series for Brough Head in 2012 with hourly resolution, using Blue Horizon and Pelamis power matrices.

## 7.3.2. Tidal stream

### 7.3.2.1. Renewable resource data

For tidal stream, data from the Thetis coastal ocean model was provided from colleagues at the University of Edinburgh to simulate the tidal hydrodynamics to provide depth averaged tidal stream velocities at hourly resolution at each site [312]. In this way, the tidal stream resource data can be said to be *predictive*, which contrasts with the *historical* wave resource. The capacity factor was then determined using a nominal tidal turbine power curve (Section 7.3.2.3) at hourly resolution, 1<sup>st</sup> January 00:00 to 31<sup>st</sup> December 23:00 for each year 2025, 2030, 2035, 2040, 2045, 2050. Using Thetis was necessary because the resolution of publicly available data was insufficient to give meaningful results at a site scale.

### 7.3.2.2. Site energy resource and order of construction

Determining the chronological order of site development is uncertain, so a two tiered approach was used as recommended by collaborating researchers [10]. The first tier was an assessment of each site's access to revenue support in Auction Round 4 (AR4) of the CfD subsidy scheme. To access support, sites must have a Crown Estate/Crowns Estate Scotland lease plot, be consented, and have grid connection. Currently, MeyGen, Morlais and the Isle of Wight are the only three tidal stream sites that have all three [307]. The second tier was the available power at each site, which was again used as a proxy for LCOE. For tidal stream sites this is proportional to the annual average of flow speeds cubed.

Table 7.10. Construction order based on consenting and average of cube of hourly velocity.

Site	Nominal installed capacity [MW]	Average power [ $\alpha$ (m/s) <sup>3</sup> ]	Construction order
MeyGen	400	13.9	1 <sup>st</sup> (1 <sup>st</sup> tier)
Morlais	240	2.4	2 <sup>nd</sup> (1 <sup>st</sup> tier)
Isle of Wight	30	5.8	3 <sup>rd</sup> (1 <sup>st</sup> tier)
Kyle Rhea	8	31.7	4 <sup>th</sup>
Westray South	200	16.9	5 <sup>th</sup>
Lashy Sound	30	12.3	6 <sup>th</sup>
Sound of Islay	12	11.9	7 <sup>th</sup>
Alderney Race	1400	11.7	8 <sup>th</sup>
Brims	200	9.6	9 <sup>th</sup>
Islay demo	100	9.1	10 <sup>th</sup>
Brough Ness	100	8.2	11 <sup>th</sup>
Mull of Galloway	30	8.0	12 <sup>th</sup>
Stronsay Sound	100	7.4	13 <sup>th</sup>
West Islay	30	6.3	14 <sup>th</sup>
Portland Bill	30	5.9	15 <sup>th</sup>
Ness of Duncansby	100	5.0	16 <sup>th</sup>
Bardsey	3	4.6	17 <sup>th</sup>
St Davids head	10	4.5	18 <sup>th</sup>
Anglesey Skerries	10	3.9	19 <sup>th</sup>
Mull of Kintyre	30	3.7	20 <sup>th</sup>
Isle of Man	210	2.0	21 <sup>st</sup>

### 7.3.2.3. Nominal tidal turbine 2MW

For tidal stream a nominal power curve (Figure 7.24) was constructed to emulate the rated power and performance of the Orbital Marine O2 floating tidal turbine [313] using a power coefficient of 0.41 from a contemporary turbine design [314]. As with the wave power

approach, only a single converter type was represented for a given site, which is expected to lead to low capacity factors at certain sites, when rated velocities are not exceeded regularly.

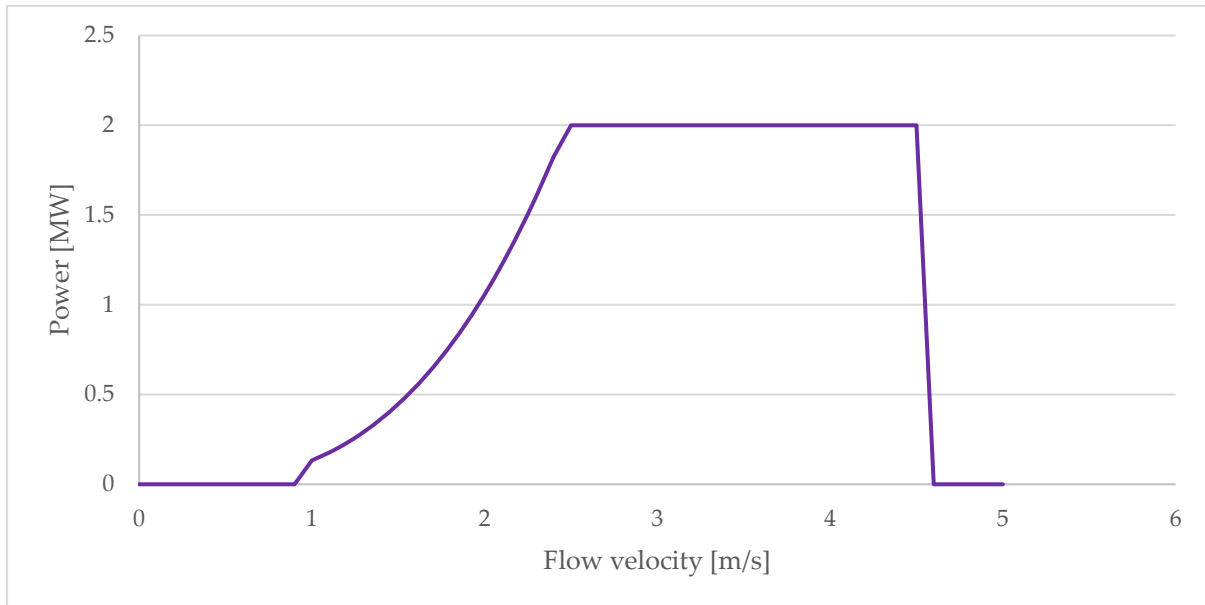


Figure 7.24. Nominal power curve assumed for tidal turbine with two rotors. The cut in, rated speed and cut out speeds are 1 m/s, 2.5 m/s and 4.5 m/s respectively. Each rotor is 20 m diameter rated power of 1 MW, power coefficient of 0.41.

### 7.3.2.1. Results

Figure 7.25 shows how the capacity factor for each site varied in the years under consideration. The predictability of power output is clearly demonstrated, in contrast to wave power, which is much more variable between years. Figure 7.26 shows the variation in capacity factor over 2025, and Figure 7.27 shows the variation over one week, clearly illustrating the sinusoidal characteristics of tidal power.

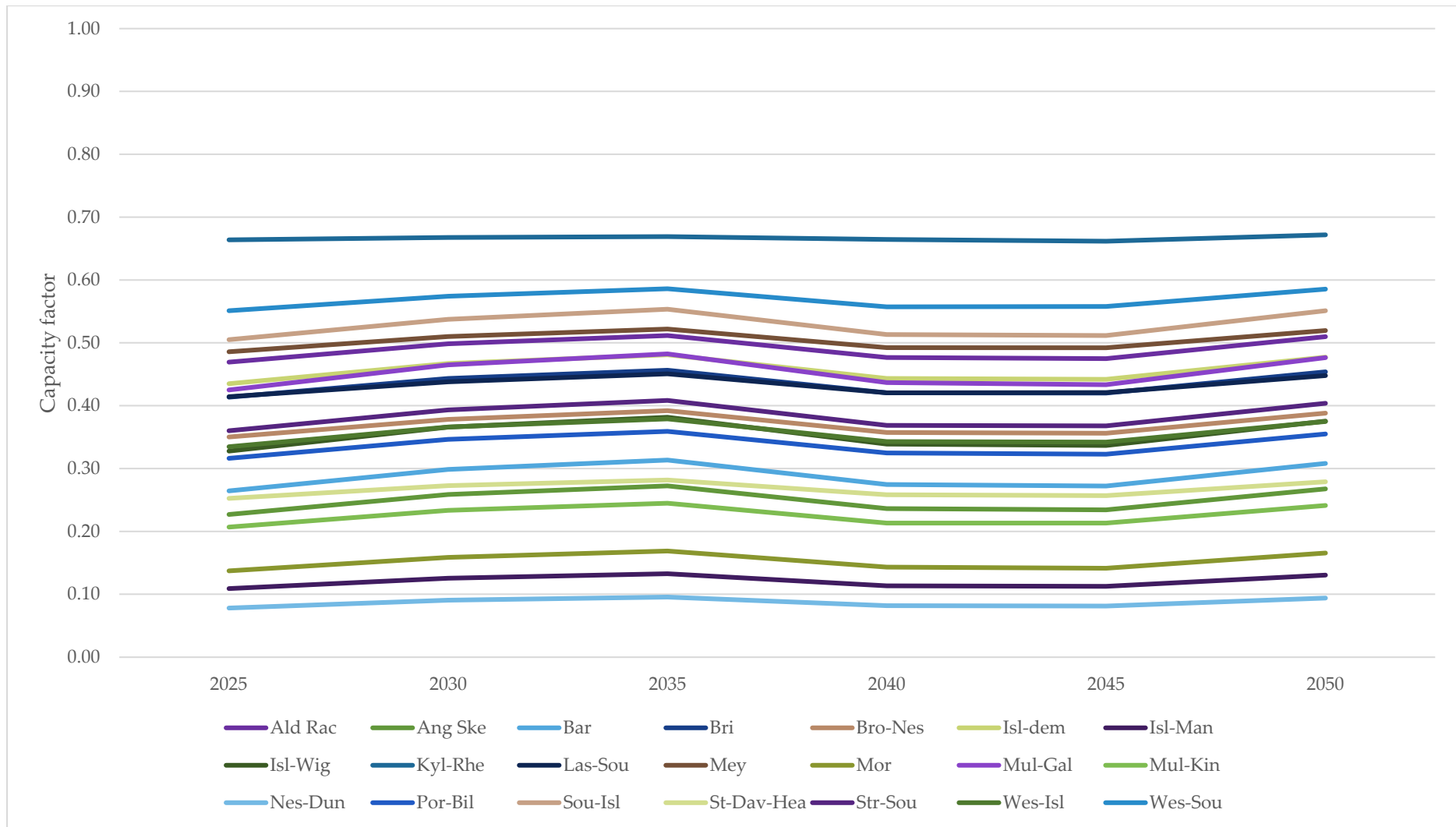


Figure 7.25. Variation in capacity factor across all sites (note scale is approximately double that of Figure 7.21 and Figure 7.22).

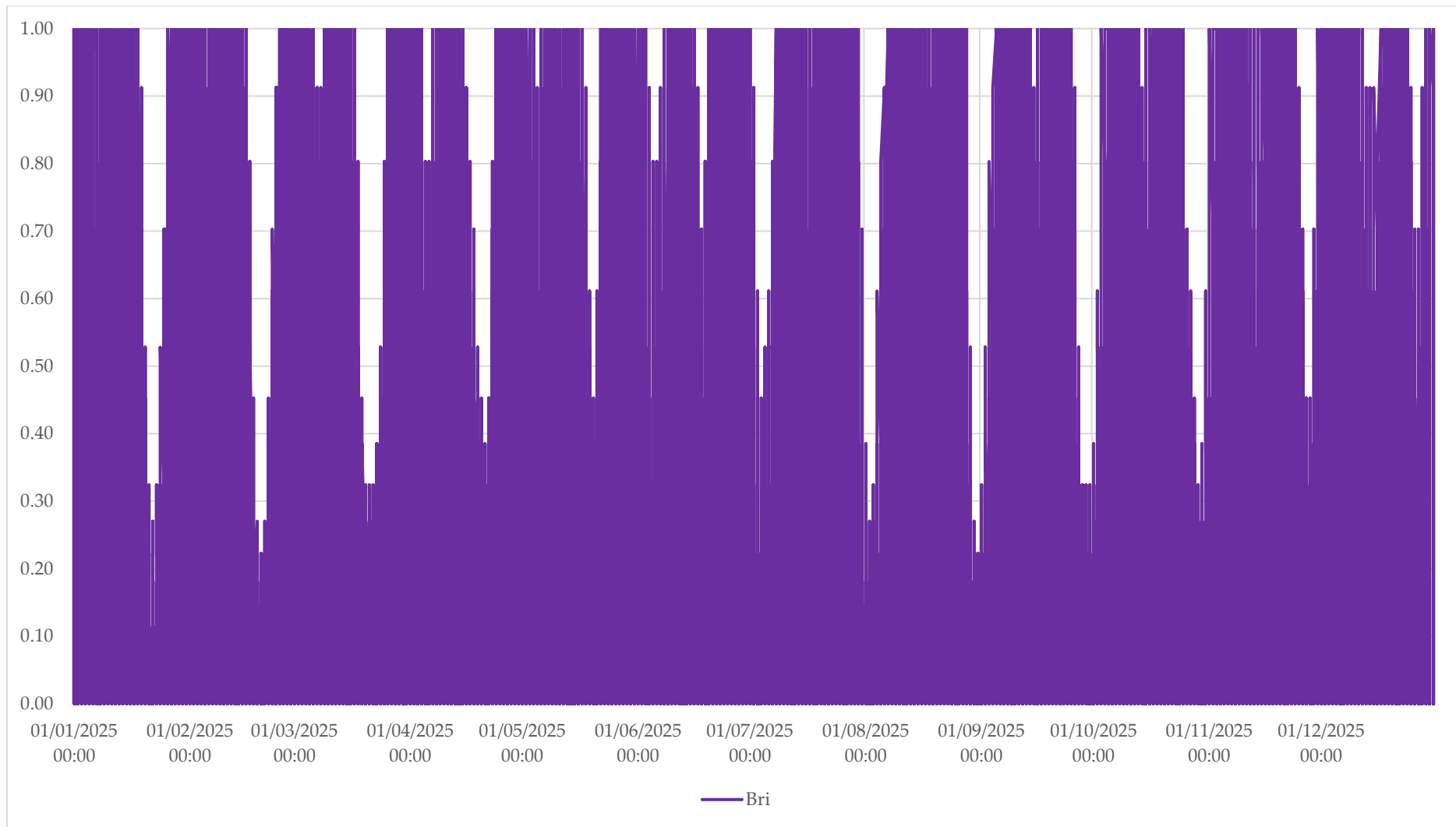


Figure 7.26. Example capacity factor variation for Brims. Note rated power achieved in multiple tidal cycles (capacity factor = 1).



### 7.3.3. Tidal lagoon

Tidal lagoon capacity factors were similarly provided by Lucas Mackie using Thetis for tidal lagoon modelling. The tidal power plants in were assumed to operate bi-directionally, generating electricity on both the ebb phase as the impoundment empties, and on the flood phase as the impoundment fills. In addition, pumping periods are implemented to increase impoundment elevation at high tide for ebb generation, and to reduce elevation at low tide for flood generation [103]. Again, these were predicted capacity factors; not based on historical reanalysis data. These were originally provided at 100 s resolution and had power drain as well due to pumping (maximises energy generation). These were modified to an hourly resolution, and to remove power consumption due to pumping for tractability with PyPSA-GB LOPF. The capacity factor of each site was independent of the year, unlike the tidal stream capacity factors.

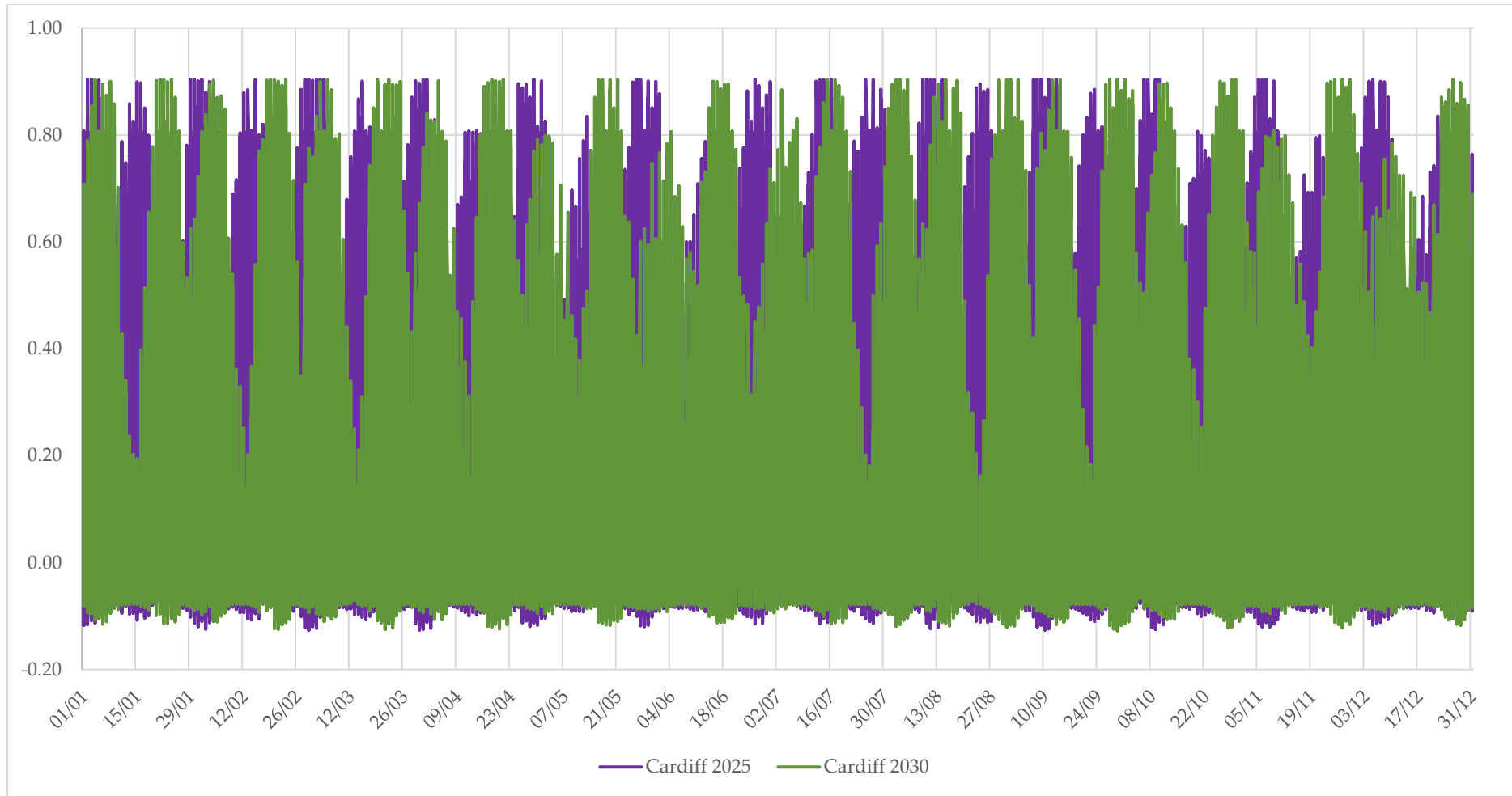


Figure 7.28. Example capacity factor time series variation for Cardiff in 2025 and 2030. Note power consumption as negative capacity factor. The average capacity factor for 2025 and 2030 is identical.

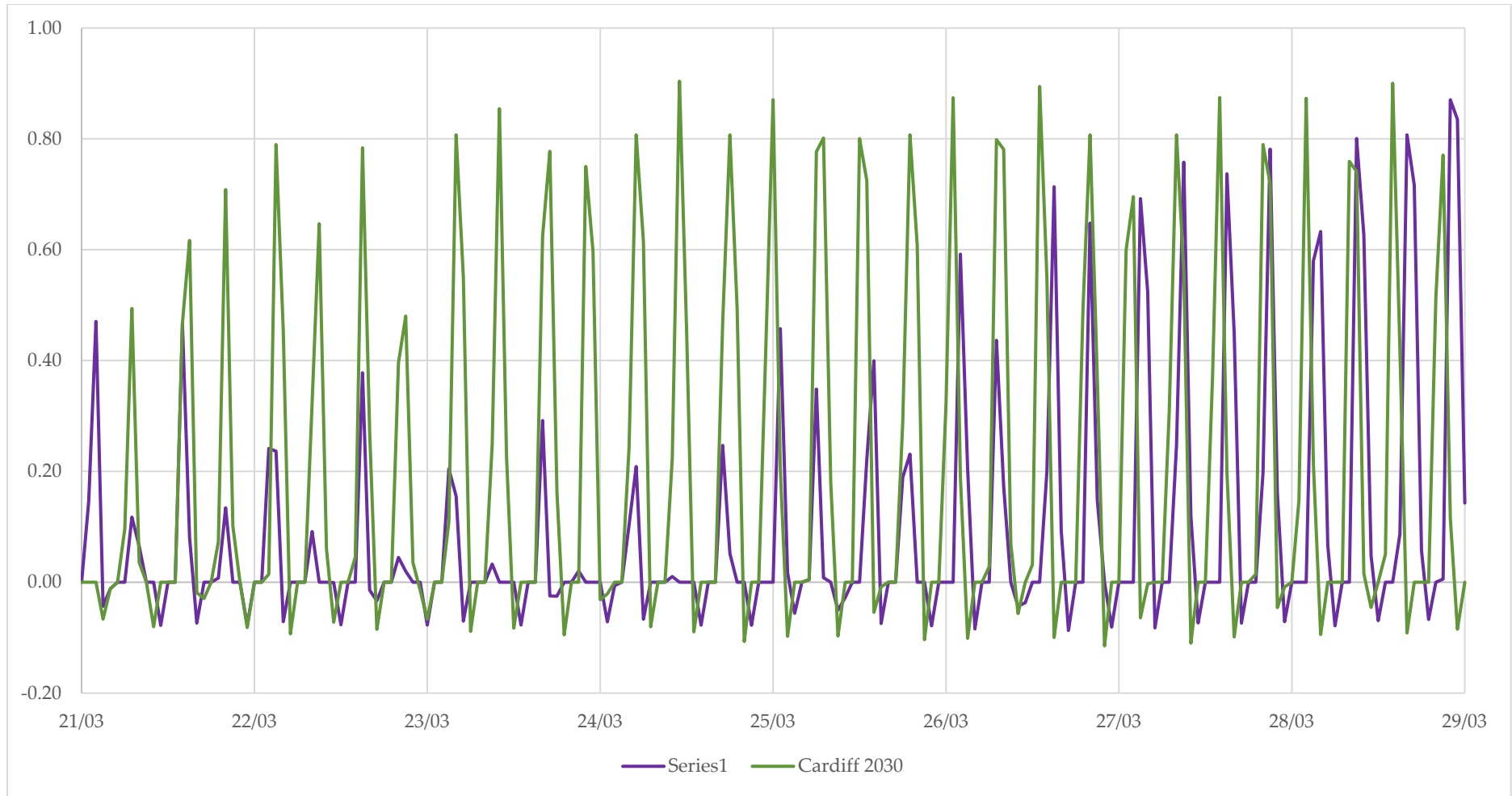


Figure 7.29. Example capacity factor time-series for Cardiff in 2025 and 2030.

## 7.4. Wave energy and tidal stream installed capacity scenarios

Section 7.2 showed that FES2022 does not feature significant installed capacities of marine energy (up to 8.3 GW nationally by 2050, and up to only 303 MW tidal stream and 42 MW wave energy by the same year). Further, there is limited data on the spatial and technological breakdown of the total installed capacity of 'Marine' energy, necessitating interpretation to replicate the results in the selected power system model, PyPSA-GB. However, one research objective of this thesis is to determine whether novel offshore renewable energy technologies can offer emissions reduction beyond that of more established technologies when integrated into future power systems. However, in general, future scenarios of floating wind, wave and tidal stream deployment are highly dependent on input assumptions and rarely spatially, temporally or technologically detailed enough to be used as suitable inputs to power system models. To test this hypothesis then, detailed spatio-temporal future development scenarios for each technology were required.

This section combines profiles from studies using energy system optimisation models (ESOMs) and site locations to create simple 'deployment scenarios' for wave and tidal stream around GB in the years 2025, 2030, 2035, 2040, 2045 and 2050. Three "deployment profiles" [315] were selected for both technologies: low, mid and high.

### 7.4.1. Method overview

As with Section 7.2 the installed capacity at each site is scaled to match the long-term profiles. At its core, the method presented here is straightforward, comprising the following steps:

1. Identify credible profiles for discrete wave and tidal stream deployment around GB for 2025 to 2050.

2. Identify credible wave and tidal stream site locations and the nominal power expected to be installed at each site, as a percentage of the total installed fleet (Section 7.2).
3. Determine the chronological order of site development and equate the cumulative site capacity to the installed capacity of future profiles.

#### 7.4.2. Installed capacity profiles

Three installed capacity *profiles* were identified (high, mid and low), where the designation refers to the installed capacity in 2050 (Figure 7.30, Table 7.13, Table 7.14) [315], [316], [317], and the term *profile* indicates that there is no information on spatial distribution (as opposed to a *scenario*, usage of which is intended to denote a data structure with *spatial* and temporal distribution). These sources are UK-specific, include a detailed breakdown of installed capacity per year and report wave and tidal stream technologies separately. This separation lends internal consistency to the profiles for wave and tidal, as opposed to separate references for each technology. A full discussion of the assumptions behind these profiles is given in their respective sources [315], [316], [317].

The high profile used the Energy System Catapult's Energy System Modelling Environment (ESME) [316] where wave and tidal stream achieve a LCOE of £90/MWh by 2030. The installed capacity of wave and tidal stream in 2050 under this analysis was 21.5 GW and 15.5 GW respectively. This tidal deployment is 35% larger than the 11.5 GW estimated by assessing resource potential, cost, system integration and environmental impacts in a later publication [307].

The reference identified for the mid profile was also output by ESME, but constrains the build rates to increase cumulatively, and assumes €150/MWh for wave energy and €100/MWh for

tidal stream is achieved by 2030 [317]. This results in 6.4 GW of wave power and 6.2 GW tidal stream respectively by 2050.

The reference for the low profile is a 2018 report from ORE Catapult [315] which assumes an average installation rate of 100 MW per year starting from a nominal demonstration fleet of 10 MW in 2030 for wave and 10 MW in 2020 for tidal stream, resulting in 910 MW of wave and 1910 MW of tidal stream by 2040. No data is available post-2040 but continuing this linear deployment rate results in 1.9 GW of wave power and 2.9 GW of tidal stream by 2050.

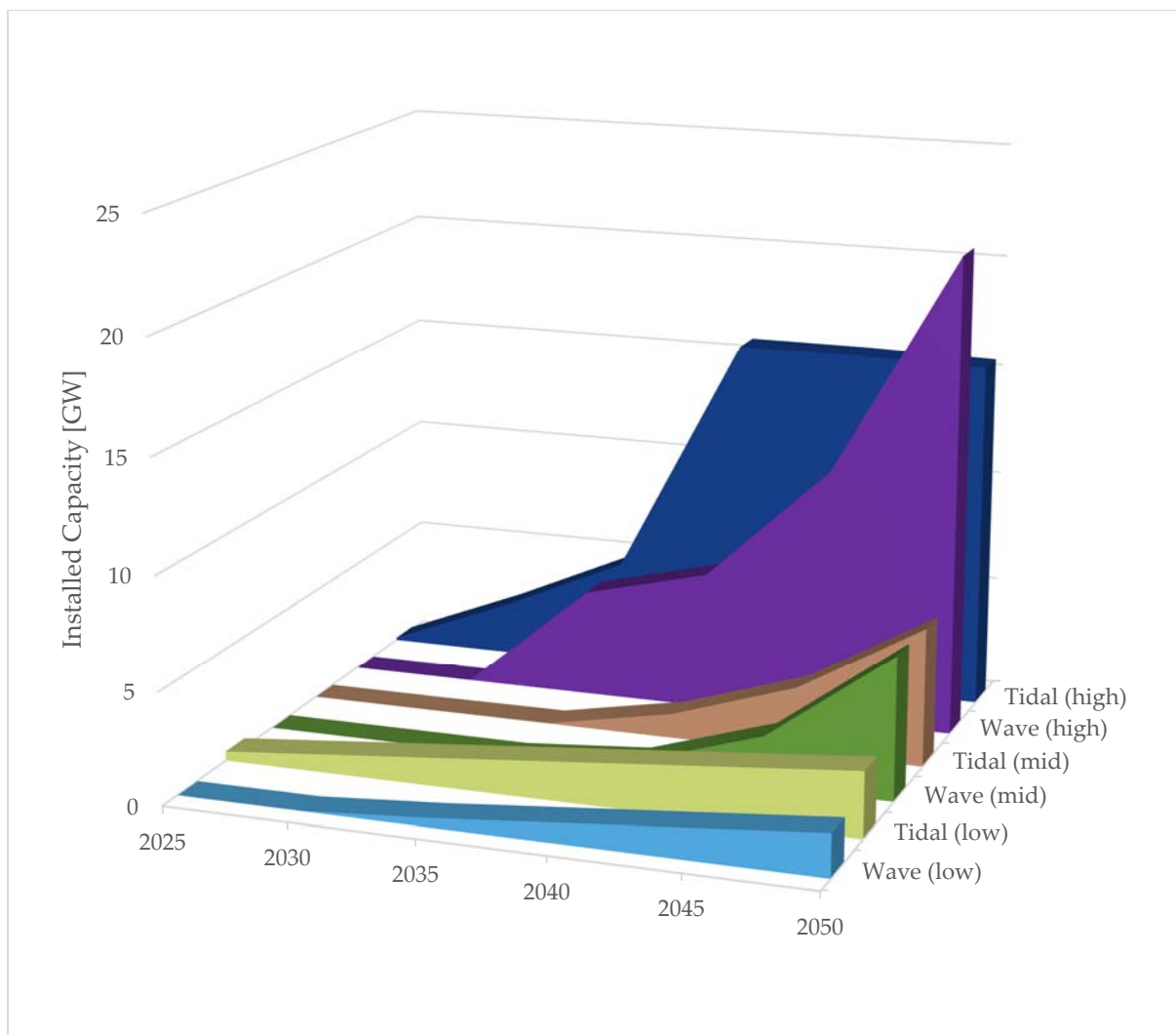


Figure 7.30. Installed capacity profiles of wave and tidal energy from the literature in the years 2025 to 2050

Table 7.11. Selected installed capacity profiles for wave energy [GW].

	2025	2030	2035	2040	2045	2050	Reference
<b>Low</b>	-	0.010	0.410	0.910	1.410	1.910	[315]
<b>Mid</b>	-	-	-	0.450	2.230	6.390	[317]
<b>High</b>	-	-	4.810	6.200	11.460	21.460	[316]

Table 7.12. Selected installed capacity profiles for tidal stream [GW]

	2025	2030	2035	2040	2045	2050	Reference
<b>Low</b>	0.410	0.910	1.410	1.910	2.410	2.910	[315]
<b>Mid</b>	-	-	0.030	1.090	2.940	6.210	[317]
<b>High</b>	0.100	2.350	4.860	15.670	15.660	15.540	[316]

### 7.4.3. Scenarios of installed capacities at each site

The scenarios of installed capacities at each site are shown in Table 7.13 and Table 7.14. Using the construction orders defined previously, the sites were scaled up (to a maximum of the contribution to the total fleet to meet the installed capacity profiles).

Table 7.13. Low, Mid, High scenarios, wave power [GW].

