



Wave energy technology development in Ireland: Employing the triple helix model of innovation for pragmatic policy interventions[☆]

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ABSTRACT

Irish wave energy technology holds significant economic potential and could be developed to establish an indigenous industry that addresses the global need for a diverse, robust, and reliable renewable energy system comprising a mix of modalities. While wave energy technology has not yet reached commercial viability, it could achieve it with adequate support facilitated by targeted public policy. It is clear that divergent stakeholder perspectives need to be considered when formulating policies, allowing for alternatives to be found, assumptions to be tested, and trust in government actions to be built. This is particularly pertinent for emerging renewable energy technologies such as wave energy, due to the interdependency between developers, policymakers, and researchers at early technology readiness levels. This study applies the triple helix innovation methodology to the wave energy technology sector within an Irish context, providing a framework within which often disparate stakeholder perspectives can be gathered and analysed, and consensus can be found. This consensus can influence pragmatic policy developments for innovation. The study also provides empirical evidence of the need for supportive policy development for wave energy technology in Ireland.

1. Introduction

130 countries have committed to funding R&D of renewable energy technologies (United Nations (2015), European Commission (2019)) in order to build a robust and reliable energy system, that will necessarily comprise a mix of technologies (Rourke et al. (2009); Guo and Ringwood (2021)). Wave energy holds immense potential as a key component of the global transition to renewable energy with the potential to generate approximately 29,500 TWh of electricity annually, exceeding global electricity consumption in 2018 IRENA (2023). By 2050, the global market potential for ocean energy, including wave energy, is estimated to reach 350 GW IRENA (2020). In addition, wave energy can complement wind and solar power by ensuring consistent supply during periods of low wind or solar output Fusco et al. (2010). The economic opportunities associated with wave energy are significant. The Irish Department of Communications, Energy and Natural Resources estimates that Irish waters alone have a wave energy potential of 27.5–31.1 GW Sustainable Energy Authority of Ireland (2024a,b), which could contribute to the creation of up to 50,000 jobs in Ireland by 2050 Government of

Ireland (2019). Opinions differ on the valuation of the global wave energy market, with conservative estimates placing the value at \$43.8 million in 2019, with projected Compound Annual Growth Rates (CAGR) of 17.8 %–19.3 % Allied Market Research (2020), therefore reaching approximately \$141.1 million by 2027. These factors underscore the potential of wave energy as a source of sustainable power, economic development, and energy security. Additionally, Ireland has a significant, globally recognised technical expertise in both fundamental and applied research, and wave energy device prototype development and testing (Hu et al. (2022)). This experience can be leveraged to create an indigenous wave energy technology industry in Ireland, benefiting from first to market status, as well as unencumbered access to the European marketplace.

Despite the availability of a significant global wave resource (Jin and Greaves (2021)), and decades of dedicated academic and industrial endeavour, wave energy technology has not reached commercial viability, lagging behind other more mature technologies, with few projects going beyond the development mid-point (European Commission (2023a,b)). Adequate public policy support at the appropriate stage

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of development, allocated to the projects most likely to succeed, will support wave energy technology development in becoming a sustainable indigenous industry for Ireland. Many wave energy technologies have foundered at mid-Technology Readiness Level (TRL) (Weber (2012)), due to an exponential increase in costs at that stage (Markham et al. (2010); Fitzgerald and Sharkey (2012)), as developers begin to move towards large-scale demonstration devices that need to be deployed and functioning at sea for sustained periods. 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 policy makers to express targets Barry and Ringwood (2023).

Supportive public policy, that provides, *inter alia*, access to funding for technology developers, is crucial, particularly at the mid-point of wave energy technology development. Fiscally prudent public funding bodies would endeavour to ensure that funding is allocated to those projects most likely to succeed.

The development towards a commercially viable indigenous wave energy technology industry involves complex problems being addressed by 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 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.

There is a paucity of literature detailing stakeholder perspectives on non-technical barriers to wave energy commercialisation. O'HaganHuertasO'CallaghanGreaves (2016) focus on the need for a streamlined consenting process, and recognise the need for early participation of stakeholders, in consultation with policy makers. Otherwise, the literature has not addressed, systematically or empirically, the TH actors' contributions to Offshore Renewable Energy (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 particular details, as described by Lerman, Gerstlberger, Lima, and Frank, Klitkou and Godoe (2013), Deakin and Reid (2018), Hettinga et al. (2018).

