Aligning policy with wave energy innovation: Opportunities and challenges in the Irish context

Ollscoil Mhá Nuad
Ollscoil na hÉireann
Má Nuad

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Abstract

Ireland's Climate Action and Low Carbon Development (Amendment) Act 2021 has passed into law, providing the mechanism to agree, review, and enforce Ireland's climate plans, and through which the country is now legally committed to achieving carbon neutrality by 2050. This is a significant step forward in the reinforcement of Ireland's energy commitments and indicates that developing alternative forms of clean energy will be central to government policy in the coming years. Ireland has one of the largest wave energy resources per capita on the planet and has significant, globally recognised, technical expertise in both fundamental research and wave energy device prototype development and testing. With policy support and investment, particularly through the mid-technology readiness levels, Ireland could produce 12.5GW of electricity from wave energy, more than twice the country's peak demand, with the potential to market this technology globally. Within this context, a strategic question that may be posed is whether Ireland should seek to develop indigenous wave energy technology for potential export, or instead wait for technological maturity and deploy imported solutions. While the broader economic strategy question lies beyond the scope of this thesis, it provides important motivation for examining the conditions under which wave energy technology development could be supported domestically. Accordingly, this thesis focuses on the policy, institutional, and innovation external factors that influence the progression of wave energy technologies towards commercial viability in Ireland. Denmark's successful development of wind energy technology is used as a comparative policy benchmark, with Denmark having a similar demographic profile to Ireland including GDP, population, geographical size, and agricultural heritage; and where wind technology is now mature with continuing technology development and global exploitation, with wind production per capita exceeding that of any other Organisation for Economic Cooperation and Development (OECD) country. The analysis concentrates specifically on policy frameworks and enabling mechanisms, rather than on wider political, economic, or cultural factors. The thesis explores external factors that are fundamental to the successful development of the burgeoning wave energy technology industry, looking in detail at policies and recent policy changes, funding availability, intellectual property protection, infrastructure availability, and social acceptance of wave energy technology. Having thoroughly examined these factors that are central to the success of a viable wave energy industry, this thesis offers conclusions that can inform practical and pragmatic policy interventions to support a robust, commercially sustainable indigenous wave energy industry.

Declaration of authorship

I, Carrie Anne Barry, declare that this thesis entitled "Aligning policy with wave energy innovation: Opportunities and challenges in the Irish context" and the work presented in it are my own. I confirm that:

- This work was done wholly or mainly while in candidature for a research degree at this University.
- Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated.
- Where I have consulted the published work of others, this is always clearly attributed.
- Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work.
- I have acknowledged all main sources of help.
- Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself.

Date: 16/12/2025

To Chris, Christina, Isabel, and Christopher.

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Personal

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Institutional

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List of abbreviations

AC	Alternating Current
AEP	Annual Energy Production
AMETS	Atlantic Marine Energy Test Site
BiMEP	Biscay Marine Energy Platform
CAP	Climate Action Plan
CAPEX	Capital Expenditure
CLD	Causal Loop Diagram
CEFC	Clean Energy Finance Corporation (Australia)
CfD	Contracts for Difference
CoP	Conference of the Parties
CoF	Creating our Future
DC	Direct Current
DOE	(United States) Department of Energy
DTU	Danish Technological University
EMEC	Europearn Marine Energy Centre
EPA	Environmental Protection Agency
EBS	Electricity Supply Board
EU	European Union
EUDP	Energy Technology Development Demonstration Programme
GDP	Gross Domestic Product
GE	General Electric
GHG	Greenhouse Gases
IEA	International Energy Agency
IEC	International Electrotechnical Commission
IECRE	International Electrotechnical Commission Renewable Energy System

ICL	Imperial College London
IP	Intellectual Property
IPC	Intellectual Property Controller
IPCC	Intergovernmental Panel on Climate Change
IPP	Intellectual Property Protection
IRA	Inflation Reduction Act
IRENA	International Renewable Energy Agency
ITE	Instituts pour la Transition Energetiques
LCoE	Levelised Cost of Energy
LNOTF	Lir National Ocean Test Facility
MAC	Marine Area Consent
MARA	Marine Area Regulatory Authority
MAPF	Marine Area Planning Framework
MIGA	Multilateral Investment Guarantee Agency
MRE	Marine Renewable Energy
MRIA	Marine Renewable Industries Association
MSP	Marine Spatial Planning
NASA	(United States) National Aeronautics and Space Administration
OECD	Organisation for Economic Cooperation and Development
OES	Ocean Energy System
ONDEP	Ondas de Peniche
OPEX	Operational Expenditure
ORE	Offshore Renewable Energy
OREDP	Offshore Renewable Energy Development Plan
ORES	Offshore Renewable Energy Support Scheme
OWC	Oscillating Water Column
PATSTAT	Patent statistical database
PCP	Pre-Commercial Procurement
PESTLE	Political, economic, social, technological, legal, environmental
PTO	Power Take-Off
P-value	Probability value

R&D	Research and Development
RE	Renewable Energy
RET	Renewable Energy Technology
Risø	Risø Test Station
SA	Societal Acceptance
SEAI	Sustainable Energy Authority of Ireland
SEI	Sustainable Energy Ireland
Siemens	Siemens Gamesa Renewable Energy A/S
SETA	Sustainable Energy Technology Acceptance
Solar PV	Solar photovoltaic
SME	Small to medium enterprises
TAM	Technology Acceptance Model
TH	Triple Helix
TQ	Technological Qualification
TPL	Technology Performance Levels
TRL	Technology Readiness Levels
TRM	Technology Readiness Management
TH	Triple Helix
UK	United Kingdom
UN	United Nations
US	United States (of America)
VoD	Valley of Death
WEC	Wave Energy Converter
WES	Wave Energy Scotland

1

Introduction

Contents

1.1 Motivation

Ireland's legal commitment to achieving carbon neutrality by 2050 is now enshrined in the 2021 Climate Action and Low Carbon Development (Amendment) Act [1] and requires a rapid transition away from fossil fuels to a renewable energy system. This legislation is mandated by international and European agreements [2] and amplifies the need to explore and invest in renewable energy alternatives.

1.1.1 Reasons for investing in renewable energy technologies

Three reasons are frequently cited as motivation for investing in renewable energy projects and technology development, namely, halting global warming, ensuring the security of the energy supply, and the economic potential of the renewable energy

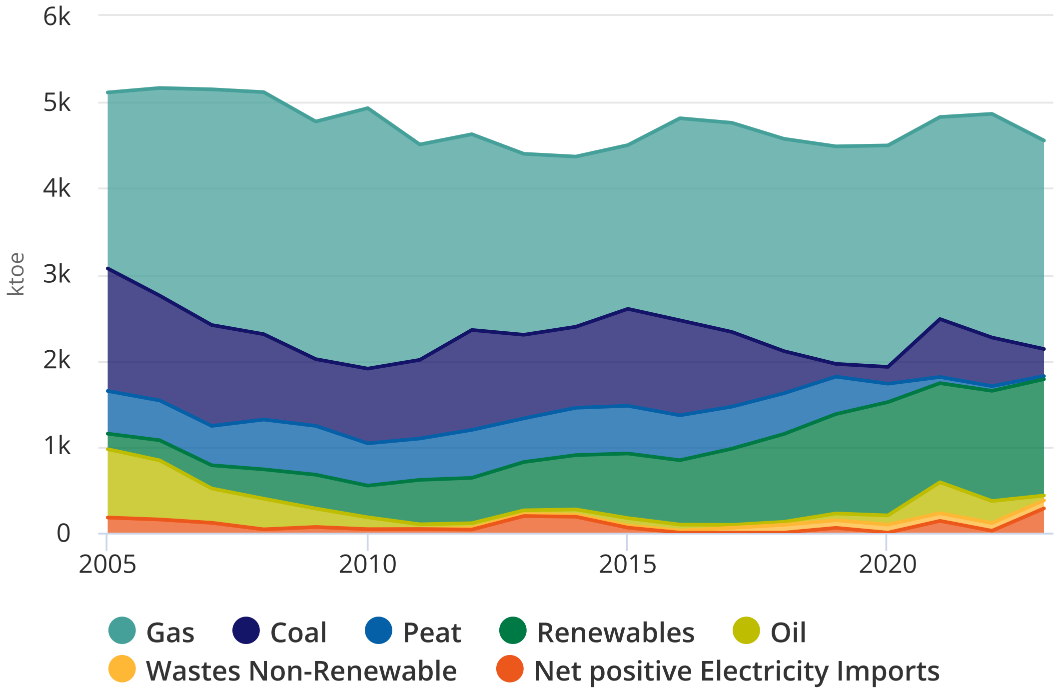

Figure 1.1: Primary inputs to electricity generation 2005-2024. Source, SEAI(2025) [3]

market [1]. The global market for renewable energy is well established. Figure **??** shows a decrease in dependence on coal and oil in Ireland between 2005 and 2024, with increases in domestically sourced natural gas and renewable energy sources, mainly wind.

The global picture is much the same across most developed countries. The United Nations (UN) 2022 Global Energy Status Report [4] describes recent key achievements, finding that the greatest success for renewable energy integration in 2021 was in the power sector. 315GW of new renewable power capacity was added to global electricity grids in 2021. 90% of all new renewable energy additions to electricity grids come from solar photovoltaics (PV) and wind energy. The UN report added the caveat that the current deployment of renewable power is still far from what is needed to keep the world on track to reach net-zero carbon emissions by 2050.

Ireland ranks among the countries with the highest growth in renewable energy use. The share of Ireland's electricity generated from renewable sources has risen from around 7.5% in 2006 to approximately 41% in 2023, supported largely by substantial growth in wind power [5].

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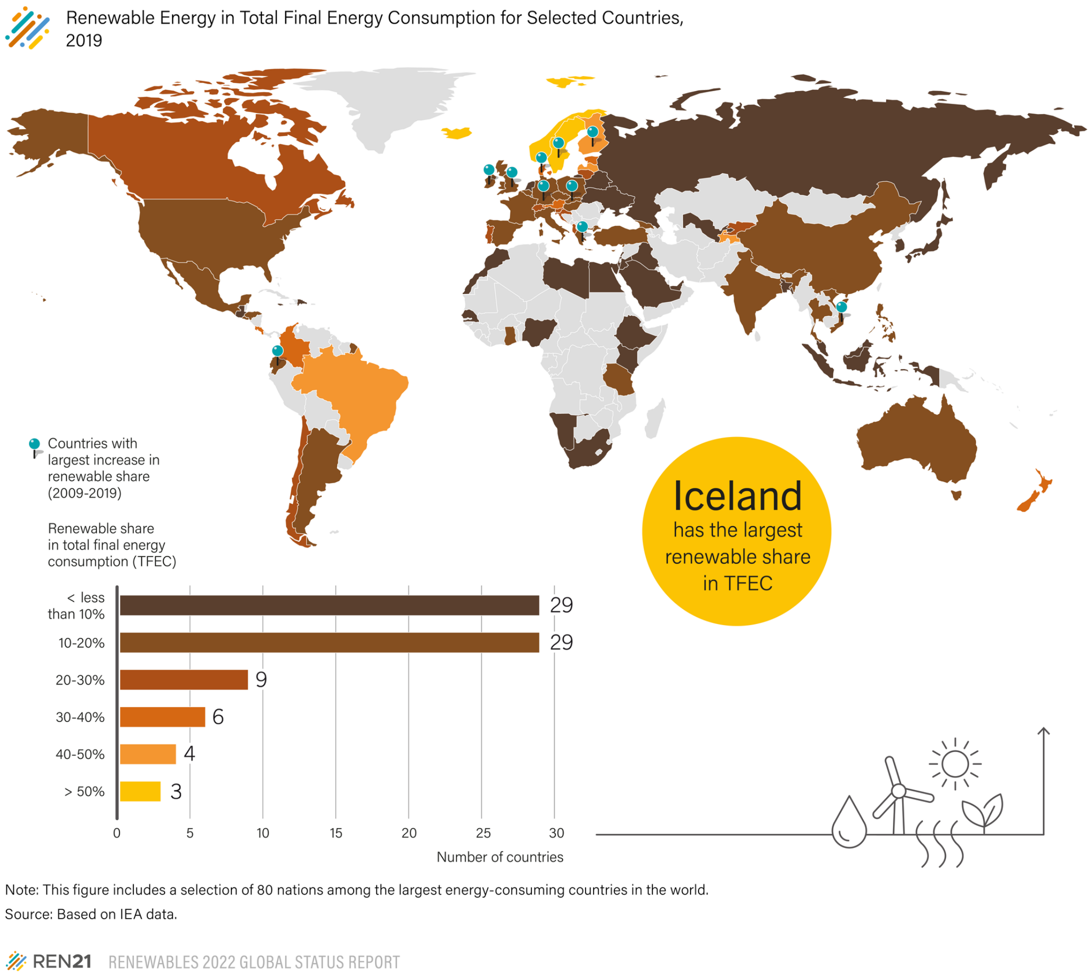


Renewable Energy in Total Final Energy Consumption for Selected Countries, 2019

Note: This figure includes a selection of 80 nations among the largest energy-consuming countries in the world.
Source: Based on IEA data.

Figure 1.2: Renewable Energy Share Global 2019. Source United Nations, (2022) [6].

1.1.1.1 Halting global warming

Developing renewable energy technologies offers a key solution to halting global warming driven by carbon-emitting fossil fuels [7]. 193 countries and the European Union (EU) have signed up to obligatory climate action targets [8], and this, as well as increased energy security concerns, maintains unprecedented focus on climate action among policymakers [9].

Integration of renewable energy resources reduces dependence on fossil fuels such as coal, oil, and gas, consumption of which releases greenhouse gases (GHGs), particularly carbon dioxide and methane, which become trapped in the Earth's atmosphere resulting in the phenomenon known as global warming [10].

If countries remain dependent on fossil fuels, it is estimated that the world's temperature will increase by up to 2°C above pre-industrial levels by 2040 [11]. This level of increase, would result in catastrophic and potentially irreversible effects, including more common profound weather events, more extreme heat waves and droughts, the almost complete dying off of the world's coral reefs, more flooding from melting ice caps, and sea levels rising by 2 metres by 2100 [12]. At the Environmental Protection Agency (EPA) Annual Conference 2022, Deborah Roberts, Intergovernmental Panel on Climate Change (IPCC) Co-Chair, stated succinctly: "The scientific evidence is unequivocal: climate change is a threat to human well-being and the health of the planet..... Any further delay in concerted global action will miss the rapidly closing window for change" [12]. A landmark study of global temperature changes over 1,000 years shows that the unique rise in temperature seen in the late 20th century is beyond that expected due to natural variability, and concluded that greenhouse gas emissions are the primary contributor [13]. Expanding the use of renewable energy sources, as fossil fuel alternatives, can play a critical role in mitigating global temperature increases.

1.1.1.2 Energy security

Energy security is a phrase used to describe the availability of natural resources for energy consumption. Since 2015, climate change mitigation has been focused primarily on reducing carbon emissions to meet international targets [8]. Energy security concerns heightened significantly in 2022, due, to a large extent, to the conflict in Ukraine, with prices for household electricity increasing dramatically (Figure 1.3).

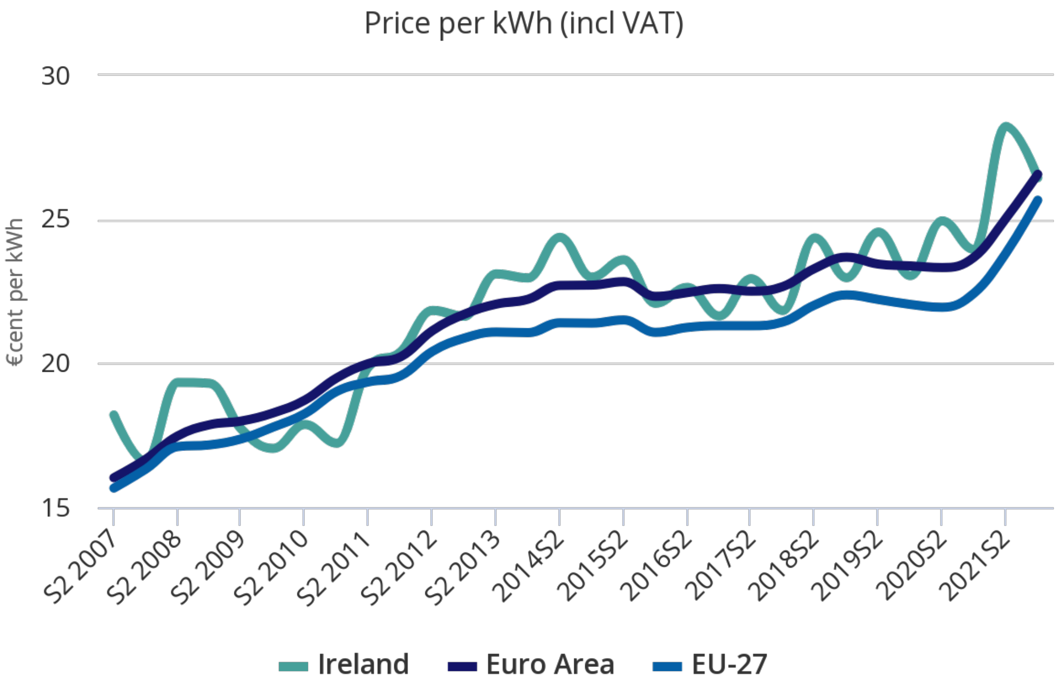


Figure 1.3: Average price of electricity for households. Source SEAI, (2022) [14].

Energy security is affected by depleting fossil fuel resources, reliance on foreign sources of energy, geopolitics, demands from large, advancing developing countries such as

China and India, and the growing demand for energy in developed nations. International Energy Agency chief Fatih Birol, writing in December 2022 [15], warns against using the current crisis as an excuse to deepen dependence on fossil fuels. Birol states that the situation strengthens the case for increased investment in clean energy, including energy efficiency, renewable energy technologies, electrification, and a range of clean fuels, to reduce dependence on imported oil and gas. Renewable energy can address these concerns by providing alternative, often indigenous, sources of electricity.

Renewable sources of energy also increase the diversity of electricity sources and contribute to the flexibility of the system and system resistance to central price shocks [16]. Indeed, the International Energy Agency (IEA) [17] concluded that rising oil demand, if left unchecked, would accentuate the consuming countries' vulnerability to a severe supply disruption and resulting price shock.

As a response to Ireland's energy security concerns, the Irish government, in 2022, launched the National Energy Security Framework [18]. The framework outlines the plans in place to deal with energy security emergencies and how the Irish government will accelerate the shift to increased energy efficiency and indigenous renewable energy systems. The framework's focus is on offshore wind; "supportive policies across Government and State agencies can reduce barriers and fast track permitting for renewable energy generation projects". This indicates that the Irish government recognises the need for supportive policies to enable renewable energy systems to develop to the point where they can ensure energy security.

1.1.1.3 Economic potential

Several financial metrics can be used to quantify the economic potential of renewable energy technologies for project developers. These generally depend on the energy yield of the system and on expenditure, including capital expenditure such as the cost of the device, its cables, or pipelines, foundations and installation costs, and operational costs such as maintenance, insurance, license costs, etc. [19].

Jobs/MW is the most common method of assessing the broader economic potential of renewable energy technologies [20]. The International Renewable Energy Agency (IRENA) [21] found that renewable energy supported 12 million jobs in 2021, an increase of 4.7 million from 2012. This, the report found, is a result of declining costs and relatively steady annual investments, with more than 260GW of renewable energy devices installed during 2020, expanding capacity by approximately 10%. Because wave energy projects remain in the pre-commercial phase, most employment in this area currently arises from higher education institutions and industry partnerships [22]. Gielen *et al* [23] used the E3ME econometric model to find that increased reliance on renewable energy sources could account for a global Gross Domestic Product (GDP) boost of around 1% in 2050. They found that the cumulative gain through increased GDP between 2015 and 2050 could amount to $52 trillion and around 19 million additional direct and indirect jobs by 2050. Although estimates vary, it is evident that the offshore renewable energy sector offers substantial employment potential, with immense economic benefits. Models suggest that by 2050, approximately 1 million jobs could be sustained in the operation and maintenance of offshore renewable installations alone [24]. While the motivations for renewable energy adoption are clear, achieving a reliable and resilient zero-carbon system requires a balanced mix of complementary renewable sources.

1.1.2 The need for a renewable energy system with complementary modalities

Ireland's transition to a zero-carbon energy system mandates a shift away from fossil fuels toward renewable sources of energy, chiefly wind and solar, which initially present the most accessible options. However, their high variability and relatively limited predictability pose major challenges.

For example, in December 2023, during an exceptionally cold and high-pressure spell with very low wind, despite Ireland having approximately 5GW of installed wind capacity, actual electricity generated from wind turbines dropped to just 0.11GW, supplying only around 2% of electricity that week, underscoring how weather extremes can sharply curtail wind output even when capacity is high [25].

A particularly problematic scenario for a renewable energy system reliant on wind and solar is known as dunkelflaute, or extended periods of calm, overcast weather. These events occur across Europe roughly once every five years, and can last several days, severely limiting renewable output [26].

Reliance on wind and solar alone compels system operators to deploy fossil-fuel backup, activate demand-side controls, or import energy during such events. This not only escalates carbon emissions and system risk, but also increases required storage capacity. One study found that during the worst-case European dunkelflaute, even with geographically balanced resources, long-duration storage equivalent to 3–7% of annual electricity demand is necessary [27]. This type of weather requires major interventions from system operators, including demand-side management, reserve power deployment, use of fossil fuels, and electricity imports from other countries [28]. Incorporating additional, complementary renewable energy modalities into the mix would improve intermittency and variability, creating a more resilient energy system. [29], [30]. In addition, having a more flexible mix of energy sources would reduce the risk of insufficient supply during extreme weather, and reduce the storage needs that would otherwise be required if relying on wind and solar energy [31].

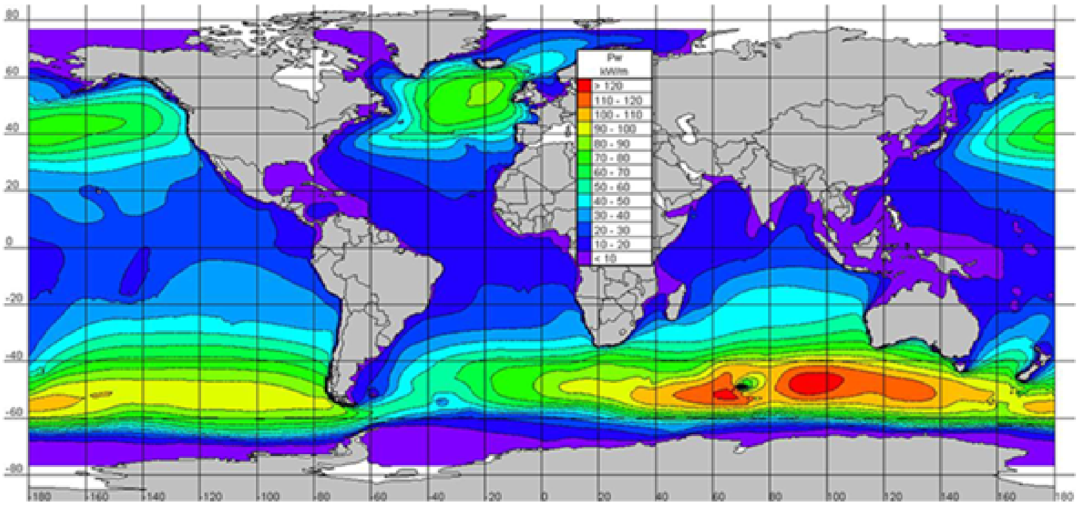


Figure 1.4: Wave energy map. Source Andrew Cornett, Univ. of Ottawa, (2019) [33].

1.1.3 The potential of wave energy

Wave energy presents a promising opportunity for Ireland. The country possesses one of the richest wave energy resources per capita globally, estimated to have a theoretical capacity of around 525 TWh annually [32], as well as possessing internationally recognised expertise in both fundamental and applied research, and device prototyping. Wave energy holds several advantages over other renewable energy modalities. Wave energy density is approximately 10 times that of solar or wind at a latitude of 15°N (northeast trades), the solar insolation is 0.17 kW/m^2. However, the average wind generated by this solar radiation is about 20kn (10 m/s), giving a power intensity of 0.58 kW/m^2 that, in turn, can generate waves with a power intensity of 8.42 kW/m^2 [34]. This advantage is in addition to high availability, complementarity with other renewable resources, and relatively good predictability [35]. Unlike wind turbines, for example, many wave energy converters are largely invisible from the shore, giving them an aesthetic and social acceptability advantage.

Despite these benefits, wave energy development has been overtaken by other, more mature, renewable energy technologies, such as solar PV and offshore wind. Technical challenges have hindered progress, as has the absence of a dominant design archetype, high Levelised Cost of Energy (LCoE) [36], and the liquidation of several wave energy firms, which has impacted investor confidence [37]. To become commercially viable, wave energy technology requires focused, long-term policy support and sustained investment in innovation.

Ireland faces a strategic choice: Should Ireland strive to become a first mover in wave energy technology, positioning itself as a global leader, or should it wait for international technology to mature and import it for domestic use?

This thesis will explore policy interventions and gaps, funding challenges, Intellectual Property (IP) protections, stakeholder perspectives, and societal acceptability of wave energy technology to uncover interventions, frameworks, models, limitations and opportunities, in order to assist developers and policymakers to bring wave energy technology to commercial viability and become an essential part of the renewable energy mix.

Denmark offers a useful benchmark. The country is widely regarded as a global leader in wind energy [38], having built a successful industry through supportive policies, public investment, and social participation. With a demographic, geographic and GDP profile similar to Ireland [39], Denmark's experience provides a valuable case study. This thesis investigates how Denmark achieved its leadership position in wind energy and explores whether similar strategies could accelerate wave energy technology development in Ireland.

Although international and national support for offshore renewable energy (ORE) is growing, most funding and policy attention remains focused on offshore wind [40]. Wave energy, despite its potential, struggles to reach higher technology readiness levels (TRL) and lacks a track record of commercial-scale deployment [41].

Global electricity demand and decarbonisation targets are driving increasing investment in renewable energy compared to fossil fuel investment (see Figure 1.5). Ireland, with its abundant wave resource and established research base, is well positioned to meet this demand if the necessary support structures are put in place. IRENA estimates that up to 29,500 TWh/year of electricity could theoretically be generated globally from ocean energy, exceeding total global electricity consumption in 2018 [43].

This work critically examines Ireland's renewable energy policy landscape, with a particular focus on the institutional and policy environment surrounding wave energy technology development. By drawing on comparative insights from Denmark and leading international initiatives such as Wave Energy Scotland [44] and EuropeWave [45], this research aims to identify targeted policy interventions that could support the emergence of a viable and export-oriented wave energy industry in Ireland.

This thesis adopts a focused scope. While the transition to renewable energy is shaped by broad political, macroeconomic, and cultural dynamics, this thesis focuses on the policy, institutional, and innovation-system factors that influence the development and commercialisation of wave energy technology in Ireland. The comparative analysis with Denmark is therefore restricted to policy, funding mechanisms, and innovation frameworks that supported the emergence of Danish wind energy technology development, rather than to wider socio-political or economic analysis enabling a deeper investigation of the policy interventions and institutional arrangements most relevant to fostering a viable wave energy sector in Ireland.

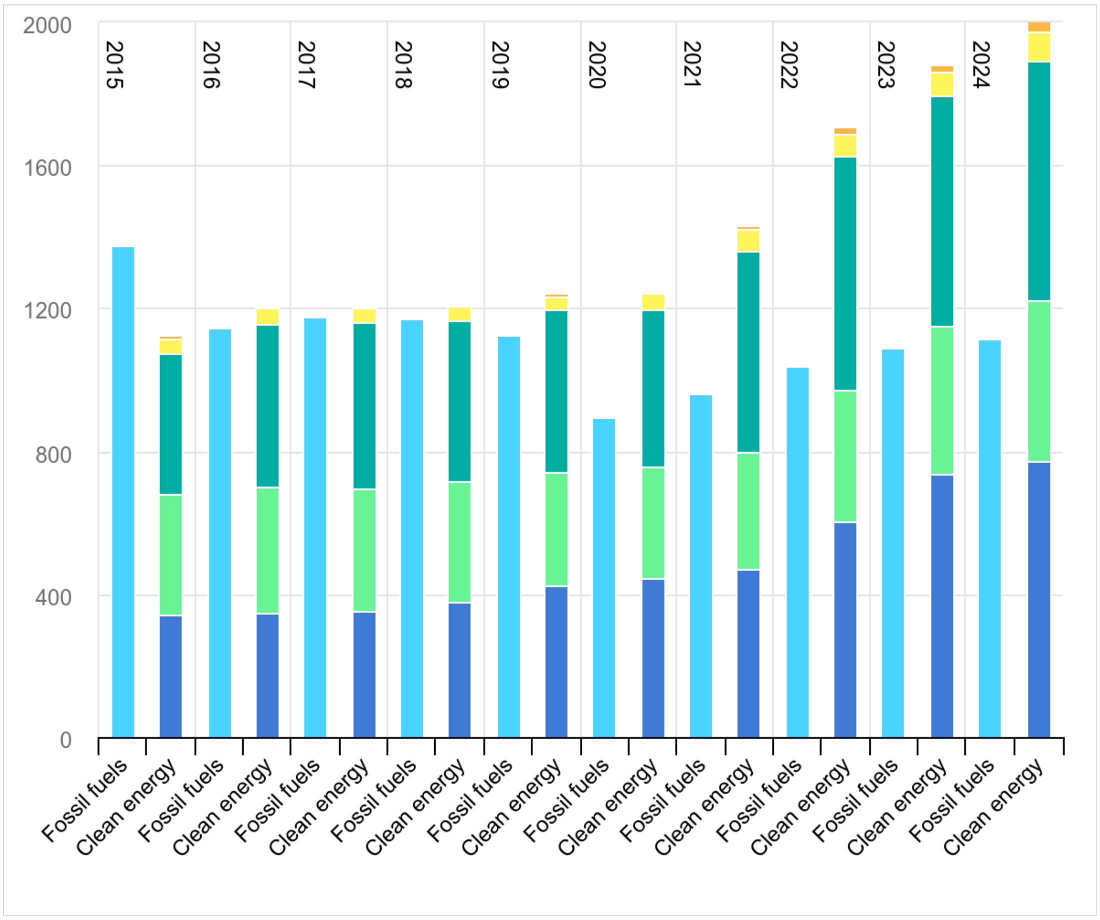


Figure 1.5: Global investment in clean energy and fossil fuels in US$ (2015-2024). Source IRENA, (2025) [42].

Evaluating those external factors that influence the feasibility of commercial projects supports strategic business planning, fosters broader strategic awareness, and helps investors identify both opportunities and threats. This thesis aims to investigate the external factors influencing the development of a domestic wave energy technology industry in Ireland, with the goal of informing a supportive policy framework. The specific factors considered are outlined below.

A key barrier to the commercialisation of wave energy lies in the significant cost escalation associated with scaling technologies for open-sea deployment at mid-TRLs. This development phase is typically underfunded and under-supported, largely due to its high-risk, capital-intensive nature, and its limited appeal to private investment. Moreover, existing national and industrial funding structures are not adequately configured to address these challenges. This thesis evaluates the metrics currently used by funding bodies in their grant allocation decisions and proposes more appropriate, performance-oriented criteria to better support innovation.

The governance of IP presents a policy challenge for wave energy innovation because fragmented ownership, unclear licensing frameworks, and limited standardisation can inhibit knowledge sharing, collaboration, and the scaling of emerging technologies [46]. While robust IP protection is essential for safeguarding commercial value and incentivising innovation, thereby enhancing investor confidence, it often clashes with the dominant culture of trade secrecy in the wave energy sector. This points to a need for policy frameworks that balance transparency and proprietary protection to foster a more collaborative and investable innovation ecosystem.

A lack of appropriate infrastructure, particularly in port facilities and test environments, further constrains Ireland's ability to position itself as a leader in wave energy technology. Without strategic investment in enabling infrastructure, Ireland risks falling behind international counterparts in the development of wave energy technologies.

Stakeholder engagement forms a crucial part of this research, offering insights into policy bottlenecks and sectoral challenges from those directly involved in the industry. A qualitative, systems-thinking approach is employed to assess the current policy landscape, industry dynamics, and societal acceptance of wave energy, recognising that public support is increasingly critical to the successful deployment of marine energy projects as they reach the planning phase.

Ireland's abundant wave resource, strong research foundation, and the global imperative to diversify renewable energy portfolios make wave energy a strategic opportunity. By learning from successful international models and addressing policy and investment gaps, Ireland can position itself at the forefront of wave energy technology development.

1.2 Contributions

This thesis provides analysis, discussion, models, frameworks, and the development or extension of methodologies to inform realisable, pragmatic policy initiatives that could support an indigenous wave energy industry for Ireland. Contributions include:

- An assessment of Ireland's current renewable energy policies, focusing on their evolution and impact on offshore renewable energy technology development.
- An analysis of available funding avenues for research and development in the renewable energy sector, identifying opportunities and gaps.
- A comparative examination of Ireland's renewable energy policies with Denmark's wind energy strategies, drawing insights and lessons applicable to Ireland's wave energy context.
- A study comparing Denmark's wind energy policies with approaches taken by Wave Energy Scotland and the EuropeWave program, assessing their applicability to wave energy technology development in Ireland.

- An assessment of the role and effectiveness of patents within the wave energy technology sector to investigate strategies employed by developers to safeguard innovations and evaluate their success. Key questions addressed include whether patents drive or hinder innovation in wave energy, whether patents are a viable metric to gauge wave energy technology developments, and whether there is an IP protection strategy best suited to wave energy technology development.
- The development of a novel systems thinking methodology to explore the societal acceptance of wave energy as it matures towards full-scale deployment at sea.
- An application of the Triple Helix innovation model (this refers to a model of innovation in which universities, industry, and government interact closely to drive knowledge creation, technology development, and economic growth.) to wave energy development in Ireland, identifying a collaborative framework involving academia, industry, and government. This model, not previously applied to wave energy, facilitates consensus-building among stakeholders, providing valuable insights for pragmatic policy formulation to support the emergence of a domestic wave energy industry. The Quadruple Helix innovation model, which adds a fourth helix of civil society, is applied in the systems thinking methodology developed to explore societal acceptance of wave energy technology development [47].
- An analysis of metrics influencing funding decisions, including TRL, TPL, and LCoE.

1.2.1 List of publications

A list of peer-reviewed studies, undertaken in the course of this research, is provided in Table 1.1. The studies are arranged in chronological order. The abbreviated notation that follows indicates the status of a publication: (P) published, (UR) under review and (A) accepted. Additionally, where a publication is closely related to the contents of this thesis, i.e. if it includes essential information offered in this thesis, this is clarified by referencing a specific chapter.

1.3 Thesis layout

This thesis is divided into two parts. Part I describes the status of wave energy technology development in Ireland, gives an overview of the history of Danish wind energy, and outlines the factors that led to Denmark's global success in the sector, while comparing these factors to the current status of wave energy in Ireland. Part II

Table 1.1: Publications in chronological order

Status	Publication title	Chapter
(P)	Barry, C. A.; Ringwood, J. (2023). Irish renewable energy policy: encouraging the wave energy sector? [48] *In Proceedings of the European Wave and Tidal Energy Conference EWTEC* Vol. 15. European Wave and Tidal Energy Conference EWTEC, 2023, Bilboa	3
(P)	Barry, C. A.; Ringwood, J. V. (2024). Navigating funding challenges in the pursuit of wave energy technology development [49]. *In Innovations in Renewable Energies Offshore. CRC Press, pp. 989-996.*	5
(P)	Barry, C.A.; Conlon, P; Tavares, A; and Ringwood, J.V. (2025) The role of patenting in emerging renewable energy technologies: The case of wave energy technology development [50]. *In Proceedings of the European Wave and Tidal Energy Conference EWTEC* Vol. 16. European Wave and Tidal Energy Conference EWTEC, 2023, Madeira	6
(P)	Barry, C. A.; Ringwood, J. V. (2025). Wave energy technology development in Ireland: Employing the triple helix model of innovation for pragmatic policy interventions [51] *Technology in Society, 81. 102872.*	7
(UR)	Barry, C. A.; Bubbar, K.; Pallonetto, F.; Ringwood, J. V. (2025). A systems thinking approach towards societal acceptability of wave energy technologies [52] Submitted to *Energy Research and Social Science*	8
	Other work	
(P)	Barry, C. A. et al (2025). Developing a data-driven micro-credential framework to enhance primary school sustainability programmes [53]. *In Proceedings of the Energy Sustainability Conference, Crete and E3S* Web of Conferences.	-
(A)	Barry, C.A. et al (2025). Supporting upskilling for the green transition through micro-credentials. An Irish university's approach. *Accepted for presentation at the Global People Practice Conference, Parys, South Africa.*	-

explores specific enabling factors influencing wave energy in Ireland, including funding gaps and metrics, IPP strategies, stakeholder perspectives, and the SA of wave energy, as well as the application of frameworks and methodologies through which these factors can be explored. Following this introduction to the research topic, Chapter 2 presents wind energy technology development in Denmark as a potential benchmark for the development of a wave energy industry in Ireland, focusing on successful policies and enabling factors. Chapter 3 describes the current status of wave energy technology concerning its commercialisation, the potential of wave energy technology to be part of a reliable renewable energy mix, and policies that affect wave energy technology development, particularly in Ireland. Chapter 4 explores whether Irish renewable energy policies are supportive of wave energy technology development and compares them to Danish wind energy (work published in [48]). Chapter 5 discusses funding challenges facing wave energy technology developers, and metrics used in the allocation of funding (work published in [54]), while Chapter 6 describes the perspectives collected from industry, academia, and government on the potential for the commercialisation of wave energy in Ireland (work published in [51]). Chapter 7 analyses how technologies are protected within the wave energy innovation sphere (work published in [50]). Chapter 8 takes a systems thinking approach to societal acceptance of wave energy compared to other renewable energy modalities (work under review in [52]), before Chapter 9 concludes the thesis, discussing the results from each part of the thesis and proposing potential future work.

Part I

2

The development of Danish wind energy: Successful policy initiatives

Contents

2.1 Introduction

Denmark is a world leader in wind energy, both in utilisation and commercial development. Wind production per capita exceeds that of any other OECD country [55], while Danish company Vestas, and Siemens Gamesa (a Spanish/German company with Danish roots) contributed almost a third of global wind turbine installations in 2018 [56]. In 2019, 15th September became the first day that wind turbine energy production exceeded Danish electricity demand [55] with Vestas bringing in revenue of €12.147 billion in the same year [57]. This thesis uses Danish wind energy as a benchmark to explore the extent to which established policy initiatives, used to propel Danish wind energy technology to the market leader position, can encourage Ireland to accelerate wave energy technology development.

Denmark is similar to Ireland in terms of climate, latitude, and population, [39] [58]. Denmark pioneered wind energy technology development throughout the late 19th and 20th centuries and has successfully exploited it commercially since the 1980s. This chapter will explore the history of Danish wind energy development, and the factors that contributed to the success of the sector.

The successful growth in Danish wind power technology development, and exploitation, is due to a number of factors [59]. The main factors that contributed to Denmark's success in this area are listed below and discussed in detail throughout this chapter:

- **Pioneers** – Danish wind has, and has had, some remarkable wind energy protagonists, dating back as far as the 1890s. These individuals forged a path, inspiring future generations as technical pioneers and also as political and community leaders.

- **Cultural and political context** - The oil crises of the 1970s, coupled with a political distaste for nuclear energy, and successive coalition left-wing governments, resulted in supportive long-term policies that provided certainty for developers, and widespread public support.

- **The Risø experimental test centre** became a research and development hub in the area of wind energy in Denmark, through significant interactions with producers and owners via an open innovation approach.

- **The Risø test centre also provided certification** and has augmented learning in wind energy. This quality control mechanism has been crucial to Denmark's international reputation.

- **The large number of small-scale producers and owners**, during the early years of Danish wind energy commercialisation, resulted in an incremental, bottom-up, trial-and-error approach to the technological development of wind energy.

Chapter 2 provides a brief history of Danish wind energy development, focusing on policy initiatives, and is followed by an analysis of the key enabling factors behind this development, conducted through a literature review and document analysis. The chapter then discusses how these factors contributed to the sector's success, and concludes with a summary of the main findings.

2.2 Danish wind energy - A brief history

In Denmark, converting wind energy into electrical energy dates back as far as 1890. Poul La Cour experimented with converting traditional windmills to DC electricity-generating wind turbines [60] (Section 2.3). One of his students, Johannes Juul, was the first person to connect a wind turbine with an asynchronous AC generator to the electricity grid. In 1956, Juul built the Gedser turbine, which became the pioneering design for modern wind turbines [61]. Further development stalled in the late 1950s and 1960s, as cheap foreign fossil fuels proved more tempting than emergent wind energy. The energy supply crises in the 1970s, coupled with public and political distrust of nuclear power, and successive left-leaning coalition governments, generated renewed interest in wind energy in Denmark [62]. Most projects at the time were small, private efforts based on scaled-down Gedser turbines although Riisager, a pioneering Danish carpenter who set up the Windmatic Company, eventually produced 30 turbines [63]. This bottom-up, incremental growth resulted in many innovative design adaptations. Power purchasing policies, and incentives in the form of capital grants, gave wind entrepreneurs enough certainty to invest heavily in wind energy.

To ensure the quality and safety of government-supported wind turbines, the Risø national laboratory, originally established in 1956 to research nuclear power, instead turned its focus to wind power in the early 1970s. Risø was given the role of providing "type approval" for wind turbines, and also acted as a hub for the wind energy community, bringing producers, scientists, and investors together to share research. The early 1980s was a period of rapid growth for Danish wind energy. Companies such as Nordtank, Bonus, Nordex and later Micon, with a tradition of manufacturing farming machinery saw the success of companies such as Windmatic, and started producing wind turbines. Some of these companies, such as Vestas [64] and Orsted [65], now feature in the top 10 wind turbine manufacturers in the world. The so-called California wind rush, a period of rapid growth of wind energy development in California, driven by renewable energy goals, strong winds and investment incentives [66] (Section 2.6), gave these companies the chance to leverage Denmark's legacy and reputation and to grow exponentially, although perhaps too quickly in some instances. When the Californian interest in wind diminished, Danish wind turbine manufacturers had to scrabble to diversify into other markets, leading to consolidation with fewer, larger, companies surviving [67]. The economics of wind energy have improved dramatically in the past 20 years. The cost of wind energy can now compete with the cost of coal and nuclear, and by 2020, there were 6,217 wind turbines in Denmark, including some 5,600 offshore [68]. 53% of electricity consumed in the country was powered by wind in 2022 [69]. Denmark uses the most wind energy per person in the world, and onshore wind energy is the cheapest source of energy in Denmark [70].

Future ambitions concerning climate goals have aligned with European Union (EU) targets, have merged with economic ambition and include being fossil fuel free by 2050, increasing stability of supply and increasing interconnectivity with neighbouring countries, the Netherlands and the United Kingdom (UK) (Denmark is already interconnected with Norway, Sweden and Germany). Future technology development in Danish wind energy will likely be focused offshore, with an increase in the number of turbines and efforts to bring the cost of offshore wind down. In 2021, plans were approved to build an artificial island which will be home to a 10GW wind farm [71], development of which is underway in 2025.

2.3 The pioneers of Danish wind energy

2.3.1 La Cour - the father of wind energy

Denmark's early success in wind energy is largely attributed to its early pioneers, particularly Poul la Cour, a community-minded meteorologist and teacher born in Aarhus in 1846. At a time when wind power was dismissed due to its intermittency and storage challenges, La Cour pursued wind energy's potential to meet rural energy needs [72]. In the 1890s, La Cour began converting traditional windmills into generators of direct current (DC) electricity. His efforts were supported by a 4,000 Dkr grant from the Danish government, enabling the construction of his first experimental windmill at Askov in 1891. This installation produced electricity and hydrogen through electrolysis and powered lighting at the local high school [73].

La Cour tackled the challenge of power stability by inventing the Kratostate, a mechanical regulator that kept wind turbines operational during high winds. [74] By 1895, he had developed a functional wind-powered electrical plant for Askov and continued researching windmill efficiency through model testing and wind tunnel experiments. La Cour's concept of the 'ideal sail optimised blade shape and angle for maximum lift [61].

In 1900, La Cour published his findings "Forsøgsmøllen I og II" (The Research Mill I and II), and launched a national competition to build the ideal windmill [73]. This laid the groundwork for the State Wind Laboratory, an early example of open innovation. He also played a key role in training rural electricians, founding the Danish Wind Electricity Society in 1905, and promoting wind power through publications and annual courses. His legacy lies not only in technical innovation but also in fostering a community of wind energy advocates and practitioners, earning him recognition as the father of Danish wind power [75].

Figure 2.1: Askov experimental windmills, (2025) [76].

2.3.2 Johannes Juul and the next generation of innovation

One of La Cour's students, Johannes Juul, carried La Cour's legacy forward. After becoming a high-voltage engineer, Juul developed the first wind turbine to successfully connect to the electrical grid using an asynchronous Alternating Current (AC) generator in the 1950s [77]. This was a major technological milestone, as grid power requires a fixed frequency while wind speed varies. To manage this, Juul introduced passive stall control, which used blade aerodynamics to regulate output without complex mechanical systems [78].

Juul's most significant contribution was the Gedser turbine, a three-bladed, 200 kW machine that ran with minimal maintenance for over a decade. It became the model for modern wind turbines and drew international attention. The turbine was later refurbished at NASA's request and now stands in the Danish Electricity Museum [79].