Site name	Cumulative	Low						Mid						High					
		2025	2030	2035	2040	2045	2050	2025	2030	2035	2040	2045	2050	2025	2030	2035	2040	2045	2050
West of Hebrides	9.5%	-	0.010	0.183	0.183	0.183	0.183	-	-	-	0.45	0.611	0.611	-	-	2.049	2.049	2.049	2.049
Bernera	10.0%	-	-	0.010	0.010	0.010	0.010	-	-	-	-	0.031	0.031	-	-	0.103	0.103	0.103	0.103
West of Lewis	19.6%	-	-	0.183	0.183	0.183	0.183	-	-	-	-	0.611	0.611	-	-	2.049	2.049	2.049	2.049
Tiree	24.3%	-	-	0.034	0.092	0.092	0.092	-	-	-	-	0.306	0.306	-	-	0.609	1.025	1.025	1.025
Farr Point	26.7%	-	-	-	0.046	0.046	0.046	-	-	-	-	0.153	0.153	-	-	-	0.513	0.513	0.513
Blackstones	36.3%	-	-	-	0.183	0.183	0.183	-	-	-	-	0.518	0.611	-	-	-	0.461	2.049	2.049
St Mary's Point	45.8%	-	-	-	0.183	0.183	0.183	-	-	-	-	-	0.611	-	-	-	-	2.049	2.049
Brough Head	55.4%	-	-	-	0.030	0.183	0.183	-	-	-	-	-	0.611	-	-	-	-	1.623	2.049
West Orkney	57.8%	-	-	-	-	0.046	0.046	-	-	-	-	-	0.153	-	-	-	-	-	0.513
Arnol	59.7%	-	-	-	-	0.037	0.037	-	-	-	-	-	0.123	-	-	-	-	-	0.410
Penzance	69.2%	-	-	-	-	0.183	0.183	-	-	-	-	-	0.611	-	-	-	-	-	2.049
Maywick	74.0%	-	-	-	-	0.081	0.092	-	-	-	-	-	0.306	-	-	-	-	-	1.025
Harris	78.8%	-	-	-	-	-	0.092	-	-	-	-	-	0.306	-	-	-	-	-	1.025
Wave Hub	80.4%	-	-	-	-	-	0.032	-	-	-	-	-	0.107	-	-	-	-	-	0.359
PDZ	89.0%	-	-	-	-	-	0.165	-	-	-	-	-	0.550	-	-	-	-	-	1.844
Pembrokeshire	98.6%	-	-	-	-	-	0.183	-	-	-	-	-	0.611	-	-	-	-	-	2.049

		Low						Mid						High					
Site name	Cumulative	2025	2030	2035	2040	2045	2050	2025	2030	2035	2040	2045	2050	2025	2030	2035	2040	2045	2050
Scarweather	100.0%	-	-	-	-	-	0.017	-	-	-	-	-	0.078	-	-	-	-	-	0.300
<b>Total</b>		-	<b>0.010</b>	<b>0.410</b>	<b>0.910</b>	<b>1.410</b>	<b>1.910</b>	-	-	-	<b>0.450</b>	<b>2.230</b>	<b>6.390</b>	-	-	<b>4.810</b>	<b>6.200</b>	<b>11.46</b>	<b>21.46</b>

Table 7.14. Low, Mid and High scenarios, tidal stream [GW].

Site name	Cumulative	Low						Mid						High					
		2025	2030	2035	2040	2045	2050	2025	2030	2035	2040	2045	2050	2025	2030	2035	2040	2045	2050
MeyGen	12.2%	0.356	0.356	0.356	0.356	0.356	0.356	-	-	0.03	0.76	0.76	0.76	0.100	1.902	1.902	1.902	1.902	1.902
Morlais	19.6%	0.054	0.214	0.214	0.214	0.214	0.214	-	-	-	0.33	0.456	0.456	-	0.448	1.142	1.142	1.142	1.142
Isle of Wight	20.5%	-	0.028	0.028	0.028	0.028	0.028	-	-	-	-	0.058	0.058	-	-	0.144	0.144	0.144	0.144
Kyle Rhea	20.7%	-	0.008	0.008	0.008	0.008	0.008	-	-	-	-	0.016	0.016	-	-	0.04	0.04	0.04	0.04
Westray South	26.8%	-	0.178	0.178	0.178	0.178	0.178	-	-	-	-	0.38	0.38	-	-	0.952	0.952	0.952	0.952
Lashy Sound	27.8%	-	0.028	0.028	0.028	0.028	0.028	-	-	-	-	0.058	0.058	-	-	0.144	0.144	0.144	0.144
Sound of Islay	28.1%	-	0.01	0.01	0.01	0.01	0.01	-	-	-	-	0.02	0.02	-	-	0.048	0.048	0.048	0.048
Alderney Race	70.9%	-	0.088	0.588	1.088	1.246	1.246	-	-	-	-	1.192	2.658	-	-	0.488	6.652	6.652	6.652
Brims	77.0%	-	-	-	-	0.178	0.178	-	-	-	-	-	0.38	-	-	-	0.952	0.952	0.952
Islay demo	80.0%	-	-	-	-	0.09	0.09	-	-	-	-	-	0.19	-	-	-	0.476	0.476	0.476
Brough Ness	83.1%	-	-	-	-	0.074	0.09	-	-	-	-	-	0.19	-	-	-	0.476	0.476	0.476
Mull of Galloway	84.0%	-	-	-	-	-	0.028	-	-	-	-	-	0.058	-	-	-	0.144	0.144	0.144
Stronsay Sound	87.1%	-	-	-	-	-	0.09	-	-	-	-	-	0.19	-	-	-	0.476	0.476	0.476
West Islay	88.0%	-	-	-	-	-	0.028	-	-	-	-	-	0.058	-	-	-	0.144	0.144	0.144
Portland Bill	88.9%	-	-	-	-	-	0.028	-	-	-	-	-	0.058	-	-	-	0.144	0.144	0.144
Ness of Duncansby	92.0%	-	-	-	-	-	0.09	-	-	-	-	-	0.19	-	-	-	0.476	0.476	0.476

Site name	Cumulative	Low						Mid						High					
		2025	2030	2035	2040	2045	2050	2025	2030	2035	2040	2045	2050	2025	2030	2035	2040	2045	2050
Bardsey	92.1%	-	-	-	-	-	0.004	-	-	-	-	-	0.006	-	-	-	0.016	0.016	0.016
St Davids head	92.4%	-	-	-	-	-	0.01	-	-	-	-	-	0.02	-	-	-	0.048	0.048	0.048
Anglesey Skerries	92.7%	-	-	-	-	-	0.01	-	-	-	-	-	0.02	-	-	-	0.048	0.048	0.048
Mull of Kintyre	93.6%	-	-	-	-	-	0.028	-	-	-	-	-	0.058	-	-	-	0.144	0.144	0.144
Isle of Man	100.0%	-	-	-	-	-	0.168	-	-	-	-	-	0.386	-	-	-	0.998	0.998	0.972
<b>Total</b>		<b>0.410</b>	<b>0.910</b>	<b>1.410</b>	<b>1.910</b>	<b>2.410</b>	<b>2.910</b>	-	-	<b>0.030</b>	<b>1.090</b>	<b>2.940</b>	<b>6.210</b>	<b>0.100</b>	<b>2.350</b>	<b>4.860</b>	<b>15.56</b>	<b>15.56</b>	<b>15.54</b>

#### 7.4.4. Combining scenarios of installed capacities and capacity factors

Thus, one outcome of this chapter is a set of low, mid, and high deployment scenarios for tidal stream and wave power deployment at specific geo-located sites around GB, for use with power system models. A short sample time series of power output illustrates the resulting data from this effort (Figure 7.31).

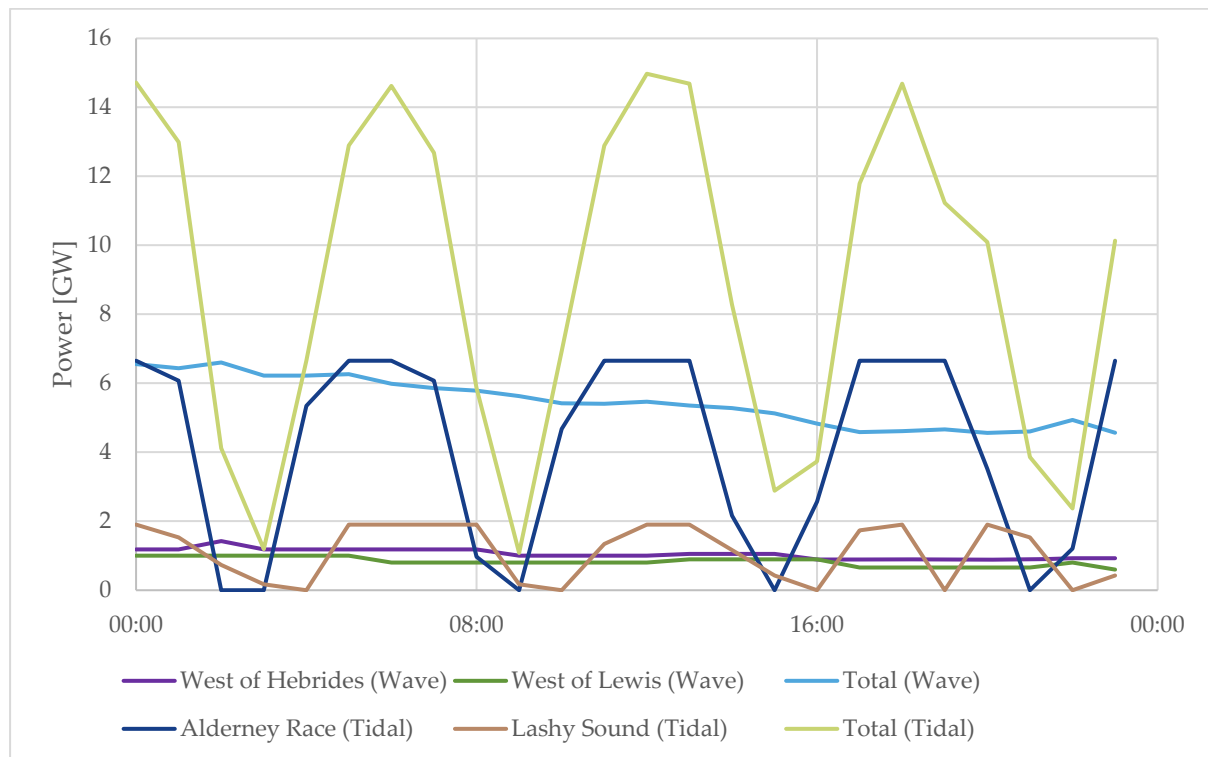


Figure 7.31. Historic wave power (2012) and predicted tidal stream (2050) generation from all sites combined, and the top two sites at the spring equinox (21st March) in the high profile.

Clearly, this treatment is limited by its combination of historical and modelled data, and by the use of only a select number of devices. However, this work represents the first implementation of marine energy in PyPSA-GB, and disaggregation of marine energy (wave power, tidal stream and tidal lagoon) in FES2022, suitable for use with power system models.

## 7.5. Floating wind scenarios

The floating wind scenarios were provided by ORE Catapult, and align with their work in partnership with the Energy Systems Catapult [318] (Figure 7.32).

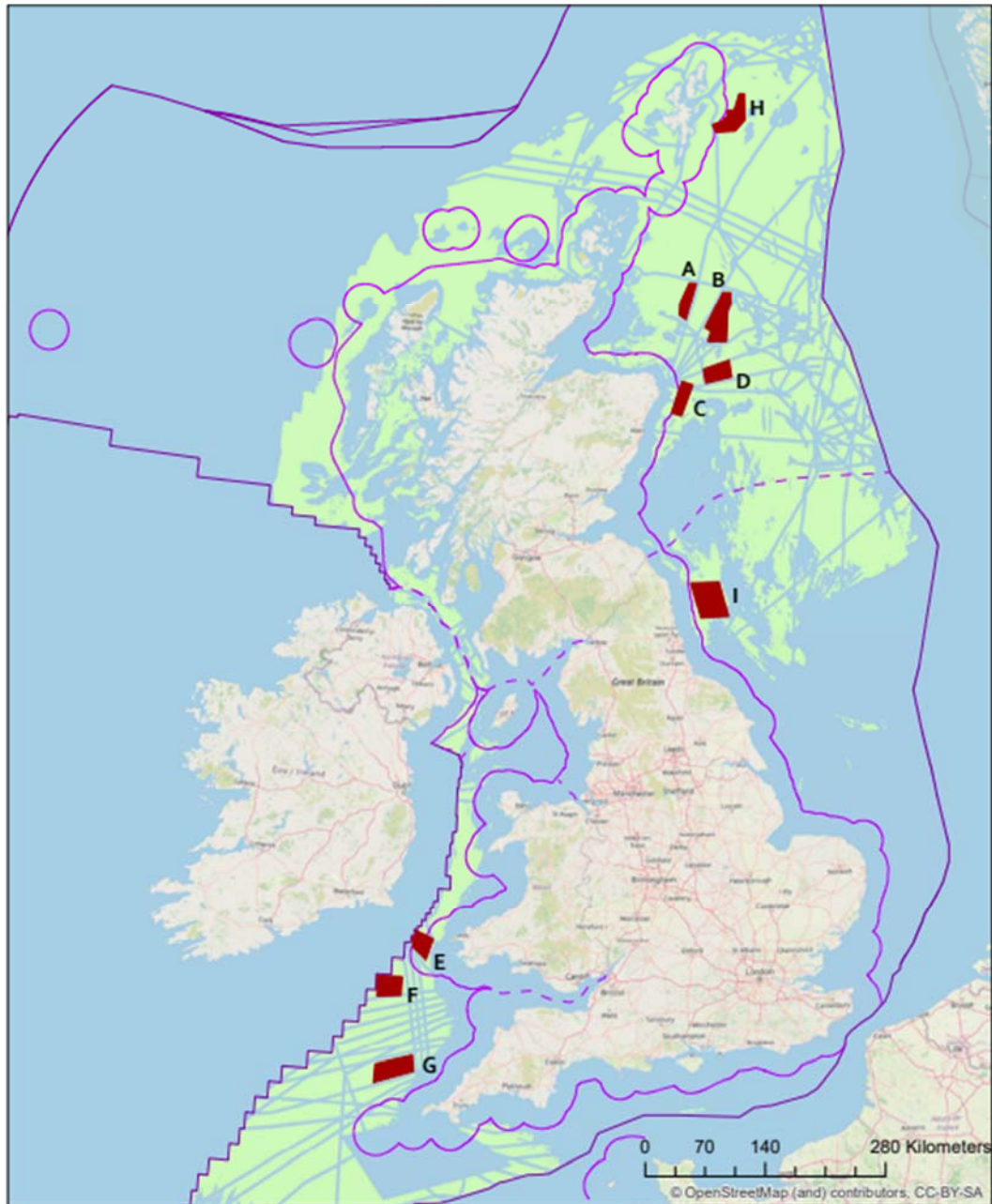


Figure 7.32. GIS map with identified floating wind development zones, adapted from [319]. Zones A, B, C, D are equivalent to NE8, NE7, E3 and E2 respectively.

Immediately, one limitation is the assumption of a 20 MW turbine after 2037 [319], however this is not replicated here in order to maintain consistency with the 15 MW turbine used in Chapter 5. The installed capacity profiles according to these sites was also provided and resolved according to ESX Laotec resolution (0.25 degrees).

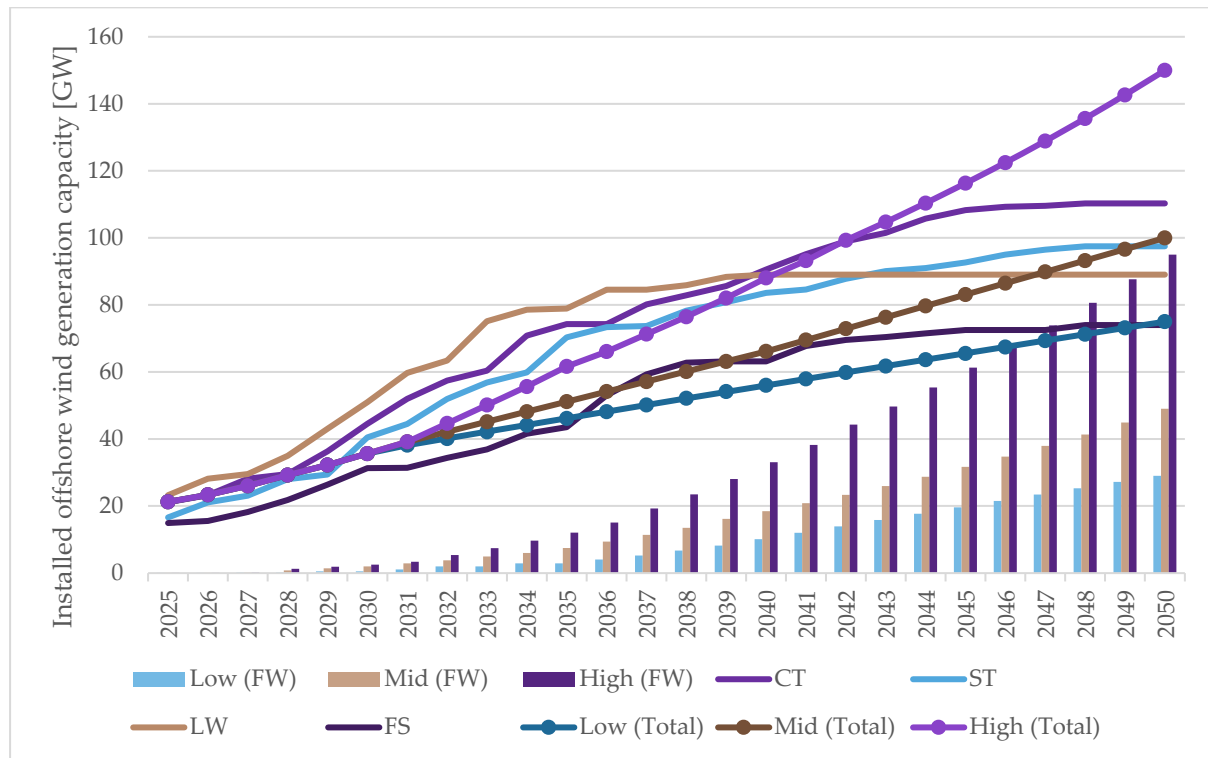


Figure 7.33. Comparison of installed capacities of offshore wind between FES2022 (CT, ST, LW, FS) and Low, Mid and High scenarios, with proportion of floating wind shown (bar chart).

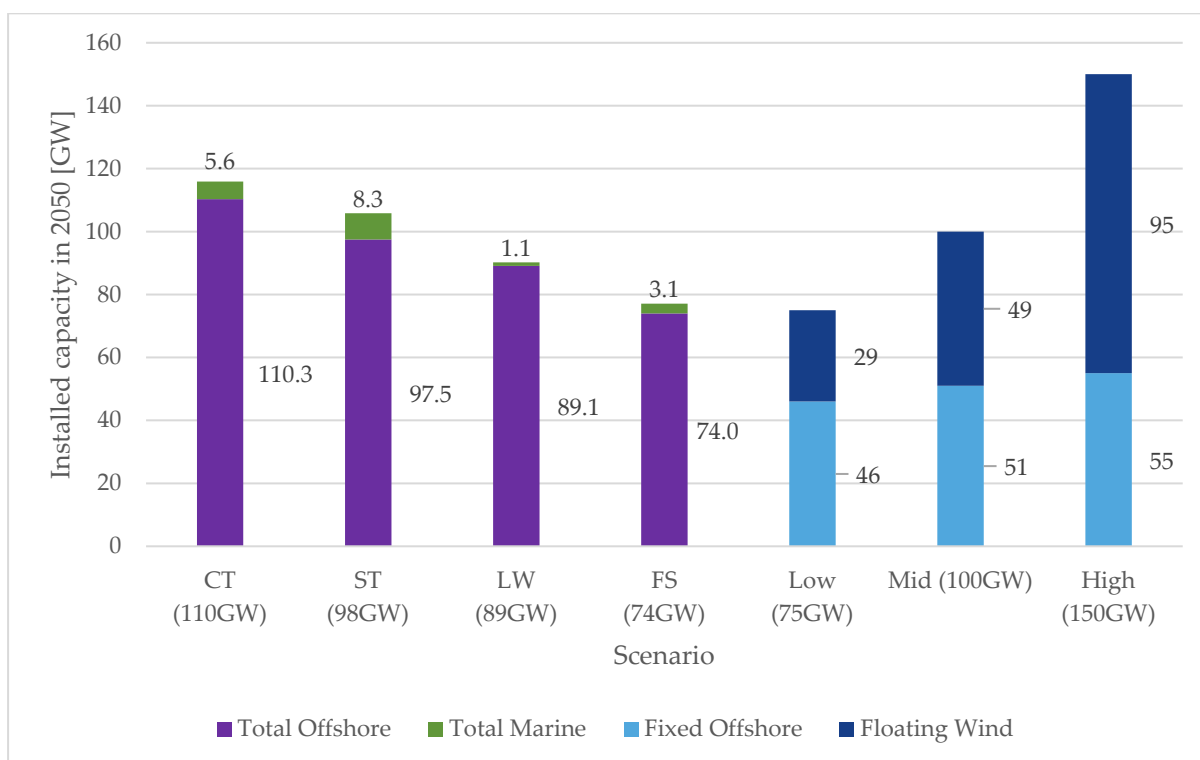


Figure 7.34. Comparison of installed capacities of offshore wind and marine in FES2022 (CT, ST, LW, FS) and Low, Mid and High scenarios, with breakdown between fixed bottom and floating offshore wind shown.

Table 7.15. Comparison of installed capacities relative to FES2022, ES.E.01 [GW]

Scenario	Total Offshore	Total Marine	Fixed Offshore	Floating Wind
CT	110.3	5.6	-	-
ST	97.5	8.3	-	-
LW	89.1	1.1	-	-
FS	74.0	3.1	-	-
Low (75 GW)	75	-	46 (61%)	29 (39%)
Mid (100 GW)	100	-	51 (51%)	49 (49%)
High (150 GW)	150	-	55 (37%)	95 (63%)

### 7.5.1. FES2022

Floating wind can be included in PyPSA-GB for the FES2022 by inspection of the similarities with the three scenarios (low, Mid, High). The ratios of final installed capacities of fixed offshore wind to floating wind being 0.61:0.39; 0.51:0.49; 0.37:0.63. The most similar cases are shown below based on final installed capacities (Table 7.16). Note that deployment rates are likely different between the two technologies, so this aspect could be improved.

Table 7.16. FES cases as a ratio of final installed capacities relative to FES2022, ES.E.01 [GW]

Scenario	Most similar	Ratio	Fixed Offshore	Floating Wind
CT (110 GW)	Mid (100 GW)	1.10	56.3 (51%)	54.0 (49%)
ST (98 GW)	Mid (100 GW)	0.98	49.7 (51%)	47.8 (49%)
LW (89 GW)	Mid (100 GW)	0.89	45.4 (51%)	43.7 (49%)
FS (74 GW)	Low (75 GW)	0.99	45.4 (61%)	28.6 (39%)

### 7.5.2. Installed capacity scenarios necessary for emission reduction potential analysis

The scenarios interpreted from the ORE Catapult data are shown in Table 7.17.

Table 7.17. Evolution of floating wind sites provided by ORE Catapult [319] through time and assumed values for this thesis.

Subsidy free [319] (Jan 2021)			ScotWind [283] (March 2021)			Leased [320] (Aug 2022)				Summary		Assumptions for thesis			
Zone	MW	Floating	Area	Max [MW]	Floating	Site	Name	Leased [MW]	Floating	Total floating	% change floating	Floating designation	LCA site	Lat	Long
A	1200	100%	NE8	990	100.00%	12	Buchan	960	100%	960	-20%	Area A	-	58.25	-1.25
B	3000	100%	NE7	3000	100.00%	11	MarramWind	3000	100%	3000	0%	Area B	NE7	58.25	-0.50
C	1425	100%	-	-	-	-	-	-	-	-	-	Area C	-	57.50	-1.25
D	1650	100%	-	-	-	-	-	-	-	-	-	Area D	-	57.75	-0.75
E	1350	100%	-	-	-	-	-	-	-	-	-	Area E	-	51.75	-5.75
F	1860	100%	-	-	-	-	-	-	-	-	-	Area F	-	51.50	-6.25
G	2580	100%	-	-	-	-	-	-	-	-	-	Area G	-	50.50	-6.25
H	2280	100%	NE1	1995	100.00%	18	Not stated	500	100%	2800	23%	Site 18	NE1	60.25	-0.50
						19	Arven	1800	100%			Site 19	NE1	60.25	-0.25
						20	Sealtainn	500	100%			Site 20	NE1	60.50	0.00
-	-	-	E1	3000	100.00%	1	Morven	2907	0%	3810	27%	-	-	-	-
-	-	-				2	Ossian	2610	100%			Site 2	-	56.75	-0.25
-	-	-				3	Bellrock	1200	100%			Site 3	-	56.75	0.25
-	-	-	E2	1995	100.00%	4	CampionWind	2000	100%	2798	40%	Site 4	-	57.50	-0.75
-	-	-				5	Muir Mhor	798	100%			Site 5	-	57.25	0.25
-	-	-	E3	990	90.82%	6	Bowdun	1008	0%	0	-100%	-	E3	-	-
-	-	-	NE2	990	100.00%	7	Ayre	1008	100%	1008	2%	Site 7	-	58.75	-2.50
-	-	-	NE3	990	100.00%	8	Stromar	1000	100%	1000	1%	Site 8	-	58.50	-2.25
-	-	-	NE4	990	33.63%	9	Caledonia	1000	0%	0	-100%	-	-	-	-
-	-	-	NE6	1995	99.14%	10	Broadshore	500	100%	500	-75%	Site 10	-	58.00	-1.75
-	-	-	N1	1995	69.02%	13	West of Orkney	2000	0%	0	-100%	-	-	-	-
-	-	-	N2	1995	100.00%	14	Mhairi	1500	100%	1500	-25%	Site 14	-	58.75	-5.50

Chapter 7: Power generation from wave, tidal stream, floating wind and tidal lagoons in future scenarios around GB

Subsidy free [319] (Jan 2021)			ScotWind [283] (March 2021)			Leased [320] (Aug 2022)				Summary		Assumptions for thesis			
Zone	MW	Floating	Area	Max [MW]	Floating	Site	Name	Leased [MW]	Floating	Total floating	% change floating	Floating designation	LCA site	Lat	Long
-	-	-	N3	1995	94.68%	15	Talisk	495	100%	495	-75%	Site 15	N3	59.00	-6.50
-	-	-	N4	990	9.35%	16	Sheena	840	0%	0	-100%	-	-	-	-
-	-	-	W1	1995	18.62%	17	MachairWind	2000	0%	0	-100%	-	-	-	-

Table 7.18. Final properties of floating sites only, reordered. Note that E3 from Chapter 5 is now absent.

DNO Zone	ScotWind Region	DNO Zone Code	Grid connection zone	FOW Deployment Area	ScotWind d Plan Option Area	ScotWind d Site	ScotWind Site Name	LCA site	Thesis FOW designation	Latitude	Longitude	MW
Scotland	North East	P	East Aberdeenshire	A	NE8	12	Buchan	-	Site 12	58.25	-1.25	960
Scotland	North East	P	East Aberdeenshire	B	NE7	11	MarramWind	NE7	Site 11	58.25	-0.50	3000
Scotland	-	P	East Aberdeenshire	C	-	-	-	-	Area C	57.50	-1.25	1425
Scotland	-	P	East Aberdeenshire	D	-	-	-	-	Area D	57.75	-0.75	1650
Wales	-	K	Pembrokeshire	E	-	-	-	-	Area E	51.75	-5.75	1350
Wales	-	K	Pembrokeshire	F	-	-	-	-	Area F	51.50	-6.25	1860
SW England	-	L	Somerset and Wessex	G	-	-	-	-	Area G	50.50	-6.25	2580
Scotland	North East	P	North Scotland	H	NE1	18	Not stated	NE1	Site 18	60.25	-0.50	500
Scotland	North East	P	North Scotland	H	NE1	19	Arven	NE1	Site 19	60.25	-0.25	1800
Scotland	North East	P	North Scotland	H	NE1	20	Sealtainn	NE1	Site 20	60.50	0.00	500
NE England	-	F	Solway and Cheviot	I	-	-	-	-	Area I	55.25	-0.75	3900
Scotland	East	P	East Aberdeenshire	-	E1	2	Ossian	-	Site 2	56.75	-0.25	2610
Scotland	East	P	East Aberdeenshire	-	E1	3	Bellrock	-	Site 3	56.75	0.25	1200
Scotland	East	P	East Aberdeenshire	-	E2	4	CampionWind	-	Site 4	57.50	-0.75	2000
Scotland	East	P	East Aberdeenshire	-	E2	5	Muir Mhor	-	Site 5	57.25	0.25	798

DNO Zone	ScotWind Region	DNO Zone Code	Grid connection zone	FOW Deployment Area	ScotWind d Plan Option Area	ScotWind d Site	ScotWind Site Name	LCA site	Thesis FOW designation	Latitude	Longitude	MW
Scotland	North East	P	North Scotland	-	NE2	7	Ayre	-	Site 7	58.75	-2.50	1008
Scotland	North East	P	North Scotland	-	NE3	8	Stromar	-	Site 8	58.50	-2.25	1000
Scotland	North East	P	North Scotland	-	NE6	10	Broadshore	-	Site 10	58.00	-1.75	500
Scotland	North	P	North Scotland	-	N2	14	Mhairi	-	Site 14	58.75	-5.50	1500
Scotland	North	P	North Scotland	-	N3	15	Talisk	N3	Site 15	59.00	-6.50	495

Table 7.19. “75 GW Offshore wind” (29 GW floating wind) [GW] – Low; “100 GW Offshore wind” (49 GW floating wind) [GW] – Mid; “150 GW Offshore wind” (95 GW floating wind)

[GW] - High

	2025	2030	2035	2040	2045	2050	2025	2030	2035	2040	2045	2050	2025	2030	2035	2040	2045	2050
<b>Area I</b>	-	-	0.915	2.795	6.195	8.798	-	-	0.915	4.695	9.671	16.352	-	-	0.915	8.695	17.475	28.866
<b>Area E</b>	-	0.096	0.996	0.996	1.290	1.290	-	0.096	0.096	1.296	1.296	1.296	-	0.096	0.096	1.296	1.632	1.632
<b>Area F</b>	-	-	-	1.500	1.906	1.906	-	-	1.505	1.505	1.505	1.505	-	-	1.505	1.505	1.969	1.969
<b>Area G</b>	-	-	-	-	1.700	3.200	-	-	-	2.900	7.293	12.778	-	-	2.200	6.600	14.803	24.312
<b>Site 12</b>	-	0.300	0.300	0.369	0.538	0.781	-	1.200	1.200	1.287	1.463	1.701	-	1.519	1.782	2.303	2.783	3.370
<b>Site 11</b>	-	-	0.600	2.023	2.553	3.312	-	0.600	1.500	2.972	3.523	4.264	-	0.760	2.228	5.347	6.847	8.680
<b>Area C</b>	0.078	0.078	0.078	1.300	1.552	1.912	0.078	0.078	1.198	1.327	1.589	1.941	0.078	0.099	1.779	2.391	3.103	3.974
<b>Area D</b>	-	-	-	0.118	0.410	0.827	-	-	1.050	1.200	1.502	1.910	-	-	1.559	2.174	2.999	4.008
<b>Site 18</b>	-	-	-	0.036	0.124	0.251	-	-	-	0.045	0.137	0.261	-	-	-	0.098	0.348	0.654
<b>Site 19</b>	-	-	-	0.129	0.447	0.902	-	-	-	0.163	0.494	0.938	-	-	-	0.354	1.253	2.354
<b>Site 20</b>	-	-	-	0.036	0.124	0.251	-	-	-	0.045	0.137	0.261	-	-	-	0.098	0.348	0.654
<b>Site 2</b>	-	-	-	0.187	0.648	1.308	-	-	-	0.237	0.716	1.361	-	-	-	0.513	1.817	3.413
<b>Site 3</b>	-	-	-	0.086	0.298	0.602	-	-	-	0.109	0.329	0.626	-	-	-	0.236	0.836	1.569
<b>Site 4</b>	-	-	-	0.143	0.497	1.003	-	-	-	0.181	0.548	1.043	-	-	-	0.393	1.393	2.615
<b>Site 5</b>	-	-	-	0.057	0.198	0.400	-	-	-	0.072	0.219	0.416	-	-	-	0.157	0.556	1.043
<b>Site 7</b>	-	-	-	0.072	0.250	0.505	-	-	-	0.091	0.276	0.526	-	-	-	0.198	0.702	1.318

	2025	2030	2035	2040	2045	2050	2025	2030	2035	2040	2045	2050	2025	2030	2035	2040	2045	2050
<b>Site 8</b>	-	-	-	0.072	0.248	0.501	-	-	-	0.091	0.274	0.521	-	-	-	0.196	0.696	1.308
<b>Site 10</b>	-	-	-	0.036	0.124	0.251	-	-	-	0.045	0.137	0.261	-	-	-	0.098	0.348	0.654
<b>Site 14</b>	-	-	-	0.107	0.372	0.752	-	-	-	0.136	0.411	0.782	-	-	-	0.295	1.044	1.961
<b>Site 15</b>	-	-	-	0.035	0.123	0.248	-	-	-	0.045	0.136	0.258	-	-	-	0.097	0.345	0.647
<b>Total</b>	0.078	0.474	2.889	10.097	19.597	29.000	0.078	1.974	7.464	18.444	31.656	49.000	0.078	2.474	12.064	33.044	61.296	95.000

### 7.5.3. Floating wind power curve

For reference in use in PyPSA-GB, the power curve for the floating wind turbine is taken from the original 2020 reference wind turbine specification [321] (note that this was updated in February 2022) with minor changes to power curve (Figure 7.35).