This study 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 development in Ireland, the authors identify a framework within which consensus among different stakeholder groups can be found, providing insights that are essential for pragmatic and practical policy formulation, that 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 this 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, the study 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.

Following the Introduction, Section 2 introduces the TH model in the context of wave energy. Section 3 provides a retrospective application of the model to wind energy technology development in Denmark as an exemplar of successful tripartite commercialisation, while Section 4 discusses the application of the methodology to Irish wave energy technology development. Section 5 provides results and discussion, and Section 6 concludes and discusses potential future work.

2. Methodology - application of the triple helix model to the Irish wave energy sector

The Triple Helix 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 Leydesdorff and Etzkowitz (1996). The growing interactions among universities, industries, and government have led to new structures, such as university centers and corporate alliances. These interactions have also fostered integrating mechanisms. It is at the point of interaction, Leydesdorff argues, that innovation takes place. Indeed, the three stakeholder groups, intrinsic to the development of wave energy technology towards commercial viability, are: universities, industry, and government. The authors apply the TH innovation model to find consensus within 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"(Anttonen et al. (2018)).

The TH model was introduced and developed in the 1990s by Etzkowitz and Leydesdorff (Etzkowitz and Leydesdorff (1995); Etzkowitz and Leydesdorff (2000)), 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 into a knowledge-based society, in which institutions develop intersections preserving not only their identities and main roles, but also assuming other roles as necessary (Ranga and Etzkowitz (2015)). The TH model aims to foster economic and social development, by promoting collaboration and knowledge sharing among these three sectors (Etzkowitz and Leydesdorff (1995)). The authors adopt the TH model, with the objective of examining how wave energy technology commercialisation can be expedited. The authors demonstrate 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.

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 role' Lawton Smith and Leydesdorff (2014), universities engaging in basic research, industries producing commercial goods, and governments that are regulating markets Leydesdorff (2006, pp. 42–76). As interactions increase, each sector evolves to adopt characteristics of the other institution, which then gives rise to hybrid institutions. Fig. 1 shows the overlap between the 3 TH sectors.

This is 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 (RI) (formerly Science Foundation Ireland (SFI)), the Sustainable Energy Authority of Ireland (SEAI), and the Marine Institute (MI), as well as from EU programmes such as Horizon Europe, European Commission (2021a,b)). Lerman et al. (2021) see the university contribution as solely the provision of knowledge transfer and generation, where universities face the "endless frontier" (Etzkowitz and Leydesdorff (1995)) of basic research, funded as an end in itself, with practical results expected only in the long-term. 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 (Callon (1998)), often stimulated by government. This can be

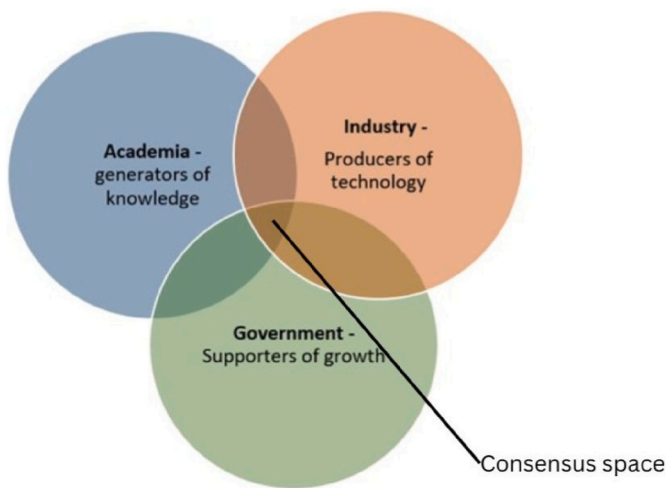


Fig. 1. Triple Helix stakeholders.

observed in the case of Irish wave energy development, where firms such as [Wave Venture \(2024\)](#) have ‘spun-out’ from universities, and multi-actor funding programmes support collaboration between industry and academia ([Enterprise Ireland Innovation Partnership Programme \(2024\)](#), [Science Foundation Ireland Industry Fellowship Programme \(2017\)](#)). 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” ([Etzkowitz and Leydesdorff \(2000\)](#)). Essentially, the TH model can be applied by policy makers as an “interface strategy” ([OECD \(1980\)](#)) in order to move projects to the ‘market pull’ phase of development, from the ‘technology push’ phase, to overcome the so-called Valley of Death (VoD) ([Weller et al. \(2014\)](#)).