2.3.3 Commercial pioneers and policy support

In the 1970s and 80s, a grassroots movement of amateur engineers, such as Christian Riisager, who built 30 small-scale turbines, coincided with political opposition to nuclear power and the oil crisis of 1973 [80]. The Danish government responded with favourable feed-in tariffs (mechanisms by which a fixed price is guaranteed for electricity fed into the grid), legislating that electricity from private turbines be purchased at 85% of retail price, and capital grants, spurring adoption.

Three key groups drove early innovation and commercialisation:

- **Amateurs**: Innovators built 10–15 kW machines for rural use, frequently owned and funded by co-operatives.
- **Scientists**: The Risø Laboratory provided quality control and type certification.
- **Manufacturers**: Companies such as Vestas, Nordtank, and Micon transitioned from farming equipment to wind turbines, positioning Denmark as a major exporter.

Modern wind turbines evolved from early Danish designs, featuring three upwind-facing blades and advanced aerodynamic control. By the early 2000s, turbines grew from 25 kW to 2,500 kW capacities, with rotor diameters expanding from 10 to 80 metres [81]. Denmark, producing nearly 60% of the world's turbines in the first decade of the 21st century [82], became the leading exporter of wind technology, with wind energy supplying 54% of domestic electricity in 2024 [83].

The legacy of La Cour and Juul, rooted in experimentation, education, and public support, set Denmark on a course to become a global leader in sustainable energy.

2.4 Political context and societal acceptance

Long-term Danish energy policy has played a vital role in the commercial success and resilience of the country's wind energy sector. This development has been consistently supported by public interest and industrial engagement. However, Danish policy has not always been consistently supportive of wind energy. Initially focused on small-scale, not-for-profit ownership in the 1970s, it later shifted between support for nuclear power, financial incentives for investors, and subsidies for early-stage producers. In recent years, it has leaned towards alignment with EU directives and support for large-scale industry [84], [85].

The first major energy policy was introduced in 1975, following the 1973 oil crisis. The oil crisis began when Egyptian forces crossed the Suez Canal into Israeli-occupied Sinai, triggering a geopolitical response. OPEC, in protest against Western support for Israel, raised oil prices and imposed an embargo. The resulting supply shock exposed Denmark's dependence on imported fossil fuels, revealing its economic vulnerability [62]. Before the 1973 oil crisis, Danish energy policy had taken a relatively passive stance, favouring decentralised, not-for-profit systems where surplus energy revenue was redistributed to consumers. At the time, nuclear power was gaining parliamentary and institutional support. In 1970, the only parties opposing nuclear development were Radikale Venstre and the Socialist People's Party [86].

The 1973 election significantly altered the political landscape. Established parties lost substantial ground, and five new parties gained parliamentary seats. Simultaneously, a grassroots anti-nuclear movement emerged, supported by scientists and activists. This movement laid the groundwork for a renewable energy vision, leading to the formation of the Organisation for Renewable Energy (OVE) in 1975 [87].

From 1975 to 1982, a succession of minority Social Democratic governments introduced centralised energy planning aimed at reducing oil dependence. The 1976 national energy plan proposed a shift toward natural gas, coal, and nuclear energy [88].

Wind power was initially absent from the plan, prompting calls for its inclusion. An Alternative Energy Plan was subsequently disseminated by independent researchers and advocates. This eventually led to the inclusion of large-scale wind turbine development in the national energy research programme, although it was co-administered by utilities, leading many to suspect this move aimed to delay genuine progress on wind.

In 1978, the government took a more concrete step by funding a test centre for small-scale wind turbines at Risø National Laboratory. A parallel investment support programme encouraged uptake among farmers and local cooperatives. This momentum helped establish the Danish Wind Turbine Owners Association [89], which became a key intermediary between stakeholders and authorities.

The second oil crisis of 1979 prompted renewed urgency. A subsequent oil embargo in 1980–81 severely impacted Denmark's balance of payments, reinforcing the need for domestic energy sources. With rising unemployment, the government linked renewable energy, particularly wind, to industrial and economic development. A Ministry of Energy was created to coordinate regional energy strategies, and household energy taxes were introduced to finance renewable investments. Wind turbine investors were granted a subsidy of 30% of total installation costs, making wind energy more economically viable [87].

The 1981 energy plan (Energi81), outlined a growing role for renewables by 2000, though it continued to list nuclear power as a possible option. Over time, however, nuclear ambitions were shelved, and wind energy gained broader institutional support.

In the 21st century, Danish policy has increasingly aligned with EU frameworks, now favouring large-scale industry and export-driven innovation, departing from the earlier cooperative, decentralised model [90]. At a general level, socio-political support for wind turbines is high, whereas local or community support is frequently mired in controversy and public opposition [91]. More than a third of the Danish people are directly involved in wind schemes or are familiar with others who are involved in such schemes [92]. A study on the potential impact of share ownership upon public perceptions of wind farms revealed that 58% of households in the Sydthy region of Denmark owned one or more shares in a co-operatively owned wind turbine

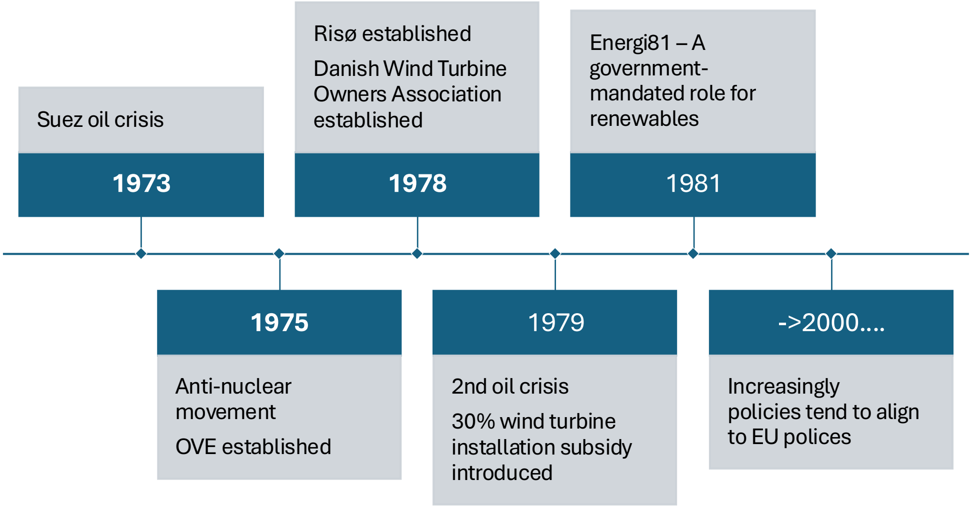


Figure 2.2: A timeline of early Danish wind energy development from a policy perspective.

[85]. Examining links between share ownership and perceptions, the report found that people who own shares in a wind turbine are significantly more positive towards wind energy than people with no economic interest. Secondly, members of wind cooperatives are more willing to accept further turbines in their locality in comparison with non-members. Additional research is required to systematically compare public acceptability in a context where shareholding was made available with one in which it was not. In Denmark, there is generally strong public support for wind energy, driven partly by geopolitical instability and the desire for energy independence. A 2023 survey showed that 68% of Danes favour more wind turbines. However, local (community) acceptance is much lower, leading to significant resistance that has delayed or cancelled many wind turbine projects [93]. Since 2009, one in five projects has been dropped due to local opposition. Some municipalities have been more successful in fostering acceptance than others [94]. Recent trends suggest growing local support, possibly due to increased awareness of the need to reduce reliance on, largely, Russian gas. To improve community acceptance, the Danish government has introduced compensation schemes for affected homeowners, which are managed and updated by the Danish Energy Agency [95].

2.5 Risø-A research and development hub

In 1978, the newly established Risø Test Station (Risø) began certifying turbines for government subsidies, elevating its status as an authoritative Research and Development (R&D) institution. Most of the wind turbines installed in Denmark in the 1980s were private, not-for-profit 10-15kw turbine projects based on Juuls' Gedser turbine; in 2010, 25% were owned by cooperatives and 63% by farmers [96]. Risø's mandate was to comprehensively test all turbine designs intended for installation, ensuring only quality-assured systems qualified for the 30% capital grant, thereby embedding an innovation feedback loop between developers and Risø scientists [97]. Risø pioneered a methodical trial-and-error testing regimen, in particular in the areas of performance, noise, structural integrity, and longevity. Risø's work included static and fatigue testing of blades, such as the AeroStar 7.5m trial in 1984, conducted in a heated tent to simulate desert climates, and integrating meteorological data into turbine analysis and certification [98]. The test station also spearheaded the creation of the Danish Wind Atlas, a modelling tool that mitigated uncertainty in turbine siting [99]. By the mid-1980s, Risø's incremental testing approach had shifted turbine development from small-scale experimentation to science-based engineering. Confronted with engineering challenges such as load variance, noise, and fatigue, both domestic and international manufacturers, increasingly relied on Risø's data to refine blade aerodynamics, materials, and safety systems [100].

Denmark deployed approximately US$95 million between 1976 and 1995 in wind-energy R&D, an indicator of sustained political commitment to innovation [101]. Crucially, the requirement of type approval ensured that Risø received access to every planned turbine design, providing proprietary data and enabling continuous technology refinement.

The iterative ecosystem cultivated by Risø empowered early adopters [102] by lowering technical risk and improving reliability. Over time, major agricultural equipment firms such as Vestas, Nordtank, Bonus/Siemens, and Micon transitioned toward turbine manufacturing, rooted in the test centre's R&D infrastructure [55]. By the late 1990s, this merging of public testing protocols, academic research, and private manufacturing had positioned Denmark at the forefront of the global wind industry. Through its testing regime, particularly during wind energy's developmental phase, Risø catalysed the transformation of Danish wind power from small-scale experimentation to a globally competitive industrial sector through a bottom-up, incremental trial-and-error approach.

2.6 Certification and standardisation

Risø was initially established in Denmark to research nuclear power. In the early 1970s, Risø's remit changed, and it was given the role of providing 'type approval' for wind turbines. Speculators who wanted to take advantage of the Danish government's 30% installation cost subsidy at the time were required to seek certification from Risø. Certification would later come to be a requirement, regardless of subsidies.

Certification led the way to regulation and improved design and quality, and Denmark quickly gained a reputation for producing high quality turbines essential for its success globally, particularly during the Californian wind rush in the early 1980s, a period of generous tax incentives amounting to a 50% tax write off in the first year of the turbine's operation [77]. During the wind rush period, Danish wind industry exports rose from 30 million Dkr in 1982 to 2.1 billion Dkr before the tax credits expired in 1985, with Danish turbines being seen as more sturdy and more reliable than other foreign designs.

The Gedser turbine was refurbished in 1975 at the request of the (United States) National Aeronautics and Space Administration (NASA) in order to run a test program for the American Department of Energy. These tests proved that the basic principles in the old turbine were so good that they were actually recommended and later on formed the basis of Risø's 6 quality standards and certification of Danish wind turbines, for which they would become world-renowned [97].

Risø leveraged its role to drive innovation through rigorous R&D in turbine components. Between 1999 and 2004, Risø developed patented airfoil families—Risø-A1, P, B1—using advanced Computational Fluid Dynamic (CFD) modelling, wind-tunnel, and full-scale blade testing, achieving significant reductions in fatigue loading, enhanced lift, and better roughness tolerance [103]. Concurrently, Danish Technological University (DTU)-Risø patented seven novel structural reinforcements, such as Shear Cross Stiffeners and Spar Cap Stiffeners, demonstrated in a 2008 blade test facility, which increased buckling strength by 30–40%, enhanced torsional resistance, and mitigated fatigue-induced cracking [104].

Innovations within Risø's certification framework led to Danish turbine designs becoming inherently more attractive to investors, insurers, and international buyers due to their improved reliability, service life, and performance.

2.7 Long-term policies

Successive Danish governments have been willing to commit to long-term, stable policies and interventions, which have provided certainty for developers, producers, and owners, and this has played an important role in fostering the commercial success

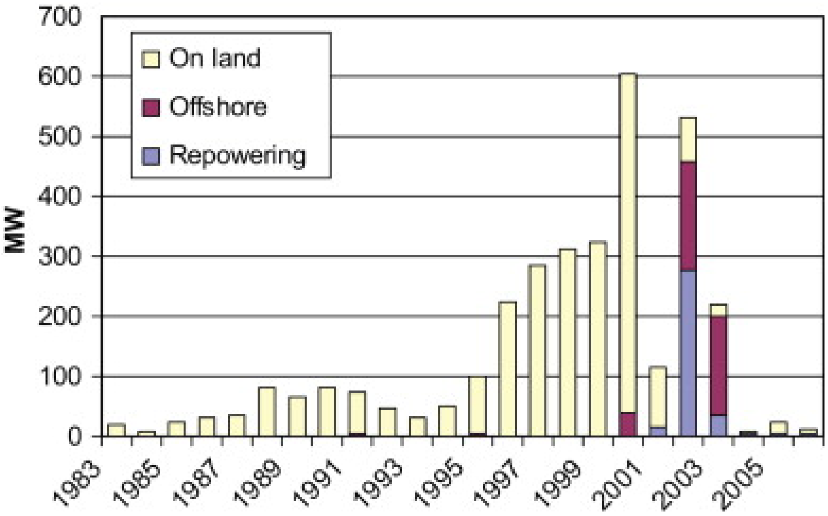


Figure 2.3: Turbine installation in Denmark, Munksgaard (2008) [108].

and commercial sustainability of Danish wind energy technology development. This has been bolstered by enthusiastic public and industrial support, leading to support from the Danish government through a process known as *innovative democracy* [105]. Quantitative targets were introduced by the Danish government for the first time in the national energy plan Energie81. 60,000 turbines were to be deployed to supply 10% of Danish electricity by 2000 [106]. Even though the number of turbines only reached 5000 in 1997, the supply target was exceeded by 1998, supplying over 21% of Denmark's electricity [88]. More targets were set in 1990 (100MW) and in 1996 (200MW). Quantitative targets provided certainty to the Danish wind industry, with results that would be impossible to achieve without investment and production incentives [107]. In 1979, the Danish government launched an initiative whereby investors were entitled to funding of 30% of their initial capital investment in wind energy projects. During the 1980s, 30% was reduced to 10%, and eventually abolished in 1989 [107]. From 1979 to 1989, approximately €38 million was granted under this capital investment scheme. Income from wind turbines was taxed favourably until 1996. Further incentives were available, including tax deductions up to a certain generation capacity threshold, and a 10-year agreement with (not-for-profit) utilities guaranteed turbine owners feed-in rates amounting to 70-85% of retail electricity prices.

When the market was deemed to have matured the Danish government introduced green certificates, where wind energy producers receive a certificate that they can sell on to consumers or electricity-trading companies, as well as obliging Danish consumers to buy at least 20% of their electricity from renewable sources. However, despite these supportive initiatives, during periods of uncertainty, installation stalled, highlighting the need for long-term, substantial, and stable policy initiatives [108].

Long-term policies, in particular the incentives plan, in the form of capital grants for installation, launched in the late 1970s and persisted until 1989, meant that small investors were encouraged by the guaranteed purchasing price and helped by capital grants. Eventually, large Manufacturers – Vestas, Nordtank Bonis Nordex, and later Micon, noticed the early success of Riisager, who had capitalised on the capital grants available, and diversified from agricultural equipment manufacturing, to developing 30 wind turbines [79]. By the early 2000s, these Danish manufacturers (Vestas, NEG Micon, and Bonus (later Siemens) comprised around 45% of the global market share [109].

2.8 Discussion and conclusions

This chapter analyses several of the factors underpinning the successful development and exploitation of Danish wind energy. The Danish case illustrates how a combination of supportive policy frameworks, cultural attitudes toward community investment, and an innovation-friendly environment can contribute to the successful development of an emerging renewable technology.

The existing literature provides a limited analysis of the development of Danish wind energy as a benchmark for wave energy technologies. Risø's approach to research and development has been cited as a potential model for advancing marine renewable energy systems [110], and manufacturing and deployment strategies have been explored [111]. This thesis seeks to address gaps in the literature by investigating external factors that have not been previously considered and by situating these within the Irish wave energy context.

One contrast emerges when comparing Denmark to Ireland. While Danish citizens demonstrated relatively high levels of interest and participation in wind farm shareholding schemes, an Irish survey found that only 16% of Irish respondents expressed any interest in wind farm investment. Notably, 93% of Irish respondents reported being unaware of any opportunity to invest [112]. This divergence underscores the crucial role of socio-cultural and institutional factors in shaping public engagement. The Danish approach was distinctly local and community-focused, contributing to public acceptance and investment, whereas the Irish model appears to have lacked this dimension in wind energy projects. This will be explored further in Chapter 8.

Despite its successes, Danish wind energy development has not been without problems. Issues have included public resistance to the visual impacts of turbines in certain regions, challenges related to intermittency and grid stability, and occasional policy uncertainty regarding tariffs and subsidies. These problems reflect broader tensions inherent in scaling any renewable technology, and they offer lessons for other countries when applied to other modalities. The Danish wind energy development trajectory demonstrates that success arises from a confluence of external factors, economic incentives, cultural acceptance, and industrial capability, combined with strong political commitment. This makes Danish wind a particularly useful benchmark for the emerging Irish wave energy sector. As subsequent chapters will show, an analysis of external factors is essential to understanding whether similar conditions could be replicated for wave energy development. Drawing inspiration from Danish initiatives highlights the need to adapt policy and community strategies to the unique context of wave energy technologies.

3

Wave energy innovation in Ireland: A global comparison

Contents

3.1 Introduction

While Chapter 2 explores the relative success of wind energy development in Denmark, identifying key drivers behind its achievements, Chapter 3 now explores the development of wave energy technology in Ireland, assessing its national progress in relation to global trends and leading international examples, with a focus on policy perspectives. Through this comparison of external factors (see Chapter 1.1.3), namely, the technological landscape, policy and regulatory frameworks, and research and development infrastructure and supports, Chapter 3 presents the current status of wave energy technology development in Ireland.

Wave energy technology development lags behind other more mature renewable energy modalities, and faces considerable challenges including a stuttering growth trajectory, a regulatory environment that has been primarily designed to support other, more established, renewable energy sources, absence of a dominant WEC design archetype, a relatively high LCoE, lengthy and labyrinthine consenting procedures, and limited access to test facilities, as well as a history of failed companies in the sector. There is, however, significant recent activity in the sector, both in Ireland and internationally, and some progress towards commercial maturity.

Chapter 3 begins by outlining the global technological maturity of wave energy systems, and places Ireland within this broader context, highlighting the types of technologies under development and their respective TRLs. This is followed by an analysis of policy and regulatory regimes in Ireland compared to international counterparts. Section 3.4 then addresses research performance in the sector, while Section 3.5 articulates the significant market challenges facing wave energy technology development. Section 3.6 examines lessons that can be learned from the failures of some wave energy projects, while Section 3.7 describes some of the international and Irish wave energy technology leaders. Section 3.8 provides discussion and conclusions.

3.2 The wave energy technology landscape

3.2.1 Global overview of wave energy technology maturity

As the wind blows over the ocean, it transmits some of its kinetic energy to the ocean surface, creating wave energy, a form of energy that contains kinetic and

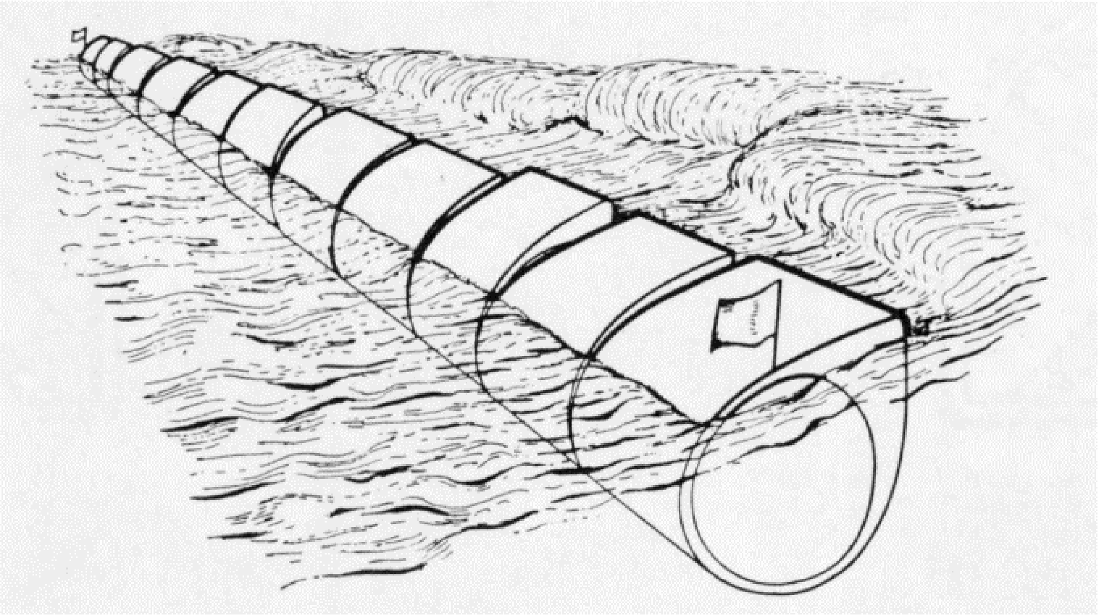


Figure 3.1: Salter's Duck - an artist's impression. From The architecture of nodding duck wave power generation, Salter (1976) [116].

gravitational potential energy that can be converted to useful (electrical) energy [113]. Wave Energy Converters (WECs) are devices designed to absorb either the ocean wave's kinetic energy, mainly through moving bodies, the potential energy, through overtopping devices or attenuators, or both.

Research has not yet converged to provide us with a design archetype, even though several thousand wave energy patents have been registered since the first in 1799 [114]. In 1973, the oil crisis that sparked wind energy innovation in Denmark inspired Stephen Salter from Edinburgh University in Scotland to develop the Salter's Duck WEC. A prototype of the device produced 20 kW of electricity in 1976, but with the 1980s glut of oil, funding was withdrawn, and the Salter's Duck WEC never made it to production [115], a pattern that has been repeated several times within the sector since this early effort.

Some of the most prevalent WEC designs can be characterised based on their location in the ocean (foreshore, nearshore, or offshore), their size, and/or the degrees of freedom that they make use of. The literature diverges on the number of different types of WECs [117], [118], [119] [35]. Table 3.1 provides a (far from exhaustive) overview of some of the most prolific device types in terms of the number of registered patents.

3.2.1.1 Technology Readiness Levels

Table 3.1 demonstrates the wide variety of WEC types, and there are no signs that developers are converging on a preferred design [128]. However, some devices are

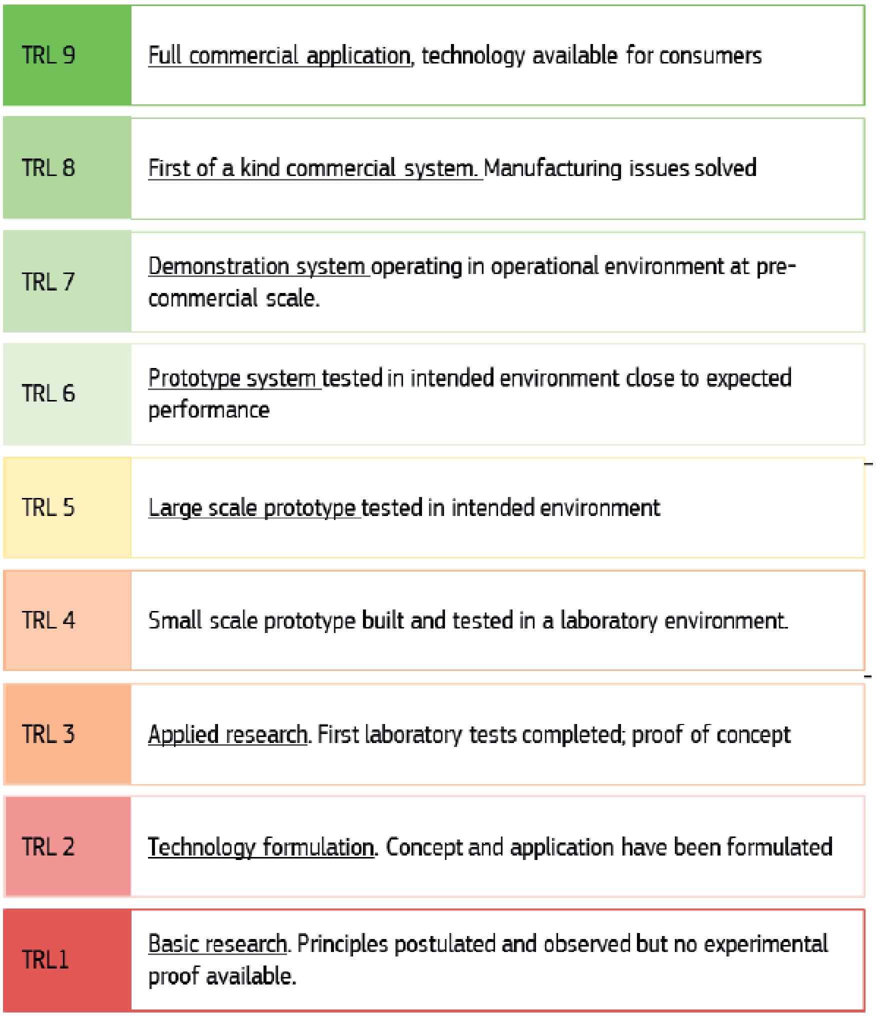
Table 3.1: WEC device type examples

Device type	Description	Example
Oscillating Water Column (OWC)	Comprises a collector chamber which takes power from the waves and transfers it to the air within the chamber, and a power take off (PTO) system, which converts the power into electricity. The pressure in the collector is pressurised as the water column rises, and rarefied as the water column falls. OWCs can be seen in nature in the form of blow holes in limestone cliffs [121]. OWCs fall into two main categories: fixed and floating, with some current full-scale prototypes.	OE35 Buoy[120]
Point absorbers	First proposed in 1975. They may be installed in a floating or submerged manner, may oscillate in single or multiple degrees of freedom, and capture wave power with single or multiple bodies. A point absorber is a floating structure that absorbs energy from all directions through its heave (bobbing) movements at or near the ocean's surface, converting the motion of the top into electrical power [123]. They apply to a wide range of sea states and sizes can be adapted to fit the wave climate. They are generally smaller than other WEC types [124].	CorPower device [122]
Attenuators	A hinged floating device which operates parallel to the wave direction and effectively bends along with the waves. These devices capture energy from the motion of the two arms as the wave passes. They are held in place by a mooring on the seabed.	Pelamis [125].
Overtopping devices	Captures water as waves break into a storage reservoir. The water is returned to the sea, having passed through a turbine which generates power [127].	Wave dragon [126]

closer to commercialisation than others. A well-used metric for describing how close to commercialisation, or the maturity of the technology under development, is the TRL scale, which was developed by NASA in 1995 [129]. Although limited in terms of describing the *performance* of technologies (See Chapter 5), TRLs are a useful tool for investors and funders, helping them to determine which stage of development a project has reached, and the commercial readiness of the technology [130].

The TRL scale, originally developed for the aerospace sector, has been applied to WECs (see Figure 3.2). This TRL scale describes the progression from concept to validation to prototype to a tested, full-scale, prototype. Many wave energy technologies have stalled at mid-TRLs (4-6) [130], due to an exponential increase in costs at that stage [54], as developers begin to transition towards large-scale demonstration devices that require deployment and sustained testing in open sea conditions. This is discussed further in Chapter 5.

Current wave energy development has stalled at the early to mid TRL level (1-6), with a few frontrunners pushing for commercialisation. Dr. Patrick Lynett, professor of environmental engineering at the University of Southern California, in 2021, pointed out that "The environmental conditions where wave energy extraction has the greatest



TRL 9	Full commercial application, technology available for consumers
TRL 8	First of a kind commercial system. Manufacturing issues solved
TRL 7	Demonstration system operating in operational environment at pre-commercial scale.
TRL 6	Prototype system tested in intended environment close to expected performance
TRL 5	Large scale prototype tested in intended environment
TRL 4	Small scale prototype built and tested in a laboratory environment.
TRL 3	Applied research. First laboratory tests completed; proof of concept
TRL 2	Technology formulation. Concept and application have been formulated
TRL1	Basic research. Principles postulated and observed but no experimental proof available.

Figure 3.2: Adapted from TRL of ocean energy technologies, according to the scale employed by European Commission – Horizon 2020 programme. Available at [131].

potential - where the waves are high and long are harsh...designing objects to function under these conditions is challenging. The engineering and design must be robust and creative, which usually means complex and expensive" [132]. When developers have a functional prototype, the cost of scaling up can make advancement through the TRLs very challenging. This has a vicious cycle effect, whereby the cost of reaching full-scale is prohibitive, but the lack of full-scale demonstration devices is off-putting for investors who require assurance and prompt returns, a 'technology push' without 'market pull'. This 'valley of death' phenomenon is discussed in Chapter 5. A proliferation of WEC devices, demonstrated in open sea conditions, is likely to lead to an improved LCoE for wave energy overall, making wave energy technology more attractive to project developers [133]. With the deployment of the first commercial WEC or WEC array, the various components of a system's economic viability become fully quantified and understood. This baseline understanding can be used to develop second-generation

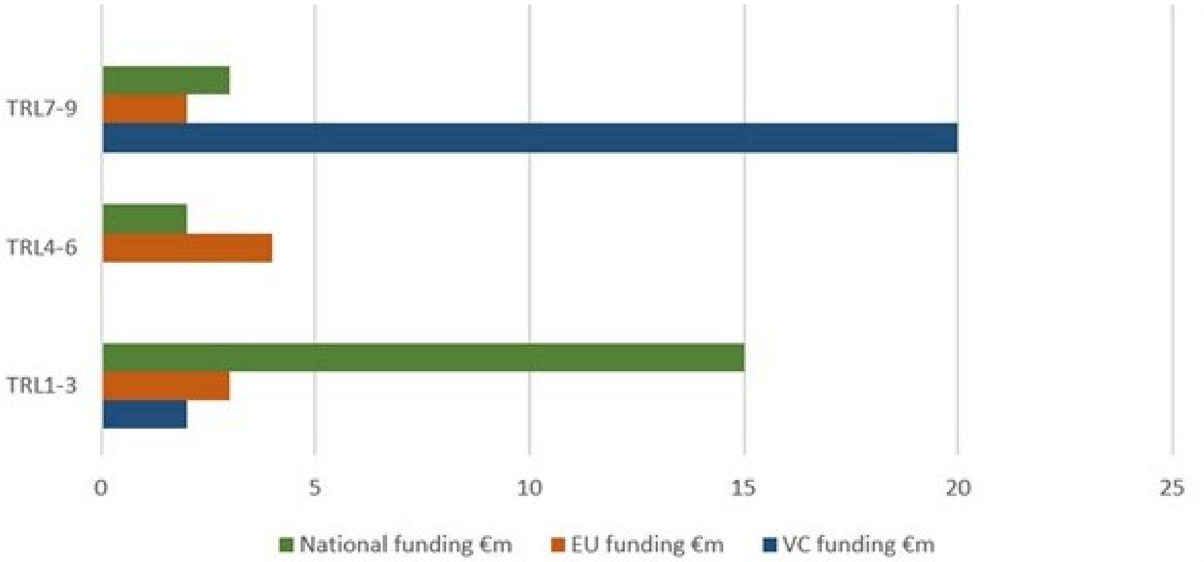


Figure 3.3: Funding for Irish wave energy projects 2012-2022, (2024).

technologies, which can be used to reduce cost. Emerging technologies need to rely on expensive installation and maintenance methods, which will reduce in cost as more devices are deployed. The high cost of finance for early projects will reduce as the sector grows, as will high initial insurance costs [134].

3.2.2 Ireland within the global WEC technology landscape

As well as one of the richest wave energy resources on the planet, Ireland has significant experience in fundamental and applied research in the area of wave energy technology development. Most of Ireland's current wave energy technology projects lie at the early to mid TRL levels (1-6), and are funded by EU and national R&D funding [135], [136], [137]. Figure 3.3 shows an analysis, conducted for this study, of funding received from the main national funders of wave energy projects, from 2012-2022, and compares them to venture capital funding within the period, and EU funding where an Irish organisation was the coordinating partner. This highlights both the country's significant potential and the gap in funding at TRLs 6-9 (this is analysed in 5.6). Ireland has had limited full-scale deployment compared to countries such as Portugal or the UK, and has suffered from regulatory and licensing bottlenecks for open-sea testing, difficulty attracting large-scale private investment, and a lack of operational test facilities. These elements are discussed in detail in Sections 3.3-3.5.

3.3 Offshore renewable energy policy and regulatory frameworks

3.3.1 Global offshore renewable energy policy comparators

Policies can take effect through subsidies and incentives, or regulations and taxes. Despite international agreements, different countries have indigenous energy policies that determine the speed at which a country transitions to a carbon-neutral energy system. Some nations are embracing the transition, whereas other countries support the exploitation of fossil fuels for economic or political reasons. For example, the U.S. is divided on energy policy, as can be seen by contrasting The Inflation Reduction Act (IRA) [138], which offers significant subsidies for renewable sources of energy, whereas some states support the growth of oil and gas production [139]. China simultaneously holds the position of the largest global investor in renewable energy and the leading consumer of coal [140], illustrating an apparent contradiction within its energy strategy. This paradox reflects the broader challenge faced by many states: reconciling the imperative of meeting immediate energy demands with the strategic objective of transitioning toward a renewable energy system.

The global leaders in offshore renewable energy innovation policy are countries that have specific deployment targets, Reliable R&D and demonstration funding, streamlined regulatory frameworks, and support for emerging technologies. Leadership in offshore renewable energy policy is exemplified through approaches to offshore wind development, which has assumed a particularly prominent role in recent policy agendas.

- **The EU** has a comprehensive Offshore Renewable Energy Strategy [141] that specifically targets 1 GW installed capacity of ocean energy, i.e. wave and tidal energy, by 2030 and up to 40 GW by 2050, which is anticipated to require an investment of €800 billion [142]. In addition, the EU has substantial funding mechanisms through, for example, Horizon Europe, of which Ireland is a beneficiary. Ocean Energy Europe [143] has been developed to coordinate development, and there are multiple test centres across member states (e.g., the Biscay Marine Energy Platform (BiMEP) [144]).

- **The UK** hosts the European Marine Energy Centre (EMEC) for WEC testing [145] and supports ocean energy through its Contracts for Difference (CfD) scheme, which provides financial incentives for renewable generators via competitive auctions [146]. Successful developers sign 15-year contracts with the government-owned Low Carbon Contracts Company, receiving payments based on the difference between a fixed ‘strike price’ and the market electricity price. In 2022, the CfD auction secured 4.9 GW of fixed offshore wind, 400 MW of floating offshore wind, and 28 MW of tidal stream energy across the UK [147].

- **Denmark** provides long-term government support for offshore renewable energy technology projects through the Energy Technology Development and Demonstration Program (EUDP) [148]. The Danish Exowave strategy targets the establishment of a 250 MW wave power plant, together with an offshore wind farm, before 2030 [149].
- **The Netherlands** has developed pre-consented offshore zones, with full site studies, to de-risk innovation. Support is available through Topsector Energy, TKI Wind op Zee, and RVO [150]. Government-supported programs are available for system integration, co-use of space, and the production of hydrogen from offshore wind (e.g., PosHYdon [151]). Dutch policy is focused on offshore wind; however, the pre-consented offshore zones are likely to be of use to wave energy technology developers in the future.
- **South Korea** included ocean energy as a key part of its Renewable Energy 3020 Plan [152] which sets a goal to produce 20% of its energy from renewable sources by 2030. This provides subsidies and R&D funding for wave and tidal energy projects. There is a growing interest in marine energy to diversify energy sources and reduce carbon emissions [153].
- **France** has a strong research focus on the potential of wave energy from the Atlantic coast, with government support for demonstration projects and participation in EU marine energy initiatives. France lacks explicit national capacity targets for wave energy, but benefits from a strong policy framework for marine renewable energy (MRE) in general [154] and a dedicated R&D ecosystem with France Énergies Marines (FEM), one of seven French 'Instituts pour la Transition Énergétique' (ITE) dedicated to accelerating renewable deployment. FEM projects received €16 million (2019–2024) in public R&D funding, matched by industry contributions.

3.3.2 Ireland's offshore renewable energy policy and regulatory environment

Ireland's regulatory framework is influenced and bound by international and European Union (EU) policies. International policies have a direct impact on the Irish renewable energy sector (see Figure 3.4). In 2015, Ireland signed up to the Paris Agreement [8], followed by the European Green Deal [2]. The EU has ambitious offshore renewable energy targets, which have supported the growth of offshore energy technology developments, and offshore wind energy in particular [155], which may indirectly pave the way for wave energy technology development.

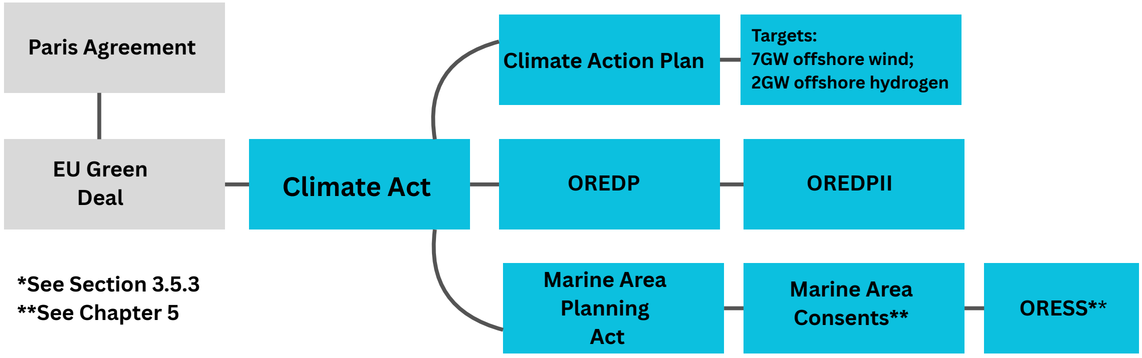


Figure 3.4: Policy Instruments Shaping Offshore Renewable Energy Development in Ireland showing influence of international instruments.

In 2015, 193 countries signed up to the 17 UN Sustainable Development Goals (SDGs), which are an urgent call for action by all signatory countries to take steps to end poverty along with strategies that improve health and education, reduce inequality, and spur economic growth, while tackling climate change, and working to preserve oceans and forests [156]. The SDGs led to the legally binding Paris Agreement, which was signed by 193 countries and the EU. Governments are held to account by the UN's annual Conference of the Party (COP) summits. At COP26 in 2021, 200 countries set new carbon emissions targets. The COP26 president, Rt Hon Alok Sharma MP stated: "It is up to all of us to maintain our goal of keeping 1.5 degrees within reach". The EU response to the Paris Agreement was the Green Deal. The targets initially set in the Green Deal have been revised a number of times, and in March 2023, the European Parliament set a binding renewable energy target of a minimum 42.5%, but aiming for 45% by 2030 [2].

EU member states were required to draft annual National Energy and Climate Plans for 2021-2030, detailing how they would meet the new targets. Ireland's response to this requirement was the enactment of the Climate Action and Low Carbon Development Act, 2021 (The Climate Act) [1]. The goal of the Climate Act is to articulate a legally binding, coherent, set of policy actions, to support Ireland in reaching a net-zero carbon energy system. The Climate Act was unanimously endorsed by the Oireachtas (the Irish Parliament), and a national climate emergency was declared. The stated aim of the Climate Act is to pursue the pathway to net carbon neutrality with the least burdens and greatest opportunities. This would imply a preference for more mature renewable energy technologies. Electricity targets defined by the Act include increased reliance on renewable energy sources for Ireland's electricity needs, taking the market share from 30% to 70%, supported by a streamlined consenting system, connection arrangements, and funding supports for emerging renewable technologies both on and offshore.

An Annual Climate Action Plan (CAP) is produced every year in order to "lay out a roadmap of actions" in order to meet climate targets. The 2025 CAP recognises that achieving 70% of electricity from renewable sources, including a capacity of at least 7 GW of offshore renewables, requires building significant infrastructure to increase the capacity for the integration of new technologies. Ireland is likely to be 25% below target for the next accounting period, with the Environmental Protection Agency (EPA) stating, in March 2022, that "the current pace of implementation will not achieve the change required to meet the Climate Act targets". Ireland's CAP 2024 set targets of at least 7 GW of offshore wind by 2030 (with 2 GW earmarked for green hydrogen production) [157]. The CAP fails to mention either wave or tidal energy; however, it does outline the significant research and innovation supports available for emerging technologies.

Ireland's Offshore Renewable Energy Development Plan (OREDP) [158] established a framework for the sustainable development of Ireland's offshore renewable energy potential in 2014. The OREDP identified Ireland's coast as one of the most energy productive in Europe, with a long-term theoretical potential of 70GW of ocean energy opportunity for wind, wave, and tidal within 100km of the Irish coastline.

The OREDP recognises a need to support the research, development and demonstration of floating wind, tidal, and wave technologies, including maximising supply chain and enterprise opportunities, and associated test infrastructure. The OREDPII, published in 2022, recognises the "immense potential for wind, wave and tidal energy that can aid in the delivery of our long-term climate goals" [159], but with an increased focus on offshore wind, wave energy is discussed in terms of potential, rather than concrete targets.

In the Future Framework for Offshore Renewable Energy, published by the Government of Ireland in 2022 [160], wave energy is highlighted as a nascent technology with significant potential, especially given Ireland's Atlantic coastline. The framework commits to supporting research and innovation to accelerate the development of wave energy. While not central to short-term targets, the framework describes wave energy as part of the long-term vision for a diversified and resilient renewable energy mix.

SEAI's Offshore Renewable Energy Technology Roadmap 2024 [161], describes wave energy as a promising, but still emerging, opportunity. Wave energy, it states, could play a substantial future role in meeting Ireland's offshore renewable energy targets, particularly under an optimistic 2050 LCoE scenario, assuming a considerable cost reduction pathway and noting significant uncertainty (LCoE is discussed in Section 3.5.2).

Recent reports from the Government of Ireland [160] and the SEAI [161], highlight several advantages that set Ireland apart from other countries. Ireland boasts some of the highest average wave power levels in Europe, especially along its Atlantic coast. Therefore, the report contends, WEC devices can generate more electricity compared to many other regions, enhancing project economics as the technology matures. Although Ringwood *et al* find that variability, rather than mean power, is the cost driver [162]. While offshore wind is already a well-established, competitive global industry, dominated by a handful of major players, wave energy remains relatively untapped, with few investors and commercial developers worldwide. This potentially allows Ireland to take an early lead advantage in a less crowded market, allowing Irish wave energy technology to potentially secure a greater share of the value chain than in offshore wind.

3.3.3 Comparative assessment

Commonalities that can be observed between some of the five international offshore renewable energy policy exemplars examined in this Section include long-term support mechanisms, developed innovation ecosystems, ambitious plans, clear targets, financial supports, streamlined consenting procedures, and a wide variety of funding mechanisms. Ireland has developed similar mechanisms for offshore wind, which could potentially benefit the development of Irish wave energy technology, such as the Maritime Area Planning Act, discussed in Section 3.5.3.

Wave energy is absent from explicit Irish renewable energy targets. Government-produced reports acknowledge Ireland's substantial wave resource and its potential for long-term integration into the energy mix, yet categorise wave energy as a nascent technology suited for commercialisation at some time in the future.

By contrast, several international comparators integrate wave and tidal energy more explicitly within their offshore renewable energy policy instruments in an effort to push the technology towards commercialisation. The UK provides revenue stability through CfD. Denmark supports pre-commercial projects with specific plans for the integration of wave energy into hybrid offshore facilities, while the Netherlands mitigates investment risk through pre-consented offshore zones, which, although primarily designed for wind, are transferable to wave energy applications. France invests significantly in public–private R&D projects targeting wave energy, albeit without fixed capacity targets, and South Korea provides direct subsidies and dedicated R&D funding for wave and tidal technologies. Relative to these approaches, Ireland's framework is aligned with the EU's long-term decarbonisation agenda, yet its absence of targets specific to wave energy may hinder its ability to establish a competitive position in the global wave energy sector.

3.4 Research and development support for wave energy technology

R&D is critical to the development of new technologies. Although some critics argue that today's R&D efforts often result in incremental improvements that do not always see their way to industrial applicability [163], there is a general consensus that investment in renewable energy R&D remains vital. Integrating investments in scientific infrastructure, talent development, and learning institutions is essential for producing breakthrough sustainable innovations [164]. This section now examines R&D bodies with an interest in wave energy in Ireland and globally, and assesses R&D performance using bibliometrics as a metric (This is covered in more detail in Section 6.6).

3.4.1 Global wave energy R&D bodies

3.4.1.1 Wave Energy Scotland

Wave Energy Scotland (WES) was established in 2014 to ensure that "Scotland maintains a leading role in the development of marine energy" [44]. WES has funded 132 contracts and committed £50 million to marine energy projects. WES purchased the IP of failed wave energy companies Pelamis Wave Power, in 2014, and Aquamarine Power, in 2015, capturing the learning gained during their development [165]. The funding scheme employed by WES involves Pre-Commercial Procurement (PCP), the objective being to stimulate innovation. WES also use a stage-gate approach to funding, with the most effective projects gaining the final prize. There is promotion of collaboration across the supply chain by WES entities (e.g. between Arup and Mocean) and use of the test facilities at EMEC. [145]. Projects have been funded in areas covering different elements of WECs, including control, PTO, materials and manufacturing, connection systems, and novel WECs. Developers AWS Ocean Energy and Mocean Energy Ltd have received funding of £7.7million, having developed devices up to TRL5 through WES.

