Digitalisation as an act of governance:

the case of wind energy

Helena M. Solman

Propositions

1. Public engagement with wind energy is essential at all the stages of design, planning and management.
(this thesis)

2. Digital technologies do not make up for the misfit of wind energy in society and landscapes.
(this thesis)

3. Multidisciplinary projects require personal relationships between researchers to be successful.

4. EU projects will better enable innovation if deliverables and project outcomes remain undefined at their outset.

5. Cycling to and from work is essential for creative research.

6. The energy sector needs more female-led consortia on research and innovation.

Propositions belonging to the thesis, entitled
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Helena Solman
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Digitalisation as an act of governance:

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Abbreviation	*Definition*
UNEP	United Nations Environment Programme
IEA	International Energy Agency
UPWARDS	Understanding the Physics of Wind Turbine and Rotor Dynamics through an Integrated Simulation Platform
IRENA	International Renewable Energy Agency
AI	Artificial Intelligence
ICT	Information and Communication Technologies
IoT	Internet of Things
EU	European Union
R&I	Research and Innovation
SSH	Social Science and Humanities

CHAPTER 1

1

Introduction

CHAPTER 1: Introduction

1.1. Introduction

1.1.1. Expertise and upscaling in energy transitions

The transition to renewable energy sources is necessary to assure a sustainable future for current and future generations and ecosystems on our planet (UNEP, 2022). Concerns about climate change, fossil fuel scarcity and the geopolitics of the fossil fuel economy are some of the key reasons for making substantial and rapid investments in renewable energy technologies (International Renewable Energy Agency, 2018). According to the International Energy Agency, the global ambition is to become “Net Zero” by 2050, and this should ideally be achieved via a “cost-effective and economically productive pathway, resulting in a clean, dynamic and resilient energy economy dominated by renewables like solar and wind instead of fossil fuels” (IEA, 2021). However, while there is growing recognition (if not consensus) of the need for these alternative sources of energy, there remains considerable debate amongst experts and societal actors on how, where and by whom renewable energy systems should be designed, planned and managed.

Wind energy is a case in point. Perhaps one of the most controversial forms of renewable energy due to the perceived visual and ecological impacts of turbines on land and seascapes, the debate centres around how and by whom problems concerning wind energy are defined and implemented through design, planning and management. These decisions, collectively referred to as wind energy governance (Elkjær et al., 2021), occur not only through traditional, state-led or private-led, rules and regulations but also through various hybrid decision-making processes and partnerships among state, private sector and community/citizen groups (Lemos & Agrawal, 2006). This diversity of actors means that a broad range of concerns, needs, values and practices are represented in wind energy governance that both align and compete with each other (Chilvers et al., 2018; Lemos et al., 2018). Collectively, these ongoing debates demonstrate that the challenge of energy transitions does not merely entail developing and deploying renewable energy technologies but also the fundamentally social challenge of aligning what is technically possible with what is ‘acceptable’ within diverse and often increasingly polarised societies.

The view that upscaling the wind energy sector is a social process of governance is being increasingly shared by technical experts faced with the challenge of designing, implementing and managing wind turbines across a range of urban and rural landscapes (and, increasingly, seascapes) (Künneke et al., 2015; Rudolph & Kirkegaard, 2019). As they have variously argued, these experts working across different domains of wind energy science suggest that technical innovation alone will not be sufficient for the sector to be accepted by society at large (Dykes et al., 2019; Firestone, 2019; Kirkegaard et al., 2022). This is because there is a broad range of concerns voiced by societal actors and wind energy experts about the impacts of wind energy on people and nature. These challenges of wind energy upscaling are also present for other renewable energy sectors, such as solar energy (Oudes & Stremke, 2021) and biofuels (Götz et al., 2017).

However, despite the recognition given to incorporating both expert and societal perspectives into the design and management of wind energy, much of the debate remains highly technical in nature. Since the 1970s, wind turbine innovation has mainly focused on increasing the size, and thus the power capacity, of wind turbines (Andersen et al., 2018; Kirch Kirkegaard et al., 2020) to ensure that wind energy can emerge as a cost-efficient and reliable source of energy on the energy market (Arshad & O'Kelly, 2019). As Veers et al. (2019) argue, to enable the further expansion of wind energy globally, the sector has to overcome key technical challenges related to the aerodynamics and structural dynamics (or 'strength') of wind turbine materials across a highly diverse (and increasingly changing) set of atmospheric conditions. To do this, wind engineers have advanced predictions concerning both wind resources and turbine performance to identify safe, feasible and efficient operating conditions for every wind farm (Chávez-Arroyo et al., 2018).

As sustainability concerns regarding wind energy have increased, relevant expertise has expanded among non-engineers focused on wider environmental impacts. Concerns of the environmental impacts of wind energy are at the heart of upscaling debates and offer both a basis for implementing or resisting wind energy projects, especially large-scale projects with land or sea-scape altering potential (e.g. Bjärstig et al., 2022). According to a review by Wang et al. (2015), the most persistent environmental concern is birds striking the tower or blades of a rotating wind turbine. However, ecologists have also identified the negative effects of constructing wind turbines on soil erosion (Nazir et al., 2020), and environmental scientists have raised concerns about the scarcity of the resources needed to manufacture wind turbines (Rabe et al., 2017) and about the ecological impact of decommissioning wind turbines (Huenteler et al., 2016). Counterexpertise has also emerged through citizen science, conducted by residents around wind farms, concerning impacts such as soil erosion or air quality degradation to resist wind energy projects, but such evidence has often been excluded from the official assessments thereof (Pesch et al., 2017). Overall, there is an ongoing debate on the need for environmental and ecological expertise to improve decision-making regarding the impacts of wind energy projects. As a result, while such expertise has been regularly included in wind energy decision-making, as outlined by Breukers and Wolsink (2007), it has not always been acted upon.

In contrast to engineering and environmental expertise, there is an ongoing lack of social scientific expertise in decisions related to upscaling wind energy. This is in spite of the growing recognition of what is commonly referred to as the 'social acceptance' of wind energy, a major barrier to upscaling the sector (Firestone et al., 2018). Social acceptance is commonly reduced to 'output'-related concerns such as the visual pollution of turbines and the obstruction of lights on landscapes (Rudolph et al., 2017), the effects of noise pollution on surrounding communities (Devine-Wright, 2008; Rand & Hoen, 2017), the annoyance of shadow flicker (Knopper et al., 2014), and safety concerns regarding 'ice throwing' by turbine blades in cold climates (Butler, 2009). While these concerns have been recognised and documented, this has typically occurred after the implementation of wind energy projects or as part of the due diligence of social and environmental impact studies—in some cases, leading to the successful opposition of wind energy projects (Reusswig et al., 2016). However, as outlined by Oosteraken (2014), it is far less common for such concerns to be incorporated into the (re)design of wind energy projects—in terms of not only where wind farms or turbines should be located but also their form and function across land and seascapes. Enabling the public and social scientists to contribute to and affect the outcomes of wind energy governance appears necessary for moving beyond technical approaches towards more integrated (with different types of knowledge and forms of expertise) and inclusive (of different actors) approaches to upscaling wind energy.

1.1.1. Governing wind energy participation

The question of enabling more inclusive forms of wind energy governance to ensure both just and sustainable energy transitions across landscapes is of great contemporary importance. Nevertheless, this question is not new. Participation in wind energy governance has long been a major focus of scholarship, policy and practice (e.g. Clausen et al., 2021; Jami & Walsh, 2016; Lienhoop, 2018; Maarten Wolsink, 2007). However, much of this literature has focused on the planned participation of local communities in siting wind parks. Hence, researchers have tended to narrow diverse community concerns to technical issues, such as wind turbine noise (Nyborg, 2022) or the visual impact of wind farms (Möller, 2006). Once narrowed, these concerns have become sites of debate and innovation that are dominated by a narrow set of technical expertise and knowledge.

There are in fact many ways that different wind energy publics (and their concerns) participate in decisions on wind energy governance. Participation processes set up by local governments or project developers commonly invite residents and representatives from different environmental and social interest groups to attend consultation meetings (Aitken et al., 2014). Ideally, during such meetings, residents have a voice regarding how wind farms are designed (Oosterlaken, 2014). Self-organised forms of participation are also evident, such as community wind initiatives (Beery & Day, 2015; Simcock, 2014) that enable residents to balance community goals and green energy production needs (Toke, 2005). In contrast, less proximate publics, such as household investors, participate financially in the development of wind energy schemes (Aitken, 2010; Sardaro et al., 2019). Finally, as Cuppen et al. (2018) suggest, resistance to wind energy can also be seen as a form of participation; even when it leads to a conflict, it provides alternatives and critical perspectives on wind energy designs, plans and management strategies.

Despite all the attempts to involve the public in wind energy decisions, technical experts remain the key actors who determine how, where and by whom wind energy technologies are designed, implemented and managed over time (Pfotenhauer et al., 2021; Veers et al., 2019). By lending their expert knowledge to the design of new technologies, such as wind turbines, they become the de facto governors of the environmental problems at stake (Gupta & Möller, 2019). However, while various kinds of professional expertise clearly have important stakes in wind energy governance, the role of experts tends to be underplayed and, in turn, poorly understood in terms of the challenges and dilemmas that these actors experience in wind energy decision-making (Verhoeven et al., 2022). Given that such experts play a dominant role in design and research and innovation, questions have arisen regarding who steers wind energy governance and what priorities and visions form the basis of this sector governance.

1.1.2. Digital technologies in wind energy governance

The advent of digital technologies in the wind energy sector offers an opportunity to address a range of challenges and rethink participation in wind energy governance. There are broad expectations that digital technologies, i.e., all the computerised devices, systems, tools and resources used to generate, process, store and communicate information, will revolutionise the design, planning and management of wind energy and, by doing so, more effectively enable the upscaling of wind energy globally (Clifton et al., 2022; Smogeli, 2017; Wagg et al., 2020). For example, this optimism has been reflected in the considerable private investment in digital technologies, employing big data, machine learning and AI to balance energy production and consumption, a problem known as renewable energy intermittency (Rhodes, 2020).

Technical advances in the design and management of wind energy with a view towards both increasing economic efficiency and addressing societal concerns are being increasingly linked to the use of sensors on wind turbines that gather large amounts of data on wind farm operation (Wagg et al., 2020). These sensor data are being increasingly digitalised and used in advanced modelling techniques for the optimisation of wind turbines, farm designs and management strategies (ibid.). Moreover, digital technologies are being used to address smart obstruction lighting (flashing lights on wind turbine blades for airplanes) (Aaen et al., 2022), in preventative maintenance simulations (Smogeli, 2017), and to develop artificial intelligence systems that prevent bird collisions (Jungblut, 2020).

Digital technologies are also being used to address public concerns about wind energy in the planning of wind energy projects. This includes digital visualisations, created during wind farm commissioning, which show how future wind farms will look and sound (Gawlikowska et al., 2018; Manyoky et al., 2014). Wind farm developers are increasingly developing such digital visualisations of future wind farms for residents and stakeholders to visualise their scale and impact, but these viewshed simulations can become a subject of controversy on their own (Phadke, 2010b). Moreover, digital visualisations might become a starting point for residents to participate in the evaluation of future wind farms (Phadke, 2010b). Digital technologies such as websites, platforms and online social groups are also being used to share information with residents in future wind farm areas and to collect their feedback, opinions and preferences regarding how or where to design wind farms (Rhodes, 2020; Sareen, 2021). Wind farm residents are also increasingly using digital technologies, such as smartphone apps, to obtain insights into how much green energy wind turbines produce (Böhm & Szwec, 2013). Underlying these different kinds of digitally enabled participation is the premise of lowering the threshold for participation by disconnecting it from a certain time and place and, by doing so, emancipating the public to codecide about wind energy.

As a result of these advances, wind energy upscaling is being increasingly linked to the large-scale adoption of digital technologies. The proliferation of digital technologies is often referred to as a broader process of digitalisation—in which “the availability of large amounts of data is starting to impact how the wind energy community works” (Clifton et al., 2022 p.1). Digitalisation is a key topic in the global agenda of energy transition as one of its key drivers (European Commission, 2021; IEA, 2017). According to this vision of the European Commission (EC), “digital technologies will make energy systems more connected, intelligent, efficient, reliable and sustainable over the coming decades. Some of the technologies that can innovate the way we use energy and help find solutions for decarbonising our energy systems including information and communication technologies (ICT), modern sensors, big data and artificial intelligence and the Internet of Things (IoT)" (European Commission, 2021). Furthermore, this digitalisation agenda encompasses the digitalisation not only of assets (e.g., energy infrastructure) but also of landscapes. For example, an EU project, Destination Earth, is developing a digital duplicate of the Earth to monitor and understand climate change and its impacts on diverse landscapes, places and economic sectors (e.g., agriculture) to foster better mitigation and adaptation policy decisions (Bauer et al., 2021). This indicates that energy transition decision-making is being increasingly enabled by digital technologies or their outcomes.

Given this importance of digital technologies, a better understanding of digitalisation and its effects on how the different concerns about wind energy are governed is needed. However, digitalisation has mainly been defined from a technical perspective that focuses on digital technologies themselves rather than experts and their role in the digital transformation, processing and communication of information. These technology-focused definitions of digitalisation explain it as a process of transformation that includes "a particularly rapid shift towards the increased use of digital and data-based technologies" (Judson et al., 2020 p.3). They argue that this process of digitalisation "promises improved efficiency and greater insight, ultimately leading to increased energy capture and significant savings for wind plant operators, thus reducing the levelized cost of energy" (*ibid.*). According to this definition, digitalisation is a transformation that extends beyond making existing data digital; digitalisation encompasses the ability of digital technology to collect data, establish trends and make better decisions.

1.2. Research objective and research questions

Despite the promises of digitalisation, it is not certain that digital technologies will lead to sustainable wind energy outcomes. Digitalisation tends to be understood through a prism of technologies, devices and promises rather than through a prism comprising the relevant people and places where the acts of digitalising and digital technology design take place. This lack of a social-scientific understanding of digitalisation in turn obscures the need for deliberation on which digital technologies should be designed and for which purposes in the wind energy sector. According to Fraune (2022), such deliberation is needed so that different societal actors can express their concerns and thus participate in energy transitions of a digital and/or analogue character. To carve out such a space for digital governance deliberation, this thesis explores the social and environmental aspects of digitalisation and its implications for wind energy governance.