Figure 7.35. Power curves from November 2020 and February 2022

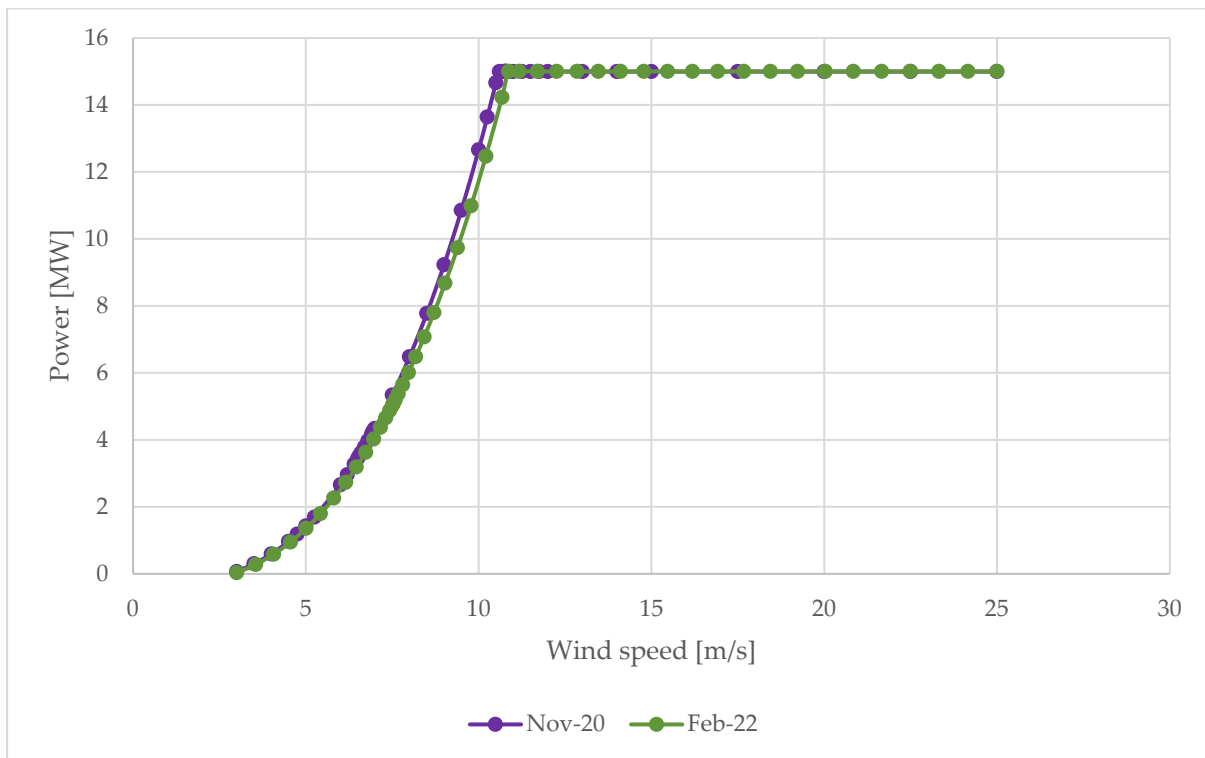


Figure 7.36. Trendline equation used to develop site AEP (as per Chapter 5).

## 7.6. Conclusions

This chapter has developed novel spatially defined deployment scenarios for:

1. Wave energy (high, medium and low), based on industrial and academic literature
2. Tidal stream (high, medium and low), based on industrial and academic literature
3. Floating wind (high, medium and low), based on data from the PhD industrial partner ORE Catapult

In addition, the geo-locations of the sites within these scenarios were used in conjunction with selected machine power characteristics (power curves or power matrices) and renewable resource data to develop hourly power generation:

1. Wave energy hourly power generation using historical reanalysis data and two device power matrices
2. Tidal stream hourly power generation using predicted velocities from the Thetis hydrodynamic model and single turbine device power curve
3. Floating wind hourly power generation using 100 m hub height historical reanalysis data and 15 MW turbine power curve

In addition, a fourth dataset of power generation was created:

4. Tidal lagoon hourly power generation (and power consumption) using consistent designs and hydrodynamic modelling, based on [103]

Each of these datasets has coverage for the years 2025, 2030, 2035, 2040, 2045 and 2050 as a minimum; the wave and floating wind sites have annual data.

### 7.6.1. Summary of all renewable energy locations defined in this thesis

Figure 7.37 shows an overview of all of the novel offshore renewable energy sites used in this thesis.

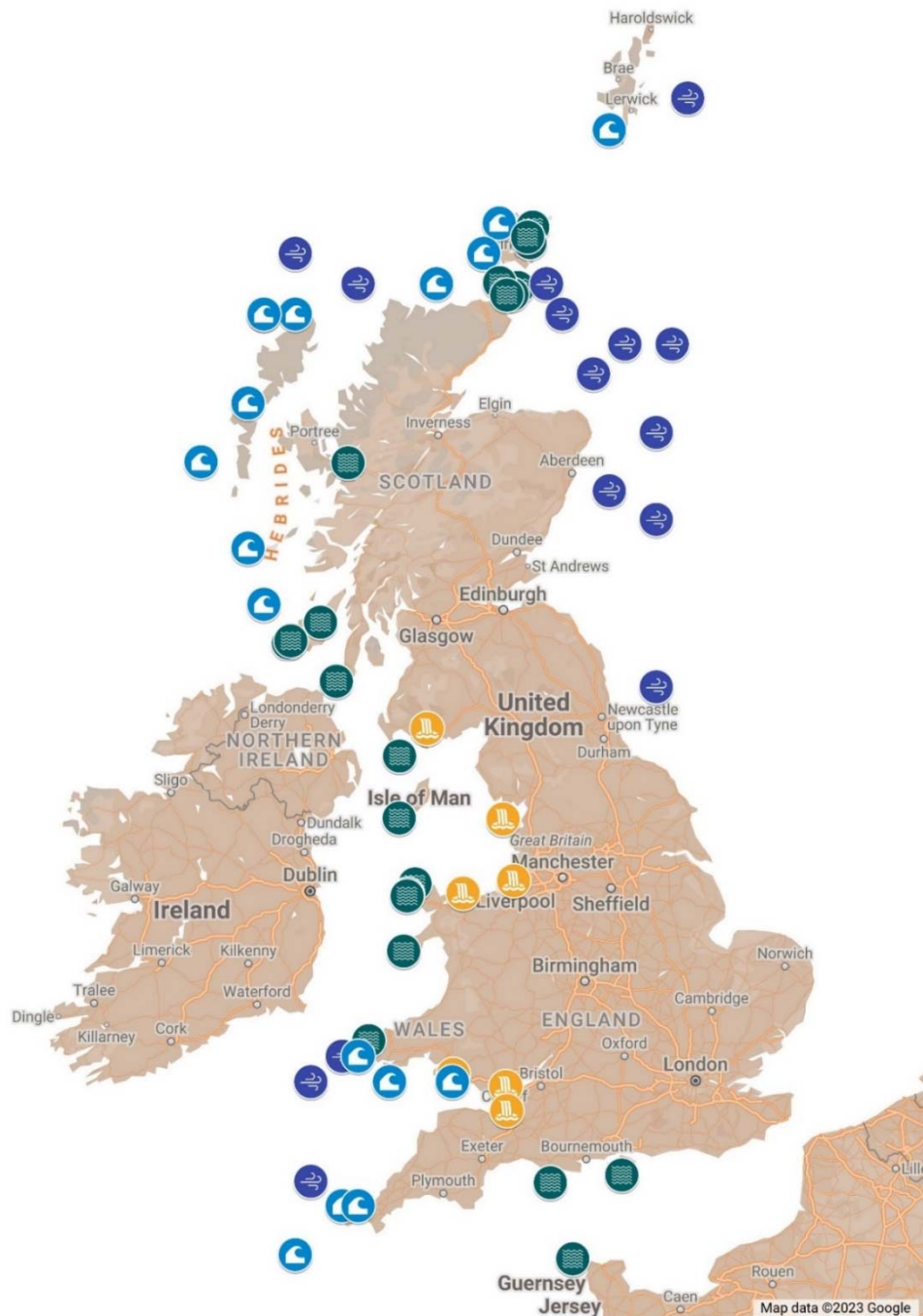


Figure 7.37. Overview map of wave energy (sky blue), tidal stream (teal), tidal lagoon (orange) and floating wind (dark blue) locations.

### 7.6.2. Limitations

The following limitations were observed for the method described in this chapter.

- Necessarily, there are no datasets identified at the suitable resolution with technological coverage of all technologies considered here, so the sources are diverse and not internally consistent (except for wave & tidal stream).
- The build order of tidal lagoon could be significant in FES given the magnitude of installed capacity (up to 7.969 GW), and references for this build order (and hence geo-location of generation in time) could be improved.
- Build order by LCOE could be misleading: high energy sites for wave and tidal stream are not necessarily most likely for nascent technologies, which may be more likely to be deployed at “nursery sites”. Similarly, there is no accounting for “distance from shore” or water depth; only average power. This could change the construction order but is unlikely to have significant impacts given the geographic clustering (and hence, likely low temporal complementary) of the resource – except for the North/South tidal stream divide.
- Availability, cable losses or O&M of the sites are not included and could significantly affect the power production of each site (see Chapter 4 and 5).
- Scaling the nominal installed capacity of each site to match ambitious high future projections could exceed the physical potential resource at some real world sites (e.g. MeyGen) [10].

### 7.6.3. Further work

In addition to addressing the limitations above, further work could include:

- Automating this process for future FES releases.
- Investigating the effect of alternative pumping strategies on tidal lagoon power output.
- Coverage for years outside of 2025:5:2050.
- Use of additional device types to improve capacity factors at each site.

# Chapter 8: Emissions reduction potential of floating wind, wave and tidal stream in future energy scenarios around GB

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This chapter concludes the thesis research and determines the emissions reduction potential of floating wind, wave and tidal stream in future energy scenarios around GB in two ways:

1. Considering the installed capacities and carbon intensity of the 2022 National Grid future energy scenarios (FES), in combination with the life cycle assessment (LCA) results from chapters 4 and 5.
2. Using PyPSA-GB as an example demonstration of the emissions reduction potential of marine energy in the year 2045.

## 8.1. Introduction

This chapter determines the emissions reduction potential of floating wind, wave and tidal stream in future energy scenarios around GB by:

1. Assessing the net emissions impact of the installed capacities of floating wind, wave energy and tidal stream energy in four 2022 National Grid future energy scenarios (FES2022), over the period 2025-2050, in combination with life cycle assessment (LCA) results from Chapters 4 and 5 (Section 8.2).
2. Using PyPSA-GB to assess the avoided CO<sub>2</sub> emissions potential of marine energy (wave energy and tidal stream) in two future energy scenarios for a single year, 2045 (Section 8.3).
3. Comparing and critically appraising the strengths and weaknesses of the two methods, and discussing the qualitative insight provided (Section 8.4).

## 8.2. Net emissions impact of floating wind, wave energy and tidal stream

This section describes an arithmetic method to investigate the net life cycle GHG emissions of the floating wind, wave energy and tidal stream technologies when their operational emissions reduction is considered, using the installed capacities and the associated carbon intensity of power according to FES2022.

### 8.2.1. Method

This approach uses a simple method to disaggregate the statically determined life cycle GHG emissions into the life stages in time, to combine this with a putative method to determine the avoided emissions using a simple relation between the installed capacity of the technology, an average AEP and an amended carbon intensity (CI) relative to the carbon intensity published in FES2022. The method uses the scenarios in Chapter 7 for three technologies (floating wind, wave energy and tidal stream), and the life cycle emissions from Chapter 4 and 5. A 25 year life is required, to simplify the method as FES2022 does not explicitly include decommissioning. Later in the chapter this method will be referred to as 'AEP-CI' and compared the 'PyPSA-GB' method. A related method can be found in [228].

#### 8.2.1.1. Distribution of carbon intensity across the life cycle

The first step is to disaggregate the life cycle GHG emissions to each life cycle stage, and to distribute this in a representative manner across the temporal coverage of FES2022, here selected as 2025-2050. Table 8.1 specifies the parameters that were assumed to discretise the life cycle stages in time according to integer years. Table 8.2 indicates the general and specific form of the discretisation method. Table 8.3 repeats the results from chapter 5, and these are converted from a 20 year design life to a 25 year design life in Table 8.4 (suitable for the period

2025 to 2050). Table 8.5 and Table 8.6 repeat this for wave energy, and Table 8.7 and Table 8.8 repeat this for tidal stream (note that tidal stream GWP is determined from the literature unlike a previous chapter for floating wind and wave energy). Table 8.9 summarises the inputs that are required for the method to follow.

Table 8.1. Nominal parameters to discretise the life cycle in time.

Parameter	Life cycle	Years	Implications
<b>a</b>	MM → Operation	-2	Array materials and fabrication occur in the single year, 2 years before commencing operation.
<b>b</b>	TI → Operation	-1	Array is completely installed in 1 year, immediately prior to beginning operational life
<b>design_life</b>	Operation → Design life	25	Design life of 25 years. Setting the design life to 25 year removes the consideration of DR and LR for the period 2025 to 2050, (around 8% of total GWP impact). This is necessary to be compatible with FES2022.
<b>c</b>	Design life → DR	1	Array is disassembled entirely 1 year immediately following the end of operational life
<b>d</b>	Design life → LR	2	Array is disposed of completely 2 years immediately after the end of operational life

Table 8.2. Life cycle stages discretised into integer value years.

	MM	TI	OM	DR	LR
<b>General</b>	$y_{i-a}$	$y_{i-b}$	$y_i \rightarrow y_{\text{design\_life}}$	$y_{\text{design\_life}+c}$	$y_{i+\text{design\_life}+d}$
<b>Specific</b>	$y_{-2}$	$y_{-1}$	$y_0 \rightarrow y_{25}$	$y_{26}$	$y_{27}$

Table 8.3. Floating wind (arrays of IEA-15-240-RWT) GWP results from Chapter 5 (20 year design life).

	GWP [gCO <sub>2</sub> eq/kWh]	Materials & Manufacturing (M&M)	Transport & Installation (T&I)	Operation & Maintenance (O&M)	Decommissioning & Removal (D&R)	Landfill & Recycling (L&R)	AEP [GWh/yr]
<b>E3</b>	17.4	78.3%	4.7%	8.9%	3.0%	5.0%	68.7
<b>NE1</b>	20.0	71.2%	6.4%	13.2%	5.0%	4.3%	70.8
<b>NE7</b>	20.5	71.6%	4.9%	15.8%	3.3%	4.3%	71.5
<b>N3</b>	26.3	79.1%	4.4%	9.8%	2.7%	4.0%	68.9
<b>Average</b>	21.0	75.0%	5.1%	11.9%	3.5%	4.4%	70.0

Table 8.4. Converting average floating wind 20 year design life GWP to 25 year design life.

		M&M	T&I	O&M	D&R	L&R	Total
20 year life	Lifetime climate change contribution [gCO <sub>2</sub> eq]	2.21E+10	1.50E+09	3.50E+09	1.03E+09	1.30E+09	2.94E+10
	Energy production [kWh]	-	-	1.40E+09	-	-	1.40E+09
	GWP [gCO <sub>2</sub> eq/kWh]	15.8	1.1	2.5	0.7	0.9	21.0
	Life cycle stage GWP [%]	75.0%	5.1%	11.9%	3.5%	4.4%	100%
25 year life	Lifetime climate change contribution [gCO <sub>2</sub> eq]	2.21E+10	1.50E+09	4.38E+09	1.03E+09	1.30E+09	3.03E+10
	Energy production [kWh]	-	-	1.75E+09	-	-	1.75E+09
	GWP [gCO <sub>2</sub> eq/kWh]	12.6	0.9	2.5	0.6	0.7	17.3
	Life cycle stage GWP [%]	72.9%	5.0%	14.5%	3.4%	4.3%	100%

Table 8.5. Wave energy (arrays of Blue Horizon) GWP results from Chapter 4 (20 year design life).

	GWP [gCO <sub>2</sub> eq/kWh]	M&M	T&I	O&M	D&R	L&R	AEP [GWh/yr]
<b>Birsay</b>	68.3	62.5%	6.7%	22.4%	6.5%	1.8%	3.22
<b>Farr</b>	69.3	60.7%	6.9%	24.7%	6.1%	1.7%	3.58
<b>Arnol</b>	87.1	54.8%	5.5%	33.4%	4.8%	1.5%	3.13
<b>Maywick</b>	94.9	64.9%	8.1%	17.3%	7.8%	1.9%	2.26
<b>Average</b>	79.9	60.7%	6.8%	24.4%	6.3%	1.7%	3.0

Table 8.6. Converting average wave energy 20 year design life GWP to 25 year design life.

		<b>M&amp;M</b>	<b>T&amp;I</b>	<b>O&amp;M</b>	<b>D&amp;R</b>	<b>L&amp;R</b>	<b>Total</b>
20 year life	<b>Lifetime climate change contribution</b> [gCO <sub>2</sub> eq]	2.96E+09	3.32E+08	1.19E+09	3.07E+08	8.29E+07	4.87E+09
	<b>Energy production [kWh]</b>	-	-	6.10E+07	-	-	6.10E+07
	<b>GWP [gCO<sub>2</sub>eq/kWh]</b>	<b>48.5</b>	<b>5.4</b>	<b>19.5</b>	<b>5.0</b>	<b>1.4</b>	<b>79.8</b>
	<b>Life cycle stage GWP [%]</b>	60.7%	6.8%	24.4%	6.3%	1.7%	100%
25 year life	<b>Lifetime climate change contribution</b> [gCO <sub>2</sub> eq]	2.96E+09	3.32E+08	1.49E+09	3.07E+08	8.29E+07	5.17E+09
	<b>Energy production [kWh]</b>	-	-	7.62E+07	-	-	7.62E+07
	<b>GWP [gCO<sub>2</sub>eq/kWh]</b>	<b>38.8</b>	<b>4.3</b>	<b>19.5</b>	<b>4.0</b>	<b>1.1</b>	<b>67.7</b>
	<b>Life cycle stage GWP [%]</b>	57.3%	6.4%	28.8%	5.9%	1.6%	100%

Table 8.7. Tidal stream GWP results (AEP assumes rated power of 2 MW, capacity factor of 0.34) [322], 20 year design life. Note this is for single device.

	GWP [gCO <sub>2</sub> eq/kWh]	M&M	T&I	O&M	D&R	L&R	AEP [GWh/yr]
<b>Average</b>	23.1 [322]	60.7%	6.8%	24.4%	6.3%	1.7%	6.0

Table 8.8. Converting average tidal stream 20 year design life GWP to 25 year design life, using same life cycle stage GWP percentage contributions as wave energy.

		<b>M&amp;M</b>	<b>T&amp;I</b>	<b>O&amp;M</b>	<b>D&amp;R</b>	<b>L&amp;R</b>	<b>Total</b>
20 year life	<b>Lifetime climate change contribution</b> [gCO <sub>2</sub> eq]	1.54E+09	1.73E+08	6.19E+08	1.60E+08	4.31E+07	2.54E+09
	<b>Energy production [kWh]</b>	-	-	1.19E+08	-	-	1.19E+08
	<b>GWP [gCO<sub>2</sub>eq/kWh]</b>	<b>12.9</b>	<b>1.4</b>	<b>5.2</b>	<b>1.3</b>	<b>0.4</b>	<b>21.3</b>
	<b>Life cycle stage GWP [%] (wave energy)</b>	60.7%	6.8%	24.4%	6.3%	1.7%	100%
25 year life	<b>Lifetime climate change contribution</b> [gCO <sub>2</sub> eq]	1.54E+09	1.73E+08	7.74E+08	1.60E+08	4.31E+07	2.69E+09
	<b>Energy production [kWh]</b>	-	-	1.49E+08	-	-	1.49E+08
	<b>GWP [gCO<sub>2</sub>eq/kWh]</b>	<b>10.3</b>	<b>1.2</b>	<b>5.2</b>	<b>1.1</b>	<b>0.3</b>	<b>18.1</b>
	<b>Life cycle stage GWP [%]</b>	57.3%	6.4%	28.8%	5.9%	1.6%	100%

Table 8.9. Summary of technology inputs.

	Variable	Floating wind	Wave energy	Tidal stream
Design life [years]	design_life	25	25	25
Average GWP converted to 25 year design life	GWP	17.3	67.7	18.1
Average machine AEP [kWh/year]	AEP	7.00E+07	3.05E+06	5.96E+06
Machine rated power [MW]	P <sub>rated</sub>	15	1	2
AEP' per MW installed [kWh/yr/MW <sub>installed</sub> ]	AEP'	4.67E+06	3.05E+06	2.97E+06
Lifetime energy production per MW installed [kWh/MW]	LEP'	1.17E+08	7.62E+07	7.45E+07
Lifetime embodied carbon per MW installed [gCO <sub>2</sub> /MW]	LEC'	2.02E+09	5.17E+09	1.34E+09

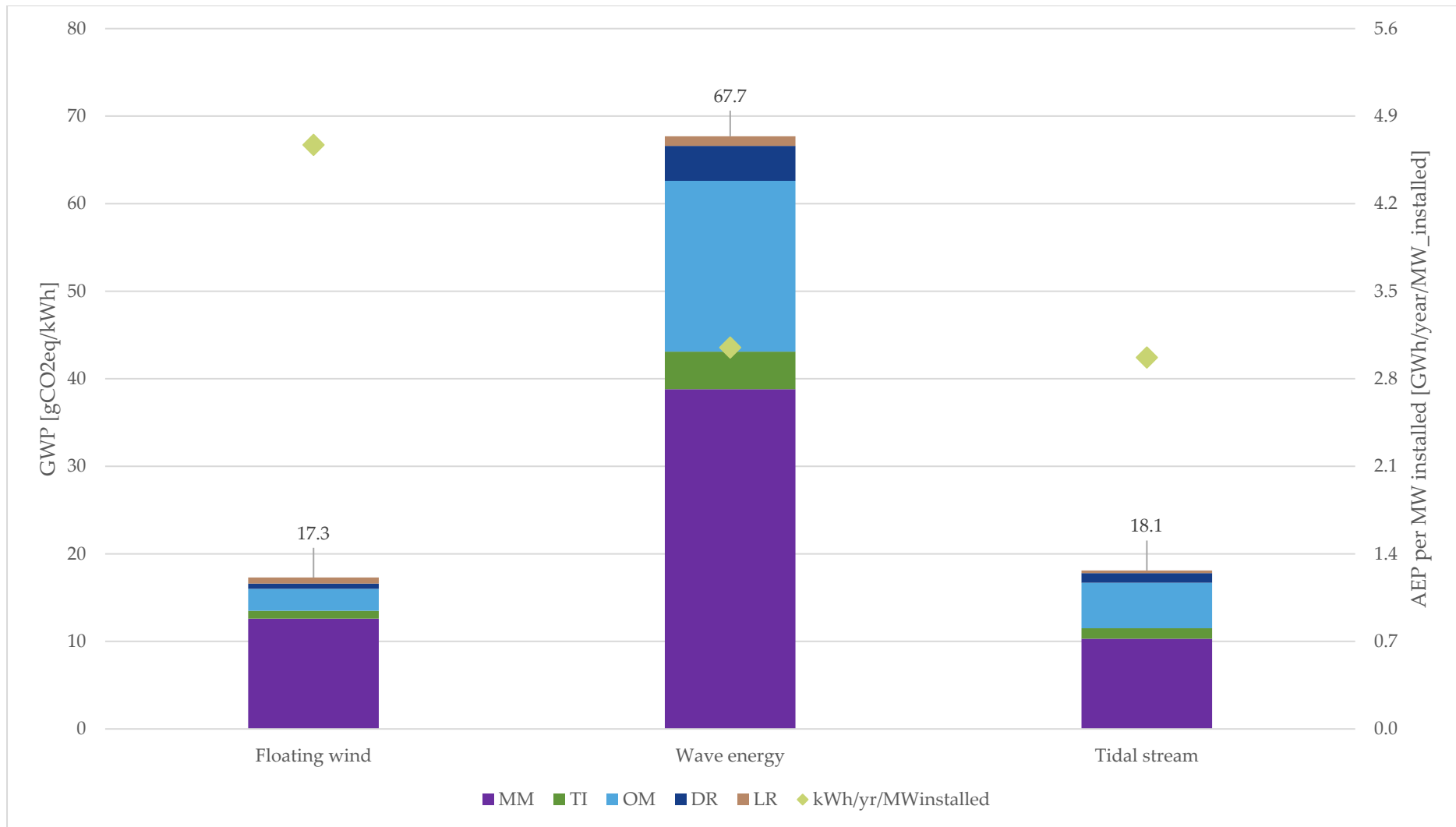


Figure 8.1. Global warming potential (GWP) adjusted to represent a 25 year life average of the three technologies.

### 8.2.1.2. Avoided emissions post-installation year to 2050

Now that the life cycle carbon intensity has been discretised to integer years, it is trivial to *subtract* the avoided emissions as those avoided annually by operation. This can be done by multiplying the AEP' [kWh/year/MW] by the installed capacity present in that year for a given area from Chapter 7 and the carbon intensity in that year. However, the emission intensity ("carbon intensity") of the scenario is assumed to be determined by the presence of the technology in question at zero emissions per unit of energy generated. It is possible to calculate the carbon intensity had that technology not been present by considering the amount of energy generated, and subtracting this from the stated generation that year. Putting to one side, that the power system would likely not operate correctly if significant volumes of installed capacity were removed in this manner, and so it does not truly represent a realistic scenario. It should also be noted that the adjusted carbon intensity is almost identical (> 0.1 % change for the year 2050, Table 8.10) relative to the original when wave and tidal are removed in this manner, although this does vary year-to-year. For floating wind this rises to a change of between 27% and 40%. This effectively skews the effectiveness of floating offshore wind slightly but was judged to be more representative than the unadjusted carbon intensity values.

$$\text{Carbon intensity, } \varepsilon, \text{ in year } i: \varepsilon_i = \frac{\text{Annual emissions}_i}{\text{Annual energy generated}_i} = \frac{GHG_i}{E_i} = \frac{[gCO_2]}{[kWh]}_i \quad \text{Equation 5}$$

$$\text{Carbon intensity adjusted for technology (k) generation (E):} \quad \varepsilon_{i_k} = \frac{GHG_i}{E_i - E_{i_k}} = \frac{[gCO_2]}{[kWh_i - kWh_{i_k}]} \quad \text{Equation 6}$$

$$\text{Energy delivered by technology (k) of installed capacity (G):} \quad E_{i_k} = AEP'_k \cdot G_{i_k} = [kWh/year / MW_{instaled}] \quad \text{Equation 7}$$

$$\text{Avoided emissions specifically attributable to technology (k) fleet:} \quad GHG_{i_k} = -(\varepsilon_{i_k} \cdot E_{i_k}) \quad \text{Equation 8}$$

$$\text{Substituting from Equation 3:} \quad GHG_{i_k} = -(\varepsilon_{i_k} \cdot AEP'_k \cdot G_{i_k}) \quad \text{Equation 9}$$

$$\sum_{i=-2}^{y=2050} GHG_{i_k} = -(\varepsilon_{i_k} \cdot AEP'_k \cdot G_{i_k}) \quad \text{Equation 10}$$

Table 8.10. Adjusted carbon intensities and ratio relative to unadjusted FES2022.

	2050 Carbon intensity [gCO <sub>2</sub> /kWh]				Ratio to FES2022		
	FES2022	Floating wind	Wave energy	Tidal stream	Floating wind	Wave energy	Tidal stream
CT	7.3	10.3	7.3	7.3	1.40	1.000	1.001
ST	5.4	7.6	5.4	5.4	1.39	1.000	1.001
LW	9.0	12.2	9.0	9.0	1.36	1.000	1.001
FS	16.6	21.1	16.6	16.6	1.27	1.000	1.001

Note that in FES2022, the carbon intensity does not account for changes to generation which would be needed to overcome network or operability constraints. Therefore real world values are likely to be higher given the non-optimal emissions intensities during power output changes (ramp-up / ramp-down) [9].

### 8.2.1.3. Carbon Payback GWP

The required GWP to meet carbon payback over the period is found when the displaced emissions from the carbon intensity of the FES2022 is equal to the embodied emissions of the technology fleet (assuming no decommissioning). This can be written:

$$AEP' \cdot \sum_i^{d_l} \varepsilon_i \cdot G_i = AEP' \cdot GWP_{payback} \cdot d_l \cdot G_{d_l} \quad \text{Equation 11}$$

$$GWP_{payback} = \frac{\sum_i^{d_l} \varepsilon_i \cdot G_i}{d_l \cdot G_{d_l}} \quad \text{Equation 12}$$

This implies that the carbon intensity should be high to ensure the arrays pay back – but this emphasises how carbon payback increasingly emerges as somewhat of a red herring for decarbonisation.

### 8.2.2. Results

The results of this method for the four FES2022 and three technologies are shown in Figure 8.2 to Figure 8.7. For floating wind, Figure 8.2 shows the build up of life cycle emissions for floating wind in FES2022 when these are attributed in the year of operation (according to the percentage breakdown of floating wind defined in Chapter 7); Figure 8.3 shows the same data but when the life cycle emissions are attributed in time according to Table 8.2. Similarly, Figure 8.4 and Figure 8.5 show the data for wave energy; and for tidal stream Figure 8.6 and Figure 8.7.

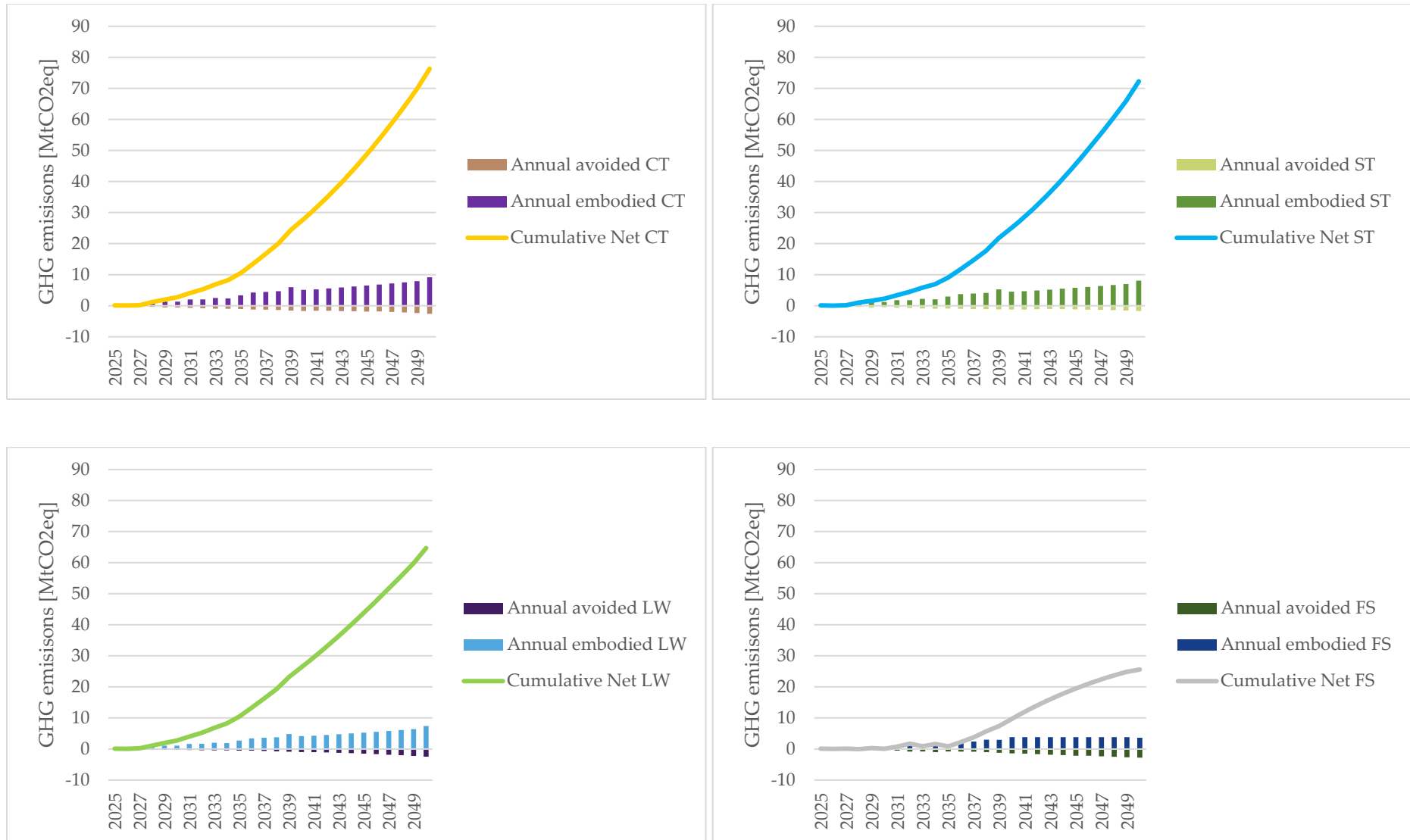


Figure 8.2. Life cycle GHG emissions across 2025 to 2050 attributable to floating wind in FES2022 (all emissions assumed in year of construction). Clockwise from top-left: CT, ST, FS, LW.