3.4.1.2 Europewave

EuropeWave describes itself as an innovative research and development programme for wave energy technology. Europewave commits to combining almost €20 million of national, regional and EU funding to drive a competitive PCP programme for wave energy. As with WES, PCP is a phased service agreement leading the winning projects to open-sea deployment and testing, where public procurers buy R&D from competing suppliers, and the suppliers retain the IP ownership rights, while procurers retain some usage and licensing rights [45].

Table 3.2: WES and Europewave commonalities

Topic	WES	Europewave
Demonstration models	✓	✓
R&D	✓	✓
Public funding	✓	✓
Consent time limits	✓	✓
Open innovation	✓	✓

The PCP programme has been adapted from the WES model, highlighting openness, collaboration, and risk sharing between public and private investors. Europewave cites the importance of large-scale demonstration models to provide certainty to potential investors and funders. Europewave projects use the EMEC test site in the Orkney Islands, as well as the BiMEP test site in the Basque Country [144]. Five wave energy projects are currently at the design and modelling phase. The projects are Arrecife Energy Systems S.L. (Trimaran), AMOG Consulting Ltd (Sea-Saw WEC), CETO Wave Energy Ireland Ltd (ACHIEVE), IDOM Consulting, Engineering and Architecture S.A.U. (MARMOK), and Mocean Energy Ltd (Blue Horizon 250) (a company also funded by WES), who will share in the €3.6 million awarded.

Table 3.2 shows some of the elements that WES and Europewave have in common.

3.4.2 Ireland's ocean energy R&D ecosystem

Although Ireland does not have a designated R&D hub for wave energy, with a vested interest in supporting commercialisation in the sector through grant schemes, it is not without resources and experience in the area.

The Marine Institute was set up under the Marine Institute Act 1991: "to undertake, to coordinate, to promote and to assist in marine research and development and to provide such services related to research and development" [113]. The Marine Institute is the State agency responsible for marine research, technology development, and innovation in Ireland. The Institute provides scientific and technical advice to the Irish Government to help inform policy and to support the sustainable development of Ireland's marine resources. Available research funding from the Marine Institute is spread across all marine projects and does not have a dedicated wave energy theme, unlike WES or EuropeWave; however, they have been vociferous in campaigning for operational Irish test facilities for wave energy for many years.

SEAI, through the Offshore Development Unit, is actively involved in implementing Ireland's Offshore Renewable Energy Development Plan (OREDP), which was published in 2014 by the former Department of Communications, Energy and Natural Resources. The OREDP highlights Ireland's focus on stimulating industry-led projects for the development and deployment of ocean energy devices and systems. These projects have been, and continue to be, supported through grant support schemes such as the Ocean Energy Prototype Development Fund, and the National Energy Research Funding Programme. To date, SEAI has supported 123 ocean-related projects and has grant-aided over €19 million in support to Ocean energy companies. SEAI provide funding through their RD&D programme. Again, SEAI does not have a particular focus on wave energy, and of the 38 projects funded in 2024 under the RD&D scheme, only one had an indirect relationship to wave energy conversion technologies. From 2009 to 2018, the SEAI prototype development fund provided over 10m in wave energy project support, with 50% of the available funding going to wave energy projects. The scheme closed in 2018.

3.4.3 Comparative assessment

Although Ireland does not have a dedicated R&D programme specifically targeting wave energy, the country performs strongly in this field. Using published research outputs as a benchmark, Ireland ranks as the third most prolific contributor to wave energy research in Europe.

Figure 3.5 illustrates the number of publications related to wave energy, by country, between 2008 and 2020, demonstrating that, despite the lack of a designated wave energy R&D hub, Irish academic institutions perform relatively well compared to their international counterparts in terms of R&D output in the area of wave energy.

In particular, in 2006, the Marine Renewable Industry Association (MRIA) lobbied for a PCP fund to support Irish technology developers to bridge the critical gap between prototype testing and full-scale sea demonstrations [167].

While Ireland benefits from both national and EU-level funding for technology development, particularly at TRLs 1-6, there remains no targeted mechanism, for deployment for energy harvesting, comparable to initiatives elsewhere. In contrast, the risk taken by WES in establishing their PCP stage-gated programme has positioned Scotland as a recognised global leader in wave energy support.

3.5 Technological and market challenges for WECs in a global and Irish context

This section discusses external factors that have a significant impact on the wave energy sector in Ireland. These factors are explored and compared to international examples.

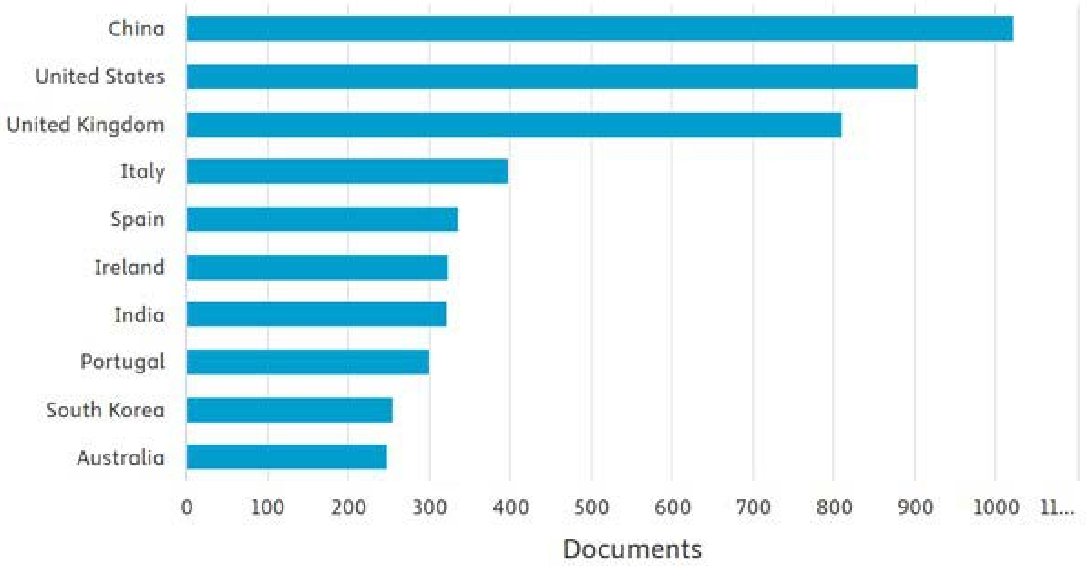


Figure 3.5: Wave energy converter publications – top performing countries (2008–2020) Source: Scopus database (2025) [166].

3.5.1 Absence of a dominant design archetype

WEC systems generally consist of a hull, a PTO system, by which mechanical energy is converted into (usually) electrical energy, and a control system to safeguard overall operations and maximise energy capture [113]. In addition to the complexity of wave energy conversion systems, there is a wide variety of designs, as described in Section 3.2, with no particular design having reached large-scale commercialisation. Due to the wide array of WEC concepts currently in the market, research efforts are diluted across many different projects and design types. This affects learning rates and effective knowledge transfer in the design phase, resulting in slower progress towards commercial viability for any single technology, but does ensure that there is commercial competition between concepts [161].

Additionally, the lack of a dominant design creates technological and market uncertainty, increasing potential investor scepticism, which can contribute to the deceleration of investments in WEC systems development, as investors face the risk of obsolescence from investing in one of multiple competing designs, highlighting the technological and market uncertainty of this development stage [168]. Therefore, the lack of a standardised design archetype presents significant barriers to both innovation and commercialisation.

This concern persists in Ireland. Some of the most advanced Irish pilot and demonstration projects have different WEC types, although, it has been argued that the presence of an established, dominant design can stifle innovation and competition [169]. In an interview with CorPower CEO Patrik Møller in 2024, when asked about this phenomenon, he stated that “wave energy is on the cusp of getting large players involved. The sector needs a few big players as it is with Siemens and Vestas in wind. Buyers need options."

3.5.2 Relatively high levelised cost of energy

The wide range of wave energy technology concepts, and the early stage of the technology, make it difficult to establish a robust LCoE calculation for wave energy. The estimated LCoE for most wave energy devices range between EUR 0.30/kWh and EUR 1.20/kWh [36], currently greater than other renewable energy sources; however, the EU-SCORES project has found that wave energy might be cost-competitive with offshore wind within a decade, with an LCoE below 70 €/MWh by 2035, if the appropriate funding and infrastructure are in place [170].

In the majority of the literature, two costs, capital expenditure (CAPEX) and operational expenditure (OPEX), are involved in the LCoE calculation, divided by the Annual Energy Production (AEP).

$$LCoE = \frac{CAPEX + OPEX}{AEP} \tag{3.1}$$

Capital and operational costs for wave energy do not, in general, compare favourably with more mature renewable technologies such as onshore wind energy. It is only through significant cost reduction that wave energy developers can compete with other renewable energy modalities. Cost reduction is heavily influenced by economies of scale and learning rate acceleration, which are gained through examination of a proliferation of devices, at demonstration scale, in open water, for an extended period of time [54].

Chozas *et al* [171], working on the EU Horizon2020-funded LiftWEC project (a TRL 4 cyclorotor-based WEC), guided the economic valuation of the wave energy concept, at early development stages, by setting up an economic frame based on a target LCoE, and evaluating the breakdown of costs based on a database of costs for WECs, to calculate the CAPEX (development plus deployment, commissioning and decommissioning), and the OPEX (operation and maintenance, site leasing and insurance) [171]. Where the data is scarce, Chozas contends that OPEX can be a percentage of CAPEX (usually 1.5%-9% of CAPEX, depending on the type of WEC and the location).

A review of CAPEX, OPEX, and LCoE for TRL6+ WECs was conducted through a survey of stakeholders in 2019 to develop a database of costs [172]. With a database of costs, it is possible to define ranges of costs for all cost centres of a project. This would assume, however, that information is correct and up to date, and that the data can be specific to a certain type of WEC and sea states. Angelopoulos *et al*, noted that, in general, capital-intensive investments are followed by high up-front costs.

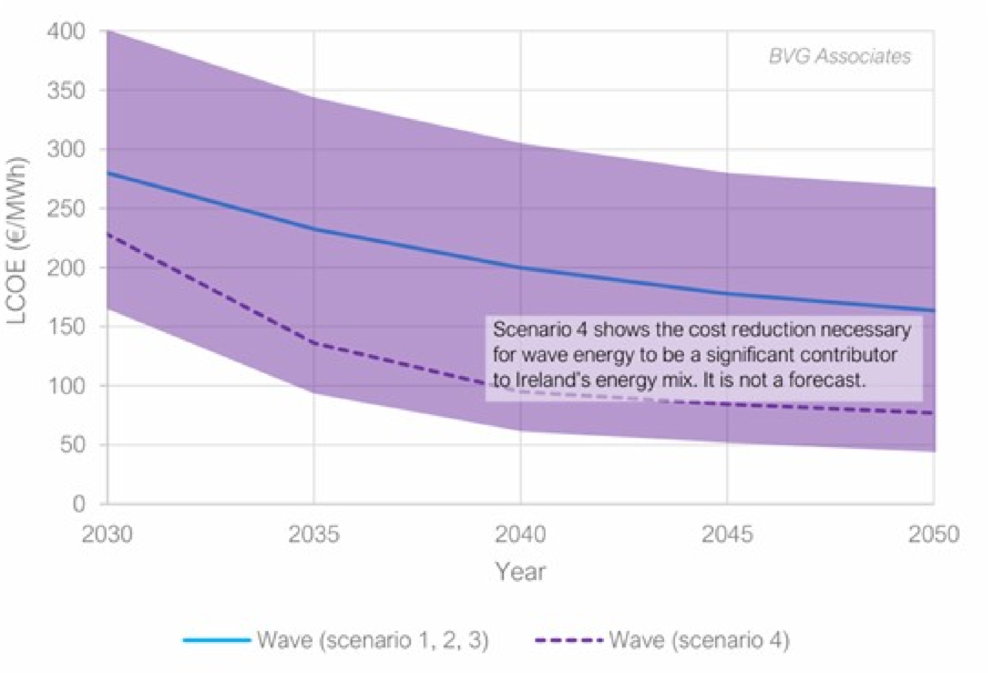


Figure 3.6: Trends in LCoE for wave energy with year of project commercial operation, under typical Irish conditions. Source SEAI ORE Technology Roadmap, by BVG Ass., (2024) [161]

They found that financing costs are critical and constitute a considerable part of the overall costs [173]. Furthermore, Angelopoulos *et al* found that the main contributors to LCoE, in renewable energy projects, are the initial investment expenditures and the discount rate, which reflects the cost of capital of the investment, i.e., the rate at which net cash flow future values are discounted against current values.

An accurate LCoE assessment is crucial for the determination of the cost-reduction needs of ocean energy technology. Estimates of operational costs, in particular, vary and capital costs, particularly the cost of finance, are likely to decrease dramatically when a proliferation of demonstration WEC devices has been tested in at-sea conditions for a significant amount of time. Indeed, in a recent survey conducted for this research, 82 wave energy stakeholders were asked what the most challenging problem facing wave energy technology development is, and 48% responded that they felt the biggest challenge was a relatively high LCoE compared to more mature renewable technologies (see Chapter 7) [51]. LCoE, although a useful tool, should be approached with the understanding that calculations are often based on incomplete data due to the emerging status of wave energy technology.

LCoE in an Irish context was considered by the SEAI in their recent ORE Roadmap [161]. The projection for LCoE for wave energy in Ireland to 2050 is shown in Figure 3.6 for typical site conditions in Ireland. The purple band indicates an uncertainty range regarding global technology and other industry progress. Scenarios 1 to 3 show a best estimate progression based on current trends and do not enable wave energy to play a significant role in Ireland. Scenario 4 shows the cost reduction pathway that would be necessary to see wave energy becoming a significant contributor to Ireland's energy mix by 2050. This shows wave energy LCoE with a decreasing premium over floating offshore wind of 50% in 2035, down to 20% in 2050. This, the report emphasises, is not a forecast, but rather an estimate of the trajectory needed to achieve Scenario 4. The report finds that this is unlikely to be realised without a significant increase in funding support and infrastructure. The report does recognise that some developers and demonstration projects, including the Saoirse project (that has now re-located to Portugal and is discussed in Section 3.7), have ambitions to drive down LCOE more rapidly than this.

3.5.3 Consenting and permitting barriers

Until 2021, Ireland lacked dedicated legislation for offshore renewable energy consenting procedures. Developers instead had to navigate foreshore, environmental, and maritime jurisdiction laws that were not designed for offshore renewables, creating what O'Hagan described as "legal ambiguity and administrative uncertainty." The labyrinthine consenting process could take up to ten years, involved multiple regulatory bodies with limited expertise in offshore energy, and offered no statutory timelines or structured licensing framework [174, 175]. This is of critical importance to wave energy technology developers, as their WEC devices move to the full-scale, at-sea demonstration phase of development. Analysts stressed the need for integration, knowledge-building, and adequate administrative resources to support the development of a more streamlined consenting and planning system [175].

By contrast, other European states have more efficient systems. Portugal typically grants offshore consents within 18 months, while Spain averages 2.5 years [176]. Scotland provides a one-stop shop under the Marine (Scotland) Act 2010, including a nine-month scoping phase based on the "survey, deploy, and monitor" principle. Marine Scotland Science supports this process by supplying technical and economic advice, evidence building, and enforcement, building on Scottish oil and gas experience.

Dalton et al. [111] recommended that Ireland establish a similar one-stop shop for planning, foreshore licensing, and grid connection, citing Denmark's wind sector as a model for innovation, deployment, and manufacturing.

The absence of a coherent framework coincided with a period of stalled development for Irish offshore renewable energy projects. Between 2005 and 2025, no new offshore wind projects were commissioned in Ireland following the 2004 Arklow Bank demonstration. Meanwhile, Scotland advanced with projects such as the European Offshore Wind Deployment Centre, Hywind Scotland, Robin Rigg, and Beatrice [177].

3.5.3.1 New offshore consenting procedures policies in Ireland

EU Directive 2014/89/EU [178] required Ireland to produce the National Marine Planning Framework (NMPF), its response to the EU mandate on Marine Spatial Planning (MSP). The NMPF sets out objectives to reduce greenhouse gas emissions, expand ORE, create a transparent consenting process with strong environmental protections, and link offshore and onshore grids. Offshore development consent applications must include visualisation assessments, although no specific criteria yet exist for wave energy projects, nor does the framework designate strategic locations for WEC demonstration project deployment.

The Maritime Area Planning Act 2021 (MAPA) established a new consenting regime within Ireland's 12 nautical mile limit [179]. Developers must now obtain a Maritime Area Consent (MAC) before applying for development consent. The Act also created the Maritime Area Regulatory Authority (MARA), which administers and enforces consents. Planning permission is granted through a single Environmental Impact Assessment, ensuring compliance with EU environmental requirements and the Aarhus Convention on Public Participation [180], while supporting Ireland's 2030 climate targets. MAPA also introduced Designated Maritime Area Plans (DMAPs), a spatial tool for identifying suitable areas for ORE development.

MACs are subject to strict timelines. Decisions must be issued within 90 days. In 2023, the first seven MACs were awarded, all for offshore wind projects with a combined capacity of 2.5 GW. Four of the six offshore wind projects, participating in the ORESS auction, secured long-term contracts, at an average price of €86.05/MWh, providing up to 20 years of stable revenue, which in turn motivates investor interest. However, although these projects advanced to the planning phase, progress has been slowed by significant additional environmental information requests from the planning authority [181].

Such delays may reflect early implementation challenges as MARA becomes fully operational. However, over time, the streamlined framework is expected to improve predictability and efficiency. Wave energy demonstration projects could benefit from these developments, particularly given their relatively low visual (depending on the WEC type) and environmental impacts.

3.5.4 Limitations of test facilities

Countries aiming to promote innovation in the wave energy sector must provide adequate testing facilities at different stages of development [182]. "Testing innovative wave energy devices. . . .is an important step towards harnessing some day, a reliable energy resource" (Franklin Oor US Undersecretary for Science and Energy at the US Energy Department, 2016).

The European Marine Energy Centre (EMEC) [145] is based at the Orkney Islands in the UK. EMEC describes itself as an "innovation catalyst" in supporting the development of marine renewable energy sources. EMEC boasts two grid-connected accredited sites (one for wave energy testing), and two scale test sites (one for wave energy testing). In 2023, Irish company Ocean Energy Ltd. signed up with EMEC to test the largest capacity WEC in the world, the OE35 OWC device, for two years. Another European facility, the BiMEP facility, managed by Basque and Spanish energy authorities, provides pre-consented, grid-connected test berths in the Bay of Biscay, making it an attractive site for wave energy system validation [144].

Different test facilities are necessary at different stages of wave energy technology development, in order to enable developers to have sufficient information to address risks, lower costs, and inform future designs to accelerate development. The Irish wave energy development protocol set out a staged pathway of test facilities, from small-scale laboratory wave tanks to intermediate sites to open-sea testing, ensuring Ireland could support all phases of device development [183]. Indeed, Ireland has developed wave energy device test facilities that cover all stages of development, from concept validation to deployment, although not all of the test facilities are operational.

The Lir National Ocean Test Facility (LirNOTF) [184] in County Cork is designed for laboratory testing of offshore wind, wave, and tidal energy devices, for scaled testing up to TRL 4, in a controlled environment. LirNOTF has four wave tanks: a deep ocean wave basin (for 1:15 scale testing) that can produce waves up to 1.2 metres high, an ocean wave basin for 1:50 scale testing, a wave and current flume for 1:50 scale testing, and a wave demonstration flume.

The SmartBay test site [185] in Galway Bay, is a 1:4 scale facility, on 37 hectares, with depths between 21 and 24m, providing relatively sheltered at-sea conditions. SmartBay can test operability, survivability, and performance. The test facility has a subsea cable that provides power and data connectivity to devices, and can test underwater parts. Smart Bay was developed for testing WECs at TRLs 4-6 and data buoys. Funded by Science Foundation Ireland (now Research Ireland) at a cost of €3.6 million, SmartBay has been operational since 2006, Ocean Energy Ltd. tested their OE Buoy there from December 2006 to September 2009; Wavebob conducted advanced development model sea trials at the testing site in 2006 and 2007; Sea Power Ltd. carried out winter survivability trials of their 1:5 scale Seapower Platform between October 2016 and March 2017 [186]. A foreshore lease (effectively granting formal authorisation) for the site was awarded in March 2017, allowing up to three marine renewable devices for a maximum of 18 months each, and was subsequently amended to permit floating wind turbine testing, which introduced significant delays due to expanded scope and consultation requirements related to local community concerns over the visual impact of the proposed wind turbines [187]. The test site is currently not operational.

The Atlantic Marine Energy Test Site (AMETS) [188] is situated off the coast of County Mayo, and has been designed to provide a cabled full-scale test site for wave energy devices in harsh open water conditions. To date, there has been no testing activity at the site, and the cable and related infrastructure have yet to be installed. AMETS was awarded a licence for underwater cabling and testing of wave energy devices in 2015, and was granted planning permission for the onshore structure in 2017. In 2018, SEAI expanded the scope of the site to include floating offshore wind technology testing. SEAI plan to apply for consent for floating offshore wind technologies through MARA's new regime [189]. The first wind turbines were due for deployment at AMETS in 2025, but, as of September 2025, the test facility is not operational, and, as recently as August 2025, SEAI have launched a tender for consultancy services to articulate a business case for AMETS.

Ireland's test facilities have increasingly prioritised offshore wind energy over wave energy, reflecting both the perceived maturity of offshore wind and the urgency of meeting 2030 renewable energy targets. Although sites such as SmartBay and AMETS were designed to foster innovation in renewable energy, particularly in wave energy, both remain non-operational, ironically due to the planned addition of offshore wind. The eventual functionality of these sites will depend on the effectiveness of the MAPF and MARA, and may indicate how policymakers value the development of wave energy technology.

3.6 Historical setbacks and project failures

Wave energy conversion globally, has experienced a fluctuating trajectory over recent decades. In the early 2000s, the sector underwent a period of rapid growth, accompanied by considerable optimism regarding its commercial potential [35]. Following this initial surge, the sector experienced significant setbacks, with multiple high-profile companies, including ABB, Abengoa, Alstom, Aquamarine Power, Pelamis, Wavebob, and Wello, ceasing operations or exiting the wave energy sector. This section reviews three of the most prominent wave energy companies: two international and one Irish company, which initially inspired considerable optimism but ultimately failed to achieve long-term sustainability. This section now highlights how policymakers and the market responded to these companies when they faced financial difficulties.

3.6.1 Insights from wave energy setbacks

3.6.1.1 Pelamis Wave Power

The inaugural deployment of Pelamis wave energy converters occurred at the Aguçadoura Wave Farm off the coast of northern Portugal in 2008, comprising three P-750 devices initially assembled on the quayside at Leixões. Operational challenges relating to mechanical bearings and subsea mooring systems, coupled with the financial insolvency of the project's principal investor, Babcock & Brown, precluded the redeployment of the devices and resulted in the termination of the project [190].

In 2004, Pelamis Wave Power demonstrated its first full-scale prototype, the P1, at the EMEC Billia Croo test site. The device was 120m long, 3.5m in diameter, and comprised four tube sections. The Pelamis P1 became the world's first offshore WEC to successfully generate electricity into a national grid, tested at EMEC until 2007. The findings from Pelamis P1 testing at EMEC led to the development of a second-generation device, the P2. The P2 comprised five connected sections with joints between the sections that flex and bend in the waves. This movement was harnessed by hydraulic rams, which in turn drove electrical generators located inside the device. The P2 device measured 180m long, 4m in diameter, and was approximately 1,350 tonnes [191]. Arriving in Orkney in July 2010, the 750kW P2 machine was installed at the EMEC Billia Croo wave test site for the first time in October 2010. Following a three-year testing programme, the P2-001 (the first second-generation Pelamis WEC, built for E.ON, a German electric utility company), returned to the ownership of Pelamis Wave Power for continued demonstration alongside the Scottish Power-owned P2-002 (the second second-generation Pelamis device).

Pelamis went into administration in November 2014 after failing to secure necessary funding. WES took ownership of the Pelamis assets and IP for an undisclosed purchase price, and 12 former Pelamis employees, including the former CEO, were granted the first WES employment contracts [192]. The P2-001 was dismantled. The P2-002 machine remains in Orkney and is now owned by the Orkney Islands Council, bought for a nominal £1. Initially, the council planned to explore alternative uses for the device, but in 2023, the Council issued a tender budgeting up to £150,000 for the decommissioning or removal of the P2-002 device. The total funding accumulated by Pelamis is estimated to be in the order of £95 million [167].

The cause of the collapse was reportedly due to high installation and maintenance costs that rendered the technology economically unviable for many potential investors. The harsh marine environment further complicated engineering and durability, leading to frequent breakdowns and decreased efficiency [145]. Following the cessation of company operations, the Pelamis IP was ultimately bought by WES, and technical insights have been published on the WES Knowledge Capture Library and shared with wave energy technologies that have followed in Pelamis Wave Power's wake [193].

3.6.1.2 Penguin WEC

15 years after its inception, in 2008, the Finnish wave-energy technology company Wello Oy declared bankruptcy in February 2023, citing financial insolvency as the primary cause [194]. Wello's flagship innovation, the Penguin WEC, was engineered around a rotating-mass principle, in which an asymmetrically weighted hull, actuated by passing waves, drives a flywheel connected to an onboard electric generator. The device was designed to contain all mechanical motion within the watertight hull and featured multiple compartments to enhance survivability [195].

Wello's first full-scale Penguin, theoretically capable of generating approximately 500 kW, was deployed at EMEC's Billia Croo test site, at the Orkney Islands, in summer 2012. The device survived two years of harsh marine exposure before sinking in March 2019, during its fourth deployment [195].

In July 2021, Wello's second-generation Penguin (rated at approximately 600kW and 44m in length) was installed at the BiMEP test site in Spain, feeding electricity into the Basque grid in September of that year. The trial was planned to last two years; however, by December 2021, the device was retrieved due to a minor leak caused by impact from a "floating object", likely incurred during towing. Following the BiMEP setback, Wello continued pursuing international collaboration efforts to revive its operations, yet ultimately filed for bankruptcy in late February 2023 in Finland. Founder and CEO Heikki Paakkinen confirmed that Wello's IP was acquired by Holvi Oy, which also absorbed most of Wello's team. Holvi, based in Espoo, Finland, is continuing development of the Penguin technology, and intends to engage with former Wello clients, with a view to future commercial deployment [194].

3.6.2 Setbacks in Ireland

3.6.2.1 Wavebob

Wavebob (Ireland) was a small innovative company, (with 20-30 employees), with a focus on WEC developments. The Wavebob concept was developed from 1999 until the company ceased operations in 2013. The Wavebob device is a point absorber WEC, designed to produce energy from waves by virtue of the relative (mostly vertical) motion of two components, the torus and the inertial 'tank'. A series of model scale testing was conducted, including testing of 1:3.2 models at the SmartBay test facility in Galway, Ireland. The development reached a TRL of 4-5. Wavebob received funding and embarked on joint ventures with a number of organisations. For example, in 2007, Wavebob signed a technical services agreement with US oil and gas company Chevron. In 2008, Wavebob signed an R&D and joint venture agreement with the

Scandinavian power company Vattenfall, under which plans were made to develop commercial wave farms off the West Coast of Ireland. In 2009, Wavebob signed an agreement with the American aerospace company Lockheed Martin. The balance of Wavebob's funding derived from public bodies such as the Irish Electricity Supply Board (ESB), SEAI, the EU, and the US Department of Energy. The company spent approximately €10 million, much of it raised from investors, including State-owned utility Bord Gáis, which invested €1.8 million into Wavebob in 2010 [196], [197]. Chairman Padraig Berry, speaking in 2013, concluded that the company could not continue to trade. "Putting it simply, we have run out of money". Mr. Berry explained that SEAI had refused a grant requested by the company, effectively spelling the end of the business. He explained that the grant was meant to act as bridging finance until the company could raise cash from investors, in the middle of the same year. According to journalistic reports, Wavebob had been hoping to raise €10 million in fresh investment [198].

3.6.3 Lessons learnt

In a 2022 interview conducted for this study, Andrew Parish, former CEO of Wavebob, recounted that the company had secured a contract with Chevron to deploy devices on decommissioned offshore oil platforms just before the financial crash. Mr. Parish recounted that Wavebob obtained millions in government support, and later won £10 million in funding from a UK venture capital bank, only for the bank to collapse the following week. According to Mr. Parish, Wavebob was close to success and might have survived had the government sustained support to protect its investment. Mr. Parish argued that wave energy should be nationalised to safeguard IP, as seen with Pelamis under WES. Parish also criticised the limited engagement between researchers and the business community, and stressed that civil servants must deliver on government commitments for emerging technology companies to succeed.

The continuation of the Wello concept through its acquisition by Holvi, and the retention of Pelamis IP, following the WES acquisition, illustrate how knowledge sharing and technology transfer can extend the impact of insights attained by companies beyond their lifespan, thereby legitimising government support provided prior to the attainment of commercial readiness. Indeed, a Scopus analysis [166] reveals that 74 journal articles have been published about the Pelamis concept since the company's closure in 2008, indicating that interest in the concept persists beyond the company's closure.

Table 3.3: International wave energy developer frontrunners

	Name	Founded	WEC type	TRL
	CorPower	2012	Point absorber	7-8
Projects:	Conducted full-scale testing off Portugal's coast, as well as winning new funding (€40 million) from the EC Innovation Fund to deliver a 10MW demonstration array. Venture Capital investment has been secured from Tokyo Gas [199], and GTT - Technology for a Sustainable World [200]. CorPower device was chosen for the Saoirse Projectthat has recently moved operations from Ireland to Portugal.			
	Carnegie	1987	Point absorber (CETO)	7-8
Projects:	CETO has reached Phase 3 of the Europewave PCP scheme (from prototype to first test products), delivered by their Irish subsidiary, and co-funded by EU+RENMRINAS and the Basque government. The company are pursuing standards certification from Lloyds.			
	Wavepiston A/S	2014	Oscillating Water Column	6
Projects:	Current projects worth approximately €9m raised across 3 largely EU-funded projects until 2027. Full-scale testing completed in 2024 in Gran Canaria.			
	Mocean	2015	Hinged raft (Blue X)	6-7
Projects:	Blue X has reached phase 3 of Europewave PCP and has support from WES. The company are also researching combined wave/solar energy with SolarDuck, a project backed by Katapult Ocean, a technology fund manager. Open sea testing at EMEC for 5 months has been completed.			

3.7 Current WEC technology developers and pilot projects

Despite persistent challenges facing wave energy development, several projects and technologies continue to progress toward commercial readiness. Table 3.3 highlights selected international frontrunners, while Table 3.4 highlights a current Irish developer and an Irish project, both tables illustrating different funding mechanisms, technology types, and maturity levels. These examples are not exhaustive, but are intended to illustrate the diversity of approaches being pursued in the sector, and the strategies that have enabled some wave energy technology developers to advance.

Ireland's most advanced WEC, in terms of proximity to commercial maturity, is Ocean Energy's OE35 OWC device. In addition, some international wave energy technology

Table 3.4: Irish wave energy developer frontrunners

	Name	Founded	WEC type	TRL
	Ocean Energy	2012	Oscillating Water Column	7-8
Projects:	Conducting testing of the full-scale OE35 WEC at a US Navy test site near Hawaii. Leading the WEDUSEA project. An EU Horizon and Innovate UK-funded project to demonstrate a 1 MW OE35 grid-connected WEC at EMEC.			
	The Saoirse Project	2023	Point Absorber (CorPower)	7-8
Projects:	The Saoirse Project is led by ESB to develop a 4.9MW grid-connected wave farm array, originally planned to be located off Ireland's Co. Clare coast, lengthy permitting procedures led to the project being relocated to Portugal in late 2025. €40million was secured for the project from the EU Innovation Fund			

developers are active in Ireland, either through national projects such as the ESB-backed Saoirse project, which plans to deploy CorPower's technology (although this has recently moved operations to Portugal), or through Irish subsidiaries, as in the case of Carnegie Carnegie Clean Energy. Furthermore, Ireland has developed a strong reputation in WEC control systems, contributing to multiple EU-funded projects as a collaborator and, in some cases, as the lead partner (e.g. The LiftWEC project [201]). An examination of these current developers and projects reveals several commonalities. The majority are financed through a combination of European Union and national funding mechanisms, which are predominantly short-term in nature (generally limited to a maximum duration of five years), supplemented by venture capital investment. Test facilities such as BiMEP and EMEC are important, as are structured programmes such as EuropeWave and WES. Also, the selected companies demonstrate that the sector is characterised by a diversity of WEC design concepts.

3.8 Discussion and conclusions

In conclusion, this chapter examines the current status of wave energy technology in Ireland within an international context and identifies several key findings.
Although the Irish government has enacted EU-mandated legislation related to offshore renewable energy, the streamlined consenting procedures envisaged under the MAPF have yet to invoke regulatory urgency, as can be seen in the delays affecting current offshore wind development projects and led the Saoirse wave energy project to move operations from Ireland to Portugal to avail of faster consenting procedures. Similarly,

while Ireland has invested in test facilities to cover all TRLs, neither SmartBay nor AMETS are currently operational.

Ireland possesses several comparative advantages in wave energy, including decades of applied and fundamental research expertise in the area of wave energy, and Ireland's position as a small but strategically located test market with direct access to the wider EU market. Academic output in the field is comparatively strong, with Ireland ranking third in Europe for the number of publications with a focus on wave energy, according to a bibliometric analysis from Scopus.

Persistent challenges remain. Ireland lacks explicit policy targets for wave energy, and the absence of a dominant technological design contributes to investor uncertainty. In contrast, other jurisdictions, such as Scotland, through EMEC, and the EU, through BiMEP and EuropeWave, have demonstrated that dedicated programmes, stable policy frameworks, and targeted funding can play a significant role in advancing wave energy technology development.

The experiences of companies such as Ocean Energy and Carnegie, contrasted with some of the wave energy companies that ceased operations, illustrate how policy support can determine whether technologies transition from concept to commercial readiness or not. Several enabling conditions for achieving renewable energy targets at the EU level are required, including reliable timelines for consenting procedures, mechanisms for knowledge building and exchange, and adequate funding where appropriate [174]. Ireland has not yet fully embedded these elements within its offshore renewable energy policies.

The combination of a relatively high LCoE, limited political commitment, slow policy implementation, and technological uncertainty continues to deter investor confidence in wave energy. Ireland has the potential to become a leader in wave energy technology development and exploitation; however, time is of the essence. Without explicit targets, sustained policy support, and a coherent long-term strategy, Ireland risks falling behind more proactive jurisdictions.

4

Danish wind energy policy initiatives as a benchmark for Irish wave energy innovation

Contents

4.1 Introduction

Building on the preceding chapters, this chapter evaluates Ireland's wave energy policy trajectory benchmarked against the period from 1973-1990 that marked the early development and growth of wind energy in Denmark. Chapter 2 analyses the policy drivers during the period of emergence that led to Denmark's wind energy success, structured around five external enabling factors [202], while Chapter 3 assesses the current status of wave energy technology development in Ireland within an international context. Now, Chapter 4 benchmarks Irish wave energy policy development against those five early Danish policy factors that contributed to the enduring success of Danish wind energy. The objective of this chapter is to identify strengths, weaknesses, gaps, and opportunities, and ultimately to identify the factors that can lead to pragmatic policy recommendations, in order to support the growth of an Irish wave energy technology sector.

The motivation for making a comparison, between a burgeoning Irish wave energy sector and the development phase of Danish wind energy, lies in understanding the policy commitments that contributed to Denmark's globally successful wind industry, while Ireland's wave energy sector largely remains at an earlier stage of development. Denmark is selected as a comparator, not only because of the country's global leadership in wind energy, but also because of its similarities to Ireland in terms of population size [58], [39], renewable resource availability [203], and political structures (both being EU members). By comparing the factors that enable the development of emerging renewable energy technologies in Ireland and Denmark, this chapter seeks to answer the following questions:

1. To what extent can Denmark's wind energy policy lessons be applied to Ireland's wave energy sector?
2. What differences between wind energy and wave energy technologies limit the effectiveness of such comparisons?
3. Which policy interventions are most likely to support Ireland in building a viable wave energy sector?

By addressing these questions, this chapter aims to contribute to ongoing considerations related to how Ireland can foster indigenous wave energy technology innovation and development, and provides specific areas of focus for the remaining chapters of this thesis.

4.1.1 Overview of Danish wind energy success factors

Chapter 2 identifies five policy-related factors that contributed to dominance in wind energy technology development for Denmark:

- The role of pioneers, both as technical innovators and political/community leaders.
- A supportive cultural and political context.
- A strong research and development ecosystem, underpinned by open innovation and collaboration between producers and owners.
- Robust certification mechanisms and structured knowledge transfer, ensuring quality and credibility.
- An incremental, bottom-up approach to technological development, characterised by experimentation and community engagement.

4.1.2 Chapter layout

This chapter is organised as follows. Section 4.2 discusses the inherent differences between wind energy and wave energy technologies that limit the comparison. Section 4.3 considers the influence of pioneers and champions in both countries. Section 4.4 compares the cultural and political contexts of Denmark between 1973-1990 and Ireland. Section 4.5 examines the research and innovation infrastructure related to the technologies in both countries, while Section 4.6 analyses certification and standards in wind energy in Denmark and wave energy in Ireland. Section 4.7 discusses incremental development and community engagement. Finally, Section 4.8 summarises the findings that can provide areas of focus for the development of pragmatic policy recommendations to support the growth of the wave energy sector in Ireland.

4.2 Limitations of the comparison

Although Denmark and Ireland share geopolitical similarities, and the focus of the study is on renewable energy technology development in both countries, there are limitations in comparing onshore Danish wind energy development from the 1970s-1990s to Irish wave energy that merit consideration.

Firstly, wind turbines are a widely recognisable technology, having developed from traditional windmills that have decorated the landscape for millennia [204]. In contrast, WECs lack a standardised design and remain unfamiliar to most of civil society (see Section 8.2). In addition to promoting societal acceptance, familiarity embeds a fundamental understanding of mechanical design, guiding the operation and design process of emerging technologies [205].

Secondly, wind turbines face primarily aerodynamic loads, with some turbulence and fatigue considerations. WECs face harsher operating conditions, including exposure to rogue waves, storms, and corrosive saltwater, which has led to many devices failing or becoming damaged during testing at sea [206], [207]. An associated issue is the facility of wind turbines to 'spill' excess, or extreme, wind energy via yawing or blade pitch control. In contrast, wave devices find it difficult to 'hide' from an excess of hydrodynamic excitation, with submergence (an expensive operation) being one of the few options [208]. These present a complex design challenge for WECs, namely how to maximise energy capture while ensuring survivability and operational reliability over a WEC's lifespan.

Third, installation, operation, and maintenance are inherently more complex and costly in offshore locations due to challenges related to access and at-sea conditions [209]. While wind turbine maintenance windows are governed by wind limitations alone, floating devices are subject to stricter limitations associated with both wind and waves.

Fourth, for wind turbines, motion is relatively constrained. Most energy capture comes from a single dominant degree of freedom, the rotation of the blades around the rotor axis. A WEC, on the other hand, is expected to actively interact with ocean waves in a specific way in order to harvest energy effectively. Moreover, WECs operate in a multi-degree-of-freedom environment (heave, surge, sway, roll, pitch, yaw). The ocean excites these motions simultaneously, making device control and energy capture more complex [210].

These differences relate to primarily technical challenges; however, they affect a number of the external factors that are considered in this study, including societal acceptance, funding challenges, stakeholder perspectives, and IP protection. For this reason, the lessons from the early efforts of Danish wind policy must be adapted with caution rather than directly transplanted. Despite this, benchmarking the development of Danish wind energy against Ireland's emerging wave energy sector offers valuable insights. The development of Danish wind energy technology provides an example of how consistent policy support, strategic investment, and infrastructure development can facilitate the transition from early-stage innovation to global leadership in renewable energy. Examining the Danish experience has the potential to inform the strategic advancement of wave energy in Ireland, enhancing the prospects for technological maturation, long-term sustainability, and the possibility for Ireland to become a world leader in wave energy technology development.

4.3 Pioneers

4.3.1 Danish wind energy champions

La Cour and Juul left a lasting impression on the development of Danish wind energy. La Cour in particular established an early link between technology, education, and government by founding the Association of Danish Wind Power, creating a school for wind energy engineers, and securing state funding for early research [78]. In the 1970s and 1980s, Danish wind power development was supported by successive left-wing governments that promoted cooperative ownership models and knowledge transfer, through institutions such as the Risø National Laboratory (see 4.7) [59]. These institutional champions facilitated an innovation system, in which communities, engineers, and small manufacturers collaborated in an incremental process of technological development [211] that enabled Danish wind to evolve into a sustainable system incorporating civil society, industry, and academia [212].

4.3.2 Key figures in Irish wave energy

In the early 2000s, Ireland experienced a surge of interest in wave energy, largely driven by an electricity supply crisis and national commitments to renewable energy [111]. A major initiative at the time was the WestWave Project led by the Electricity Supply Board (ESB) to develop Ireland's first pre-commercial wave energy array, targeting 5 MW capacity. Multiple wave energy device developers were involved, reflecting Ireland's early push to test different technologies. These included Wavebob Ltd., Ocean Energy Ltd., Aquamarine Power Ltd., and Pelamis Wave Power Ltd. The project secured foreshore licences for offshore testing/demonstration sites [213]. The WestWave project was intended as a demonstration of feasibility. However, of the four developers involved in the project, only Ocean Energy Ltd remains operational; the other three developers folded between 2013 and 2015. This period also saw the

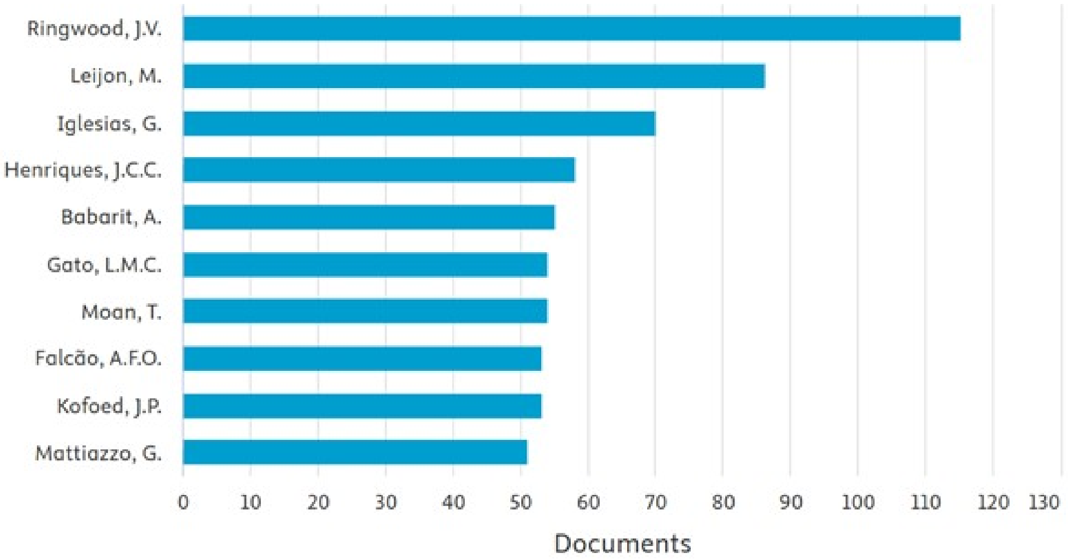


Figure 4.1: Wave energy publications by author from 2008-2020. Source, Scopus database, 2025 [166].

establishment of the MRIA, with Peter Coyle serving as its Chairman to advocate for policy support and industry development [214].

As Head of the Ocean Energy Development Unit at Sustainable Energy Ireland (SEI), and having been involved in the establishment of the Marine Institute, Eoin Sweeney shaped Ireland's first marine energy policy and laid the groundwork for research programs and funding schemes, working with other Irish wave energy pioneers such as Tony Lewis of Ocean Energy Ltd. He also helped to establish the Smart Bay test facility and advocated for decades on behalf of the sector. Sweeney navigated between developers, government, and academia to the benefit of Irish wave energy until his premature death in 2017 [215].

Today, Ocean Energy Ltd., founded in 1996, is Ireland's most prominent wave energy company, currently leading the €20 million WEDUSEA project with the OE35, the world's largest-capacity floating wave energy device. In fundamental research, Ireland boasts influential contributors such as John Ringwood, the most prolific author on the subject of wave energy (see Figure 4.1, and discussed further in Section 6.6). Despite these achievements, wave energy remains a lower policy priority, and the momentum initiated by Sweeney and Lewis has been overshadowed by the government's focus on commercially available technologies that are perceived to make climate targets more readily achievable.

The global recession of the late 2000s and early 2010s disrupted the wave energy sector, contributing to the collapse of several pioneering companies. Relatively large wave energy companies such as Pelamis and Aquamarine Power faced difficulties due to economic constraints, underscoring the vulnerability of emerging renewable energy technologies to financial instability [190].