Given this objective, the research question in this thesis is as follows:

What are the implications of digitalisation for wind energy governance?

To answer this question, this thesis explores how digitalisation affects the choices, actions, preferences and opinions of experts and different publics concerning wind energy and how wind energy transitions are shaped by the design and use of digital technologies. These insights in turn inform how digitalisation affects the participation of different experts and diverse publics by shaping whose knowledge impacts the design, planning and management of wind energy technologies and landscapes.

To answer the main research question, the research is divided to answer three sub-questions:

1. *How do experts translate concerns, knowledge and expertise related to wind energy into digital technologies*?

This question focuses on the knowledge and expertise needed to address the complexity of the various and sometimes contradicting concerns about wind energy and the inherent limitations regarding what and whose knowledge and expertise enables digitalisation and to what extent. The development and use of digital technologies can be(come) a controversy on its own in terms of what constitutes a matter of concern, what kinds of knowledge are being used and whose expertise is being recruited. For example, concerns about wind turbine noise are subject to ongoing debates on the evidence for its impact (Taylor & Klenk, 2019), the appropriateness of any legislation that defines noise limits (Dällenbach & Wüstenhagen, 2022) and the expertise that is involved in determining noise pollution and its impacts (Nyborg, 2022). Noise experts can offer their acoustic knowledge about wind turbine noise and its impacts on humans' health, and it is likely that this knowledge will be seen as legitimate regarding the digitalisation of a wind energy system. However, wind turbine noise is also an issue being investigated by alternative or layman experts, who might also want to be represented in decisions of how noise is defined and managed (Taylor & Klenk, 2019). This example shows that little is known about how such governance challenges in wind energy are affected by the experts involved in digitalisation and whether they open new or limit the possibilities for the inclusion and recognition of diverse concerns, knowledge types and expertise levels.

2. *To what extent do experts who design and deploy digital technologies enable different publics to engage in decisions about the design and management of wind energy technologies and landscapes?*

While public participation in wind energy governance can take different forms—formal or informal (Chilvers & Longhurst, 2016)—that are continuously evolving (Chilvers & Longhurst, 2016), little is known about what other opportunities and challenges accompany digital technologies in terms of public participation. In particular, this relates to how experts can shape participation processes (Felt, 2016), for instance, by designing a digital framework for a participation context that shapes what is needed, what is necessary and what is considered a good practice. For example, ongoing debates on the timeframe for public engagement with wind energy projects are increasingly stating that there is a need for an early-stage and continuous involvement of the public and stakeholders in wind energy projects (Jami & Walsh, 2017). It is, however, uncommon to involve the public in the design of technologies such as wind turbines. Nevertheless, according to Garud and Karnøe (2003), the initial success in the expansion of wind energy is largely due to input from the residents around and the 'first users' of wind turbines. Similarly, it is being increasingly argued that wind farms should be collaboratively managed to ensure that the needs of different stakeholders are met, especially in areas that serve multiple purposes, such as offshore wind farms that combine energy production with aquaculture and shipping (Jay, 2010). To date, there have been no attempts to examine how the emergence of digital technologies has affected the ability of experts to involve the public in these different stages of wind energy decision-making technologies and landscapes.

3. *In what ways do the experts who design and deploy digital technologies steer how wind energy landscapes are defined and interacted with?*

This question examines the role of experts in shaping how wind energy landscapes are digitally represented and how different actors interact with these digital landscapes to govern wind energy. As Phadke (2010b) has demonstrated, visualisation can be used strategically by different actors in wind energy project communication, both favourably and unfavourably. The choices made by the experts who represent wind energy landscapes in a digital format thus shape whether and how landscape-related concerns (and their costs and benefits) are visible (Bouzarovski & Simcock, 2017). This means that the ways in which experts digitalise landscapes may affect how different actors digitally experience wind energy landscapes and in turn the decisions they make regarding wind energy.

1.3. Theorising the effects of digitalisation on governance

The effects of digitalisation on governance have been addressed within various disciplines of environmental governance and beyond (Judson et al., 2020; Rhodes, 2020; Sareen, 2021; Van der Velden, 2018). These discussions often build on earlier debates concerning the politics involved in the particular design of technologies as well as the design of expert systems (e.g. Collins et al., 2010; Pesch, 2021; Taebi et al., 2014). This is a result of the aspiration to open both digital and analogue technologies to a more deliberative and inclusive way of design (Jasanoff, 2016; Miller & Wyborn, 2020; Wyborn, 2015). These different research streams have collectively pointed out that experts play a key role in defining the problems and solutions that technologies convey (Jasanoff, 2016). These debates on the effects of digitalisation on governance coalesce around three analytical dimensions: 1) the translation of concerns, knowledge and expertise; (2) the effects on the participation of different publics; and (3) the representation of diverse spatial ontologies.

1.3.1. Analysing whose concerns, knowledge and expertise are translated into digital technologies

The effects of digitalisation on governance represent a process of translating concerns, knowledge and expertise into digital technologies. The concept of translation, originating in the work of Michel Callon (Callon, 1984) and Bruno Latour with Steve Woolgar (Latour & Woolgar, 2013), describes the active process of decision-making among experts involved in the design and use of digital technologies. Translation is a complex process of negotiating meanings, claims and interests (Wæraas & Nielsen, 2016). According to Nicolini (2010), the outcomes of translation are likely to reflect the interests and interpretations of the actors who are involved and to exclude those of actors who have not participated in relevant translation processes. Translation also captures the active process of technology design and innovation in terms of how it requires experts to set priorities for the kinds of research questions being asked, the concepts being used, how they are defined and how this focus will ultimately lead to new technologies and innovation in general (Verbeek, 2006). This means that the translation of concerns, knowledge and expertise is driven by knowledge and scientific expertise that is neither neutral nor follows a 'natural logic of innovation' (Fujimura, 1992). In this thesis, digital translation is thus a site for politics regarding what and whom to include in or exclude from digital representations.

To understand how translation manifests in practice, Michael Callon (1998) used the concepts of framing and overflowing. According to Michael Callon (1998), the act of framing entails constructing a dominant explanation for what a given problem is and how it can be defined. Accordingly, "framing is a political strategy in which opposing parties—sometimes intentionally, sometimes not—attempt to persuade others of their interpretation" (Benford and Snow, 2000 in Metze, 2017, p. p.37). Overflows are the unintended consequences of framing that might occur because framing always excludes some aspects of a given problem or certain alternative interpretations (Callon, 1998). To understand the implications of 'problem frames' in the context of technological design, Henderson (1991) proposes that design itself is an active process of translation in which lines are drawn by experts literally (in designs, maps and sketches) and figuratively to demarcate what is included in and what is excluded from the experts' ontology of what constitutes the design of digital or wind energy technology. Finally, the process of translation is also an act of developing a frame for the 'problem at stake' through boundary work among experts and possibly also the public (Epstein, 2011; Metze, 2017; Owens et al., 2006). This boundary work is often organised around boundary objects, which can be material or discursive, which delineate what is included in and excluded from translation (Star & Griesemer, 1989). All these different concepts of framing and overflowing, boundary object and boundary work, collectively help reveal how experts work with each other and how their work affects decisions on the translation of knowledge concerns and expertise into digital technologies.

While these works have illuminated the processes of translation in 'analogue contexts', there has been little work regarding translation in digitalisation processes. Contributions towards understanding how and whose concerns, knowledge and expertise are included in and excluded from digital technologies have been provided in the critical social science literature on the politics of digitalisation (Kitchin, 2014; Korenhof et al., 2021; Musiani, 2013; Verran & Christie, 2007). This stream of literature has generated debates concerning digitalisation as an expert system that needs to be unpacked and understood from the perspective of the actors involved to be reformed and managed. One way to understand the translation of concerns, knowledge and expertise is by unpacking what data are used by experts for digitalisation, how these data reflect the concerns of different actors and how they have been measured (Korenhof et al., 2021). Furthermore, an important aspect in the translation of knowledge into digital technologies is the decision-making on what kind of expert and layman knowledge is being used (Verran & Christie, 2007). Whose knowledge is translated is important because it affects what knowledge can be generated by digital technologies (Kitchin, 2014) and, in some cases, how technologies, such as algorithms, steer the production of new knowledge (Musiani, 2013). According to Kitchin (2014), digital technologies 'push' for gathering increasingly large amounts of (e.g., sensor) data and generating knowledge revealed by the patterns in these data. The key point from this literature in terms of this thesis is understanding how the experts who design and use digital technologies affect the kinds of wind energy knowledge that is being generated—what kind of insights can be extracted from digital technologies and to what extent they can help meaningfully explain and resolve issues in wind energy governance.

1.3.2. Analysing public participation in the context of digital technologies

Public participation is conditioned by the expert design choices embedded in digital and wind energy technologies. While public engagement in the context of digital technologies and (wind) energy governance remains relatively unexplored, a prolific literature has debated the definition of public participation in the context of technologies and innovations (mainly Felt, 2016; Felt & Fochler, 2010; Macnaghten et al., 2005; Marres, 2016; Marres & Lezaun, 2011; Rommetveit & Wynne, 2017; Wynne, 2007). This literature tends to argue that such public engagement is diverse, emergent, and co-produced (Chilvers & Longhurst, 2016)—both concern-driven and dependent on the broader political and technological context that conditions whether and how public concerns can be voiced (Marres & Lezaun, 2011). Furthermore, building on John's Devey's understanding of publics as informed, capable and self-determined actors in the democratic policy arena, Marres (2016) proposes that the public emerges from and around matters of concern. Her understanding of these publics captures how the emergent nature of engagement is facilitated by material devices of participation, including the digital technologies that become devices for everyday participation in matters that are of concern and interest to individuals (Marres & Lezaun, 2011). However, while the information and social media revolution brought by digital technologies have been a focus for many governance domains, wind energy scholarship seems to also lack a similar focus on this topic.

To unpack how wind energy experts enable (or constrain) public participation, this thesis focuses on experts' definitions of the public in the context of digital and wind energy technologies. There are different kinds of publics in wind energy governance and in energy transition governance more broadly. First, there are local publics, the residents of areas affected by wind farm development and who have a right to participate in matters of wind farm design, planning and management. This definition of the public is often the base with which the wind energy literature defines a 'community' of place (e.g. Simcock, 2014; Toke, 2005) around local wind farm developments and a community of interest (Bauwens, 2016) around the networks that connect people based on their goals rather than place of residence. Second, there are broader publics (also referred to as general publics) who are citizens of a nation, state or region (Pesch, 2019) and audiences that are affected by or involved in larger wind energy developments, research and innovation as well as energy and digitalisation policies more broadly. This variation in the definitions of the public can be reflected in technologies' design and in the extent to which their design is a 'public issue' or an expert-driven system (Pesch, 2021). Following Latour and Woolgar (2013), expert systems, such as new technologies or innovation processes, tend to steer how societal actors engage with the matters of concern that these technologies address. In sum, this perspective on how experts enable public engagement produces debates on the priorities for innovation in wind energy technologies and the role of experts in the processes of industrial innovation in wind power.

1.3.3. Analysing (digital) spatial ontologies

Experts' decisions on how wind energy landscapes are digitally represented and interacted with have been widely explored in both the human geography (Chilvers & Kearnes, 2020; Chilvers & Longhurst, 2016; Chilvers et al., 2018) and spatial planning literature (Duineveld et al., 2017; Lenzholzer et al., 2013; Pasqualetti & Stremke, 2018). Common to both bodies of work are the various 'spatial ontologies' of experts versus those of the local public. This literature helps reveal how the different ways of viewing and interacting with wind energy landscapes are likely to be transformed from analogue into digital spatial ontologies.

First, there is a 'positivist perspective' on wind energy landscapes, which applies an objectified and scientific gaze, entailing that landscapes are constituted by the natural phenomena and people who shape, interact with, and observe them (Lenzholzer et al., 2013). This is a Cartesian understanding of landscapes as a primary natural unit composed of biophysical objects and features that can be objectively represented on maps and with visual representations. Second, there is a relational landscape ontology that assumes that the material qualities of landscapes can be perceived and valued differently across cultures and individuals (Duineveld et al., 2017). Third, between these two ways of understanding landscapes—as relational or Cartesian—landscapes have been conceptualised as entanglements of human and nonhuman elements that coconstitute each other (Lata & Minca, 2016). As different actors might choose to view landscapes from these distinct perspectives, wind energy landscapes can be examined as 'inherent sociogeographical configurations' (Labussière & Nadaï, 2014) as well as human-made 'energy landscapes' (de Jong & Stremke, 2020; Pasqualetti & Stremke, 2018). In summary, there are multiple ways of viewing landscapes, depending on what different actors focus on—whether their tangible, material features or the largely intangible connections that people build with energy landscapes.

Discerning these different ways of looking at landscapes is important because they influence how wind energy landscapes are visually represented and interacted with. Analysing how landscapes are digitally represented and interacted with therefore requires examining how different actors choose to visually (or digitally) represent wind energy landscapes to communicate certain concerns or ideas (Phadke, 2010a, 2010b). This has been observed in the case of maps that define areas suitable for wind energy development (Vasstrøm & Lysgård, 2021) and of GIS-based visual-acoustic 3D simulations for wind farm assessment (Manyoky et al., 2014). Experiencing landscapes digitally cannot equal the embodied experience of landscapes (Bender et al., 2007). This is because, as Opitz (n.d.) argues, "senses are closely interlinked and…all sensory experience and perception is socially, culturally and personally specific and cannot be translated across cultural and temporal divides" (p.11). All these digital ways of representing and interacting with landscapes in the context of wind energy governance might also have justice implications because the spatial demarcations of wind farms are a common reason for conflicts that result from spatial exclusions (Simcock, 2014). Building on the fact that spatial demarcations and landscape representations are inherently political, in that they reflect choices by different actors, this thesis focuses on the actors involved in digitalisation who translate their spatial demarcations and ways of seeing landscapes into digital technologies. In addition, attention is given to how the digital representations of landscapes might be contested or resisted by the actors whose spatial ontologies are excluded.