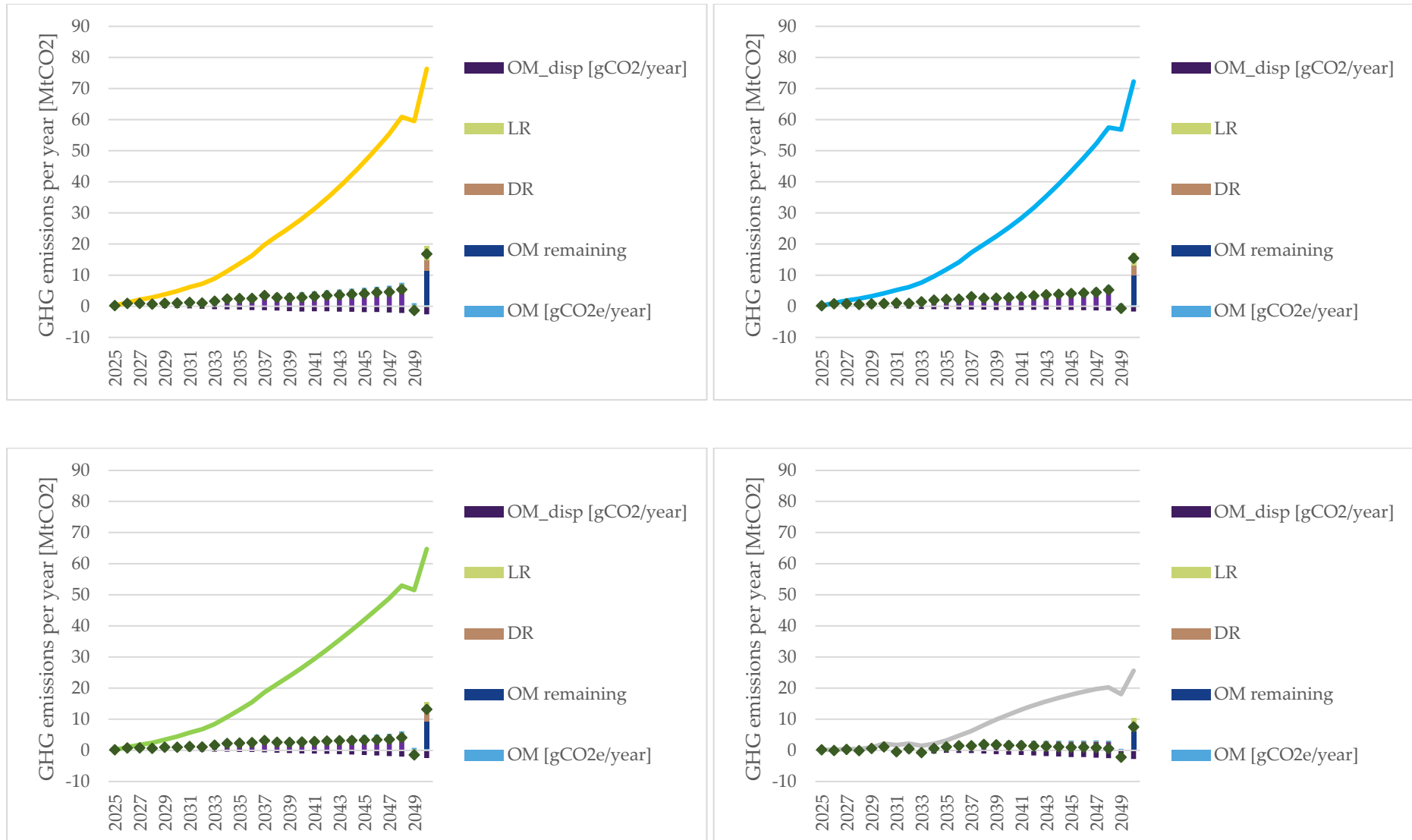


Figure 8.3. Life cycle GHG emissions across 2025 to 2050 attributable to floating wind in FES2022 (emissions assumed as per Table 8.2). Clockwise from top-left: CT, ST, FS, LW.

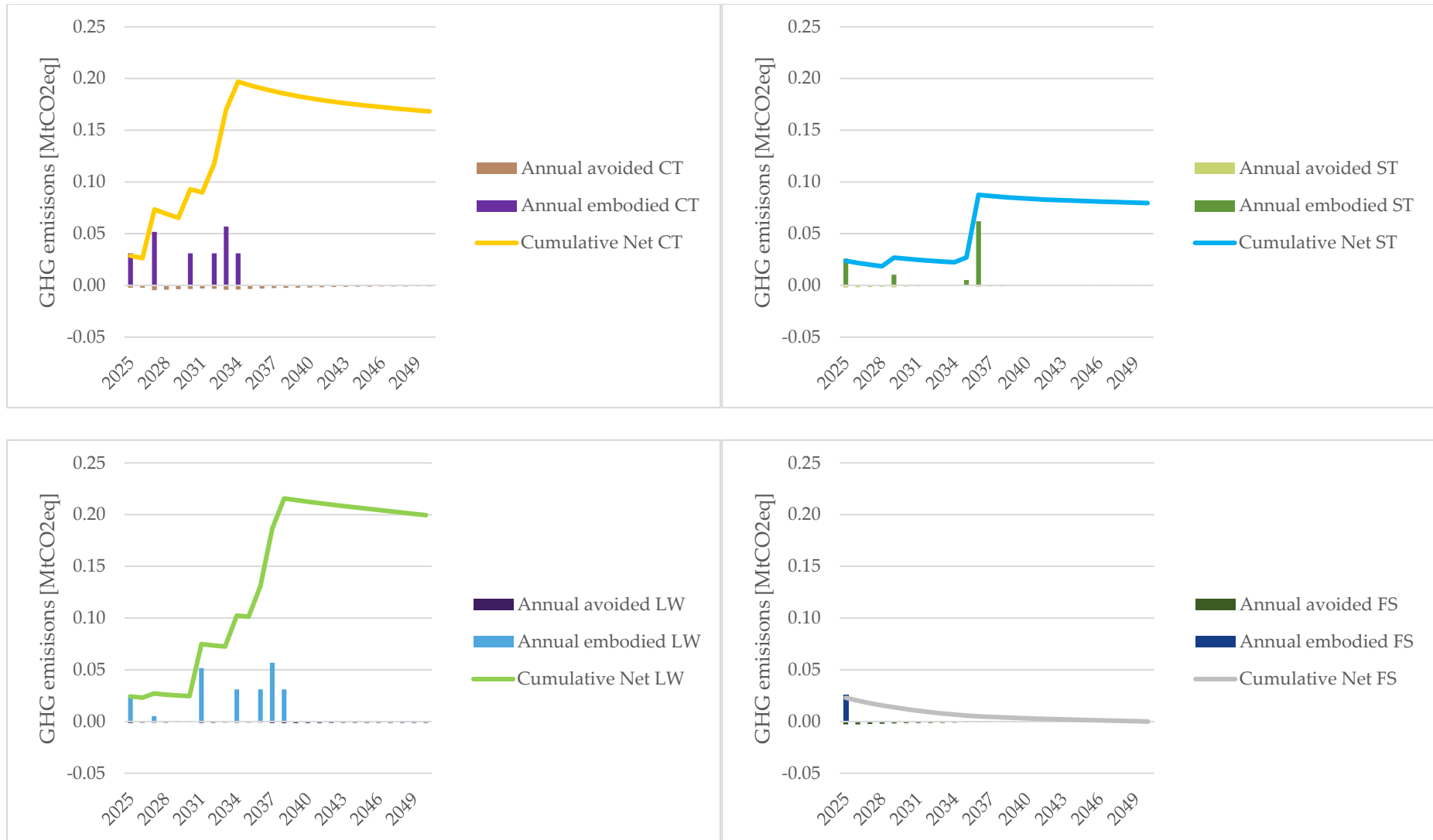


Figure 8.4. Life cycle GHG emissions across 2025 to 2050 attributable to wave energy in FES2022 (all emissions assumed in year of construction). Clockwise from top-left: CT, ST, FS, LW.

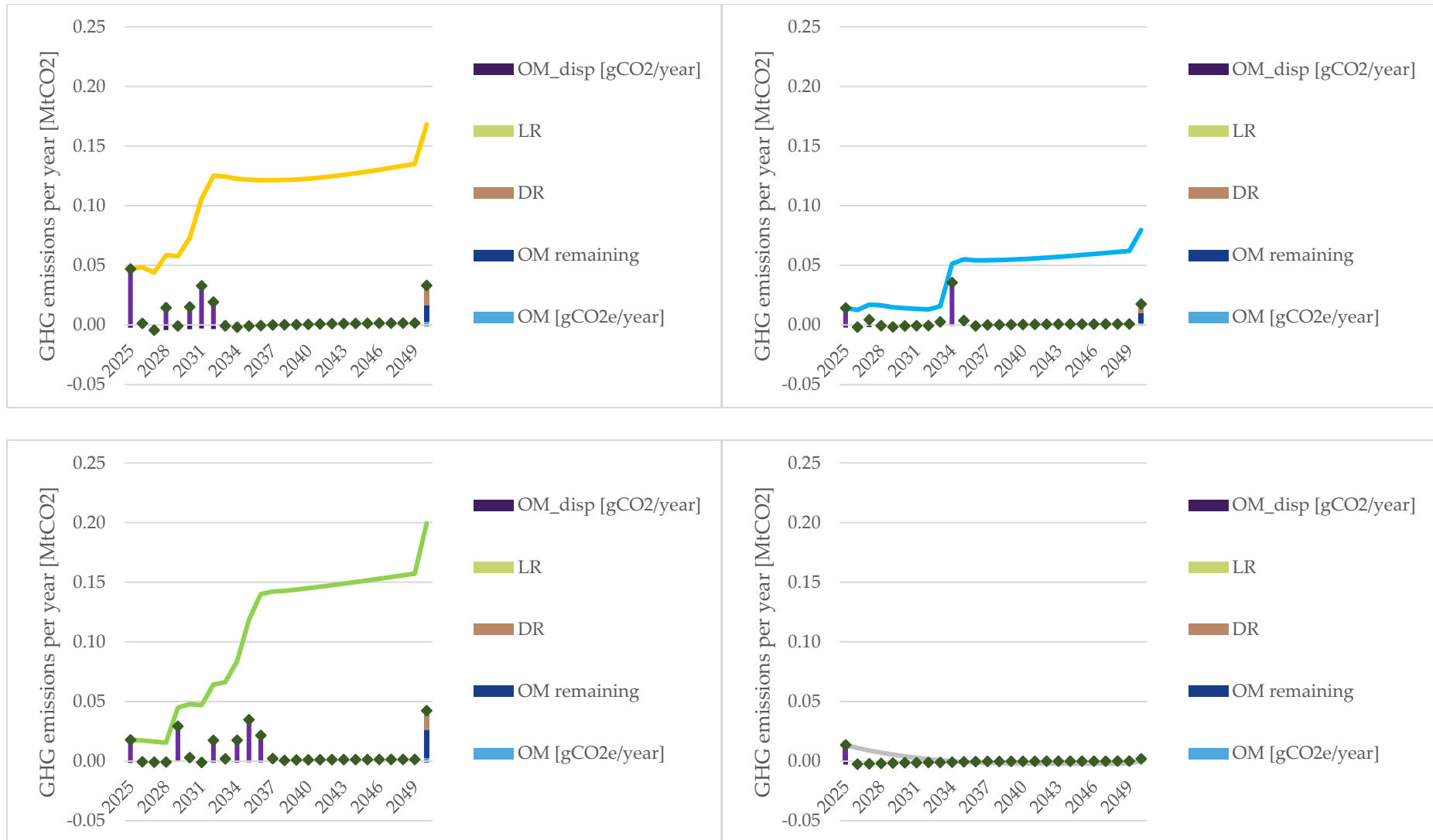


Figure 8.5. Life cycle GHG emissions across 2025 to 2050 attributable to wave energy in FES2022 (emissions assumed as per Table 8.2). Clockwise from top-left: CT, ST, FS, LW.

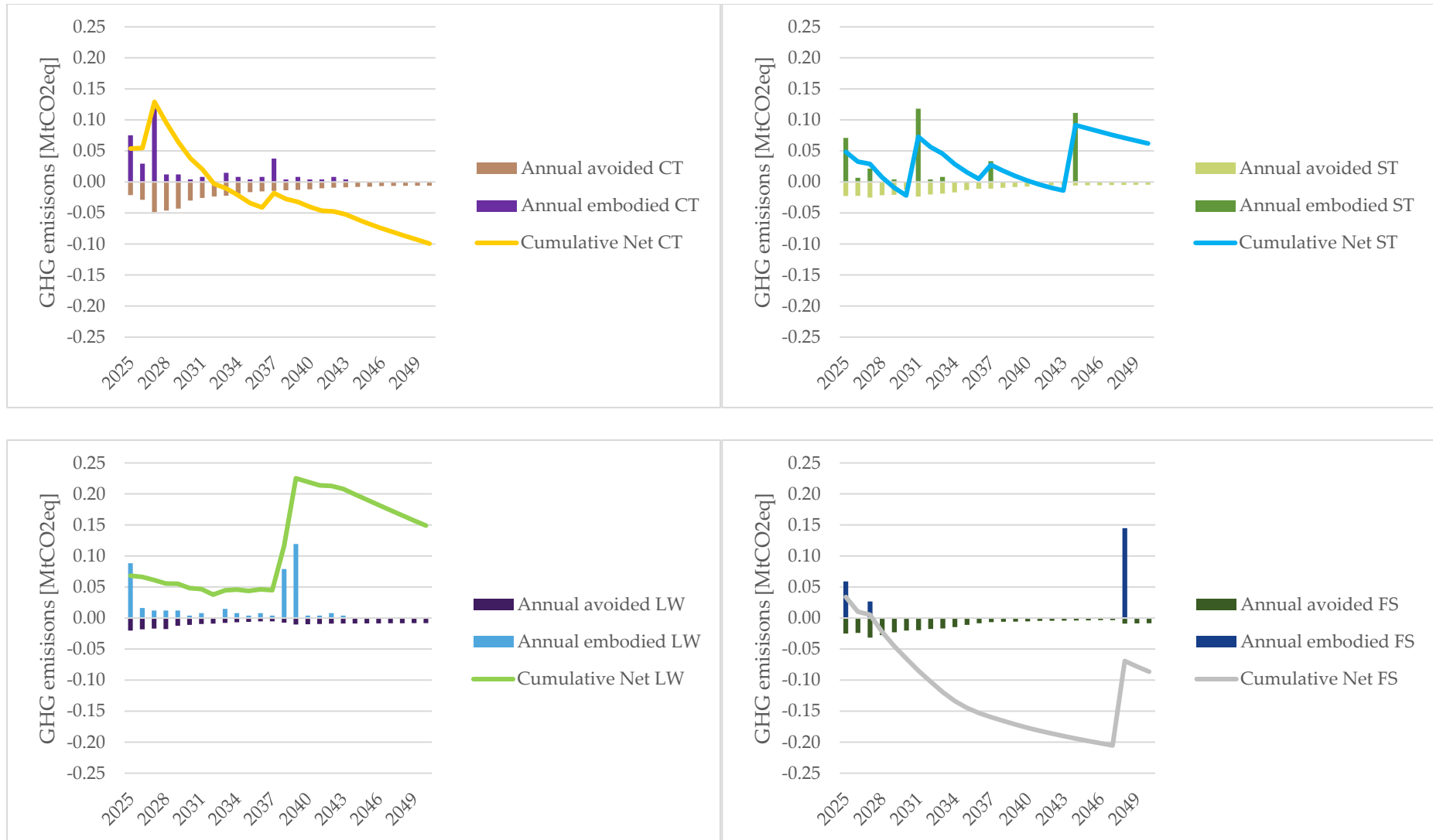


Figure 8.6. Life cycle GHG emissions across 2025 to 2050 attributable to tidal stream in FES2022 (emissions assumed in year of construction). Clockwise from top-left: CT, ST, FS, LW.

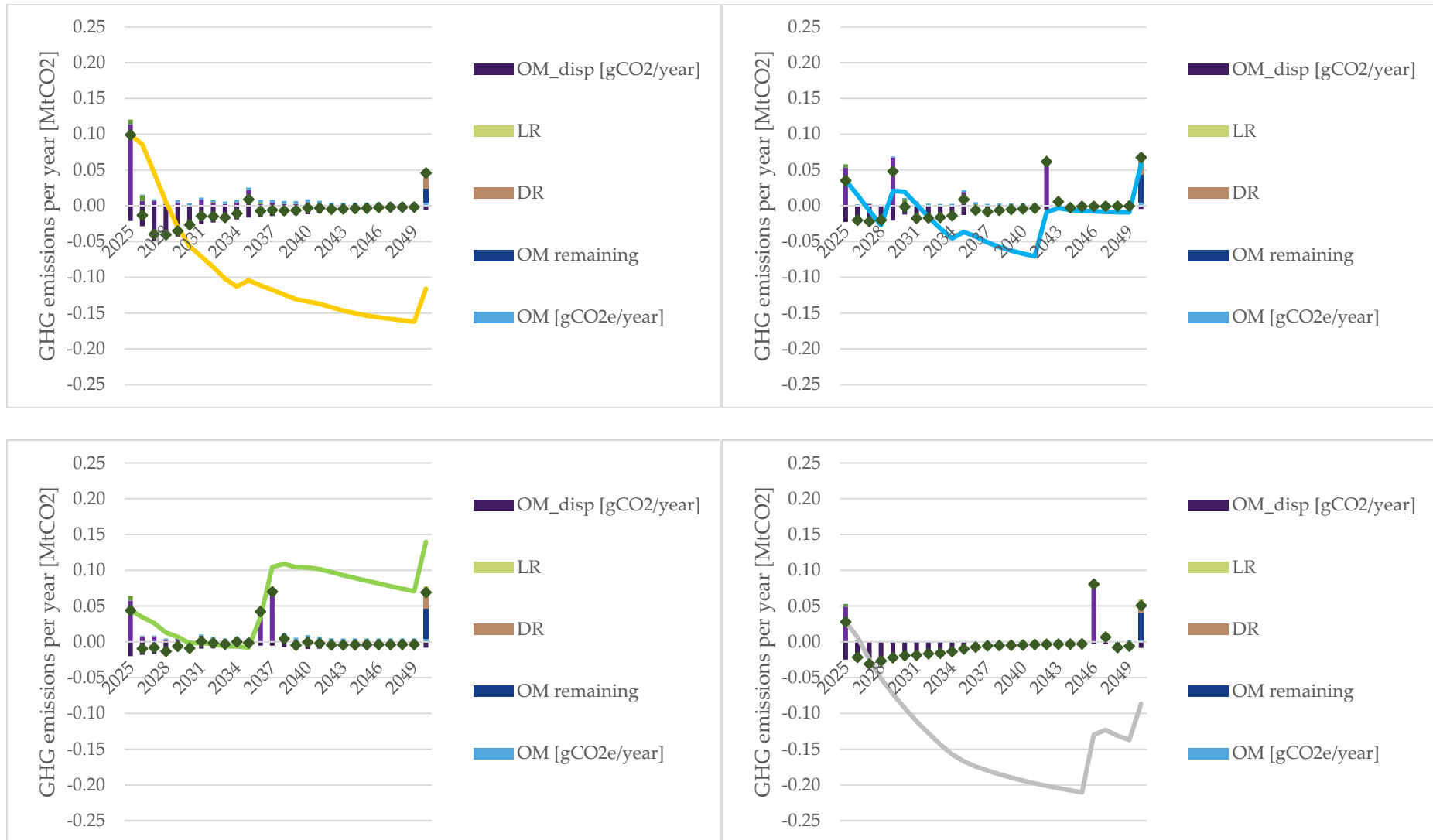


Figure 8.7. Life cycle GHG emissions across 2025 to 2050 attributable to tidal stream in FES2022 (emissions assumed as per Table 8.2). Clockwise from top-left: CT, ST, FS, LW.

Table 8.11. Emissions reduction potential of floating wind in FES2022, assuming displacement of an adjusted annually averaged GB power sector carbon intensity from FES2022, floating wind proportions as per ORE Catapult projections (Chapter 7), average AEP and life cycle emissions of the four sites considered in Chapter 5 over a 25 year life in the years 2025 to 2050, and no change to historically derived background systems of production (ecoinvent v3.3).

FES	Embodied emissions (2025 – 2050) [MtCO <sub>2</sub> ]	Avoided emissions (2025 – 2050) [MtCO <sub>2</sub> ]	Net emissions (2025 – 2050) [MtCO <sub>2</sub> ]	Generation (2025 – 2050) [TWh]	2050 Installed capacity [GW]	Net climate impact per unit energy, including avoided emissions [gCO <sub>2</sub> /kWh]	Net climate impact per unit installed capacity, including avoided emissions [MtCO <sub>2</sub> /GW]	GWP required to achieve carbon payback [gCO <sub>2</sub> /kWh]	Carbon payback?
CT	1.1E+02	-3.3E+01	7.6E+01	2247	54.0	34.0	1.41	5.2	No
ST	9.6E+01	-2.4E+01	7.2E+01	1986	47.8	36.4	1.51	4.3	No
LW	8.8E+01	-2.3E+01	6.5E+01	1815	43.7	35.7	1.48	4.6	No
FS	5.8E+01	-3.2E+01	2.6E+01	1159	28.6	22.1	0.90	9.6	No

Table 8.12. Emissions reduction potential of wave energy in FES2022, assuming displacement of an adjusted annually averaged GB power sector carbon intensity from FES2022, wave energy proportions of 'Marine' BB12 as per Chapter 7, average AEP and life cycle emissions of the four sites considered in Chapter 4 over a 25 year life in the years 2025 to 2050, and no change to historically derived background systems of production (ecoinvent v3.3). Note the result in FS driven by the tiny installed capacity.

FES	Embodied emissions (2025 – 2050) [MtCO <sub>2</sub> ]	Avoided emissions (2025 – 2050) [MtCO <sub>2</sub> ]	Net emissions (2025 – 2050) [MtCO <sub>2</sub> ]	Generation (2025 – 2050) [TWh]	2050 Installed capacity [GW]	Net climate impact per unit energy, including avoided emissions [gCO <sub>2</sub> /kWh]	Net climate impact per unit installed capacity, including avoided emissions [MtCO <sub>2</sub> /GW]	GWP required to achieve carbon payback [gCO <sub>2</sub> /kWh]	Carbon payback?
CT	2.3E-01	-6.4E-02	1.7E-01	2.855	0.045	58.9	3.74	18.7	No
ST	1.0E-01	-2.4E-02	8.0E-02	1.128	0.020	70.6	3.98	15.5	No
LW	2.3E-01	-3.3E-02	2.0E-01	2.373	0.045	84.1	4.43	9.6	No
FS	2.6E-02	-2.6E-02	8.8E-06	0.396	0.005	0.02	0.002	67.7	Yes (to one decimal place)

Table 8.13. Emissions reduction potential of tidal stream in FES2022, assuming displacement of an adjusted annually averaged GB power sector carbon intensity from FES2022, tidal stream proportions of 'Marine' BB12 as per Chapter 7, average AEP and life cycle emissions of the four sites considered in Chapter 4 over a 25 year life in the years 2025 to 2050, and no change to historically derived background systems of production (ecoinvent v3.3), using life cycle proportions as per WECs and GWP as per Uihlein (23.1 gCO<sub>2</sub>/kWh).

FES	Embodied emissions (2025 – 2050) [MtCO <sub>2</sub> ]	Avoided emissions (2025 – 2050) [MtCO <sub>2</sub> ]	Net emissions (2025 – 2050) [MtCO <sub>2</sub> ]	Generation (2025 – 2050) [TWh]	2050 Installed capacity [GW]	Net climate impact per unit energy, including avoided emissions [gCO <sub>2</sub> /kWh]	Net climate impact per unit installed capacity, including avoided emissions [MtCO <sub>2</sub> /GW]	GWP required to achieve carbon payback [gCO <sub>2</sub> /kWh]	Carbon payback?
CT	3.5E-01	-4.7E-01	-1.2E-01	17.5	0.275	-6.6	-0.42	22.9	Yes
ST	3.7E-01	-3.2E-01	5.8E-02	14.3	0.282	4.1	0.21	15.0	No
LW	4.0E-01	-2.6E-01	1.4E-01	15.7	0.306	8.9	0.46	11.5	No
FS	2.3E-01	-3.2E-01	-8.7E-02	5.8	0.172	-14.9	-0.50	24.8	Yes

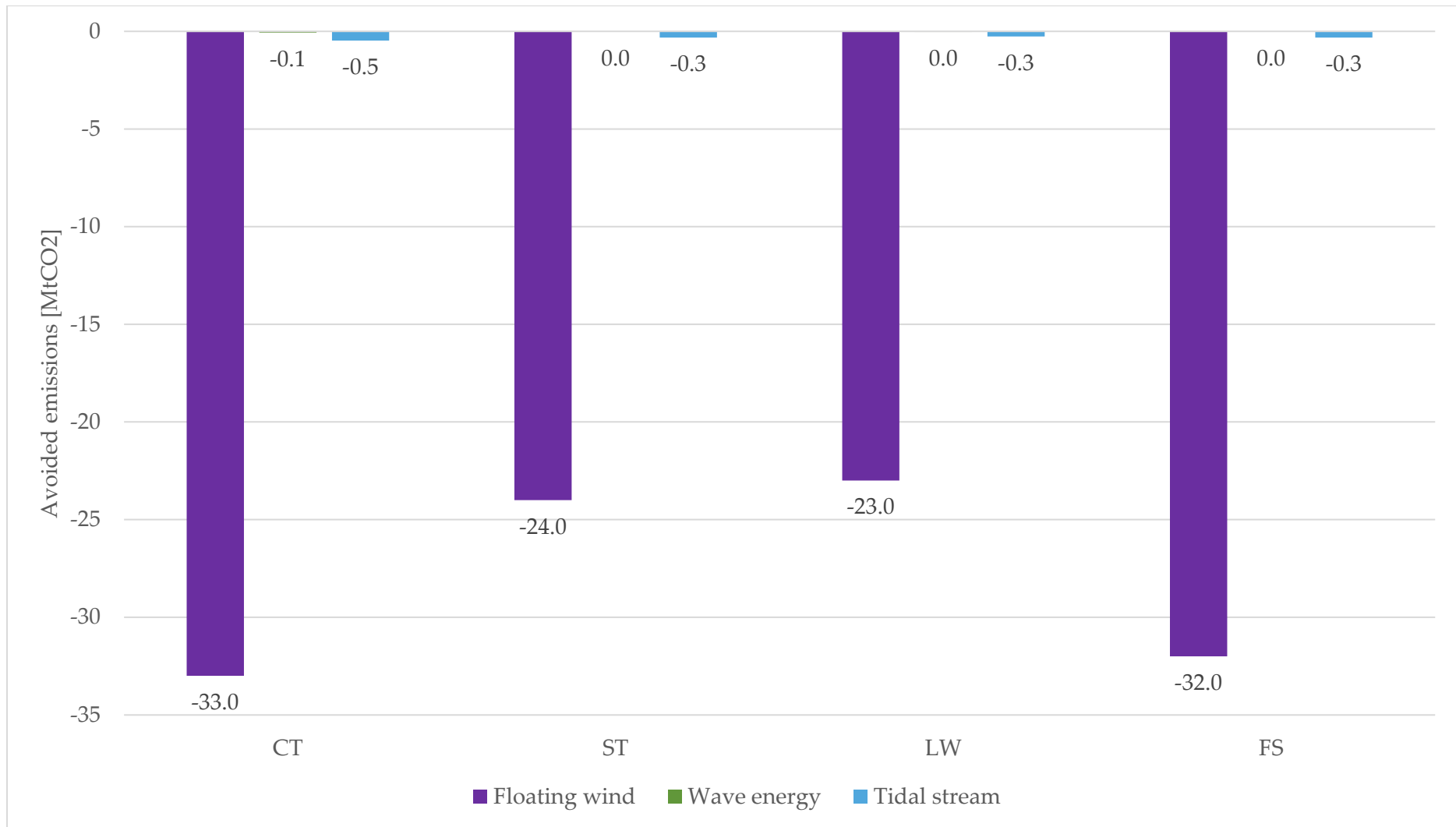


Figure 8.8. Avoided emissions attributable to each technology using this method over the period 2025 to 2050. Does not include life cycle embodied emissions.

Chapter 8: Emissions reduction potential of floating wind, wave and tidal stream in future energy scenarios around GB

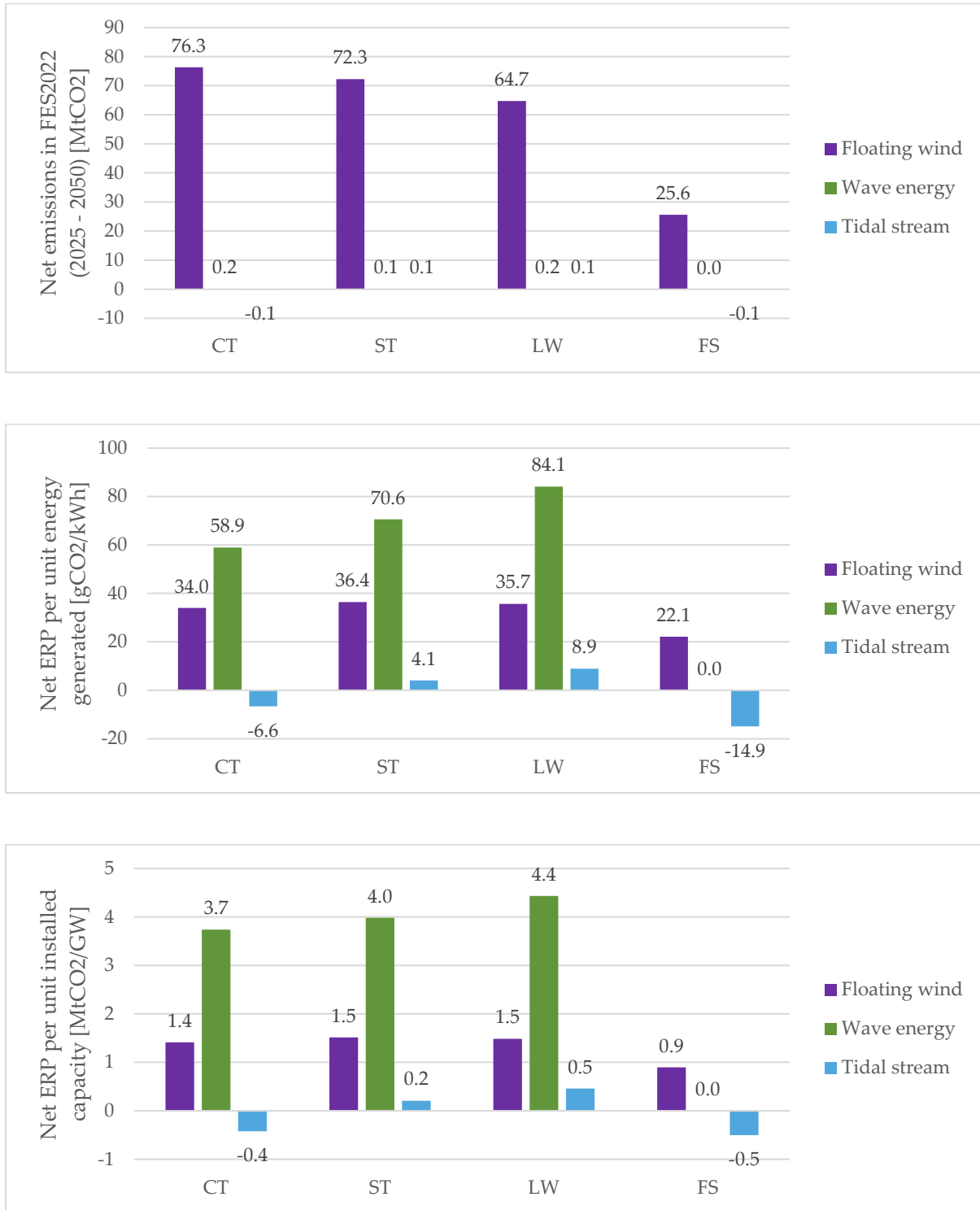


Figure 8.9. Three metrics for emissions reduction potential for floating wind, wave energy and tidal stream using LCA results from Chapter 4 and 5 and adjusted carbon intensity data from FES2022. Includes embodied emissions. Note only a few instances for tidal stream where net emissions are negative.

