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Article

Validating the "Seven Functions" Model of Technological Innovations Systems Theory with Industry Stakeholders—A Review from UK Offshore Renewables

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Abstract: Technological Innovation Systems theory, and its "functions" framework, have demonstrated their value as tools for exploring socio-technological transitions. Although the "seven functions" model has demonstrated its academic value across a vast literature, there have been few attempts to explore the model through the lens of industry stakeholder opinion. We believe that involving a relevant stakeholder group offers the potential for validating this approach, and even potentially enriching it. This research aims to address that shortfall. In 32 interviews with senior participants in the UK offshore wind, tidal stream and wave sectors and associated supply chain, policy makers, support organisations and other stakeholders, the validity of the seven well-established "Hekkert" functions was tested. The research found that the interviewees confirmed that all seven functions were necessary in characterising the emergence of the focal technologies, and analysis of the interviews allowed the definition and scope of each function to be enriched. The research also found that an additional function—defined as "Demonstrating Value"—was helpful in providing a more complete description of technology emergence. This function is defined and appropriate metrics for it are discussed. The authors suggest that this proposed enrichment of the "functions" model may provide a greater understanding of socio-technological transitions in the face of volatile external contextual factors, whose importance the current COVID pandemic has made all too obvious.

Keywords: functions; TIS; innovation systems; validity

1. Introduction

Technological Innovation Systems (TIS) theory has proven itself as a powerful lens through which to explore socio-technological transitions, particularly in the energy sector, see e.g., [1–6]. It is commonly operationalised through the definition and evaluation of "functions" which are described by Bergek et al. as key processes which "directly influence the development, diffusion and use of a new technology, and thus the performance of the innovation system" [7]. In the context of societal disruption, such as that caused by the current COVID pandemic, the functions model can provide a structured means of considering factors which will enable socio-technological change.

While different researchers, including Bergek et al. [7], Hekkert et al. [8] and others have proposed alternative inventories of functions, it appears that the "seven functions" model of Hekkert et al. [8] has become prevalent. Hekkert et al.'s functions inventory has been applied in wind [9–11] and wave energy [3]. However, while there appears to be a broad consensus amongst academics on which functions are relevant and important, we have not been able to identify any critical validation of any functions inventory in the literature involving stakeholders of the transition being studied.

Ostensibly, it may appear that stakeholders in a particular aspect of the energy transition would have little to offer the development of academic theory about it. However, the authors of the current paper contend that practical participants in a transition are precisely the group which can be expected to have insights into how a transition might or might not occur. We propose that these actors are likely to have unique and valuable perceptions of the model and of the specific functions within it. Although the model has been used widely as an academic tool, and despite the stakeholder's lack of familiarity with its academic underpinnings, we believe that their direct empirical experience may render additional understanding on its utility and relevance.

This paper describes the application of this functions model and considers questions of whether Hekkert et al.'s "seven functions" [8] model provides a necessary and sufficient inventory with which to assess the emergence of a particular technological innovation—that of offshore renewable energy (offshore wind, tidal stream and wave) in the UK. It addresses this question by engaging stakeholders in this TIS with the functions framework, to gather their views on the validity of each function and to identify whether there was evidence for any extension of the model.

This paper is divided into six sections. This section comprises the introduction and briefly reviews the literature on functions within TIS and their application in the area of renewable energy. Section 2 sets out the methodology adopted to consider (i) the necessity of each function and (ii) whether the seven functions inventory is sufficient to characterise and explain the socio-technological transition relating to offshore renewable energy in the UK. It also describes the cohort of interviewees, which comprised 32 stakeholders across the offshore renewable energy sector in the UK.

Section 3 considers each of Hekkert et al.'s functions and summarises how the interview cohort characterised each function and its inter-relationships, and describes the importance attributed to each. It addresses the question of whether each of the seven functions in the Hekkert inventory is necessary for characterising the transition in question.

Section 4 addresses the question of whether the Hekkert et al. functions are sufficient to characterise the transition: drawing from interview findings, a new function may be required in addition to the Hekkert et al. functions. This new function, "Demonstrating Value", is defined and some potential metrics identified and discussed.

Section 5 discusses these findings and draws conclusions relevant to TIS and transition theory more generally and Section 6 concludes.

Functions in Technological Innovation Systems

The concept of functions in innovation systems was first proposed around the turn of the millennium by Johnson [12] and has been developed, adjusted and refined by many authors since then.

The notable authors considering functions within TIS have included Bergek et al. [7] (Note that Anna Johnson (ref [6]) adopted the married name of Bergek (ref [7] and others) in 2001), Carlsson and Stankiewicz [13], Galli and Teubal [14] and Hekkert et al. [8]. Each developed a set of functions, which differ in their details whilst broadly addressing the same themes.

Bergek et al. [7] reviewed the relevant literature and found a total of 70 specific functions defined in the literature by themselves and others [7,8,13,14]. They then defined their own seven function inventory and fitted each of these 70 functions into it. Bergek et al.'s inventory comprised knowledge development and diffusion, entrepreneurial experimentation, influence on the direction of search, market formation, development of positive externalities, legitimation and resource mobilisation.

Hekkert et al. [8] proposed a slightly different functions inventory, in which Bergek et al.'s "development of positive externalities" was included in legitimation, and knowledge development and diffusion were split into the two functions of "knowledge development" and "knowledge diffusion and networking". This inventory appears to have been widely adopted by researchers in the area and has formed the basis for this research.

The "seven functions" model of TIS has been applied to renewable energy by a number of authors, for example in the offshore wind sector by Jacobsson and Karltorp [9], and Wieczorek et al. [10,11] and in wave energy by Hannon et al. [3].

Jacobsson and Karltorp [9] considered the requirement for offshore wind capacity in Europe by 2050 and applied TIS ideas to identify obstacles to this deployment. They used an existing functions inventory and attempted to measure the "strength" of each function (i.e., the degree to which each function had been completed) with their own qualitative metrics.

Wieczorek et al. [10,11] applied a similar approach to Jacobsson and Karltorp, and compared the relative performance by function of the offshore wind TIS across Denmark, the UK, the Netherlands and Germany to identify potential blockages to large scale offshore wind development.

Edsand [15] applied the functions model in the case of wind farm development in Colombia and explicitly addressed the "landscape factors" from Geels' Multi-Level Perspective approach (MLP) [16]. The MLP approach explicitly recognises that the functions inventory "does not adequately consider wider contextual factors": Edsand addressed this weakness by hybridising the TIS functions approach with the MLP: we found a similar issue, but, as we set out in Section 5, we suggest it can be addressing by extending the functions framework.