The TH government’s objectives centre around economic drivers and policy targets ([European Commission \(2021a,b\)](#), [Government of Ireland \(2021a,b\)](#)). The industry sphere highlights business opportunities, and the academic objectives centre around the generation of knowledge. [Anttonen et al. \(2018\)](#) noted that conceptual differences can inhibit progress. In wave energy device development, industry aspires to full-scale devices in the water, 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 et al. \(2018\)](#) called the “consensus space”, 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, we demonstrate the applicability of the TH model 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.

3. A retrospective application of the TH model to Danish wind energy development

As an exemplar of successful tripartite commercialisation, this study 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.

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, in applying the TH theory that innovation resides at the intersection between TH groups, it is clear that 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” ([De La Porte et al. \(2022\)](#)).

Table B in the Appendix describes some of the key stakeholders involved in wind energy development in Denmark from 1980 to 2000, 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.

The Risø Test Centre was initially established by the Danish government to conduct research into nuclear power. In the early 1970s, it was given the role of providing ‘type approval’ for wind turbines and also 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 ([Barry and Ringwood \(2023\)](#)). Data gathered by Risø scientists from developers led to improvements in capacity, output, noise reduction and, later, power quality. 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.

Although comparisons can be drawn between the path to commercial readiness for wind energy technology in Denmark, and for wave energy technology in Ireland, particularly with regard to availability of resource, population size, political will, and high capital costs, two of the differences that are worth noting due to their effect on public and investor perception, include lack of consensus on a design archetype, and lack of public awareness for wave energy.

Wind turbines, from a non-technical perspective are recognisable as close relations to their historical wind mill counterparts that people have been familiar with for hundreds of years. Wave energy, on the other hand, has many device design types, differing widely in terms of appearance and effectiveness ([Falcao, 2010](#); [Guo et al., 2021](#)). The design challenges for wave energy converters and uncertain technological, economic, and ecological systems, overcoming the structural challenges of ocean deployment, and dealing with complex system dynamics—have led to a disjointed progression of research and development ([Truworthly et al., 2020](#)). Interestingly, one of the perceived drawbacks of wind energy, NIMBYISM, or public acceptability, ([Devine, 2005](#)), could be an argument in favour of wave energy for less visibly intrusive devices, although the lack of public awareness of wave energy dilutes this benefit.

The Danish scheme takes account of the university objective to generate knowledge by having access to turbine plans, for the industrial sphere 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 policy makers, 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 centers 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.

4. Employing the TH framework for Irish wave energy commercialisation

The authors conducted a survey to extract valuable data about the commercialisation of wave energy technology in Ireland. The target population of this survey comprises TH stakeholders with some interest or involvement in wave energy technology development. The study is focused on 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 wave energy technology.

4.1. Description of respondents

Over a 12-month period, 82 questionnaires and 14 interviews were conducted with stakeholders from within the wave energy sector, including students, researchers, technology developers, policy professionals, and other actors who provide support to the area, such as consultants, lawyers, and finance professionals. Table C in the Appendix shows the demographics of the final sample group, divided by TH classification and Table D 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 (Leydesdorff, 2006). Indeed, it is clear from the list of respondents, that many of the stakeholders could hold a position in 2 or 3 of the TH groups, which the TH theory suggests creates a positive environment within which innovation can flourish.

The questionnaire consisted of 8 questions (Appendix, Table A), including single-answer multiple choice questions, Likert scale questions (Joshi et al. (2015) 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 the authors employ a process known as "coding". Codes may be described as "tags or labels for assigning units of meaning to the descriptive or inferential information compiled during a study" (Miles (1994). This allows the clustering of key issues in the data (Young et al. (2018).

4.2. Limitations

Certain limitations were encountered when relying on the questionnaire as a sole source of qualitative data, particularly when answers required a level of respondent expertise or experience. Limitations included differences in understanding of the challenges. 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 D of the Appendix. It is relevant to note that many of the 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 study 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.

5. Results and discussion

The following section will analyse the results of the questionnaire and the interviews, while comparing responses from each TH group. In analysing the data, we will make use of Chi-Square test (McHugh (2013) and ANOVA Analysis (St, Wold et al. (1989)). The Chi-Square test is primarily used to analyse categorical data, where the variables are non-numerical, and can be divided into distinct categories. It 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. It compares the mean responses of these groups to determine if there is a significant difference between them.