### 8.2.3. Discussion

From the tables and figures above, some details emerge:

- The net emissions impact of three novel technologies has been investigated over the period 2025 to 2050 using FES2022. An expression for GWP has been set out which calculates the GWP necessary in 2025 to achieve carbon payback for a given scenario.
- Only tidal stream achieved net negative emissions reduction when embodied emissions of preceding life cycle stages are accounted for, and only this in two scenarios. This paucity is in contrast to findings from a similar approach for onshore wind, but this can be explained by the high and static carbon intensity of power from the Chinese electricity system (866.3 gCO<sub>2</sub>/kWh) [228].
- By definition, the cumulative avoided emissions calculated in this method are dominated by the installed capacities of the technologies in all scenarios. Floating wind installed capacity and hence avoided emissions continue to grow over the period, while marine energy levels off.
- A picture emerges whereby the purportedly unique 'performance' of the technology, and subsequent emissions reduction potential is simply dictated by the carbon intensity of the future energy scenario considered. This suggests that the complementary potential of these three technologies is not necessarily *innate* or at least, that it is not the dominant factor in emissions reduction potential at a nationally and annually averaged resolution.
- Nevertheless, floating wind offers the deepest avoided emissions, driven by its significant installed capacity in the FES2022 (29 to 54 GW). However, the net emissions are still positive due to the significant installed capacity has an associated-ly high

embodied emissions (dwarfing wave energy and tidal stream three orders of magnitude, in line with the relative installed capacities in 2050). Unlike floating wind, wave energy and tidal stream see almost no new installed capacity which makes the capacity installed appear extremely efficient. The fleet here does not payback its embodied carbon, unlike the arrays in Chapter 5. This is due to the rampant build rate, set against the dwindling carbon intensity in each FES as time progresses.

- Wave energy has installed capacities in 2050 three orders of magnitude smaller than floating wind in every FES. This has a similarly significant impact on the avoided and net emissions over the period). Wave energy also performs poorly per unit of energy generated and unit of installed capacity due to its relatively high GWP, low AEP and low AEP'. In one case it achieves carbon payback due to the high carbon intensity of the scenario and very low installed capacity in 2025 (Figure 8.4 and Figure 8.5).
- Tidal stream has similarly small installed capacities in 2050, and achieves carbon payback in two scenarios (CT and FS, both which have high carbon intensity of power). The avoided emissions are two orders of magnitude less than floating wind, and the bulk emissions reduction potential is -0.1 MtCO<sub>2</sub> over the period.
- FES with sustainedly high nationally averaged carbon intensity per year observe the largest emissions reduction potential for each technology. This is not surprising and so the method clearly does not describe the emission reduction potential of the technologies themselves: rather the poor (or otherwise) performance of the FES from an emissions perspective.
- At the resolution of this treatment, it is not possible to argue that the temporally diverse complementarity of generation is the cause of this efficiency. Unless temporal

resolution is increased, the complimentary benefits of the different technologies are likely to be “masked”; and the emissions reduction efficacy is instead will be dictated by the scenario under consideration. Similarly, the relative installed capacities are so wildly disparate, that the differences in bulk emissions reduction potential are similarly stark.

- These results are of course, not comparable to other LCA literature without considering system expansion.

#### 8.2.4. Limitations

This method has a number of limitations:

- The carbon intensity is exogenously provided by the FES2022 data in this usage. Apart from an arithmetic adjustment, there is no investigation of the sensitivity of the carbon intensity emissions to the presence of these technologies. However, the simplicity of this method is deliberately intended to avoid a more complex treatment which follows in the next section.
- Tidal stream has the same life cycle distribution of emissions as wave (by percentage) – in reality, this is likely to be different.
- The treatment assumes a single generation technology for the fleet of generation when realistically, the floating wind, wave, and tidal stream technologies will comprise multiple diverse generation technologies from dissimilar OEMs; changing their AEP on a site-by-site and year-by-year basis. Over a 25 year period climate change, innovation in control systems and device rated power could affect the net energy production and capacity factors significant.

- Floating wind is simply assumed as a ratio of installed capacity of offshore wind, relative to the scenarios described in chapter 7.
- GWP is taken as a single static value (an average of the preceding chapters, or a single value from the literature) rather than a distribution. Different devices, arrays, and technological improvements would change these results. Other limitations described in chapter 4 and 5 also apply.
- There is no accounting for network topology or locational generation: carbon intensity is assumed for an annual timestep and at a national spatial resolution which is simply not the case. This increased resolution cannot be explored without using an alternative method.
- There is no allowance for part-load start-up shut down impact on emissions at this first integration into PyPSA-GB.
- The LCA is not prospective; a significant limitation given the temporal coverage of this method. At these time horizons, one would expect to see significant differences in the material production systems which contributed to the life cycle impacts of the arrays. Much impetus abounds on the decarbonisation of vessel propulsion, but in a slightly deflationary observation T&I and O&M contribute only slightly, relative to material production. Disposal methods are also hoped to be significantly different for far future arrays.
- System expansion would technically be required before these results were comparable with the literature. One approach to this might be to subtract bulk emissions reductions from median GWP by integration with SimaPro as an avoided product.

This would be challenging, as the carbon intensity would change so much as to require a new processes to be made, approaching the complexity of a prospective treatment.

- The method assumes an integer value for the number of years that each stage of the life cycle takes. In reality, the installation of offshore renewable energies takes multiple years, and the materials may be produced many years in advance. Further, the effect of life extension is not considered directly.

### 8.2.5. Conclusion

This basic method has shown that even in the deployment projections of FES2022, no technology consistently achieves carbon payback.

However, the results of this method show that it is not possible to assess the interaction of emission reduction potential at a sub-national or sub-annual level without using a more sophisticated method. The next chapter explores some resolution to this issue using power system modelling.

### 8.3. Emission reduction potential using power system modelling

As discussed in previous chapters, national, future net-zero energy scenarios for GB typically do not include substantial marine energy capacity (wave and tidal stream) based on their current costs and technological readiness [301]. However, these technologies have the potential to deliver a renewable energy mix with higher availability and improved supply-demand matching [116]. Tidal energy has also been shown to reduce system costs from balancing, reserve capacity and curtailment [323]. The presence of marine energy can also maximise efficient use of existing infrastructure relative to a single type of generation [237], which is particularly relevant for grids which are highly constrained, and face lengthy timescales for network expansion.

Accordingly, this final section of novel analysis explores the emissions reduction potential of marine renewable generation. Bulk CO<sub>2</sub> emissions and associated carbon intensity from hourly power generation are computed by power system modelling [324] and the impact of co-locating wave and tidal stream power generation on the rate and depth of decarbonisation is investigated by comparing National Grid future energy scenarios (FES) [301], with novel scenarios including higher capacities of marine energy. This work utilises the scenarios and the power generation time-series developed in [10] (Chapter 7 of this Thesis) as inputs to PyPSA-GB.

Floating wind is omitted from the scope of this analysis on the basis of available time and funding, and is highlighted as an opportunity for further work.

### 8.3.1. Method

Two interpreted future energy scenarios from National Grid (Section 8.3.1.1) were simulated using the open dataset and power dispatch model (PyPSA-GB) with renewable resource data and 29 bus transmission network model (Section 8.3.1.3) [13].

As an introduction to this method, only a single year is considered here. 2045 was selected as an exemplar where decarbonisation is well underway – indeed, beyond the 2035 target for delivering a decarbonised power system [325] – but contemporary with projections for substantive installed capacities of marine energy (Chapter 7). The CO<sub>2</sub> emissions results in the year 2045 considered are:

- Bulk emissions of generation nationally (Section 8.3.2)
- Carbon intensity of generation nationally
- Carbon intensity of generation at each bus (Section 8.3.2.8).

This process is then repeated using two novel scenarios(Chapter 7 and [10]) which replace the installed capacities of wave and tidal stream technologies in the FES. Each element of this method is described in the following sections.

#### 8.3.1.1. National Grid Future Energy Scenarios (FES2022)

For the purposes of this study, only two FES were selected for analysis: Consumer Transformation and Leading the Way (CT and LW). System Transformation (ST) was not selected on basis of high hydrogen heating – as independent evidence does not support widespread use of hydrogen for space and hot water heating [326] –while Falling Short (FS) is not compliant with the UK Net Zero targets.

As a primer, the emissions from the national power sector in 2045 as calculated in FES2022 are -32.3 MtCO<sub>2</sub>eq/year and -14.2 MtCO<sub>2</sub>eq/year, as a result of high deployment of bioenergy with carbon capture and storage (BECCS), Table 8.14. This dependence on BECCS is itself is arguably a motive for exploring the emissions reduction potential of alternative forms of low carbon generation (including marine energy), as BECCS remains largely unproven [327].

Table 8.14. Future Energy Scenarios 2022 Data Workbook, WS2: Whole System & Gas Supply – Emissions

[MtCO<sub>2</sub>eq/year] [301].

	CT	LW
<b>Power Sector BECCS</b>	-39.6	-21.1
<b>Electricity without BECCS</b>	7.3	6.9
<b>Total</b>	-32.3	-14.2

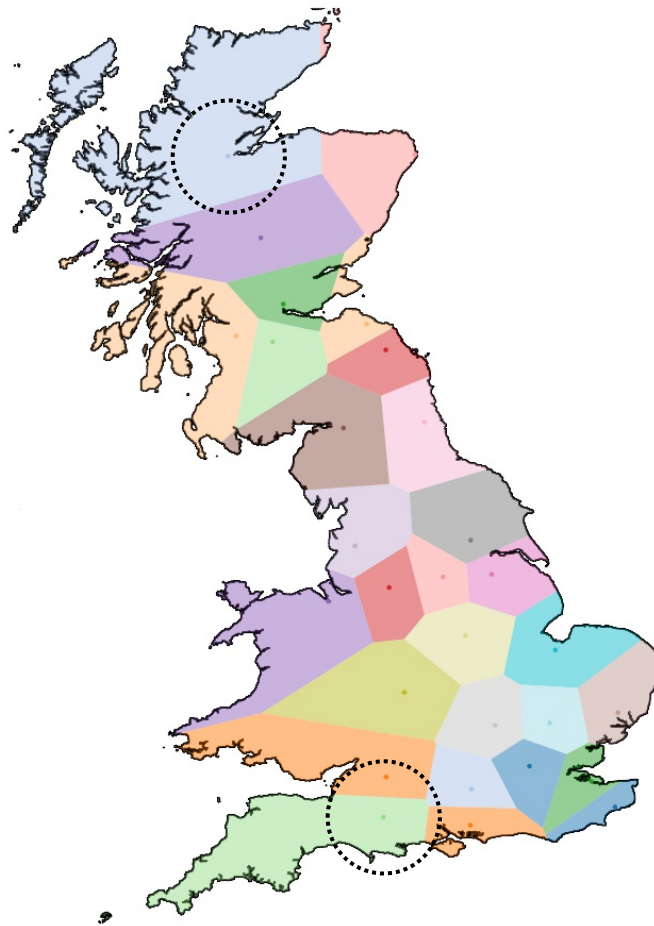
### 8.3.1.2. Integrating the installed capacity scenarios with FES 2022

The marine scenarios described in Chapter 7 are integrated into the FES by simple find and replace of marine installed capacities per year. This represents overbuilding outside of the original optimisation performed to develop the FES. The code in PyPSA-GB automatically “injects” the power from these additional renewable sites into the nearest transmission network node.

### 8.3.1.3. Power dispatch model: PyPSA-GB

PyPSA-GB is an open dataset and power dispatch model of the GB transmission network developed at the University of Edinburgh which uses National Grid’s Future Energy Scenarios as inputs for future power system modelling [13]. PyPSA-GB is executed in Python and based on the PyPSA open-source python environment [13].

This study uses network constrained linear optimal power flow (LOPF), using a 29 bus network model [328] and 2012 as the historic year for renewable resource data, other than tidal lagoon and tidal stream which were predicted directly using the Thetis coastal ocean model [10], [312].



*Figure 8.10. 29 bus model with associated Voronoi cells. The two nodes representing some of the most remote cells and communities of this network are highlighted by dotted circles: Beaulieu (top) and South West Peninsula (bottom).*

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Table 8.15. Interpreted locations of Marine energy from FES2022. Proximal locations are based on grid coordinates.

DNO License Area (FES2022)	GSP (FES2022)	Latitude (FES2022)	Longitude (FES2022)	Assumed location	Assumed network	Proximal location technology	Proximal site with largest capacity
NGET	Direct(NGET)	Not present	Not present	England/Wales	Transmission	Tidal lagoon	Various
SHETL	Direct(SHETL)	Not present	Not present	North Scotland	Transmission	Tidal stream	[10] (MeyGen)
SPTL	Direct(SPTL)	Not present	Not present	South Scotland	Transmission	Tidal lagoon	[103] (Solway)
SHEPD	Port Ann	56.026	-5.350	West coast Scotland	Distribution	Tidal stream	[10] (Sound of Islay)
South Western	Alverdiscott	51.006	-4.137	South west England	Distribution	Wave energy	[10] (Scarweather)
SEPD	Chickerell	50.624	-2.489	South England	Distribution	Tidal stream	[10] (Portland Bill)
NPgY	Elland	53.695	-1.823	Midlands	Distribution	Tidal lagoon	[103] (Liverpool)
SEPD	Fawley	50.821	-1.330	South England	Distribution	Tidal stream	[10] (Isle of Wight)
SHEPD	Lairg	58.008	-4.395	North Scotland	Distribution	Wave energy	[10] (Farr Point)
SEPD	Melksham	51.392	-2.150	South west England	Distribution	Tidal lagoon	[103] (Cardiff)
South Wales	Pembroke	51.682	-4.987	South Wales	Distribution	Wave energy	[10] (PDZ)
South Western	Taunton	51.017	-3.153	South west England	Distribution	Tidal lagoon	[103] (Watchet)
SHEPD	Thurso	58.572	-3.509	North coast Scotland	Distribution	Tidal stream	[10] (Brims)
SPM	Wylfa	53.414	-4.482	North Wales	Distribution	Tidal stream	[10] (Anglesey Skerries)

### 8.3.1.4. Marginal costs

Marginal costs were selected to reflect a semi-regulated dispatch order, that is: nuclear and BECCS should always run. BECCS is assumed as *negative* operational emissions. Hence, dispatching variable renewables with *zero* operational emissions to avoid running BECCS actually leads to an increase in operational emissions. The energy delivered from BECCS to the grid is not trivial in CT so BECCS was set to a negative cost in this analysis to achieve this dispatch order. Otherwise, the default values from PyPSA-GB were used.

Table 8.16: Assumed future marginal costs of generation.

Type	Marginal cost [€/MWh]	Object	Dispatch order
BECC	-5 {120}	Generator (Thermal)	1 <sup>st</sup>
Hydro	0	Generator (Renewable)	= 2 <sup>nd</sup>
Solar Photovoltaics	0	Generator (Renewable)	= 2 <sup>nd</sup>
Tidal lagoon	0	Generator (Renewable)	= 2 <sup>nd</sup>
Tidal stream	0	Generator (Renewable)	= 2 <sup>nd</sup>
Wave power	0	Generator (Renewable)	= 2 <sup>nd</sup>
Wind Offshore	0	Generator (Renewable)	= 2 <sup>nd</sup>
Wind Onshore	0	Generator (Renewable)	= 2 <sup>nd</sup>
Interconnectors Import	0	Interconnection	= 2 <sup>nd</sup>
Battery	0	Storage	= 2 <sup>nd</sup>
Compressed Air	0	Storage	= 2 <sup>nd</sup>
Liquid Air	0	Storage	= 2 <sup>nd</sup>
Pumped Storage (Hydroelectric)	0	Storage	= 2 <sup>nd</sup>
Nuclear	5	Generator (Thermal)	3 <sup>rd</sup>
Biomass (co-firing)	44	Generator (Thermal)	= 4 <sup>th</sup>
Biomass (dedicated)	44	Generator (Thermal)	= 4 <sup>th</sup>
Hydrogen	80	Generator (Thermal)	5 <sup>th</sup>
CCS Gas	100	Generator (Thermal)	6 <sup>th</sup>
CCGT	High (year dependent)	Generator (Thermal)	7 <sup>th</sup>
Unmet Load	999	Unmet Load	8 <sup>th</sup>

### 8.3.1.5. Cases, installed capacities and future energy scenarios

For this chapter, six cases were considered for the year 2045:

- **FES2022 interpreted installed capacity scenarios:** Within FES2022, 'Marine' energy includes wave, tidal stream and tidal lagoon, and is not disaggregated explicitly. This makes it impossible to accurately represent the temporal complementarity arising from the site installed capacity, spatial distribution and diversity of renewable resource (sea surface waves, tidal current and tidal range) without some interpretation. To overcome this, these capacities were interpreted manually according to coordinates from the Regional Breakdown of FES2022 data, which were inspected to deduce the location and installed capacity as per Chapter 7.
- **Novel installed capacity scenarios:** the marine energy installed capacity scenarios were selected from [10]. Two scenarios were selected, 'Low' and 'High', to bound the maximum possible range of installed capacity of marine energy expected outside of FES2022. For the two FES considered, the wave and tidal stream installed capacities were simply removed and replaced with the installed capacity of the novel scenarios. Note that the 'Low' augmented scenario still has significantly more marine energy installed than either CT or LW.
- **Years:** in general, marine energy has lower technological readiness than more established renewable energy technologies such as onshore wind, solar and offshore wind. This can be observed from nationally installed capacities and projections, which do exceed GW-scale in the 2040s for wave power. The year 2045 was selected to best highlight the impact marine energy could make while aligned with contemporary scenarios for future power system evolution.



Figure 8.11. Visual comparison of the installed capacities of wave power (blue) and tidal stream (orange) between 'Low Marine' (top left), 'High Marine' (top right), CT (bottom left), LW (bottom right). There is only a very slight difference between CT and LW. Installed capacity is indicated by the area of the bubble.

### 8.3.1.6. CO<sub>2</sub> emissions modelling and assumptions

This analysis uses carbon intensity of each generator type to represent the operational CO<sub>2</sub> emissions for the power system in each time step (one hour). A wide range of generation and storage technologies are permitted in PyPSA-GB and FES2022. The emissions by fuel type are input to the BID3 power market dispatch model [300], for which the carbon intensity assumptions were provided directly to the author by National Grid [310] in personal communication. These were reviewed for coherence with other sources [8], [329], [330]. In general, more conservative (higher) values for emissions intensities have been used relative to BID3 (Table 8.17). No data on BID3 emissions intensities of storage or interconnectors were provided.

The carbon intensities of all types of energy storage are assumed as zero, in lieu of a more detailed treatment, such as [331] CCS Biomass is assumed as carbon negative as per [310] and on the basis of the balance of literature – especially [8]. However, it should be noted that the life cycle climate impact of biomass combustion remains an active area of research, where assumptions of climate neutrality could underestimate the impact of biomass consumption and long-term CO<sub>2</sub> storage [332], [333], [334]. Alternatively, some sources attribute even larger negative emission potential to BECCS [335], [336].

Carbon intensity data for interconnector imports are challenging to obtain, especially at a time horizon of 2045: 2022 data has been used where alternatives were unavailable [337], which is likely to be a conservative assumption, as future power system carbon intensities are expected to fall as climate change targets are pursued. Any unmet load is assumed as zero emissions, as are interconnector exports from GB.

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Table 8.17. Table of operational carbon intensity of generation used in this analysis. FES inputs are shown in braces where different.

PyPSA-GB Generator Type	Carbon intensity [gCO <sub>2</sub> /kWh]	Reference
Advanced Gas Reactor (AGR)	0	[310]
Anaerobic Digestion	354	[310]
Biomass (co-firing)	120 {0}	[329]
Biomass (dedicated)	120 {0}	[329]
CCGT	394 {182}	[329]
CCS Biomass	-329	[310]
CCS Gas	57 {18}	[8] *
Coal	937 {322}	[329]
Diesel	935 {n/a}	Oil [329]
EfW Incineration	117	Waste [310]
Floating Wind	0	Renewable [310]
Hydro	0	[310]
Hydrogen	11	[310]
Landfill Gas	300 {117}	Other [330]
Open cycle gas turbine (OCGT)	651	[329]
PWR	0	[310]
Sewage Sludge Digestion	300 {117}	Other [330]
Solar Photovoltaics	0	Renewable [310]
Tidal lagoon	0	Renewable [310]

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PyPSA-GB Generator Type	Carbon intensity [gCO <sub>2</sub> /kWh]	Reference
Tidal stream	0	Renewable [310]
Wave power	0	Renewable [310]
Wind Offshore	0	Renewable [310]
Wind Onshore	0	Renewable [310]

\* IPCC AR5, Annex III, Table A.III.2

Table 8.18. Table of operational carbon intensity of storage types used in this analysis.

Storage	Carbon intensity [gCO <sub>2</sub> /kWh]	Reference
Battery	0	Assumed zero
Compressed Air	0	Assumed zero
Liquid Air	0	Assumed zero
Pumped Storage Hydroelectric	0	Assumed zero

Table 8.19. Table of carbon intensity of electricity supplied from GB interconnectors used in this analysis.

Interconnector	Carbon intensity [gCO <sub>2</sub> /kWh]	Reference
BritNed	513	Netherlands [330]
EastWest	426	Northern Ireland [330]
Moyle	426	Northern Ireland [330]
Nemo	132	Belgium [330]
IFA	48	France [330]
IFA2	48	France [330]
NSL	9	Norway [330]
ElecLink	48	Assumed as IFA/IFA2
Viking Link	231	West Denmark 2022 [337]
Greenlink	426	Assumed as EastWest
GridLink	48	Assumed as IFA/IFA2
NeuConnect	494	Germany 2022 [337]
NorthConnect	9	Assumed as NSL
FAB Link	48	Assumed as IFA/IFA2

## 8.3.2. Results

### 8.3.2.1. Snapshot of optimal dispatch and operational emissions

A snapshot of the dispatch order and energy generation per hour is shown Figure 8.12 and Figure 8.13 (excluding interconnection export).

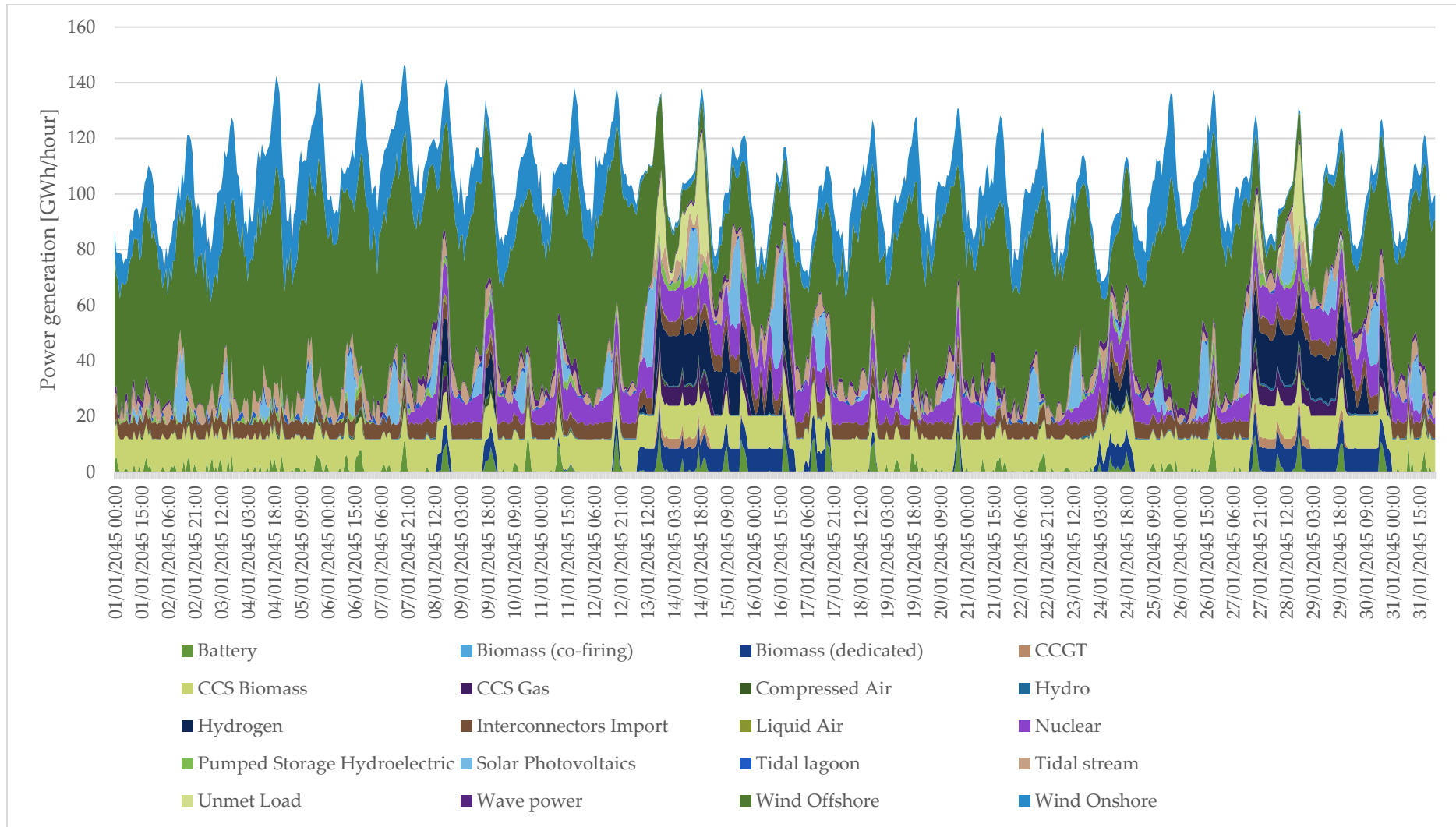


Figure 8.12. Optimal dispatch from 1st January 2045 to 31st January 2045 for FES2022, Consumer Transformation at hourly resolution.

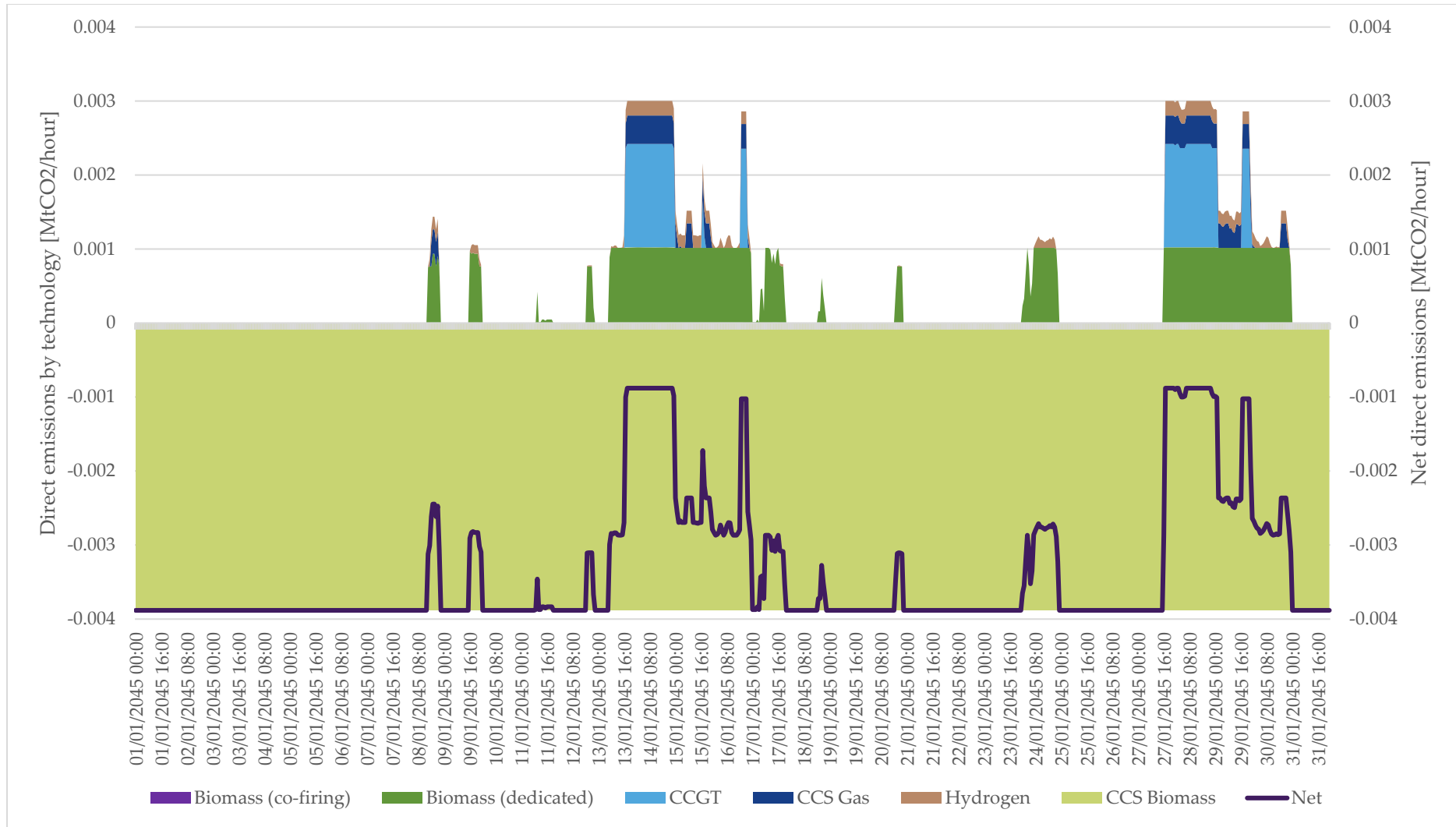


Figure 8.13. Direct emissions from power generations from 1st January 2045 to 31st January 2045 for FES2022, Consumer Transformation at hourly resolution.

8.3.2.2. Comparing national energy mix of base FES2022 scenarios

For the base cases, in general, CT has more energy delivered from BECCS, and slightly less interconnector imports than LW, but otherwise the differences are fairly minor (Figure 8.14). Of note is that unmet load is always reduced (up to around a third in the high marine scenarios) by the increased installed capacity of marine energy. This is an operationally advantageous outcome, echoing findings from [116] – however for LW unmet load is still significant (around 4% of the total energy demand). With increasing marine renewables, the largest changes are only observed in thermal dispatch (which decreases with more installed capacity of marine) and renewables (which naturally increases with more installed capacity of marine energy). The breakdown can be seen by technology in Figure 8.15. Total energy generation is effectively constant, subject to rounding errors in the optimisation.