In wave energy, Hannon et al. [3] undertook a review of wave energy innovation policy through the lens of TIS. They adopted Hekkert's functions and provided useful insights into the success of innovation policy in UK wave energy, demonstrating the applicability of the TIS framework in this context.

Despite these functions inventories being proposed and widely adopted, we have not found any examples in the literature describing attempts by researchers to validate their proposed functions inventories, either in terms of the validity of the functions proposed, or to test whether the inventory is sufficient to fully characterise the emergence of the TIS. The authors of this paper take the view that stakeholders in the TIS are likely to have unique insights into the effectiveness and validity of the functions; they form the sample set for the interviews in this study. As the Hekkert functions inventory appears to be most widely used in the literature, this inventory has formed the basis of this research.

Considering the field of transition theory more broadly: it is a broad church, encompassing many theoretical approaches. Sovacool and Hess, in a recent paper exploring conceptual frameworks useful in explaining socio-technological change, identified "96 theories and conceptual approaches spanning 22 identified disciplines" [17]. It is immediately clear that no single framework has a unique insight on transitions. Practitioners both within and outside the "functions" tradition of TIS have found weaknesses in this approach and there appears to be a particular tension between academics in TIS and MLP (as defined by Geels [16]); these are well summarised in Markard et al.'s "response to six criticisms" [18]. Equally, there has been vigorous debate on the perceived weaknesses of MLP (perhaps best summarised in Geels' rebuttal of criticisms of MLP [19]).

We feel that these apparent tensions between the TIS approach (as applied by Hekkert, Bergek and others (e.g., [4,7,8]) and MLP as introduced by Geels [16], may be caused by a difference in the underlying methodological approach, where a meeting of minds between interpretivist (MLP) and positivist (TIS) approaches has yet to be achieved.

Although the research discussed here was founded in TIS theory, we suggest that the introduction of our proposed new function may help the TIS "functions" approach address the specific criticism of "how does the TIS address context" identified by Markard et al. [18], and therefore provide a means of achieving some degree of reconciliation between the approaches, both of which have much to offer.

2. Materials and Methods

Our research set out at first to explore the validity of the TIS framework in the specific context of the UK offshore renewables industry. The Hekkert et al. seven functions inventory [8] was used to develop the research instruments for the study, at which point we separated out the concepts of "necessity" and "sufficiency" in our exploration of the validity of the framework. Two initial research questions were formulated; firstly, are each of the Hekkert seven functions necessary to describe the transition in this context; and secondly is the framework sufficient to fully describe the transition? In order to offer a fresh and highly practical perspective on the framework, we adopted the approach of conducting semi-structured interviews with offshore renewable industry practitioners. An interview cohort of 32 senior individuals in the UK offshore wind and marine energy (tidal stream and wave) was assembled, drawing initially from the lead author's personal network and developed through snowball sampling. Efforts were made to ensure a representative range of interviewees, comprising technology and project developers (in both wind and marine energy), supply chain participants, support organisations, policy makers and other stakeholders. We recognise that this cohort—who were mainly business acquaintances of the lead researcher—could present non-representative views. Every effort was made to make clear to them that objective answers were sought, but further research to validate the emergent themes would be valuable. Interviewees were allocated a random index number and categorised as set out in Table 1.

Table 1. Interviewee industry codes.

Industry Category	Category Code	Number of Interviewees
WTD	Wind Turbine Generator Manufacturer	3
WPD	Wind Project Developer	4
MTD	Marine Technology Developer	3
MPD	Marine Project Developer	3
SC	Supply Chain Participant	4
SO	Support Organisation	4
PM	Policy Maker	4
SH	Stakeholder	7

Interviews were semi-structured to brief interviewees on the Hekkert functions, to seek their perceptions on the importance of each of the functions and to allow wider discussion on other factors. Interviewee anonymity was guaranteed, to encourage frank discussion on each interviewee's perception of the importance of each function, on the factors which either helped or blocked delivery of each function and to allow any other themes to emerge.

As interviews were undertaken, they were transcribed and uploaded to NVivo [20] for qualitative analysis. Once the first few interviews had been uploaded, an initial read-through was undertaken which allowed definition of classification "nodes". These were broadly aligned with the seven Hekkert functions whose necessity was being tested, but the read-through also identified that another node was required to capture additional substantive comments.

As the interviews were analysed, those interviewee comments fitting into the nodes for each of the seven functions were appropriately categorised. In parallel, substantive comments from interviewees which did not fit cleanly into the existing nodes were coded into the new node. This node was initially described as "techno-economic viability" but came to include comments on the actual and potential economic, social and environmental value of the emergent technology, often in the context of competing emergent and incumbent technologies, as further interviews were undertaken. This additional node forms the basis of our proposal for a novel function, "Demonstrating Value", that we describe in more detail in Section 5.

The nodes were:

- Entrepreneurial activities (F1)
- Knowledge development (F2)
- Knowledge diffusion and networking (F3)
- Guidance of the search (F4)

- Market formation (F5)
- Creation of incentives (F5)
- Resource mobilisation (F6)
- Legitimation (F7)
- Techno-economic viability—this node emerged during the analysis of the interviews and comprised interview comments relating to the comparative technical and economic potential of the focal technology

In addition, to provide a quantitative data set, each interviewee was asked to score each function for its perceived importance on a modified Likert five point scale [21], with scoring from 1—"very unimportant" to 5—"very important". The perceived importance question was phrased as "how important do you consider this function to be in contributing to the emergence of offshore renewable energy?"

The interviews therefore provided both qualitative and quantitative data: the qualitative data provided context and colour on each of the seven functions, and the quantitative data provided a quasi-objective measure of the perceived importance of each function.

The novelty of this approach was in using the interview cohort of 32 senior stakeholders in the UK wind and marine renewables sector—a cohort uniquely available to the lead author as a result of his work in this sector. This cohort has a distinctive, practitioner's view on the evolution of these technologies, and provided a unique perspective on the transition.

3. Results

The Hekkert et al. functions inventory [8] forms the basis for this research, which sought to address two research questions: "are the Hekkert functions each "necessary" to describe the transition in question?", and "is the Hekkert functions inventory sufficient to fully describe the transition?"

The following sections summarise Hekkert et al.'s definition of each function, together with interview comments and quotes which enriched or expanded the definition, and any significant themes which emerged during the discussions. Finally, the perceived importance of each function as scored by the interviewees is shown in Figure 1.

