PART IV

CLIMATE CONSEQUENCES AND ENERGY FUTURES

21. Knowledge infrastructures for sustainable energy transitions: marine renewable energy in Scotland

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INTRODUCTION

As governments around the world search for ways to transition to lower-carbon energy systems, nascent and early-stage alternative technologies have become more desirable. One of these emerging technologies includes marine renewable energy – wave, tidal, and current energy. Marine energy is often posited as a renewable, reliable, abundant, and predictable energy source that can complement existing energy generation, and its potential to power emerging sectors in the 'blue economy' such as aquaculture, ocean mining, ocean observation, or other applications and industries, is only beginning to be recognized (LiVecchi et al., 2019). Despite this potential, marine energy research and development is still at an early stage, especially when compared with the wind energy industry, which began earlier and has advanced at a much faster pace (Mueller and Wallace, 2008). This is due to a number of challenges, including logistical and engineering issues caused by the nature of the marine environment, long design cycles, a lack of technological convergence, as well as a lack of financial incentives for development due to the structuring of energy economics and policy (Hannon et al., 2017). Globally, marine energy is therefore at a stage where support for innovation, research, and development is critical (OES, 2018).

For some nations with ample access to marine resources, energy derived from waves and tides has become a locus of innovation and investment. In Scotland, fostering innovation for marine energy has gone hand-in-hand with the emerging narratives and strengthening national imaginary of Scotland as a place for renewable energy innovation. The Scottish Government has marketed Scotland as a 'climate pioneer', positioning itself as different from the rest of the UK by drawing on the politics of territorial identity (McEwen and Bomberg, 2014).

Yet the Scottish Government's success is partly due to its investment in knowledge infrastructures to support innovation in marine renewable energy. Knowledge infrastructures support scientific work. They are the ecosystems and networks of material, conceptual, and institutional actors and artifacts that produce and extend knowledge (Bowker and Star, 1999; Edwards, 2010). Thus, knowledge infrastructures include both 'abstract' elements such as protocols, standards, and collaborations, as well as 'concrete' elements such as test sites, instruments, demonstration projects, and financial resources (Bowker et al., 2010).

Because the marine energy industry is at an early stage of development and scaling, knowledge infrastructures to support research and innovation in this domain are particularly dynamic at this point in time. Energy transitions are also enmeshed in national (Anderson, 1983), sociotechnical (Jasanoff, 2015), and environmental (Peet and Watts, 2002) imaginaries of energy futures, and the Scottish Government has used these imaginaries to make the relatively small nation of Scotland have an outsized impact on the global marine energy sector. Yet innovation in renewable energy does not occur in a stepwise process from idea to policy to implementation. Instead, ongoing experimentation is required in order to both cultivate imaginaries and translate strategies, white papers, and long-term visions into futures (Verschraegen and Vandermoere, 2017). While these dynamics are often highlighted at the macro-scale, they also take place at the micro- and meso-scale of designing and creating knowledge infrastructures to support renewable energy innovation.

This chapter uses a grounded-theoretical approach (Charmaz, 2005; Clarke, 2005) to explore how knowledge infrastructures support or hinder innovation in marine renewable energy. Through this case analysis I demonstrate the importance of considering knowledge infrastructures in understanding innovation and developing research policy to support sustainability transitions. In doing so, the study also argues that qualitative, grounded-theoretical methods that uncover the role of knowledge infrastructures make an important contribution to energy research more broadly. The chapter begins with an overview of the case of marine energy innovation in Scotland, followed by an outline of relevant literature on knowledge infrastructures that identifies the gap that this kind of analysis can fill in energy research. Finally, using qualitative data from an empirical study, three examples of knowledge infrastructures in marine energy in Scotland are given, along with the implications for energy research more broadly. These examples demonstrate the way that knowledge infrastructures are an often invisible, but crucial part of fostering innovation in this emerging energy sector.