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 the Irish electricity grid. Fig. 2 clearly shows that there is clear consensus

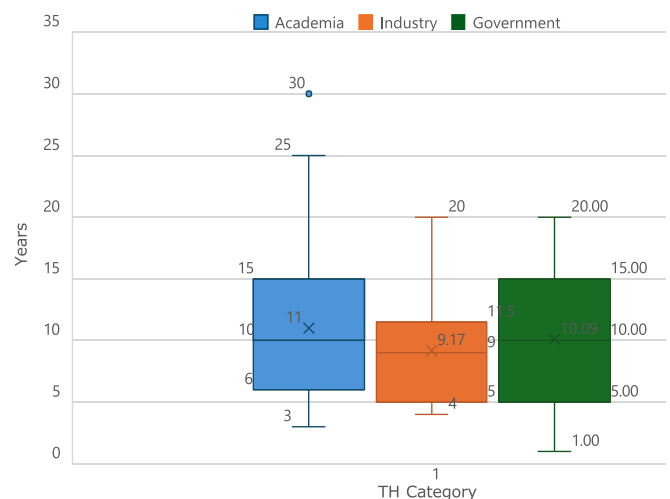


Fig. 2. Number of years to grid integration of wave energy in Ireland by TH group.

between TH groups, with a mean of 10 years across all three TH groups, and few outliers.

The authors perform an ANOVA analysis, as demonstrated in Tables 1 and 2, 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, we can deduct that the difference between the groups is not statistically significant.

Additionally, since the P-Value (probability 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), we can conclude 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 (CAP) (The Oireachtas (2023)) provides an annually-updated road-map 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 (Government of Ireland (2021a, b)). The CAP 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 5 GW installed capacity by 2030.

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.

"Wave energy is running out of time. Governments need to support"

Anders Köhler, Floating Power Plant

5.2. Finding 2. There is a need for more focused funding from national funding bodies

The authors asked survey respondents 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 (Malali and Marchand (2020))). 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 follows Bertram (2020); Ruehl and Bull (2012); Ji et al. (2016):

- TRL 1–3 Concept validation. (Wave flume tests at a small scale).
- TRL 4 Design validation, (intermediate scale testing, Flume tests scale 1:10, Survivability; Computational Fluid Dynamics; Finite Element Analysis Dynamic Analysis; Engineering Design (Prototype); feasibility and costing.

Table 1

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 2

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 (probability value) for each source of variation. DoF* denotes degree of freedom.

Variation source	Sum of squares	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				

- TRL 5–6 Testing operational scaled models at sea and subsystem testing at large scale.
- TRL 7–8 Full-scale prototype testing at sea.
- TRL 9 - Economic validation. Pre-commercial devices tested at sea for an extended period.

Respondents answered the question of funding needs based on 3 TRL phases: TRL 1–3, the research phase; TRL 4–6, technology development and demonstration 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.

The authors find that most respondents (62 %), believe 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, we can see that there is good agreement among the TH groups (Fig. 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.

The authors use a Chi-squared test of independence (Plackett (1983)) as a means to determine whether the observed deviations between the TH groups are statistically significant or can be attributable to chance.

Table 3 shows that the chi-square statistic is 2.9354, and the p-value is 0.938. Since the p-value is greater than 0.05, the authors conclude that 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.

Barry and Ringwood (2024) look at research and development funding received from 3 of the main Irish public funding bodies for wave

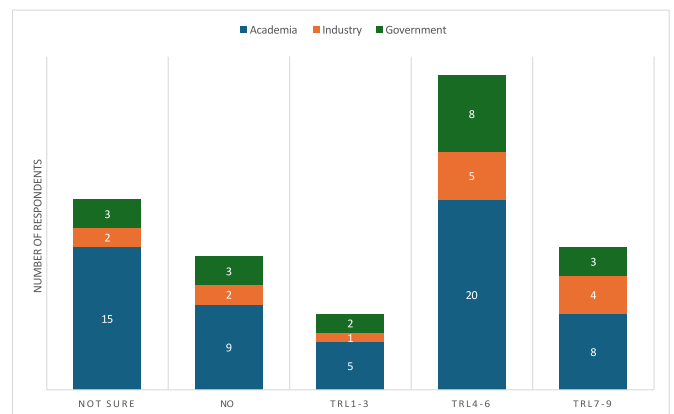


Fig. 3. Survey responses by TH group - Should public funding be targeted at a particular TRL.