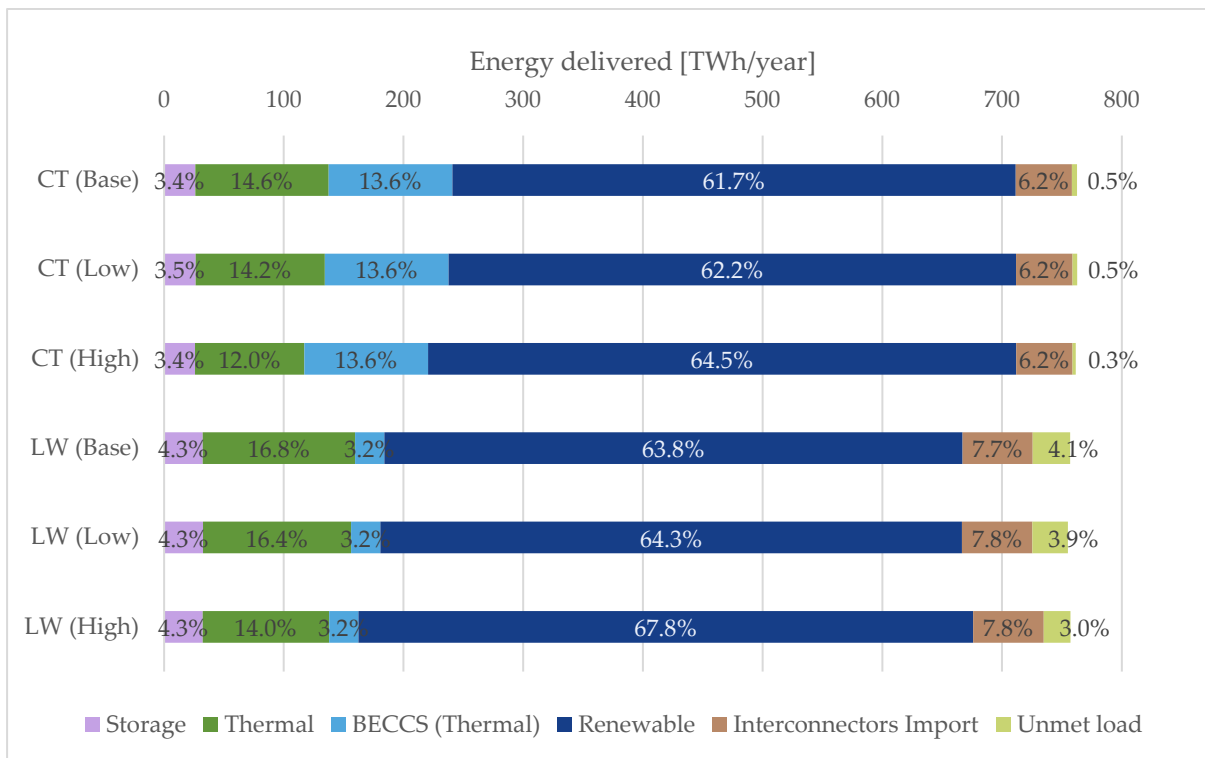


Figure 8.14. Comparison of energy delivery by technology categories between scenarios in 2045.

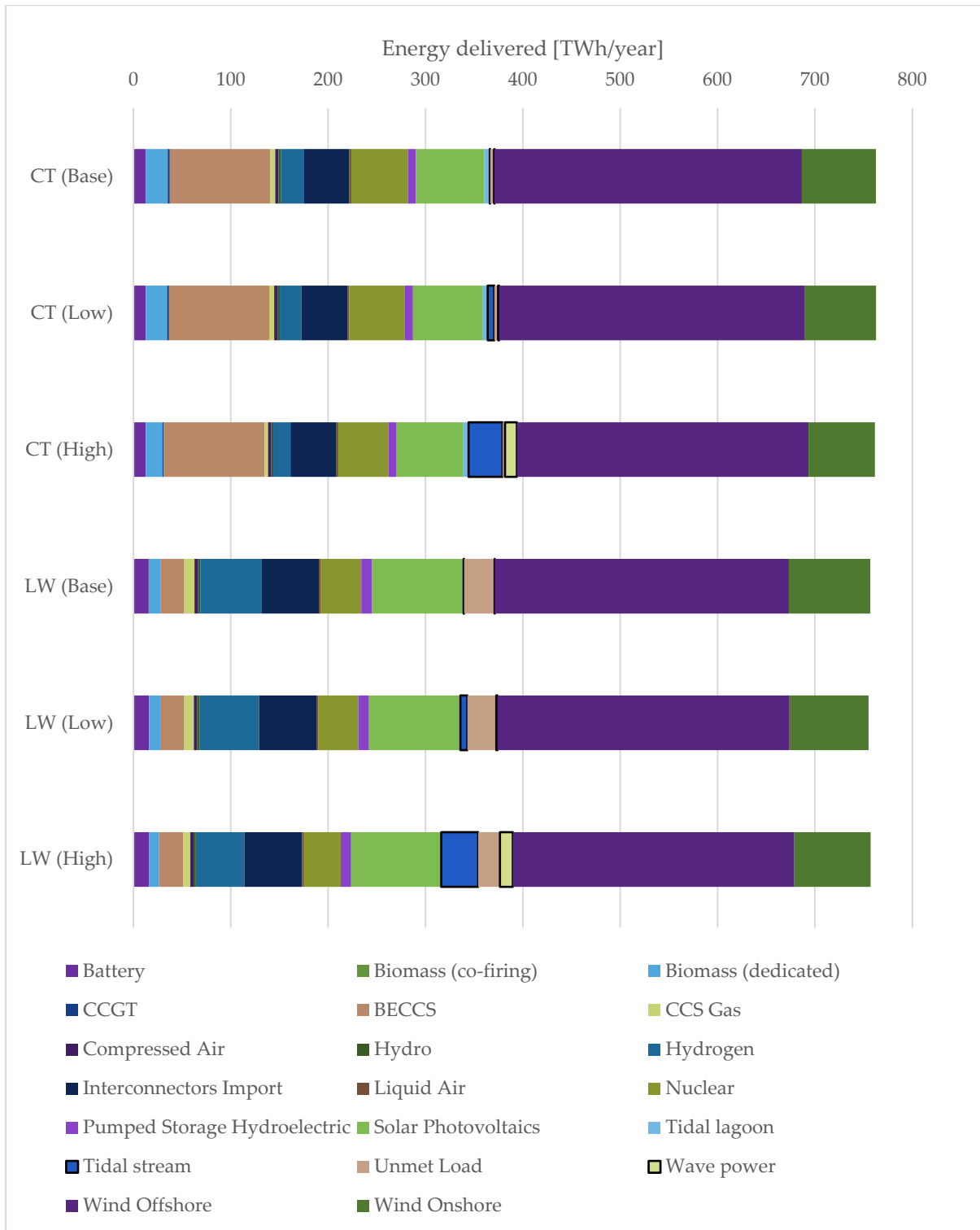


Figure 8.15. Comparison of energy delivery by technology between scenarios in 2045.

### 8.3.2.3. National power sector total emissions

The aggregate emissions from the GB power sector in the year 2045 for scenarios CT and LW were negative (-29.9 and -5.3 MtCO<sub>2</sub> due to operation of BECCS plant), and this deepened in

all cases with the addition of marine renewables; as much as 1.1 and 0.6 MtCO<sub>2</sub> for the high marine cases of CT and LW (Figure 8.16).

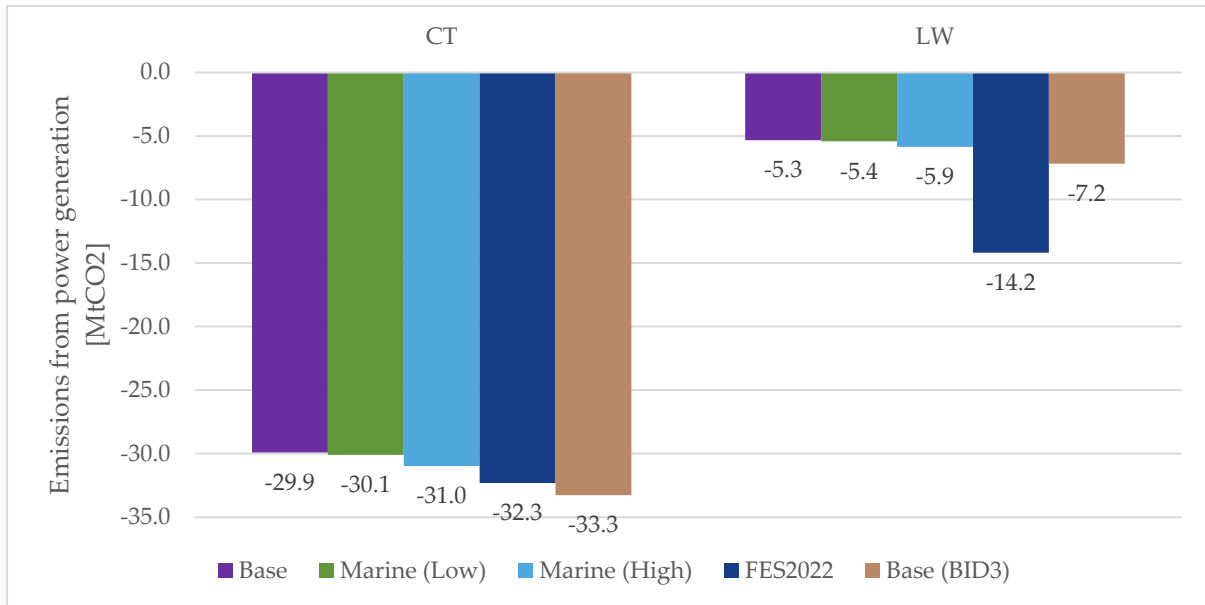


Figure 8.16. National emissions for the year 2045 in various cases.

Box 8.1. Changing the carbon intensity inputs.

Figure 8.16 also shows that when the BID3 carbon intensities are used the PyPSA-GB results for CT is +3% of the BID3 calculated value – “FES2022” compared to “Base (BID3)” in Figure 8.16 – but for LW the difference is much larger (-49%). These sources of these differences are not clear, but could arise from several dissimilarities between the two models. For example, PyPSA-GB does not include a pan-European model for interconnectors, the accounting of emissions from imported power itself, or explicit modelling of demand side flexibility such as vehicle-to-grid (V2G).

### 8.3.2.4. Emissions by technology type

In terms of emission intense generation, each of these drops off in proportion to the energy delivered by marine in each scenario seen by the distinctive step changes in Figure 8.17.

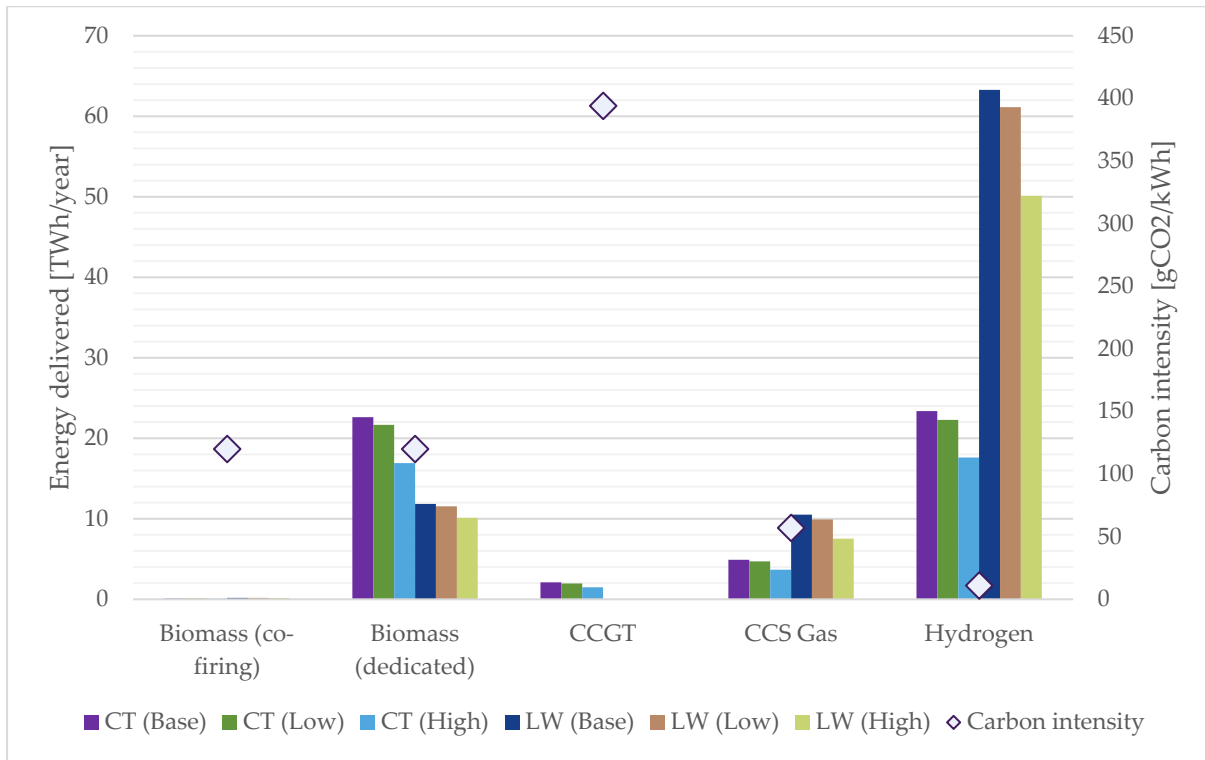


Figure 8.17. Energy delivery by Emissions intense generation.

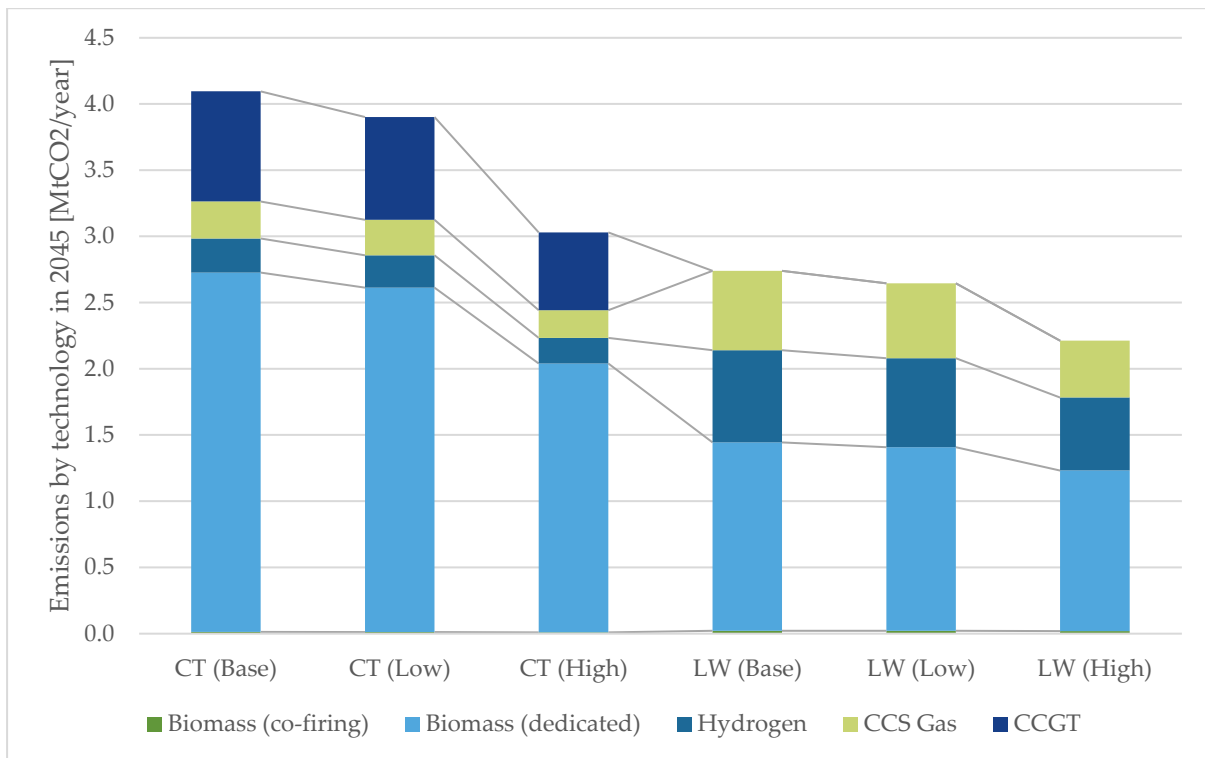


Figure 8.18. Emissions by dispatchable power source.

In general, terms, all dispatchable power systems see a reduction in power delivery due to the presence of increase marine renewables. The interplay between the product of power generation and carbon intensity is captured in Figure 8.18. In CT, the majority of emissions reduction is observed in dedicated biomass plant, followed by unabated CCGT, CCS gas and hydrogen. LW has overall lower emissions of which dedicated biomass is avoided, then CCS gas and hydrogen.

Table 8.16 shows that the dispatch order will be biomass, hydrogen, CCS gas, CCGT; the amount of power is also dependent on the generation fleet. Overall, the low marine case reduces emissions by around 4% to 7% in CT; 2% to 6% in LW, while High creates around 25% to 29% in CT and 15% to 28% in LW.

Table 8.20: Ratio of change in emissions due to marine renewables relative to base case.

		<b>Biomass (co-firing)</b>	<b>Biomass (dedicated)</b>	<b>Hydrogen</b>	<b>CCS Gas</b>	<b>CCGT</b>	<b>Total (ex. BECCS)</b>
<b>CT</b>	Low	0.96	0.96	0.95	0.96	0.93	0.95
<b>CT</b>	High	0.75	0.75	0.75	0.75	0.71	0.74
<b>LW</b>	Low	0.98	0.98	0.97	0.94	-	0.97
<b>LW</b>	High	0.85	0.85	0.79	0.72	-	0.81

BECCS is not included here as it skews the results and does not change between scenarios. BECCS does not change between scenarios due to its negative marginal price (it also has negative emissions accounted). Unmet load is reduced with increasing marine renewables, but never enough to avoid it completely.

### 8.3.2.5. National carbon intensity

Higher installed capacities of marine energy also deepened the negative carbon intensity of the power sector (Figure 8.19). However, as per Box 8.1, the FES2022 reported values (“FES2022”) are more deeply negative than those calculated in PyPSA-GB, even when the BID3 carbon intensities (Table 8.17) are used in PyPSA-GB (“Base (BID3)”).

Like the results in Figure 8.16, for CT the FES2022 and for BID3 values are relatively comparable, seeing an increase of 10% between the official FES2022 values and the same calculation in PyPSA-GB. However, for LW, the FES2022 is nearly twice as large as the PyPSA-GB case using the BID3 carbon intensity input figures. The significant difference in LW results may arise from the increase in storage, interconnectors and unmet load (Figure 8.19), relative to CT.

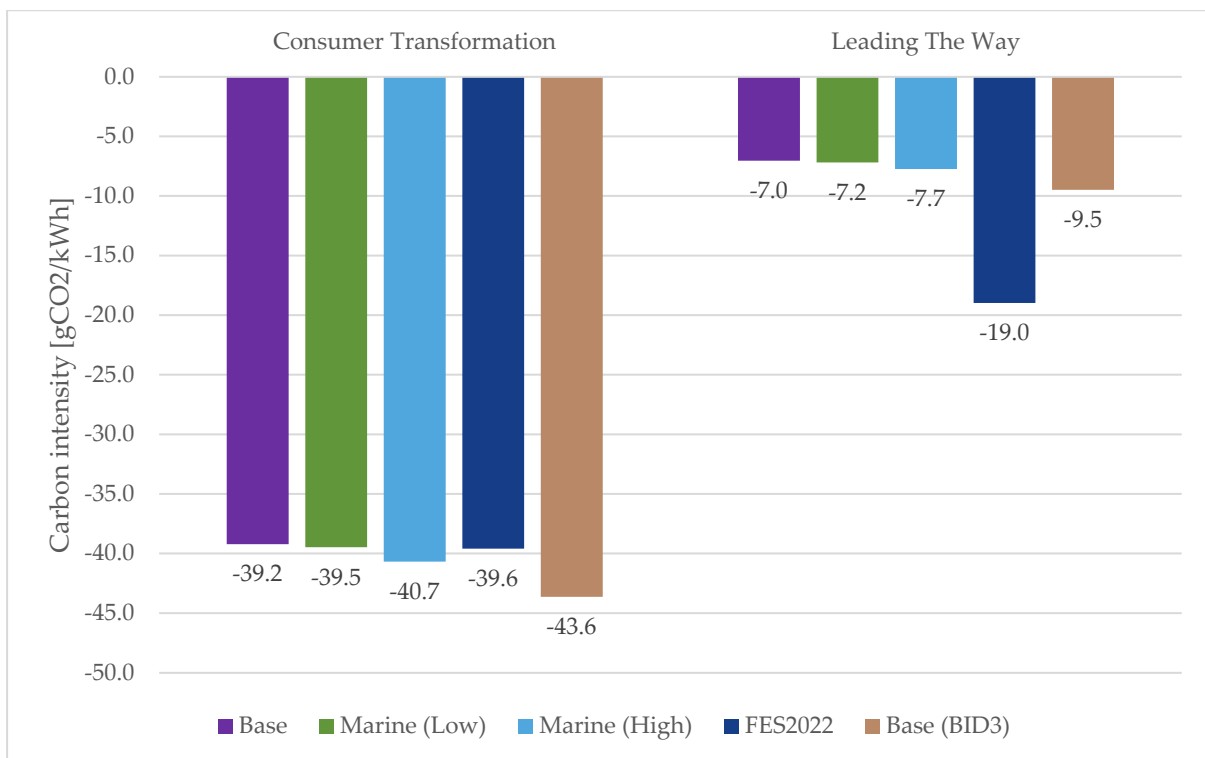


Figure 8.19. National carbon intensity for the year 2045 in various cases.

### 8.3.2.6. Nodal carbon intensities

A significant advantage of using a power system model to investigate these scenarios is the insight into the spatial emissions reduction performance of marine energy, illustrated at a high level in Figure 8.20. Looking at the results in detail, Figure 8.21 shows the carbon intensity of generation at each node in the Consumer Transformation (CT) scenario, as well as the change observed when increased capacities of marine energy are included according to the Low and High scenarios (nodes Beaulieu, Peterhead, Neilston, Harker, Penwortham, Deeside, Melksham, Lovedean, and S.W. Peninsula have additional marine generation). It can be clearly seen that the carbon intensity in 2045 in CT is negative; dominated by negative emissions generation from BECCS. Figure 8.22 shows the difference in carbon intensity from the CT base scenario directly, where a reduction in carbon intensity indicates an improvement from a climate change mitigation perspective. Overall, the inclusion of additional marine energy reduces the total carbon intensity (as in the previous section), but the results are not consistent for each node: carbon intensity is increased at Peterhead, Penwortham, Deeside and S.W. Peninsula (as well as Thornton, Ratcliffe and Pelham) in the Low scenario, before improving in the High scenario.

For Leading the Way (LW) Figure 8.23 shows less deeply negative carbon intensity of power than CT in Figure 8.21. Figure 8.24 shows that overall, the addition of marine energy improves the carbon intensity of generation at every node in every case, except S.W. Peninsula. The effect of additional marine energy generation on the carbon intensity at Peterhead, Harker, Penwortham, Deeside, and S.W. Peninsula can be clearly seen, with many improvements observed in the wider network (notably Daines, Kemsley and London). Conversely, for nodes with very low volumes of positive carbon intensity (that is, fossil fuels), the impact of

additional zero carbon marine energy has limited effect, but can cascade outwards into the network, for example at Beaulieu and Peterhead in Figure 8.24. The unusual results at S.W. Peninsula are explained in Section 8.3.2.8.

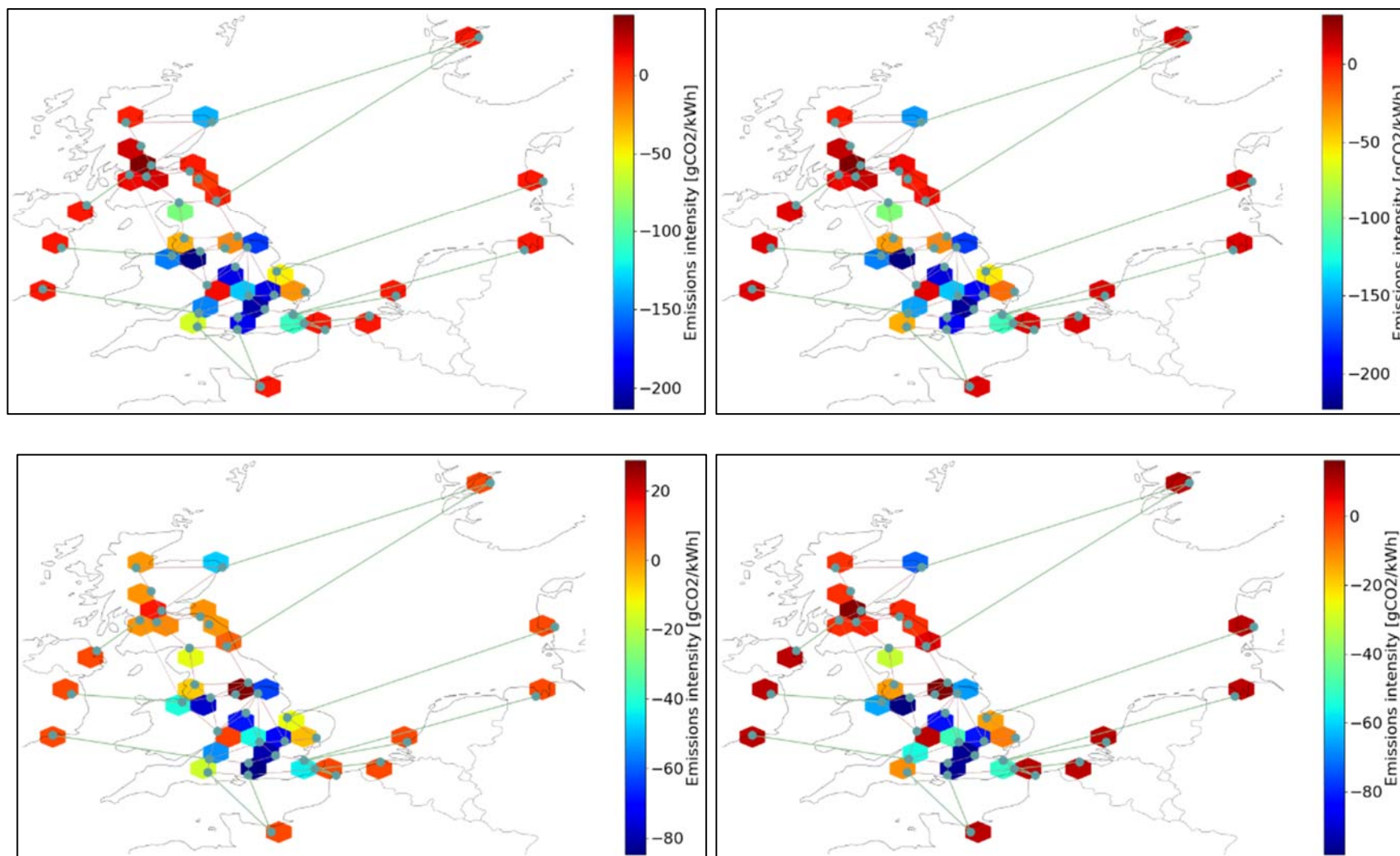


Figure 8.20. Illustration of the spatial distribution of carbon intensity of generation calculation in PyPSA-GB for four scenarios: CT 'Base' (top left) and CT 'High' (top right); LW 'Base' (bottom left) and LW 'High' (bottom right), average of hourly values over the year 2045.

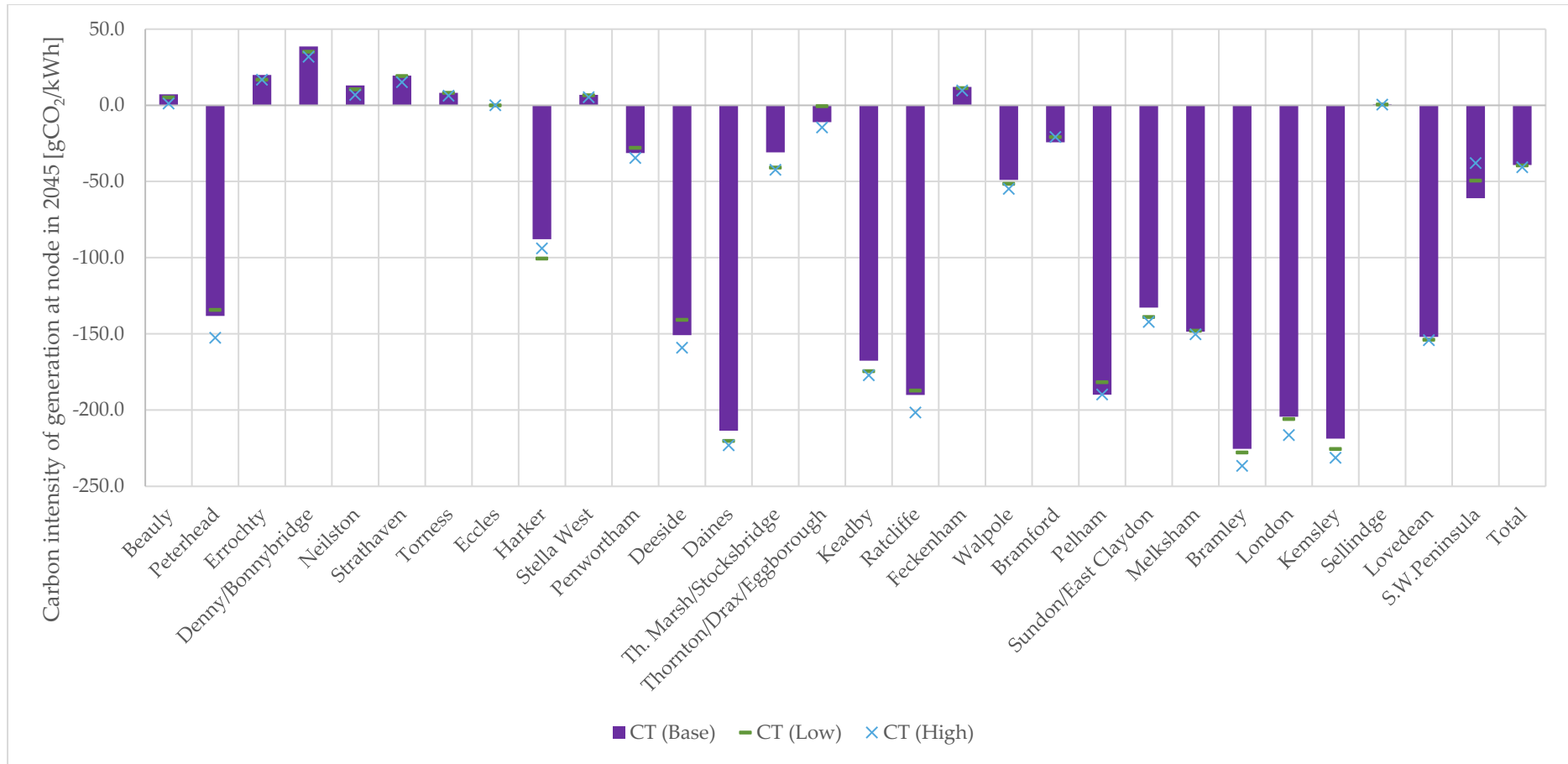


Figure 8.21. Carbon intensity of generation at each transmission network node for Consumer Transformation (CT) with scenarios of increased installed capacity of marine energy (Low and High). The nodes with additional marine energy are: Beaulieu, Peterhead, Neilston, Harker, Penwortham, Deeside, Melksham, Lovedean, and S.W. Peninsula (by far the most significant are Beaulieu and S.W. Peninsula).