Finally, these different ways of viewing and interacting with wind energy landscapes are likely to be transformed from analogue into digital spatial ontologies, which likely has governance implications. On the one hand, digitalisation enables the creation of dynamic, interactive and detailed representations of (wind energy) landscapes, likely enabling the novel view among certain actors of energy landscapes as targets that are removed from the personal experience of observers (Wohl 1985 p. 286 in Cosgrove et al., 2001). Furthermore, as digitalisation affects the degree of dynamism with which landscapes and objects in the landscape are made sense of, decision-makers are likely to face a new kind and volume of information, which might change how these objects or even the sectors at large are governed (Toonen & Bush, 2020). In the case of wind energy, for example, digitalising landscapes might have an effect on how they are experienced and thus in turn how and by whom the decisions about future wind farms are made (Manyoky et al., 2014). On the other hand, digitalising landscapes is likely a process of producing and reproducing the 'social order' and spatial demarcations "through, produced by, and of the digital" (Ash et al., 2018 p.25). This means that while digitalisation on its own might change how landscapes are governed, it might also reproduce and strengthen the 'old' ways of managing energy landscapes.

1.4. Methodology

The methodological approach in this research is abductive, combining elements of both deductive and inductive approaches in data collection and analysis (Morgan, 2007). It is deductive because the three dimensions are used as an overall guide to structure the research (Lund, 2014), as presented in the following chapters: 1) translating concerns, knowledge and expertise into the digital; 2) participation and the publics; and 3) spatial ontologies. Meanwhile, it is inductive because empirical observations are used to determine the effects of digitalisation on governance to confirm these three dimensions, how they might intersect, and what these intersections mean in terms of generalising through abstraction (Lund, 2014). Combining these perspectives allows me to explore and build an understanding of this new and rapidly changing field of digitalisation in the context of wind energy governance without imposing a single framework.

To explore the effects of digitalisation in the context of wind energy governance, this research employs multiple qualitative research methods to better understand the 'social' within these digitalisation processes. A qualitative approach is useful for exploring an emerging area of research (Mohajan, 2018), revealing the active role that experts play in the design and deployment of digital technologies and exploring what forms of public engagement with digital technologies emerge in the context of wind energy. The value of using multiple qualitative research methods is that combining a number of methods—interviews, workshops, text-based analysis, and elements from reflexive self-ethnography—allows us to explore a range of cases of digitalisation and to ensure internal and external validity by triangulating our results across these different methods (Grix, 2018). In the chapters below, we employ and provide justifications for different combinations of these methods in a way that is suitable for each study. At the thesis level, this qualitative and multimethod approach strengthens the confidence in the conclusions that I draw in this thesis based on each of the cases and across them. Below, I describe the process of selecting the focal cases of digitalisation in the context of wind energy governance.

To answer the research questions, I take two methodological steps. First, I explore the literature though a systematic review to identify what is already known about the challenges in wind energy upscaling and the different modes of public engagement. Through this review, I find that there are three modes of public engagement, local, collective and virtual, and that this last mode of virtual engagement is both emerging and relatively underexplored. This review also reveals that while different modes of engagement can be found across different stages of design, planning and management, most engagement occurs in the planning stage. This means that the stages of design and management involve little public engagement, which is surprising, given that many of the concerns about the sustainability of wind energy technologies and landscapes are related to their design and management decisions. I then extend these findings to conduct an in-depth investigation of how digitalisation affects wind energy governance in the stages of design and management.

Building on the findings in the first step of the review together with my experience in the UPWARDS project, which introduced me to the innovations concerning digitalisation in wind energy, and scoping research on the emerging forms of virtual engagement with wind energy, I focus on two kinds of emerging digital technologies: ones that are expert-focused and those that focus on enabling public engagement. In doing so, I use the findings of the above review—wind energy governance is organised across different stages of design, planning and management—to select empirical cases of emerging digital technologies in the stages of design and management. This focus on unexplored stages allows me to assure the novelty of this research, and the focus on the variation in expert/citizen-focused digital technologies entails that I am able to draw conclusions on how different kinds of digital technologies steer the processes and outcomes of wind energy governance.

Applying these selection criteria, I select single cases that allow an in-depth exploration (Lund, 2014) of how emerging digital technologies are designed and used in the context of wind energy. I use a case study approach to generate rich and exploratory information (Yin, 2011) about how experts design emerging digital technologies for wind energy and, by doing so, how they enable public participation and interaction with wind energy landscapes.

The first case of emerging digital technology that is primarily expert driven and used at the stage of design comprises digital twins. According to a technical definition, “a digital twin is a virtual representation of an object or system that spans its lifecycle, is updated with real-time data, and uses simulation, machine learning and reasoning to help decision-making” (IBM, 2022). As digital twins are arguably the key emerging technology that drives digitalisation in the energy sectors, the process of designing digital twins is a relevant case for analysing how experts shape the design of wind turbines and their implementation on landscapes. The case of designing digital twins is investigated from two angles. First, I explore examples of three digital twin projects in the context of the EU to reveal the similarities and differences in how different experts define and develop digital twins (Chapter 3). Specifically, I evaluate semi-structured interviews with a range of experts on wind energy and digitalisation, information from project websites and a workshop discussion with experts on the design of wind energy technologies and landscapes. Second, I deeply examine how digital twins are designed in the context of one EU-funded research and innovation project (UPWARDS, in Chapter 5). The data that I use in this chapter include the content of the proposal and project deliverables, which focus on acceptance, insights derived from two workshops and a reflection piece. With this approach, I gain an in depth—though shaped by personal experience and acquaintance with project partners—impression of the process of digital technology design. Moreover, this approach is relevant because it offers a unique possibility for exploring how such digital technologies are designed from the perspective of an insider. The focus on only EU projects has been motivated by the need to limit the scope of potential cases amidst a potentially much larger pool of globally emerging digital twin projects operating under varying research and innovation schemes. While this global variation is relevant and interesting, its broad geographic scope is beyond that of this thesis.

Moving from an expert-focused technology at the stage of design to a citizen-focused technology at the stage of management, I perform a case study of a noise app, a recently launched digital device designed and deployed in the Netherlands by experts to manage concerns with wind turbine noise. The case of this noise app is unique, as it exemplifies a recent and novel way of engaging residents in a wind farm area in the management of concerns during the operational phase of this wind farm. The selection of a digital, citizen-focused technology used in the stage of management was influenced by the constraints of the COVID-19 pandemic, which limited international travel. Conducting fieldwork in the Netherlands and partly online via semi-structured interviews with experts and residents in the wind farm area was a feasible option that did not affect the quality of the data gathered. While the case of the noise app is unique, it is also very relevant, as there are plans for upscaling this technology to other wind farm locations in the Netherlands, and because it represents a broader trend (Sareen, 2021; Van Summeren et al., 2021) of how virtual participation in energy projects might be organised and the governance implications thereof.

1.5. Thesis reading guide

This thesis consists of four chapters that present the results of my research on wind energy governance in the digital era. Chapter 5 aside, Chapters 2 and 3 have been published, and Chapter 4 is under review in peer-reviewed academic journals. All these chapters are building blocks for a new way of understanding digitalisation, as an act of governance in the context of wind energy. They interrogate this topic of digitalisation in the context of wind energy governance from different angles as follows:

Chapter 2 presents a systematic literature review on public engagement beyond the invited forms of participation, including virtual forms of engagement as well as local and collective modes of public engagement. This review creates the base from which this thesis further examines how emerging digital wind energy technologies are designed and used to govern wind energy.

Then, building on the results of this review, I explore expert-focused digital technologies in the stage of their design. I do this in Chapter 3, shedding light on how the wind energy experts involved in EU-funded projects for the design of digital twins innovate wind turbine technology and thereby affect how and where the wind energy sector is being upscaled. In this chapter, I unpack how the experts who design digital twins explain what digital twins are, what they can do and how they can help solve problems in wind energy governance. Presenting cases of recent or ongoing digital twinning projects funded by the Horizon 2020 framework, this chapter shows that 'twinning' is an act of governance on its own. The chapter concludes that twinning involves design choices for including and excluding different aspects of wind energy systems and their socio-spatial context in the digital domain.

Moving from the case of digital twins, Chapter 4 analyses a mobile phone app, a case of a digital technology that aims to involve wind farm residents and address their concerns with wind turbine noise. By focusing on how this noise app was designed and implemented, this case study highlights the differences among experts and residents in terms of their framing of ‘the problem' and what solutions they think should be implemented. This chapter reveals the practical difficulties in assuring a just representation of the different ways in which concerns are voiced and of involving residents via the focal noise app in the management of concerns and of wind farms.

Finally, building on the insights derived from the different digital twin projects, Chapter 5 focuses on one EU-funded R&I project to reveal how digital twins are designed in light of the various challenges of upscaling wind energy. In this chapter, I focus on how the experts involved in the UPWARDS project—an EU funded project in which I participated myself—have translated the concept of wind energy acceptance into digital simulations. Exploring this case, I reflect on how wind energy acceptance is approached as a problem of noise annoyance and the consequences of this for decision-making concerning wind energy design and planning. With this focus, the chapter provides lessons for how the design of digital technologies can be improved and how concepts such as acceptance should (not) be digitalised and used in wind energy governance.

The final chapter synthesises the findings in Chapters 2-5 and concludes the thesis by presenting a new perspective on digitalisation as an act of governance and by providing an agenda for future research. Specifically, this concluding chapter discusses how digitalisation is an inherently social process, as it relies on the ideas and choices of societal actors, experts in particular. Whose choices and ideas are included in digitalisation processes is a function of how decision-making power is concentrated or distributed among experts and the publics. Viewing digitalisation from this perspective provides a basis for deliberation over whether and how digitalisation might be used to govern the wind energy sector, as well as other domains of environmental governance.

CHAPTER 2

Co-production in the wind energy sector: A systematic literature review of public engagement beyond invited stakeholder participation

This chapter has been published as: Solman, H., Smits, M., van Vliet, B., & Bush, S. (2021). Co-production in the wind energy sector: A systematic literature review of public engagement beyond invited stakeholder participation.

Energy Research & Social Science, 72, 101876.

CHAPTER 2: Co-production in the wind energy sector: A systematic literature review of public engagement beyond invited stakeholder participation.

ABSTRACT

Public concerns surrounding landscape conservation, noise pollution and impacts on bird populations are commonly incorporated into the planning phase of wind energy projects. However, public involvement tends to be highly localized and procedural, aimed at informing local stakeholders and gaining their acceptance for implementation. At the same time, other ways of engaging the public have emerged that move beyond invited stakeholder participation to facilitate the co-production of wind energy technologies and the landscapes in which they are placed. This paper systematically reviews the academic literature with the aim of identifying and characterizing these modes of co-production. A total of 230 papers published between 2009 and 2019 that report on public engagement with wind energy were included in our review. From this sample, we characterise public engagement into three modes of co-production: (1) local co-production, in spatially proximate wind energy projects; (2) collective co-production, performed through collaboration among different actors in the wind energy sector, joined ownership or consumption of wind energy; and (3) virtual co-production, mediated through information technology. These different modes of co-production cover a broad spectrum of ways in which local and non-local publics engage in decisions about where, when, how and by whom wind energy projects are designed, developed and managed over time. Combined, they can offer guidance for future research on how the wind energy sector can further support a transition to sustainable and inclusive energy systems.

This chapter has been published as: Solman, H., Smits, M., van Vliet, B., & Bush, S. (2021). Co-production in the wind energy sector: A systematic literature review of public engagement beyond invited stakeholder participation. *Energy Research & Social Science*, 72, 101876.

2.1. Introduction

Offshore and onshore wind is an increasingly efficient and price-competitive renewable source of energy, contributing 16% of electricity produced globally by renewable sources of energy in 2016 (International Renewable Energy Agency, 2019). In countries such as Denmark, wind energy has emerged as critically important energy infrastructure, and many other countries plan to increase their share in wind energy production in the coming decades (Wind Europe, 2020). However, plans for upscaling wind energy infrastructure are increasingly met with growing public opposition (Nadaï & Van Der Horst, 2010; Maarten Wolsink, 2007). Such resistance tends to be voiced by local communities, local and non-local interest groups and also sparks debates at regional and national levels (Hirsh & Sovacool, 2013; Pasqualetti, 2011). Central to this opposition are concerns over the visual, auditive and ecological impacts on landscapes (Dai et al., 2015; Karydis, 2013; Nadai & Labussière, 2010), as well as concerns related to the reliability, safety and aesthetics of the wind turbine technology (Künneke et al., 2015; Oosterlaken, 2014).

Growing opposition to wind energy indicates a clear need to assess the ways in which different publics are engaged in the design and development of wind energy systems (Kirch Kirkegaard et al., 2020; Pidgeon et al., 2014; Rydin et al., 2015). To increase the involvement of the public in decisions on wind energy, public planning agencies have experimented with different forms of participation (e.g. Jami & Walsh, 2016; Janssen et al., 2015). Emphasis has been particularly given to increasing the involvement of local communities in issues related to the design and location of specific wind energy projects (Jerpåsen & Larsen, 2011; Nordman et al., 2016; Oosterlaken, 2014) and more generally to participation in creation of local (Gustafsson et al., 2015) and regional (Igliński et al., 2015) energy strategies and plans. In most instances, these forms of public engagement fall under what is termed 'invited stakeholder participation' (Cuppen, 2018). These, legislated procedures aimed at informing local stakeholders and gaining their acceptance for implementation of wind energy have so far predominated (Wolsink, 2010).

Although invited stakeholder participation can be successful, there are at least three limitations of selecting this approach as dominant way to govern public engagement with wind energy. First, the substantive involvement of stakeholders in the design of wind turbines and wind parks remains problematic because of the highly technical nature of industrial innovation (Künneke et al., 2015) and project development (Wolsink, 2010). Second, participatory forms of spatial planning tend to predefine who can participate, with a dominant focus on nearby residents to the exclusion of publics outside 'planning areas' (Pesch, 2019). Third, invited stakeholder participation commonly focuses on public engagement during the planning stage (Felt, 2016) and not during the stages of technical design, implementation and ongoing operation of wind energy installations. As a result, public participation in the governance of wind energy has been largely symbolic (Ellis et al., 2009; M. Wolsink, 2007; Wolsink, 2010) and has not accommodated societal debates over the form and function of wind energy in the wider energy transition.