An example of a positive Irish coordinated effort between political, industrial, and community actors is the rural electrification push of the 1940s in Ireland. In 1946, 400,000 homes in Ireland were without electricity. By 1965, 81% of Irish homes were connected. This massive logistical undertaking involved the installation of 49,000 miles of cable and the erection of one million poles, as well as the investment of the equivalent of €1.5 billion in today's money. These endeavours were complemented by the appointment of influential spokespeople in each parish (usually the parish priest and ESB canvassers) and significant state subsidies [216]. Another earlier example of coordinated national-scale effort is the construction of the Ardnacrusha hydro scheme under the Shannon Hydroelectric Scheme. The project, begun in 1925 and completed in 1929, was carried out within seven years of Irish independence and cost about IR£5.2 million, almost one fifth of the Irish Free State's annual budget at the time. The generating plant of approximately 85-86 MW was sufficient, in its early years, to meet the electricity demand of the entire country [217]. These examples illustrate that, with political will and a coordinated effort between stakeholders, fundamental change is possible in Ireland.

4.3.3 Comparison

The contrast between Danish wind energy and Irish wave energy development, particularly in terms of pioneering efforts, is notable in two main ways. In Denmark, support for wind energy has been sustained and consistent over several decades and has fostered close alignment among industry, academia, and government. By contrast, support for Irish wave energy has been intermittent, failing to fully leverage the contributions of early Irish pioneers.

The contemporary Irish wave energy sector exhibits limited interaction among industry, academia and government agencies [54]. Current policy frameworks, though more robust than previous efforts, often fail to integrate industry and community perspectives effectively, resulting in slower commercialisation and limited public engagement. This lack of coordination contrasts sharply with successful examples from wind energy and the Irish rural electrification initiative of the 1940s. Despite the dedication of a few key individuals, policymakers have yet to make the strategic investments necessary to realise the potential of a domestic wave energy industry.

4.4 Cultural and political context

4.4.1 Danish wind socio-political context

The initiation of government support for the development of Danish wind energy coincided with the oil crisis of 1973 and marked a fundamental change in Denmark's energy policy. In October 1973, the Yom Kippur War, an offensive led by Egypt and Syria against Israel, broke out. OPEC agreed to reduce the output of oil by 5% every month until Israel withdrew from the territories it had occupied since 1967. OPEC also placed embargoes on the US and the Netherlands due to their support of Israel, leading to a quadrupling of the price of oil [218]. In Denmark, this coincided with a period of significant transition, including a new administrative division in the country, accession to the European Community in 1972, and a fully restructured tax system [219].

At that time, 90% of Denmark's energy consumption was based on oil, and 90% of that was imported from the Middle East, leaving Denmark very exposed to market fluctuations without the regulatory tools to tackle the problem [219]. This prompted a shift toward the promotion of energy efficiency and the development of indigenous, diverse sources. Between 1973 and 1979, the market-driven model previously in place in Denmark was replaced by a classic welfare state model, where the state takes responsibility for ensuring that the market operates well, and a national energy policy was implemented, with Denmark taking control of its energy assets in addition to heavy taxation on energy consumption, leading to a culture of energy consumption awareness [220], [221].

This context provided the long-term, government-led commitment that led to the policy initiatives discussed in Chapter 2 that promoted the growth of the Danish wind energy industry, as well as self-sufficiency in natural gas by 1984, and oil by 1993.

4.4.2 Irish wave energy social and political will

At present, wave energy in Ireland is predominantly regarded by government agencies as falling within an R&D category. This has not always been the case. In the early 2000s, wave energy benefited from considerable political and financial support and attention from Irish government agencies. However, this momentum dissipated after 2010, following a series of company failures within the sector (see 3.6), compounded by the enduring impacts of the global economic recession [222].

Ireland is legally bound to meet its climate obligations, and in doing so, has established the requisite legislative measures, institutional frameworks, and regulatory bodies (which, for offshore renewable energy technologies, are described in 3.3.2). Nonetheless, progress towards national renewable energy targets has fallen markedly short [223]. In contrast, offshore wind energy has become the central focus of Ireland's most recent CAP, which sets a target of 7 GW of installed capacity by 2030 and an aspirational 37 GW by 2050 [224]. To facilitate this expansion, the government has introduced what was described as a streamlined consenting process for offshore renewables with the introduction of th MNPF and conducted an offshore wind auction under the ORESS scheme 3.5.3.1. Despite these measures, the four offshore wind energy projects that secured support under the auction are currently facing delays pending requests for substantial additional environmental impact assessments, suggesting that the efficiency promised by the new system has yet to take effect.

4.4.3 Comparison

The social and political contexts underpinning Ireland's and Denmark's approaches to renewable energy technology development reveal a contrast in motivation, design, and outcomes. Ireland's renewable energy strategy has been predominantly shaped by obligations under European Union climate and energy directives, with the motivation being compliance rather than fundamental change. While there is cross-party consensus on the importance of sustainability, the policies implemented to achieve these objectives have lacked effective enforcement mechanisms and political commitment and have produced limited progress toward national targets. Even the prospect of significant financial penalties (€8-26 billion) for underperformance [225] has not resulted in the political commitment required to meet Ireland's renewable energy targets. Ireland's renewable energy policies have been externally-driven, reactive, and compliance-focused, and this political context leaves little opportunity for wave energy to garner the support required for progression towards commercialisation.

Denmark's experience between 1973 and 1990 is markedly different. In the wake of the oil crisis, when the country was over 90% dependent on imported oil, Denmark reoriented its energy policy from a market-driven model to a welfare-state model prioritising energy self-sufficiency. This shift was a pragmatic response to energy insecurity, which evolved into a strategy to establish international leadership in wind energy. Unlike Ireland, where EU targets act as the primary motivation, Denmark's pursuit of renewable energy was domestically motivated and proactive, and compliance with EU targets was achieved as an incidental outcome based on a commitment to energy security, industrial innovation, and global leadership in wind energy.

A further difference concerns the electricity market at the time of the oil crises in the 1970s. During the early years of Danish wind energy technology development, the electricity system was characterised by a fragmented, regional utility structure [67]. This decentralised structure allowed independent producers, cooperatives, and small manufacturers to enter the market. In contrast, Ireland's electricity sector historically developed under the ESB monopoly, retained centralised control over generation, transmission, and distribution [226].

While the ESB played a crucial national role in projects such as rural electrification and Ardnacrusha, this traditional centralisation limited the scope for energy initiatives comparable to the Danish model. The WestWave project [227], for example, was led by ESB rather than emerging from a distributed ecosystem of small producers. This difference has implications for innovation pathways in that Denmark's fragmented system enabled bottom-up experimentation, whereas Ireland's centralised system has tended to favour large-scale, top-down initiatives.

4.5 Research and innovation infrastructure

4.5.1 Danish wind energy: The Risø test centre and open innovation

Risø has been widely acknowledged as central to the institutional and technological foundations of the Danish wind sector. Established in the late 1970s, the national test centre functioned as a scientific research hub, and to raise technological standards and transfer knowledge in close collaboration with emerging industrial stakeholders [228, 211]. Unlike the more academically oriented approaches prevailing elsewhere [100], Risø pursued an application-driven research agenda closely aligned with industry needs, thereby accelerating technological knowledge transfer and a consolidation of standards in wind energy technology. Risø's early focus was closely aligned with small and medium-sized enterprises rather than purely academic research institutions. This focus shaped perceptions of the centre as a facilitator of industrial economic development rather than a detached academic entity. By working directly with turbine manufacturers and cooperative owners, communities felt that wind energy research was linked to tangible local economic opportunity. This reinforced societal legitimacy and strengthened feedback loops between experimentation, certification, and commercialisation.

A notable outcome was the development of the Wind Atlas [229] and the WAsP software in the 1990s, which translated research knowledge into widely adopted planning tools for both industry and policymakers. Over time, Risø, now DTU Wind Energy, expanded expertise in resource assessment, aerodynamics, and systems control, maintaining a link with industry and government agencies. This model of 'interactive innovation' [230] illustrates how Risø, as a research and development hub for wind energy in Denmark, acted not only as a knowledge producer but also as a regulatory authority and facilitator of industrial development.

4.5.2 Irish wave energy: Innovation without a top-down imperative

Unlike Denmark's centralised hub at Risø, Ireland lacks a dedicated, national research hub for wave energy. Support is dispersed across agencies such as the Marine Institute, SEAI, Entrprise Ireland, and Research Ireland, all of which support a variety of technologies and development agendas. While three test facilities have been established across different TRLs, only one remains operational. Institutional initiatives, such as the OREDPII [159] and more recently MARA, were intended to streamline deployment and demonstration, yet their effectiveness has been limited, and regulatory delays continue to impede progress (as discussed in Section 4.4).

Despite these institutional weaknesses, Ireland performs strongly in wave energy research and boasts a company with the largest (global) capacity floating wave energy device [120]. Bibliometric analyses place Ireland as the third most prolific in Europe in publication output in the area of wave energy, reflecting considerable innovative capacity. However, in the absence of mechanisms to support progression beyond the R&D phase, this expertise risks remaining confined to academic outputs, rather than enabling the emergence of a viable indigenous wave energy industry.

4.5.3 Comparison

Denmark's success in wind energy has been underpinned by Risø, a sustained research hub that, for over four decades, has integrated applied research with industrial collaboration [231]. Risø has provided a stable framework for innovation, standardisation, and industrial scaling. By comparison, Ireland's wave energy sector remains fragmented. Research performance is strong, but facilities are underutilised or non-operational, institutional frameworks lack enforcement, and no clear policy targets exist to support innovation toward commercialisation in the Irish wave energy sector. The absence of an equivalent to Risø represents a barrier that can help to explain the divergence between Denmark's global leadership in wind energy and Ireland's stalled wave energy technology development trajectory. In Ireland, wave energy research is strongly embedded within universities and publicly funded research centres such as the Centre for Ocean Energy Research in Maynooth University [232] or MaREI [233]. While this has generated high-quality academic output, it may not be as clear to industry or communities that wave energy development is directly tied to economic growth. The absence of an industry-linked national hub comparable to Risø may therefore affect both investor confidence and societal perception.

4.6 Certification and standards

4.6.1 Danish wind: Certification at Risø and quality assurance

International standardisation work on wind energy commenced at Risø in 1987–88, focusing on quality assurance, implementation requirements, and certification. At this stage, the department had already established rigorous procedures for measuring wind turbine power curves, assessing performance, and identifying load conditions [234]. These methods provided a systematic framework for evaluating whether turbines were sufficiently reliable and safe for deployment, as described in Chapter 2.

This approval regime was instrumental in mitigating technological risks, ensuring product reliability, and creating stable conditions for industrial growth that provide assurance to potential international investors. Denmark's certification and approval system became a distinctive policy instrument that strengthened international competitiveness, particularly in export markets [78], [235]. The development of certification and standards at Risø was closely linked to Denmark's political commitment in the aftermath of the 1970s energy crisis to promote sustainable alternatives to imported fossil fuels. A key outcome of this process was transparency to aid knowledge transfer; testing procedures, approval regimes, and performance results were openly accessible, which fostered trust between policymakers, manufacturers, and export partners and was fundamental to the early successes of the Danish wind energy sector.

4.6.2 Irish wave energy: The status of certification

In 2007, the International Electrotechnical Commission (IEC) established Technical Committee 114, Marine Energy – Wave, Tidal, and Other Water Current Converters, to develop international standards for marine energy technologies [236]. This work was complemented in 2014 by the establishment of the IEC Renewable Energy System (IECRE), tasked with developing conformity assessment processes to provide internationally recognised certification of compliance with these standards. The standards outline best practices, based on experience from industry, research institutions, and government agencies, for the safe, compatible, and interoperable design, construction, testing, operation, and maintenance of marine energy systems. The anticipated benefits include reduced technology development risks, lower costs, and improved access to global markets [237].

One of the most relevant documents is IEC 62600-4, which provides a technical specification for technology qualification (TQ), assessing whether systems and subsystems of a WEC are capable of performing reliably in defined operating environments [238]. Certification frameworks are intended to assure safety, reliability, and availability, thereby reducing investment risks and increasing market confidence. Jonathan Colby, convener of the IECRE Marine Energy Sector Working Group, observed, third-party verification of compliance with consensus-based standards plays a critical role in the commercialisation of marine energy technologies [239].

Despite these advances, significant challenges remain. IECRE membership is currently limited to only 18 participating countries, including Ireland, and certification remains voluntary rather than mandatory. Moreover, the lack of convergence in WEC designs complicates the application of generic standards, as does the lack of full-scale demonstration projects, leading to reliance on technical specifications rather than full certification. Lloyds and DNV are the primary certifiers internationally and approach certification from an insurance perspective. The Finnish company AW-Energy Oy pursued certification for its WaveRoller device through Lloyd's Register [240], underlining the importance of such processes for reducing financing costs and demonstrating credibility in the absence of a dominant industry design.

4.6.3 Comparison

Risø's six-step certification process was mandatory for all wind turbines under development in Denmark and reinforced through a 30% capital cost subsidy in the early years of wind energy technology development. This combination of regulation and financial incentive created strong alignment between public policy, industry practice, and research institutions. The certification reduced technological risk, accelerated knowledge transfer, and gave Danish wind manufacturers a competitive advantage in international markets.

By comparison, the existing certification system for WECs is voluntary and relatively immature. Several wave energy companies, such as the Finnish company WaveRoller, CorPower, Carnegie, and Orbital Marine Power, have pursued, or are pursuing certification through Lloyds or DNV. However, without compulsory requirements or guaranteed financial incentives, certification has yet to reach the scale necessary to provide sufficient assurance to investors or to drive standardisation across diverse WEC designs.

Wind energy technology development in Denmark benefited from early institutional frameworks that coupled certification with market incentives. A more coordinated approach, drawing lessons from Denmark's wind sector, could be critical for moving wave energy towards demonstration and ultimately large-scale deployment. However, while Denmark's wind sector could pioneer national certification due to its early leadership in wind energy technology commercialisation, Ireland currently lacks sufficient influence in wave energy to establish a certification framework, which is dominated by DNV and Lloyd's from an insurance perspective. Linking certification processes more explicitly to TPL could offer a structured pathway for assessing maturity and reducing investor uncertainty in emerging WEC technologies.

4.7 Incremental development and community engagement

4.7.1 Danish wind: Community ownership and an incremental trial and error approach to innovation

The development of Danish wind power was underpinned by a distinctive ownership model and a trial-and-error bottom-up approach to technological advancement. Policy embedded three key principles: first, farmers and rural households were granted the right to install wind turbines on their own land; second, local residents could form cooperatives, with exclusive local ownership made a condition for operating permits; and third, utilities were permitted to construct large wind farms only with government approval and only if doing so respected the preferences of local farmers and communities [102]. This cooperative structure drew on Denmark's long tradition of collective ownership in agriculture and other sectors [241], ensuring that local communities directly benefited from wind projects. This culture has persisted to include offshore wind projects, although to a lesser extent, and even though the area of deployment, the sea, is not privately owned.

The Danish cooperative framework, in addition to fostering social acceptance, also contributed to technological advancements in Danish wind energy technology. With many small-scale owners engaged in experimentation, turbine design evolved through an incremental "trial-and-error" process, enabling rapid learning. Rather than relying on large-scale, centralised, top-down innovation, the Danish model allowed for an accumulation of technical improvements and operational expertise. Over half of the total existing installed wind capacity in Denmark in December 2016 contained a citizen ownership model [242].

Despite all of these efforts, public interest in wind energy in Denmark has waned in recent years, largely because wind has shifted from being a world-leading innovation to an ordinary part of national infrastructure following decades of success, led by companies such as Ørsted [65] and Vestas [64]. Rising costs, higher electricity prices, and local opposition to new turbines have made the technology more controversial and a recent offshore wind energy project tender failed to receive any bids [243]. As a result, while most (60%) Danes still support wind energy in principle [244], it generates less public enthusiasm and more debate than it did during its earlier period of rapid expansion.

Broader socio-political policies have reinforced the Danish community involvement approach. High energy taxes and public awareness campaigns supported a culture of energy conservation, and the strong Danish anti-nuclear movement of the 1970s promoted public support for alternatives, including wind power. Together, these elements created a generally supportive environment for cooperative ownership and bottom-up innovation, which proved crucial for establishing Denmark's global leadership in wind energy.

4.7.2 Community involvement in Ireland

ORESS requires companies to engage with local communities in the development of renewable energy projects [245]. This engagement will likely be a requirement for wave energy projects when they reach full-scale deployment. However, evidence from the survey conducted for this study (see Section 8.3) suggests that public awareness of wave energy in Ireland remains very limited. A central difficulty is the absence of a dominant technological design, leaving many members of the public uncertain about what such devices look like or how they operate, and how they will interact with the ocean and ocean life.

This low level of awareness poses risks for social acceptance. Before large-scale demonstration projects are deployed, targeted education and outreach campaigns are essential to familiarise communities with the technology and its potential impacts. This may pose challenges in the case of wave energy, as deployment is at sea, and not related to private ownership; however, solutions are being rolled out in other countries for offshore wind farms (examples are given in subsection 4.7.3). Ideally, such initiatives provide mechanisms for some local community ownership or participation, thereby ensuring that residents share in the benefits of development.

Ireland's experience with community involvement in renewable energy is limited. However, the Templederry Community Wind Farm in Tipperary saw the construction of two 2.3 MW wind turbines, led and owned by a community cooperative [246]. Despite the project having faced planning and resource challenges, the wind farm was ultimately successful and illustrates the potential of community-led schemes. Without proactive efforts to build awareness and foster local ownership, wave energy risks replicating past conflicts in renewable energy siting rather than building the societal acceptance required for long-term success.

4.7.3 Comparison

The Danish wind experience highlights the importance and benefits of embedding community ownership and bottom-up experimentation at an early stage of technological development. Cooperative structures secured social acceptance and promoted innovation through trial-and-error incremental improvements. In contrast, the Irish wave energy sector is emerging in a context of low public awareness, the absence of a dominant design, and limited collaboration with civil society. Ireland's renewable support schemes, including ORESS [247], provide for community benefit funds but do not ensure local equity participation. The absence of local ownership limits the development of the social legitimacy that characterised Danish wind energy.

Denmark's approach to the development of wind energy enabled communities to become direct beneficiaries, while Ireland's approach to renewable energy technology deployment, where social acceptance is addressed only after projects are already designed, risks missing opportunities for knowledge exchange, bottom-up innovation, and overall societal acceptance. A defining feature of the Danish model was the formal requirement that residents be offered ownership shares in wind energy projects, embedding financial participation within the regulatory framework. This model showed that wind energy was not merely a national imperative but a community enterprise, adding social legitimacy [248]. This support has persisted, with 60% of Danes reportedly supportive of wind energy schemes, despite significant public debate and the fact that one in five onshore projects are abandoned due to public opposition [249]

Cooperative ownership schemes do not have to be limited to deployment on privately owned land. Indeed, current Danish legislation mandates that local community groups are offered up to 10% equity in offshore wind energy projects [250]. Germany also has a strong cooperative offshore wind energy ownership culture "Bürgerwind", where some offshore wind projects offer shares in large offshore wind farms to regional energy cooperatives (although often for a modest 5-10% equity) [251]. Hollandse Kust Zuid also offers limited options for local financial participation in wind farms, often through green bonds or cooperative investment funds rather than full ownership [252].

Ireland's wave energy policy could benefit from incorporating cooperative or shared-ownership schemes at an early stage of development, as a means of promoting community trust and societal acceptance. As Danish, Dutch, and German wind farm examples demonstrate, these policy mechanisms can strengthen both innovation and societal support in communities.

Table 4.1: Irish wave energy policy compared to Danish wind energy development

Enabling factor	...in Ireland	Description
Pioneers	**No**	There have been wave energy pioneers, but currently there is fluctuating support and little industry, academic, and government cohesion
Socio-political context	**Yes**	but with a reactive, compliance-based approach to meeting targets
Research & Development	**No**	lack of specific targets, facilities, and designated research hub
Certification & standards	**No**	the certification available for wave energy is immature and voluntary
Incremental development & community engagement	**Yes**	but not until projects reach deployment phase which may be too late

4.8 Conclusion

Benchmarking Irish wave energy against Danish wind energy during its development phase provides areas of focus for the development of pragmatic policy recommendations to support the growth of the wave energy sector in Ireland. There are limitations to the comparison, mostly related to technological and siting differences, so that any lessons learnt must be adapted with caution rather than directly transplanted.

Denmark can boast a number of pioneers in technology innovation and political will, including successive supportive governments. Irish wave energy lacks a wave energy champion who can rally civil society, academia, government, and industry stakeholders to support the growth of an indigenous wave energy sector.

The Danish socio-political context saw Denmark very vulnerable to oil market fluctuations (as Ireland is with oil and gas). The measures that were taken were done so with conviction and commitment that lasted until the targets were achieved, and had a transformative effect. In contrast, although the 2030 EU Green Deal targets loom large over Irish policymakers, the consequent policy changes in Ireland are very recent and are not yet fully operational. The Irish government's reactions to EU climate-related mandates have been reactive and compliance-based, and lack full commitment.

The Risø test centre provided a hub for innovation, standardisation, and industrial scaling and, as such, was fundamental to the early successes of wind energy technology development and exploitation in Denmark. Ireland performs well in wave energy research and has some leading industrial operators, but the sector lacks facilities, policy targets, and a specific research hub.

Certification and standardisation were implemented in the early years of the development phase of wind energy technology in Denmark, becoming mandatory for all wind turbine developers, and were incentivised through substantial capital grants. In contrast, a global rather than Ireland-specific challenge is that certification for wave energy devices is voluntary, immature, and has not been embraced globally. This weakens investor confidence and slows knowledge transfer.

Danish wind evolved from community and cooperative projects, which secured societal acceptance and promoted incremental innovation that persists today. In Ireland, ORESS requires community involvement, but not until the technology reaches full-scale deployment. This lack of community involvement may hamper social acceptance and lead to the risk of community challenges to the technology.

For Ireland to grow a sustainable wave energy sector, there must be collaboration from the bottom up and a push from the top down. There must be collaboration between civil society, research and industry, supported by the government. These elements were fundamental to the success of Danish wind, where commercial viability was the driving force behind early policies coupled with a strong, lasting commitment to specific, self-imposed, national renewable energy targets.

In summary, Ireland's wave energy sector requires commitment and proactivity rather than reactive compliance-driven mechanisms and policies. Figure 4.1 shows that R&D in the area is thriving, and demonstrates leadership in the area, whereas Table 4.1 shows that policies have not recognised the potential to support the research towards commercialisation. A champion is required who can bridge academia, industry, and government and ensure that all stakeholders benefit and buy into projects by creating a culture that supports the development of wave energy technologies.

Part 1 of this thesis has compared the evolution of Danish wind energy from a policy perspective from 1973-1990, to the current status of Irish wave energy. This comparison has highlighted areas of focus that can lead to pragmatic policy interventions that could support a sustainable and world-leading Irish wave energy sector.

Part II

5

Funding challenges and evaluation criteria for Irish wave energy innovation

Contents

5.1 Introduction

Part 1 of this thesis compares Danish wind energy policy from 1973-1990, its development phase, to the current status of wave energy technology development in Ireland. By comparing these two technology pathways, it is possible to uncover the enabling factors that can contribute to the development of a robust indigenous wave energy sector. Part 2 of this thesis now investigates several of these factors in detail to provide recommendations for pragmatic policy interventions that can contribute to this goal.

Specifically, Chapter 5 investigates public funding for wave energy technology projects, the metrics used to assess wave energy project success, the need for funding at particular development phases, and public funding availability.

Chapter 1 highlights the potential for wave energy to contribute to an optimal renewable energy system [32], helping to service the global need for renewable energy. Indeed, as mentioned in Chapter 1, Ireland has a significant, globally recognised technical expertise in both fundamental and applied research, and wave energy device prototype development and testing [253]. The advantages of wave power are significant, and include an energy density 10 times that of solar or wind at a latitude of 15°N [34]. This is in addition to high availability, complementarity with other renewable resources, and predictability [35]. Additionally, and of paramount importance, international, European, and national carbon emission targets provide additional motivation to policymakers to support technology development [1].

Chapter 3 describes how, despite the availability of a significant wave resource [165], and decades of dedicated academic and industrial endeavour, wave energy technology has not yet reached commercial viability, lagging behind other more mature technologies, with few projects going beyond the development mid-point (TRL4-6) [254]. Adequate public financial support, targeted at the appropriate stage of development, is essential. Directing funds to projects with the highest potential increases the chances of creating a sustainable indigenous industry in Ireland. Many wave energy technology projects have foundered at TRL 4-6 due to an exponential increase in costs at that stage, where the technology is not yet supported by market demand. This phenomenon is known as the Valley of Death (VoD) [255], a period in commercial development characterised by an increase in costs coupled with a decrease in available funding, where 'technology push' does not meet 'market pull'. This is particularly true in the case of wave energy, where costs can increase dramatically from TRL 4 [256], when developers begin to move towards large-scale prototypes and demonstration devices that need to be deployed and functioning at sea for sustained periods.

Public funding is crucial in order to ensure that wave energy technology reaches commercial maturity, and fiscally prudent public funding bodies would endeavour to ensure that funding is granted to the wave energy projects that are most likely to reach commercial viability. To this end, public funding bodies should make use of an assessment metric that includes a performance measurement element.

To allocate funding more effectively, and avoid the pitfalls of the VoD, funding bodies typically rely on assessment metrics such as TRL and LCoE. This chapter analyses metrics frequently used in wave energy technology research and development that influence funding decisions. These metrics include the TRL scale adapted for wave energy from the aerospace industry [257], and measurements of LCoE [172]. Weber has developed the TPL, [130], which is complementary to TRL and includes a performance metric. Additionally, a stage-gated approach to funding is sometimes used to assist public funding bodies in making informed decisions in some jurisdictions [258] which is inherently performance-based, and the International Energy Agency (IEA), has recently developed a framework that recognises that performance and stage-gating across a standardised framework are necessary elements in assessing the maturity and viability of wave energy technologies [259].

In addition to an analysis of metrics used to measure the development of wave energy technology, this chapter discusses the VoD in relation to the maturity development timeline of wave energy technology. The study analyses funding awards for wave energy projects in Ireland, Spain and the Basque Country, with data drawn from the main public funding bodies, and compared with EU funding and private investment, to determine where funding has been allocated in recent years.

Following the Introduction, Section 5.2 analyses TRL and LCoE in terms of their use as assessment metrics by public funding bodies. Section 5.3 looks at Weber's TPL framework, the IAE-OES Framework, and the stage-gating approach used by WES. Section 5.4 discusses the VoD, as it pertains to wave energy technology development, while Section 5.5 investigates complementary de-risking policy initiatives. Section 5.6 focuses on funding that has been awarded to wave energy projects in Ireland and the type of national funding available in Spain and the Basque Country as case studies. Section 5.7 focuses on stakeholders' perspectives in relation to what they believe the most effective interventions from national bodies would be to assist the progress of the commercialisation of wave energy technology, while Section 5.8 provides discussion and conclusions.

5.2 Metrics used to assess wave energy projects and funding allocations

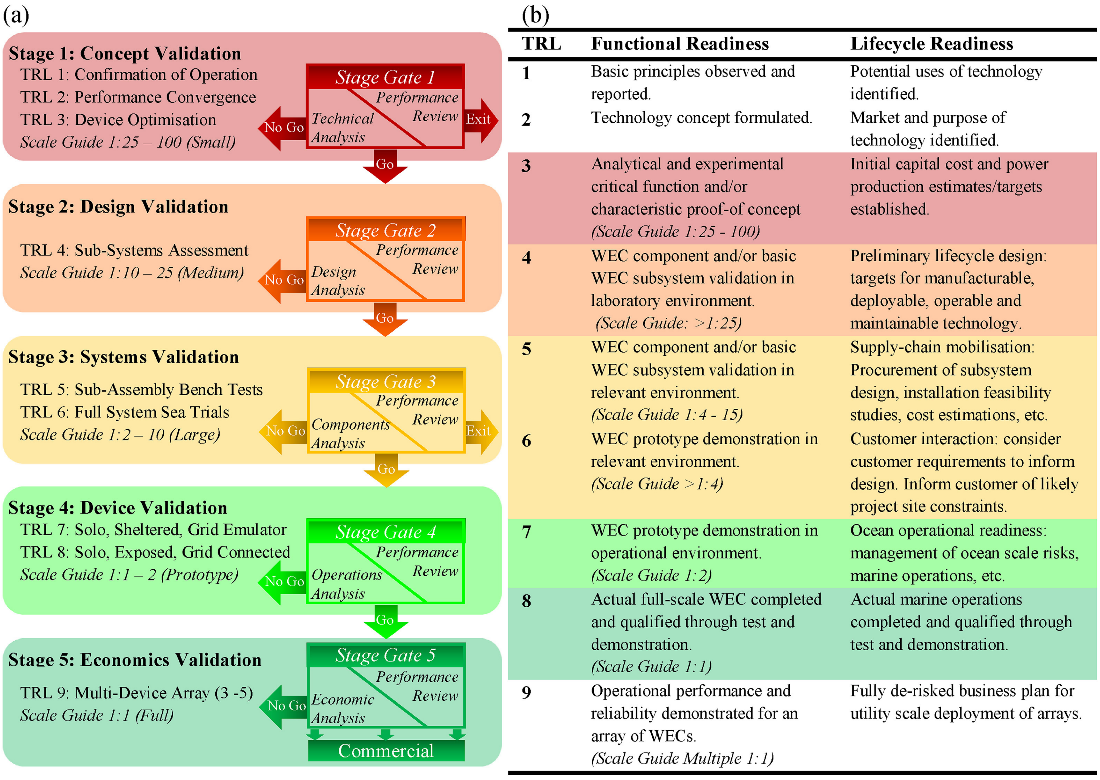
5.2.1 Technology Readiness Levels

TRL is a metric commonly used by researchers and public funding bodies to assess and express the readiness of individual wave energy technology projects. TRL is also used by policymakers to express targets. For example, the 2023 EU Horizon framework programme's theme "Next Generation of Renewable Energy Technologies" requires applicants to "validate its concept to TRL 3 or TRL 4" [260]. Similarly, China's trajectory for marine renewable energy up to 2030 is described in terms of TRL. In China's Phase I (to 2020), the objective was to raise TRLs; in Phase II (up to 2025), apply technologies for harnessing ocean energy in remote islands; in Phase III (up to 2030), commercialise the technology to TRL 9.

TRL is internationally recognised as a benchmarking tool for tracking the advancement of emerging technologies, and TRL is often used as a method to measure the risk of introducing new technologies into existing systems [261]. The International Structured Development Plan, developed by the IEA-OES group, incorporates TRLs, setting out the requirements for a WEC concept to reach commercialisation [262]. The ESB [263] and Vattenfall [264] adapted this 5-stage model to take account of both functional and lifecycle readiness, where technical aspects are recognised. This adaptation of TRL to wave energy systems looks at whether the technology is manufacturable, operable, and subject to external risks. In general, TRL models describe the progress of a wave energy converter from concept design to design validation to systems validation to device validation to economic validation.

Bertram cautions that TRL assessment is partially flawed due to "the lack of an all-encompassing taxonomy" as a WEC will not perform the same way in different locations, and since different designs can perform differently at the same location. Imperial College London (ICL) provided a structured 5-point test programme to develop buoyant-type WECs in 2013, with the objective being to mitigate technical and fiscal risk. ICL found that costs greatly increase during Phase 4 and that public (financial) support is essential through all phases, with little private sector funding available from phases 1-3. Funding gaps are discussed in Section 5.4.

Sandia National Labs also developed a wave energy development roadmap [265]. The roadmap assumes the target to be the deployment of a WEC array and is related to TRL. Sandia's roadmap incorporates modelling and experimental expectations at corresponding TRLs. Sandia contend that early-stage developers can use the TRL roadmap to guide their understanding of the development process, and investors



TRL	Functional Readiness	Lifecycle Readiness
1	Basic principles observed and reported.	Potential uses of technology identified.
2	Technology concept formulated.	Market and purpose of technology identified.
3	Analytical and experimental critical function and/or characteristic proof-of concept *(Scale Guide 1:25 - 100)*	Initial capital cost and power production estimates/targets established.
4	WEC component and/or basic WEC subsystem validation in laboratory environment. *(Scale Guide: >1:25)*	Preliminary lifecycle design: targets for manufacturable, deployable, operable and maintainable technology.
5	WEC component and/or basic WEC subsystem validation in relevant environment. *(Scale Guide 1:4 - 15)*	Supply-chain mobilisation: Procurement of subsystem design, installation feasibility studies, cost estimations, etc.
6	WEC prototype demonstration in relevant environment. *(Scale Guide >1:4)*	Customer interaction: consider customer requirements to inform design. Inform customer of likely project site constraints.
7	WEC prototype demonstration in operational environment. *(Scale Guide 1:2)*	Ocean operational readiness: management of ocean scale risks, marine operations, etc.
8	Actual full-scale WEC completed and qualified through test and demonstration. *(Scale Guide 1:1)*	Actual marine operations completed and qualified through test and demonstration.
9	Operational performance and reliability demonstrated for an array of WECs. *(Scale Guide Multiple 1:1)*	Fully de-risked business plan for utility scale deployment of arrays.

Figure 5.1: TRL scales for WECs: International Structured Development Plan, Bertram, (2020) [262].

can use the roadmap to evaluate the TRL level at which a device currently resides, leading to an accurate assessment of progression.

Although TRL is attractive because it communicates maturity simply, its weaknesses, particularly its lack of consideration of device performance, make it insufficient as a sole funding metric to assess the potential of wave energy projects.

TRL functions as a simple means of communicating a level of commercial maturity to funding bodies and investors. The use of a simple system, that is well-known, has clear benefits. The TRL scale is useful to offset risk concerns for potential investors and funding bodies. However, different iterations focus mainly on experimentation and prototype demonstration, but do not adequately address technical issues such as control strategies, telemetry design, and large-scale testing, or non-fiscal supports, such as the availability (or not) of testing facilities, making TRL incomplete as an assessment tool. TRL does not take into account the diverse design of WECs, and that different WECs operate differently in different sea-states. The TRL scale does not take into account the fact that commercial readiness does not necessarily equate to performance readiness.

5.2.2 LCoE

The European Commission (EC) has set ambitious targets for ocean energy, and by 2025, the LCoE for wave energy has a target of €200/MWh, against the current estimated level of €600/MWh [254].

Capital and operational costs of wave energy do not, in general, compare favourably with more mature technologies such as onshore wind energy. It is only through significant cost-reduction that wave energy developers will be able to push ocean energy technologies into the electricity market. See Table 5.1.

Table 5.1: Global weighted-average LCoE by renewable energy technology

Technology	LCoE (USD/kWh)	LCoE (USD/MWh)
Onshore Wind	0.033–0.035	33–35
Solar PV (Utility-scale)	0.043–0.049	43–49
Offshore Wind	0.075–0.081	75–81
Hydropower	0.047–0.057	47–57
Geothermal	0.067–0.073	67–73
Bioenergy	0.061–0.074	61–74
Wave Energy (current estimates)	0.20	200

Adapted from International Renewable Energy Agency (IRENA), Renewable Power Generation Costs, (2025) [266].

However, it is important to remember that cost reduction is heavily influenced by economies of scale and knowledge transfer, which are gained through examination of a proliferation of devices at demonstration scale in open water for an extended period of time.

An accurate LCoE assessment is crucial for the determination of the cost-reduction needs of ocean energy technology. It is clear that estimates of operational costs in particular vary, and that capital costs, particularly costs of finance, are likely to decrease dramatically when a proliferation of demonstration WEC devices have been tested in at-sea conditions for a significant amount of time. This is investigated further in Section 3.5.

LCoE, as a metric for emerging technologies, is insufficient and potentially inaccurate and cannot reliably be used to inform investment or funding decisions in isolation.

5.3 Technology Performance Level

5.3.1 An overview of TPL

While TRL measures the commercial readiness of the technology, TPL measures how well a technology performs, or the economic ability of the technology throughout its development [267]. In particular, TPL assesses the cost drivers such as environmental, social and legal acceptability, power absorption and conversion, system availability, capital expenditure and lifecycle operational expenditure. TPL is designed to be complementary to TRL and was designed for a continental-scale utility system. TPL, when combined with TRL, can:

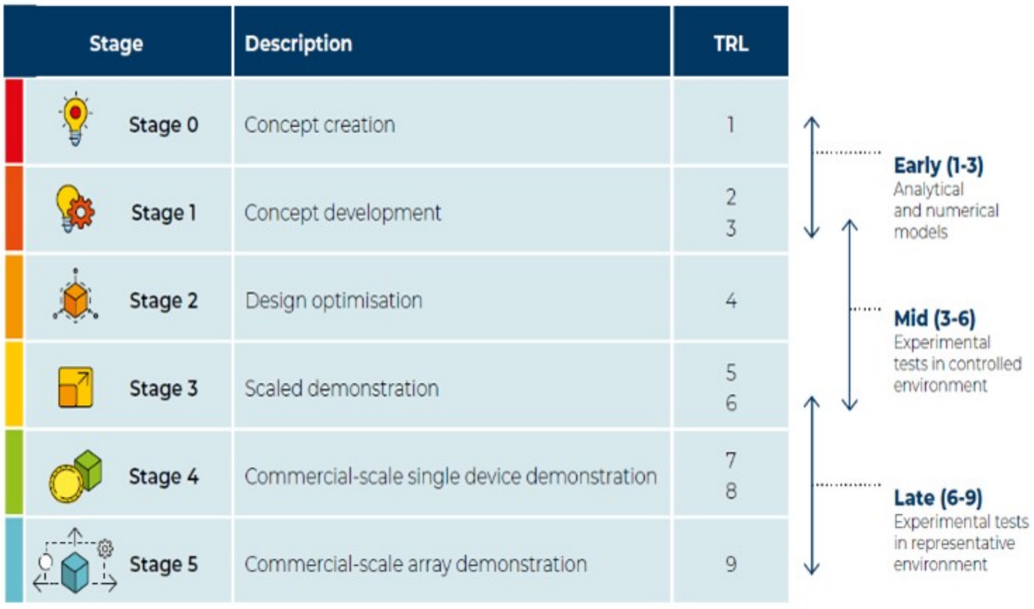
- Identify requirements for successful entry and survival in the electricity market, and
- Assess the value of the technology when making investment/funding decisions.

TPL measures the economic performance of the technology. TPL 7, for example, describes a device that is economically viable, under favourable market conditions, and that is competitive with other renewable energy forms. TPL can be used by technology developers for iterative design feedback, and to identify areas of improvement and find fatal flaws early; by investors to conduct due diligence; by reviewers to assess wave energy technology project proposals, and make funding decisions; and by researchers to formulate R&D strategies. There are limitations in that data derived from full-scale WEC deployment is scarce, but taking device performance into account, when assessing the maturity of a WEC project, can ultimately save time and money.

5.3.2 A new framework incorporating performance

IEA-OES Task 12 has developed a framework to support funding decisions for wave energy technology projects [259]. The framework was developed by the IEA, Ocean Energy Systems (OES) and Technology Collaboration Programme in consultation with the EC, WES, the United States Department of Energy, and Tecnalia (Spain). The objectives of Task 12 include:

- Building consensus on technology evaluation,
- guiding activities, throughout the technology development process, and
- supporting decision-making associated with technology evaluation and funding allocation.



Stage	Description	TRL
Stage 0	Concept creation	1
Stage 1	Concept development	2 3
Stage 2	Design optimisation	4
Stage 3	Scaled demonstration	5 6
Stage 4	Commercial-scale single device demonstration	7 8
Stage 5	Commercial-scale array demonstration	9

Early (1-3)
Analytical and numerical models

Mid (3-6)
Experimental tests in controlled environment

Late (6-9)
Experimental tests in representative environment

Figure 5.2: IAE-OES task 12 framework [259].

The framework encompasses a 6-stage development process (See Figure 5.2) that references both qualitative and quantitative evaluation measures, which include measures of performance.

The IAE-OES task 12 framework has taken an iterative approach, with each version adding more detail to the framework for technology evaluation, and guidance of engineering activity. Should this framework, which encompasses the benefits of TPL, proliferate within public funding bodies as an assessment tool, the framework could help to ensure that the projects most likely to become commercially and economically viable are those that receive financial support at the most critical stages.

5.4 Wave energy and the Valley of Death

The VoD is used to describe the phenomenon in which a technology, while ready to be deployed from a technological standpoint, is not yet prepared to compete with similar or alternative technologies, and full commercialisation has yet to be achieved. It is important to note that the VoD is separate from the technology itself, and reflects the risk that companies run out of investment cash before reaching positive cash flow. Therefore, companies must adopt specific long-term funding models, including private investment, loans, and grants, to successfully cross the VoD and reach market viability [268]. There is an additional, vital requirement for policy mechanisms that support emerging renewable energy technologies to bridge the VoD [268].

Weller *et al* [269] suggest that in order to overcome the VoD, new technologies need to be de-risked, in terms of component reliability and durability, i.e. when the technology push support runs out, but there is no market pull, public support needs to step in until technology performance has been validated.

The cause of the gap, according to Weller [269], is that, from an investor's perspective, economic viability is limited because projects require large-scale capital and a long-term commitment. Commercial viability must be proven before investing, and the absence of this proof, coupled with what is considered by some as a highly regulated and conservative ocean energy marketplace, is off-putting. There is also concern among investors related to the longevity of public policies, with companies leaning toward proven, more mature technologies.

The European Commission (EC) recognise that there are significant challenges in raising funding for emerging offshore renewable energy technologies that need to complete technical development, become fully operational, and prove to the market the efficient operational performance of the innovation through demonstration in open water. The Commission suggested that the scale of finance required for such projects has yet to be recognised by policymakers [270], [271].

Indeed, IRENA [272] reported that solar PV and wind energy, as some of the more mature technologies, absorbed most of the total investment in renewable energy, leaving other sectors relatively underfunded. The EC Joint Research Centre mentions the lack of (affordable) risk insurance and guarantee services, for renewable projects relying on new technologies, as a barrier to commercialisation [273].

Examining subsidies distributed by the EU in 2022, it is clear that the largest share of subsidies for renewable energy technologies is allocated to mature renewable energy technologies: 40% to solar PV, 23% to onshore wind, and 22% to bioenergy, leaving very little committed to emerging technologies such as wave energy.

Hoppmann *et al* [274] suggest that investors in new technologies are likely to require strong policy interventions in order to create favourable conditions for innovation. Therefore, there is a need for public financial support for innovation and 'market pull' policies. Recent Irish policies and policy instruments, related to renewable energy in general, and offshore renewable energy in particular, such as RESS [275] and MAPA [276], favour mature technologies in an effort to fill the need for a seamless route to market.

Several wave energy companies have fallen into the VoD (See 3.6), and this threat remains within the sector. Ford *et al* suggest that governments are willing to fund early research and development stages, as this is driven by social welfare criteria rather than private welfare gains [277]. After the early phases, governments may consider the technology 'too commercial' to continue funding, while the private sector is not

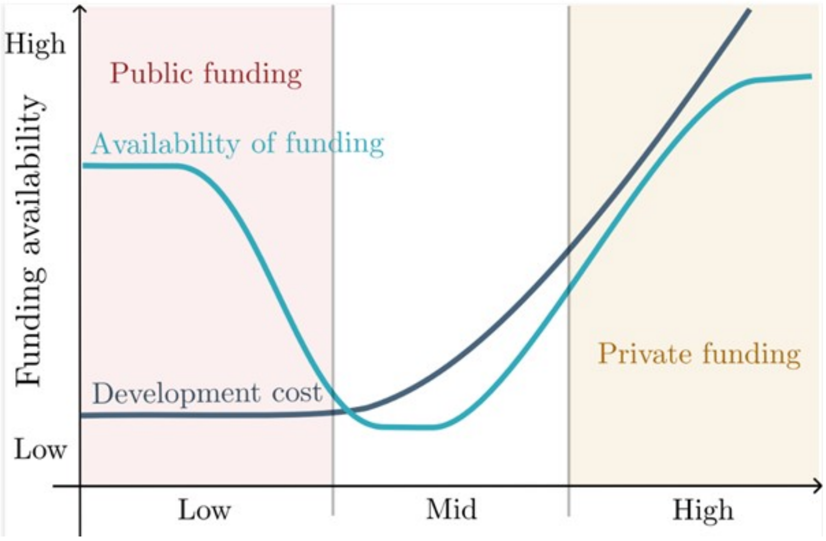


Figure 5.3: VoD: Funding availability and wave energy project costs. Funding availability data taken from funded project awards reported by SEAI, SFI, MI, and EU between 2012 and 2022. See also Figure 5.4.

yet willing to invest enough capital and time to allow for commercialisation. This funding gap has been identified as one of the main obstacles to new RE generation capacity in the EU [278].

5.5 Complementary de-risking policy interventions

Since investors often perceive emerging technologies as high-risk, due to uncertain and new policy frameworks, long payback periods, and limited track records, financial mechanisms that lower risk exposure can significantly improve investability. Public interventions, beyond direct funding, have been recommended to help de-risk investments, with the objective of attracting investors and stimulating market pull. Insurance can "encourage productive investments and innovation through the mitigation of the consequences of financial misfortune" [279]. Beyond traditional insurance cover for construction and operational risks, novel insurance mechanisms can be designed for climate-related risks (e.g., resource variability), political risks, or even technology underperformance, directly addressing barriers specific to emerging renewable energy technologies. The Multilateral Investment Guarantee Agency (MIGA), part of the World Bank Group, provides political risk insurance and credit enhancement specifically tailored to renewable energy investments in emerging markets. Risks that are covered include breach of contract, expropriation, currency fluctuations, transfer restrictions, and war or civil disturbance. In countries where policy reversals or political instability deter private investment in renewable energy projects, MIGA's guarantees de-risk the environment, allowing international developers and financiers to enter. MIGA supported the Lake Turkana Wind Power Project in Kenya (310 MW, Africa's largest wind farm) by providing guarantees to investors and lenders against political and breach-of-contract risks [280]. This was crucial to reduce financial risk in a high-risk environment.