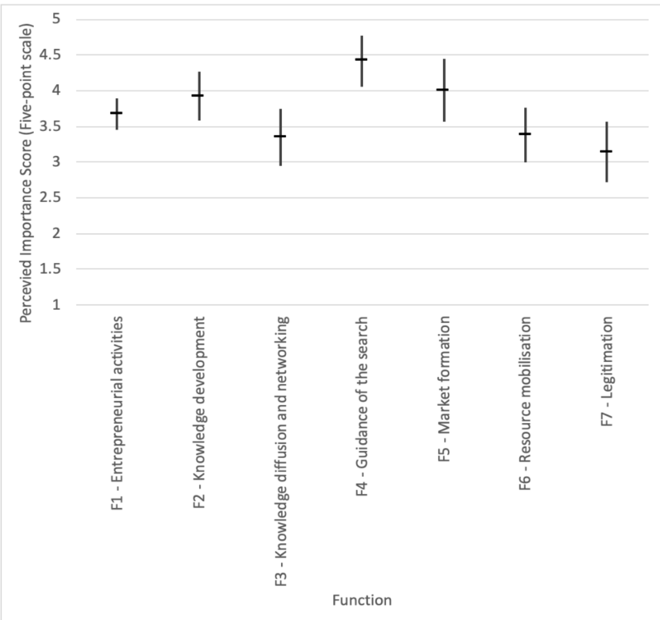

Figure 1. Mean and error bars (+/− 2 s.e.) for "perceived importance" of functions to the emergence of offshore renewable energy as scored by interviewees on a five-point Likert scale where 1 = "very unimportant" and 5 = "very important" (authors' analysis).

3.1. F1—Entrepreneurial Activities

Hekkert et al. say that "the role of the entrepreneur is to turn the potential of new knowledge, networks, and markets into concrete actions to generate, and take advantage of, new business opportunities" [8].

The interviews confirmed the importance of this function and further characterised entrepreneurial activities as those which enable the early stages of a transition to take effect. Interviewees pointed out that they may be undertaken by new participants in the sector or involve diversification activities undertaken by existing participants. The activities can include R&D activities (which may overlap with F2—Knowledge development) and/or market validation and awareness building (which may run into F5—Market formation or F7—Legitimation). Interviewees emphasised that entrepreneurial activities included not just the focal technology, but related activities including permitting, regulatory issues and financing. As one stakeholder said:

"I think that it took innovative individuals—it always does—those who are willing to forge new paths in consenting, leasing and regulations as well"—SH36

One marine technology developer agreed, noting that the supply chain played a key role:

"Obviously in the supply chain there has been grand commercial entrepreneurial behaviour"—MTD58

Interviewees noted that the motivation of entrepreneurs could be simple curiosity but was most likely the expectation or hope that the results of the entrepreneurism would be a financial return. As one stakeholder pointed out, the perceived opportunity was critical:

"You won't have the entrepreneurs unless there's a genuine opportunity for them to exploit"—SH43

Others recognised an existential pressure to participate in the energy transition:

"If you want to be in the future of the big organisations, in whatever shape or form, you will have to be in the energy transition"—SO60

This pressure could be resolved by adopting a forward-leaning strategy in the sector. For example, one supply chain participant said that his company was:

"Very interested in being a leader in the market … to deliver something now"—SC14

They also suggested that an entrepreneurial culture was essential to the emergence of a TIS and that the impact of competitive pressures on entrepreneurial activities could foster or block these activities.

In summary, as Figure 1 shows, interviewees attributed a high score to the perceived importance of entrepreneurial activities and recognised a wide variety of factors motivating them.

3.2. F2—Knowledge Development

Knowledge development was described by Hekkert et al. in the following terms: "R&D and knowledge development are prerequisites within the innovation system. This function encompasses 'learning by searching' and 'learning by doing'" [8].

The research interviews confirmed the importance of these activities, which they described as activities which comprise research and development, which improve the technology itself, or the value of applying the technology, through innovations in ancillary technologies (e.g., installation of offshore wind turbines), funding strategies, risk management strategies, consenting frameworks, financial support systems or other improvements. Different interviewees identified different foci for knowledge development—often reflecting their own specialism or interest. For example:

"Look what happens when you make your turbines bigger"—WPD1

"There has been a lot of process improvement and 'leaning' ("leaning" here means making more efficient.) of that process … we've got better lifting equipment, better offshore"—WTG12

"When I look at what we've done on offshore wind ... nearly all of it has been developed by us on the job. We're mostly installing cables and foundations"—SC14

"There has been quite a lot of developments around the foundation side"—O32

"A radical rethinking of the construction sites themselves"—SO34

"A lot of the innovation that we're doing now is really around the fringes in offshore wind in reducing costs—such as optimising boat movements"—SH43

"Ørsted have really been trailblazers for the multi-contracting model"—SC56

The interviews enriched the definition of the function in a number of ways. Perhaps most importantly, interviewees described the importance of competitive factors in driving innovation. The desire to stay ahead of the competition was seen as critical factor in motivating spending on knowledge development.

One wind project developer summarised this:

"Cost reduction continues. It has to, and that's driven by competition and the technology that competition is engendering"—WPD1

A supply chain participant added:

"The strive to gain a competitive advantage drives knowledge"—SC56

They noted that knowledge development can be undertaken by research bodies, such as universities or support organisations (such as the Offshore Renewable Energy Catapult), by industry participants directly or by joint industry projects funded by industry participants and coordinated by support organisations (such as the Carbon Trust's Offshore Wind Accelerator programme). This range was expressly confirmed by one stakeholder who noted the variety of sources of knowledge development:

"Some innovation comes from R&D, some innovation comes from doing things" —SH36

As with F1—Entrepreneurial activities, F2—Knowledge development was widely seen to be an important aspect of the development of the new technology. Figure 1 shows that F2 scored slightly higher than F1—Entrepreneurial activities on the five point scale of perceived importance.

3.3. F3—Knowledge Diffusion and Networking

Hekkert et al. considered that networking was "a precondition to 'learning by interacting'. When user producer networks are concerned, it can also [be] regarded as 'learning by using'" [8].

Interviewees described knowledge diffusion and networking as the exchange of information among stakeholders to the transition, including both formal information sharing efforts, such as Government dialogue with trade associations to better define policy choices, and informal diffusion of knowledge, such as happens when employees move employer.

The diffusion of knowledge and networking was widely agreed amongst the interviewees as an important factor in the emergence of the TIS. Although its importance was agreed, there were divergent views on the degree to which the diffusion was taking place in the case of offshore wind. For example, one supply chain participant lamented the reluctance to share knowledge:

"I think the offshore renewables sector is the worst place I've ever seen for non-disclosure agreements. Nobody will talk to anybody without a non-disclosure agreement"—SC14

The strongest theme which emerged in the interviews was the tension between the benefits for a company of maintaining confidentiality in relation to competitively important Intellectual Property and the benefits to the industry of sharing it. The desire to preserve competitive advantage developed through the creation of IP was seen to be directly at odds with the function of knowledge diffusion. Although interviewees noted that some degree of knowledge diffusion was inevitable, as employees moved employer and as the supply chain developed its own expertise useful to all project developers, they recognised that this tension existed.