Next to invited stakeholder participation in the (wind) energy sector, a more diverse set of ways to engage concerned publics is needed (Chilvers & Longhurst, 2016; Chilvers et al., 2018; Felt, 2016; Marres, 2016; Papazu, 2016; Ryghaug et al., 2018; Wynne, 2007). Notably, experiments in active and self-selected engagement by concerned publics have emerged with the aim of 'co-producing' plans, policies and public services related to wind energy (Albrechts, 2013; Corsini et al., 2019). Co-production involves means of public participation that include and go beyond invited stakeholder participation by opening up multiple ways through which different publics choose to engage with wind energy based on their concerns, needs and motivations (Chilvers & Kearnes, 2020; Chilvers & Longhurst, 2016). Instead of focusing on how acceptance for wind energy can be gained through invited forms of participation, co-production focuses on how publics continually shape decisions related to wind energy. In doing so, co-production opens up an analytical approach for assessing the extent to which existing and emerging modes of public engagement can contribute to the democratisation of sustainability technologies (Chilvers & Kearnes, 2020).

Examples of co-production in the wind energy sector include cases in which wind parks are developed by energy cooperatives in ways that enable publics to invest and contribute to their design (Hufen & Koppenjan, 2015; Schreuer & Weismeier-Sammer, 2010). Similarly, web-based applications are increasingly used to collect public concerns related to the ongoing operation of wind turbines (Hofstra, 2019). These examples go beyond invited stakeholder participation by opening up wind energy on both land and at sea to otherwise 'excluded' spatially distant publics (Hall & Lazarus, 2015). But while there is also growing academic attention to these new kinds of public engagement that enable co-production (Wolsink, 2018), the wind energy literature remains very fragmented and no attempt has been made to review its current status.

We address this gap by undertaking a systematic review of literature focused on different forms of public engagement that include and go beyond invited stakeholder participation. We review academic articles from 2009 to 2019 focused on diverse forms of public engagement with wind energy and distinguish what modes of co-production exist and how they can be defined. In doing so, we contribute to a broader understanding of how different publics engage with emergent technologies like wind energy to co-produce their materiality and their socio-spatial configuration over the full lifecycle of a wind turbine. Our results also contribute to calls for shifting research focus away from technological 'acceptance' (Devine-Wright, 2005) towards a more inclusive and dynamic processes of co- producing technologies and the landscapes in which they exist (Albrechts, 2013; Chilvers & Kearnes, 2020; Jasanoff & Kim, 2013; Taebi et al., 2014).

In the following section we provide a detailed explanation of the methodology used for our systematic literature review, followed by a presentation of our results. The final two sections of the paper discuss how the findings contribute to a broader understanding of co-production in the wind energy sector, and beyond, and identify areas for further research.

2.2. Methodology for a systematic literature review

Our systematic review is delimited to peer reviewed academic articles published between 2009 and 2019. This time period was selected after an initial examination of the literature suggested a substantial increase in papers focused on the role of public engagement in (wind) energy transitions after 2009.

Our systematic review methodology, following Haddaway et al. (2015) and Pullin et al. (2018), is based on a transparent protocol for searching and analysing the academic literature. This information is organised into four sequential steps following the Search, Appraisal, Synthesis, and Analysis (SALSA) Framework (Grant & Booth, 2009).

2.2.1. Step 1: Search - strategy

We limited our search to peer-reviewed academic articles published in English and discoverable in the subscription-based Scopus abstract and citation platform (using subscription of Wageningen University and Research Library). Scopus is deemed to be the most inclusive platform for systematic and repeatable literature searches (Gavel & Iselid, 2008) and, as such, suitable as a principal resource for systematic reviews (Gusenbauer & Haddaway, 2020). In doing so we excluded other publication types such as book chapters, conference proceedings or grey literature. We further refined our search to the Scopus-defined disciplines of "social science" and "environmental science" – assuming these broad categories are most relevant to our target literature. The search terms were defined using a combination of keywords related to public engagement and wind energy. For the purpose of transparency and reproducibility of our study, all the keywords are listed in the Table 1. The list of keywords was developed based on analytical frameworks and concepts developed by extant literature that theories about participation from the perspective of co-production. We did this in four sub-steps.

First, following Chilvers et al. (2018), we define the scope for the review by asking first order social scientific questions. We did this by linking keywords that describe materiality of wind energy infrastructure and landscapes (what), the actors or networks of publics engaging in decisions related to wind energy (who) and the ways in which they engage (how). Inspired by the work of Felt (2016), we also explores what evidence there is of when (i.e. with what degree of time sensitivity) wind energy is co-produced.

Second, we listed keywords for identifying practices of engagement that reflect or go beyond conventional practices and timeframes of invited stakeholder participation. These keywords enabled the identification of literature focused on the ways in which different publics are engaged over the 'lifespan' of a wind turbine - from turbine design to ongoing management after installation. These key words included forms of engagement that can express both support as well as forms of resistance to wind energy (Chilvers et al., 2018; Kloppenburg & Boekelo, 2019; Walker et al., 2013).

Table 1: Keywords used for sampling the literature.

Focus	Main keywords
Actor/ networks of publics influencing decision-making process	Local Network Consumers network Non-local Collectives Citizens Community End-users User Residents
Active (and long-term) notions of participation, including practices of design	Public engagement Collaboration Cooperation Alliance Partnership Public opinion Collective engagement Cooperatives Co-production/ coproduction Co-design Co-creation
Private and everyday engagement	Local engagement Local involvement Local participation Proximity Private Financial participation
(New) technologies of participation	Smart devices Internet Virtual

Third, we completed our search terms with synonyms. Every keyword was used in a search with combinations of synonyms for wind energy (wind power, wind park, wind turbine, windmills, wind energy infrastructure).

Our final list keywords were translated into the following query string:

> TITLE-ABS-KEY () AND DOCTYPE (ar) AND PUBYEAR > 2008 AND PUBYEAR < 2020 AND (LIMIT-TO (SUBJAREA , "Soci") OR LIMIT-TO (SUBJAREA , "Envi")) AND (LIMIT-TO (LANGUAGE , "English"))

For a paper to qualify for initial inclusion in the sample the search terms used in the query needed to appear in either title, abstract or keywords of an article. The initial result using search for each keyword combination in this query string yielded a total of 1650 papers.

2.2.2. Step 2: Appraisal - strategy for determining relevance and validity of final sample

A final selection of publications was made by appraising of their validity and relevance, inspired by the qualitative approach of Vicente- S´aez and Martínez-Fuentes (2018). Publications that did not meet the following four 'relevance' criteria developed by the team of authors were excluded: (1) papers had to have a predominant focus on wind energy, (2) papers had to have a social scientific focus on wind energy, (3) papers had to have an explicit focus on public engagement and (4) papers had to be available for download via university library subscriptions, open access, contacting the authors or by direct purchase. Applying these criteria led to exclusion of 1420 papers and yielded a final set of 230 papers (all of which are listed in the supplementary material file of the published article).

2.2.3. Step 3: Synthesis - strategy for retrieving data

The review was synthesised by systematically coding all papers in the final sample using Atlas.ti software. The content of sampled papers was parsed using a pre-defined set of codes which was developed based on the criteria of co-production outlined in the step of search strategy. That is, papers were coded for spatial aspects and the materiality of wind energy projects that are co-produced, actors involved, the extent to which publics influence design of wind energy technologies and landscapes, and the stages at which publics are involved (see appendix 1). We then complemented the list with new codes that emerged from the literature. Finally, we grouped the codes into categories based on their relations. This enabled our characterisation of co-production in the next step of analysis.

2.2.4. Step 4: Analysis - strategy for making sense of the data

Finally, the papers were analysed by grouping all the coded papers based on their content in relation to insights about public engagement with wind energy. This was done by drawing on the list of codes that coalesced around three themes of co-production: local, collective and virtual. As these themes were mentioned to various extents across the papers, we grouped the papers based on their relevance and focus on co-production. Our framework is interpretative (inspired by Dixon-Woods et al., (2006)) meaning that we organised and qualitatively synthesized the literature in a way that helped to answer our research question. Researchers asking different research questions might propose other way of ordering these papers - including more quantitative approaches to synthesis.

2.3. Results: modes of co-production

As expected, the papers reviewed distinguish a variety of ways in which public engagement has moved beyond invited stakeholder participation that highlight extant and novel forms of wind energy co-production. The review demonstrates a spread of ways in which publics are engaged and contribute to the co-production of wind energy across three stages of wind energy projects: (1) design, (2) planning and (3) operational management. Furthermore, the literature documents different forms of co-production across these stages of wind energy projects and is focused on the key concerns related to the procedural justice and the materiality of wind energy technologies and their positioning in landscapes.

Out of the 230 papers reviewed three clusters of papers emerge, representing three distinct modes of co-production. The distribution of sampled papers among the clusters and within their sub-clusters is visualised by the graphs in the Fig. 1.

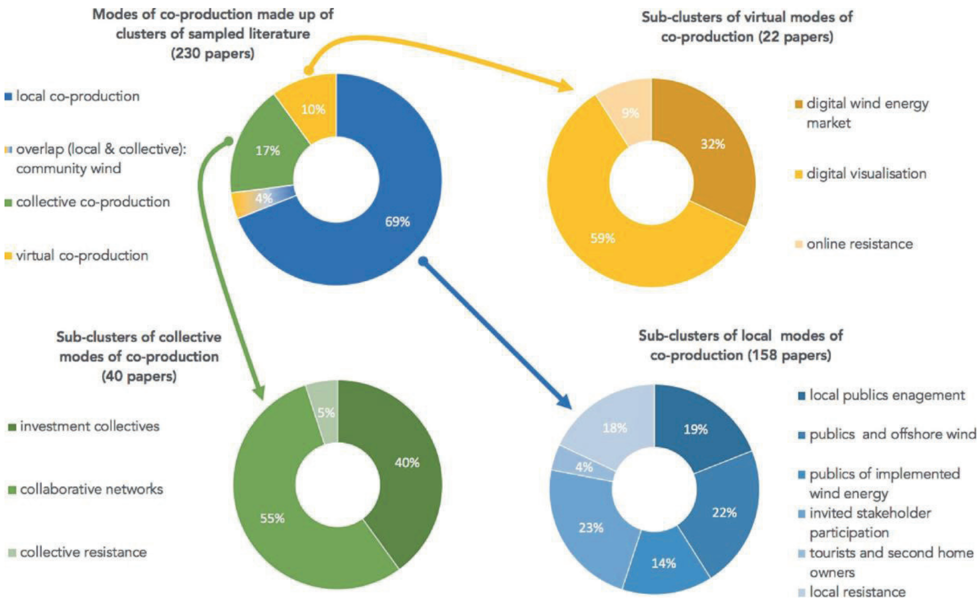

Fig. 1. Clusters and sub-clusters of sampled literature.

The first cluster, representing 69% of all papers sampled, is made up of papers that shed light on the nature of public engagement with wind energy exclusively in a local context. In this literature, the demarcation of locality is an important determinant of who can engage and how, which is why we label this cluster 'local modes of co-production'. Within this cluster multiple ways in which different local actors co-produce wind energy projects are reported on.

The papers covering local modes of co-production define local publics as local stakeholders including farmers, landowners, indigenous communities or residents in urban or residential areas. Amongst the papers included in the cluster of local modes of co-production, there is a clear line of literature focusing on invited stakeholder participation in local, onshore wind energy projects. We then identify a cluster of papers documenting a range of alternative forms of local co-production in onshore wind energy projects and a cluster of literature devoted to public engagement with offshore wind energy. Another sub-set of papers focuses on public engagement with implemented wind energy projects and reports on how publics engage with wind turbines after their implementation and until decommissioning. We also grouped together a small cluster of papers describing how local wind energy projects include engagement of actors who do not live in the area permanently, including tourists and second-home owners. Lastly, there is a set of papers documenting cases of and reasons for locally organised resistance to wind energy.

The second cluster covering collective modes of co-production consists of papers that document the networked-like relationships among involved actors. In contrast to the first cluster, this smaller cluster of papers, accounting for 17% of all papers sampled, focuses on the organisation of collective, beyond-local public engagement. Within this cluster of literature, we identify a sub-set of papers focusing on public engagement organised through investment collectives, such as wind energy cooperatives. Next to that, we found that there is another group of literature focusing on how public engagement can be integrated in collaborative networks of the wind energy sector, in which publics form partnerships and alliances or participate in open research and innovation. A final sub-set of papers document networked forms of collective resistance that transcend the local scale.

Finally, the third cluster of virtual modes co-production represents 10% of the final sample and it covers digital and online forms of public engagement. These papers describe a spectrum of online or virtual reality-based ways of engaging both local and non-local publics in a diverse set of issues around wind energy. One subset of papers in this cluster focuses on how publics become involved in wind energy projects through digital wind energy markets (including online forms of financing and investment). A second subset of paper focuses on techniques for enabling public engagement with wind energy infrastructure through different digital visualisation techniques (e.g. GIS visualisation, virtual reality). Whereas these forms of virtual co-production most commonly explore supportive or neutral forms of engagement to wind energy, a final sub-set of papers did report on virtual forms of resistance. While distinct, these three clusters of papers are not mutually exclusive. For instance, one set of papers discussed 'community wind energy' (representing 4% of all papers sampled), which covers both local and collective means of public engagement. We also found that while 'community wind energy' could represent a mode of co-production of its own, there seems to be a lack of coherence in these papers on the definition of a 'community' – the term is used to describe both 'local groups' and 'communities of interest'.

In the next sections, we present the qualitative results of the review in terms of the state of knowledge about each of the modes of co-production, as presented in the clusters of papers.