Table 3

Chi-Square 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-square statistic, and p-value. Govt.* denotes government.

	Not sure	No	TRL1-3	TRL4-6	TRL7-9	Row Totals
Academia	15 (12.67) [0.43]	9 (8.87) [0.00]	5 (5.07) [0.00]	20 (20.90) [0.04]	8 (9.50) [0.24]	57
Industry	2 (3.11) [0.40]	2 (2.18) [0.01]	1 (1.24) [0.05]	5 (5.13) [0.00]	4 (2.33) [1.19]	14
Govt.*	3 (4.22) [0.35]	3 (2.96) [0.00]	2 (1.96) [0.06]	8 (6.97) [0.15]	3 (3.17) [0.01]	19
Totals	20	14	8	33	15	90 (grand total)

¹Note that, for reference, Ireland's peak demand (2023) is 5.5 GW.

energy projects: Science Foundation Ireland ([Science Foundation Ireland \(2017\)](#)), the Sustainable Energy Authority of Ireland ([Sustainable Energy Authority of Ireland \(2024a,b\)](#)), and the Marine Institute ([Marine Institute \(2022\)](#)), within a 10 year period, and attempt 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 coordinating (lead) partner, and also to venture capital investment.

[Fig. 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, in the authors' findings in this study. TRL was used as a metric in this study due to its proliferation across stakeholder groups, functioning as a simple means of communicating a level of commercial maturity. 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 concerns such as control strategies, telemetry design, and large-scale testing, or non-fiscal supports, such as availability (or not) of testing facilities, making TRL incomplete as an assessment tool. The TRL scale does not take account of the fact that commercial readiness does not necessarily equate to performance readiness.

Weber, in 2012, [Weber \(2012\)](#) introduced the Technology Performance Level (TPL) metric, complementary to the TRL scale, that considered the economic performance of WEC systems early in their development. TPL shows that funding is required across the TRL scale ([Fig. 5](#)). Weber's study described the TPL scale as a value map for visualisation, qualification and comparison of the technology development status with respect to overall commercial readiness and performance,

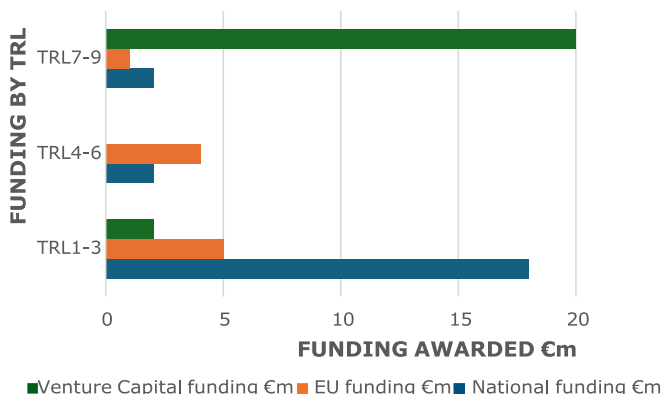


Fig. 4. Irish funding for wave energy projects 2012–2022.

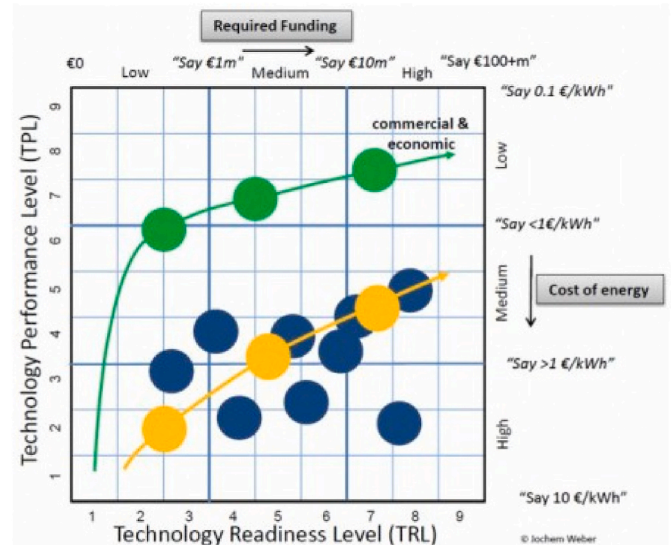


Fig. 5. Technology performance Levels, [Weber, 2012](#).

and as such is more related to innovation than TRL. [Barry and Ringwood \(2023\)](#). Where 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 ([Weber, Costello, and Ringwood 2013](#)). 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 TPL, when combined with TRL, can identify requirements for successful entry, survival in the electricity market, and 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 feed-back 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 [Barry and Ringwood \(2024\)](#). For this reason, TPL, if it gains popularity, would be a preferable metric from which to evaluate stakeholder perspectives.