RENEWABLE ENERGY INNOVATION: THE CASE OF MARINE ENERGY IN SCOTLAND

The United Kingdom (UK) Government has looked to both energy policy and investment in infrastructure, research, and development to facilitate innovation in the marine energy sector (Corsatea, 2014). Much of this investment, either from the UK, European Union (EU), or Scottish governments, and the research, development, and testing that has occurred has taken place in Scotland. Yet, as a devolved part of the UK, Scotland has jurisdiction over some of the policies that might be used to facilitate marine energy development, but not all of them. Therefore, the Scottish Government has been forced to be creative in terms of furthering its own energy agenda. Even though most regulatory power over energy was not devolved to Scotland, devolution of some powers to the Scottish Parliament in 1998 set off a move to create a Scottish national energy strategy. These strategic shifts were followed by an increase in UK-wide decarbonization policy in the later 2000s, which also spurred investment in renewable energy innovation in Scotland (Winskel et al., 2014).

Following the International Energy Agency, the Scottish Government has emphasized ‘accelerated technological development as the key to facilitating a rapid energy transition from reliance on North Sea oil to renewables’ (Winskel et al., 2014). The Scottish Government’s 2008 energy policy overview states: ‘Scotland is rich in energy resources and we must be ambitious in their exploitation. We are planning now for the huge export potential of renewable energy and clean energy technology’ (Scottish Government, 2008, p. 4). In order to realize this ambition, the Scottish Government invested heavily in onshore and offshore wind, solar, as well as marine renewable energy (indeed another Scottish case, on the Isle of Lewis, is discussed in Pinker, Chapter 20).

Despite lacking control over the ability to regulate energy transmission and pricing, the Scottish Government has looked for novel ways to foster development in the renewable energy sector. This has included facilitating both marine and terrestrial spatial planning, modifying environmental regulation, and granting planning consent (see Cowell, Chapter 16). To overcome the inability to make structural changes in energy policy, the Scottish Government has also launched several high-profile research enterprises and initiatives and invested in knowledge infrastructures to support renewable energy innovation, especially marine renewables (Graziano et al., 2017). Some examples of investments that specifically target marine energy (to varying degrees) include: the Saltire Prize for marine renewable energy, the Forum for Renewable Energy Development in Scotland (FREDS), the Scottish Energy Laboratory, the European Marine Energy Centre (EMEC), the International Technology and Renewable Energy Zone (ITREZ), the Energy Technology Centre, the Energy Technology Partnership, as well as multiple regional and local grants for community-based energy such as Community Energy Scotland, and local development of industrial supply chains or research through Scottish Enterprise and Highlands and Islands Enterprise.

Although some investment for these projects has come from the UK and the EU, the Scottish Government has successfully framed Scotland as a globally important location that supports innovation in marine renewables (Hamilton, 2002). These investments in marine energy have not only benefited Scotland: the testing and demonstrations projects that are taking place in Scotland have the potential to reduce costs of marine energy generation globally, making deployment of commercial, large-scale devices possible (Wright et al., 2018; UK Marine Energy Council, 2019). In Scottish waters, large-scale tidal installations, including Simec Atlantis Energy's MeyGen project have already generated over 30GWh of energy to the grid. Meanwhile, wave energy converters at EMEC have also generated over 130MWh (UK Marine Energy Council, 2019). In both of these instances, Scotland was able to claim global firsts in marine energy generation to the grid.

Yet there have also been setbacks in this effort to accelerate marine energy R&D. Devices have been slow in reaching commercial scale. Public failures of devices have influenced perceptions, and some projects have fallen short of the economic benefits promised to local communities. In addition, UK-wide, energy pricing has not aligned to facilitate investment in renewables, especially nascent technologies such as marine energy, therefore stifling research and development across the country.