2.3.1. Local modes of co-production

Local modes of co-production are represented as a set of ways in which local publics are engaged with spatially-proximate wind energy projects (Mundaca et al., 2018; Pinker, 2018; Wolsink, 2012). This cluster of papers explores the ways in which local publics invest in wind energy on their land (e.g. Jacquet, 2015) or take an active or leading role in planning and managing spatially-proximate wind energy projects (Mundaca et al., 2018), both onshore and offshore (Hall & Lazarus, 2015; Soma & Haggett, 2015). Most of the papers reviewed focus on micro-scale projects in remote areas (Bassett & Semple, 2012), on-farm wind energy projects (Jacquet, 2015), and urban or semi-urban projects (Evans et al., 2011). The review shows that whereas invited stakeholder participation at local level often focuses on gaining acceptance from local stakeholders for implementing pre-existing wind energy plans (Hall et al., 2013), all together, local modes of co-production tend to focus on active and self-selected engagement of local publics (Chezel & Labussière, 2018). Local modes of co-production also tend to enable local publics to remain engaged across the lifetime of the wind energy projects (Kahn, 2013; Konkel, 2013).

Within this literature, being landowner or a resident of an area is commonly seen as a defining determinant of (1) who these local publics are, (2) their degree of involvement in the development and management of wind energy projects (Costello, 2011; Simcock, 2014), and (3) how benefits are distributed (Aitken, 2010; Evans et al., 2011). The degree of influence on and benefit from wind energy production is seen in direct relationship to either the share-holdings of individuals (Beery & Day, 2015; Warren & McFadyen, 2010) or their proximity to operational wind parks (Macdonald et al., 2017).

Within the literature on local modes of co-production, there are however alternative perspectives on how to define local publics. As a whole, literature on local modes of co-production does not treat local publics as a predefined set of actors. Instead, local co-production appears to focus on constellations of local actors that coevolve with agendas linked to wind energy, such as electrification (Bassett & Semple, 2012), economic benefits (Guiney, 2018) or transitioning local areas towards renewable energy (Barry & Chapman, 2009). Even though some papers define local publics as homogeneous entities (Dimitropoulos & Kontoleon, 2009; Lindén et al., 2015), there is also recognition that within each community of place differences are found in terms of opinions and attitudes towards wind energy (Anderson, 2013). Indeed, literature on local modes of production moves beyond homogenising treatment of local publics by unpacking resistance as a complex and gradually evolving response to wind energy that goes beyond public opinion as for or against wind energy (e.g. Borch, 2018) to include a degree of support or resistance (Walker et al., 2015) and how it changes over time (Wilson & Dyke, 2016). Some of these papers demonstrate that space for resistance and contestation is in fact a central part of the co-production process and that diversity in opinions, needs and practices is intrinsic to any local wind energy development (Hindmarsh, 2010; Reusswig et al., 2016).

In contrast to invited stakeholder participation, which tends to predefine the issues around local wind energy projects (Walker & Baxter, 2017), all the different local modes of co-production together include a diverse set of bottom-up motivations of local actors involved with wind energy (Karnøe & Garud, 2012; Thøgersen & Noblet, 2012; Vecchiato, 2014). Environmental motivations are reported as the most common reasons for individuals or local communities concerned about energy transition or climate change to favour wind energy developments (Otto & Leibenath, 2014). However, environmental concerns also extend to the impacts of wind turbines on local landscapes and nature (Solli, 2010). Finally, motivations for getting involved in local wind energy projects can be purely financial, indicating that support for wind energy does not imply opposition to fossil fuel-based energy sources (Jepson et al., 2012).

The papers reviewed collectively highlight two overarching debates of moving beyond invited stakeholder participation and exploring the potential for co-production as including more diverse set of open and responsive modes of public engagement.

First, delegating decision-making power on local energy provision to local publics is reported as a way of democratising the design, implementation and/or use of energy infrastructure (Pinker, 2018). Building on this idea, several papers focus on the consequences of including local knowledge and expertise in the design of wind energy projects. For example, Baker (2016) and Jami and Walsh (2016) emphasise the value of local (and indigenous) knowledge in improving the decisions over if, where and how wind energy projects should be developed at the local scale. They argue that local wind energy projects require an early stage and open process of participation that allows for experimentation with renewable energy technologies, incorporation of broader sustainability agendas and self-governance. Similarly, Chezel and Labussi`ere (2018) argue that locally managed wind energy projects can optimise the use of local capital, landscape and local knowledge which in turn increases the sense of justice of these projects and the probability of their positive effects on local communities. In spite of the perceived benefits of engaging local publics at the stage of design, only a few studies were found that outline processes for and benefits of engaging local publics in the work of wind turbine manufacturers (Karnøe & Garud, 2012; Tanner, 2018). However, we did find examples of synergies between local modes of co-production and work of landscape architects (Nadaï & Labussière, 2017; Oosterlaken, 2014) and spatial planners (Christie et al., 2014; de Sousa & Kastenholz, 2015). These studies propose novel methods of planning and envisioning local wind energy landscapes in an open process of co-design and integration of economic sectors (e.g. tourism, recreation and fishing) with wind energy.

Second, engaging local publics is seen as a means of enabling political action related to, but extending beyond, direct concerns of wind energy projects in regional and/or national public debate (Devine-Wright, 2011). For example, Delicado et al. (2014) explores the complexities of setting regional or national goals around wind energy while creating space for locally self-determined planning. Others respond to this challenge by arguing that decisions on large-scale wind energy need to engage local publics (Rydin et al., 2015), but highlight the difficulties of doing this across all land and seascapes. Devine-Wright (2011), for instance, demonstrate that it is difficult to define local publics in offshore wind energy projects given these projects represent substantial national investments and transcend the local scale. Nevertheless, the literature presents abundant evidence that offshore wind energy projects raise similar kinds of public concerns as onshore wind energy (Rudolph et al., 2017; Rudolph & Kirkegaard, 2019) and, as such, require equal attention to engaging local publics in their co-production (Firestone et al., 2012a, 2012b; Hooper et al., 2015; Ten Brink & Dalton, 2018).

2.3.2. Collective modes of energy co-production

The cluster of papers representing collective modes of co-production focus on all forms of collaboration in both single and multiple wind energy projects, as well as issue-oriented networks established for collaboration within the wind energy sector. The papers reviewed reveal collective modes of co-production that purposively seek out spatially dispersed publics who hold concern over and self-define as participants in decisions relating to the development of wind energy (Bauwens & Devine-Wright, 2018; Bauwens et al., 2016; Musall & Kuik, 2011).

Collective publics tend to be broadly defined as formalised networks of societal actors that include, but are not limited to, voluntary and often self-organised collectives (e.g. Bauwens & Devine-Wright, 2018; Bauwens et al., 2016), partnerships and networks of collaboration (e.g. Cullen et al., 2012; Karnøe & Garud, 2012; Martins et al., 2011), also including networks lobbying against wind energy (Avila, 2018; Moragues-Faus & Ortiz-Miranda, 2010). The composition of these networks is mostly not dependent on a given spatial category, such as local, regional or national, but instead links publics who share common goals and concerns related to wind energy. These networked 'communities of interest', have a broader scope than the local 'communities of place' (Bauwens & Devine-Wright, 2018; Holstenkamp & Kahla, 2016), as they can bring together dispersed actors into contact and dialogue over the design and operation of wind energy.

Two distinct types of practices of co-production by collective publics emerge from this cluster of papers, both focused on the concerns and aspirations of collective publics linked to wind energy technology and the embedding of these technologies in landscapes.

First, collective co-production is demonstrated through financial participation, found in literature on energy cooperatives (Bauwens & Devine-Wright, 2018; Bauwens et al., 2016) and community-owned wind energy projects (Simcock, 2014; Simcock, 2016; Warren & McFadyen, 2010). A common finding of this literature is that such co-production is based on a collective ownership model for wind turbines which in turn distributes energy back to its members and/or provide financial benefits to the investors. Wind energy collectives tend to involve collective publics as investors who in turn receive the right to financial benefits or energy produced individually (Bauwens & Devine-Wright, 2018) or as a community (Simcock, 2014). Seed funding might be sought from members enrolling in the scheme at early stage who then receive future rights to financial benefits (Miller et al., 2018) or to the energy that is produced from the turbines when operational. Wind energy collectives are seen as a promising model for developing wind energy projects given their ability to overcome financing constraints and also to generate support at local level by taking a more tailor-made approach to project development and by involving users and local communities over time (Wallmeier & Thaler, 2018). Warren and McFadyen (Warren & McFadyen, 2010), demonstrate how collective (financial) ownership of wind turbines can even translate into affirmative attitudes by collective public, expressed by for instance naming wind turbines.

Second, the involvement of collective publics also extends to engagement with wind turbines and their management across different stages of wind energy development. Collective publics in wind energy have been shown to seek involvement in decisions concerning operation of wind farms, including their ongoing management and maintenance (Hyland & Bertsch, 2018), and even decommissioning and repowering wind energy installations (Del Río et al., 2011; Meyerhoff et al., 2010). Karnøe and Garud (2012) and Tanner (2018) for instance, show that close collaboration between early users of wind turbines and wind turbine manufactures in the Danish wind energy sector was an important step in finetuning subsequent designs. In this Danish case, collective publics were defined as users of wind turbines who contributed to 'wind meetings', organised to foster collective learning and feedback to the design process (Karnøe & Garud, 2012). Despite being one of few examples of its kind, this case demonstrates that collective co-production can not only lead to better design but also foster positive engagement of collective publics in the wind energy sector at large.

This literature extends the notion of co-production by pointing to the role of networked collaboration between collective publics with professional actors, such as developers, energy providers and governments in initiating, developing and maintaining wind energy projects over time (Sovacool & Enevoldsen, 2015). Collective co-production can, in this sense, materialise in private–public partnerships focused on joined development of wind energy projects (Martins et al., 2011; McComas et al., 2011) or in cooperation focused on improving assessments and evaluation of wind energy projects and their impacts (Moragues-Faus & Ortiz-Miranda, 2010). The literature also points to how experts relate to publics and how their understanding of public concerns influences the process of technology innovation for the wind energy sector. Nevertheless, while there is evidence that collective co-production can enable effective cooperation between publics and experts, there are very few such examples in the literature (Heidenreich, 2015).

A common assumption in the literature on collective co-production is that the input provided by collective publics is likely to be reached through deliberation (Costello, 2011; Phadke, 2013). It is furthermore assumed that the more inclusive these networks are the more deliberation they can foster and the greater the likelihood that technical and landscape related decisions will be seen as legitimate by the publics involved (Phadke, 2013). However, our review also reveals there has been limited analysis of the inclusion or exclusion of different opinions within these networked collective publics. There is also limited evidence within literature on wind energy collectives on how deliberation feeds into different stages of wind energy development, and where deliberation is documented, the content of debates appears largely limited to financial and technical efficiency.

2.3.3. Virtual modes of co-production

Virtual modes of co-production in wind energy are observed in the literature as a set of practices of engagement with wind energy projects mediated by information technology, which connects people located across any distance from wind energy projects into digitally-networked publics (Brady & Monani, 2012; Buntaine & Pizer, 2015; Gamel et al., 2016; Grashof, 2019; Miller et al., 2018). Such engagement is linked to the emergence of online platforms, websites and apps that mediate public involvement in wind energy projects and to the proliferation of visualization and geo- spatial tools for public engagement in the wind energy planning (Phadke, 2010a). The papers reviewed in this cluster all demonstrate that virtual co-production significantly breaks down spatial, temporal or social re- strictions to public engagement. Virtual modes of co-production are, as such, seen as an efficient means through which public concern materialise (Phadke, 2010b) and are communicated online (Hindmarsh, 2014) across different stages of wind energy projects. For instance, the emergence of websites, platforms and social media groups devoted to wind energy, are reported to enable large numbers of people to express interest in supporting and financing (Miller et al., 2018), or indeed resisting (Reusswig et al., 2016), wind energy projects long before they are developed. At such an early stage virtual co-production can take a form of an online crowdfunding initiative that searches for investors among broader publics who are willing to provide funding for wind energy (Miller et al., 2018). For instance, a USA-based study reported on an online crowdfunding initiative that enabled residents of a whole state to participate in financing of a large wind energy project (Miller et al., 2018). Little evidence was found, however, on how investors living far away from wind energy projects relate to them and interact with the online means of engagement across the projects' lifetime.

There is also evidence on the motivations of publics to digitally engage with wind energy projects. A study of Gamel et al., (2016), found that people concerned about the environment in Germany are "more likely to invest in wind energy and even seem to accept financial dis- advantages for such 'environmentally-friendly' projects" (Gamel et al., 2016 p.29). However, it remains unclear how choices of these publics reflect their concern and preferences over where and how wind energy projects are developed. Here the reviewed literature that touches upon the issue of location, while limited, is split. For instance, Brady and Monani (2012) show that remote and marketed as sustainable wind energy projects tend to appeal to digitally-networked publics who are interested in buying carbon offsets form such projects. In contrast, Gamel et al. (2016), find that digitally-networked publics prefer making investments within their own region (radius 30 km) or neighbourhood (radius 5 km) as opposed to investments in foreign wind energy markets.

While this literature draws on the potential of virtual engagement for generating broader networks of support for wind energy projects, we also found evidence for that opening up wind energy projects to dispersed publics can lead to conflicts. For example, resistance was observed in case of wind energy projects developed in Ireland for export of green energy to the UK (Brennan et al., 2017). In this study, the authors found that “whilst local residents would bear the brunt of the external costs, most of the benefits would not be felt in Ireland (…) but instead be distributed further afield to wind farm operators, private corporations and their distant shareholders” (Brennan et al., 2017 p.1984). As such, virtual modes of co-production that involve dispersed consumption and production of wind energy can lead to the emergence of new concerns about how costs and benefits are distributed.

Finally, the literature shows that virtual modes of co-production enable novel ways of engaging with digitalised versions of wind energy technologies and landscapes. Increasingly common are visualisation and geospatial tools that simulate the possible outcomes of different decisions about wind energy designs (Phadke, 2010a, 2010b; Simao et al., 2009). The premise of virtual modes of co-production that engage publics with digital representations of wind turbines or wind parks is that such engagement can foster high levels of public influence over how and where wind energy should be developed (Berry & Higgs, 2012). For example, web-based visualisation tools are proposed as channels of effective communication between the publics and experts to discuss concerns and alternative wind energy designs (Simao et al., 2009). Additionally, we found studies reporting on that energy suppliers and researchers working on wind turbine innovation are also using virtual reality to engage publics to estimate noise impacts of new wind turbines (Manyoky et al., 2014; Yu et al., 2017) and evaluate how wind energy projects might be integrated in areas of cultural heritage (Wieduwilt & Wirth, 2018).