VoD is used to describe the phenomenon whereby a technology, while ready to be deployed from a technological standpoint, is not yet ready to compete with similar technologies, and full commercialisation has yet to be achieved. ([Muscio et al. \(2023\)](#)). [Weller et al. \(2014\)](#) 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 responses to our surveys and interviews show a recognition of this phenomenon, where the majority of respondents (59 %) would prefer public funding aimed at mid-TRLs.

"The best way to support companies is to create clear and sustained market pull that will motivate investors to support companies for the entire development and roll out."

Christopher Ridgewell, CEO, AW-Energy

Previous research such as that of [Ford et al. \(2007\)](#), 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 [Weller et al. \(2014\)](#), 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 that 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

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 4 options derived from the studies of Aderinto and Li (2018), Guo et al. (2023), Bailey et al. (2011) etc., and from interview responses:

- Public perception of wave energy
- Lack of a wave energy champion; someone who can exert influence at policy level
- LCoE, compared to other sources of renewable energy
- Lack of design convergence
- Other

LCoE 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 lack of a champion, a person who can exert influence at policy level, is seen as a slightly more pressing need for wave energy technology development in Ireland. The results can be seen in Fig. 6.

A chi-square 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-square statistic is 32.8606. The p -value is 0.000065. The result is significant where $p < 0.05$.

Table 4 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

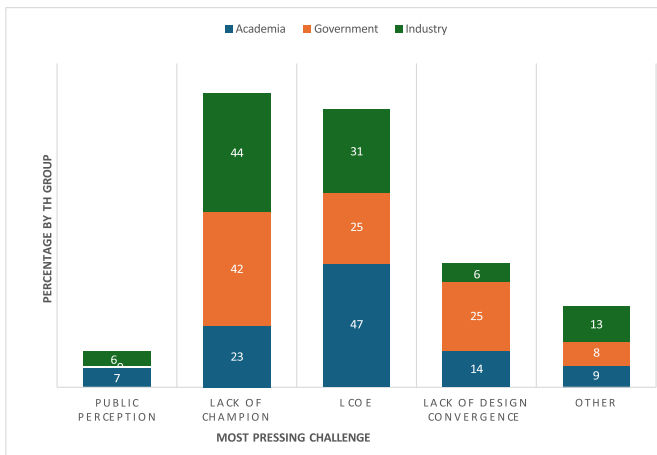


Fig. 6. Survey responses by TH group - Most pressing challenge for wave energy technology developers.

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.

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 (European Commission (2023a,b)) 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, 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 (Têtu and Fernandez Chozas (2021)).

"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

5.4. What can national governments do (or do more of), to assist wave energy developers in bringing wave energy closer to 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-ended question (Tasker and Cisneroz (2019)).

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 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.

Fig. 7 and Table 5 present 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.

6. Conclusions and policy implications

This study 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 Triple Helix Framework (THF) is instrumental in ensuring that data is gathered, and analysis is conducted beneficially in a manner that supports effective future policy formulation.

The consensus among Triple Helix stakeholder groups demonstrated in this study supports the theory that innovation thrives when it aligns with shared priorities across academia, industry, and government, fostering synergistic collaboration and mutually beneficial outcomes. This underscores the need for policies that encourage dialogue, bridge stakeholder interests, and create frameworks to support collaborative ecosystems (Peter Hamilton, interview 2024), ultimately driving

Table 4

Chi-Square Analysis of the Most Pressing Challenges Facing Wave Energy Developers by TH Group. The table presents observed and expected frequencies, degrees of freedom, Chi-square statistic, and p-value. Govt* denotes government.