A recent report by Hannon et al. (2017) examined the effectiveness of innovation policy and research support for wave energy in the UK. The authors found that despite almost 200 million GPB of public funding investment in wave energy innovation since 2000, the sector has not delivered a commercially viable device. Yet many (but by no means all) of the technological challenges faced by the sector are problems that must be supported by science and innovation policy (Mueller and Wallace, 2008). Hannon et al.'s (2017) analysis found that lack of knowledge exchange and support at critical turning points in the sector has resulted in poor innovation outcomes and a withdrawal of multi-national investors. Their research also highlighted that more recent investment in establishing new R&D programmes, facilitating actor networks, and creating world-leading testing sites has led to increased and measurable innovation performance in the wave energy sector, attracting developers from around the world (Hannon et al., 2017). Interdisciplinary understanding is needed to overcome these challenges, and social science research on knowledge and innovation in the marine energy sector has been recognized as a key gap (Kerr et al., 2014). Hannon et al.'s (2017) report not only highlights the important ways in which innovation policy has significant and measurable impacts on an emerging industry, but it also points to the need to understand how innovation is being supported (or hindered) by knowledge infrastructures.

CONCEPTUALIZING KNOWLEDGE INFRASTRUCTURES

Knowledge infrastructures are the 'robust networks of people, artifacts, and institutions that generate, share, and maintain specific knowledge about the human and natural worlds' (Edwards, 2010, p. 17). Knowledge infrastructures support scientific work – both the way it is conducted and how it is applied (Bowker and Star, 1999). Knowledge infrastructures can be material, but they can also be conceptual or social in nature. Either way, knowledge infrastructures can have material effects, having lasting consequences for the science that results from their use (Edwards et al., 2013). Infrastructures are thus 'paradoxical' because they can be used to facilitate change in research trajectories, but they can also hinder adaptation (Star and Ruhleder, 1994). According to Bowker and Star (1999), this is tied to the nature of infrastructures: in order to facilitate knowledge exchange, knowledge infrastructures must be standardized enough to extend work practices across organizations while at the same time remaining locally useful. The infrastructures constructed today will therefore impact knowledge production in the future, and considering the way they may be able to adapt to changing technologies or environmental conditions is therefore important. This tension between the need to be rigid yet remain flexible becomes especially clear in large-scale infrastructures where sociotechnical systems have a spatially and temporally broad reach (Star and Ruhleder, 1994), like those surrounding energy innovation and development. In marine energy development, the dynamics of change and adaptation in knowledge infrastructures are particularly apparent because the nascent technology and emerging sector necessitates a highly flexible knowledge infrastructure.

Knowledge infrastructure studies has its roots in science and technology studies (STS), and as such, draws on qualitative and ethnographic methods that focus on the techniques that actors use to deal with and work within knowledge infrastructures. Examples of these techniques include using grounded theoretical methods (Charmaz, 2005). Using these methods, researchers gather qualitative data from participants and then use coding techniques to locate themes and devices that participants use to explain, interact with, or relate to knowledge infrastructures (Star, 1999; Ribes, 2014). By employing grounded-theoretical methods, scholars have been able to explore the ways that researchers rely on knowledge infrastructures, sometimes in surprising ways.

For example, Ribes (2014) found that researchers working on a large-scale geosciences network (GEON) used scalar devices, or tools to facilitate work across a large-scale project in order to build and maintain a lasting knowledge infrastructure (Ribes and Finholt, 2009; Ribes, 2014). Actors may also be actively involved in creating infrastructure, or infrastructur-*ing* (Pipek and Wulf, 2009), which can be observed at both the individual and organizational level (Ribes, 2017). Since infrastructures can be studied by recognizing the techniques that actors use to deal with them and work within them, by focusing on these dynamics, it can even be possible to normatively design and implement adaptive knowledge infrastructures. For example, by tracing the shifting needs of HIV researchers, Ribes and Polk (2015) conclude that by 'repurposing, elaborating, and extending' the 'kernel of research' infrastructure, researchers were able to meet current infrastructural needs while at the same time remaining flexible to future changes. Importantly, for understanding energy transitions, those researching knowledge infrastructures have found that, once established, knowledge infrastructures can be difficult to reverse, as they institutionalize norms, values, and virtues that endure into the future (Ribes, 2017).