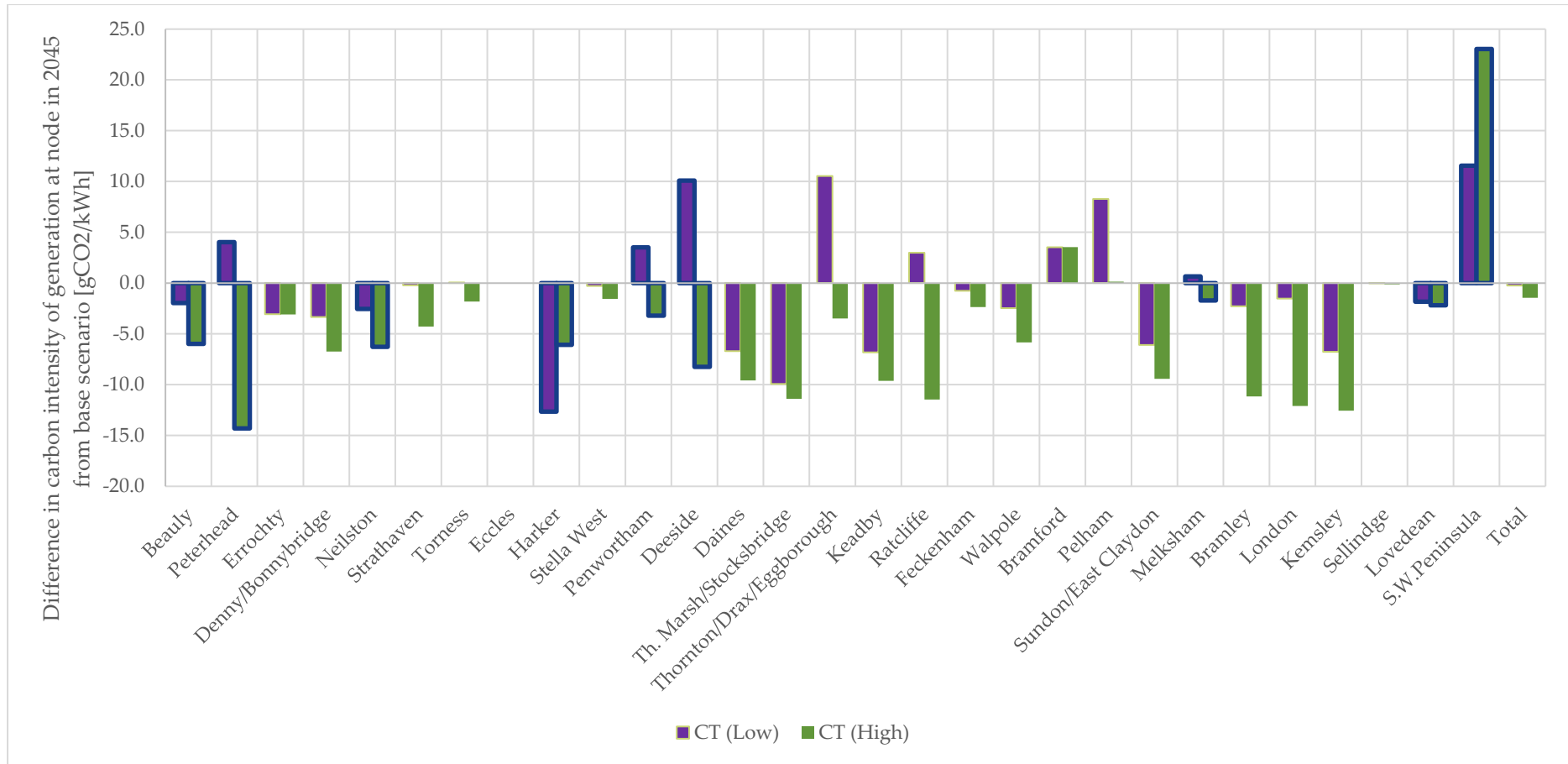


Figure 8.22. Difference in carbon intensity of generation at each transmission network node for Consumer Transformation (CT) with scenarios of increased installed capacity of marine energy (Low and High). A reduction in carbon intensity indicates an improvement from a climate change mitigation perspective.

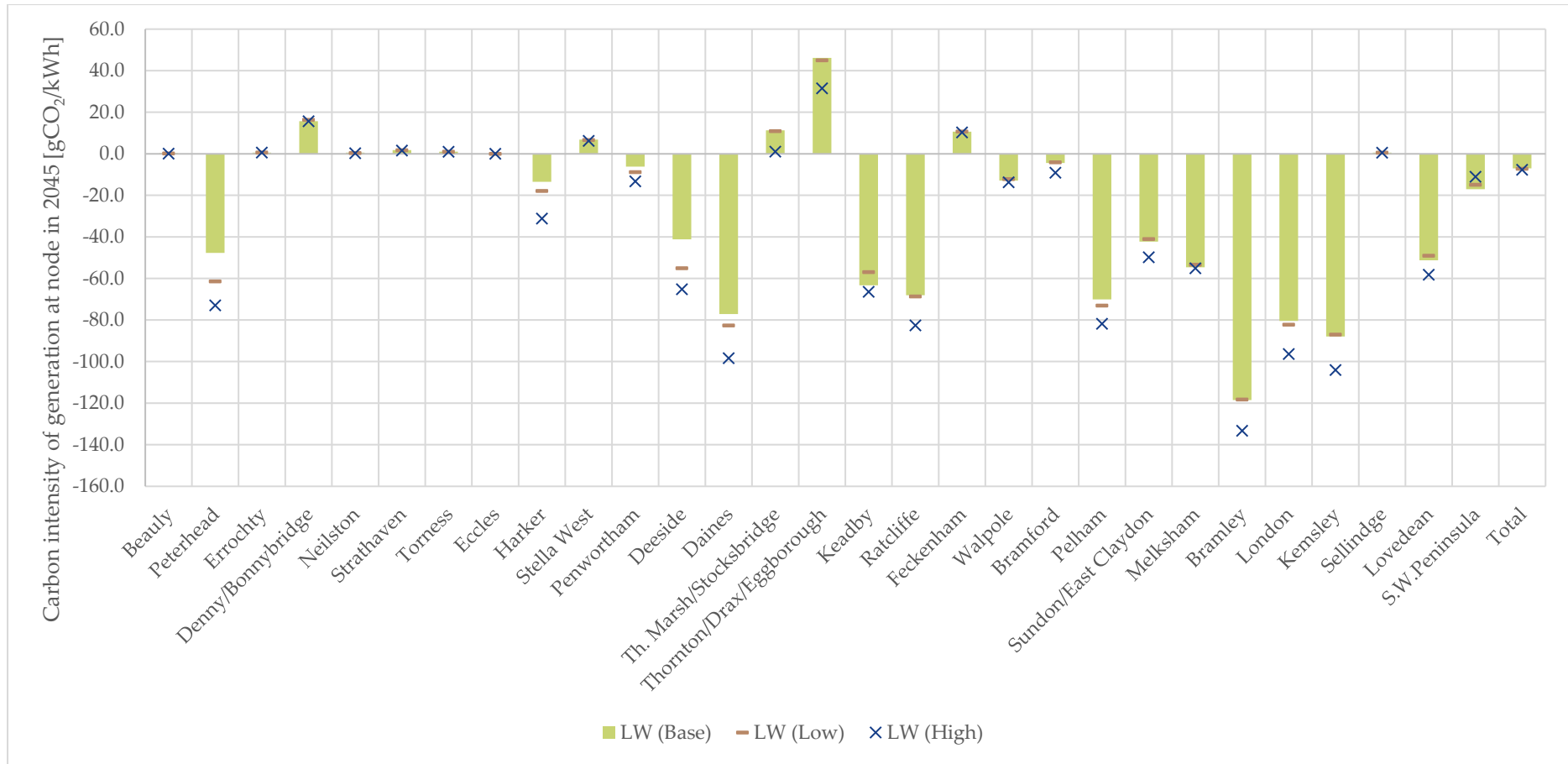


Figure 8.23. Carbon intensity of generation at each transmission network node for Leading the Way (LW) with scenarios of increased installed capacity of marine energy (Low and High). The nodes with additional marine energy are: Beauty, Peterhead, Neilston, Harker, Penwortham, Deeside, Melksham, Lovedean, and S.W. Peninsula (by far the most significant are Beauty and S.W. Peninsula).

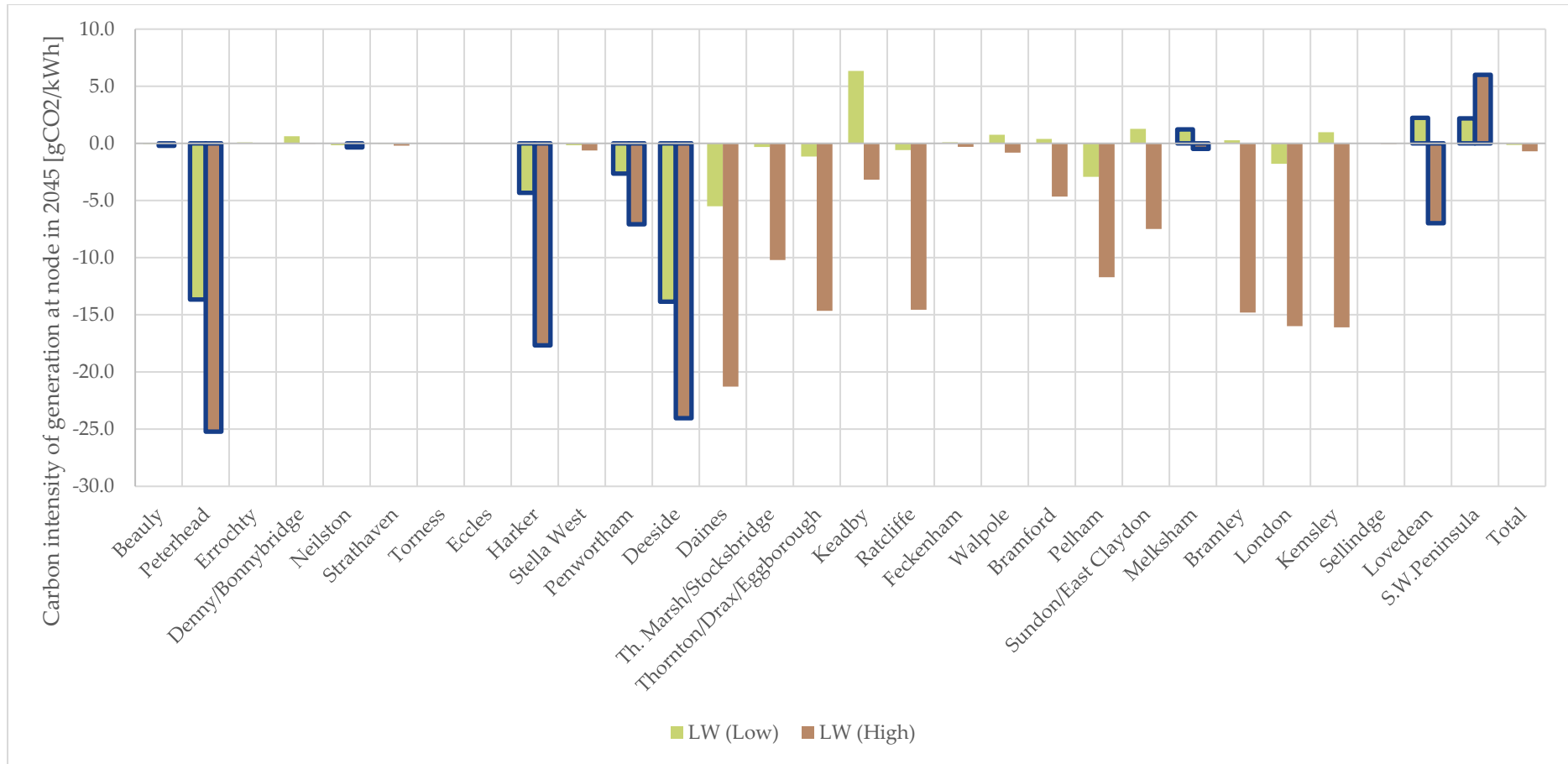


Figure 8.24. Difference in carbon intensity of generation at each transmission network node for Leading the Way (LW) with scenarios of increased installed capacity of marine energy (Low and High). A reduction in carbon intensity indicates an improvement from a climate change mitigation perspective.

### 8.3.2.7. Beaulieu and S.W. Peninsula total emissions

Given the significant volumes of injected marine energy at Beaulieu and S.W. Peninsula, these were considered in more detail, starting with the total emissions from each node. The generation mix at Beaulieu is characterised by multiple types of renewable generation (offshore wind, onshore wind, marine) and some dedicated biomass. The absence of any negative emissions BECCS means that the co-location and injection of marine energy reduces emissions at this bus in all scenarios. By contrast, S.W. Peninsula has more dispatchable thermal plant including BECCS. Again, the zero emissions marine energy is beneficial, causing the emissions from generation at this bus to become more negative.

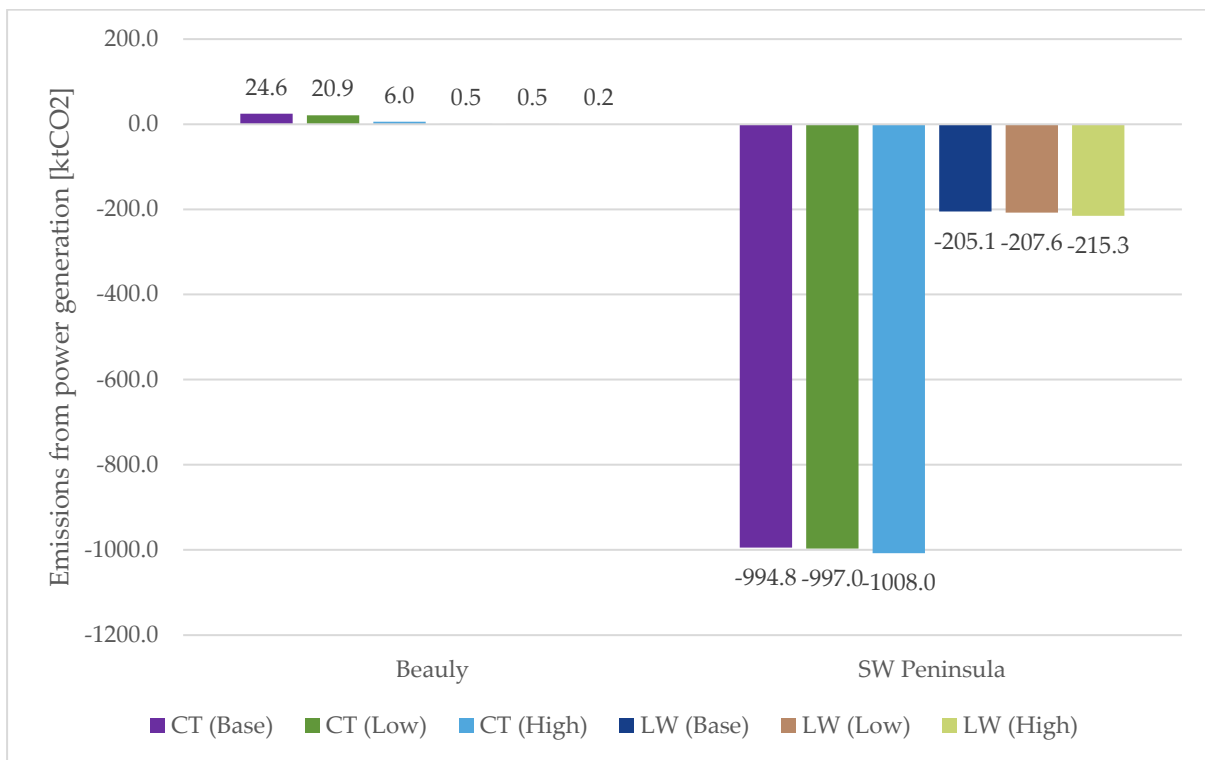


Figure 8.25. Emissions from power generation at Beaulieu and S.W. Peninsula in 2045 determined in PyPSA-GB.

### 8.3.2.8. Beaulieu and S.W. Peninsula carbon intensity

This pattern is replicated for the carbon intensity of generation at Beaulieu which falls significantly in high marine cases. The case of S.W. Peninsula is less straightforward and

instructive to explain. Here, the negative carbon intensity becomes more *positive* with the addition of zero carbon intensity marine. Given that the dispatch order is regulated by the marginal costs, this cannot be a case of marine energy displacing BECCS. Conceivably, this appears to arise because additional marine energy reduces the *unmet load* at the node (which is excluded from the calculation of carbon intensity). This increases the denominator of ‘energy generated’ in the expression for carbon intensity, and dramatically reduces the carbon intensity value for very small changes in power generation.

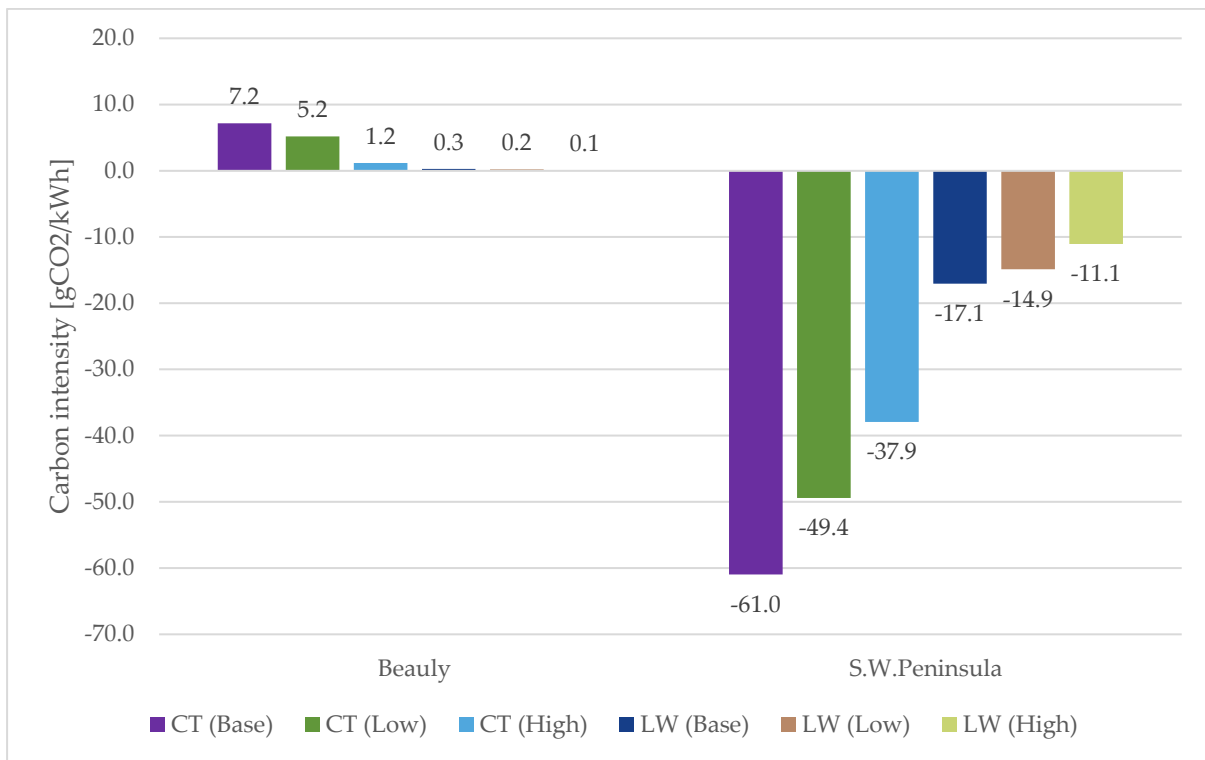


Figure 8.26. Carbon intensity of power generation at Beauly and S.W. Peninsula in 2045 determined in PyPSA-GB.

### 8.3.3. Conclusions

This study has demonstrated that significant installed capacities of marine energy can reduce the bulk emissions from power generation, reduce carbon intensity of generation nationally and locally, and reduce unmet load, at both the national and sub-national scale – although this can lead to accounting issues in the definition of carbon intensity. These results were achieved using the results from Chapter 7 of this thesis and the PyPSA-GB tool [13].

#### 8.3.3.1. Limitations and Further Work

The limitations of this study which could be investigated and resolved in further work include:

- The method of augmenting the FES with increase installed capacity of marine energy is not optimised. Furthermore, there is no investigation of the impact on emissions of simply overbuilding *other* forms of generation, storage or interconnection.
- It is not possible to isolate the contribution from wave and tidal technologies at this resolution. However, this is comparable with the results from the previous section and is explored in more detail in the next section.
- As with the previous section, a single generation technology for the fleet of generation was assumed when in reality the renewable generation will be very diverse.
- The method requires python and power system modelling skills (although the model and dataset is open-source). To be tractable on a personal laptop, the method requires multiple runs of non-trivial computational time to explore aggregate effect over multiple years.
- Uncertainty has been considered in terms of coverage by two scenarios with augmentations, however only one temporal year, with one ‘weather year’ has been

considered. Further work could explore the impact of novel technologies throughout the period to 2050, and for different weather resources.

- The model uses a 29 bus transmission network – distribution networks are neglected at this scale. The advantage of this methodological choice is that the national network can be interrogated for systemic impacts, such as national emissions and spatial impacts. The results of this method therefore cannot not extend into the distribution network or smart-energy system scales, where further innovation for zero-carbon communities can be expected.
- The results do not align exactly with the BID3 findings even when BID3 carbon intensity inputs are used. Further work would be required to understand the source of this discrepancy.
- Solutions to unmet load are not investigated in detail despite being a significant issue for power system operation, although it is observed that scenarios with higher installed capacities of marine have less unmet load than the base scenarios.
- Further work could explore the seasonal component in energy delivery and the relation to the historical year selected in High marine scenarios.
- Unmet load, storage and interconnectors are assumed at zero carbon intensity.
- A solution is intractable unless there is significant network expansion; this is not modelled in the life cycle assessment, nor are realistic projections for network expansion considered.
- Nuclear is modelled as a dispatchable plant – in reality this is more likely to be “always on” much like BECCS in this treatment. However, given its operational emissions are accounted for as zero this unlikely to have any effect on the emissions, only on the

amounts of energy generated by renewable energy. Arguably dispatchable nuclear could represent Small Modular Reactors (SMR), but this is not truly defensible. The dispatch order is strongly dependent on the marginal price inputs and the results will change accordingly.

## 8.4. Comparison of approaches

This section compares the two methods to round off this exploration of life cycle impacts of wave and tidal stream technologies in future energy scenarios.

Unlike Section 8.2, here, only the avoided emissions during operation can be considered, because the method considers only the performance in the year 2045. The results here for the “AEP-CI” method are only for the displaced ‘OM\_disp’ emissions in the year 2045.

### 8.4.1. Energy generation

First of all, consider the energy that could potentially be generated by each technology in the two methods. They are significantly different: calculating the potential for energy generation by multiplying the installed capacity by the capacity factor, is clearly less sophisticated than the LOPF method in PyPSA-GB which takes into demand and generation on an hourly resolution across a constrained network. Accordingly, the AEP-CI method is usually larger than the PyPSA-GB results.

For the base cases the AEP-CI method estimates energy generation by a factor of 1.95 and 1.63 compares to PyPSA-GB. For low the precision is best at 1.45 and 1.35, and for high it rises again to 1.73 and 1.59. This has a knock-on effect on the emissions reduction potential of the technologies.

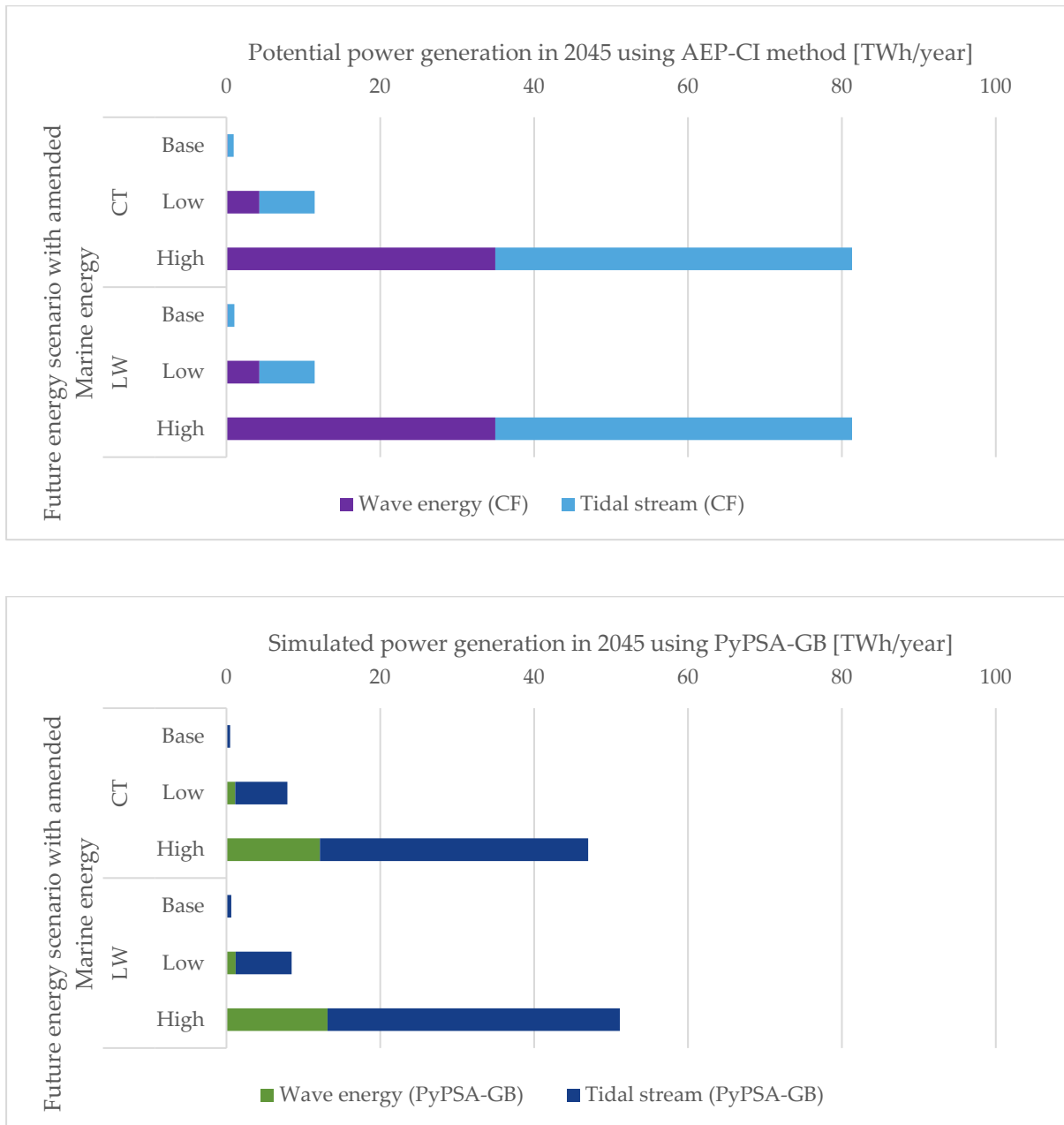


Figure 8.27. Comparison of the marine energy generation calculated in AEP-CI and PyPSA-GB methods.

### 8.4.2. Avoided emissions attributable to marine energy

Unlike the potential and simulated energy generation, no clear pattern emerges when the two methods are considered in terms of bulk (total) avoided emissions across scenarios CT and LW.

Overall, both the AEP-CI method and the PyPSA-GB method finds deepening negative emissions with the increase in installed capacity of marine energy, in line with previous section. The AEP-CI method finds almost identical values across all scenarios, given the very similar installed capacities and low percentage of overall FES installed capacity and demonstrates its insensitivity to the complexity of the system under consideration and suggests the importance of considering spatial topological constraints and temporal complementarity in emissions reduction potential calculations. These values of avoided emissions can be read from the graphs in Section 2.

For CT, PyPSA-GB finds deeper avoided emissions than AEP-CI. However, the opposite is true for LW. This is likely a product of the emissions reductions observed in the emissions by technology mix: CT simply has a higher amount of emitting power plants (Section 8.3.2.4), lending marine energy extra decarbonisation potency.

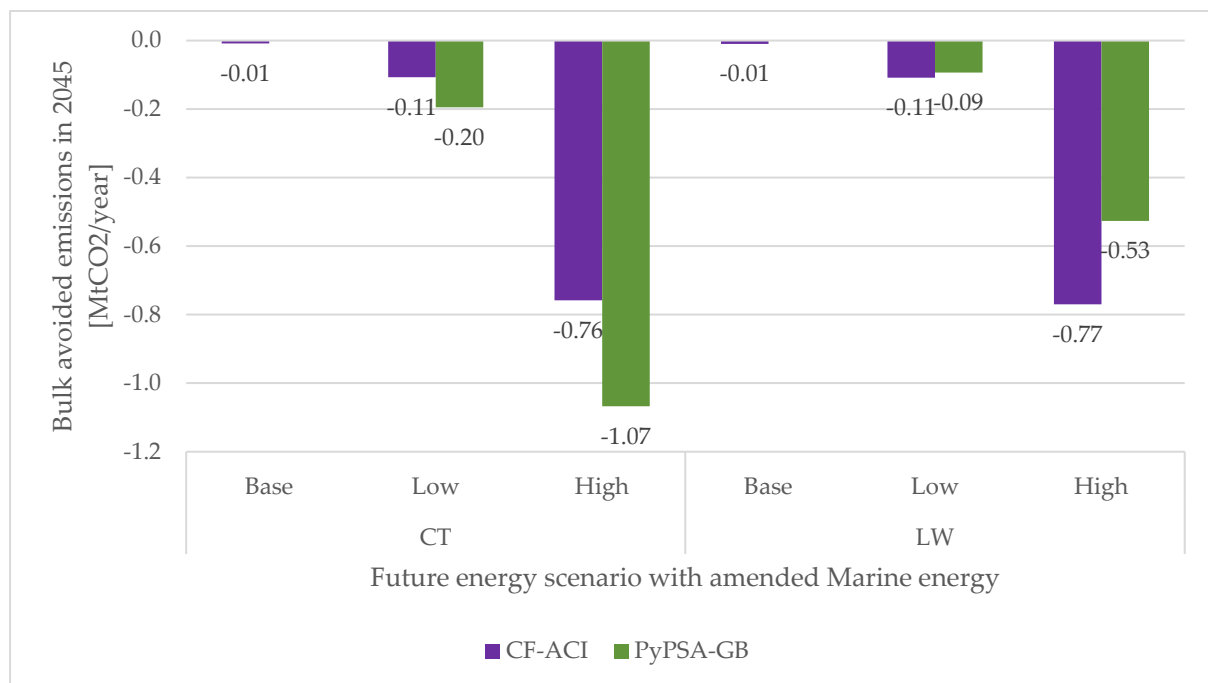


Figure 8.28. Comparison of the bulk avoided emissions calculated in AEP-CI and PyPSA-GB methods in the year 2045.

### 8.4.3. Avoided emissions per unit of marine energy generated

Following Section 8.2.2, the avoided emissions are examined in terms of units of energy generated. Here, we observe that the avoided emissions of marine energy on a per unit basis are of course equal to the amended carbon intensity in the year of the FES, but that using PyPSA-GB, this becomes more negative, unexpectedly deepest for the Low scenario (Figure 8.29). Perhaps this arises from the unmet load as per Section 8.3.2.8, and suggests an optimum energy delivery from some installed capacity – however, if maximum emissions reduction is the goal, maximising installed capacity of marine looks to be the best approach (Figure 8.28).

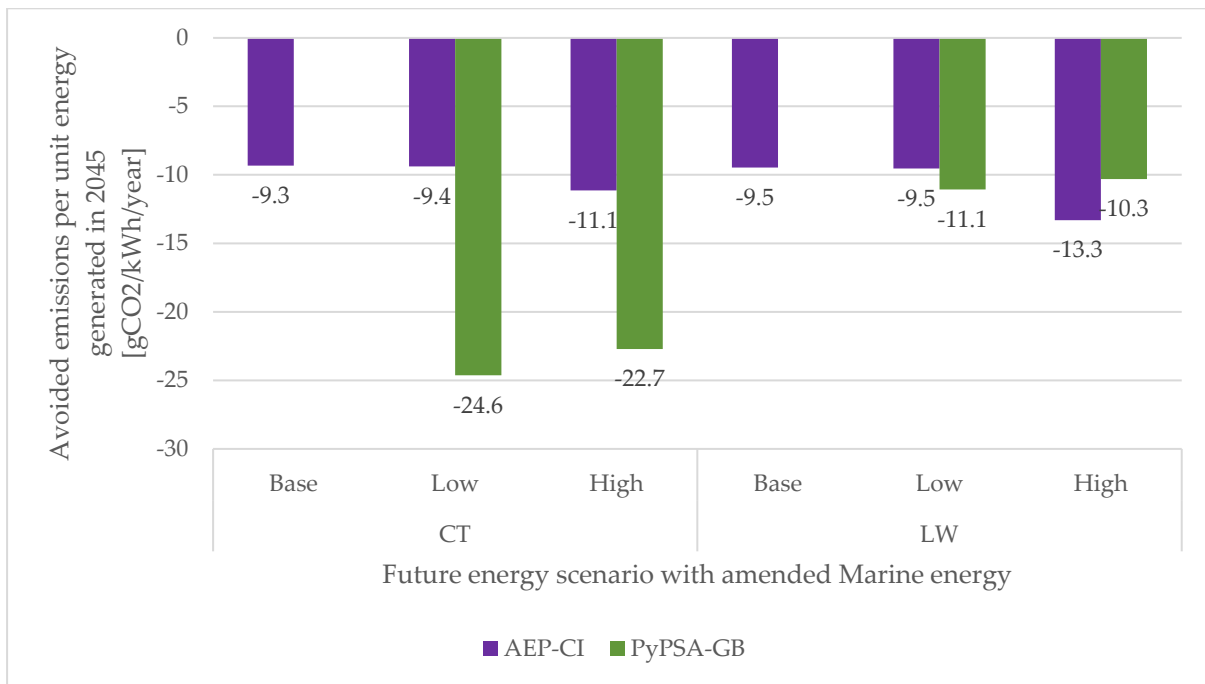


Figure 8.29. Comparison of the avoided emissions per unit of energy delivered in AEP-CI and PyPSA-GB methods.