	Perception	Champion	LCoE	Design convergence	Other	Row Totals
Academia	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
Industry	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
Totals	14	109	103	45	30	300 (Total)

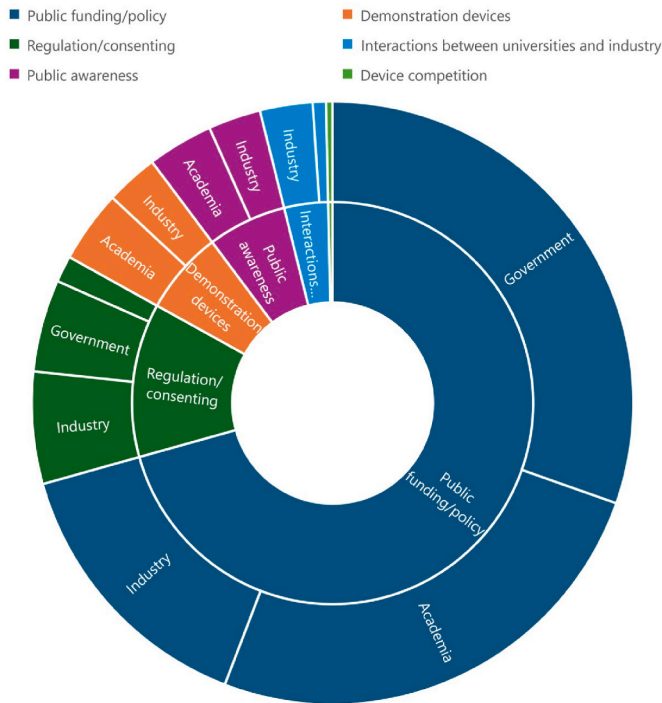


Fig. 7. Survey responses by TH group - What should policy makers do or do more of.

sustainable innovation and economic growth.

Specifically, applying the THF 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 THF, to Danish wind energy development in the 1980s and 1990s, serves as a valuable case study. It 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.

Our analysis reveals evidence that the current 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, 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.

Furthermore, we find that LCoE is of concern to stakeholders, particularly those in the academic field, and despite difficulties with an accurate assessment, it is not an appropriate metric for evaluating wave energy technology in 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 study provides a framework from which different emerging renewable energy technologies in other countries can benefit. 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, has buy-in, is robust, and practical.

Public perception of wave energy is limited and, as such, was not part of this study. As wave energy technology progresses through the TRLs, future research might consider a quadruple helix approach, incorporating public perspectives more comprehensively into policy formulation.

This study emphasises the necessity of aligning policy with stakeholder needs, showing how innovation resides at the intersection between stakeholder groups, through the use of the THF, 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.

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CRediT authorship contribution statement

C.A. Barry: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **J.V. Ringwood:** Writing – review & editing, Validation,

Table 5

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

	Funding policy	Demo projects	Consenting	academia-industry	awareness	competition
Academia	76 %	15 %	6 %	3 %	15 %	3 %
Industry	42 %	8 %	17 %	8 %	8 %	0
Government	86 %	0	14 %	0	0	0

Supervision.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix

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Table A
Survey questions

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 B
Danish wind energy technology stakeholders 1980–2000

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 (eg Vestas)	Industry	Investment	ROI
Citizen owners	Industry	Investment	Security of supply, ROI

Table C
Survey respondents by TH classification

Industry	Academia	Government
Corpower	U 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 U	MRIA
Wood	U of Galway	Bluewise Marine
Flotation Energy	Loughborough U	Bluewise Marine
Norri.ie	U Edinburgh	Aer Finance Group
Source Gallileo	U Strathclyde	Bremore Irel port DAC
Simply Blue	Dublin Tech U	LK Shiels Solcs
Anonymous (ind)	Queens U Belfast	Creavan and Doherty Solcs
	Politecnico di Torino	ERM Consulting
	TU Dublin	Anonymous (govt)
	U College Dublin	
	Trinity College Dublin	
	Centec	
	Anonymous (academic)	

Table D
Interviewees with TH classification

Name	Affiliation	TH sphere
Patrick Möller	CEO, CorPower	Industry
Tony Lewis	CTO, Ocean Energy Ltd.	Industry
Anders Köhler	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, Marine Renewables Industry Association Ltd	Industry
John Walsh	Emerging Technology and R&D Manager, Electricity Supply Board	Industry
Peter Hamilton	Green Party Candidate Member Kildare County Council at Kildare County Council	Government
Christopher Ridgewell	AW-Energy	Industry

Data availability

Data will be made available on request.

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