But while the potential of engaging dispersed, digitally-networked publics is a key feature of the papers reviewed, evidence of co-producing wind energy in such ways remains very limited. The characteristics of those publics most likely to engage with virtual technologies or the extent to which these publics contribute to decisions on the design, implementation and management of wind energy projects also remains unclear. The current literature most likely does not provide a complete overview of the full spectrum of possibilities for virtual co-production of wind energy technologies and landscapes. There is also little published information on the roles of the actors developing these online services and mediating interaction with wind energy; especially in terms of their influence on opening or closing down the decisions of digitally-networked publics that affect wind energy projects across the different stages of wind energy development.

2

2.4. Discussion

Our review distinguishes between different modes of co-production in the literature on public engagement with wind energy. The identified local, collective and virtual modes of co-production are an attempt to represent the diversity of ways in which different types of publics engage with and shape the materiality of wind energy technology and their placement in landscapes over time. In contrast to the dominant approach of invited stakeholder participation, these three modes of co-production together open up at least five ways of understanding how diverse publics can contribute to the design, planning and ongoing management of wind energy (Figure 2).

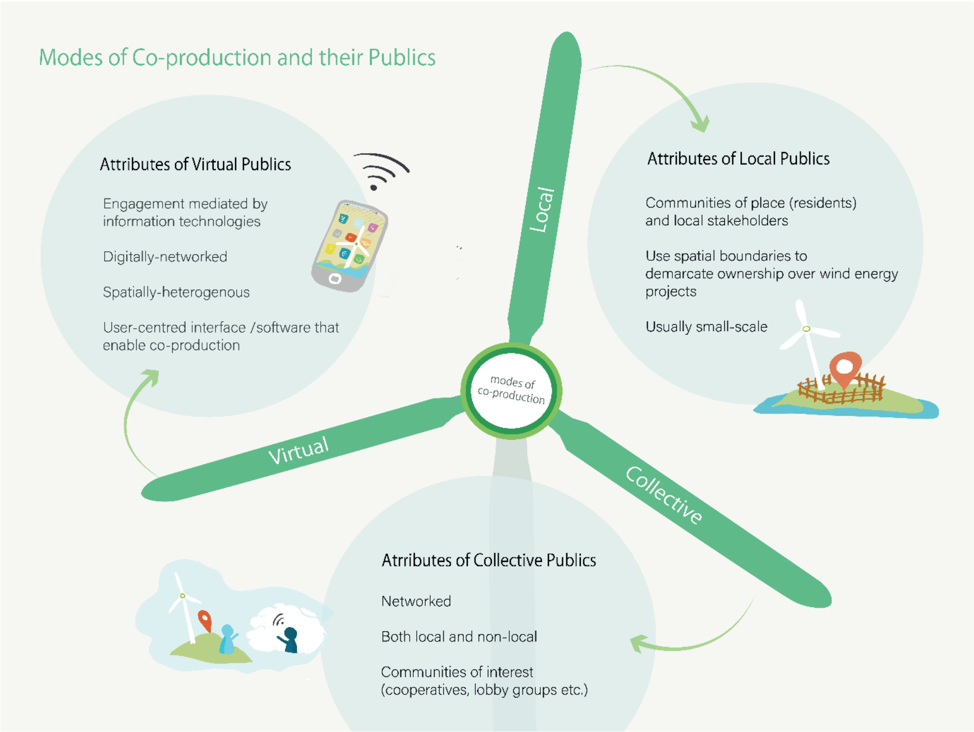

Figure 2. Co-production modes and their publics.

First, local, collective and virtual modes of co-production, all appear to enable both local and spatially-dispersed, 'non-local' publics to engage with wind energy. Whereas a local mode of co-production relies on a specific geographic or administrative area to determine who has the right to be involved and how (Simcock, 2014), collective and virtual co-production enable the emergence of spatially dispersed publics to form networks by sharing a common interest in wind energy (Bauwens & Devine-Wright, 2018; Bauwens et al., 2016). This means that instead of proximity alone, different publics emerge depending on the concerns and needs (Marres, 2005) that motivate them to become actively involved in wind energy projects. By opening up to co-production and hence to non-local publics, which generally get less attention as actors in governance of energy systems (Pesch, 2019), different modes of co-production can enable multiple concerns and values to be expressed and translated into the design, implementation and management of wind energy projects.

Second, local, collective and virtual modes of co-production enable a dynamic understanding of concerned publics, in contrast to static and idealised publics of invited stakeholder participation. Each of the modes of co-production views publics as plural and consisting of dynamic constellations of actors that coalesce and disband around wind energy over time (see e.g. Chilvers & Longhurst, 2016). Understanding publics in this way underscores the value of moving from energy 'planning' to energy co-production. That is, a shift from predetermining publics and their concerns and values (Cuppen, 2018; Taebi et al., 2014) in the planning phase of a wind energy project to continually engaging the concerns and values of diverse publics across the entire life span of a project (Rudolph et al., 2017). In doing so co-production, when seen across the various modes elaborated in this review, can enable the continual emergence of publics to define the agenda around wind energy developments, where they should be and what concerns should be addressed.

Third, the review demonstrates the importance of understanding the reasons why different publics may choose to engage through different modes of co-production. We found that the motivation to be engaged in the wind energy sector is not always linked, as is commonly assumed, to 'green' political values (Jepson et al., 2012). The review instead indicates that different publics engage in the co-production of wind energy for reasons that may go beyond environmental concerns alone. For instance, a degree of support or opposition to wind energy appears to be based on a mix of financial (dis)benefits (Bristow et al., 2012; Hyland & Bertsch, 2018; Jepson et al., 2012), demand for local (or national) renewable energy (Leary et al., 2012) in addition or in combination with green political values. How each mode of co-production can draw on these different motivations to increase the input from the publics on design, planning and long-term management of wind energy technologies and landscapes, either individually or in combination, however, remains less clear and should be the subject of further research.

Fourth, our review indicates that by engaging publics at different spatial scales co-production may be able to overcome some of the prevailing concerns associated with wind energy landscapes and technology (especially around noise and landscape pollution) (Phadke, 2010b; Yu et al., 2017). In contrast to invited stakeholder participation, a co-production perspective focuses on opening up to, not only compensating for, concerns in the hope of finding novel solutions to issues ‘saturated’ (at least in part) by the predefinition of publics and their concerns (Cuppen, 2018; Simcock, 2014). By breaking down these predefined publics and concerns, modes of co-production can enable new forms of ‘energy citizenship’ (Ryghaug et al., 2018), whereby the publics take responsibility for long-term management of wind turbines and embrace both positive and negative aspects of wind turbine developments and co-decide on how benefits and costs associated with wind energy should be distributed. Nevertheless, different modes of co-production also appear to enable the emergence of new concerns around wind energy (e.g. around perceived justice of online investments in remote wind energy projects (Gamel et al., 2016; Pesch, 2019). Much of this literature reviewed is, however, only indicative of the emerging concerns and issues rather than providing examples of good practices for conflict resolution. Overall, there is space for further research on the extent to which different modes of co-production can internalise these concerns and contribute to conflict resolution in different empirical settings.

Finally, the review indicates that the modes of co-production enable a more flexible understanding of what wind energy technology (and infrastructure) entails and how it can be configured in landscapes (Karnøe & Garud, 2012; Phadke, 2013; Vecchiato, 2014)[82,84,120]. By fostering such an understanding of flexibility in design and management within diverse publics many of the concerns held over wind energy projects can be mitigated (Karnøe & Garud, 2012). But while the review shows that publics can play a role in decisions about wind turbine technology, including how different wind turbine models are designed, operated and maintained, empirical examples of such engagement remain limited (except e.g. Karnøe & Garud, 2012). There is more evidence of local and collective modes of co-production enabling publics to influence decisions about where and how wind energy is developed (Labussière & Nadaï, 2014). Virtual co-production is recognised in some papers as holding promise for interactive visualisation of design principles (Phadke, 2010a, 2010b). However, it is apparent that further empirical research is needed to understand the ways in which these technologies (visualisation software, apps or platforms) are used in practice (for example as already done for smart meters (Kloppenburg & Boekelo, 2019)).

These five ways of understanding how diverse and emerging publics can contribute to the design, planning and ongoing management of wind energy demonstrate that these three modes of co-production are not mutual exclusive. They instead can co-exist, enabling different publics to influence different material aspects of wind energy systems, related to technology and landscape, across the stages of wind energy development. Not only does this once again contrast with the dominant approach that focuses only on invited forms of stakeholder participation (Felt, 2016; Marres, 2016), it also opens up the potential for enabling (dynamic and dispersed) publics to have long-term influence over wind energy projects (Leary et al., 2012; Vecchiato, 2014), even up until they are decommissioned (Dannemand Andersen et al., 2007).

Realising any form of synergy between these forms of co-production, however, also requires recognising their clear differences and (potential) contradictions. Collective and virtual modes of co-production are more focused on the engagement of networked, non-local publics across the different stages (e.g. Gamel et al., 2016; Miller et al., 2018). But in doing so they do tend to focus on stages of development that match the needs or aims of project developers – for example financing (Miller et al., 2018). Furthermore, local and collective modes of co-production appear to be more dominant at the stage of planning and ongoing management, whereas virtual modes of co-production were more often found at the early stage of planning. It is also evident that there is overall little attention to the stage of design – perpetuating the black-boxed nature of wind turbines (as also found to in case of other technologies (Wynne, 2007)). However, to understand how these different modes of co-production can have synergistic effects across the full lifespan of wind energy projects more research appears necessary; especially as ambitions shift to developing carbon–neutral energy systems in many regions of the world.

2.5. Conclusion

The current literature reveals three modes of co-production that demonstrate the multiple ways in which local and non-local publics can influence the design, implementation and ongoing management of wind energy. These modes of co-production enable these publics to express concerns about both wind technologies and the location of wind energy in landscapes at relevant stages of wind energy projects. This review shows how these modes of co-production offer an approach to public engagement that goes beyond invited stakeholder participation which has so far dominated in the wind energy sector and tends to focus on the concerns of local publics and landscape planning alone.

The three modes of co-production have not received the same amount of attention in the literature. Local and collective modes of co-production have been the focus of more academic research than virtual modes of co-production. It is likely, however, that virtual co-production will continue to expand in practice as energy companies and governments seek to increase online involvement of publics in the design and management of wind energy projects. The value of virtual co-production may become even more important as wind energy projects are located in distant landscapes, for instance at sea, and as a means of linking to other smart technologies employed in the everyday lives of energy consumers.

Further research is needed to unravel the degree to which all three modes of co-production influence the sustainability of wind energy infrastructure in practice, taking both different stages of wind energy development as well as their interaction with landscapes and technologies into account. Empirical research is needed to improve the understanding of how each mode enables different publics to become engaged and with what consequences for existing and future wind energy configurations. Finally, research is also needed on the interaction between local, collective and virtual modes of co-production, to assess whether and how they are complimentary in shaping the role of wind energy in the wider energy transition.

CHAPTER 3

3

Digital twinning as an act of governance in the wind energy sector

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CHAPTER 3: Digital twinning as an act of governance in the wind energy sector

ABSTRACT

Digital twins have emerged as novel technology in the wind energy sector that enables the design, monitoring and prediction of wind turbine performance. Despite growing attention on their potential, little is known about how digital twins are designed, by whom and how their design choices affect multiple aspects of decision making in the development of wind energy. Using a framework of co-production, this paper examines digital twins as boundary objects and the role of *twinning* as boundary work that involves an active process of design and affects multiple aspects of decision making in the development of wind energy. Our results demonstrate how the design of digital twins evolves throughout the twinning process, affected by regulation, choices of expert twinners on data and models, and what constitutes a matter of concern. We shed light on the role of these twinners in influencing which actors and their matters of concern are included and excluded during the twinning process. Our understanding of twinning as an active process of governance by design more clearly reveals how digital twins are not objective representations of reality, but a function of boundary work. We conclude that more transparency is needed over how digital twins are designed to enhance their role as technologies that foster a transition towards more sustainable energy systems and decision-making over wind energy technologies and their integration in landscapes.

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3.1. Introduction

Digital twins are virtual representations of an object or system and how it changes over time (Jones et al., 2020). Emerging across multiple sectors of the economy and domains, digital twins have enabled virtual, as opposed to analogue, ways in which individual technologies, infrastructural systems, urban areas and even nature are managed (Bauer et al., 2021; Dembski et al., 2020; Nochta et al., 2020). The design of digital twins in the wind energy sector is a case in point, where they are being developed to increase the safety, reliability, and optimal efficiency of turbines by enabling pre-emptive monitoring and maintenance (Wagg et al., 2020), and to support decision making over their design and use (Smogeli, 2017; Wright & Davidson, 2020). Yet despite growing aspirations for using digital twins to enhance technology development and implementation, little is known about the process of 'twinning' and its role in design, planning and ongoing management of these energy infrastructures.

Jones et al. (2020) define twinning as "the act of synchronising the virtual and physical states (…) such that the virtual and physical states are 'equal'" (p. 42). While focused on defining the goal or outcome of twinning, we argue that this definition, like others before it, fails to emphasise twinning as an active process of design that includes boundary work by multiple actors that includes negotiations about which elements of the material world are included and excluded in their digital 'equivalents'. Seen as such, twinning is less about mirroring reality in the virtual realm (i.e. a 'twin'), and more about the aspiration and actions required to produce a virtual reality (Tomko & Winter, 2019). Given multiple interpretations of what any given digital twins represents are possible (Van Der Burg et al., 2021) we argue attention is needed to understand the role of digital twins as "boundary objects" – that is, artefacts or concepts that have multiple meanings for different people based on their background and expertise – and as products and effects of boundary work.

To understand twinning as a set of active design processes that hold consequences for how wind energy is designed and managed, we examine decisions made by experts about what to include and exclude in the design of digital twins. We look at twinning as a process of governance by design in which decisions related to twinning may steer developments in wind power as well as steer the choices and behaviour of different actors in the wind energy sector (following Jasanoff, 2016). More specifically, we focus on how boundaries are set for determining which aspects (technical, societal and environmental) are twinned, and then on how these boundaries influence the design and function of wind energy technologies over time, and in whose interest.