> *"There's no doubt we have technology that gives a competitive advantage that we don't share with anyone"—WPD1*

> *"As soon as you disseminate that knowledge in the market you haven't got the intellectual property any more"—MTD22*

There is a clear paradox here for sponsors of the TIS: it is best for the emergence of the focal technology if participants collaborate and network, but it is best for individual participants if they do not share their sources of competitive advantage. The emergence of any focal technology must find ways to address this issue. One specific mechanism for fostering knowledge diffusion, mentioned by a number of interviewees, was the definition of technical and regulatory standards in the emergent TIS.

One stakeholder felt that their organisation had a role in developing standards and thereby encouraging the diffusion of knowledge—at least knowledge that was not "privileged":

> *"We can help drive standards but we can also point out where efficiencies can be made in the process. And I think as long as they benefit everyone, as long as we're not revealing privileged information, then I think we can play a role"—SH40*

While F3—Knowledge diffusion and networking was considered by interviewees to play a role in the development of the TIS, it was the second lowest scoring function among the seven (see Figure 1).

3.4. F4—Guidance of the Search

Hekkert et al. [8] note that "since resources are almost always limited, it is important that, when various technological options exist, specific foci are chosen for further investments". They add that Guidance of the Search can be provided "by a variety of system components such as the industry, the government, and/or the market."

The interviews supported this view and demonstrated that Guidance of the Search was widely considered to be the single most important factor in the emergence of the TIS. One stakeholder summed this up:

> *"Nothing would happen without government guidance in this industry. Having the level of political will to effect this transition is absolutely critical"—SH43*

The analysis of the interviews suggested that guidance of the search was founded on policy design, at international, national, subnational, regional, and local levels, whilst also including regulatory developments aimed at enabling a transition (such as Strategic Environmental Assessments for offshore wind development areas and development of standards).

The then-Minister of State for Energy and Clean Growth, Claire Perry, certainly felt that Government's role was key, taking full credit for the deployment of renewable energy:

> *"Through our policies we have massively increased our deployment of renewable generation"*—[22]

Interviewees were generally in agreement that the weight of responsibility lay with Government:

> *"I think the onus is on the government to produce a policy which drives the market"—MTD22*

Government was understood to be constrained both by its own policies and by the overarching international environment (what Geels [16] would consider a "landscape" factor) as well as by its own competence in delivering a robust and consistent policy framework. A number of interviewees discussed the damage that inconsistent policy design could inflict, in reducing investor confidence, demotivating knowledge development, constraining resource mobilisation and damaging legitimacy. One support organisation, talking about the needs of sector participants, noted that policy stability was important—and had not always been delivered:

> *"What they all say is they need - what they need most is continuity … and I think certain changes in government policy have made things more stop/go"—SO37*

The interviewee scores on F4—Guidance of the search were the highest among all seven functions, further confirming its perceived importance (see Figure 1).

3.5. F5—Market Formation

Market formation describes the creation of special circumstances in which emerging technologies can develop. Hekkert et al. [8] said that "it is important to create protected space for new technologies". These protected spaces might include "temporary niche markets ... favourable tax regimes ... or minimal consumption quotas".

Interviewees widely agreed that that market formation was a necessary step in the development of the TIS. However, there was a strong focus in the interviews on the creation of incentives and their effect and effectiveness in encouraging the development of cost-competitive technologies.

One supply chain participant described the success of Government policy (and its co-evolution with offshore wind technology):

> *"There's one major reason why offshore wind is so competitive now. Beyond the wildest dreams of anyone five years ago—is competition and the CfD process. You have to take your hat off to the Government. In that regard, it's not perfect, but they got it right. Because it was instrumental in driving cost down. And it's instrumental in developing the 12 megawatt, the 15 megawatt, future turbines"—SC10*

The themes relating to incentives included their structuring and perceived generosity, the importance of continuity in incentives and the paradoxical need for them to evolve at the same time as offering continuity.

A support organisation participant described both of these facets of continuity and evolution:

> *"How consistent has it [the support regime] been? Not very—it's been consistent in its slow steady incremental approach"—SO74*

Other key themes which emerged were the wider role of government and communities in enabling market development, the importance of confidence in a future market, the roles of developers in building this market, the importance of developing a healthy supply chain and the road map to subsidy-free operation. In this area, one policy maker noted the ways in which Government could actually help the sector's development:

> *"Well obviously it's the economics tools, through tax incentives, it can offer support in terms of research grants, it can drive research working with the universities and the further educational institutes, it can support small companies get off the ground and get into the sector through all these various fields, it can offer support"—PM55*

Finally, the challenge of forming a market for marine technologies, especially in the context of the relative advancement of the offshore wind sector, was a strong theme among the marine-sector interviewees. One support organisation participant felt that the change to support mechanisms had impacted the marine sector:

> *"At the same time, a generation subsidy is very important to any new technology. And I think in the same way that the government sort of pulled the rug on solar maybe too early, it's definitely done that for wave and tidal"—SO77*

F5—Market formation scored the second highest among all of the seven functions, only marginally behind guidance of the search in perceived importance (see Figure 1).

3.6. F6—Resource Mobilisation

Hekkert et al. [8] said that "resources, both financial and human capital, are necessary as a basic input to all activities within the innovation system". Resource mobilisation describes the function of allocation of people, resources, equipment and funding to enable the maturation of the focal technology in the TIS.

Resource mobilisation was generally acknowledged as a vital element in the emergence of the TIS, although there was a strong suggestion that the mobilisation of resources into a clear market opportunity was "business as usual" and often took place later in the life of a TIS. Participants explained this industry response to the emerging market opportunity:

> *"So for the globals to really take an interest, it's got to be seen as a likely candidate for core business or something where they can make some money"—SO77*

> *"So, thinking about offshore wind for a moment. I think what happened there was the market size got interesting. People realized: 'well actually we could make some money out of this'. So you started seeing utility companies get serious about project development"—SH40*

F6—Resource mobilisation is closely related to F1—Entrepreneurial activities, in that both are concerned with the allocation of necessary resources. The key difference is that F1 is concerned with those activities which typically take place at the early stage of the focal technology's niche breakout, in the form of invention and innovation, early fund raising, market creation and legitimation, while F6—Resource mobilisation is more concerned with the allocation of conventional resources to deliver the upscaling of a transitional technology.