Public guarantees, such as loan guarantees or partial risk guarantees, can reduce exposure to the risk of default, making financing terms more favourable for renewable energy developers. Credit enhancement mechanisms can also help emerging technologies achieve investment-grade ratings. The Desert Sunlight Solar Project (USA) was given a $1.46 billion loan guarantee by the U.S. Department of Energy (DOE) for its 550 MW PV project solar photovoltaic project in Riverside County, California [281].

By stabilising future revenue, long-term contracts, backed by public institutions, can provide predictability and reduce market price volatility exposure. This revenue certainty is especially valuable for emerging technologies such as wave energy that are not yet cost-competitive with more mature technologies. Examples of this are the Contracts for Difference (CfDs) scheme in the UK and RESS in the Republic of Ireland.

The CfD scheme is the UK government's main mechanism for supporting low-carbon electricity generation [282]. CfDs incentivise investment in renewable energy by providing developers of projects, with high upfront costs and long lifetimes, with direct protection from volatile wholesale prices, and they protect consumers from paying increased support costs when electricity prices are high. Renewable generators located in Great Britain can apply for a CfD by submitting a 'sealed bid' to an auction. Successful developers of renewable projects enter into a contract with the Low Carbon Contracts Company, a government-owned company. Developers are paid a flat indexed rate for the electricity they produce over a 15-year period; the difference between the 'strike price' (a price for electricity reflecting the cost of investing in a particular low-carbon technology) and the 'reference price' (a measure of the average market price for electricity in the market).

Publicly backed green investment banks can encourage private investment by absorbing initial losses, co-investing, or leveraging finance. This approach is particularly effective in scaling early-stage projects that struggle to attract commercial funding. Australia's Clean Energy Finance Corporation (CEFC), a Government-backed green bank, established in 2012, uses public capital to co-invest with private financiers in renewable energy projects, energy efficiency, and low-carbon technologies. By mid-2023, CEFC had committed A$12.7 billion to clean energy projects, mobilising over A$33 billion in private capital [283].

The pre-commercial public procurement model introduced by WES, and subsequently adopted by the EuropeWave programme, applies a stage-gated process in which only the highest-ranked wave energy projects progress at each funding stage. EuropeWave has allocated around €22.5 million of national, regional and EU funding, beginning with seven projects in Phase 1, of which five advanced to Phase 2. Three finalists, CETO Wave Energy Ireland Ltd. (a wholly owned subsidiary of Carnegie Clean Energy) and their ACHIEVE project, IDOM's MARMOK Atlantic, and Mocean Energy's Blue Horizon 250, are now progressing to full-scale demonstration in the final phase [258]. This framework helps de-risk the market, making it more attractive to private investors. To be effective, market pull must be complemented by public funding and other risk-reduction measures. Emerging technologies, such as wave energy, developed through research and development, cannot, before deployment at scale for an extended period, compete with more mature technologies already diffused through the energy system. Bridging the funding gap, between the publicly funded technology push and the commercialisation-driven market pull phase, is therefore essential if wave energy projects are to avoid the VoD.

5.6 Funding trends for Irish wave energy projects with international comparisons

5.6.1 Irish funding for wave energy projects

The VoD is characterised by a company's inability to overcome significant increases in costs at a particular stage of development. An analysis of funding received by wave energy projects in Ireland, over a 10-year period, when contrasted with the national funding programmes of Spain and the Basque Country, clearly shows a gap in funding that corresponds to a significant increase in costs as projects move to scaled-up prototypes and demonstration devices, potentially increasing the risk of wave energy technology developers falling into the VoD.

In order to evaluate the profile of wave energy project funding in Ireland, this chapter looks at research and development funding received from three of the main Irish public funding bodies of wave energy projects: Science Foundation Ireland (now Research Ireland), SEAI, and the Marine Institute within a 10 year period, and attempt to discern whether each project would be placed at low (1-3), mid (4-6) or high (7-9) TRLs. These findings are compared to EU funding, where Ireland was the coordinating (lead) partner, and also to venture capital investment received over the period.

Figure 5.4 shows that most funding was focused on the lower TRLs (1-3), and that private investors are not inclined to invest until a project is close to commercial readiness.

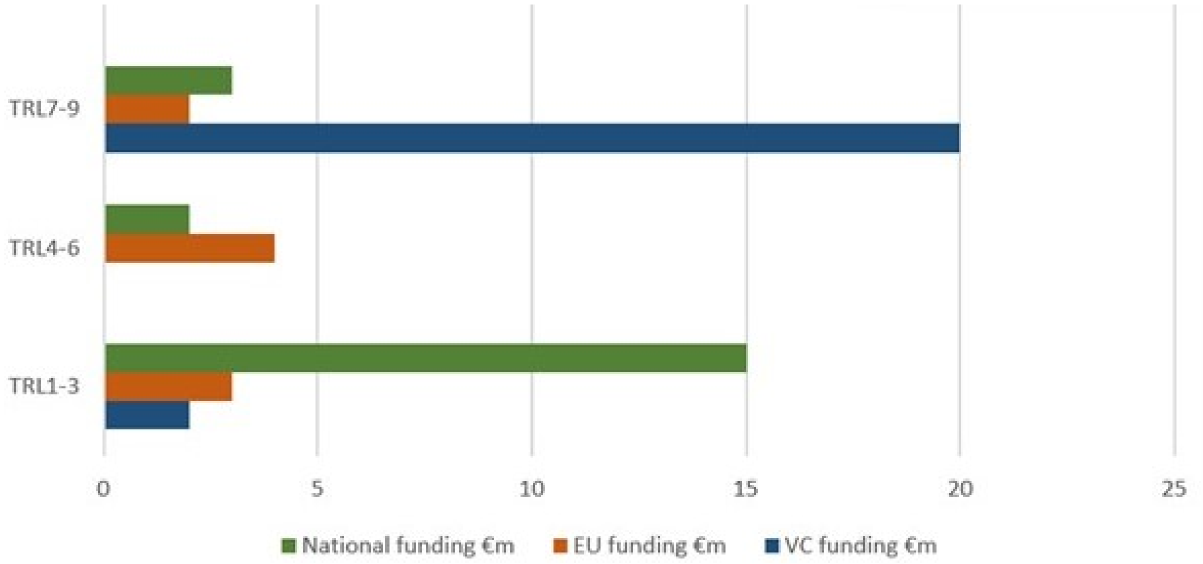


Figure 5.4: Irish funding (2012-2022).

5.6.2 A comparison: Spanish funding for wave energy projects

Spain's approach differs from Ireland's, in that there seems to be a proliferation of financial supports in conjunction with non-financial, or not only financial, supports. Eco Wave Power has benefited from the Rising UP in Spain program [284]. This program provides legal advice for developing wave energy projects and introductions to partners and potential customers. Carnegie Clean Energy has secured a significant grant from the Basque Energy Agency for developing wave energy devices in Spain. Renmarinas Demos grants, worth €240 million in total, were established to encourage test platforms and demonstrations of new prototypes [285]. This initiative would seem to be pushing wave energy projects along the mid-TRLs (4-6). However, the entire financial contribution derives from the EU and, although a national imperative, is not nationally funded.

The Generación de Conocimiento [286] is a potential source of funding for wave energy developers in Spain. Similar to ELKARTEK in the Basque Country [287], this initiative funds new PhD students and Postdoctoral researchers on individual or collaborative projects with other national research groups. The Colaboración Público-Privada offers companies a loan with 0% interest.

The EU's Horizon Europe [288] and CET Partnership calls [289] are beneficial to wave energy technology developers and have stated mid-TRL targets. However, the competition for funding is steep. Data from May 2023 show that the average success rate for a Horizon Europe application is 15.9%, more than a third higher than the success rate for Horizon 2020 [254].

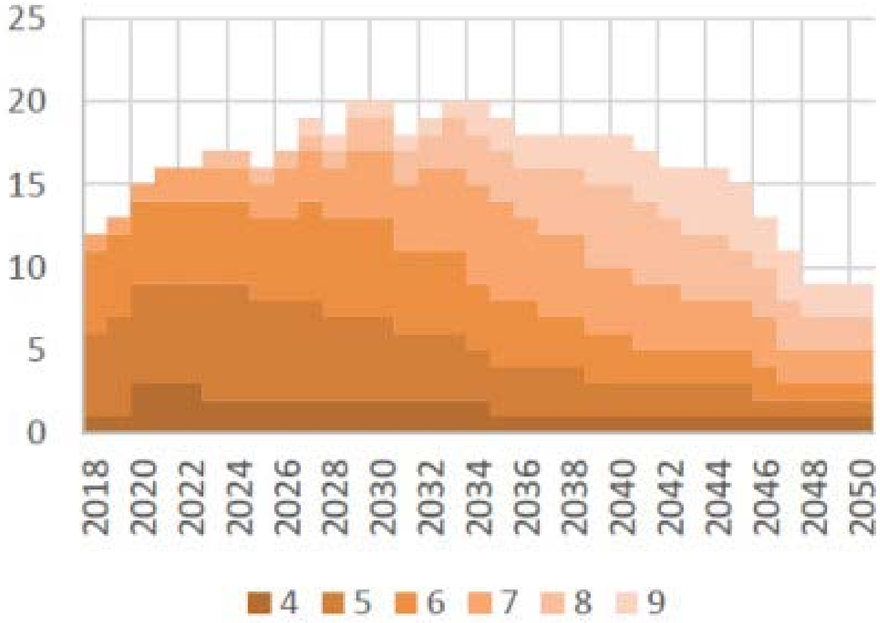


Figure 5.5: Projects by year and TRL, Ocean Energy Europe, (2023) [290].

Ireland's funding model for wave energy remains concentrated at the early TRLs (1–3), with Irish funding agencies treating wave energy largely as a research activity. This leaves a structural funding gap at TRLs 4–6, where costs rise sharply, but private investment is not forthcoming. By contrast, Spain and the Basque Country deploy a broader mix of supports that explicitly target the mid-TRLs (4-6), including large-scale demonstration grants (e.g. €240 million Renmarinas Demos) and complementary non-financial supports such as legal advice, industry networking, and business development. Importantly, these initiatives combine national, regional, and EU resources, reducing reliance on EU competition alone. This coordinated approach reduces developer risk and helps attract private investment in a way the Irish model does not.

Traditional forms of direct state aid are now more constrained under EU competition rules than in earlier periods of renewable energy development, established under Articles 107–109 TFEU and enforced by the European Commission [291]. This does not prevent public support. Support must comply with state aid regulations while still enabling targeted technological advancement [292]. Stage-gated, competitive public procurement models, such as those implemented by Wave Energy Scotland and the EuropeWave programme, demonstrate how governments can fund high-risk, mid-TRL technologies in a performance-based yet compliant manner. Similarly, examples from Spain and the Basque Country show how instruments, including zero-interest or soft loans, and publicly supported demonstration programmes, can reduce developer risk without distorting competition. EU-level funding programmes also operate through competitive tendering processes analogous to pre-commercial procurement models

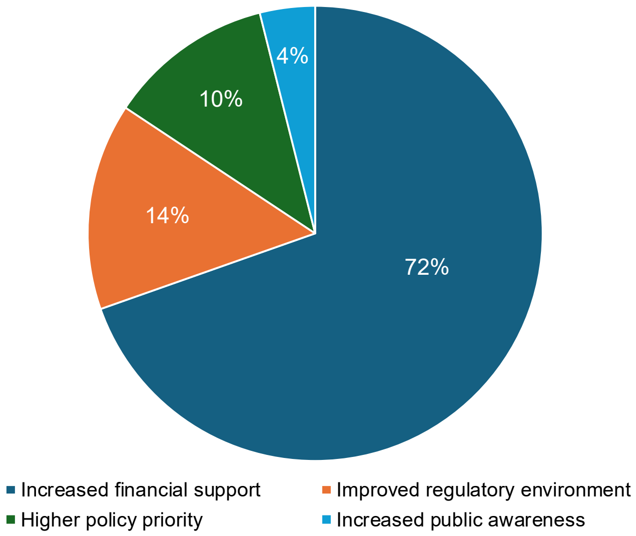


Figure 5.6: Stakeholder perspectives into policy interventions.

[293]. These approaches illustrate that, while the policy instruments have changed, the government retains a critical role in bridging the VoD through performance-based funding structures that de-risk investment and enable emerging technologies such as wave energy to progress toward commercial viability.

Unless national public funding bodies complement the funding initiatives of the EU in addressing the mid-TRL funding gap, so that the technology is brought to a level where technology viability has been proved and de-risked for private investors, wave energy technology development companies run the risk of falling into the VoD.

5.7 Stakeholder perspectives on the availability of funding for wave energy projects in Ireland

Section 7.5 analyses stakeholder perspectives in detail and finds that and 72% of 83 wave enrgy stakeholder respondents felt that there should be increased financial support for wave energy projects, when asked what the Irish government should do or do more of. 14% believed that there should be an improved consenting regime, 10% felt that wave energy should be a higher priority to policy makers, and 4% felt that increasing public awareness would most help wave energy technology to advance (Figure 5.6). The vast majority of the survey responses focused on improving financial supports, with 20% of the respondents suggesting that there is a need for increased funding, 44% suggesting a need for increased but more focused funding, 20% wanted to see financial measures with the specific objective of attracting private investors, such as CPO or feed-in tariff schemes specific to the wave energy industry, or policy measures that would improve financial supports for links between industry and academia.

The importance of public funding was emphasised during interviews with sector leaders. During an interview in November 2023, Tony Lewis, Chief Technical Officer of Ocean Energy Ltd., went as far as to say that "without public funding, wave energy will not go ahead". He also expressed the need for policy makers to make wave energy a higher priority: "when offshore wind has been fully exploited, then wave might have a shot", and to de-risk potential investments, Tony Lewis agreed with some of the survey respondents that "A guarantee, or insurance scheme, is a possibility for wave energy". Anders Køhler, CEO of Floating Power Plant A/S, a company that is developing a hybrid wind/wave device, stated that private investors see wave energy as "extremely high risk". Combining it with another modality, he believes, will prove the technology and assuage concerns of potential investors. Antonio Saramento, WaveEc Offshore Renewables President, agrees with this view, stating that "Hybrid arrays may increase effectiveness, thus improving operational costs." Patrick Møller, CEO of CorPower, on the other hand, believes that three or four developers need to have full-scale devices at sea for an extended period. This, he feels, along with a guaranteed price for emerging technologies, such as feed-in tariffs, and a more efficient consenting process, will satisfy private investors' risk concerns.

Wave energy technology stakeholders believe there should be more focused public funding and that policy supports are essential in bringing wave energy to commercial viability.

5.8 Discussion and conclusions

Funding remains the critical determinant of whether Ireland can establish a viable wave energy industry. Chapter 5 shows that, while Irish public agencies have provided consistent support for early-stage research, the bulk of national investment has been concentrated at the lower TRLs (1–3). This leaves a gap at the mid-TRLs (4–6), precisely where projects face the steepest cost escalations, and where private investment is least forthcoming. International examples from Spain and the Basque Country demonstrate the importance of coordinated national and EU initiatives that explicitly target the mid-TRLs, through demonstration-scale support and complementary non-financial measures.

Existing evaluation metrics also present challenges. TRL and LCoE are widely used and easily understood, but their limitations are significant. TRL does not account for techno-economic performance or market viability, while LCoE is highly uncertain at early development stages, compounded by a lack of data and a lack of a dominant

WEC design. Performance-inclusive frameworks, such as Weber's TPL [267], and the IEA-OES Task 12 model [259], offer more holistic approaches by integrating technical, economic, and performance factors, particularly when combined with stage-gating mechanisms that progressively de-risk investments.

Stakeholder evidence confirms that industry, academia, and policymakers largely agree on the need for stronger and more focused public funding, particularly at the mid-TRLs. Highlighting that funding alone is insufficient, complementary policies such as guarantees, insurance schemes, and predictable market incentives (e.g., feed-in tariffs tailored to emerging marine renewables) are necessary to attract private investors. These findings suggest the need for a framework based on the following factors for policy intervention in Ireland:

- **The adoption of performance-inclusive funding metrics**

  Moving beyond TRL and LCoE as project success and technology maturity metrics. Integrating frameworks that incorporate performance such as TPL and IEA-OES Task 12 into national funding criteria ensures that both technical readiness and performance potential are considered when allocating resources, and that funding is granted to those projects most likely to succeed.

- **Mid-TRL funding to bridge the VoD**

  Establishing dedicated national programmes to support projects at TRLs 4–6, using stage-gated mechanisms similar to those adopted by WES and EuropeWave. This would ensure that only the most promising projects progress, maximising the impact of public expenditure.

- **De-risk private investment through complementary policy tools**

  Introducing insurance schemes, public guarantees, or market-pull incentives (e.g., technology-specific feed-in tariffs) to lower investor risk perception. Such measures would provide a bridge from public 'technology push' to private 'market pull'.

Ireland could implement these recommendations, while complying with State Aid rules, by establishing a dedicated, competitive mid-TRL wave energy funding programme administered by SEAI, Research Ireland, and the Marine Institute, using a stage-gated, performance-based model similar to Wave Energy Scotland. Funding should be allocated through grants and loans designed to support projects at TRLs 4–6, with progression dependent on technical and economic performance. Complementary measures, such as state-backed loan guarantees within existing renewable energy schemes, would further reduce investor risk. By delivering support through competitive, performance-based calls, Ireland could remain compliant with EU state aid rules while providing a clear pathway for wave energy technologies to progress from prototype to commercial deployment.

Without interventions of this type, Ireland risks continuing the cycle of early-stage research support, without progressing technologies to commercial demonstration and deployment, or innovation without imperative. By adopting performance-based evaluation criteria, strategically focusing funding where it is most needed, and integrating financing with risk-reduction policies, Ireland can provide the wave energy sector with a realistic opportunity to bridge the VoD and emerge as a global leader in wave energy technology development and exploitation.

6

Intellectual property protection strategies within Irish wave energy innovation

Contents

6.1 Introduction

This chapter examines the role of intellectual property protection (IPP) in the development of wave energy technologies. IPP plays a role in fostering innovation and protecting technology from competitor exploitation in jurisdictions covered. One of the rationales for patent registration as an IPP strategy is that patents stimulate technological development and promote competition by creating a financial motivation for invention, in exchange for the disclosure of the invention to the public [294]. Organisations can use patents as an asset to attract investment, or as a means to dissuade competitors from activity in the same area. From a government's perspective, patents are important in helping to understand the source of new technologies, and can help to fund their development [295]. Patent statistics provide indicators to measure and examine trends in innovation, commercialisation, and knowledge transfer across international markets [272], as governments require a detailed analysis of technological innovation trends to design appropriate policies. This is particularly pertinent in the area of renewable energy [296].

One of the main functions of the patent system is the controlled dissemination of technical information. Patent information is a valuable source of technical, commercial, and legal knowledge that can be used for scientific purposes, and as a basis to stimulate the adaptation and improvement of the technology described in patent documents [294]. Patents also provide insights into changes in technology trends and identify new actors in the area through patent trend analysis [272].

This chapter explores strategies used by wave energy technology developers for the protection of innovations and examines their efficacy while providing information to interested actors and policy advisors on the *status quo* of wave energy technology innovation. The chapter also explores challenges in relation to patent registration, including long development timelines and patent expiration, as well as costs considered prohibitive by some organisations. Attempting to analyse trends by looking at patent behaviour may be difficult due to the lack of a dominant WEC design and the unwillingness of some wave energy developers to patent. As such, this chapter also looks at bibliometric analysis as being a complementary trend indicator, particularly in the instance of emerging renewable energy technologies such as wave energy. Alternative IP strategies, specifically trade secrets and the impact on licensing agreements, are considered. This chapter addresses the following questions:

1. Do patents drive or hinder innovation in wave energy?
2. Are patents a viable metric to gauge wave energy technology developments?
3. Is there an IPP strategy best suited to wave energy technology development?

Following the introduction, Section 6.2 discusses IPP in relation to renewable energy technologies and the challenges facing patent registration for wave energy technology developers, particularly those in Ireland. Section 6.3 provides illustrative accounts of IPP in the wave energy and renewable energy sectors, while Section 6.4 describes alternative IPP strategies. Section 6.5 examines trends in wave energy patenting.

Section 6.6 compares trends in academic publications on wave energy technology with trends in patent registration, while Sections 6.7 and 6.8 provide discussion and conclusions.

6.2 Background and context

Patent registration has been considered a valuable form of IPP for many years; indeed, the first patent, in relation to wave energy, was registered in 1799. A patent translates technology into legal writing in order to protect technological advances. A patent confers the right to exclude others from making, using, selling, or importing the patented invention, in a particular jurisdiction. This 'industrial property' can be assigned, transferred, licensed, or used by its owner [297].

In order for an invention to be held to be patentable, it must have industrial applicability, the invention must not exist in the state of the art, including through the inventor's own publications, and there must be an observable inventive step. Patents give the inventor control over their technology, in that they are legally entitled to object to use of the invention by others. Patents also provide assurance to potential investors.

An early wave energy patent of 1873 (Fig. 6.1) describes improvements made to a floating buoy type WEC. The patent distinguishes between what was known and what the inventor now claims the improvements are. The protection granted only includes the improved elements (in this case, the piston and floating buoy combination). The requirements of industrial applicability, novelty, and an inventive step are satisfied.

In determining whether an invention is patentable, the patent office asks whether the invention solves a technical problem and whether it provides a solution to that problem. Reviewers look at the next closest invention and make an assessment as to whether the change was obvious from the existing art.

John Flaherty, from leading Irish IP Solicitors firm FRKelly, gives some insight into the patenting process. Mr. Flaherty clarifies that the art of patent registration is in the description of the patent. The description cannot be too general or too broad, and what is described in the claim must be comprehensive, but must not include the prior art. When drafting a patent, the closest prior art must be found, and the description must show the novel steps and advantages claimed in the application. A balance must be achieved between showing inventiveness and not publicising details unnecessarily.

The steps for patent registration are similar in many countries. In Ireland they are as follows:

1. **Evaluation:** Patent attorneys assess corporate risks, benefits, and existing art.

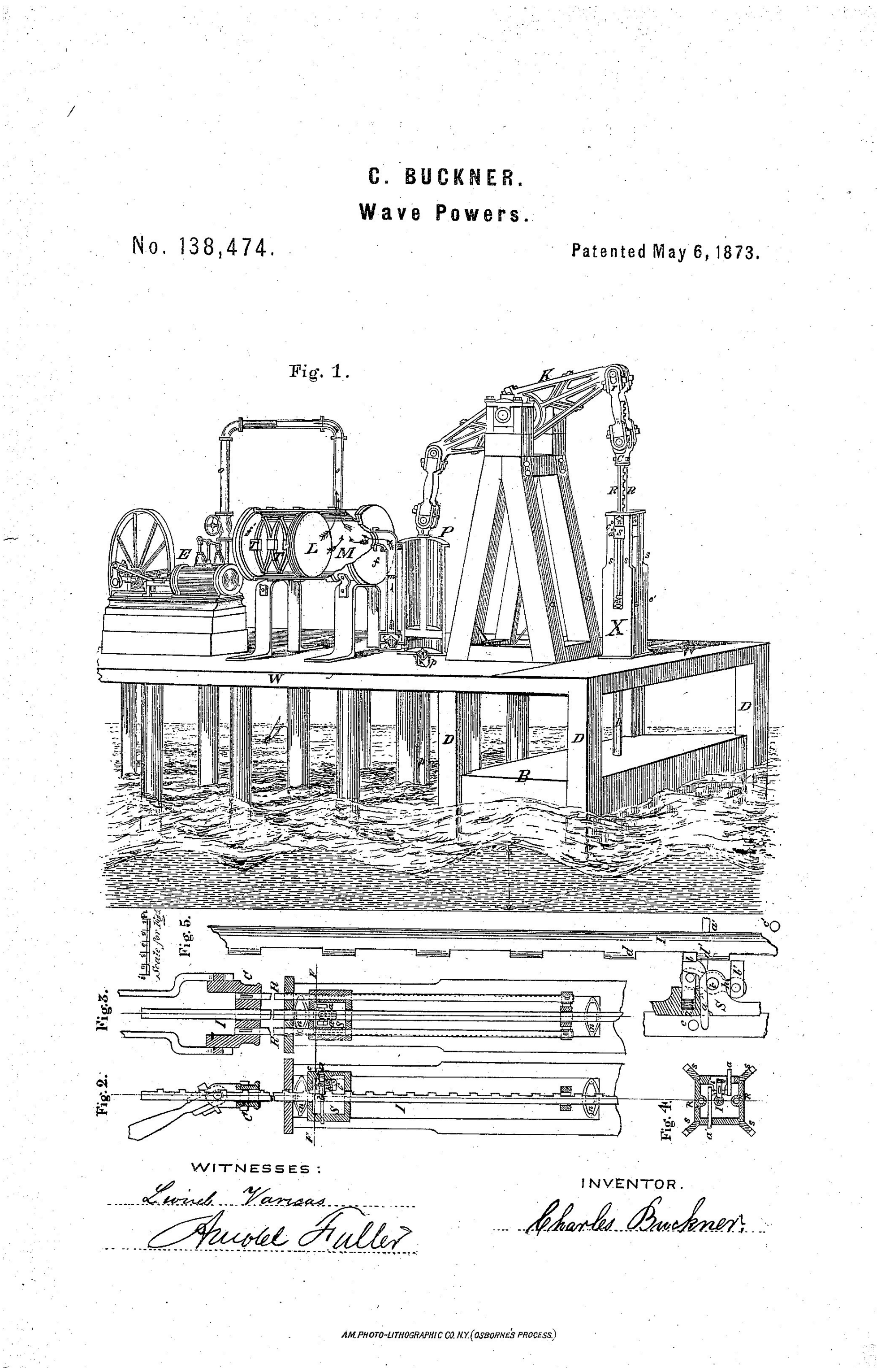


Figure 6.1: Patent US138474A. Buckner, C. Wave Powers (1873) [298].

2. **First filing:** Applications are submitted with specifications, claims, and drawings [299]. From the date of first filing, the applicant is entitled to claim the priority date of that application.

3. **Examination:** The IP Controller reviews compliance, and upon approval, the patent is published and takes effect [300].

. The patenting process takes approximately 22 months.
A number of sanctions are available to plaintiffs whose patent has been found to be infringed. The infringing party can be subject to an injunction, a legal order to stop the offending action. This may include mandatory licensing and/or damages. Alternatively, compensatory monetary remedies may be awarded, based on a calculation of profits or a calculation of potential royalties. Other potential sanctions include delivery-up (handing over all infringing goods), or destruction of infringing goods, a recall order, publication of the decision, and declaration of infringement [299].
Patent data serves as an indicator of innovation due to its long availability, verification by patent examiners, and easy access [301]. The extended data period is valuable for linking trends to policy or legislative changes [302]. However, patents are sometimes filed for defensive reasons, such as maintaining a competitive advantage, or meeting funding agency requirements, rather than to protect innovation. For example, Research Ireland mandates open access publishing, while Enterprise Ireland favours IPP through spin-outs, licencing, and patenting. Inventors may also patent to attract investment or satisfy shareholders, particularly in publicly listed companies.

6.2.1 Limitations of patents

Patents can be costly, and decisions must be made about the countries in which to register patents. The application process can be time-consuming, and legal language can be difficult to understand. The following are some of the challenges faced by those who choose patent registration as an IPP strategy.

- **Lack of case law** There is very little patent infringement case law and, despite relatively similar legislation in different jurisdictions, outcomes in different jurisdictions can differ widely, largely due to local procedural differences [303].

- **Visibility** Patents are publicly available and, as such, it can be preferable to delay the release of the invention until the device is commercially viable, unless the inventor is actively seeking investment.

- **Lack of dominant design** WEC systems generally consist of a hull; a PTO system, by which mechanical energy is converted into (usually) electrical energy; and a control system to safeguard overall operations and maximise energy conversion [304].

In addition to the complexity of wave energy conversion systems, there are a wide variety of designs, and no particular design has reached a TRL that facilitates large-scale commercialisation [305]. There is little consensus on the number of distinct WEC designs, although international bodies such as the International Renewable Energy Agency (IRENA), describes the major device types [304]. The lack of a dominant design makes it challenging to secure innovation through patent applications, as the degree of novelty becomes harder to define [306]. Moreover, multiple competing designs can exert an influence on patenting efforts, complicating proprietary rights, and hindering the commercialisation efforts of new technologies [307]. This level of technological and market uncertainty can contribute to the deceleration of investments in WEC systems development [308]. Therefore, the lack of a standardised design archetype presents significant barriers to both innovation and patenting activity.

- **Cost** The cost of a patent filing has two components: the attorney costs (between €3000 and €10000 for a preliminary application with, for example, the UK Patent Office or the European Patent Office (EPO)). Subsequent progress into the Patent Cooperation Treaty phase costs €5000-€7000 in attorney fees. Nationalisation requires both attorney (in addition to any translation cost required) and official fees, for each jurisdiction.

  To limit spend, organisations may decide to seek protection in countries according to key markets by sales volume, competitor location, manufacturing, or R&D location.

- **Timelines** A further limitation of patent trend analysis is that it does not reveal whether individual patents were essential to technological progress. In the Danish case study (see Chapter 2), innovation has been driven largely by publicly funded programmes and iterative technology development, rather than by IPP. Moreover, the long development timelines typical of wave energy, often more than a decade from concept to deployment, reduce the practical value of the 20-year patent term. This may partly explain the observed decline in patenting.

6.3 An illustrative account

In 2012, The Guardian reported a burglary at Pelamis Wave Power in Scotland, during which several laptops were allegedly stolen shortly after a visit by a Chinese delegation [309]. Two years later, a structurally similar wave energy device, the Hailong (Dragon) 1, emerged in China.

Figure 6.2: Pelamis Wave Energy Converter and Hailong (Dragon) 1. Source: The Guardian newspaper, (2012) [309].

Although observers noted visual and mechanical similarities, such as hinged joints and deployment mechanisms, these do not constitute evidence of IP infringement. The Chinese Embassy denied any copying, stating that the Hailong was independently developed [310]. Pelamis, which ceased operations in 2014, after investments totalling approximately £95 million [191], had not secured patent protection in China, and no legal action was pursued.

This case is included not as verified infringement, but as a journalistic account, cited to illustrate the challenges of international IPP in wave energy, not least due to the lack of case law in the area. The case highlights perceived risks, but should be interpreted critically, given the lack of conclusive technical or legal validation.

In a closely related area, recent patent infringement litigation involving wind turbines for offshore arrays [303] was brought before the US District Court, in which a Boston federal judge, in 2022, banned General Electric (GE) from making and selling its Haliade-X wind turbines in the United States, after a jury found in June of the same year, that the turbines infringed a patent owned by rival Siemens Gamesa Renewable Energy A/S (Siemens). Judge William Young found that Siemens was entitled to the ban because it suffered irreparable harm, including a significant loss of market share to GE, due to the infringement. However, Young allowed GE to continue making and operating the turbine for existing projects off the coasts of Massachusetts and New Jersey with royalty payments to Siemens, allowing GE to 'design around' the patents. A jury had found that Siemens was entitled to royalties of $30,000 per megawatt produced from GE's infringing turbines. The infringement involved patent 8575776, relating to the enhanced performance of the turbine by improving the operation of cooling and maintenance.

An interesting element to this judgment was that Judge Williams permitted the operation of the existing turbines, due to the effect that decommissioning them would have on climate targets and employment in the New Jersey area, should the company be forced to cease trading.

However, when Siemens took the dispute to the United Kingdom High Court, they lost. Judge Richard Meade found that Siemens, which had sued GE claiming that the Haliade-X infringed its European patent related to the use of bearings in rotor hubs for wind turbines, did not have a valid patent. Even if the patent was held to be valid, Meade found that "neither the fully assembled Haliade-X nor its hub" fell within the scope of Siemens' patent [311].

With this level of uncertainty, it is unsurprising that there is scant litigation in the area of renewable energy technology patenting, and this demonstrates that the decision as to whether or not to patent is nuanced and complicated.

6.4 Developing Intellectual Property strategies

A trade secret can often be considered an alternative to patent registration, as an IPP strategy. A trade secret is a piece of information that derives economic value from not generally being known to those outside the organisation, and is the subject of reasonable efforts to maintain its secrecy [312]. Trade secrets do not suffer from complex procedures and long timelines, and are less costly than patents. Trade secrets may be protected in law by the doctrine of inevitable disclosure, i.e. when it is inevitable that an employee would divulge trade secrets, whether deliberately or not, they may be prevented from joining another company in the absence of a non-compete agreement. Therefore, an employer-friendly trade regime may limit innovation [312]. In general, when considering whether to patent or maintain trade secrecy, wave energy technology developers have to assess the trade-off between information disclosure and maintaining a temporary monopoly.

Patents may be preferred over secrecy if there is a higher risk of imitation. If the details revealed in the patent registration reveal nothing more than might be gleaned through careful observation of the invention, there is more incentive to patent. For process innovations, trade secrets are often preferred, as they are generally more difficult to reverse engineer. In the case of wave energy, the WEC hull could be seen to be more easily replicated than the device controller, by way of example.

The complexity of the patenting procedure, as well as the timeline involved, described in Section 6.2, is off-putting for many inventors. The Intellectual Property Action Plan 2020 [313] recognises, and attempts to address this challenge, through a unitary patent system [314]. However, a lack of harmonisation among jurisdictions complicates this endeavour.

The most significant reason that start-ups choose trade secrecy over patenting is cost [315]. Crass [316] finds that, for single innovations, a combination of trade secrecy and patenting provides the highest sales. Patent applications are mainly undertaken by innovators who develop new (physical) goods. In contrast, service and process innovations show low patenting rates [317].

6.5 Patenting trends in wave energy technology development

This section provides an overview of international patenting activity in the ocean energy area from international reports and literature. According to the EU Commission Clean Energy Technology Observatory November 2022 report [318], between 2010 and 2019, 3,561 patent applications involving ocean energy were submitted globally, with 1677 granted, 710 of which were considered high value (in terms of market impact and economic significance). China was responsible for 49% of applications. Inventors from the EU were responsible for 12% of applications, with 73% of submissions made by companies. The EU submitted most high-value inventions (34%). According to the report [318], in terms of international protection, inventions originating from the EU account for 18% of the total international inventions. Around 15% of the EU inventions are protected internationally while, for China, only 1% of inventions are internationally protected.

Trends in patenting, in renewable energies in general, show that the number of high-value inventions is steadily decreasing in the European Union, and increasing in China. Moreover, solar Photovoltaic (PV) and PV thermal hybrid technologies are both increasing at the highest rate, and make up the largest portion of patent filings (Figure 6.3). The rate of patenting in fossil fuels has remained stagnant since 2001 [16]. The dominant activity of solar PV patenting suggests that solar PV technologies are extensively used in the marketplace, while marine energy is shown to be at a prototype deployment, demonstration, or R&D phase, and therefore shows relatively less activity. According to WIPO [294], wave and tidal (combined) make up 3% of patent filings of renewable energy technologies from 2010-2019. In general, WIPO find that patent filings for renewable energies have increased at a rate of 10% per year, starting in 1990. Countries that have policies that support renewable energy development, such as feed-in tariffs, generally have more patent filings. Germany, for example, is a market leader in the fields of solar and wind power and has enshrined policy support in their 2000 Renewable Energy Sources Act.

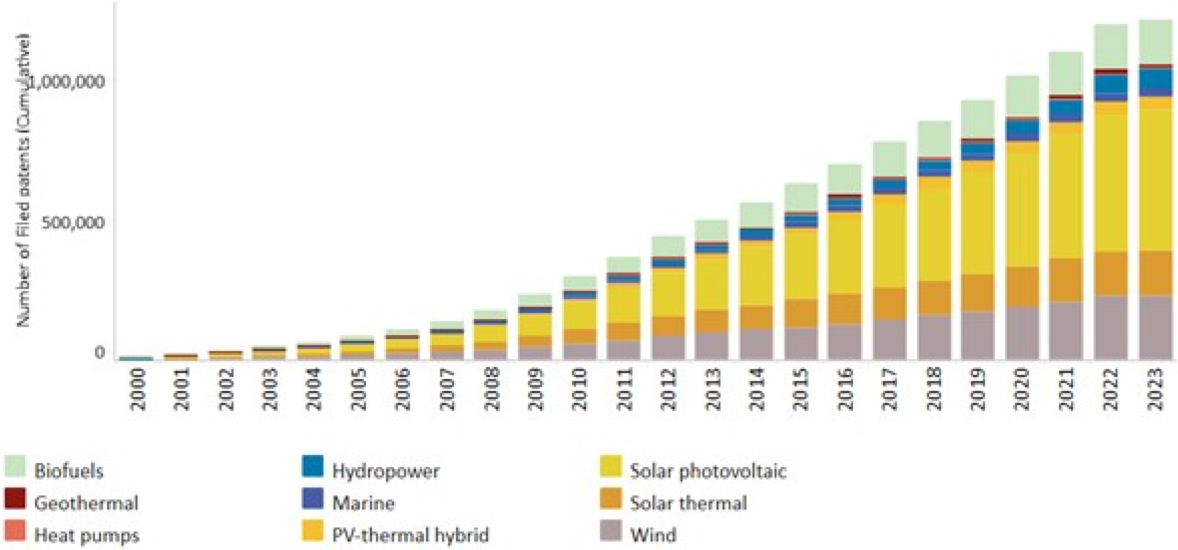


Figure 6.3: Evolution of Renewable Energy Patents (2000-2023) - Data derived from the EPO PATSTAT 2023 Autumn edition on Climate Change Mitigation Technologies (Y02) classification [319].

In order to delve more deeply into the relationship that wave energy technology has with patenting, as a form of IPP, and as a potential indicator of innovation, this study uses the EPO worldwide patent statistical (PATSTAT) database [320] to construct patent counts using the International Patent Classification (IPC) System [321], a hierarchy of codes at different levels. The PATSTAT platform corresponds to the EPO register of European patents. The patent publication period from 2008-2020 is considered. Data mining and curation through keywords is conducted, the keywords being derived from a comprehensive literature review of technological developments (this approach was used, for example, in an International Energy Agency (IEA) report [322].

Figure 6.4 shows that WEC patenting activity saw a sharp increase between 2010 and 2012. These dates are based on the publication date of the patent, which usually comes 1-2 years after first filing. This would put commercial interest in WECs as coincidental with a period of governmental and international organisational interest, in the integration of renewable energy, at a time where nearly all international events, such as G8 summits and UN General Assemblies, placed climate change mitigation at the top of their respective agendas [323]. Pazhouhan [324] looks at wave and tidal publication dates over a longer period, and found that global patenting rates increased from 2000 onward.

Table 6.1 shows patent registration trends, observed from the PATSTAT database, that were published between 2008 and 2020. There is significant variation in the type of inventions being patented in this area. Most patents relate to the device itself,

Table 6.1: Number of patents published according to PATSTAT database (2008-2020), where Pats. publ'd denotes patents published, pats. denotes patents and uni. denotes university

Country	Pats. publ'd	Withdrawn	Company	Uni.	Individual
Australia	13	7	11	0	2
Austria	1	0	0	0	1
Azerbaijan	1	1	0	0	1
Belgium	1	0	1	0	1
Brazil	2	2	1	0	1
Canada	1	0	0	1	0
Chile	3	2	0	0	3
China	9	0	3	0	6
Denmark	17	5	15	0	2
Egpyt	1	0	0	0	1
Finland	26	3	23	1	2
France	22	6	13	0	9
Germany	33	13	23	0	10
India	2	0	0	0	2
Ireland	9	3	8	0	1
Israel	3	2	1	0	2
Italy	18	2	13	1	4
Japan	14	3	6	5	3
Korea	17	9	11	3	3
Mexico	1	1	0	0	1
Moldova	1	0	0	0	1
Netherlands	7	2	5	0	2
Norway	20	7	13	1	6
Poland	1	0	0	0	1
Russia	3	0	0	0	3
Saudi Arabia	1	0	1	0	0
Serbia	1	0	0	0	1
Singapore	1	0	1	0	0
South Africa	1	1	1	0	0
Spain	9	5	4	0	5
Sweden	33	7	33	0	0
Switzerland	3	0	3	0	0
Taiwan	5	2	0	1	4
Tunisia	1	1	0	0	1
Turkey	3	0	3	0	0
UK	58	23	44	1	13
US	45	12	35	1	9
Total	**387**	**119**	**272**	**9**	**94**

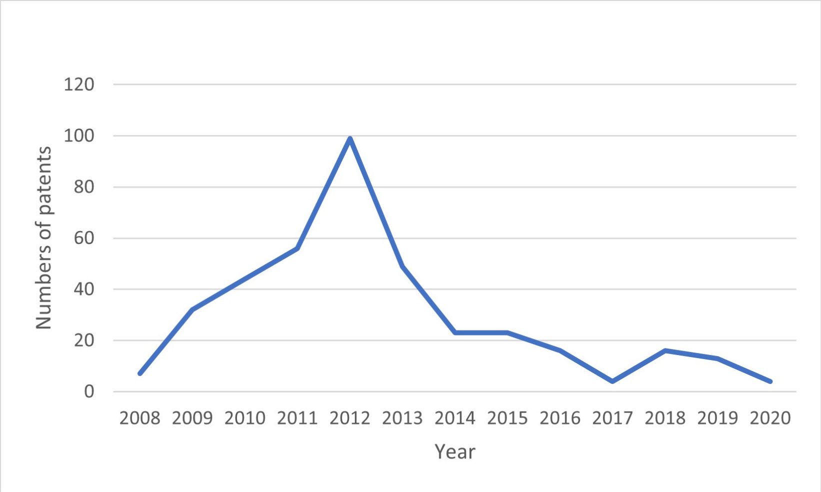


Figure 6.4: WEC global patenting trends (2008-2020) Source; PATSTAT database 2025 [320]

arguably the simplest element to replicate through observation. 3% of patents were for PTO devices, and 1.5% were for controllers, while 46% of patents published were for methodologies or models, innovations that focus on conceptual, computational, or procedural aspects of wave or tidal energy systems rather than on physical hardware. This chapter also analyses the number of patents that were withdrawn. This makes up a significant minority of patents (31%). A withdrawal indicates that the application has been withdrawn at the applicant's request. This occurs when the applicant decides not to pursue the patent application and withdraws it from the examination process. There are several reasons why an applicant may withdraw a patent application:

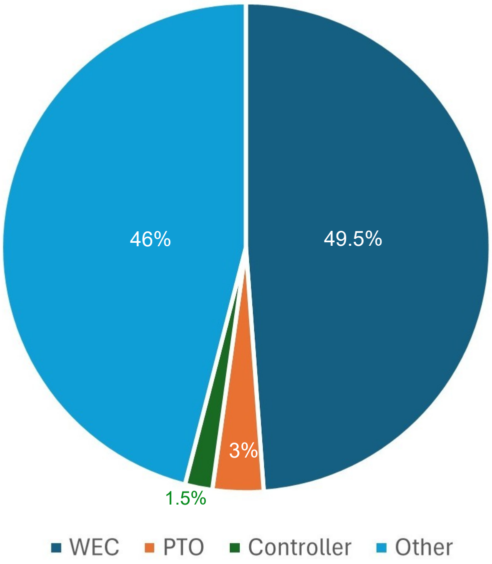


Figure 6.5: WEC patents by type (2008-2020).

- **Change in strategy:** The applicant may change plans or business strategy and determine that it no longer makes sense to continue the patent application.
- **Lack of likelihood of success:** The applicant may discover, during the examination process, that the chances of success in obtaining a patent are low. In such cases, the applicant may decide to withdraw the application to save time and resources.
- **Cost Reasons:** Proceeding with a patent application may involve significant costs, especially if additional examination requirements or third-party oppositions arise. The applicant may then decide to withdraw the application for financial reasons.

The advantage of withdrawing a patent application is that secrecy may be maintained. It is noteworthy to consider the originators of the patent filings (Table 6.1). This is expressed in Figure 6.6, and shows that companies are, by far, most likely to register patents over individuals or academics. This may indicate the greater need for companies to hold a patent portfolio, in order to attract private investment; however, this does not indicate actual numbers of companies as a percentage of applicants, as companies are much more likely to hold a portfolio of patents than individuals or universities. In Germany, of the 33 WEC patents registered during the period 2008-2020, 14 were registered by Robert Bosch GmbH (although this company has more recently turned their attention to hydrogen electrolysis). Another example is Russia, where 3 patents were registered, all by the same individual, who also registered the only patent in the area of wave energy technology in Serbia.

While reduced patent filings can be interpreted as evidence of a lack of commercial potential, this conclusion is not necessarily justified. Patent counts are not a perfect indicator of innovation or market viability, particularly in energy sectors characterised by long development timelines and heavy reliance on publicly funded R&D programmes. In both Danish wind and wave energy contexts, technological progress has often been driven by publicly supported R&D, collaborative testing environments, and incremental technological improvements rather than by patent portfolios. Moreover, wave energy firms operating at mid-technology readiness levels frequently prioritise survivability, performance validation, and cost reduction over formal IPP, and many rely on trade secrecy or engineering know-how instead of an extensive patent portfolio. The financial concerns of start-ups in this sector may also lead to reductions in patenting due to cost constraints. Therefore, declining patent activity should not be interpreted as definitive evidence that investors are questioning commercial potential; rather, it reflects the innovation pathway of an emerging offshore renewable energy technology.