Understanding the dynamic of change in knowledge infrastructures has been identified as one of the key research challenges for infrastructure studies (Edwards et al., 2013). This aligns well with research in energy and sustainability transitions, which seeks ways to adapt socio-technical systems to increase sustainability. Understanding how socio-technical systems can support societal goals for sustainability in sectors such as energy, transport, and agro-food has been a goal of sustainability transitions research (Grin et al., 2011), and a growing number of empirical case-studies have tested and refined methods and analysis, providing a rich set of tools for science and innovation policy researchers to draw from (Kohler et al., 2019). Research in the field of sustainability transitions is usually explicitly prescriptive and focuses on ways to facilitate and manage sustainability transitions (Kemp and Rotmans, 2005; Kemp and Loorbach, 2006), often through 'strategic niche management' (Hoogma et al., 2002; Smith, 2003). While transitions management considers the role of power and agency in transformative work (Avelino and Rotmans, 2009), the field has also been criticized for focusing too much on meso-level analysis of socio-technical systems (Geels, 2004), as opposed to macro-scale political-economic analysis or micro-scale individual behaviors and practices. Recently, however, there has been increased interest among STS and sustainability transitions scholars in calling for interdisciplinary studies that bring concepts from both fields together to help fill this gap (Hess and Sovocool, 2020). Knowledge infrastructures is one such concept, and the following case will give examples of the empirical and conceptual work that can be done by adopting knowledge infrastructures as a frame.

In the case of innovation in the Scottish marine energy sector, for reasons outlined above, many policy and economic reforms are not available as transition tools for the Scottish Government. Instead, national sustainability transitions are relying on constructing and maintaining appropriate knowledge infrastructures that will support the innovation necessary to make these sociotechnical shifts. A need for new knowledge to support an emerging technology means that existing knowledge infrastructures must be adapted to align with new research trajectories. Therefore, conceptual and empirical work on knowledge infrastructures can provide a nuanced view of how sustainability transitions take place across many contexts, and the Scottish case provides an interesting one because it highlights how energy transitions may be advanced by building supporting knowledge infrastructures.

LOCATING KNOWLEDGE INFRASTRUCTURES IN MARINE ENERGY

Research on knowledge infrastructures uses grounded theoretical methods to identify knowledge infrastructures from the perspective of individuals themselves (Star, 1999). Using these methods, this study located several ways that knowledge infrastructures are supporting marine energy research, development, and innovation in Scotland. The following analysis is based on 27 semi-structured interviews with policymakers, researchers, engineers, and developers involved in the marine renewable energy sector in Scotland. In addition, the research included participatory observation at eight conferences on marine renewable energy (three in the United States and five in Scotland); webinars and workshops aimed at marine energy researchers and developers; as well as both online and physical archives, including meeting minutes, historical political files, and policy documents from the Scottish Government, Scottish Parliament, and the Scottish National Party, among others. These materials were coded and analyzed using a modified grounded-theoretical situational analysis approach. Situational analysis is a multimodal approach to doing grounded theory that uses situational mapping techniques to analyze diverse sets of data including interview transcripts, policy documents, ethnographic memos, and visual collections (Clarke, 2005).

Participants identified many knowledge infrastructures that were supporting their work, but only three are outlined below. They were chosen because they were discussed by participants across many roles within the sector and they became important sensitizing concepts when viewed through a knowledge infrastructures perspective. The three described include: (1) networked and nested testing and demonstration centres, (2) standards for instrumentation and testing, and (3) university–industry collaboratives. After brief examples of each, I describe how they act as important knowledge infrastructures for supporting innovation in marine energy, and then consider the implications for understanding these knowledge infrastructures in energy research more broadly.