Key additional themes which emerged in the interviews were the mobilisation of resources in response to a perceived market opportunity and how the investment potential of emergent technologies changed the availability and sources of capital. The rationale for resource mobilisation was seen to be the market opportunity:

> *"It's got to be a clear understanding of the market opportunity and a return on investment"—SO77*

The investment potential of offshore wind was seen to have evolved as the risk had reduced:

> *"Offshore wind is absolutely bankable"—SC56*

> *"If you look at the offshore wind, it's also interesting that pension funds are now funding some of it. So you've got that long term investment infrastructure play"—PM29*

At root, the mobilisation of resources was considered to result from clear visibility of an economic opportunity. Its perceived importance score was towards the lower end of the range exhibited by the functions, perhaps because of its "business as usual" nature (see Figure 1).

3.7. F7—Legitimation

Bergek et al. defined a function comprising "the development of positive external economies" [23]. While they accept that renowned researcher and writer Michael Porter describes positive externalities as "central to the formation of innovation systems", they note that the process by which these positive externalities emerge are "not independent of other functions but works through strengthening the other six functions". Hekkert et al. [8] developed this function into "Legitimation" and extended the definition to include the broader factors of building "advocacy coalitions" and societal support and counteracting resistance to change, together with the creation of positive externalities.

This broader legitimation function was widely confirmed by the interviewees, who noted that there was broad societal support for offshore wind, wave and tidal as demonstrated by regular Government polling [24]. They also felt that the growing legitimacy of the emergent technology could stimulate a challenge to the social licence to operate of incumbent technologies (in this case, coal and gas-fired and nuclear power generation).

The "energy trilemma", in which the three drivers of decarbonisation, security of energy supply and low cost compete, informed discussion of legitimation amongst the interviewees. The energy trilemma was recognised as a factor affecting the legitimacy of renewables, as their perceived higher cost offset their recognised environmental benefit. One marine technology developer described how the offshore renewables industry could address this, and reinforce its legitimacy, by offering additional societal benefits:

> *"I think that offshore wind ticks the same box. And it's also helped by the fact that offshore wind has come to some very economically challenged areas that traditionally governments have supported—I'm talking about Barrow in Furness, Heysham and areas like that—Hull, Grimsby"—MTD58*

Interviewees also noted the role of the industry in building its own legitimacy, especially as the successful delivery of capacity was seen to enhance the legitimacy of all projects. A stakeholder described this process:

> *"Offshore wind has worked pretty well. And I think offshore wind has managed to get successes in the right order, as they pledged to government; government has seen more progress than they expected ... They've over delivered on that promise and that's given Government a huge amount of confidence"—SH40*

The interplay between onshore and offshore wind was surprisingly complex, where, in essence, the successful delivery of onshore capacity was seen to generate public resistance to additional onshore deployment whilst legitimising offshore activity. One stakeholder summarised this complexity:

> *"I think certainly the acceptance of offshore wind at a time when onshore wind became a real hot potato in political terms, offshore wind certainly became more favoured because it's 'not in my backyard', further from shore"—SH43*

Although legitimation achieved one of the lower scores amongst all of the functions, it still scored more than the mid point score of 3.0 and its necessity as a function is considered to have been confirmed through the interview process (see Figure 1).

3.8. Relationships between Existing Functions

The existing functions are closely intertwined. The interviews revealed that the interviewees identified operational relationships between many of the functions, as set out in Table 2, which shows the effect of each function on the others, with colour-coding giving an indication of the perceived strength of the effect, as determined from analysis of the interviews (green—high, amber—middle, red—low).

3.9. Necessity of Existing Functions

The detailed analysis of more than 30 interviews with a wide ranging sample of participants in offshore wind and marine renewables has confirmed that each of the seven Hekkert functions was considered to be necessary in the case of these emerging technologies. This was supported both by the quantitative scoring and by the qualitative comments.

The interviews suggest that each of the functions has been executed to some degree and has contributed to the development of each of offshore wind, tidal stream and wave energy to their current state.

Table 2. Operational relationships between Technological Innovation Systems (TIS) functions (authors' analysis). Key: green—strong relationship, amber—moderate relationship, red—weak relationship.

Function	F1—Entrepreneurial Activity	F2—Knowledge Development	F3—Knowledge Diffusion and Networking	F4—Guidance of the Search	F5—Market Formation	F6—Resource Mobilisation	F7—Legitimation
F1—Entrepreneurial Activity	NA	F1 inspires and often funds early knowledge development	F1 creates a network of knowledge developers amongst whom diffusion occurs	F1 can provide input to policy formation	F1 can inform incentive design	F1 has limited effect on F6	F1 creates early legitimacy
F2—Knowledge Development	F2 reassures entrepreneurs of a route to success	NA	F2 creates knowledge for diffusion	F2 provides knowledge for policy making	F2 informs incentive design and potential scale of market	F2 has limited effect	F2 creates foundation around which legitimacy can develop
F3—Knowledge Diffusion and Networking	F3 allows for early learnings to diffuse, providing reassurance	F3 enables faster knowledge development	NA	F3 supports policy making	F3 enables widespread appreciation of market potential	F3 has limited effect	F3 creates wide base of knowledge to support legitimacy
F4—Guidance of the Search	F4 provides direction and incentive for entrepreneurs	F4 drives direction of knowledge development	F4 has limited effect on knowledge diffusion	NA	F4 critically drives market formation and incentive design	F4 gives resource providers confidence in policy support	F4 provides "official" legitimacy
F5—Market Formation	F5 provides prospect of financial reward for entrepreneurs	F5 incentivises knowledge development and defines the market	F5 supports diffusion by creating market pull	F5 closely inter-related with Guidance of the Search	NA	F5 defines the market giving providers confidence in market finances	F5 defines market incentives, supporting legitimacy
F6—Resource Mobilisation	F6 generally takes place later than F1	F6 increases population of "learners by doing"	F6 involves adding to active population in sector, with potential for diffusion	F6 demonstrates industry confidence in sector, driving policy support	F6 confirms industry confidence in market, confirming market validity	NA	F6 shows that industry and investors are ready to commit to the sector, giving legitimacy
F7—Legitimation	F7 provides reassurance for entrepreneurs	F7 provides confidence for researchers	F7 justifies diffusion of knowledge	F7 validates supportive policy formation	F7 justifies market incentives	F7 encourages resource mobilisation	NA

4. Sufficiency of Functions and Introduction of "Demonstrating Value" as a New Function

4.1. Emergence of a New Function

The analysis of interviews confirmed that each of the Hekkert functions was necessary in describing the emergence of the focal TIS. However, a common theme which was not captured within the existing seven functions also emerged, indicating that the seven functions inventory was not entirely sufficient to fully characterise the emergence of the focal technology in the TIS.