We illustrate five acts of governance by design (steering wind turbine design, data use, facilitating or constraining public engagement, opening/closing down decision-making about siting, production of legitimising evidence for wind energy policy and management). We argue that the process of twinning constitutes an active site of governance by design that steers and 'performs' the developments in the wind energy sector with consequences for wider societal objectives such as the energy transition. These consequences manifest through the materiality of wind energy technologies (including digital twins) and by how they are implemented in landscapes (Kirch Kirkegaard et al., 2020; Solman, Smits, van Vliet, et al., 2021). For example, the increasing concern about the impacts of wind turbines on landscapes (Stremke, 2010) wildlife (Arnett & May, 2016) and on the extent to which local communities are meaningfully engaged (Aitken et al., 2016). While all these concerns are to varying degrees related to choices about the design of wind energy technologies, little is known about how these concerns are internalized into digital twins, by whom and with what effect on their overall governance. To overcome this, we focus on twinning actors (or 'twinners') to unravel how they translate the problems, the technologies as well as the needs and concerns of other actors into digital twins. Twinners tend to be experts involved in projects that design digital twins as well as any other actors enacting this translation and working for governments, private sector or research. These twinners can also include representatives of interest groups or the public at large, as digital twins increasingly become tools for decision-making over public space or infrastructure (Nochta et al., 2020). This in turn may open up a question about direct public involvement in design of digital twins. How the role of twinners is allocated is thus imperative for revealing the dynamics of decision-making over both physical and virtual states of systems like wind energy.

Our focus on the twinning process reveals the challenges faced by twinners when reducing the technical complexity of wind energy systems, their interaction with environmental factors and the value and concerns of other societal actors to a virtual state. In this respect, twinners might steer the development and management of wind energy systems in a similarly influential way to policymakers and planners when giving (or not) a place to public concern (Harbers, 2005; Jasanoff, 2016; Latour, 2004); for example, by reducing a multitude of landscape-related concerns to a variable such as 'visual impact' (Wolsink, 2018). However, it remains unclear whether twinning represents a more inclusive and dynamic means of designing and managing systems that are twinned (here wind energy) than analogue processes (Dembski et al., 2020). Clarifying these points, we argue, can help to more precisely understand the current and future role of digital twins in the energy sector and beyond.

The following section presents our co-production framework for analysing twinning as active process of governance by design. We do this by unpacking how digital twins, as boundary objects between virtual and physical states, are twinned through an active process of boundary work. We then outline our methodological approach for better understanding the twinning process and present our results in section 4. Finally, we reflect on the important role of twinning and its implications for the wind energy sector in section 5 and present the conclusions in section 6.

3.2. Digital 'twinning'

We examine twinning through the lens of co-production, which focuses on how scientific ideas and technological artefacts co-evolve with society, the institutions and discourses that create their meaning and enact them in practice (building on Jasanoff, 2004). A co-production perspective is thus useful for better understanding the complex relationship between science and innovation, such as those around wind energy and digital twins, and how they spark concern and engagement of the public (Macnaghten et al., 2005; Turnhout et al., 2020; Wyborn, 2015). Taking the lens of co-production, a digital twin represents a series of decisions made largely by experts to represent social, technical and biophysical systems in digital 'equivalents'. These decisions are based on choices about which elements of these systems are twinned (and which are not) and about the ways in which these elements should be represented and programmed to behave in a digital format. As such twinning, can be seen as an active process of 'becoming' (building on Callon, 1991a); that is, boundary work that includes a translation of system elements into digital objects whose "meaning is imposed, contested, reflected upon, created, and agreed upon" (Metze, 2017 p. 37). Collectively, these twinning decisions hold consequences for what subjects, objects and matters of concern are included and excluded, involving categories of experts and expertise, and 'stakeholders' and their stakes (building on Henderson, 1991; Latour, 2004).

Taking this perspective of co-production, we analyse twinning as an active design process by positioning it at the interface between the material and virtual realms. Inspired by Miller and Wyborn (2020) we reflect on the "forms and arrangements of credibility, legitimacy, and accountability present and their implications for what knowledges and arrangements hold sway" (p. 92) in how digital twins are designed. Then, building on prior research about boundary work in design (Tharchen et al., 2020), we analyse the interaction between different domains of expertise in their collaboration on digital twins' design and between twinning and public policy and wind energy planning. Figure 3 (below) illustrates how a boundary object (digital twin) co-evolves through boundary work (twinning where inclusion and exclusion takes place) within networks of actors and their concerns.

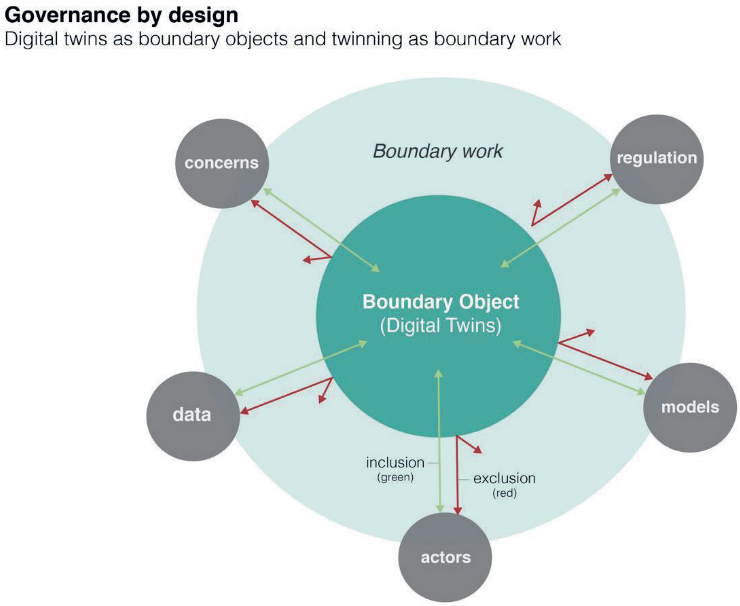

Figure 3: Twinning as an act of governance: the emergence of digital twins as boundary objects through boundary work.

Our analysis proceeds in two steps. First, we unpack the digital twins as boundary objects, that are products of ontological assumptions about how to represent and demarcate components of wind energy systems, their behaviour and purpose. Following Leigh Star and Griesemer (1989) and Harvey and Chrisman (1998), we treat boundary objects as artefacts or concepts that have multiple meanings for different people based on their background and expertise, arguing that they have material effects on the energy transition. We analyse how the meaning of digital twins as boundary objects varies across different twinning actors and how these interpretations are a base for their boundary-work. Next to the interpretive flexibility of meaning that boundary objects have, we follow Leigh Star (2010) in how boundary objects coordinate work of the different actors, despite and sometimes because of the difference in meanings (see Tharchen et al., 2020). Following this work, we understand that boundary objects "form the boundaries between groups through flexibility and shared structure—they are the stuff of action". This means that a digital twin as a boundary "object is something people (or, in computer science, other objects and programs) act toward and with" (p. 603).

Second, we focus on how boundaries are set around digital twins as a function of the interactions between experts, their expertise and their framing of how and why matters of concern are included in a twin (Henderson, 1991; Tharchen et al., 2020). These boundaries are informed by both an understanding of what counts as credible, reliable and relevant knowledge (Gieryn, 1995; Guston, 2001) and the ways and degree to which different kinds of data can be combined (Howe, 1988; Rundstrom, 1995). In this way, the making of boundaries holds consequences for whose matters of concern are incorporated and which are not (Funtowicz & Ravetz, 2008). Here boundary work is unpacked by the interrogation of the composition of decisions and rationales for the inclusion and exclusion of data, models, concerns, regulation and stakeholders (inspired by Judson et al., 2020; Toonen & Bush, 2020). By critically interrogating these decisions and rationales it is possible to better understand what kinds of and whose aspirations and realities are digitally represented in the twinning process. It is also possible to understand the influence on and of digital twins for grand societal challenges including (but not limited to) the energy transition (Bauer et al., 2021; Nochta et al., 2020).

3.3. Methodology

Our analysis is based on a selection of ongoing cases of digital twin design in the wind energy sector. These cases enabled an in-depth understanding of twinning, including how experts define, design and intend to use digital twins (Lund, 2014). Data collection was conducted in three stages.

Secondary data was analysed, including online materials about how digital twins are designed and marketed by a major wind turbine manufacturer, and information from related research projects on digital twins (listed in Appendix 2). This analysis fed directly into the preparation for the expert interviews and panel discussions.

A total of 20 interviews were then conducted with purposefully sampled experts in the domain of wind energy from different academic disciplines, industry and policy on wind energy research and innovation (following Suri, 2011). That is, we interviewed experts involved in different projects that design digital twins for wind energy, all of which happen to be focused within Europe: UPWARDS (in which two of the authors of this paper participate), DigiTwin, and ReliaBlade (for a complete overview of these projects see Appendix 2). In addition, we interviewed experts and representatives of interest groups working across Europe and involved in wind energy planning and policy as well as industry-based experts on wind energy innovation and management at a leading wind turbine manufacturer in Europe. We then expanded our network to other wind energy experts by focusing on experts on digital twins and digitalisation at a leading European institution in the domain of wind turbine research and innovation. All the interviews were semi-structured and individualised to ensure there was room for follow-up questions or anecdotal remarks.

Finally, we held a panel discussion with experts at a meeting of a project that aims to develop a digital twin of a new 15MW wind turbine (called UPWARDS, funded under Horizon 2020). A choice was made to organize a workshop in order to foster interaction and open discussion among experts. These experts were divided over three tables, each moderated to discuss from their perspective as members of a digital twin project (1) the design of wind energy technologies, (2) accounting for landscapes and (3) enabling stakeholder engagement.

All interview transcriptions and the summary of workshop discussions were collected and analysed iteratively (Tolley et al., 2016). Based on this, we evaluated the quality of the data by reflecting on the kind of insights gathered, checking whether the information was relevant, and identifying aspects that were missing (Belotto, 2018). This in turn enabled internal validation of the data and strengthened the generalizability of the findings (Silva et al., 2014). All interviews were coded thematically (Gibbs, 2007) using our theoretical framework to derive concepts and codes that help to understand twinning as boundary work, and digital twins as a boundary object.

3.4. Digital twins as a boundary object – negotiating ontology

Our results confirm that digital twins constitute boundary objects that link virtual and physical states within the dynamic setting of specific sites and conditions. However, as dynamic boundary objects, the definition of a digital twin is not set. How a digital twin is understood may change over time, depending on the disciplinary backgrounds and on the different kinds of organizational goals of twinning actors. Many of the experts reported that it is only by working together that a shared understanding of what a ‘digital twin’ is and what it can achieve is developed. Once a twin is designed or a twinning project completed, this shared understanding is rarely if ever carried over to a following project.

We found three ontological assumptions made by twinners that demonstrate why multiple definitions of digital twins and expectations about what digital twins can do as boundary objects are possible, each with performative effects on the physical and virtual states of wind energy.

First, definitions of digital twins as a boundary object are constructed based on assumptions about the meaning of the concept of a ‘digital twin’ to each individual expert and based on what a digital twin in the domain of wind energy should represent. Most experts argue that digital twins for wind energy should represent existing wind turbines, or their components, and should ideally show

how a virtual twin of a physical turbine interacts with its environmental conditions in a landscape. Others argue, however, that digital twins can be used during the design phase, to virtually represent wind turbine prototypes, for example of new wind turbines, and to simulate their performance. This distinction is seen to be important for experts who think it is incorrect to use the label of digital twin for simulations of wind turbine prototypes because simulations do not include data from in-field measurements nor real-time data that is being fed into a twin but existing data sets that offer an approximation of real-life conditions. As a result, a digital twin that is a prototype may be deemed objective but not a twin of reality, while digital twins of existing wind turbine or wind park tend to be portrayed as mirror of reality.

Second, digital twins are boundary objects in that their degree of dynamism is negotiated by twinners. Among experts interviewed there was consensus that digital twins cannot be static representations because they need to change in step with their physical twin. They argued that dynamism distinguishes digital twins from other types of simulation or modelling. We found a shared ambition among the experts to increase the dynamic capacity of digital twins by feeding in real-time data across a range of parameters, such as changing atmospheric conditions or noise annoyance. However, several experts interviewed recognised that it is difficult, if not impossible, to meaningfully cover the complexity of social and environmental aspects of a given wind energy system in real time, including how people feel about wind energy or how different species or ecosystems are impacted by it. One of the experts said that making too much complexity in modelling can create vulnerabilities, arguing that "the more complicated the system becomes to monitor something, the more likely it is to fail because if one part of that system fails, then the entire system fails". Nevertheless, digital twins as boundary objects are mostly expected to be as dynamic as possible as complexity of modelling affects the degree to which these virtual representations can be seen as 'twins' on all the aspects of 'reality'.

Third, digital twins are boundary objects because their purpose is being actively envisioned and negotiated in the context of a twinning project. For example, for wind turbine manufacturers, or other private actors, the purpose of digital twins is most often determined by a demand for overcoming technical challenges in wind energy, mainly focusing on upscaling wind turbine size or economic optimisation of wind farms. On the other hand, for social or environmental researchers, the most relevant purpose of digital twins is to simulate and better understand social and environmental issues of wind energy (e.g. visualising wind farms and reducing noise, shadow flicker and bird strikes) and to adapt the design and/or management of wind turbines. We found that when digital twins enable action on these issues, they become a relevant tool for policymakers and planners who want to better visualise and communicate wind energy plans and designs. In this way, digital twins can act as boundary objects that coordinate the activities of actors from different disciplines and bring different stakeholders of wind energy together. Even though digital twins as boundary objects bring different actors of wind energy together, in the following section, we also show that the constellations of actors involved are also a function of boundary work.

3.5. Boundary work in digital twins: inclusion and exclusion

Our findings also demonstrate that the process of twinning is not simply one of mirroring reality. It is a process of creating new, parallel versions of reality that represent ideal visions of the wind energy sector held by expert twinners, which in turn affects how social, spatial and technical concerns are conditioned for the purpose of decision-making. What is included and excluded from these digital twins depends on (1) decisions on the data, models, concerns and regulation that determine which different aspects of 'reality' are digitalised and how, and (2) the degree to which expert and societal actors influence these decisions.