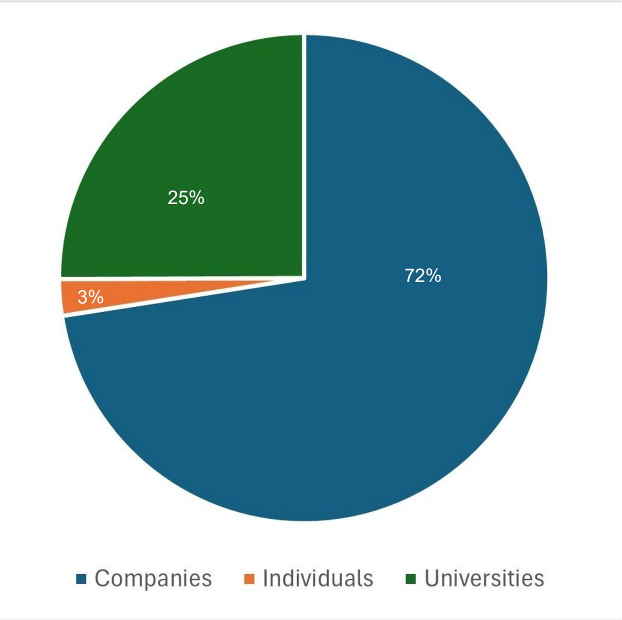


Figure 6.6: Wave energy patents by organisation type (2008-2020).

6.6 Bibliometric trends in wave energy technology development

A bibliometric analysis of academic publications may provide an alternative or complementary indicator of activity within the wave energy sector. Bibliometric analyses can provide an overview of the state of the art in a field, highlight gaps in the sector, and may provide an opportunity to derive novel ideas and to position contributions within a field. A bibliometric review can provide evidence and mapping of scientific knowledge in a field [325]. Bibliometric analysis can also summarise the evolution and current state of research and emerging research fronts, and can give a global perspective [324]. Eligibility criteria for contributions to high-ranking academic journals have some commonalities with patents. In order to be academically publishable, the concept must be novel, and for technical academic journals, it must show some applicability; and funding agencies such as the EU require open access publication. Indeed, some journal articles are required to go further than the requirement of patent examinations, in that the concept must be validated by robust, peer-reviewed simulations and/or modelling., and where (ideally comparative) evidence of performance is needed. Prior publication in academic journals nullifies eligibility to patent, unless the patent application is made before the academic paper is made public.

Scopus [166] is a database of peer-reviewed literature that includes scientific journals, books, and conference proceedings. Scopus was selected as a data source for the bibliometric analysis in this chapter, due to its coverage, citation data from a wide range of sources, a wide range of metrics to evaluate research impact, and a significant amount of open-access content.

The analysis uses keyword search terms with Boolean operators (combinations) from 2008 to 2020 to facilitate comparison with the patent registration data in this study.

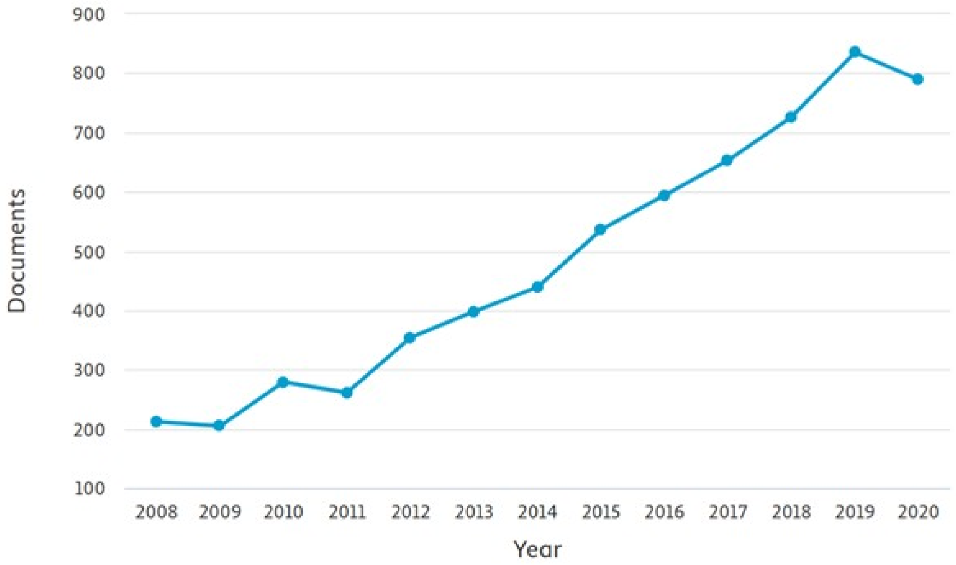


Figure 6.7: Number of wave energy converter papers per year (2008-2020), Source: Scopus database, 2025 [166].

Figure 6.7 shows the number of wave energy converter articles per year from 2008-2020. Though the trend for wave energy technology patent registration has declined, the number of wave energy converter published articles has increased, as shown in Figure 6.8. This is indicative of the stage of development of the technology; the technology shows significant innovation, but has not reached commercial maturity.

Figure 6.9 ranks wave energy publication authors by the numbers of articles written over the period 2008-2020. The authors listed are all based at academic institutions. The relative proliferation of papers by individuals is not replicated in patent registrations, possibly due to cost, given that most of the cost for academic publications in the area is generally covered by funding agencies, by 'transformational' agreements between universities and publishing companies, or due to the commercial organisation choosing a different form of IPP, such as trade secrecy.

The highest numbers of patent registrations during the period are from the UK, the US, Sweden, Germany, and Finland. China is the top performer in terms of academic publications in the area during the period, but ranks 13th (on the PATSTAT database) in terms of patents registered. Spain and Ireland perform significantly better, in terms of the number of academic papers produced, than in the number of patents registered.

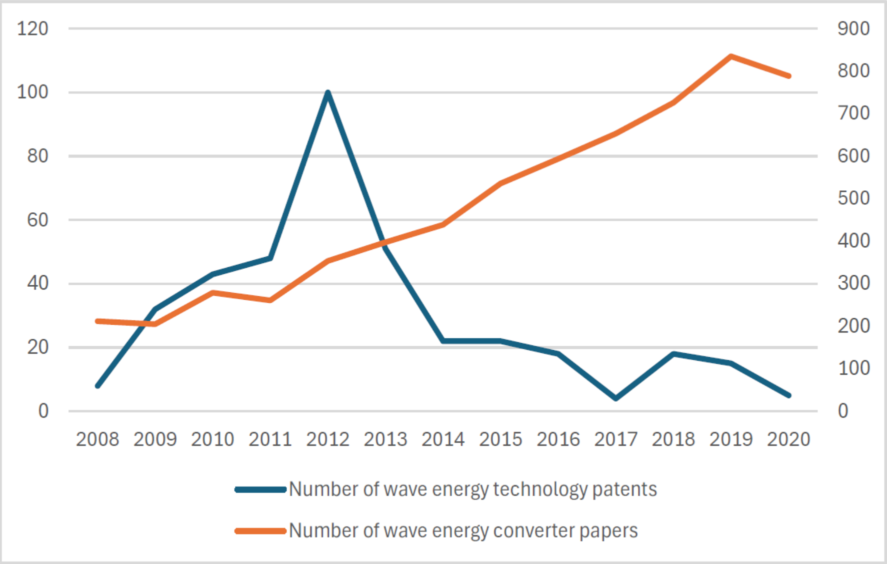


Figure 6.8: Trend comparison between WEC articles published and wave energy technology patents registered with EPO (2008-2020).

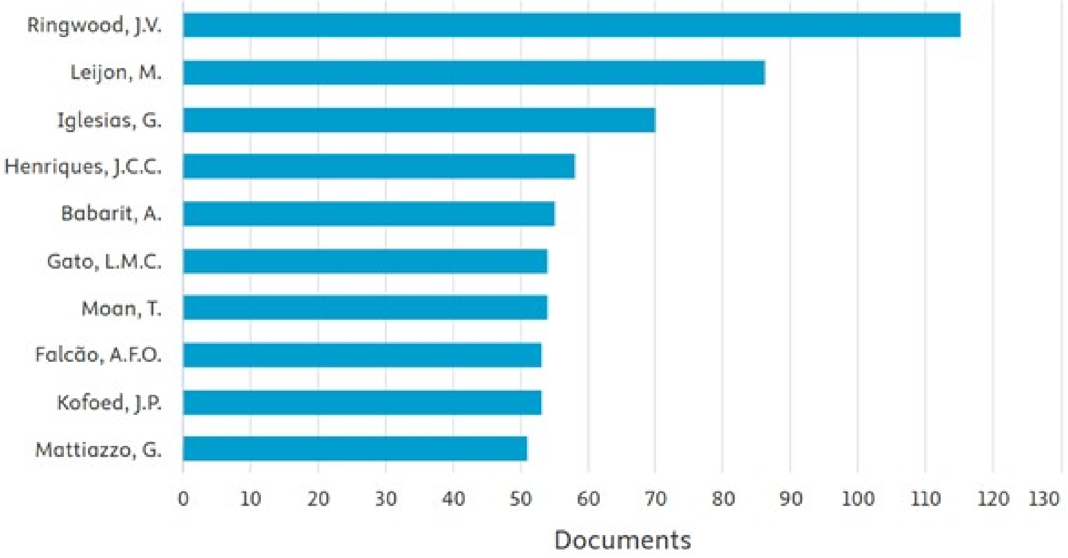


Figure 6.9: Top wave energy publications by author (2008-2020) Source: Scopus [166].

Figure 6.11 takes the most prolific WEC-related publishing countries (see Figure 6.10) and normalises the number of WEC publications by population, where

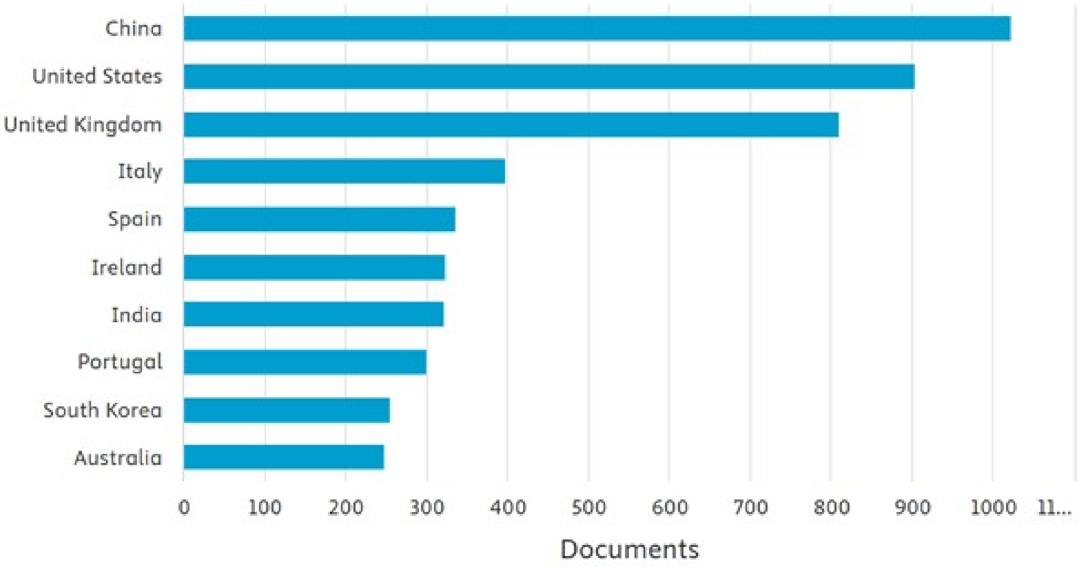


Figure 6.10: Wave energy converter publications: Top performing countries (2008-2020) Source: Scopus [166].

$$WEC\ publications\ by\ population = \frac{Total\ WEC\ publications\ by\ country}{Population\ of\ country\ (in\ millions)} \tag{6.1}$$

This reveals that Ireland outperforms all other countries in terms of WEC-related research output. This finding highlights that, although patent registration data may not immediately indicate Ireland's leadership in this area, publication data clearly demonstrate its strong performance.

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In general, observing bibliometric data, alongside patent registration trends, gives a more complete picture of technology development and shows where innovation is derived from. Analysing academic literature can provide information on non-patented inventions, as well as highlighting new areas of interest, and may be useful when considering where hubs of innovation activity can be found.

6.7 Discussion

6.7.1 Patentability and innovation in wave energy

The Danish wind energy case (see Chapter 2) provides context when assessing whether patents provide evidence technology development. Analysis of the Danish wind industry shows that its early development was driven less by strong patent activity and more by publicly funded R&D programmes, and incremental, trial and error-based

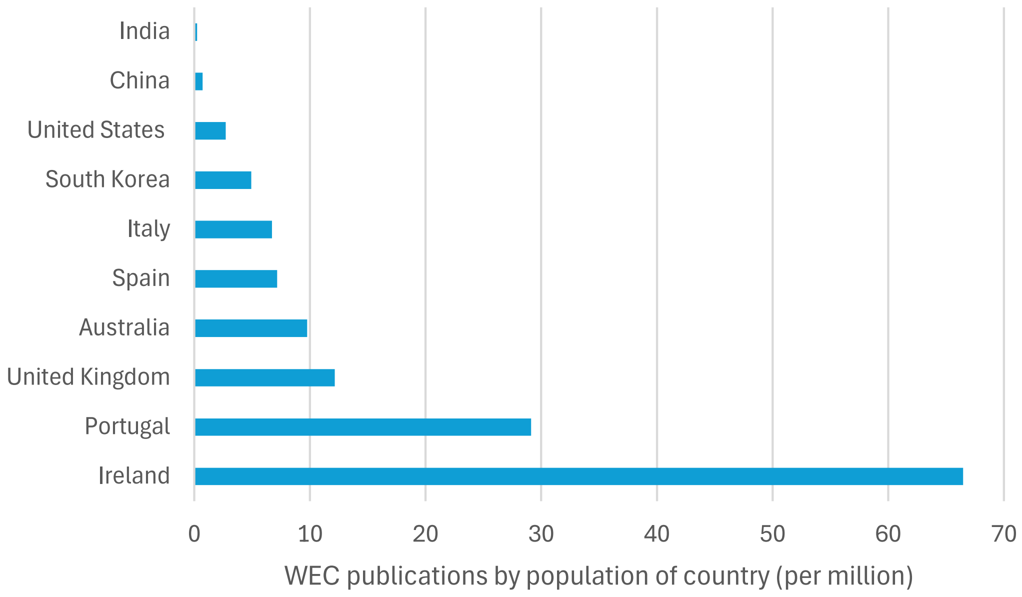

Figure 6.11: WEC publications per capita by country, where top performing country data is taken from Scopus [166], and country population (in millions in 2020) is taken from the World Bank's World Development Indicators [326]

learning among manufacturers and turbine owners [211]. Firms such as Vestas later accumulated substantial patent holdings, but these largely followed significant industrial growth and increased exports. Patenting activity, therefore, appears to be related to commercial maturity rather than technology development. This interpretation aligns with broader innovation theory. Teece's framework [327] on profiting from innovation emphasises that in sectors characterised by complex systems and bottom-up learning, complementary assets such as manufacturing capabilities and supply chains, may be more decisive than formal intellectual property protection. The Danish experience suggests that patent statistics alone cannot determine whether patents were essential to technological progress. Patents are instead one component of a broader innovation system, where the importance of IPP may increase as technologies approach commercial scale and international competition grows.

Additionally, patent applications predominantly arise from innovations that develop new physical goods, whereas service and process innovations exhibit significantly lower patenting rates [317]. Collaboration, by inventors with universities, has been shown to increase the likelihood of patenting, as academic institutions often engage in formalised IPP to secure funding and investment supported by a commercialisation office. However, not all patents are indicative of genuine innovation or technological progress; in some cases, patents are filed strategically to block competitors rather than to commercialise new inventions. Generally, funding in the area of wave energy technology is seen to be relatively accessible at early TRLs (1 to 3) [49], but falls away at TRL 4 and over, when costs increase exponentially, and the need for IPP becomes more important as innovators seek external investor funding.

Patent filing is a critical decision for technology developers, often driven by a balance between cost, time, and the stage of technological development, as well as the requirement to maintain secrecy. This decision is further complicated by competing pressures, such as the 'publish or perish' culture in academia, versus the need for IPP to attract investors in the commercial world. The uncertainty surrounding future market potential can also influence whether developers choose to patent their innovations or rely on alternative IPP strategies such as trade secrets.

6.7.2 The role of appropriability regimes and complementary assets

Klevorick *et al.* [328] highlight that disruptive technologies can gain market traction when appropriability regimes (the regimes that govern an innovator's ability to capture the profits from an innovation) do not adequately meet the company's needs, and firms instead secure complementary assets such as manufacturing, distribution, and supply chain capabilities. This approach has been taken by wave energy technology company CorPower Ocean [122], arguably to secure against the risk of appropriability regime failure, as they have developed mobile assembly units at port facilities, reducing reliance on fixed manufacturing sites, enabling more agile deployment, and providing a local community dividend. Having available test facilities, a streamlined consenting system, and suitable infrastructure are essential for development in the area [329], and will contribute to an improved appropriability regime.

One of the challenges, in assessing patenting trends in wave energy, is the lack of information on non-patented inventions. Bibliometric analyses can partially address this gap by identifying scientific publications that disclose innovations outside the patenting system. Additionally, the ability to reverse engineer a component or system influences whether developers choose to patent an innovation or not. Klevorick [328] suggests that digitalisation has shifted the locus of innovation, with key system functionality increasingly dictated by software and control systems, rather than hardware. This is particularly relevant in wave energy, where control system algorithms play a pivotal role in device performance, but that has yet to impact patenting trend data significantly.

6.7.3 Evaluating the usefulness of patent trend data

Patent trend data offer several advantages as an indicator of innovation: The novelty of inventions is evaluated by patent examiners, the data are accessible through platforms such as the EPO, and longitudinal analysis can reveal technological shifts over time [317]. However, patents are not always the most effective protection mechanism. Maurseth *et al* [330], argue that lead times and secrecy often provide better protection than formal patents, particularly in industries where knowledge is tacit and difficult to codify. Pisano [331], in his review of Teece's "Profiting from Innovation", [327], further notes that not all technological advancements receive the same level of IPP. Open-source software innovations may struggle to secure patents, while hardware innovations can be more easily protected. Additionally, there are cases where patented technologies fail to capture economic returns, as seen with IBM's early computing patents, and Bowmar's calculator [332], the first handheld LED display calculator. Bowmar relied heavily on Texas Instruments for components and failed to secure strong patents, enabling Texas Instruments and other competitors to enter the market with cheaper, more advanced models, ultimately driving Bowmar into liquidation.

6.7.4 The innovation ecosystem

The wave energy sector operates within a broad innovation ecosystem, which includes academia as generators of knowledge, industry as generators of technology, and government as supporters of growth [51] (See Section 7.1). The role of government is essential in supporting emerging renewable energy technologies, and should extend to financial support for IPP for organisations in this area of national and global importance. The need for such support can be gleaned by observing the difference in the number of published academic articles compared to the number of patents published in the same period. That is not to say that academic research should not be supported. In fact, Mansfield [333] found that 11% of new industrial products and 9% of new processes could not have been developed without substantial delay and cost, in the absence of recent academic research. Additionally, organisations that have an extensive patent portfolio in the area of wave energy tend to be large companies, with greater access to finance, such as Bosch Gmbh, rather than the small to medium enterprises (SME) that are more commonly seen in the wave energy sector. Generally, funding in the area of wave energy technology is seen to be relatively accessible at early TRLs (1 to 3) [49], but falls away at higher TRLs, when costs increase exponentially, and the need for IPP becomes more important as innovators seek external investor funding. Patents can foster technology transfer, facilitating the sale or licencing of protected technology, whereas trade secrets may adversely effect knowledge transfer [334]. This is particularly relevant in the case of renewable energy technology, given that the United Nations Framework Convention on Climate Change (UNFCCC) discusses the urgent need to encourage licencing for technology transfer to developing countries [335]. Providing funding for patent registration, if that is the preferred protection strategy, may also facilitate this imperative for knowledge transfer to developing countries, as firms are more confident in disclosing technology when negotiating a licensing contract, as patents offer a delineation of technological assets, combined with the assurance of market exclusivity.

By addressing these considerations, governments and funding agencies can create a more effective innovation ecosystem that supports both scientific discovery and the commercialisation of wave energy technologies.

6.8 Conclusions

This chapter underscores the value of bibliometric analysis, in complementing patent data, in the assessment of innovation trends in wave energy technology development. While patents indicate technological progress, bibliometric analysis of academic publications captures research activity, identifies knowledge gaps, and maps scientific advancements.

The findings in this chapter indicate that wave energy research is expanding, even as patent registrations decline. This suggests that the area remains in an R&D phase, rather than being considered commercially mature. Publishing and patenting share novelty and industrial applicability requirements, yet open-access mandates of both strategies may lead companies to adopt trade secrecy as an alternative IPP strategy. Furthermore, academic institutions are at the forefront of wave energy technology research, benefitting from institutional and funding agency financial support, while patenting faces financial barriers. Having financial support for patent protection will help companies to attract investment.

The long development cycles typical of wave energy mean that the 20-year patent term often expires before technologies reach commercial maturity, reducing incentives to patent and further limiting the role that patents can play in this sector.

Geographic trends highlight different innovation strategies, with China, UK, US, Italy, Spain, and Ireland leading in research publications, whereas the UK, USA, Sweden, Germany, and Finland dominate patenting registrations for the same period. This divergence mirrors national variations in commercialisation and IP policies.

The protection and promotion of innovation is an external factor affecting wave energy technology development. Patents should be considered alongside other indicators of innovation in order to provide a more comprehensive understanding of the sector's progression toward commercial viability.

These findings suggest that patents alone provide an incomplete picture of innovation in wave energy, as academic research activity continues to expand even where patenting declines. The long development cycles typical of the sector reduce the practical value of the 20-year patent term, while financial barriers limit patent registrations, particularly for the SMEs that characterise the wave energy technology community. Wave energy technology developers may benefit from a hybrid approach that combines patenting and trade secrecy. Policymakers and funding agencies can support this by providing funding for patent protection, facilitating knowledge transfer, and bridging the gap between scientific research and commercial deployment. Such measures would strengthen Ireland's position in wave energy innovation and ensure that emerging technologies are protected.

7

Triple Helix insights into Irish wave energy commercialisation

Contents

7.1 Introduction

The development of a commercially viable indigenous wave energy technology industry involves addressing complex problems through diverse stakeholder groups across multiple projects and stages of technological development. High levels of cooperation between different stakeholder groups are required for the progression of wave energy technology development. The Triple Helix (TH) innovation model, described in Section 7.2, is based on the dynamic relationships between industry, academia, and government stakeholder groups, and can be used to develop pragmatic and practical policy measures evolving from consensus between the three stakeholder groups. This is particularly pertinent in the instance of emerging technologies.

There is a paucity of literature that focuses on stakeholder perspectives of non-technical barriers to wave energy commercialisation. However, there is a clear recognition of the need for early participation of stakeholders, in consultation with policy makers [329]. Otherwise, the literature has not addressed, systematically or empirically, the TH actors' contributions to ORE development, in terms of overlapping and or divergent perspectives. Few studies have associated the TH role with renewable energy sources, and then only focusing on specific details [336], [337], [338], [339].

Chapter 7 addresses a significant gap in renewable energy policy formulation by proposing a framework that facilitates data collection, promotes collaborative innovation, and integrates diverse stakeholder perspectives. By applying the TH innovation model to the case of wave energy technology development in Ireland, a framework is identified within which consensus among different stakeholder groups can be found, providing insights that are essential for pragmatic and practical policy formulation, which would help an indigenous wave energy industry to emerge.

Given the emergent status of wave energy technology, the TH framework is particularly relevant, set within a diverse stakeholder landscape, with recent policy changes, and Ireland's recognised expertise in the wave energy sector. This approach not only contributes to the advancement of wave energy technology in Ireland, but also offers a replicable model for other emerging renewable energy technologies, in Ireland and in other countries.

Furthermore, through comprehensive surveys and interviews with wave energy technology stakeholders, the research discussed in Chapter 7 delivers empirical evidence on the fundamental requirements that stakeholders believe policymakers need to address in relation to wave energy, thereby offering valuable guidance for policy development both in Ireland and internationally.

The TH framework is employed in this chapter to analyse current stakeholder perspectives relevant to wave energy commercialisation, however, the role of society lies beyond its scope. Recognising the importance of societal acceptance in the development of offshore renewable energy technologies, as it proceeds towards commercialisation, is crucial, and this is addressed explicitly in Chapter 8 using a Quadruple Helix framework grounded in systems thinking.

Following the Introduction, Section 7.2 introduces the TH model in the context of wave energy. Section 7.3 provides a retrospective application of the model to wind energy technology development in Denmark as an exemplar of successful tripartite commercialisation, while Section 7.4 discusses the application of the methodology to Irish wave energy technology development. Section 7.5 provides results and discussion, while Section 7.6 concludes and discusses policy implications.

7.2 Methodology - Application of the triple helix model to Irish wave energy

The TH model differentiates along the traditional lines of universities, industries, and government as its starting point, taking account of the expanding role of the knowledge sector in relation to the political and economic infrastructure of society [340]. The growing interactions among universities, industries, and government have led to new structures, such as university centres and corporate alliances. These interactions have also fostered integrating mechanisms. It is at the point of interaction, Leydesdorff [340] argues, that innovation takes place.

Indeed, the three stakeholder groups, intrinsic to the development of wave energy technology towards commercial viability in its current phase of development, are: universities, industry, and government. The TH innovation model is applied to find consensus among the differing interests and obligations of each stakeholder group, in order to influence positive and pragmatic policy development, towards “systemic innovations that transcend the technologies and competencies of their individual spheres” [341].

The TH model was introduced and developed in the 1990s by Etzkowitz and Leydesdorff [342], [343], and is described as an innovation model, based on the dynamic relationships between universities, industry, and government institutions. The TH model describes the actions of universities as generators of new knowledge, industry as producers of new technologies, and governments as regulators and potential supporters of new technologies. The model reflects the change to a knowledge-based society, in which institutions develop intersections preserving not only their identities and main roles, but also assuming other roles as necessary [344]. The TH model aims to foster economic and social development, by promoting collaboration and knowledge sharing among these three sectors [342]. The TH model is therefore adopted here, with the objective of examining how wave energy technology commercialisation can be expedited and demonstrating how the TH model can be used to find consensus among the main stakeholder groups, which is essential for the formulation of supportive renewable energy policy, and the integration of energy policy with practice.

7.2.1 Why is TH relevant for wave energy technology development?

The TH model of innovation is based on the interactions between the three following elements and their associated 'initial roles' [345]: universities engaging in basic research, industries producing commercial goods, and governments that are regulating markets [346]. As interactions increase, each sector evolves to adopt characteristics of the other institution, which then gives rise to hybrid institutions. Figure 7.1 shows the overlap between the three TH sectors.

These interactions are evident within Irish wave energy technology development, the university actors, or knowledge generators, are principally involved in incremental technical improvements at lower TRLs. In Ireland, the availability of funding is seen as reasonable or good within this sector, and is accessible from national funding bodies such as Research Ireland, the SEAI, and the Marine Institute, as well as from EU programmes such as Horizon Europe [293]. The university contribution can be seen solely as the provision of knowledge generation and transfer [336], where universities face the 'endless frontier' [342] of basic research, often funded as an end in itself. However, it is difficult to categorise respondents as solely existing within the academic TH sector, as the role of universities is changing to an extent to an 'endless transition' model, in which basic research is linked to utilisation through a series of intermediate processes [347], often stimulated by government. This can be observed in the case of Irish wave energy development, where firms such as Wave Venture Ltd. [348] have 'spun-out' from universities, and multi-actor funding programmes support collaboration between industry and academia [349], [350]. This shows an overlap between respondents from the academic TH sector with those from the industry TH sector.

Industry stakeholders involved in wave energy technology development also rely heavily on public funding at early TRLs, and can benefit from academic collaborations "when two helices are shaping each other mutually, co-evolution may lead to stabilisation along a trajectory...where governments can intervene by helping to create a new market or changing the rules of the game" [343]. Essentially, the TH model can be applied by policy makers as an 'interface strategy' [351] in order to move projects to the 'market pull' phase of development, from the 'technology push' phase, to overcome the so-called VoD described in Section 5.4 [269].

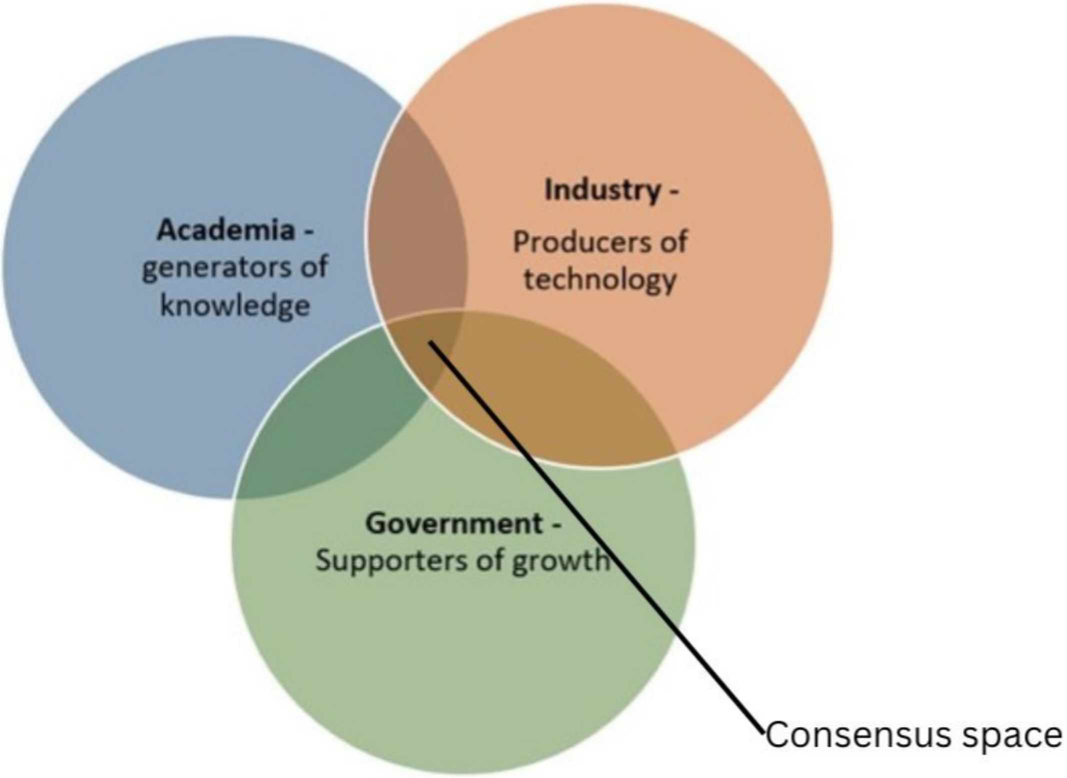

Figure 7.1: Triple Helix stakeholders.

The TH government objectives centre around economic drivers and policy targets [352], [353]. The industry sphere highlights business opportunities, and the academic objectives centre around the generation of knowledge. Anttonen *et al* [341] noted that conceptual differences can inhibit progress. In wave energy device development, industry aspires to the production of full-scale devices in the water, for an extended period of time, producing energy, to demonstrate efficacy and reliability to potential private investors, whereas universities face the 'endless frontier' of fundamental research, which does not hold the same constraints. Governments seek renewable energy sources that can economically compete with other mature technologies. The purpose of the TH model is to find what Anttonen called the 'consensus space' [341], essentially where the competencies and objectives of each stakeholder group can be aligned to achieve progress and enhanced development.

By analysing survey and interview data from stakeholders in the wave energy sector in Ireland, many of whom hold a position in a hybrid space between TH sectors,

Table 7.1: Danish wind energy technology stakeholders 1980-2000. Where agri denotes agricultural, govt denotes government, and ROI denotes return on investment

Stakeholder	TH sphere	Role	Motivation
Agri co-ops	Industry	Investment	Reliability, financial ROI
Test facility	Academic	Testing	Best practice, knowledge transfer
Danish govt	Govt	Policy making	Security of supply, self-sufficiency
Danish Energy Agency	Govt	Setting targets	Grid connection for wind energy
Manufacturers	Industry	Investment	ROI
Citizen owners	Industry	Investment	Security of supply, ROI

the applicability of the TH model is demonstrated in identifying a consensus space for the advancement of wave energy technology. This consensus space is crucial for facilitating informed and pragmatic policy development, required by wave energy technology developers, to reach commercial viability.

7.3 A retrospective application of the TH Framework to Danish wind energy

As an exemplar of successful tripartite commercialisation, this section applies the TH model to Danish wind energy technology development through the 1980s and 1990s. Denmark pioneered wind energy technology development from the late 19th and through the 20th centuries, and successfully developed the technology and exploited it commercially, to the extent that Denmark exported €8.9bn of wind energy technology in 2022. The most significant period of growth for Danish wind energy technology development was during the 1980s and 1990s, as a response to the global oil crisis in 1973, as discussed in Chapter 2. The Danish wind energy technology development TH stakeholders, much as in the case of wave energy in Ireland, could be said to have divergent motivations for supporting this emerging renewable energy technology. However, policy played a crucial enabling role in ensuring the successful development of wind energy technology in Denmark through “a visionary consensus over a long period of time" [354].

Table 7.1 describes some of the key stakeholders involved in wind energy development in Denmark from 1980-1990, their roles and motivations, including members from each TH group. It is clear that, although the ultimate prize of commercial viability is important to all TH actors (although it has been argued that this is perhaps to a lesser extent within the university sphere), there are differing areas of focus, as well as different goals.

As discussed in detail in Section 2.5, the Risø Test Centre acted as a technology hub for the wind energy community, by sharing research gathered from companies seeking type approval. Speculators that wanted to take advantage of the government 30% installation cost subsidy at the time were required to seek certification from Risø, in the knowledge that findings would be shared with other developers [355]. Data gathered by Risø scientists from developers led to technological improvements, and Denmark quickly gained a reputation for producing high quality turbines, essential for its success globally. The Danish scheme takes account of the university TH stakeholder objective to generate knowledge by having access to turbine plans, for the industrial stakeholder group's objective to generate technology through the requirement of type approval, and a vehicle through which the government could support both the industrial and academic partners. Such a scheme shows an understanding by policymakers that different stakeholder groups must work in a symbiotic manner to achieve progress.

The Danish government has been willing to commit to long-term, stable, policies and interventions, which have provided certainty, and have played an important role in fostering the commercial success and longevity of Danish wind energy technology development. From 1979 to 1989, approximately €38 million was granted under the capital investment scheme. Funding was also available for test centres to disseminate knowledge. Income from wind turbines was taxed favourably until 1996 when the technology had matured. Further incentives were available, including tax deductions, and a 10-year agreement with (not-for-profit) utilities guaranteeing turbine owners feed-in tariffs amounting to 70-85% of retail electricity prices. When the market had matured, the Danish government introduced green certificates, and Danish consumers were obliged to buy at least 20% of their electricity from renewable sources.

These Danish wind energy policy initiatives could be described as stakeholder co-design in policy development. In other words, stakeholders are built into policy formulation from its conception. Adopting strategies of this kind, provides vital support for emerging renewable technologies such as wave energy, as they strive to reach commercial viability.

7.4 Employing the TH framework for Irish wave energy commercialisation

Section 5.7 discusses funding gaps in wave energy technology development as perceived by wave energy stakeholders. The remainder of this chapter now expands significantly on the results of that work, with data drawn from 82 questionnaires and 14 interviews, including students, researchers, technology developers, policy professionals, and other TH actors who provide support to the area, such as consultants, lawyers, and finance professionals. The TH convention is applied to stakeholder interactions in relation to wave energy technology development in order to extract valuable data about the commercialisation of wave energy technology in Ireland. The target population of this survey comprises stakeholders in TH with some interest or involvement in the development of wave energy technologies. The research is particular to the Irish marketplace, due to the accessibility of data, as well as Ireland's reputation, both academically and commercially, in wave energy, the prevalence of new policy measures in the renewable energy sphere, and its unencumbered proximity to the EU market. Additionally, the extent of Ireland's abundant wave resource can provide motivation for the development of indigenous wave energy technology. This methodology can be replicated by other countries developing a wave energy technology industry.

7.4.1 Description of respondents

Table 7.3 shows the demographics of the final sample group, divided by TH classification, and Table 7.4 lists the interviewees. The TH model presumes that, as interactions increase between actors, respondents might come to occupy a hybrid space between TH groups. In these cases, the starting point of the organisation determines the TH group [346]. Indeed, it is clear from the list of respondents that many of the stakeholders could hold a position in two or three of the TH groups, which the TH theory suggests creates a positive environment within which innovation can flourish.
The questionnaire consisted of 8 questions (Table 7.2), including single-answer multiple choice questions, Likert scale questions [356] to measure attitudes and opinions, rank order questions allowing respondents to compare potential answers, demographic or firmographic questions to determine respondents' backgrounds, and an open-ended question to gather in-depth qualitative data. The interviews were conducted either in-person or online, were semi-formal, and were 30 minutes in duration. Although 68% of the survey respondents requested anonymity, all of the interviewees gave their consent for their names and affiliations to be made public.

For semi-structured interviews, a process known as 'coding' is employed. Codes may be described as "tags or labels for assigning units of meaning to the descriptive or inferential information compiled during a study" [357]. This allows the clustering of key issues in the data [358].

Table 7.2: Survey questions

	Survey question
1	I am a .... student, researcher, technology developer, policy professional, other
2	Should wave energy be part of the renewable energy mix?
3	How long do you think it will take before wave energy can supply a national grid (Ireland or other)?
4	Rank the following challenges facing wave energy technology development in order of significance
5	Do you think the level of public funding available to wave energy technology developers is adequate?
6	Should public funding for wave energy device developers be directed at a particular TRL range? If yes, which?
7	Do you believe that policy makers see the development of wave energy as high priority?
8	What can national governments do (or do more of) to assist wave energy technology development?

Table 7.3: Survey respondents by TH classification

Industry	Academia	Government
Corpower	Uni. of Manchester	Ocean Energy Europe
Ocean Energy	UIUC	Marine Inst
Ocean Harvesting	National Marine College	IDA
Limerick Wave	Dundalk IT	Sandia National Labs
Data Only Greater	Maynooth Uni.	Centec
Wood	Uni. of Galway	Bluewise Marine
Flotation Energy	Loughborough Uni.	Bluewise Marine
Norri.ie	Uni. Edinburgh	Aer Finance Group
Source Gallileo	Uni. Strathclyde	Bremore Irel port DAC
Simply Blue	Dublin Tech Uni.	LK Shiels Solcs
Anonymous (ind)	Queens Uni. Belfast	Creavan and Doherty Solcs
	Politecnico di Torino	ERM Consulting
	TU Dublin	MRIA
	Uni. College Dublin	Anonymous (govt)
	Trinity College Dublin	
	Centec	
	Anonymous (academic)	

Table 7.4: Interviewees with TH classification

Name	Affiliation	TH sphere
Patrick Möller	CEO, CorPower	Industry
Tony Lewis	CTO, Ocean Energy Ltd.	Industry
Anders Køhler	CEO, Floating Power Plant	Industry
Antonio Saramento	President, WavEC Offshore Renewables	Government
Thomas Kelly	Assistant Professor, Dundalk IT	Academia
John Miller	CEO, WaveForce Energy Ltd.	Industry
Patrick Walsh	CEO, Limerick Wave Ltd.	Industry
Rémi Gruet	CEO, Ocean Energy Europe	Government
Andrew Parrish	Former CEO, Wavebob	Industry
John Flaherty	Solicitor, FR Kelly	Industry
Peter Coyle	Chairman, MRIA	Industry
John Walsh	Emerging Technology and R&D Manager, ESB	Industry
Peter Hamilton	Green Party Candidate. Kildare County Council	Government
Christopher Ridgewell	AW-Energy	Industry

7.4.2 Limitations

Certain limitations were encountered when relying on the questionnaire as a sole source of qualitative data, particularly when answers required a substantial level of respondent expertise or experience. Limitations included differences in understanding of the challenges specific to wave energy technology development. In addition, respondents may not have given equal consideration and time to their responses. For this reason, in-depth, semi-structured interviews were conducted with high-level wave energy experts, listed in Table 7.4. It is worth noting that many industry TH stakeholders also have an academic affiliation, reflecting the emerging nature of wave energy technology development. The interviewee responses feed into the analysis of the survey results, and provide clarity and validation, as well as a more in-depth insider perspective.

Although this chapter focuses on the commercialisation of the Irish wave energy technology industry, views were sought from wave energy technology developers, from multiple jurisdictions, reflecting the reality of cross-jurisdictional project funding schemes, and in order to gain perspectives from senior employees of some of the globally leading wave energy companies.

7.5 Results and discussion

The following section analyses the results of the questionnaire and the interviews, while comparing responses from each TH group. In analysing the data, the Chi Squared test

[359] and ANOVA Analysis [360] are used. The Chi-squared test is primarily used to analyse categorical data, where the variables are non-numeric, and can be divided into distinct categories. The Chi-squared test determines if there is a significant difference between the observed and expected frequencies within different groups. ANOVA is used to analyse numerical data between three or more groups. ANOVA compares the mean responses of these groups to determine if there is a significant difference between them.

7.5.1 Finding 1: Wave energy will be supplying the (Irish) electricity grid within 10 years, but is not high priority for policy makers

Although 95.8% of respondents believe that wave energy should be part of the renewable energy mix, there is a presumed bias, in that the target respondent group are those involved, in either an academic or professional capacity, in ocean energy. However, respondents were also asked how many years they believe it will take for wave energy to supply electricity to the Irish electricity grid. Figure 7.2 clearly shows that there is consensus between TH groups, with a mean of 10 years across all three TH groups, and few outliers.

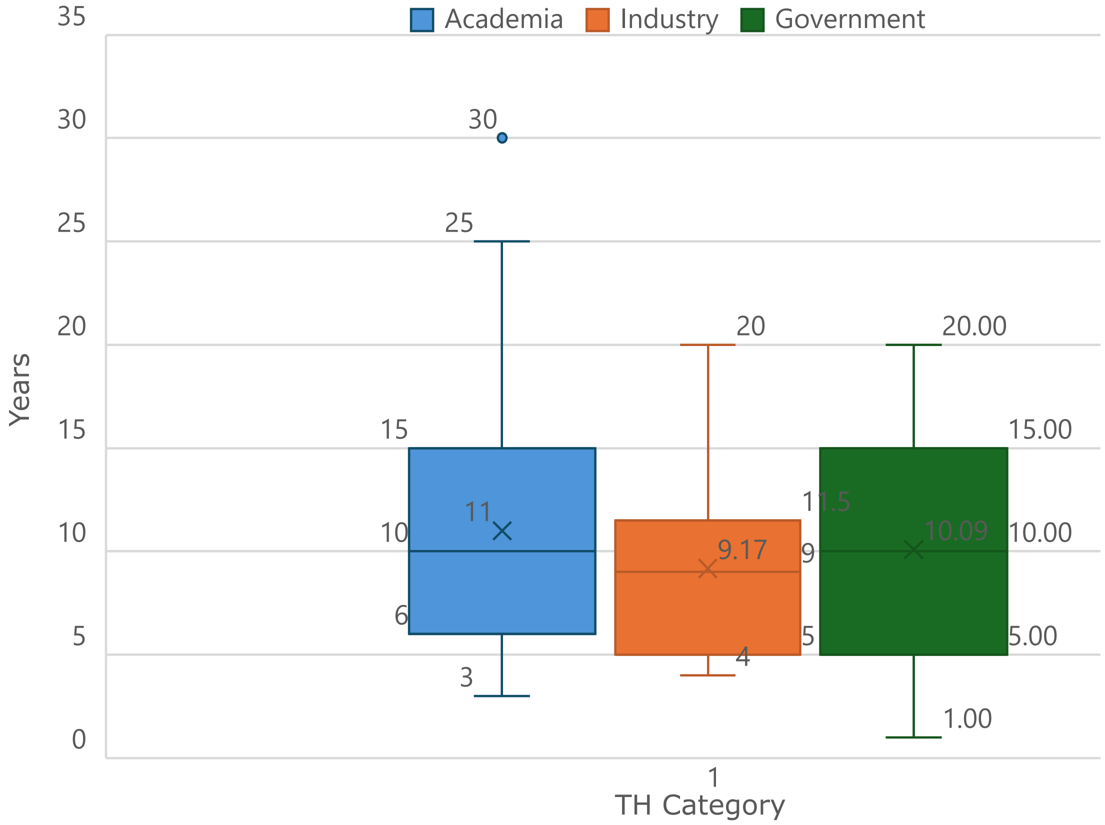

Figure 7.2: Number of years to grid integration of wave energy in Ireland by TH group.

Table 7.5: Summary - Number of years to grid integration for wave energy in Ireland by TH group

Groups	Count	Sum	Average	Variance
Industry	11	127	11.55	69.27
Academia	55	589	10.71	29.76
Government	13	132	10.15	30.14

Table 7.6: ANOVA - Number of years to grid integration for wave energy in Ireland by TH group response. The table includes the sum of squares, degrees of freedom, mean square, F-value (analysis of variance between groups), and P-value for each source of variation. SoS* denotes sum of squares, Dof** denotes degree of freedom.

Variation source	SoS*	DoF**	Mean square	F ratio	P-value	F crit
Between groups	11.65	2	5.83	0.17	0.85	3.12
Within groups	2661.77	76	35.02			
Total	2673.42	78				

An ANOVA analysis is performed with results displayed in Tables 7.5 and 7.6, to determine whether the similarities in mean responses between groups occur by chance, or if they are statistically significant. The F-Value is the ratio between the 'between groups' variation and the 'within groups' variation. Since the F-Value is smaller than the 'within group' variation, it can be deduced that the difference between the groups is not statistically significant.