Networked and Nested Testing and Demonstration Centres

The network of physical testing and demonstration centres that have been established across the region is enabling marine energy innovation across Scotland. Yet, while the physical infrastructures, such as the testing facilities themselves, are important, participants also identified the formal and informal social networks that have formed between them as critical to their functioning: participants rely on the networked and nested nature of the centres to forge connections between industrial and academic research.

The marine energy research and testing demonstration centres in Scotland stand out as the most extensive and developed globally, and researchers and developers come from around the world to use Scotland's testing infrastructure. Scotland is home to the largest full-scale offshore marine energy testing and demonstration site in the world, the European Marine Energy Centre (EMEC). Located in the Orkney Islands in Scotland, it has been granted 36 million GBP in public funds, and has the most comprehensive facilities for open water testing of marine energy devices. EMEC attracts developers because it has both demonstration-scale and full-scale, grid-connected berths for testing both wave and tidal devices.

The marine energy testing infrastructure in Scotland also includes smaller-scale testing facilities, many of which are located at universities that have had long-standing research programmes in marine energy. One of these is FloWave, a test tank located at the University of Edinburgh. FloWave opened in 2014, but has a much longer history stretching back to some of the earliest wave energy experiments (Salter, 2016). It is a circular, multi-directional wave and tidal testing tank with the ability to simulate complex sea states, including the EMEC test centre's seas in Orkney. As one researcher pointed out, the tank is able to replicate a 'piece of the sea' from Orkney (Billa Croo, where the EMEC is located), so that smaller-scale devices can be tested in the tank before heading to the open ocean test births (Draycott et al., 2019). One participant spoke of the usefulness of this kind of nested test-centre network, that brings 'real-world ocean conditions into the lab', stating:

> I guess the real advantage is that you get truly realistic conditions and you start to learn about what your device might be like in a very specific site (if you already know where you're going to go). You can use that data to actually recreate those conditions and understand the performance and the survivability as well. So, if you know the site-specific nature of the extreme conditions, you can also reproduce those and de-risk it for that site.

The network of testing facilities is helping developers scale-up devices so that they do not have to put them in the ocean until, as another participant put it, 'you think you have nothing more to learn'. This nested network of testing and demonstration centres allows researchers to save resources and time, supporting them in testing out potential devices and technologies in simulated seas.

Researchers and developers in this study not only found the nested nature of the testing sites supportive, but also highlighted the ways the informal and formal research networks and relationships between these facilities supported their work. The test centres provide networking and cyberinfrastructure, assistance with the creation of testing protocols and standards, and workshops and training for researchers from around Europe and the world. They also work closely with clients to make sure that they can use their test time effectively. Through interaction at these workshops, researchers not only gain knowledge, but relationships between them are also strengthened, enabling interdisciplinary ideas to converge. Because of their nested nature, many researchers work across the testing sites, for example bringing Orkney's seas into the test tank and simulating conditions using models from EMEC's test facility. These connections build relationships and exchange knowledge in both formal and informal ways, making them an important knowledge infrastructure.

Standards for Instrumentation and Testing

Engineering standards are developed to ensure safety and reliability, but also to enable more seamless and faster communication of information and knowledge transfer. These standards for instrumentation and testing are another, less visible, but no less important, knowledge infrastructure supporting innovation in marine energy. A lot of time and effort is being put toward creating and establishing these industry technical standards in the marine energy sector. This is being facilitated through the International Electrotechnical Commission (IEC). Established in 1906, the IEC is made up of committee members from around the world, and both academic and industry researchers in Scotland have played a leading role in creating industry standards through the creation of standards such by TC-114 – the technical committee for marine energy, including wave, tidal, and other water current converters.

Standard setting is an important aspect of enabling innovation, and the work often goes unnoticed or taken for granted once they have been established (Bowker and Star, 1999; Lampland and Star, 2009). It is also a key component of 'infrastructuring' (Karasti and Blomberg, 2018; Parmiggiani and Karasti, 2018). Infrastructuring refers to the creating and becoming of infrastructure – a process that includes diverse participants and relationships.