This common theme was derived from analysis of the interviews, where it was found that all of the interviewees made substantive comments regarding the potential or actual economic, social and environmental contribution of the emergent technologies relative to both incumbent and other emerging technologies. The need for the focal technology to demonstrate its value within the wider TIS emerged as a recurring theme for interviewees, who made it clear that the successful emergence of a "niche" technology was, in large part, driven by its potential to create value.

One interviewee described the motivations of participants as driven by a profit motive:

> *"They [technology and project developers] are not just doing it for the good of mankind. They are doing it bring down their future costs or to increase their future revenue"—PM49*

Interviewees also explained that the role of policy makers had to take account of the commercial potential of the focal technology, and that they should not invest in technologies with little potential:

> *"But it [Government] shouldn't be doing so at the expense of other sectors which might be more commercially viable . . . But at its core, taking it back to simple levels, it's all about economics"—PM55*

This view was shared by support organisations, which were aware that the profit motive was critical in driving participants to dedicate resource to the emerging technology:

> *"So for the globals to really take an interest, it's got to be to be seen to be a likely candidate for core business or something where they can make some money and then maybe pass it on"—SO77*

The research focussed on the comparative emergence of offshore wind and marine renewable energy technologies (defined, in this research, as wave and tidal stream). During the period studied, the prices received by offshore wind fell from c. £150/MWh (as determined by value received under the Renewables Obligation and the Contracts for Difference awarded under the FIDER arrangements) to less than £60/MWh (based on recent bids for Contracts for Difference) [25]. This radical change in the economics of the technology which was competing with marine renewables undermined the potential for these technologies to demonstrate their value, as their development could no longer show a path to cost competitiveness with offshore wind. In essence, the goal posts for marine renewables drastically shifted, undermining their potential competitiveness with offshore wind, and wrecking marine renewables' ambitions towards "utility-scale" electricity generation.

The review of the literature found that the existing functions definitions did not adequately address the importance of the potential for the focal technology to demonstrate its value and therefore supported the introduction of the proposed new function.

One interviewee summarised this problem for marine renewables thus:

> *"Offshore wind is almost the worst thing that could have happened to wave and tidal"—SC56*

4.2. Definition of the New Function, "Demonstrating Value"

Analysis of the interviews has therefore allowed the identification of a potential new function, which we have named "Demonstrating Value" and which we define as "*the potential or actuality of the focal technology in the TIS being competitive with relevant incumbent or emergent technologies*".

This definition has four parts:

- "Potential or actuality"—the function addresses whether the focal technology in the TIS either has already or can potentially demonstrate a roadmap to economic or other competitiveness

- “Competitive”—the focal technology in the TIS can make a case for existence without special treatment in the context of the technologies with which it emerges to compete (e.g., the emerging technology no longer requires a subsidy or offers other benefits)
- “Relevant incumbent technologies”—existing technology or technologies which already operate without special protection in the broader technological system (Geels’ “regime”) where the focal technology in the TIS exists (e.g., thermal power generation)
- “Relevant emergent technologies”—any emergent technology or technologies which have the potential to compete with the focal technology in the TIS (e.g. wave energy technology competing with offshore wind)

4.3. Validity of New Function in Relation to Hekkert et al.’s Framework

In proposing a new function for the well-established functions framework it is important to make the case robustly. This requires two questions to be answered: “should the proposed function be subsumed into an existing function?”; and “is the scope of the proposed function broad enough to warrant it being a function in its own right?”.

Hekkert et al.’s seven functions are: Entrepreneurial activities, Knowledge development, Knowledge diffusion and networking, Guidance of the search, Market formation, Resource mobilisation and Legitimation. A review of the definitions of these functions identifies that the proposed new function of “Demonstrating Value” has some overlap with both market formation and legitimation.

Hekkert et al. focus their definition of market formation on the creation of “protected spaces” in which the focal technology can develop without being exposed to the normal economic and competitive stresses of a new technology. The focus of “Demonstrating Value” is on the potential for the focal technology to demonstrate a roadmap to commercial viability outside any protected space, and thereby justify investment. The critical difference is that “market formation” is inward-looking towards the focal technology and its local competitive environment, and “Demonstrating Value” is outward looking, forcing an evaluation of the potential for the focal technology to establish a route to commercial viability.

Hekkert et al.’s “Legitimation” evolved from Bergek et al.’s earlier proposed function of “creation of external benefits” and was extended to include the “formation of advocacy coalitions” which help to make the case for the focal technology. While there is some overlap with “Demonstrating Value” where the functions both consider the public acceptance or “social licence to operate” of the new technology, the proposed new function has a much wider technical, economic and commercial scope. However, it is noted that “Demonstrating Value” is likely to involve moving forward on the function of legitimacy too, as being able to make a case for the emergent focal technology without any special treatment obviously contributes to its legitimacy.

This research concludes that the rationale is sufficiently strong to justify the proposed new function’s introduction, to complement the existing seven Hekkert et al. functions.

4.4. Metrics for the “Demonstrating Value” Function

A number of authors have operationalised the “seven functions” model, notably Jacobsson and Karltorp [9] and Wieczorek et al. [10,11] in wind and Hannon et al. [3] in wave energy innovation. These authors developed metrics and indicators which they used to evaluate the level of completion of each of the seven functions. If it is to be operationalised, the proposed new function requires similar measures.

Potential measures for the new function of “Demonstrating Value” have to address all aspects of the proposed definition. “Potential or actuality” means that the measures must take account of both current and potential future performance, and can include conventional “internal” economic factors, and externalities. “Competitive” means that the measure should be used to compare the focal technology with other technologies, and, as the last two elements of the definition establish, these should include both incumbent and competing emergent technologies.

A well-established measure of technological readiness is available in the nine-level Technology Readiness Level (TRL) scale, defined by NASA's John Mankins [26] as "a systematic metric/measurement system that supports assessments of the maturity of a particular technology and the consistent comparison of maturity between different types of technology". It ranges from TRL 1 ("Basic principles observed and reported") to TRL 9 ("Actual system 'flight proven' through successful mission operations"). TRLs have now been widely adopted and adapted; for example, the European Marine Energy Centre has modified the TRL scale to allow for evaluation of the technological readiness of wave and tidal stream energy capture devices [27].

TRL can be used to assess the actual technological readiness of technology alternatives, but the proposed new function also requires a measure for economic performance and potential. A number of measures of unit cost of energy have been used in the literature and Levelised Cost Of Energy (LCOE) has emerged as the leading metric. Aldersey-Williams and Rubert [28] explored the LCOE measure in some detail, and concluded that the definition of LCOE used by the UK Government Department of Business, Energy and Industrial Strategy was both justifiable and widely used.