Additionally, since the probability value (P-value), which describes the probability that the results could have happened by chance, is more than 0.05 (the value that commonly serves as the threshold for statistical significance), it may be concluded that there is no statistically significant difference between the mean responses of the groups being compared.

The ANOVA analysis shows that there is good agreement between wave energy technology TH groups, in that wave energy TH stakeholders believe that wave energy will be in a position to supply the Irish electricity grid within 10 years. However, this is not supported by national policy. The Climate Action Plan 2024 (CAP24) [361] provides an annually-updated roadmap for actions that will be taken to halve Ireland's emissions by 2030, and reach net zero by no later than 2050, as committed to in the Climate Action and Low Carbon Development (Amendment) Act 2021 [1]. The CAP24 expresses the "significant potential to develop offshore renewable energy from wind, wave and tidal sources", and details the importance of research and innovation infrastructure for ocean energy projects, such as test sites. It does not set any targets for deployment for wave energy, focusing instead on more mature technologies, such as offshore wind, for which it sets a target of 5GW installed capacity by 2030 [1].

It is clear that, although TH stakeholders agree that wave energy will be part of the Irish electricity grid within 10 years, wave energy is treated as being within the research and development remit of public policy, rather than as a high-potential, near-future constituent of the renewable energy mix. National policy does not set targets for wave energy because the technology is still considered insufficiently mature and commercially uncertain, with unresolved issues around cost, reliability, scalability, and survivability at sea. As a result, policymakers view the technology as higher risk than established technologies such as offshore wind and therefore limit support to R&D rather than committing to deployment targets.

> "Wave energy is running out of time. Governments need to support"
> *Anders Køhler, Floating Power Plant*

7.5.2 Finding 2. There is a need for more focused funding

Survey respondents were asked whether public funding for wave energy developers should be directed at a particular phase of technology development maturity (i.e. at a particular TRL range [257]). Although there is a lack of an all-encompassing taxonomy for TRL levels, in general they have been adapted for wave energy technology development as described in Section 5.2 [262], [265], [261].

Respondents answered the question of funding needs based on three TRL phases: TRL 1-3, the research phase; TRL 4-6, technology development and early deomonstration phase, where academia and industry are most likely to intersect and where costs increase exponentially between TRLs; and TRL 7-9, system development and launch phase. Most respondents (62%), stated that funding should be targeted at a particular maturity level, but with a significant minority either not sure (22%), or who do not believe that funding should be targeted at a particular maturity level (15.5%). Of those who do believe funding should be targeted at a particular maturity level, 59% believe that funding should be targeted at TRL 4-6, or the mid-maturity point. Applying the TH model, shows that there is good agreement among the TH groups (Figure 7.3). The only anomaly would seem to be that 29% of the industry group believe that funding should be targeted at the upper maturity levels, whereas only 14% and 16% of the academic and government groups agree with this.

A Chi-squared test of independence [362] is used as a means to determine whether the observed deviations between the TH groups are statistically significant or can be

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[1] For reference, Ireland's peak demand (2023) is 5.5 GW

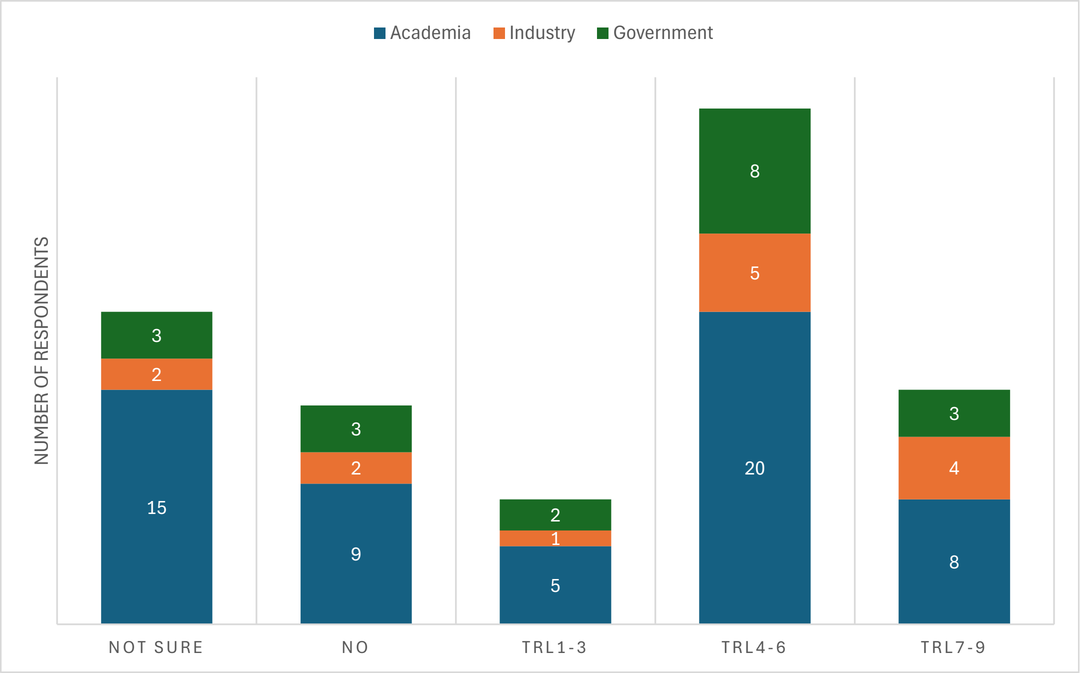

Figure 7.3: Survey responses by TH group - Whether public funding should be targeted at a particular TRL.

Table 7.7: Chi-squared Analysis of whether funding should be targeted at a particular TRL range by TH group. The table presents observed and expected frequencies, degrees of freedom, Chi-squared statistic, and p-value. Govt.* denotes government.

	Not sure	**No**	**TRL1-3**	**TRL4-6**	**7-9**	**Total**
Academia	15(12.67)[.43]	9(8.87)[.00]	5(5.07)[.00]	20(20.90)[.04]	8(9.50)	57
Industry	2(3.11)[.40]	2(2.18)[.01]	1(1.24)[.05]	5(5.13)[.00]	4(2.33)[1.19]	14
Govt.*	3(4.22)[.35]	3(2.96)[.00]	2(1.96)[.06]	8(6.97)[.15]	3(3.17)[.01]	19
Total	20	14	8	33	15	**90**

attributable to chance. Table 7.7 shows that the Chi-squared statistic is 2.9354, and the p-value is 0.938. Since the p-value is greater than 0.05, there is no statistically significant difference in the distribution of responses between the groups, meaning there is no evidence of a difference between the variables. Additionally, 59% of respondents believe that funding should be targeted at TRL 4-6, which represents the largest proportion of respondents from each of the TH groups. This indicates that a majority of respondents who favour targeted funding believe public support should focus on mid-maturity wave energy technologies (TRL 4–6), where concepts move from research into prototype development and early demonstration. This reflects the shared opinion that the main constraint is not basic research (TRL 1–3) or near-commercial deployment (TRL 7–9), but the costly and high-risk transition phase where technologies are proven at scale and industry–academia interaction is strongest.

Section 5.6 looks at research and development funding received from three of the main Irish public funding bodies for wave energy projects: Science Foundation Ireland [363] (now Research Ireland), the SEAI [305], and the Marine Institute [364], within a 10 year period, and attempts to discern whether each project would be placed at low, mid, or high TRL. These findings were compared to EU funding distributions, where Ireland was the co-ordinating (lead) partner, and also to venture capital investment.

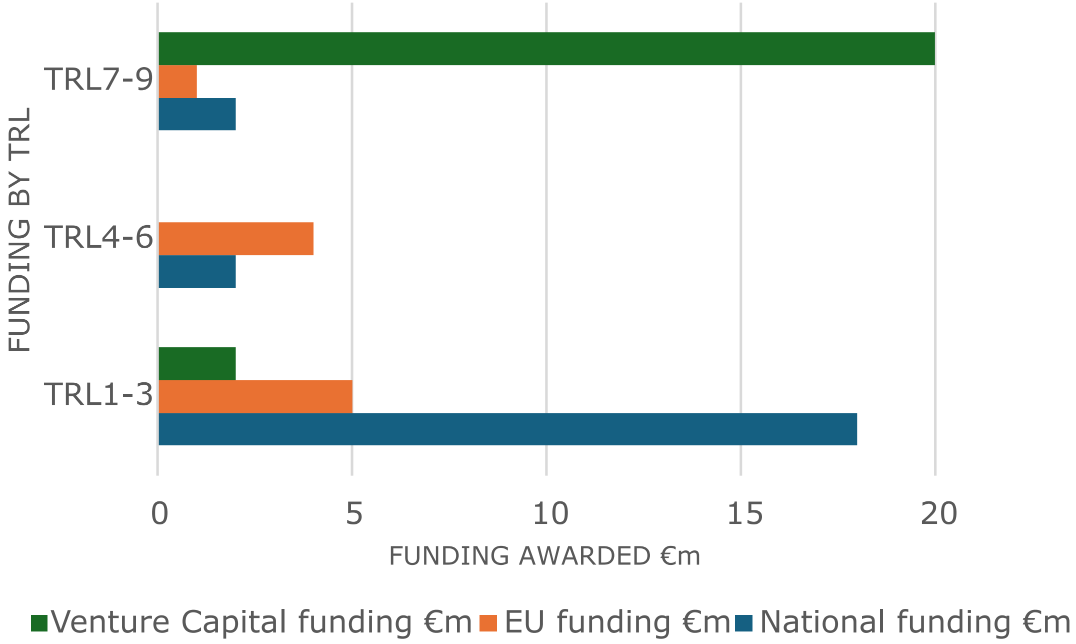

Figure 7.4: Irish funding for wave energy projects.

Figure 7.4 shows that most funding was focused on the lower TRLs. It is important to note that patterns in public funding do not match the stated funding preferences of stakeholders from any of the TH groups, according to the findings in this section. As discussed in Section 5.3, TPL is designed to be complementary to TRL and TPL, when combined with TRL, can identify requirements for successful entry, survival in the electricity market, and can assess the value of the technology when making investment/funding decisions as it measures the economic ability of the project. TPL can be used by all TH stakeholder groups: technology developers for iterative design feedback and to identify areas of improvement and find fatal flaws early, by investors to conduct due diligence, both of which increase the likelihood of successful deployment and investment readiness, as well as being an important tool for reviewers to assess wave energy technology project proposals, and make funding decisions, and by researchers to formulate R&D strategies. For this reason, TPL, if it gains popularity, would be a preferable metric from which to evaluate stakeholder perspectives.

> “The best way to support companies is to create a clear and sustained market pull that will motivate investors to support companies for the entire development rollout"
> *Christopher Ridgewell, CEO, AW-Energy*

Research such as that of Ford [277] indicates that governments are often willing to fund early-stage research, driven by social welfare considerations, but may withdraw support as technologies advance and become more commercial. In [269], the need for de-risking technologies, and providing public support until technology performance has been validated is emphasised, as a means to overcome the VoD, and address investor concerns about economic viability and policy stability.

Responses from interviewees show a disconnection between policy makers and those working at the coal face. Patrick Walsh, CEO of Limerick Wave, mentioned the the “biggest problem facing wave energy is the difficulty of getting funding at mid-TRLs". Rémi Gruet, CEO of Europewave agrees “[wave energy technology developers] need to source public funding as the cost of finance is too high".

> “We need funding supports at mid-TRLs, and guarantees for investors."
> *Tony Lewis, Ocean Energy Ltd*

7.5.3 Finding 3. Lack of a wave energy champion and Levelised Cost of Energy are the most pressing challenges facing wave energy technology development

Survey respondents were asked to rank the most pressing challenges facing wave energy development in Ireland in terms of commercialisation potential. They were given four options derived from the studies of [209], [36], [365] etc., and from interview responses:

- Public perception of wave energy. This is investigated in detail in Chapter 8
- Lack of a wave energy champion who can exert influence at policy level
- LCoE, compared to other sources of renewable energy
- Lack of design convergence
- Other

LCoE, in comparison to other, more mature technologies, is found to be one of the most pressing challenges facing the development of wave energy technology overall. However, industry and government representatives both stated that the lack of a champion, a person who can exert influence at the policy level, is seen as a slightly more pressing need for wave energy technology development in Ireland. The results are presented in Figure 7.5.

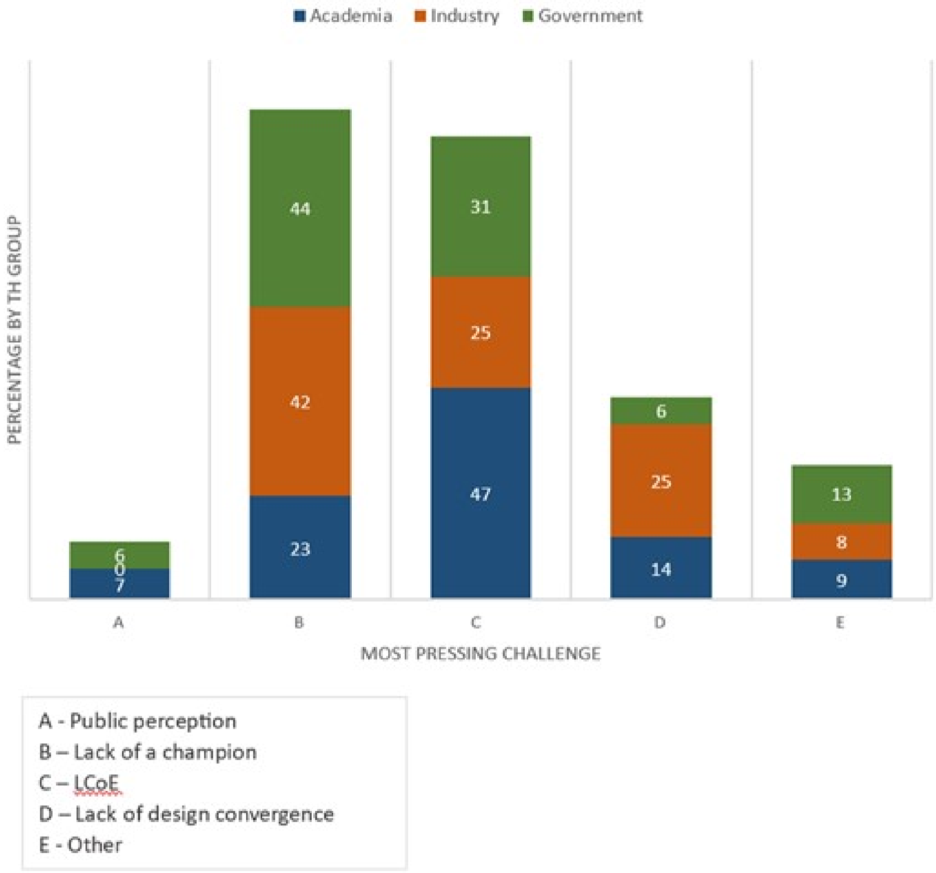

Figure 7.5: Survey responses by TH group - Most pressing challenge for wave energy technology developers.

A Chi-squared test of independence is used to examine the relationship between TH groups and their respective perspectives on the most pressing challenges facing wave energy development, to determine whether the observed deviations between the TH groups are statistically significant or can be attributable to chance. The contrast between these variables was significant; the Chi-squared statistic is 32.8606. The p-value is .000065. The result is significant where $p < 0.05$.

Table 7.8 shows that there is a difference between the responses from different stakeholder groups, in that the academic TH group believe that the relatively high LCoE for wave energy, is the most pressing challenge facing wave energy technology development, whereas the industry and government groups feel that a wave energy champion might have more impact if they meet their goal of garnering the required policy support for the development of an Irish wave energy technology industry.

Table 7.8: Chi-squared - Most pressing challenges facing wave energy developers by TH group. Design conv. denotes design convergence, Aca. denotes Academia, Ind. denotes industry, Govt. denotes government, and Ttl denotes total

	Perception	Champion	LCoE	Design conv.	Other	Ttl
Aca.	7(4.65)[1.19]	23(36.21)[4.82]	47(34.22)[4.77]	14(14.95)[0.06]	9(9.77)[0.09]	100
Ind.	1(4.7)[2.91]	42(36.57)[0.80]	25(34.56)[2.65]	24(15.10)[6.49]	8(10.07)[0.42]	100
Govt.	6(4.65)[0.39]	44(36.21)[1.67]	31(34.22)[0.30]	6(14.95)[5.36]	13(9.98)[0.92]	100
Ttl	14	109	103	45	30	**300**

Several respondents added commentary, stressing that the role of the champion is to drive supportive policy initiatives for the wave energy community. They commented *inter alia* that there is a “lack of a policy driver to allow for sustained R&D investment"; “many developers are very small-scale business-wise and need support to develop"; “a research institution for the EU .... would be good"; “the government needs to support full-scale demonstrations"

In relation to LCoE, it is unsurprising that the academic TH group noted this as a pressing challenge facing wave energy technology development. The EU have ambitious LCoE targets for wave energy technology [366] and research proposals seeking funding regularly state an LCoE target as a measurable deliverable. However, it is very challenging to obtain a true LCoE estimate at the early design stages, due to considerable uncertainties (especially in OpEx, and true economic valuation can only be obtained through economies of scale and maturation of knowledge, which cannot be obtained until there are more demonstration devices at sea [172].

> “Governments need to be ready to take risks. We know we can make [wave energy] work, but at what price?"
> *Rémi Gruet, CEO, Ocean Energy Europe*

7.5.4 What can national governments do (or do more of), to bolster wave energy commercial viability?

This open-ended question was asked in an effort to give respondents an opportunity to freely express their opinions about the topic. It also provides qualitative data from each TH group. Open-ended questions can, in general, also provide a greater depth of insight than a closed question [367].

The open-ended responses to this question have been grouped thematically, and have been categorised according to the broad themes of the need for additional public funding and policy support, the need for improved regulations and consenting

Table 7.9: What policy makers should do or do more of to support the development of wave energy technology by TH group

	Funding	Demo. projects	Consenting	Academia-ind	Awareness	Comp.
Aca.	76%	15%	6%	3%	15%	3%
Ind.	42%	8%	17%	8%	8%	0
Govt.	86%	0	14%	0	0	0

procedures, the need for improvements to infrastructure, the importance of supporting more demonstration projects, the need for supported and more interaction between academia and industry, and the need to improve public perception of wave energy. Figure 7.6 presents the results, showing that each TH group, including the government group, recognises that the government need to provide supportive policies and funding to wave energy technology developers in order for wave energy technology to be commercially viable in the short term. This corresponds with the quantitative data discussed in some of the other findings. This is discussed in Section 5.6.

7.6 Conclusions and policy implications

This chapter underscores the importance of incorporating stakeholder perspectives into the formulation of policy, particularly in the context of emerging technologies such as wave energy technology development. Furthermore, the use of the TH framework is instrumental in ensuring that data is gathered, and analysis is conducted beneficially in a manner that supports effective future policy formulation.

Specifically, applying the TH framework can significantly influence Irish wave energy policy, which is crucial for advancing wave energy technology commercialisation, ensuring that policymakers identify a consensus space where the needs of various stakeholder groups are adequately addressed, formulating pragmatic and practical policies, thereby facilitating the achievement of policy objectives.

The retrospective application of the TH framework to Danish wind energy development in the 1980s and 1990s serves as a valuable case study. This highlights the importance of balancing different stakeholder needs and objectives in policy formulation, providing a framework that could enhance awareness and integration of diverse perspectives in policy development.

The analysis reveals evidence that the current Irish policy landscape for wave energy is misaligned with stakeholder needs, particularly regarding funding at the mid-TRLs. To bridge the VoD, and ensure the successful and timely integration of wave energy into the grid, policymakers must prioritise and invest in technologies at mid-TRLs. Notably,

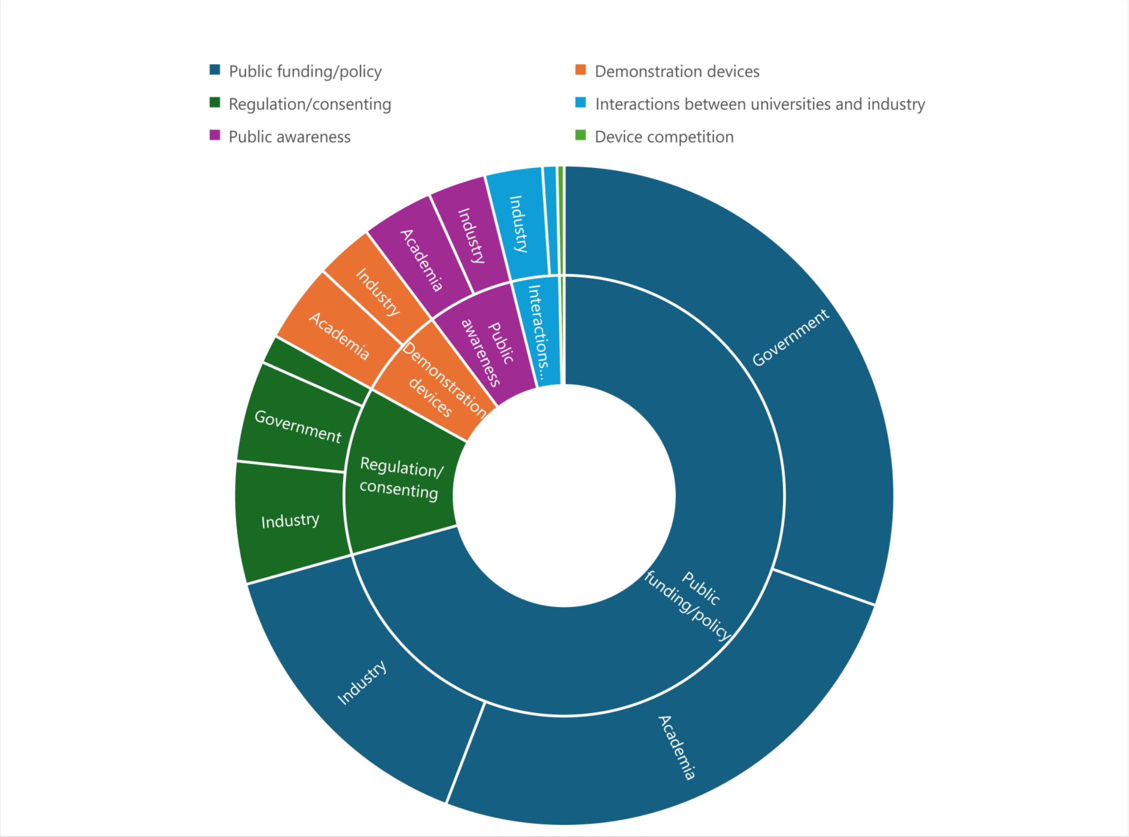

Figure 7.6: Survey responses by TH group - What should policy makers do or do more of?

the expectation among all stakeholder groups, that wave energy will supply the grid within the next decade, is not reflected in Irish policy, despite having more visibility in EU policy.

Additionally, results show that LCoE is of concern to stakeholders, particularly those in the academic field, and despite difficulties with accurate assessment, is not an appropriate metric for evaluating wave energy technology at its current stage of development. There is a need for new or adapted models, to better guide funding decisions and assess where investments can be most impactful.

The need for a wave energy champion, expressed in the analysis of the results, shows that stakeholders recognise the need for additional cooperation between TH groups, led by someone who can move between the three groups, act as a spokesperson, and exert influence at a policy level.

This chapter provides a framework from which different emerging renewable energy technologies in other countries can benefit. Using a TH framework combined with stakeholder-informed analysis, benefits emerging renewable energies in other countries because it provides a structured way to capture and integrate the perspectives of key stakeholder groups (industry, academia, and government) into policy formulation. This ensures that policies are practical, targeted, and widely supported. By identifying consensus areas, highlighting gaps (such as a lack of funding at mid-TRLs), and addressing potential barriers early, such a model can accelerate technology development. Moreover, the framework is adaptable to different national contexts and different modalities, helping countries design policies that are responsive, inclusive, and capable of fostering successful commercialisation of emerging renewable technologies. New policy is being developed rapidly in the renewable energy area, in line with national and international priorities. It is essential that any new policy recognises and analyses stakeholders' perspectives, to ensure that new policy is targeted where it is most needed, and is pragmatic and practical.

This chapter emphasises the necessity of aligning policy with stakeholder needs, through the use of the TH framework, and provides empirical evidence to show stakeholder perspectives for the Irish case of wave energy. This will help to ensure that future policy in the area of marine renewable energies, are robust and responsive to the often divergent views of its stakeholders.

8

Societal acceptance of wave energy technologies in Ireland: A systems thinking approach

Contents

8.1 Introduction

Beyond the technical, legal, and economic factors examined in the preceding chapters lies the overarching consideration of Societal acceptance (SA). For any technology to become widespread, it must first be socially accepted. As wave energy remains in a pre-commercial phase of development, understanding and fostering SA is essential to prevent delays, opposition, or project failures during the transition to full-scale deployment. Accordingly, this chapter examines the SA of wave energy technology in Ireland, recognising that insufficient SA represents a major non-technical barrier to renewable energy integration. Integrating SA considerations at early development stages can help ensure smoother commercialisation and long-term sustainability.

To address this challenge, this chapter develops a methodology that follows the principles of systems thinking to understand how SA plays a role in this complex, multi-stakeholder RET system. The chapter explores public perceptions and the interactions among stakeholders to develop a qualitative model that can describe the dynamics of this complex system with the goal of identifying leverage points for system change through pragmatic policy interventions.

This chapter develops a methodology that employs a mixed-methods approach to data collection, utilising surveys, literature reviews from diverse disciplines, and focus groups to identify the key variables affecting the system and to postulate the relationships between these variables. These findings are validated through interviews with wave energy technology stakeholders from industry, academia, and government. In addition, this chapter takes a novel approach by utilising a systems thinking lens to retroactively present a qualitative model of the Danish wind energy system to explore how SA influenced the system dynamics during the development phase of Danish wind energy technology from 1973-1990. Throughout this thesis, Danish wind energy has provided a benchmark for Irish wave energy, and now this approach provides a means to identify relevant system archetypes for informing, comparing, and proposing relevant interventions in the current wave energy system in Ireland.

Applications of a systems thinking approach to the SA of renewable energy are largely absent from the literature (although renewable energy trends, policies, and energy transitions have been scrutinised through a systems thinking lens in [368], [369], [370], and [371]). The contributions of this chapter offer the following as a way of informing planning and decision-making for wave energy technology developers, project developers, policymakers, and funding agencies:

- Illustrating the complexity of societal dynamics concerning wave energy technology deployment through the development of a qualitative modelling tool.
- Establishing a systematic mechanism to compare against the Danish wind energy system through the identification and analysis of system archetypes.
- Identification of leverage points and intervention strategies for policy development through the use of the Iceberg Model.
- Proposal of a systems thinking methodology for RETs.

Following the chapter introduction, Section 8.2 provides background on the importance of SA for RETs, with a focus on wave energy. Section 8.3 describes the methodology, while Section 8.4 retrospectively applies systems thinking to the SA of Danish wind energy during its development phase to identify system archetypes that might be pertinent to the SA of wave energy in Ireland. Section 8.5 presents the qualitative modelling tool as a Causal Loop Diagram (CLD) of the wave energy SA system. Section 8.6 articulates findings and policy implications through interventions and leverage points, followed by discussion and conclusions in Section 8.7. A Glossary of Terms specific to the field of systems thinking and the methodology developed in this chapter has been compiled and follows in Subsection 8.1.1.

8.1.1 Glossary of terms

- **Balancing loops** A self-correcting feedback loop that aims to maintain stability and bring a system to a desired state
- **Causal loop diagram** Graphical representations that depict the feedback loops and causal relationships between different variables in a system
- **Iceberg Model** A systems thinking tool which uses the metaphor of an iceberg to illustrate how the surface-level events we react to are underpinned by less visible patterns, structures, and beliefs.
- **Leverage points** Areas within a system where small, strategic changes can lead to significant impacts
- **Mental models** Deeply held beliefs, values, and assumptions that shape how people perceive and react to situations,
- **Not In My Back Yard (NIMBY)** Opposition to development or infrastructure in a resident's local area
- **Quadruple Helix Framework** A framework for innovation that integrates four key societal subsystems: academia, industry, government, and civil society
- **Reinforcing loops** A self-growing feedback loop. It causes a trend to accelerate, or grow, in one direction
- **Societal Acceptance** Community, socio-political, and market acceptance (in this study of RETs)
- **Sustainable Energy Technology Acceptance (SETA) model** A framework developed to explain why individuals adopt or reject new technologies that also reflects the socio-technical nature of renewable energy adoption
- **System archetypes** Recurring patterns or trends in systems that can help us understand and address complex problems.
- **Systems thinking** An approach to understand the complexity of systems by looking at interactions between system components
- **Technology Acceptance Model (TAM)** A framework developed to explain why individuals adopt or reject new technologies
- **Wicked problem** A term used to describe a challenge characterised by complexity, multiple stakeholders, and no single optimal solution

8.2 Background and context

8.2.1 Societal acceptance, renewable energy technologies, and wave energy

SA of RETs extends beyond public opinion and is a multidimensional social construct. Wüstenhagen et al. [372] conceptualise SA as comprising three interrelated dimensions: *socio-political acceptance*, *community acceptance*, and *market acceptance*. Acceptance is influenced by diverse socio-cultural, political, and contextual factors that must be understood to achieve sustainable energy transitions [373].

Figure 8.1: The triangle of social acceptance of renewable energy innovation. Adapted from Wüstenhagen et al. (2007) [372].

While socio-political acceptance of RETs is often high among policymakers and institutional stakeholders, local resistance can be significant [372] and can have significant consequences. Despite broad public support for renewable energy in principle, opposition, often associated with Not In My Back Yard (NIMBY) attitudes, frequently delays or halts project implementation [374, 375]. However, contemporary research suggests that such resistance is rarely due to NIMBYism alone. Segreto et al. [376], in their review of 25 case studies, highlight factors such as perceived procedural injustice, insufficient community engagement, and concerns over environmental impacts as equally influential. Addressing these multidimensional challenges, for an emerging technology such as wave energy, requires an understanding of the broader system in which wave energy projects are embedded. The Quadruple Helix framework provides a useful lens through which to identify key stakeholders, namely, government, industry, academia, and the public [377], and to examine how their interactions shape innovation processes and social acceptance. Indeed, Chapter 7 utilises the related Triple Helix Framework [51] to advance this approach by identifying and analysing stakeholder perspectives for wave energy in Ireland. This chapter now builds upon that foundation, through an application of systems thinking, to more deeply explore the interdependencies, feedback loops, and dynamic relationships among these stakeholders with a focus on the SA of wave energy technology development as it progresses towards deployment.

The present chapter draws upon two complementary theoretical frameworks to explore the three dimensions of SA within the context of wave energy: the Technology Acceptance Model (TAM) [378] and the Sustainable Energy Technology Acceptance (SETA) model [379]. TAM was developed to explain why individuals adopt or reject new technologies. The model describes how actual usage behaviour is influenced by perceived usefulness and perceived ease of use, which, in turn, shape attitudes toward the technology. Although TAM has been influential, its usefulness is limited to contexts where social, environmental, and emotional factors also influence acceptance [380]. To overcome these limitations, the SETA model incorporates additional constructs, such as trust, perceived cost, risk perception, and problem salience, that better reflect the socio-technical nature of renewable energy adoption and is particularly useful for an emerging technology such as wave energy, which is not well known by the general public. These models underpin the design of the survey and interview questions used to gather data in this chapter.

Norway's experience with nuclear energy provides an example where public scepticism persisted despite technological viability, largely due to a lack of dialogue and trust-building mechanisms [381]. This example shows the importance of incorporating SA measures early in project planning to ensure social legitimacy and long-term viability of emerging RETs such as wave energy.

8.2.2 Systems thinking

Systems thinking can be used to identify and analyse the interconnected mechanisms and feedback loops underlying the dynamics of the complex system that underpin the SA of wave energy. In this sense, the SA of wave energy can be viewed as a 'wicked problem', a term of art used to describe a challenge characterised by complexity, multiple stakeholders, and no single optimal solution [382]. Systems thinking provides a framework to explore such complexity by identifying relationships, feedback loops, and exposing leverage points for meaningful intervention. The framework enables decision-makers to anticipate unintended consequences and avoid superficial, short-term solutions that fail to address root causes by viewing the system through a holistic lens [383].

Systems thinking permits the identification of systems archetypes and leverage points. Leverage points are places within a complex system where a small shift can produce significant changes in overall system behaviour [384]. They are strategic areas for intervention that allow practitioners to influence system behaviour towards more preferable outcomes. Systems archetypes provide a structured way to understand, diagnose, and anticipate recurring patterns of behaviour in complex systems [385]. They describe recurring behavioural patterns in complex systems, such as *limits to growth*, *fixes that fail*, and the *tragedy of the commons*. These archetypes reveal how feedback structures, whether reinforcing or balancing, shape system behaviour over time. For example, in the *tragedy of the commons* archetype, overexploitation of a shared resource leads to collapse, illustrating how reinforcing feedback can produce unintended decline.

This chapter proposes a visualisation of the SA of wave energy technology development in Ireland using system mapping approaches. The method utilised in this work is the development of a CLD, which visualises the interconnections, and causality between variables in a system through directional arrows and feedback loops. CLDs reveal how reinforcing loops amplify change, while balancing loops stabilise the system over time [386].

Visualising these relationships makes complex systems intelligible, providing a shared reference for stakeholders to interpret and discuss system dynamics and potential interventions [387]. This visual and conceptual clarity is critical in the context of the SA of wave energy, where technical, social, and ecological variables interact.

8.2.3 Mental models and public perception

The Iceberg Model (Figure 8.2) provides a framework for understanding the visible and hidden layers of ‘wicked problems’ within complex systems [388]. The visible events, such as public controversies, media debates, or project outcomes, represent only the tip of the iceberg. Beneath the surface lie patterns of behaviour, systemic structures (such as policies that direct the patterns of behaviour), and the deepest layer, mental models, which are the assumptions, beliefs, and values shaping those structures [389]. In the case of SA of wave energy technology, a mental model to be aware of, and that featured strongly in the survey data, is the connection that coastal residents feel with the ocean and their consequent need to protect this resource. Using the Iceberg Model in conjunction with developing a CLD is synergistic because it helps analysts 'see' beyond visible events to uncover the deeper systemic structures and mental models that generate recurring patterns of behaviour [385]. Mental models influence how individuals interpret information, assign meaning, and make decisions [390]. In the context of renewable energy, these models can affect public perceptions of risk, trust in institutions, and overall acceptance of technology.

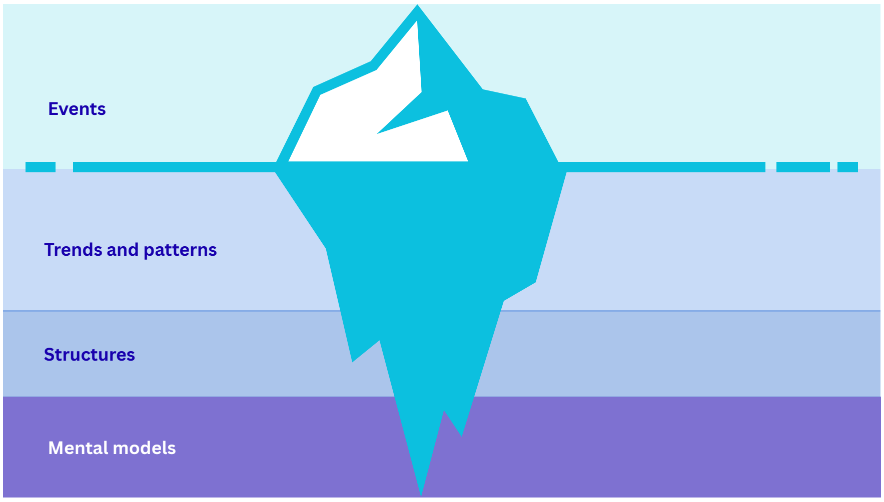

Figure 8.2: The Iceberg Model. Adapted from Senge, (1990) [385].

Drawing on the theory of bounded rationality [391], people make decisions that are 'good enough' within the limits of available information and cognitive capacity. Therefore, transforming acceptance of wave energy, when it reaches the stage of development where full-scale prototypes are being tested in open sea conditions for extended periods, requires engaging not only with external factors (such as information campaigns or financial incentives) but also with the underlying mindsets that promote either resistance or support. Tools such as CLDs and the Iceberg Model help reveal these deeper layers, enabling more effective policy and communication strategies.

8.2.4 Systems thinking and the societal acceptance of wave energy

In policymaking and planning, systems thinking acts as a sense-making tool, helping to visualise interconnections, feedback paths, and ripple effects of decisions [383]. Understanding these interdependencies allows for more adaptive, forward-looking strategies that anticipate social and environmental challenges [392].

Stakeholder engagement is central to a systems thinking approach. Policymakers, industry, academia, and civil society each hold distinct but complementary roles within the ecosystem. Real engagement ensures that technological feasibility aligns with social legitimacy. Early and transparent engagement builds trust and mitigates conflict. The methodology developed in this chapter adopts a Quadruple Helix framework when targeting stakeholders for data gathering, ensuring representation from the traditional four helices of government, industry, academia, and civil society [393] and drawing on the Triple Helix methodology employed in Chapter 7. Such an approach is particularly relevant for wave energy, where familiarity and awareness of the technology are limited. By mapping stakeholder interactions and identifying feedback loops, systems thinking can highlight where interventions, such as targeted communication, are most likely to enhance acceptance. Understanding the SA of wave energy through the lens of systems thinking, making use of mental models, and technology acceptance frameworks, as well as acknowledging the diverse stakeholder groups, provides the foundation for this chapter. These concepts enable the identification of key variables, feedback loops, and stakeholder dynamics that shape SA and, therefore, project viability. Building on this, Section 8.3 outlines the methodology used to investigate these relationships empirically, combining qualitative and quantitative techniques to capture the complex factors influencing the SA of wave energy.

8.3 Methodology: A systems thinking approach

8.3.1 Overview

The primary aim of this chapter is to examine the factors influencing SA of wave energy and its hypothesised deployment in Ireland as a key driver for wave energy technology development. The objective is to develop a systems thinking framework, visualised through a CLD, that captures the key interconnections and feedback loops that underpin SA of this emerging RET in Ireland to provide insights to all stakeholders, including project developers, government agencies, and potential investors in the sector. Systems thinking provides a valuable methodology for understanding how social, technological, environmental, and policy systems interact within the RET context. Systems are composed of interconnected components that influence one another through feedback loops. Positive (reinforcing) feedback loops amplify change, whereas negative (balancing) loops promote stability [387], [394].

A CLD is a qualitative tool, from systems thinking, used to visually represent interconnections within a complex system. CLDs depict variables as nodes and causal interconnections as arrows, each with a polarity indicating the direction of influence (positive or negative) [395]. These diagrams, once fully constructed, aid in identifying leverage points and unintended consequences in complex socio-technical systems, such as the SA of wave energy technology as it approaches full-scale deployment at sea. Figure 8.3 provides an example of a reinforcing feedback loop.

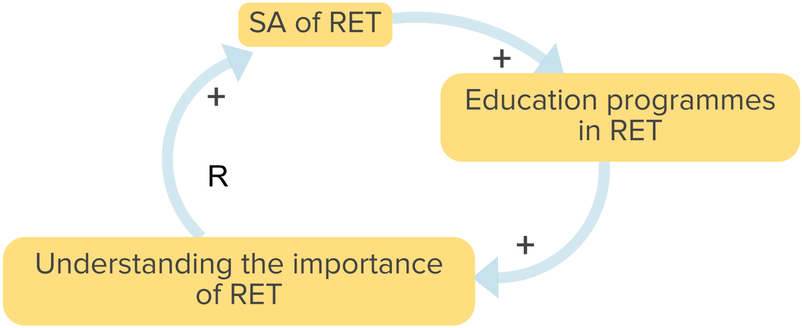

Figure 8.3: Reinforcing feedback loop. Societal Acceptance of renewable energy technology where SA denotes Societal Acceptance, RET denotes renewable energy technologies, R indicates a reinforcing loop.

8.3.2 Research Design

Due to the complexity of the socio-technical challenge of SA of wave energy technology deployment, a mixed-methods approach is adopted [396]. Quantitative data from surveys identify the main variables influencing SA of wave energy technologies, while qualitative data from interviews provides understanding and enables the validation of the CLD. The overall methodological process aligns with systems thinking principles and the framework proposed by Laimon [386], which emphasises refinement through stakeholder engagement. To critically analyse the SA of wave energy CLD, a second analogous CLD is developed for the Danish wind energy industry, which has previously overcome its own SA barriers. Using this benchmark, a comparative analysis is performed, and transferable insights are identified, while also validating the variables used for the SA of wave energy CLD.

The methodology draws on Laimon's [386] three-stage systems thinking process, described below and visualised in Figure 8.4.

- **Identification of key issues (variables):** For this chapter, variables influencing SA are identified through a literature review from diverse disciplines, policy analysis, and a structured survey using TAM and SETA, targeting diverse stakeholder groups using a Quadruple Helix framework.

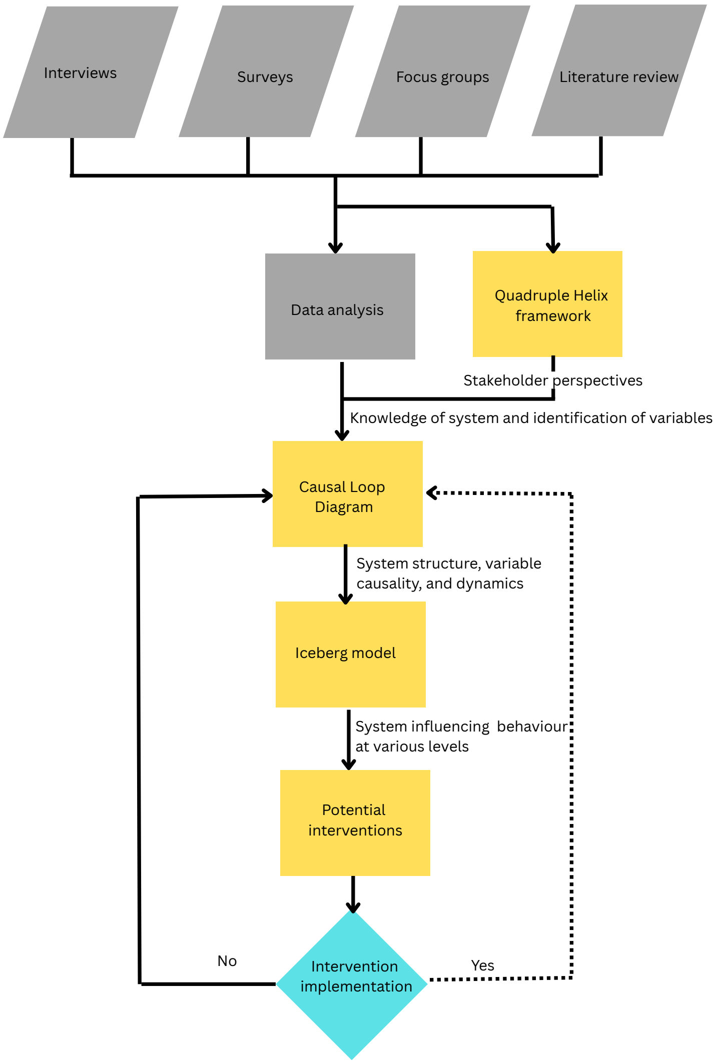

Figure 8.4: Systems thinking methodology for SA of wave energy in Ireland.

- **Development of the initial CLD:** Initial causal interconnections and polarities are mapped to produce a preliminary CLD describing the hypothesised system structure.
- **Validation and refinement:** The CLD is refined and validated through stakeholder interviews and workshops, incorporating feedback from academia, industry, and government representatives.
- In addition to Laimon's three steps, a comparison is made between the CLD developed to visualise the SA of wave energy technology and a CLD developed to express the retrospective application of systems thinking to the SA of wind energy in Denmark during its development phase (1973-1990).

8.3.3 Data collection

8.3.3.1 Literature review

A comprehensive review of peer-reviewed articles from diverse disciplines, government reports, and industry publications identifies key variables of the SA of wave energy. Comparative insights are drawn from the Danish wind energy transition to identify potential analogous loops, system archetypes, and leverage points that could inform the SA of Irish wave energy technology.

8.3.3.2 Survey design and implementation

A structured online survey was developed to quantify attitudes and perceptions toward wave energy technology in Ireland. The survey includes both closed-ended and Likert-scale items [397] designed to capture:

- Perceived benefits and risks of wave energy.
- Levels of trust in government, industry, and scientific institutions.
- Environmental and social concerns.
- Awareness and familiarity with wave energy technology.
- Identification of events, patterns, structures, and underlying mental models pertaining to the SA of wave energy in Ireland.

The survey was disseminated to members of the general public, coastal residents, policymakers, industry representatives, and academics. In total, 210 valid responses were collected, including 42 coastal dwellers and 85 participants from other stakeholder groups (industry, academia, and government). Survey questions were chosen for their suitability in capturing patterns across a diverse sample.

8.3.3.3 Qualitative data collection

To complement the quantitative data, semi-structured interviews and focus group discussions were conducted with selected stakeholders from academia, industry, and government. These discussions elicit deeper insights (from mental models) into perceived causal interconnections, interdependencies, and feedback loops within the system. The qualitative phase also serves to refine and validate the causal interconnections identified in the survey and literature.