While development of the international standards is ongoing, the location of the cutting-edge testing infrastructure in Scotland has encouraged engineers and developers working with this infrastructure to take a leading role in standard-setting. Their work, along with others on the international committee is helping facilitate the measurement and modelling of marine energy devices globally. Some of the first standards for wave energy converters were developed for EMEC's test site, and as such, many of the IEC standards have been built off them. In August, 2020, EMEC also became the first marine energy testing center to be certified as a Renewable Energy Testing Laboratory (RETL) by the IEC. The IEC standards also extend to tank testing guidance and instrumentation that is used at FloWave and other testing sites.

Engineers at EMEC and FloWave have therefore played a key role in establishing standards for marine energy that will be used internationally, and have created a baseline from which other devices will be measured globally. As studies of knowledge infrastructures have shown, once standards are created, they can become embedded and difficult to change (Star and Ruhleder, 1994). Yet, this does not mean that they are not adaptable. In fact, many researchers adapt previous infrastructures as they shift to focus on different objects of research (Ribes and Finholt, 2009; Ribes and Polk, 2015). This adaptive infrastructuring process can also be seen taking place in relation to the standards being developed for the marine energy sector. As one participant noted, these standards aren't 'built on a blank slate', but instead have been evolved from other energy industries – they have been developed from other standards, both from the oil and gas industry, and from wind energy.

By paying attention to the work that standards do as supporting knowledge infrastructures, energy researchers can see how different standards are enabling different technologies in different fields, and how knowledge infrastructures may be resistant or flexible to changes in research occurring as developers shift to renewable energy.

University–Industry Collaboratives

The challenges introduced by marine energy innovation require collaboration between different disciplines and sectors, many of which are beyond those traditionally engaged by energy engineering and research. Bringing tools and concepts from multiple disciplines and fields can help solve problems and generate new ideas, but interdisciplinary and cross-sectoral innovation requires novel knowledge infrastructures. One way the sector is addressing this need is through increasing university–industry interaction. While this transaction is often viewed as relatively straightforward, for example, a university can provide consultancy research for industry or industry can commercialize university-developed ideas (Poyago-Theotoky et al., 2002), when focusing on the knowledge infrastructures that support these interactions, we find that these interactions are complex and multivalent, as well as both formal and informal (Gray, 2011).

Examples of knowledge infrastructures that support university–industry interaction include cooperative research centres that promote collaboration to address a single problem or goal, such as innovation hubs or university-led research centres. In Scotland, examples include: the International Technology and Renewable Energy Zone (ITREZ) in Glasgow, or the Fife Renewables Innovation Centre. Another type of university–industry collaborative includes educational programmes that engage cohorts of graduate students from different disciplines in order to address an interdisciplinary issue or collaborate with industry. The Industrial Doctoral Centre for Offshore Renewable Energy (IDCORE) was created to fill this need. IDCORE is a partnership between several universities and industry leaders that funds students to train for a four-year Engineering Doctorate, in which they are partnered with one or two companies, who then sponsor a project. In addition to coursework, their research project focuses on an industry problem. So, in addition to producing much-needed trained experts in marine renewables, the programme also generates partnerships between academia and industry, and prepares graduates for leadership roles. Participants highlighted how important it was to them to make sure that their research was 'industry relevant'. The strength of this kind of programme is that it can ensure research relevance in an emerging sector.