However, one critical weakness of the conventional LCOE definition is that it does not attempt to include "externalities" [29], being the costs and benefits which relate to the technology alternatives under consideration which are not endogenous to the devices and projects being deployed. These may include, for example, the health disbenefits and costs relating to pollution from coal-fired electricity generation, or the amenity disbenefits arising from an offshore wind farm.

In order to account for externalities, this paper proposes a modified version of the LCOE formula presented by Aldersey-Williams and Rubert [28]. This has been defined as Full Cost Of Energy (FCOE) and is set out in Equation (1).

$$\mathrm{FCOE} = \frac{NPV_{Costs} + NPV_{Externalities}}{NPE} = \frac{\sum_{t=1}^{n} \frac{C_t + O_t + V_t + Ex_t}{(1+d)^t}}{\sum_{t=1}^{n} \frac{E_t}{(1+d)^t}} \quad (1)$$

where t is the period ranging from year 1 to year n, C_t is the capital cost in period t (including decommissioning), O_t is the fixed operating cost in period t, V_t is the variable operating cost in period t (including fuel cost and sometimes taxes, carbon costs etc.), E_t is the energy generated in period t, d is the discount rate, and n the final year of operation.

This equation adds a term to Aldersey-Williams and Rubert's equation: the new term, Ex_t, is the externality cost in period t.

In using this formula, it is critical to attribute the relevant costs and benefits to the technology to which they relate. Although it seems appealing to include the value of pollution saved in the LCOE for a renewable energy technology, it is more accurate to include it as part of the cost of the counterfactual technology. Put another way, the relative value of the renewable option depends on the conventional thermal technology with which it is being compared.

This formula allows for the calculation of the FCOE, including the externalities, to allow the comparison of technology alternatives.

4.5. The Valuation of Externalities

Having proposed FCOE as a metric for the new "Demonstrating Value" function, it is important to consider how to try to evaluate it. The valuation of externalities is challenging, as externalities range from those which are fairly readily estimated to those which are much harder to value, and a number of techniques have emerged to attempt their evaluation.

First, an inventory of externalities to be included in the analysis must be developed. Mattmann et al. [30] undertook a wide ranging meta-analysis of the externalities of wind power and identified a wide range of externalities. They grouped these under the headings of air pollution and climate change, fuel independence, biodiversity, visual impacts, noise impacts, green policy and other (comprising location, type of ownership, stakeholder consultation, reduced number of blackouts, land area affected and recreational activities associated with an artificial reef). The interviews in this research suggested additional externalities, and it seems to the authors that the development of a full list might only be realistically limited by the time available to develop the list. That said, the Mattman et al. listing may be a good place to start.

Having developed a list of externalities, an approach for evaluation must be developed. The literature describes a number of approaches to valuing externalities: some of these are tabulated in Table 3 [30–34].

Table 3. Evaluation methods for externalities (authors' analysis).

Name	Methodology	Suitable for
Direct estimation/Damage cost	Estimated from measures of known impacts	Pollution and waste products, health impacts. Value limited to known impacts
Control cost	Value estimated with reference to costs required to control or mitigate impact	Pollution and waste products. Limited as only accounts for known costs of control/mitigation and cannot include unknown impacts
Willingness to accept/willingness to pay	Affected stakeholders (or sample of them) asked what payment they would require to compensate for perceived impact or what they would pay to avoid perceived impact	All factors
Choice experiments	Aims to explore alternatives with equivalent utility, to "convert" unquantified into quantified assessments	Applicable for factors where direct estimation and control costing not available
Surrogate market	Value with reference to appropriate surrogate market where externalities are included	Externalities where surrogate market is available
Social Cost of Energy	Estimates job creation (direct, indirect, induced jobs)	Social impacts, specifically local content

Roth and Ambs [35] presented a full cost approach to incorporating externalities in LCOE calculations, including the discounted value of each externality in their LCOE calculations to present a FCOE for a range of technologies in the United States. They included externalities including "damage from air pollution, energy security, transmission and distribution costs and other environmental impacts" [35] and applied a "control cost" methodology to estimating environmental costs for atmospheric pollutants.

It is unfortunately beyond the scope of this paper to attempt a full cost of energy estimate for UK offshore wind against an appropriate counterfactual, but this would be a rich opportunity for further work in applying the FCOE metric.

5. Discussion

The functions model of TIS has shown itself to be an invaluable framework within which to consider socio-technological transitions. However, hitherto it had not had a practical validation amongst practitioners in a specific industry sector.

It seemed to the authors that while earlier researchers in this sector have created a powerful architecture for enquiry, this could be reinforced with an external validation. Accordingly, this research has been founded on discussions with a range of participants in the offshore wind, tidal stream and wave energy industries and associated policy makers, suppliers, support organisations and others with the aim of reinforcing and challenging the seven functions foundation.

The researchers who developed the functions framework did so based on their own conceptualisations and case studies. This research, based on interviews with actors in a specific TIS, has substantially supported their work, and has found that an additional function may be justifiable, to allow the functions model to take account of contextual factors and the perceived need for emergent technologies to demonstrate the value.

Specifically, we found that the answer to our first research question—"are the Hekkert functions each 'necessary' to describe the transition in question?"—was a clear "yes", and the answer to our second—"is the Hekkert functions inventory 'sufficient' to fully describe the transition?"—was "no", and that our research led us to propose the new function of "Demonstrating Value".

The evaluation of externalities has a rich literature, and application of the proposed FCOE metric will require an engagement with this literature to ensure that appropriate methods for evaluating externalities are applied. In all of this analysis, a guiding principle must always be to ensure that the externalities relating to each technology alternative are applied to the relevant technology. For ecample, one obvious benefit of offshore wind over coal power is the reduced pollution (and associated costs). It is vital to include the costs of the pollution as a negative externality (i.e., cost) of coal, rather than as a positive externality (i.e., benefit) of the renewable choice. This is because if the coal is replaced with (for example) nuclear, the externality no longer arises and the analysis must reflect this.

The authors feel that the proposed new function, "Demonstrating Value", could offer some potential for a partial reconciliation of the TIS and MLP approaches, as the new function requires the TIS practitioner to look outside the "niche" in considering the roadmap by which an emergent technology can become an established part of the energy system. It forces consideration of both "regime" and "landscape" factors in considering the emergence of the focal TIS technology. It is hoped that this leads to richer characterisation of the factors driving socio-technological change.

This research has found that the "functions" approach can offer insights into the detailed processes of niche break-out, especially when reinforced with the proposed new function.