### 8.4.4. Avoided emissions per unit of marine energy installed capacity

Finally, considering the avoided emissions per unit of installed capacity, again, the Low scenario is shown to be the most effective (Figure 8.30). AEP-CI method results are actually slightly different due to the change in amended carbon intensity from the potential energy delivered as a proportion of the total energy delivered system-wide.

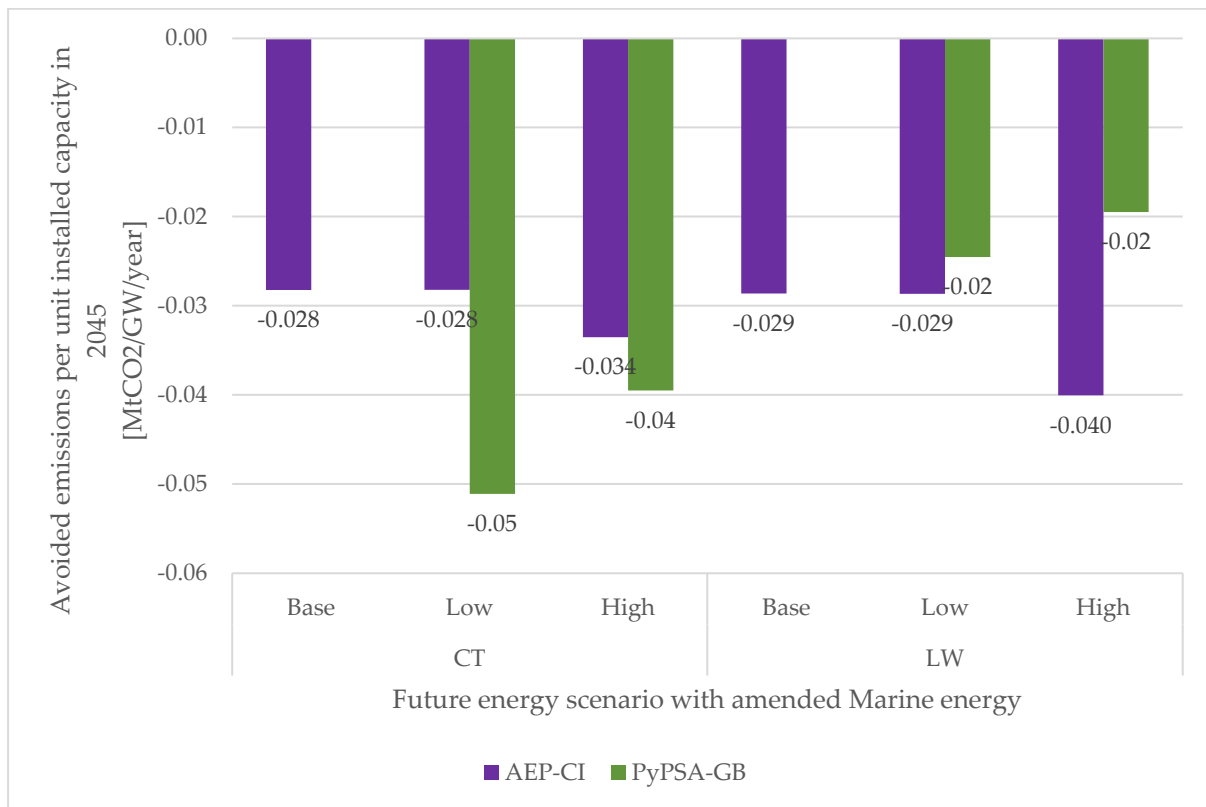


Figure 8.30. Comparison of the bulk avoided emissions calculated in AEP-CI and PyPSA-GB methods.

Table 8.21. Comparison of the bulk avoided emissions calculated in AEP-CI and PyPSA-GB methods.

		Technology type	CT Base	CT Low	CT High	LW Base	LW Low	LW High
Scenario	Installed capacity in 2045 [GW]	Wave	0.043	1.4	11.5	0.043	1.4	11.5
		Tidal stream	0.273	2.4	15.6	0.304	2.4	15.6
		Marine	0.3	3.8	27.0	0.3	3.8	27.0
	Amended Carbon Intensity in 2045 (excluding BECCs) [gCO <sub>2</sub> /kWh]	Wave	9.3	9.4	11.0	9.5	9.5	13.1
		Tidal stream	9.3	9.4	11.2	9.5	9.6	13.4
	Energy Production in 2045 [MWh/year]	AEP-CI	Wave	1.4E+05	4.3E+06	3.5E+07	1.4E+05	4.3E+06
Tidal stream			8.2E+05	7.2E+06	4.6E+07	9.1E+05	7.2E+06	4.6E+07
Marine			9.6E+05	1.1E+07	8.1E+07	1.0E+06	1.1E+07	8.1E+07
PyPSA-GB		Wave	2.3E+04	1.2E+06	1.2E+07	2.47E+04	1.2E+06	1.3E+07
		Tidal stream	4.6E+05	6.8E+06	3.5E+07	6.1E+05	7.3E+06	3.8E+07
		Marine	4.8E+05	7.9E+06	4.7E+07	6.3E+05	8.5E+06	5.1E+07
Ratio (AEP-CI / PyPSA-GB)		-	1.95	1.45	1.73	1.63	1.35	1.59

Avoided emissions in 2045 (OM_disp) [MtCO <sub>2</sub> ]	AEP-CI	Wave (see Figure 8.4)	-0.001	-0.040	-0.326	-0.001	-0.041	-0.331
		Tidal stream (see Figure 8.6)	-0.008	-0.067	-0.433	-0.009	-0.068	-0.439
		Marine	-0.01	-0.11	-0.76	-0.01	-0.11	-0.77
	PyPSA-GB	Marine	-	-0.20	-1.07	-	-0.09	-0.53
	Ratio (AEP-CI / PyPSA-GB)		-	0.55	0.71	-	1.16	1.46
Avoided emissions per unit energy generated in 2045 [gCO <sub>2</sub> /kWh]	AEP-CI	Marine	-9.3	-9.4	-11.1	-9.5	-9.5	-13.3
	PyPSA-GB	Marine		-24.6	-22.7		-11.1	-10.3
Avoided emissions per unit installed capacity in 2045 [MtCO <sub>2</sub> /GW]	AEP-CI	Marine	-0.028	-0.028	-0.034	-0.029	-0.029	-0.040
	PyPSA-GB	Marine		-0.05	-0.04		-0.02	-0.02

## 8.5. Conclusions

This chapter has determined the emissions reduction potential of floating wind, wave energy and tidal stream in future energy scenarios around GB (FES2022) in two ways:

1. **'AEP-CI' method:** By considering the installed capacities and carbon intensity of the 2022 National Grid future energy scenarios (FES2022) in combination with the life cycle assessment (LCA) results from Chapters 4 and 5 (Section 8.2).
2. **PyPSA-GB method:** By using PyPSA-GB to demonstrate the emissions reduction potential of marine energy in an example year (Section 8.3).

Using simple assumptions from the life cycle assessment chapters of this thesis (4 and 5) and data from to scenarios from FES2022, nearly all fleets of floating wind, wave energy and tidal stream were shown to contribute to climate change impacts at the end of the period 2025 to 2050. Only the fleet tidal stream achieved carbon payback in two scenarios by virtue of their low cumulative installed capacity and GWP. This aligns with Chapter 4 (wave energy) but not Chapter 5 (floating wind), where it is surmised that the mammoth build rate and amount of embodied emissions quickly eclipses the ability of the generation to avoid emissions via the dwindling carbon intensity of power. This shows that the installed capacities do not achieve carbon payback, and possibly suggest that carbon payback should be retired from the discourse, instead progressing towards the discussion of minimising environmental harms by delivery of some function unit.

The example use of PyPSA-GB showed that the amount of power delivered using a more sophisticated method was lower by around 1.3 to 1.7 times, suggesting the simpler method would overstate the emissions reduction potential relative to an LOPF method. Using PyPSA-

GB found that in the year 2045, increased capacity of marine energy avoided GHG emissions from dispatchable thermal plant, and had a beneficial effect on unmet load and emissions reduction. The influence of marine on the wider network was fairly localised as demonstrated by the changes in emissions intensity of generation at each node but could be discerned in some locations. However, the potential complimentary benefits of marine energy as an emission reduction potential metric is perhaps only relevant at sub-annual timescales – any benefit disappears when the aggregate of the annual average carbon intensity is considered, and total installed capacity dominates the efficacy of the technology.

Comparing the two methods showed that

- The volumes of delivered power were far lower than those from the AEP-CI method by 1.35 to 1.73 times.
- No clear pattern emerged for which method was more conservative for estimating avoided emissions. For CT, PyPSA-GB calculated deeper avoided emissions, for LW it was the AEP-CI method. Arguably though, simpler methods could lead to potentially misleading results over a large number of years.
- Given the relatively close values of avoided emissions, it is not possible to say whether using PyPSA-GB for multiple years would change the conclusions of the AEP-CI method. It may be carbon payback for the fleets in FES2022 is a target that is beyond credible - this does not mean decarbonisation via these methods should not be pursued, rather that GWP may be an emerging benchmark for technologies to assess their climate mitigation credentials - for most offshore renewable technologies in FES2022.

Overall, the method and examples laid out in this chapter demonstrate the opportunities and pitfalls of combining static attributional LCA to dynamic assessments of emissions reduction potential.

- The complimentary of floating wind, wave energy and tidal stream was not really observable at these scales.
- At annual scales, it is not really to do with the complimentary of a *technology* and more of the total generation capacity.
- Complimentary as an emission reduction potential metric is perhaps only relevant at sub-annual timescales – any benefit disappears when the aggregate off the annual average CI is considered.
- Total capacity is dominant at these disparate levels of installed capacity, and “the starting gun has already been fired”.

### 8.5.1. Further work

Further work from this research includes:

- Explore the seasonal component in energy delivery and the relation to the historical year selected in High marine scenarios and how that interacts with the emission reduction potential of storage.
- Incorporation of Zihui Yang’s method of node consumption (via Dr. Wei Sun at University of Edinburgh)
- Time series of power generation have been produced, which would enable marginal emissions displacement analysis to be performed.

Future work from this chapter would include:

- A more rigorous examination of the time horizon of the avoided impacts and how this relates to the persistence of the GHGs considered, beyond the coverage of the FES (up to 2050).
- Additional emissions from ramp rates are significant in some studies but will not be captured in the current formulation of PyPSA-GB.

# Chapter 9: Conclusions

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This chapter summarises the findings of this research and draws overall conclusions. The implications of these and the contribution to knowledge are also reviewed, and the central hypothesis is answered. Opportunities for further work are also discussed.

## 9.1. Thesis summary

This research was a broad-ranging examination of the life cycle of floating wind, wave energy and tidal stream technologies, in isolation, and when integrated into the future energy system of Great Britain, set in the context of the environmental and ecological planetary crises. The earlier chapters (2, 3, 4 and 5) considered the environmental impacts of floating wind and wave energy machines in the context of contemporary science. The latter chapters (6 and 7) consider the methods of integrating these findings into the wider energy system, and develop select data necessary to operate a new power system modelling tool, PyPSA-GB. The final chapter of analysis (Chapter 8) combines these perspectives to present an estimate of the emissions reduction potential and characteristics of these technologies when integrated into future energy scenarios of Great Britain.

### 9.1.1. Chapter 2: Setting in context

Chapter 2 presents a multi-disciplinary literature review of the characteristics, drivers and implications of human decisions on the planetary crises. Human consumption practices and activities (indicated by increasing GDP, growth) are devastating Earth's biotic and abiotic

planetary systems, to such a degree as to risk driving the Earth out of the climatically stable Holocene state of the last 10,000 years, with unprecedented conditions in many metrics of assessment, including species' extinction rates. 'The Great Acceleration' beginning in the 1950s has seen dramatic increases in consumptive behaviours suggesting fundamental challenges for the precepts of a circular economy. The energy system (and animal agriculture) – underpinned by fossil fuels – are primary contributors to the planetary crises. Replacing fossil-based systems with renewable energies can reduce operational emissions, with associated increase in demand for non-fossil minerals. Huge inequalities in consumption and contribution to environmental harms exist across income and historical demographics. Modern consumption is underpinned by historical exploitation. Massive gaps exist between stated climate targets for achieving the Paris Agreement targets; and 1.5°C warming by the year 2100 is rapidly dwindling. Renewable energy, primarily wind and solar, will form a significant (nearly 70%) amount of electricity supply in many net zero scenarios [107], requiring careful management of the life cycle environmental impacts from increased extraction and mineral use.

### 9.1.2. Chapter 3: Literature review of floating wind & marine energy life cycle impacts

Chapter 3 reviews, sets out and characterises the floating wind, wave and tidal stream LCA literature. Materials and manufacturing typically comprised the largest GWP impact for these technologies, always more than 50% and even beyond 95%. Transportation, installation and O&M are typically the second largest contributor to GWP, but this is significant (around 30%) in only a few studies. In general, assumptions on transport, operation and maintenance (O&M) are rarely described in detail in the literature and significantly different results could arise from methodological choices, such as: fuel use assumptions, distance to shore, O&M

strategy, site conditions, frequency of interventions and generation availability. For wave energy specifically, a great deal of variation in almost every aspect of the wave energy LCA literature was noted, apart from the functional unit, and (mostly) the background databases and impact assessment methods. In terms of novelty, the opportunities identified in the literature are: to consider an array-scale reference flow: up to end of export cable, including array infrastructure with an assessment of water depth using novel machines. Several opportunities were noted for novel research in floating wind LCA, specifically: to model turbines larger than 10 MW, with HVDC architecture in arrays far from the grid-connection; to use site-specific wind resource data to assess annual energy production; incorporating dedicated O&M model outputs. Overall, the floating wind LCA was more well established and developed. Outputs from this chapter were presented at conferences in 2019 (WESAC19) and 2020 (FWM20 and ETP20). The literature review for floating wind LCA contributed to a published paper on floating wind LCA [12].

In addition, Chapter 3 finds numerous approaches for assessing the environmental impacts of energy generation technologies when integrated into an energy system. Explicit modelling of floating wind and marine energy technologies; considering the 'avoided emissions' within the climate change impact, and; the accuracy of using annual average values for grid carbon intensity were identified as specific gaps in the literature.

### 9.1.3. Chapter 4: Life cycle assessment of the Blue Horizon wave energy converter in four arrays around Scotland

Chapter 4 presents an LCA of the Blue Horizon wave energy converter (WEC) arrayed in four near-future wave farms around Scotland. The assessment includes site-specific resource, detailed representation of vessel operations, an uncertainty assessment and sensitivity

analyses. There is a particular focus on WEC operation and maintenance (O&M), with foreground data estimated from LCA and levelised cost of energy (LCOE) literature of adjacent technologies. The median Global Warming (GW) impact of electricity from across the four sites ranged from 68.3 to 94.9 gCO<sub>2</sub>eq/kWh, or around four to five times less than from a contemporary British Combined Cycle Gas Turbine (CCGT) power plant. The materials and manufacturing (M&M) life cycle stage was generally the most impactful across all environmental impact categories, followed by operation and maintenance (O&M) and landfill and recycling (L&R). Array infrastructure (array cables, floating substation and export cables) has a non-trivial impact on the GW impact (approximately 10 to 16%). Diesel combustion and steel use are the most GW impactful processes, while at a subassembly level, the WEC structure, mooring and generator are largest contributions. WEC retrieval/reinstatement during O&M, subsea maintenance of moorings and array cables and WEC mooring installation/decommissioning are the most GW impactful vessel operations. Carbon payback is not achieved within the 20 year design life when decarbonising annual average emissions intensities are considered; albeit excluding any account for future vessel decarbonisation. All impact categories are sensitive to design life and device mass, while relatively insensitive to water depth and distance to O&M port. The preliminary results of this chapter contributed to an industrial report for the technology developer Mocean Energy and were presented (remotely) at conference in 2020. This work identifies that validated vessel operation data, dynamic process inventory (prospective LCA) and dynamic systems inventory are key areas for future wave energy LCA research.

#### 9.1.4. Chapter 5: Life cycle assessment of four floating wind farms around Scotland

Chapter 5 presents an LCA of the 15 MW reference wind turbine on floating platforms in sites representative of four floating wind farms in the ScotWind leasing round (E3, NE1, NE7 and N3) with a mixture of HVAC and HVDC transmission systems. The median Global Warming (GW) impacts for the E3, NE1, NE7 and N3 sites were 17.4, 20.0, 20.5 and 26.3 gCO<sub>2</sub>eq/kWh. Life cycle impacts across most categories were dominated by the materials and manufacturing stage of the life cycle. For global warming this was 78%, 71%, 72% and 79% for the same sites. Although the O&M burden was smaller than other studies; O&M (mainly using SOVs) comprised 9 – 16% of global warming and 10 – 17% of cumulative energy demand impacts. Sensitivity studies showed that the environmental impacts are fundamentally affected by design life, making life extension a crucial priority for the sustainability of these arrays. Following that, material use – not vessel use – is the next most significant contribution on balance, suggesting “greening” the supply of materials (via recycled materials, or alternative low impact processes such as the use of hydrogen as a reducing agent in steel making) should be a research priority, with decarbonizing vessel propulsion following, echoing the results from Chapter 4. In almost every case the floating wind arrays were less environmentally impactful than the wave energy arrays in Chapter 4 and achieved ‘carbon payback’ in only a few years. Select findings of this chapter were presented at conference in 2023 (FWM23) and published in a journal paper in the same year [12].

### 9.1.5. Chapter 6: Methodology and model selection for assessing operational emissions displacement impact of renewables

The methodology for addressing the gaps in the literature in Chapter 7 and 8 using an operational power system model (PyPSA-GB) was proposed, as well as presenting a discussion of the concept of complementarity and the power system model selection process.

### 9.1.6. Chapter 7: Power generation from wave, tidal stream, floating wind and tidal lagoons in future scenarios around GB

Chapter 7 presents two important datasets. Firstly, *installed capacity scenarios* for wave energy, tidal stream, floating wind and tidal lagoon sites across GB from 2025 to 2050. Secondly, the *time series of capacity factors* for the technologies at the respective sites is presented along with the associated methodology. The combination of these data provides the detailed *spatial* and *temporal* variation in capacity factors from wave, tidal stream, floating wind (and tidal lagoon), and enables the FES to be replicated and elaborated on in PyPSA-GB for the next part of the thesis. When integrated into PyPSA-GB, the outputs of this research will be used directly by other power system modellers to analyse the contributions of these technologies to the future power system of Great Britain. Select findings from this chapter were presented at conference (including a paper) [10].

### 9.1.7. Chapter 8: Emission reduction potential using power system modelling

Chapter 8 determines the emissions reduction potential of floating wind, wave and tidal stream in future energy scenarios around GB in two ways: by considering the installed capacities and carbon intensity of the 2022 National Grid future energy scenarios (FES), in combination with the life cycle assessment (LCA) results from chapters 4 and 5; and by using PyPSA-GB to demonstrate the emissions reduction potential of marine energy in an example

year (2045). Nearly all fleets of floating wind, wave energy and tidal stream were shown to contribute to climate change impacts at the end of the period 2025 to 2050: only tidal stream achieved carbon payback in two scenarios by virtue of its low cumulative installed capacities concurrent with relatively high carbon intensities, and low GWP. This shows that the installed capacities do not achieve carbon payback, and suggest that carbon payback should be retired from the discourse, instead progressing towards the discussion of minimising environmental harms by delivery of some function unit.

The example use of PyPSA-GB showed that the amount of power delivered using a more sophisticated method was lower by around 1.3 to 1.7 times, suggesting the simpler method would overstate the emissions reduction potential relative to LOPF method. The second method showed that the complimentary of marine energy as an emission reduction potential metric is perhaps only relevant at sub-annual timescales – any benefit disappears when the aggregate off the annual average CI is considered, and total installed capacity dominates the efficacy of the technology. Select findings from this chapter were presented at conference [11].

## 9.2. Implications

### 9.2.1. Climate change efficacy of offshore renewable energy by technology and location

One of the objectives of this thesis was to determine the climate change mitigation efficacy of different diverse renewable energy technologies, especially offshore wind compared to marine energy: wave energy and tidal stream.

To do this, this thesis has tried to take a robust approach to possible future scenarios, either using the FES from National Grid, or using low, mid or high scenarios from reputable sources to consider possible futures of installed capacities of these technologies; and to bring rigour also to the geo-locating of the possible distribution of installed capacities according to sites considered most favourable for deployment.

In doing so, a realistic picture of the 'resource' of marine energy has attempted to have been painted. Considering these realistic pictures then (from FES and from other agglomerated sources), these scenarios have been compared to scenarios for offshore wind and floating wind, the thinking being that the unique complementarity of the wave and tidal stream generation would enable access to significant climate change mitigation benefits producing energy "when the sun isn't shining and the wind isn't blowing".

Unfortunately for wave and tidal stream, the climate change mitigation benefit has not really been realised as a credible dimension to justify the development of these technologies in this thesis, relative to (the other novel offshore renewable energy technology considered here) floating wind. Other studies have demonstrated the value of the diversity of supply from marine energy's unorthodox temporal profiles, and this is demonstrated here, but even with the extremely ambitious deployment rates in the highest scenario considered here, the bulk

climate change mitigation benefits are minor relative to floating wind using the simple AEP-CI method: bulk emissions reduction is proportional to the installed capacity in the unamended FES and the three order of magnitudes between floating wind and marine energies installed capacities is reflected in the bulk emissions reduction potential. For ERP relative to energy generated (and for per unit of installed capacity), tidal stream performs best in two scenarios (CT and FS) where emissions intensity of power is high, and installed capacities are low. Wave performs least well in three of four FES. While not assessed in this thesis, a situation exists that overbuilding other assets (interconnection; nuclear, wind or solar generation; storage; transmission or distribution networks) could have comparable system benefits.

On the other hand, while the complementarity doesn't appear to "turn up" in the PyPSA-GB section of Chapter 8 the installed capacities do govern the efficacy of marine energy. If for example, there is a hypothetical bottleneck in offshore wind deployment (perhaps due to supply chain or consenting issues) there is an opportunity for marine to step into the breach. But in this hypothetical situation, the challenge of the scale of deployment (and absence of established supply chain) would still apply.

Chapter 8 also confirmed the issue with the current grid structure. Even in very favourable deployment scenarios for installed capacity and time, wave and tidal stream power is typically injected into grid with largely decarbonised generation – at both local and national scale – meaning that the operational benefits from power from a diversity of renewable energy resources have limited coupling to emissions reduction benefits.

Thus, we can say indeed that offshore wind *should* form the backbone of the British Net Zero power system, and hence low emissions strategy, over the 'competition' of marine energy.

However, as this thesis has adjacently shown, the *embodied* emissions of this fleet (floating only considered here) are not trivial (marine fans; before you crow, your average GWP is even higher than floating wind) compared to future carbon budgets. This is arguably a feature of the carbon budgets themselves, which only consider operational – not embodied – emissions. Other studies taking a wider stance (for example, [217]), have assessed these emissions in other ways, finding them minor, but the results of this study seem to confirm the challenge of achieving emissions reductions at the rampant pace necessary to achieve the goals of the Paris Agreement, while protecting environmental impacts.

### 9.2.2. Methods to reduce global warming potential and achieve carbon payback in future scenarios

Using the simple AEP-CI method, the results of Chapter 8 demonstrate that significant reductions in the static attributional GWP would be required to achieve emissions neutrality of the installed capacities in the FES. This ‘target’ GWP for carbon payback for floating wind is 4.3 to 9.6 gCO<sub>2</sub>/kWh (down from an average of 17.3 assuming a 25 year design life), for wave 9.6 to 67.7 (down from 67.7), and tidal stream 11.5 to 24.8 (down from 18.1) in the unamended FES2022. Wave and tidal stream thus achieve carbon payback in FES2022 over the period 2025 to 2050 in Consumer Transformation and Falling Short; a function of the relatively higher carbon intensity of power in these FES and the very low volumes of installed capacity.

It is clear from Chapter 4 and 5 that decarbonising material production, vessel propulsion and disposal are crucial to reducing the GWP of these novel offshore renewable energy technologies, however, it remains to be seen whether innovation in these sectors (along with improvements in power capture, structural efficiency and asset life extension) can reduce

GWP sufficiently to achieve carbon payback of the fleets of these technologies by 2050 independent of the future energy system architecture.

### 9.2.3. Power system network reinforcement and operation

As with the wider discourse on highly renewable power systems, Chapter 8 also shown that maintaining and upgrading the power system is crucial to the UK achieving its Net Zero ambitions, enabling effective transmission of power from distal nodes of the networks to displace high carbon generation which tends to be nearer to urban load centres.

### 9.2.4. Life cycle impacts of future energy scenarios

It is conceivable that FES data could be utilised to output the environmental harms of the energy system design of each scenario: a brief demonstration of this approach is shown in Chapter 6. Alternatively, the energy system design itself could be optimised to reduce specific life cycle impacts, which could lead to markedly different energy system designs, as under investigation in some of the literature, notably [198].

### 9.2.5. Validity of life cycle assessments for future products and production systems

Chapter 4 and 5 demonstrated the uncertainties and assumptions behind LCA outputs for two types of products. As the use of this technique grows in future years, it is a timely reminder of the susceptibility of the results to inputs and practitioner assumptions, masked behind a single number.

### 9.2.6. Open-source power system modelling tool PyPSA-GB

The tool PyPSA-GB is available for use as a result of this work and others [13].

## 9.3. Recommendations for further work

### 9.3.1. Life cycle assessment innovations

There are many specific innovations that could be explored from an LCA perspective.

- **System boundary:** the system boundary of the life cycle model could always be expanded. Obvious opportunities include spare parts [274], detailed consumables [228], coatings [155], onshore works [338], turbine design details (for example, the IEA-22-280-RWT, a 22 MW reference wind turbine in development, or with actual data from OEMs), emissions of microplastics from blade erosion, cable abandonment and disposal, and circularity potential [339].
- **System expansion:** more challengingly, aspects of the functional unit and interconnecting energy system could be researched, such as: the variability of power and how this relates to the definition of the functional unit, further energy system integration and the impact of the temporal phase between generation and use imparted by energy storage. However, the findings of this thesis suggest that the gross effect of the fine temporal resolution will be dominated by installed capacities in the associated scenarios.
- **Prospective life cycle assessment:** the historical background data used in this thesis is not necessarily representative of future production systems [101]. Dynamic process inventories [277], or Prospective LCA, have been identified as a technique which could more robustly explore the impacts of these technologies in future scenarios and many sophisticated tools to facilitate this are emerging [340], [341]. Interestingly, if climate change mitigation targets are pursued, the global warming potential of most

technologies should decrease: marine ecotoxicity, marine eutrophication and metal depletion are also shown to decrease by around 20% in [164].

- **Vessel decarbonisation:** No suitable processes for modelling vessels representative of those required for offshore renewable energies were identified in the ecoinvent v3.6 database. Furthermore, new vessel propulsion systems (rather like electric car vehicles) are being 'eagerly' pursued, however research is lacking on the potential for burden shifting. The gradual replacement of diesel propelled vessels by alternatives throughout the operational stage of the life cycle would require a 'dynamic systems' life cycle assessment [277]. This environmental impact assessment could also be integrated with existing O&M modelling tools.
- **Coupling with Planetary Boundaries:** some studies consider the global impacts of offshore renewable energy and the transition away from fossil fuels, however, there is an opportunity to utilise PB LCIA methods directly. Some interesting research could pursue the methods for downscaling PB shares at a national, sectoral, organisational scale using multiple allocation principles.
- **Global warming potential:** using more sophisticated understanding of the composition of GWP would be interesting especially around fugitive emissions of methane from the gas network, and the impact of biogenic CO<sub>2</sub>, which is a contested area of research [333], [342]. Arguably, other improved LCIA categories could also be pursued, particularly those relating to biodiversity or other transgressed planetary boundaries.

### 9.3.2. Coupling power system modelling and life cycle impact assessments

A multi-criteria optimisation problem whereby the lowest impact network could be developed, expanding on [198].

### 9.3.3. Regionality of emissions reduction potential

While this thesis has set out some geographical distributions of emissions reductions this could be explored in further studies to determine the optimal locations for novel offshore renewables. However, the sites available are far more constrained by other stakeholders and network topology, so the usefulness of this enquiry at a national scale is perhaps questionable.

### 9.3.4. Marginal emissions

The phrase marginal emissions has not been used frequently in this thesis. It may be that it can be shown that renewable energies can displace more emissions than the grid average. The hourly time series of generation can be produced from PyPSA-GB which would enable marginal emissions displacement analysis to be performed.

### 9.3.5. Incorporating life cycle impacts into the future energy scenarios

Chapter 8 found a total impact over the period 2025-2050 of around 70 MtCO<sub>2</sub> for floating wind. This is around 10% of the carbon budget in the period 2033 to 2037 [343]. The sum of all the other infrastructure could approach these decreasing budgets.

- Gross inventories of impacts from these technologies (other than carbon emissions) have not been considered - this would be of interest in future work for comparing technologies on a functional unit basis.
- Understanding future material demands (non-fossil fuel resource consumption) and global impacts of their extraction on the living world such as: mining tailings, effluent,

land use, geographical distribution of impacts, recoverable/economic reserves and production rates. In particular, an investigation of leading edge erosion from wind turbine blades would be of interest.

## 9.4. Thesis conclusion

This research has demonstrated that the environmental impacts of floating wind & marine energy arrays are profoundly multi-faceted.

Life cycle assessment is a comprehensive and structured approach to quantifying environmental impacts. However, the depth and rate of systemic changes required to address environmental degradation add potentially significant uncertainty to contemporary assessments of future developments. Further, individual practitioner decisions yet increase the potential for miscommunication. And all of this without mention of the integration of these systems into a wider energy system facing similar radical change.

This thesis has reviewed the limits of what is published about these difficulties and used scenario-based modelling to explore possible futures.

By combining life cycle assessment with modern power system analysis and future scenarios, the research has shown that floating wind plays a significant role in the decarbonisation of the future GB energy system and the life time global warming impacts (when considering avoided electricity generation) are lower than conventional LCA techniques when avoided emissions are considered. In parallel, wave and tidal stream energy generation is effective at displacing carbon dioxide emissions by virtue of their locations, but are simultaneously limited by their location relative to the topology of the power system in future scenarios. Even in very favourable deployment scenarios, wave energy and tidal stream are typically injected into grid with largely decarbonised generation – at both local and national scale – meaning that the operational benefits from power from a diversity of renewable energy resources has limited coupling to emissions reduction benefits.

The power system dataset and modelling tool PyPSA-GB has been supported by research in this thesis.

Many avenues for future research have been identified. In particular, dynamic LCA (background and foreground systems) and use of the planetary boundaries framework with multiple allocation principles.

Finally, it is possible to negate the hypothesis that the complementarity of wave and tidal stream technologies deliver significant emissions reductions, relative to floating wind. In future scenarios, the emissions reduction potential of fleets of floating wind, wave energy and tidal stream are likely to be outweighed by the embodied emissions of their construction, suggesting 'carbon payback' should be removed from discourse on the environmental impacts of such systems, and shifting to the lowest environmental harm per functional unit, echoing the dimension of efficiency to minimise environmental impacts of human societies on the Earth.

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