While ITREZ and IDCORE are good examples of support mechanisms designed to foster university–industry collaboration, using a knowledge infrastructures perspective to ask participants what they are relying upon to do their work, we uncover some other, less formal networks, often initiated by industry needs. Collaborative organizations between the oil and gas industry and renewables are one surprising example of this. There are now several of these organizations located in Aberdeen, Scotland alone, including the Oil and Gas Technology Centre and the National Subsea Research Initiative. Organizations like these are focused on making sure that expertise, industrial infrastructure, and technologies are transferred from oil and gas to the renewables industry as the energy transition takes place, and part of this work includes interfacing academic and industrial research. As many participants pointed out, subsea technologies, engineering infrastructure, and expertise with many marine energy applications already exists, where people are 'already used to working offshore'. Fostering collaboration across subsea sectors could provide much of the innovation that is needed for offshore renewables. For example, moorings, connectors, materials, and instruments and monitoring devices from oil and gas can be more-or-less directly adopted for applications in renewables. As one participant put it: 'there is no reason to reinvent the wheel'. These surprising dynamics between renewables and oil and gas – often viewed as competing, or even incompatible, sectors – were identified as important by participants. Individuals have found creative ways to solve some of their problems by relying on engineering tools, environmental data, or industry knowledge that cross disciplinary landscapes.

Prior experience and relationships between individuals and organizations, both informal and formal, are also important (Bruneel et al., 2010; Meyer-Krahmer and Schmoch, 1998). Informal, previously established ties between industry and universities are crucial in determining successful collaboration because they have already established trust (Thune, 2007). These kinds of relationships can introduce flexibility into a dynamic field such as marine energy. In the end, cultures that view interdisciplinary work as valuable and foster interaction between diverse disciplines and sectors need to be created, and one way that this occurs is through supportive knowledge infrastructures.

Many of these networks began at meetings and conferences, as individuals from across the subsea engineering sector interact across disciplines. A contextual understanding of the frameworks, barriers, and mechanisms that facilitate interdisciplinary work across institutions is therefore necessary, and a focus on knowledge infrastructures can provide this potentially overlooked perspective to energy researchers seeking ways to foster innovation through collaboration between universities and industry, and across potentially diverse, or even competing sectors.

CONCLUSIONS

In order to meet climate change goals, technology- and location-specific innovation policies will be needed (Jacobsson and Bergek, 2011). While not exclusively hinged on research support, the technology innovation and knowledge transfer necessary to address sustainability can be facilitated by science policy (Biagini et al., 2014). Research has shown that investment in national-scale innovation policy and infrastructures that facilitate testing and demonstration are important for driving innovation (Gray, 2011). But this perspective can often lead to a focus on top-down policy mechanisms, which are often unavailable to those working towards renewable energy transitions.

Employing a grounded-theoretical approach to explore how individuals relate to the knowledge infrastructures that support their work highlights different dynamics. This includes locating knowledge infrastructures that might be otherwise overlooked by understanding what individuals rely on to support their research. It also involves exploring the diverse ways that individuals interact with and create infrastructures through practices of 'infrastructuring'. While it is no doubt important to consider how national systems of innovation develop in materially different ways, we cannot ignore micro-scale practices of individual researchers as they work to innovate in the energy system. In order to ensure innovation in renewable energy research, we therefore must understand the knowledge infrastructures that currently exist, the ways in which they are fostering or hindering innovation in the sector, and how they might be developed in order to increase the capacity for innovation.

This chapter has outlined some of the ways that knowledge infrastructures enable innovation by facilitating the work that engineers and scientists do: in training experts, facilitating connections between academia and industry, setting standards, and facilitating adaptation by transitioning knowledge from one sector to another. Understanding knowledge infrastructures is therefore an important aspect of understanding the underlying support mechanisms that facilitate or hinder innovation to enable sustainability transitions and energy research in contexts well beyond marine energy in Scotland.

ACKNOWLEDGEMENTS

I would like to thank Robin Williams and the Institute for the Study of Science, Technology and Innovation at the University of Edinburgh for the opportunity to present this work to them. I would also like to thank David Ribes and the Data Ecologies Lab at the University of Washington for their feedback on an earlier version of this manuscript. Thank you to the anonymous reviewers for their thoughtful feedback. Funding for this research was provided by the US National Science Foundation SES-STS grant #1826737.

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