In contrast, MLP clearly defines the static, dynamic and contextual aspects of the socio-technological system, by defining the regime, niches and landscape respectively, but does not clearly address the specifics of how niche technologies can break-out into what Geels [16] would call the "regime".

The proposed new function explicitly forces consideration of the evolution of the TIS to take account of "landscape" and "regime" factors—in other words, forcing a consideration of the value potential of the focal technology relative to incumbent or other emergent technologies. This suggests that the new function may offer a route to a partial reconciliation of TIS and MLP.

With the proposed addition of the new function, the extended functions approach could be applied to a focal technology, operating in what Geels [16] would characterise as a "niche", to throw light on the precise mechanisms which permit (or prevent) niche technologies to break out into the "regime" layer whilst also considering the enabling or blocking roles of incumbents in the socio-technological regime and of "landscape" factors.

Through this extension, the TIS functions approach could be extended to consider the effect of the exogenous (to the niche) actors on functional success.

As the field continues to develop, clarity as to the underlying methodological approach, where a tension between interpretivist (MLP) and positivist (TIS) has given rise to reciprocal criticisms between MLP and TIS practitioners in the past (see Geels [19]), will also be essential. This research has found that a pragmatic approach, positivist where possible and interpretivist where necessary, has nonetheless made useful findings.

Figure 2 shows the Geels et al. [16] characterisation of the MLP niche/regime/transition framework overlain with the functions approach from TIS. The proposed integration of the functions approach into the MLP conceptual architecture, through the introduction of the new function of "Demonstrating Value", is new and is offered as a contribution to the literature.

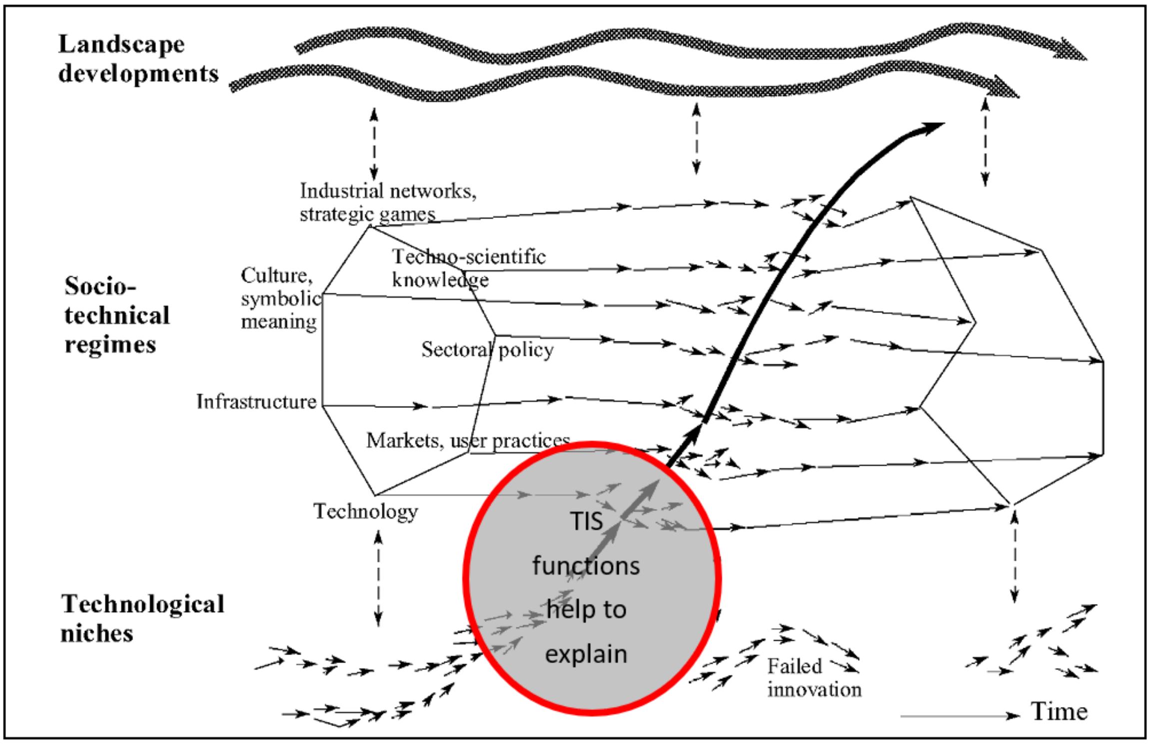

Figure 2. From Geels (2002), authors' modifications. TIS functions comprising the original seven functions of Hekkert et al. in addition to the Demonstrating Value function could be helpful in explaining the mechanisms by which technological niches break out into the regime.

While both TIS and MLP models offer valuable means for understanding socio-technological transitions, we feel that the conventional "seven functions" model has little room for what Geels would call landscape factors. The current COVID pandemic is an unimpeachable example of this: it is causing significant changes in Government policies towards "building back better" (F4—Guidance of the Search) [36], and over the medium term is likely also to influence F5—Market Formation and other functions too.

As we have suggested, the proposed new function of Demonstrating Value that has emerged from our work adds a contextual dimension to the TIS model, allowing it to take earlier notice of landscape changes.

6. Conclusions

This research has tested whether Hekkert et al.'s well-established seven functions framework provides a comprehensive framework within which technological transitions can be understood. It concludes that, in the case of offshore wind and marine renewables, all of the seven Hekkert functions are 'necessary' and offer explanatory power to the model. The current research has provided insights into the perceived relative importance of these functions and finds that F4—Guidance of the Search was considered to be the most important among the stakeholder group interviewed.

However, it also finds that the roadmap by which an emergent technology can become an established part of the energy system (what Geels [16] calls the "regime"), may not be adequately captured in the seven functions framework. Accordingly, this paper proposes the addition of a new function—"Demonstrating Value"—to the seven functions model, and it defines this new function.

The functions model exists to be used, and in order to operationalise the new function of Demonstrating Value, it is necessary to define metrics for it. This paper has proposed an improved version of the LCOE—"Full Cost of Energy"—which includes externality costs and benefits in the calculation of the value of technology alternatives. Application of this metric requires a full engagement with the literature on the valuation of externalities, in which a range of approaches to valuing these sometimes intractable quantities is presented.

Further work in the field of externalities is called for. By applying the FCOE metric, it may now be possible to move beyond simply listing externalities to evaluating them and including their effects in an integrative metric, and thereby informing societal technology policy decisions in a holistic way.

The current COVID pandemic has shown the potential impact of "landscape" factors. We hope that our proposed enrichment of the functions model will increase the value of the TIS functions approach by helping it to take these into account.

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