8.3.4 Data analysis

8.3.4.1 Quantitative analysis

Survey data were analysed to identify key patterns and trends in stakeholder perceptions. An analysis was conducted to explore interconnections between variables such as perceived benefits, trust, environmental concern, and policy support. The most salient variables were extracted as inputs for the construction of the CLD.

- **Qualitative analysis** Interview and focus group data were transcribed and analysed thematically using a hybrid inductive (data-driven) and deductive (theory-driven) coding approach [398]. Codes and themes were mapped to the identified variables. Causal links between themes are incorporated into the CLD (See Table 8.2).
- **Integration and synthesis** Quantitative and qualitative findings are integrated to align statistically significant patterns with qualitative insights. This process allows for the identification of reinforcing and balancing feedback loops, ensuring that the CLD reflects both empirical evidence and stakeholder understanding.
- **Development of the CLD**

  The integrated dataset informs the development of an initial CLD capturing hypothesised causal interconnections among system variables influencing SA. Arrows representing causal links are assigned positive (+) or negative (–) polarity depending on the direction of influence.
- **Validation**

  The preliminary CLD is validated through stakeholder consultation involving experts from academia, industry, and government. Semi-structured interview data informs the plausibility of the causal interconnections. Adjustments were made to reflect consensus views and eliminate redundant links (See Figure 8.6).

The SA of wave energy in Ireland CLD is compared to a CLD that visualises wind energy development in Denmark during its development phase in order to identify analogous leverage points and system archetypes. This combination of stakeholder validation and comparison to Danish wind energy strengthens the model's validity and ensures that the final CLD accurately represents the Irish context of SA of wave energy technology development. The validated diagram (Figure 8.6) serves as a conceptual framework for understanding how multiple feedback mechanisms shape the SA of wave energy technology deployment in Ireland that might inform pragmatic policy interventions to support the development of the technology to reach the deployment phase. The methodology might also be used as a template that can be used for other emerging RETs.

8.3.5 Methodology summary

The methodology employed in this chapter integrates quantitative and qualitative data to capture the complex nature of SA of wave energy. Through iterative data collection, analysis, and stakeholder validation, the resulting CLD provides a holistic representation of the socio-technical system that can provide insights to inform practical policy interventions, while avoiding costly delays or project cancellations that can be a result of a lack of awareness of the underlying causes of SA.

8.4 A retrospective application of the systems thinking approach to Danish wind energy development

In order to gain insights that might inform the application of systems thinking to the SA of wave energy in Ireland, this chapter retrospectively applies the proposed methodology to wind energy deployment in Denmark, a RET that emerged as commercially viable throughout the 1970s to 1990s, resulting in Denmark becoming, and remaining, a world leader in the sector (as discussed in Chapter 2). Denmark's success in wind energy was shaped by a system constructed with social, political, economic, and technological feedback loops. Table 8.1 lists the key systemic variables that influenced the SA of wind energy in Denmark from 1973 to 1990, organised into categories (social, policy, economic, technological, environmental, and cultural). The variables that form this CLD are drawn from a literature review, including much of the work in Chapter 2, and particularly the works of [399], [400], [48].

Figure 8.5 shows a CLD representing a system composed of interconnecting variables that describe the factors related to SA of wind energy in Denmark during its development phase (1973-1990). There are more than 70 feedback loops, which represent the role of long-term government policies, policies of energy self-sufficiency, scarcity of imported fossil fuels, increasing prices, and availability of resources, among others. All of these elements were discussed in detail in Chapter 2 and Chapter 4. Four feedback loops are highlighted for brief discussion.

- **R1 - Community activism**. *Community movements → public support → environmental consciousness → community movements.*

  This reinforcing loop highlights the importance of community involvement that was a cornerstone of Danish wind energy SA with groups such as OVE – Organisationen for Vedvarende Energi (The Danish Organisation for Renewable Energy) [401], which advocated for wind energy, distributed technical information,

Table 8.1: Systems thinking variables for SA of Danish wind energy technology development between 1973-1990

Category	Variable	Description
Policy and Governance	Energy security concerns	The 1973 oil crisis exposed dependence on foreign oil, creating strong motivation for energy diversification.
	Government R&D support	Funding for testing and innovation (e.g., Risø) National Laboratory) increased turbine reliability.
	Cooperative ownership policy	Allowed local communities to own turbines collectively, strengthening legitimacy and acceptance.
Economic	Rising fossil fuel prices	Made wind power more economically attractive and politically urgent.
	Financial incentives	Subsidies and tax benefits for cooperatives encouraged citizen investment.
Technological	Improved turbine design	Standardised testing led to safer, more reliable systems, reducing public skepticism.
	Certification	Established credibility through verified performance data.
Social and cultural	Community movements	Grassroots activism fostered environmental awareness and local ownership models.
	Trust in cooperatives	Social cohesion and trust reinforced acceptance through perceived fairness.
	Energy self -sufficiency values	Cultural preference for autonomy and resilience resonated with wind energy ideals.
Environmental	Environmental consciousness	Growing awareness of pollution and sustainability made wind energy more desirable.
	Wind resource potential	Reliable wind conditions increased perceived feasibility.

and organised cooperatives. OVE worked alongside organisations such as Tvind [402], which promoted educational programmes related to wind energy.

- **R2 - Cooperative ownership**. *Cooperative ownership →community trust →community movments → public support → cooperative ownership.*

  The global leadership position that the Danish wind energy industry holds has roots in community ownership. Around 100,000 Danes (2% of the population at the time) owned shares in a community wind turbine. Over 80% of installed wind capacity was owned by private individuals or cooperatives [403].

- **B1 - NIMBY**. *NIMBYism → (a decrease in) public trust → (a decrease in) public support → (increased) NIMBYism.*

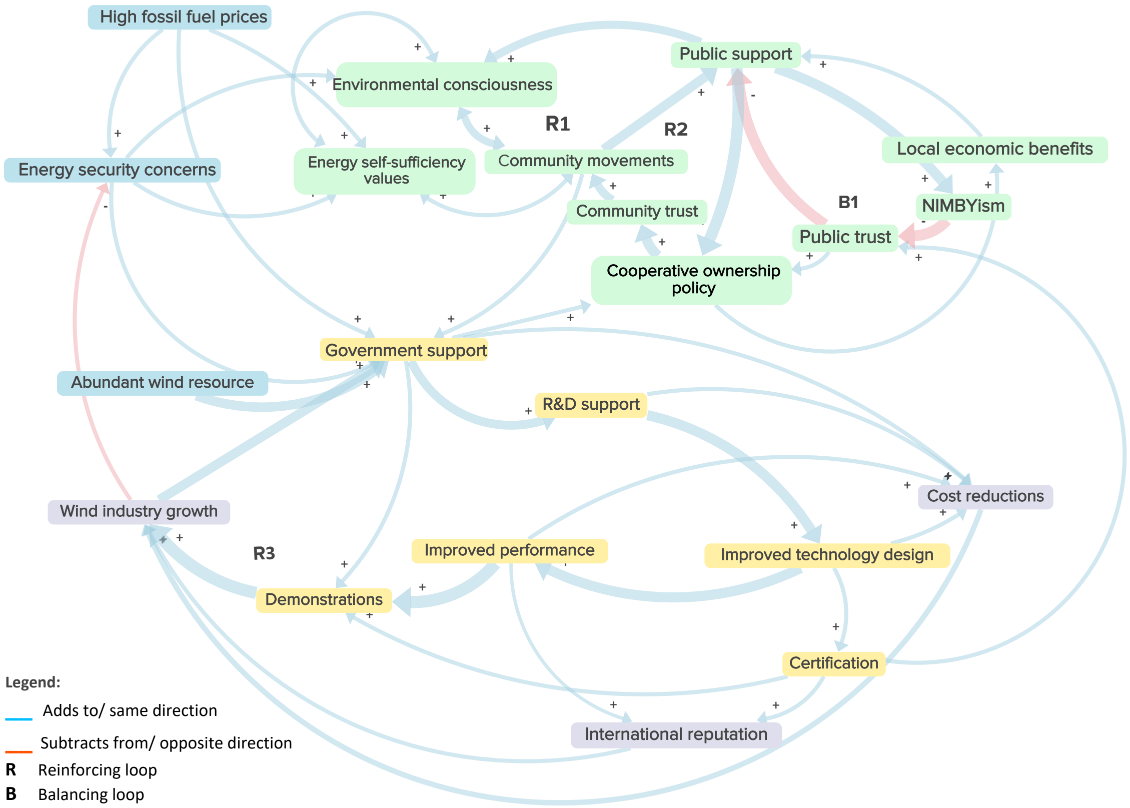

Figure 8.5: Societal Acceptance of wind energy technology in Denmark 1973-1990. Where thick lines denote influential feedback loops and polarity is indicated by + and -. R denotes reinforcing loops, and B denotes balancing loops. External elements are coloured blue, community-related variables are green, R&D variables are yellow, and industry variables are lilac.

This balancing loop (a loop that counteracts change) shows the effect that a lack of public trust can have on the deployment of RETs. In Denmark, this was mitigated to a large extent by cooperative ownership and government incentives.

- **R3 - Industry growth**. *Government support → R&D support → improved technology design → improved performance → more full-scale demonstrations → wind industry growth → government support.*

  One of the reinforcing loops related to industry growth stems from government support for R&D projects, which leads to improved technology design, enhanced performance, and an increased number of demonstration projects. This, in turn, creates market interest and drives wind industry growth.

The retrospective analysis of Danish wind energy, through a CLD, presents a model of how SA emerged from the interaction of social, policy, economic, and technological feedback loops. From this model, four key leverage points can be deduced which include: 1) government prioritisation and long-term R&D funding, yielding improved turbine reliability and reduced costs, promoting technology development; 2) cooperative ownership and community engagement, which built trust and mitigated NIMBYism as the technology advanced to full-scale deployment; 3) education, which fostered acceptance of renewable energy; and 4) financial incentives, which encouraged both community and industrial investment. These reinforcing and balancing feedback loops promoted technology maturation and market growth, showing how targeted interventions can shape the SA of emerging renewable technologies, and providing a benchmark for a comparative wave energy technology analysis.

8.5 A qualitative modelling tool for societal acceptance of wave energy device deployment

Following the methodology employed in Section 8.3, the variables exposed through the surveys, multi-disciplinary literature review, and government report review are described in Table 8.2, before a CLD is developed, following validation from extensive stakeholder interactions from industry, academia, and government actors, with insights from the Danish wind CLD. Table 8.2 describes the variables captured through the surveys, literature review, government report review, and validated through interviews with wave energy stakeholders, while Figure 8.6 provides a visualisation of the variables and how they interact in a CLD.

8.6 Interventions and leverage points

There are 68 feedback loops reflected in the CLD (Figure 8.6). The most influential feedback loops are highlighted with thick connection lines and described in this section to reveal potential leverage points, following the hierarchy developed by Meadows [384]. Identifying these leverage points enables their categorisation by potential impact, highlighting key areas of focus to support the sustainable commercialisation of wave energy technology in Ireland.

- **R1 - Government prioritisation loop.** *Government prioritisation → government regulatory policy → consenting procedures → availability of test facilities → industry investment → government prioritisation.*

  This reinforcing feedback loop captures a core policy feedback central to systemic leverage. Investment in policies that support an improvement in consenting

Table 8.2: Systems thinking variables for SA of Irish wave energy technology development

Category	Variable	Description
Policy and governance	Climate disaster concerns	Increasing natural disasters due to climate change exerts pressure on the government to speed the green transition
	Government prioritisation	More mature RET such as wind and solar energy are preferred in national policies
	Marine spatial conflict	Concerns from shipping and fishing communities on the use of marine space
	Investment in RET education	Literature review and survey data indicate that RET education significantly affects SA of RET
	EU and UN target	Ireland faces up to €26bn in fines for missing carbon emission targets
	Consenting procedures	New policies (e.g. the Marine Area Planning [404] and agencies (e.g. Maritime Area Regulatory Authority [405]) to improve consenting, but improvements are slow
	Test facilities	Have been developed to cover all TRL but 2 of 3 test facilities are not operational
Economic	Relative LCoE	Relatively high LCoE [36]
	Government financial supports	Such as Feed-in Tariffs, CfDs or preferential insurance schemes can boost investment in emerging RETs
	Industry investment	Factors such as company failures in the sector, relatively high LCoE of wave energy, and lack of design archetypes have affected investment in wave energy
Technological	TRL	Wave energy projects struggle to proceed beyond TRL 6, due to an increase in costs not met by market demand [49].
	TPL	Introducing performance metrics e.g. TPL can encourage investment and attract government support [49] (also Section 5.3)
	R&D activities	Well funded within universities from national and EU sources. Ireland ranks highly in wave energy R&D (See Section 6.6)
	Successful WEC deployment	Few large-scale demonstration projects at sea affects awareness and raise reliability concerns
Social and cultural	Understanding RET importance	Growing awareness of RET importance (e.g. through education campaigns)
	Low familiarity	Most people are unaware of wave energy technology
	Visual impact	Concerns about the ocean views from coastal dwellers
	Sensitivity of location	Deep connection with the ocean, and worry over treatment of this resource
	Community trust	Concerns over government-mandated adoption of new technologies are compounded by ocean location
	Residential costs	Perception that if visual impact is interfered with at high cost coastal locations, house values will depreciate
	NIMBYism	More nuanced than the implied recalcitrance involving many factors. See Chapter 8
	Financial wellness	Can affect acceptance of new technologies on a community scale

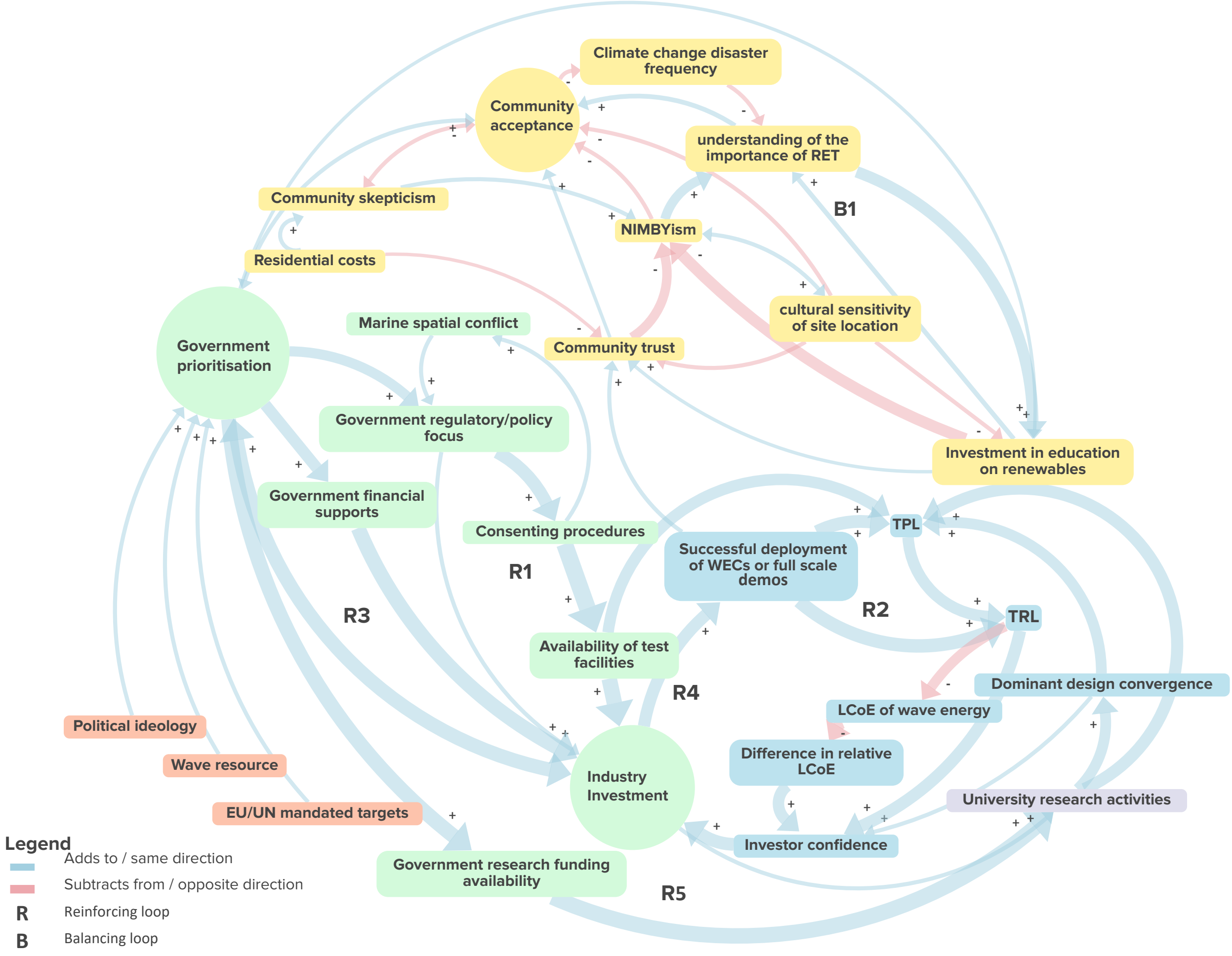

Figure 8.6: Societal Acceptance of wave energy technology in Ireland. Where thick lines denote highlighted feedback loops and polarity is indicated by + and -. R denotes reinforcing loops, and B denotes balancing loops. External elements are coloured orange, community-related variables are yellow, industry variables are blue, government-related variables are coloured green, and academic variables are lilac.

procedures will lead to the development and availability of test facilities that can be usefully exploited by industry. Industrial activity will, in turn, prompt government prioritorisation. This reflects a movement to the *success to the successful* archetype as resources (attention, funding, policy support) tend to flow toward areas already showing success. As industry investment grows, it validates government policy, prompting even more prioritisation, a self-reinforcing pattern. This loop could also exhibit traits of a reinforcing growth loop that risks stagnation due to the balancing constraints, including the non-operation of wave energy test facilities for TRLs 4-9 that persist in Ireland.

This reinforcing loop exposes an information and policy structure leverage point; specifically, the rules and processes (consenting procedures) that govern how easily test facilities can be developed and accessed. Improving consenting procedures changes the structure of information and delays in the system. By reducing resistance at that node, the reinforcing loop strengthens more efficiently [394].

- **R2 - Deployment loop.** *Industry investment → Successful deployment of WECs or full-scale devices → TPL [267]→ TRL [129] → Investor confidence → Industry investment.*

  This reinforcing loop captures how successful deployment and long-term testing of full-scale devices at sea improve performance (reflected by higher TPL). Performance improvements drive progression in TRL, leading to greater investor confidence and, consequently, increased industry investment.

  This loop represents the *success to the successful* archetype within an innovation or technology context rather than a policy context. However, R2 could evolve into a *limits to growth* archetype if physical resources (e.g., funding and/or test sites) become limiting, or if device failures during sea trials reduce confidence, introducing a balancing feedback.

  The main leverage in R2 lies in information and capability structures, particularly the rate and success of deployment, and the feedback mechanisms that enable TRL progression. Leverage arises from improving learning efficiency and knowledge transfer between deployments, for example, by accelerating iteration and feedback between prototype testing and design refinement, or by reducing the cost and delay between TRL stages.

- **R3 - Government financial supports.** *Government prioritisation → government financial supports → industry investment → government prioritisation.*

  This reinforcing loop emerged as critically important to the industrial stakeholders interviewed and surveyed for this chapter. Stakeholders consistently emphasised that financial support is essential for wave energy projects to proceed, particularly at mid Technology Readiness Levels (TRLs 4–6) when costs increase exponentially (see Section 5.4).

  Reducing LCoE depends on improving performance and lowering capital costs (See also R5). However, 'market pull' has not yet developed in this sector, leaving industry progress dependent on government financial support as discussed in Section 5.7. Targeted and predictable funding mechanisms can attract private investment, which in turn reinforces government prioritisation, driving regulatory and policy focus, investment in skills and education, and greater community acceptance.

The key leverage point within this loop lies in the structure and predictability of financial support mechanisms. A higher-leverage intervention would involve a policy shift from short-term subsidies for emerging technologies toward strategic, innovation-focused investment in wave energy.

- **B1 - Social resistance loop.** *Investment in education on RETs → reduces NIMBYism → understanding of the importance of RET → investment in education.*

  This balancing loop describes how an investment in RET education reduces NIMBYism and promotes understanding of the need for RET, which encourages investment in education. This is a balancing loop because education acts to counteract growth in opposition, keeping public resistance under control. The system archetype revealed is the *balancing with delay* archetype. Public opposition tends to increase when new projects are planned. Education and awareness campaigns take time to influence attitudes, causing a delay in the system. Without timely intervention, opposition could hinder project deployment. Education acts as a balancing mechanism, reducing public resistance over time. The key leverage point is related to the timing and participation in education campaigns.

- **R4 - University research loop.** *Government prioritisation → research funding availability → improved TPL → TRL → A change (improved) LCoE of wave energy → change (improved) difference in LCoE relative to other modalities → investor confidence → industry investment → government prioritisation.*

  This innovation-driven reinforcing loop shows how government prioritisation drives research funding, which improves technology performance and commercial readiness and reduces the LCoE for wave energy. Lower LCoE relative to other energy sources improves investor confidence and attracts industry investment, which reinforces government prioritisation, creating a virtuous cycle. This loop exemplifies the *success to the successful* archetype, with key leverage points including the effective distribution of funding and ensuring that research is translated into practical, cost-reducing results that have a positive impact on technology performance, and shows the importance of incorporating a performance metric, such as TPL, when making funding decisions. This loop interacts with deployment, policy, and financial support loops, showing the impact of supported innovation on the overall system.

- **R5 – Dominant design convergence loop.** *University research activities → dominant design convergence → TPL → TRL → investor confidence → industry investment → government prioritisation → university research activities.*

  One of the key challenges facing wave energy technology development is the absence of a dominant design [406] (see also Section 6.2). Due to the inherent complexity of wave energy conversion systems and the wide diversity of device concepts, no particular design has yet achieved a TRL sufficient to enable large-scale commercialisation [305]. The R5 Dominant Design Convergence Loop represents a reinforcing feedback process in which increased university research promotes design convergence, raising both commercial readiness and technological performance, enhancing investor confidence, and stimulating greater industry investment and government prioritisation, reinforcing further research activity. However, in the current context of wave energy, this reinforcing loop is constrained by a *limits to growth* archetype, arising from the lack of a dominant design. Secondary dynamics such as *shifting the burden* (where the emphasis is placed on short-term TRL improvements) and *success to the successful* (for early wave energy developer frontrunners) may also emerge. Key leverage points include enhancing information flows, integrating TPL assessments, aligning policy objectives toward design convergence, and analysing funding mechanisms.

When comparing the SA of wave energy technology to a retrospective analysis of wind energy in Denmark, where the key leverage points include government prioritisation, long-term R&D funding, cooperative ownership, and community engagement, education, and financial incentives, there is much in common with the leverage points revealed from the analysis of wave energy. Missing from the wave energy-related data are cooperative ownership and long-term government strategies, which are influential factors that contributed to the success of Danish wind.

The CLD in Figure 8.4 reflects the dynamics of the early phase of Danish wind energy technology development (1973–1990). However, the system has evolved significantly since (See Figure 8.7). In particular, the role of stakeholder incentives and power has shifted. During the early development phase, cooperative ownership structures ensured that local communities directly benefited from wind energy deployment [102]. This alignment of incentives strengthened the reinforcing loop between community activism, public support, and wind energy development (R1 and R2 of Figure 8.4). However, as the industry matured and ownership structures shifted toward larger commercial developers, the direct economic benefits to local communities declined. As a result, community influence was increasingly more apparent through political pressure, where local opposition could create controversy and influence permitting decisions [249]. While local communities may have limited authority, their ability to generate political pressure can significantly affect project approvals. Recent slowdowns in wind installations in Denmark have been partly attributed to changing societal acceptance, highlighting how evolving stakeholder incentives can alter previously reinforcing feedback structures [243]. This evolution provides a useful comparison with the Irish wave energy system, where questions of community benefit, ownership structures, and political incentives are also likely to influence SA.

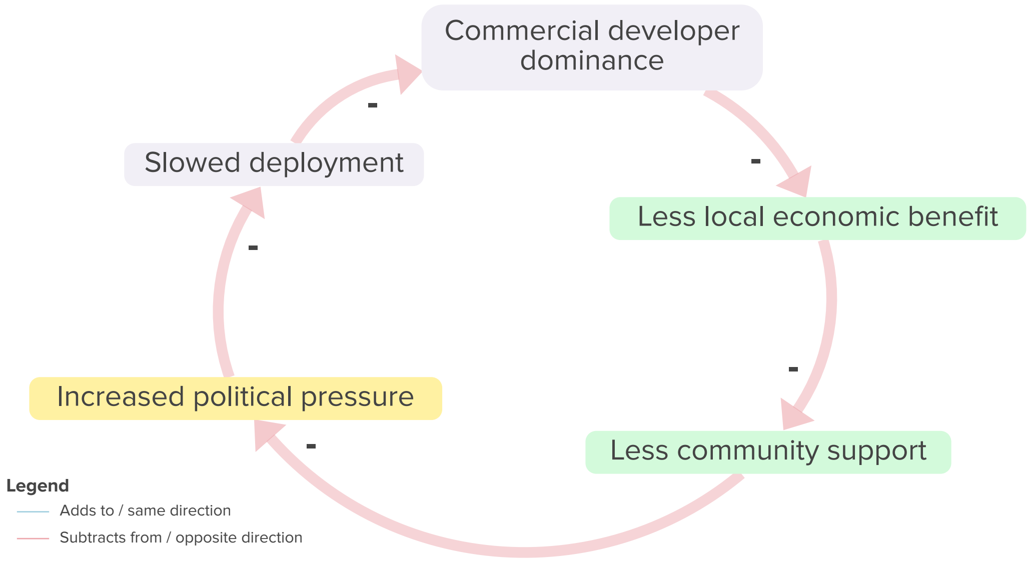

Figure 8.7: Societal Acceptance of wind energy technology in Denmark in a modern context. Where polarity is indicated by + and -. Community-related variables are green, Industry variables are lilac, and government-related variables are coloured yellow.

Also, Danish wind energy technology, did not have to contend with a lack of dominant design, as the Gedser turbine design proliferated for many years (see Section 2.3). Funding, financial incentives, and education appeared in both CLDs, recognised as key influencing factors.

In developing a CLD of the SA of wave energy technology, this work has presented a mechanism to describe the dynamics of the system. This CLD has enabled the identification of leverage points within key feedback loops. These leverage points target deeper structures and mental models rather than surface events, revealing intervention opportunities in a complex, evolving system that can strengthen the SA of wave energy technology.

8.7 Discussion and conclusions

The lack of SA is a major non-technical barrier to RET integration, and should be factored into wave energy project plans. This is particularly pertinent at the current stage of development as wave energy progresses towards testing of full-scale demonstration devices at sea, and ultimately deployment, in order to mitigate risks of civil protest that could cause costly delays or project failures.

SA should be considered from the perspectives of socio-political acceptance, community acceptance, and market acceptance, and goes beyond NIMBYism. TAM and SETA are models that can be used to effectively explore SA for wave energy technology.

The Systems thinking methodology employed in this chapter incorporates SA frameworks (TAM and SETA), as well as a framework through which it is possible to analyse stakeholder perspectives (Quadruple Helix), and the Iceberg Model, which encourages a deeper dive than surface-level events to uncover underlying mental models. This methodology, aligned with systems thinking principles, enables us to assess how variables in a complex system interact in order to expose system archetypes and leverage points that shape the system governing the SA of wave energy and can inform practical and pragmatic policy and funding decisions derived from the identification of root causes to foster durable social legitimacy.

The retrospective analysis of Danish wind energy, through a CLD, demonstrates how SA emerged from the interaction of social, policy, economic, and technological feedback loops. The retrospective application of systems thinking to Danish wind technology during its development phase identified, *inter alia*, the importance of cooperative ownership to the development of wind energy technology, the effect of NIMBYism (although this should not be oversimplified), and the links between government support and industry growth. This, at least, shows that civil society is a crucial factor in ensuring emerging RET development. Moreover, policies should avoid short-term quick fixes. An intervention in policy reform should be long-lasting and should involve industry, civil society, academia, and government stakeholders.

CLDs can usefully be employed to visualise a system and its interacting variables. The CLD of wave energy SA in Ireland (8.6) revealed 68 feedback loops as part of a complex system. A number of loops stood out as being of particular influence. Meadows' hierarchy of leverage points [384], is applied to underscore the potential policy changes and long-term systemic drivers that could support wave energy technology growth in Ireland.

- R1, the government prioritisation loop, showed that improving consenting procedures reduces resistance in that loop, which would, in turn, lead to industry investment and government prioritisation, the reinforcing loop being strengthened considerably.

- R2 shows the feedback loop between industry confidence and investment, TPL, TRL, and demonstration device deployment. A higher leverage point would be shifting the goal from building single successful wave energy converter prototypes to accelerating industry learning, a change in purpose that could accelerate TRL growth.
- R3, the government financial support loop, suggests a shift in policy from subsidising emerging technologies to strategically investing in a robust renewable energy system that includes wave energy.
- B1 represents a learning loop. Education builds understanding and influences attitudes, which mitigates the risk of social resistance.
- R4, the university research loop, shows a strong link between research activity and the maturation of wave energy technology, when performance is considered, which promotes industry interest and government prioritisation.
- The R5 dominant design convergence loop illustrates how increased university research can potentially drive convergence toward a dominant wave energy device design, which improves TPL and TRL, boosting investor confidence, industry investment, and government support, thereby reinforcing further research. The loop is currently constrained by the absence of a dominant design, limiting the potential for large-scale commercialisation.

Viewing SA of wave energy in Ireland through a systems thinking lens enables the inclusion of an interdisciplinary lens into this complex problem that helps incorporate a wide view of perspectives that is typically challenging, leading to oversimplications. The method proposed in this work is applied to wave energy in Ireland, as the technology progresses toward full-scale commercialisation, and can be used as a replicable template for the use of systems thinking with other RETs for effective, pragmatic policy and funding interventions.

Finally, as evident from both the Danish wind energy CLD and the Irish wave energy CLD, SA emerges from the interaction of social, policy, economic, and technological feedback loops. This suggests the need for a wave energy champion, a person or body capable of navigating the complex interactions between government, industry, civil society, and academia. Such a champion could facilitate knowledge exchange, align policy and funding incentives, and coordinate technical development alongside civil expectations, promoting broad acceptance and improving the likelihood of commercial sustainability. The CLDs show that SA emerges from multiple reinforcing and balancing loops, highlighting the importance of strategic interventions to strengthen positive feedback and mitigate limiting dynamics.

Future work in this area could introduce a stock and flow diagram [387] to represent and analyse the system's dynamic structure, enabling the testing of policy interventions, simulation of scenarios, and assessment of system responses. This approach could potentially provide deeper insight into the interactions between TRLs and TPLs, thereby clarifying the behaviour of underlying variables. Further research could also extend the current methodology by integrating additional analytical frameworks, specifically, Futures/Foresight [407] and the Theory of Change [408]. These frameworks could help explore plausible pathways for implementing the interventions identified in this chapter, as well as determine the dependencies among actions required to achieve sustainable outcomes.

9
Conclusion

Contents

Part I of this thesis describes the status of wave energy technology development in Ireland, gives an overview of the history of Danish wind energy, and outlines the factors that led to Denmark's global success in the sector, while comparing these factors to the current status of wave energy in Ireland. Part II explores specific enabling factors influencing wave energy in Ireland, including funding gaps and metrics, IPP strategies, stakeholder perspectives, and the SA of wave energy, as well as the application of frameworks and methodologies through which these factors can be explored.

9.1 Key findings

The overall purpose of this thesis is to determine a path to commercialisation for wave energy in Ireland by looking at external enabling factors and how they can be supported, particularly through policy interventions. This is conducted through a thorough benchmarking against the enabling factors enjoyed by Danish wind during its technology development phase, through an analysis of funding availability and metrics for wave energy technology, an analysis of IPP and trends in the area through patent and bibliometric analysis, an analysis of stakeholder perspectives using a TH framework, and SA of wave energy technology through a systems thinking lens. The key findings of this thesis can be summarised as follows:

9.1.1 Policy and governance

An in-depth analysis is conducted in Chapters 2-4, through the extant literature, public reports, and interviews, of the policies affecting wind energy technology development in Denmark, benchmarked against policies affecting Irish wave energy technology development. Denmark's long-term, politically consistent, commitment to renewable energy contrasts with Ireland's reactive, compliance-driven approach. Ireland needs clear, long-term wave energy targets, consistent policy interventions, and a "wave energy champion" to bridge the gap between academia, industry, and government.

9.1.2 Research and development, and infrastructure

Through the analysis conducted in Chapters 2-4, it is evident that Denmark's success was driven by open innovation and institutional hubs (i.e. the Risø Test Centre), combining R&D, certification, and industry collaboration. In contrast, and despite significant evidence of leadership in this sector, Ireland's fragmented research environment and non-operational test facilities (SmartBay and AMETS) hinder progress, revealing innovation without a policy-led imperative. A dedicated wave energy innovation centre, or national research hub, could emulate the Danish model and improve technology transfer from academia to industry.

9.1.3 Funding and evaluation metrics

An analysis of available funding and metrics used to determine the commercial progression of wave energy projects through an analysis of funding agency reports, literature, and stakeholder interviews. Data shows that persistent funding gaps exist at mid-TRL levels (4-6), exposing the "Valley of Death", where wave energy technology projects struggle to transition from prototype to full-scale, at-sea demonstration, due to an exponential increase in costs at that stage, coupled with a lack of ‘market pull’ resulting in critical cash flow challenges. Current reliance on TRL and LCoE metrics limits the ability to assess commercial potential, particularly when assessing projects for potential pubic funding. A shift toward metrics that include performance (e.g., TPL, IEA-OES Task 12), and stage-gated funding frameworks such as those seen at WES, could improve resource allocation. In addition, public funding must be matched by de-risking tools (such as insurance, guarantees, or feed-in tariffs) to attract private investment.

9.1.4 Intellectual property and innovation protection

A patent trend analysis for wave energy is conducted along with a bibliometric analysis. These are coupled with an examination of IPP trends in Irish wave energy technology development. The analysis shows that patent registration in the wave energy sector remains low and uneven around the world due to the predominance of small to medium scale operators in the sectors and cashflow challenges, along with the sentiment that IPP related to large scale devices is less likely to be effective, and trade secrecy is often preferred. Another finding from the patent and bibliometric trend analysis is that innovation in wave energy is largely at the R&D phase indicating that projects require some external support to move toward commercial maturity. Bibliometric analysis reveals growing research activity in wave energy, but with limited commercial translation. As long as wave energy is an emerging technology, bibliometric analysis can reveal new trends in the sector. Mixed IPP strategies, or a combination of patents, trade secrets, and collaborative agreements, may better suit small firms in early-stage markets, such as in the wave energy sector.

9.1.5 Stakeholder collaboration and the Triple Helix model

The main stakeholders observed in this thesis are drawn from academia, industry, government, and the general public. The TH framework (describing collaboration between stakeholder groups from academia, industry, and government) offers a pathway for consensus-based innovation policy, and is particularly useful for analysing perspectives on emerging technology developments, such as in wave energy. An analysis focusing on societal acceptance in chapter 8 introduces the quadruple helix framework, bringing in the fourth stakeholder group, the general public. Stakeholder interview data revealed strong alignment on funding priorities, but exposed a lack of coordination and leadership. The retrospective application of the TH model to Danish wind highlights the importance of an integrated “innovation ecosystem.”

9.1.6 Societal acceptance and systems thinking

SA is a non-technical barrier, crucial to the successful deployment of renewable energy technologies, and will be vital for wave energy technologies as projects move towards full-scale demonstration and deployment. Systems thinking visualised through CLDs reveals dynamic feedback between policy, technology, funding, and public attitudes, particularly those underlying mental models linked to individuals' connection to the ocean. A systems thinking approach to the societal acceptance of wave energy provides a visualisation of the systems, and assists with the identification of policy interventions which should target high-leverage points such as education, transparent governance, community participation, and long-term policy stability, in order to avoid costly delays and project failures. The need for a wave energy champion re-emerges as a systemic leverage point across policy, innovation, and social domains.

In short, Ireland's wave energy trajectory can mirror Denmark's wind energy success only if a systemic, coordinated, and proactive approach is adopted. Moreover, success depends on alignment across policy, technology, funding, and society, i.e. a "whole-system" approach, rather than piecemeal reform. This aligns with broader research on energy transitions, which emphasise that the shift to renewable energy constitutes a systemic transformation involving technological, institutional, and geopolitical change [409]. Lessons from Danish wind highlight the interdependence of political commitment, societal buy-in, institutional learning, and consistent, sustained investment.

9.2 Policy recommendations

Governance and leadership

- Appoint a national "Wave Energy Champion" and/or coordinating body. This theme arises multiple times throughout this thesis through survey and stakeholder interview data, from benchmarking against Danish wind energy technology development, and from the funding analysis conducted in Chapter 5. The wave energy technology sector needs someone who can exert influence at the policy level, who is a credible representative of academia and industry, and who can involve civil society in a meaningful way.The findings reveal that political and institutional power imbalances significantly shape wave energy commercialisation. Government decision-making is constrained by short-termist policies, while early-stage developers have limited influence over policy, highlighting the need for champions to navigate these power dynamics.

- Establish explicit wave energy deployment targets within Ireland's renewable strategy. An analysis of current ORE policies shows that Ireland, unlike many global counterparts, including the EU, does not have quantitative targets for wave energy development or deployment. Danish wind energy technology development benefitted from long-term, specific targets, where early R&D efforts in the industry were supported with clear commercial objectives (See Chapter 2).
- Ensure long-term political and regulatory stability. Wave energy technology development in Ireland shows a stuttering trajectory, especially when compared with the long-term policies that supported the development of Danish wind energy. Given the length of time required to bring a wave energy device from concept validation to commercial validity (at least 10 years), long-term, quantifiable policy measures are essential.

Funding and investment

- Create a dedicated mid-TRL support scheme to bridge the Valley of Death. An analysis of funding received from the main funding bodies in Ireland from 2012 to 2022, compared to funding programmes in other countries (Chapter 5), along with stakeholder surveys and interviews (Chapter 7) indicate that targeted funding for mid-TRL wave energy projects is not currently available, and is required to push commercial maturation.
- Adopt stage-gated, performance-based funding mechanisms (as in WES and EuropeWave). Funding should be allocated, and viability measured with an incorporation of performance-based metrics to ensure that the projects most likely to succeed are those projects that receive funding
- Introduce market-pull instruments (e.g., guaranteed tariffs or revenue support) to complement the R&D push. As well as providing support to bridge the VoD, these measures would demonstrate lasting government commitment similar to that shown in the Danish wind case through dedicated market-pull instruments.

Research and innovation infrastructure

- Establish a national wave energy research hub, modelled on Risø, integrating testing, certification, and collaboration. such as hub would centralise expertise, avoid duplication of effort, provide Ireland with a base from which to demonstrate leadership in wave energy technology development, and, like Risø, serve as a link between academia, industry, and government bodies.

- Foster open innovation and data-sharing between academia and industry. As seen in the CLD in Chapter 8, and the TH stakeholder surveys and interviews in Chapter 7, this would build investor and government confidence, and prevent costly repetition of failures at an early stage of development.

- Develop test facilities that are operational across all TRLs. The closure of SmartBay and AMETS test facilities indicates a lack of sustained strategic commitment to wave energy infrastructure, undermining investor confidence and disrupting the continuity required for technology progression from prototype to commercial demonstration despite the efforts of organisations such as the Marine Institute (see Chapter 3).

Societal engagement

- Integrate SA analysis into early project design to mitigate the risk of costly delays and project failures. A systems thinking approach to SA of wave energy can identify feedback loops between community trust, policy stability, and project performance, enabling technology developers, policy-makers, and potential investors to identify leverage points to decrease risk.

Monitoring and evaluation

- Replace linear technology maturity assessment metrics with metrics that encompass commercial readiness, performance, and SA. Current evaluation metrics face notable limitations. While TRL and LCoE are widely adopted and easy to interpret, they do not fully capture the commercial and techno-economic realities of early-stage wave energy projects. TRL does not consider either performance or market viability, and LCoE estimates are highly uncertain due to limited data and the absence of a dominant WEC design. More comprehensive approaches, such as Weber's TPL [267] and the IEA-OES Task 12 model [259], integrate technical, economic, and performance considerations, and when combined with stage-gating frameworks, can progressively de-risk investments while providing a more holistic assessment of project potential.

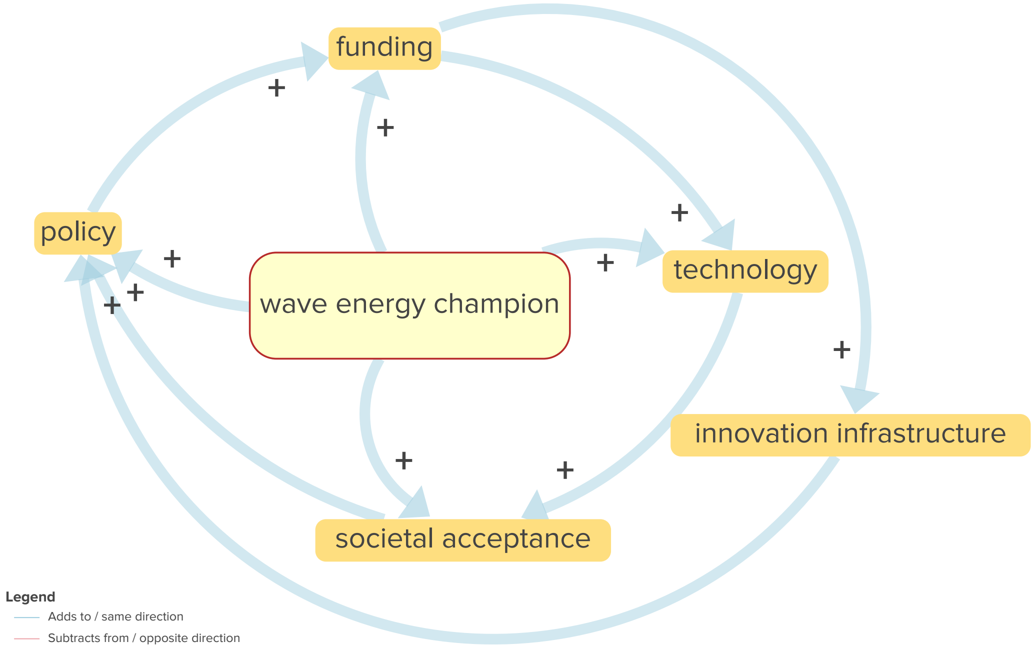

Figure 9.1: Wave energy CLD.

9.3 Limitations

This work, and its conclusions, are necessarily subject to certain limitations. Technical differences between wind energy technology and wave energy technology limit direct transferability. Also, due to the emergent nature of wave energy technology, there is limited stakeholder representation and data available. Moreover, much of renewable energy policy, both national and EU-based, is relatively recent and requires more time to fully take effect. While an econometric analysis could provide quantitative insight into investment dynamics, such an approach is not feasible within the scope of this thesis. The Irish wave energy sector is at an emergent stage, with limited historical data on costs, revenues, and commercial outcomes. Many key variables are either unavailable or highly uncertain, making robust econometric modelling impractical. Consequently, this thesis focuses on qualitative and systems-based methodologies such as stakeholder analysis and CLDs that are better suited to capture the socio-technical and policy factors influencing early-stage wave energy development. That said, future work, as the industry progresses, could usefully include econometric analyses to quantitatively evaluate market drivers, cost trajectories, policy impacts, and investment risks.

9.4 Future research directions

The findings of this thesis could be extended through a follow-up to the systems thinking approach to SA of wave energy using quantitative modelling (e.g., stock and flow simulation of policy impacts). The current systems thinking methodology could also be extended by integrating additional analytical frameworks, specifically, Futures/Foresight and the Theory of Change . Additionally, exploration of SA of wave energy could be examined in an island community where geographic isolation and high energy costs often shape unique socio-technical dynamics. Such a case study would provide valuable insights into how local cultural values, community engagement processes, and energy security concerns influence public perceptions and acceptance pathways to emerging RETs. Another extension to the work could be a more detailed analysis of the political factors at play in Ireland today, in contrast to Danish political sentiment during the development phase of Danish wind. This could also look at Irish politics at the time that Denmark began to invest in wind energy technology, asking why Ireland did not follow a similar path.

9.5 Conclusion

The maturation of commercially viable wave energy technology involves complex socio-technical transformations that require coordinated policy frameworks, innovation systems, and financial mechanisms to enable emerging technologies to move from experimentation to commercial deployment [409] Within the wave energy technology sector, the transition from publicly funded research to privately financed deployment remains a critical bottleneck, requiring targeted policy interventions and risk-sharing mechanisms to attract long-term investment. In addition, recognising and communicating the economic benefits associated with ocean renewable energy projects may strengthen SA and enhance the long-term viability of the sector.

In short, long-term, well-defined support mechanisms, including funding, policy, and infrastructure measures, with clear targets, are essential for the sustainable success of wave energy technology development in Ireland. Above all, this progress requires the presence of a dedicated wave energy champion, an individual or institution capable of leading and bridging the boundaries between industry, academia, government, and civil society. Such a champion can shed light on the influential external factors explored in this thesis, facilitate coordination, maintain momentum, and ensure that innovation efforts align with both national policy goals and community values.

> "Change does not happen without a champion — someone willing to cross boundaries, challenge inertia, and translate vision into action."
> *Kotter, Leading Change, (1996)*

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