3.5.1. Negotiations over data, models, concerns and regulation

We found that expert decisions on what is and what is not twinned are dependent as much on (1) the perceived importance of different matters of concern and regulation and (2) expert visions on the function and future of wind energy landscapes, as it is on (3) the availability, selection and alignment of different data and models. Together this combination of how different aspects are valued, and prioritised, future visioning and data handling reflects the implicit assumptions held by expert twinners over which 'desirable' states or landscapes are digitally twinned.

First, we found that expert decisions on what is included or not in the digital twin environment rests on experts' ideas about the importance of different matters of concern and the regulations governing them. This can be illustrated by decisions made by twinners on turbine noise. While most experts argued that noise can be objectively measured, a subset of respondents expressed doubt about the legitimacy of noise as a dominant societal concern, arguing that there are other (more) relevant matters of societal concern such as shadow flicker or the extent to which local communities are invited to financially participate in wind energy. In addition, several experts argued that the high variation in how wind turbine noise is regulated at both national and sub-national levels further complicate decisions on whether to twin noise or not. The more complicated concerns such as noise become, the greater the chance that twinners will seek to either simplify or exclude them from digital twins. It is then important, one expert reflected in context of his own project, that the outcomes of modelling might not be applicable globally, as in different countries, one is likely to include different maps, select different criteria, and rate them differently.

Second, expert decisions on what wind park data (geolocation, landscape morphology, built environment) are and are not twinned are dependent on visions and assumptions for the performance of wind energy in different landscapes. For example, both the manufacturers and wind energy experts interviewed favour the development of digital twins for offshore wind energy. This is because, they offered, offshore wind farms tend to yield higher financial returns because of the economies of scale from high-capacity wind turbines. Digital twins of these offshore wind farms enable increased efficiency in design, planning and management which in turn justifies the cost of developing the digital twin in the first place. This optimisation logic in turn affects what kinds of matters of concern are twinned, with offshore locations often assumed to have significantly fewer 'social' issues. The consequence of these explicit and implicit biases to offshore wind energy is that fewer digital twins are being developed for onshore wind energy, which means less knowledge and innovation is likely to emerge for onshore sites and technologies.

Finally, all expert twinners interviewed consistently reported that the material, social or environmental aspects of 'reality' included in a digital twin are determined by availability, selection and alignment of different data and models. As one expert explained, a lack of data means "there are limits in terms of things that you can measure", which in turn means that "your digital twin will be blind in this area. Maybe you can do some estimations, but you will never have a chance of matching these estimations with reality". However, available data also affects twinning. 'Noise' data are commonly included in digital twins precisely because it is easily measurable and, as such, readily available. There are also different kinds of noise data available at different spatial and temporal scales of noise propagation, which increases the choice experts have on the kind of noise data they can integrate into their digital twins. Ultimately, most experts did not see data availability as a major issue for the technical aspects of wind energy systems given such data tend to be precise. However, it is the ability to accurately measure and fairly represent the social and environmental aspects of a wind energy system that is often beyond the scope of most twinning projects.

3.5.2. Twinning experts, stakeholders and their stakes

The twinning teams and their actions and decisions draw boundaries around whether and how the concerns of stakeholders, users, policymakers are included and excluded from digital twins. We found that how twinning affects design and management of wind energy is determined by who is directly involved in or can contribute to twinning. We identified three ways in which the agency in twinning is affected: (1) by whom the expert twinners are, (2) the role of wind turbine manufacturers, and (3) which experts or actors are excluded from twinning.

First, we found that teams of experts in twinning projects differ in their composition and that this composition is strongly influenced by the scope of a wind energy system being twinned. Furthermore, while wind energy systems in landscapes interact with both social and environmental systems, many of the twinning problems are framed as technical and thus as requiring expertise on wind energy technology. For example, the technical expert twinners often provide expertise on material strength of wind turbines, wind turbine physics and dynamics, acoustics and noise, atmospheric modelling and on twinning itself. We found that, which experts are involved in part depends on which components of wind turbines, what types of wind turbines and which physical and social environments are twinned. When social and environmental issues are included, experts on public acceptance and environmental impacts are also being included. As the number of parameters increases, the demand for interdisciplinary collaborations has also expanded. These collaborations are seen as a positive trend that can enhance how twinning identifies different kinds of issues and consequently different kinds of solutions.

Second, we found that wind turbine manufacturers not only participate and benefit from twinning; they also may affect which kinds of wind turbines are being twinned and for what purpose. Their position is observed to be lucrative. As twinning project managers reported, collaboration with manufacturers can be decisive in securing (EU or national level) research funding. This collaboration can affect the properties of wind turbines being twinned, not only because of direct commercial interest, but also because of concern about intellectual property rights over patented wind energy components. In addition, the declining number of wind turbine manufacturers, due to industry consolidation, makes it increasingly difficult to ensure diverse collaborations. The majority of our respondents observed that digital twins become an exclusive domain of large and established manufacturers. Nevertheless, twinning technology is still used beyond the mainstream. For example, twinning is also used to develop niche wind turbines, such as vertical-axis turbines for urban applications.

Finally, the exclusion of certain experts from twinning projects shapes the potential that digital twins have for governing wind energy. The exclusion of any kind of expertise from twinning was not found to be viewed by expert twinners as a limitation, but it was commonly rationalised in terms of being out of the scope. While technical experts are seen as ‘necessary’, social or environmental experts are often considered optional partners. However, anticipating that concerns about marine environment will increase as wind energy moves offshore, one of the experts argued the importance of expertise on marine life to be included in future twinning projects to account for the potential impact of wind turbines on fish and birds' populations. Such expertise is particularly important, this respondent stated, because of the proliferation of wind turbines as floating structures and the uncertainty surrounding how these structures interact with and affect the marine environment. In twinning, such proactive accounting for public concerns is possible, but for matters of societal or environmental concern to be included, one of the experts argued it is up to the societal actors and policymakers to demand or to make compulsory that certain aspects, for example bird collisions, are always taken into account.

3.6. Discussion

Our results demonstrate the broad range of decisions made in the process of twinning that hold consequence for which experts and matters of concern are included and excluded in digital twins. These decisions, we also show, in turn hold consequences for what digital twins can do and for whom. It is this decision-making, we argue, that highlights how twinning constitutes an active process of design in which boundary work of inclusion and exclusion has broader implications for both the ongoing management of operational wind farms and for the future of wind power.

Based on our results we now we reflect on how twinning, as a process of co-production, produces and reinforces existing ways of knowing and ordering society around technological innovation (following Jasanoff, 2016, 2018). We do this by arguing that there are at least five areas in which twinning as an act of governance already holds socio-material implications for wind energy transitions (summarised in Table 1). Together they demonstrate possible implications of knowledge-production through twinning and how twinning of wind turbine technologies is used to solve problems and steer developments in wind power.

First, twinning is an act of governance because it can steer the way in which the physical counterparts of a twin are designed by prioritising some issues related to wind energy in its design process and excluding others. This becomes tangible when twinning is used to design new wind turbines and for that it includes and predicts social or environmental impacts of new wind turbines. To do this, twinning tends to steer digital twins to act as calculative devices (Callon & Muniesa, 2005) by prioritising quantifiable and institutionalised concerns such as noise. By doing so, twinning emphasises and legitimises such quantifiable concerns, establishing specific threshold levels of wind turbine noise as a benchmark for public acceptance. Aligning with prior research (Wolsink, 2018), we argue that there are many other factors that influence issues like annoyance, acceptance or perceived sustainability of wind energy, depending on what is being measured and included, where, when and how. Thus, while including noise data could be seen as a way of internalizing public concerns into design of digital twins, we recognise that including or excluding other societal and environmental aspects may shape wind turbine designs in different ways.

Second, twinning is an act of governance as twinners have agency over what data is used, which has a range of implications for both future and existing wind energy infrastructure. In digital twins developed for wind turbine innovation, expert twinners select datasets that represent wind turbines of their interest and often opt to align twinning choices to optimise the design for increasing wind turbine size and efficiency. Through boundary work of twinning, expert decisions about design (e.g. of wind turbine prototypes) are legitimised and embedded in the broader narrative of upscaling wind energy infrastructure to achieve the energy transition. There is as such a possibility that twinning may marginalise alternative movements in the wind energy sector, for example smaller wind turbines (Wade et al., forthcoming). In cases of digital twins developed for existing wind farms, there is a reason to caution about how twinners gather, select and use data for twinning, as this may raise ethical challenges around privacy and data ownership (Jones et al., 2020; Wagg et al., 2020). With only few wind turbine manufacturers left who can afford to develop digital twins, attention is needed on how this dominant position and leadership in twinning enables control over data ownership in twinning.

Third, governance by design is present in the twinning process as twinners affect the extent to which digital twins can invite or discourage societal actors to be involved in decision-making about both physical and virtual counterparts of a twin. By inquiring into processes of setting boundaries, we have been able to better understand what kind of public concerns are digitally represented in the twinning process as well as to inquire about the weight of these concerns in digital twins. Even though we found that societal actors are commonly excluded from the twinning process, we argue that there are areas in which twinning could contribute to inclusiveness of different publics and their concerns about wind energy (Pesch, 2019). Depending on the stage at which a twinning process may be opened to societal actors, digital twins could either limit or facilitate public engagement. For example, including a wider range of societal actors in twinning than currently is the case could enable a space for public input on the management of wind farms. Such an approach could yield new insights about how to adjust operation of wind energy; for example, minimising bird strikes by using sensors to switch off wind turbines (Desholm et al., 2006), or by improving the aesthetics of wind turbines by incorporating data on people's design preferences.

Fourth, twinning as an act of governance can be observed in the affordances of digital twins as boundary objects, as they can open up or close down how decisions about where to locate wind energy are made and how wind energy landscapes look like. While we found that landscape data are selectively included in twinning of existing wind farms, multiple assumptions about potential and desirable locations for future wind farms are made – with a bias to offshore development. Furthermore, as digital twins commonly do not include visualisations or dynamically represented landscapes, it is not possible to observe or evaluate a twin of a turbine in its bio-physical environment, experience how landscapes change over time and how nature is impacted by wind energy. The limitations related to virtual representations of landscapes, in turn affect the value of twinning to address landscape-related challenges. In the longer term, this exclusion may lead to a 'blind spot' for consequences of wind turbines on landscapes. This is why we argue that digital twins should take dynamic interactions between technologies and their surroundings into account, including soil, landcover, birds, bats and other elements of natural landscapes (cf. Mercier-Laurent & Monsone, 2019).

Fifth and lastly, twinning is an act of governance because it is expected to produce objective evidence for wind energy policy and management. This expectation may however be elusive, as digital twins, seen as boundary objects, are not merely 'equivalents' that 'mirror' the social, technical and material systems they mean to represent, and hence should not be automatically assumed to be objective. Rather than being 'innocent' or 'mundane' objects, they have performative effects on the transition to renewable energy, which need to be explored further. Despite Big Data and advancements in modelling techniques offering increasingly accurate representations of complex socio-technical systems, we concur the finding of Tomko and Winter (2019) that "the metaphor of a 'twin' is axiomatically ill-conceived when referring to a replica or a mirror image" (p. 395). This does not mean that twins cannot play a role in decision making but that this demands enhanced transparency over how digital twins are designed and modesty over what can be achieved within their current limits. It is also important that policymakers understand these limitations of digital twins and recognise the aspects for which they can and cannot offer clear insights. Twinning processes in this way should be understood as a function of boundary work, with digital twins as a prism of the time and place reflecting the twinning process, rather than 'virtual reality'.

Table 2. Twinning as an act of governance: Five areas in which twinning holds socio-material implications for wind energy transitions

	Five acts of governance	**Processes of inclusion/exclusion (boundary work of twinning)**	**Implications of boundary work**
1	Steering wind turbine design	Prioritising some issues related to wind energy systems in turbine design process and excluding others	Emphasises and legitimises quantifiable concerns
2	Use of data by twinners	Twinners including/excluding data to be used in boundary object/digital twin	Co-producing future and existing wind energy infrastructures
3	Facilitating or constraining public engagement	What kind of public concerns are digitally represented in twinning process and how they are weighted	Impacts how and whether societal actors can be involved in decision-making about wind energy infrastructure
4	Opening or closing down decision-making about siting of wind energy	Simplification of data, e.g. reducing landscape-related challenges	Co-production of wind energy landscapes, including unintended consequences of wind turbines on landscapes
5	Legitimising evidence for wind energy policy and management	Selecting 'objective' parts of reality to be mirrored	Potential contestation such as social opposition from prioritization of certain parts of reality and overlooking their 'political ontology'

Despite the complexity of these five consequences of twinning as an act of governance we remain optimistic about the potential of digital twins to create more inclusive governance of wind energy. Digital twins reconfigure the socio-technical-environment interfaces and open up possibilities to think about how it might support ambitions for "designing otherwise—in locations and moments of collective work that address a wider arrangement of humans and technology" (Devendorf & Rosner, 2017). But for this potential to be realised, we caution that attention is needed to how twinning, as a process of boundary work, re-produces framings and categories of experts and expertise, and in doing so define who and what is included as legitimate stakeholders and matters of concern (Henderson, 1991; Latour, 2004). Following Wolsink (2018) we also caution against objectifying public concerns about wind energy in a way that reduces their situatedness. While simplifications and black-boxed framings of reality are necessary in order to make sense of the world around us and to make knowledge actionable (Callon & Muniesa, 2005), it can also lead to the exclusion of non-quantitative concerns. This too limits inclusion of actors and their concerns in twinning and can play a direct role in producing controversy (Kirch Kirkegaard et al., 2020; Labussière & Nadaï, 2014). This argument has been also put forward in the emerging scholarship on the software algorithms (e.g. Gillespie, 2014) and other digital tools (Kirkegaard, 2015; Kirkegaard, 2018), arguing that these are "not just mundane, technical, or scientific artifacts, but also become political as they perform multiple controversies of a scientific, technical, economical, and political character" (Kirkegaard, 2015 p.439). A key step to avoiding this is to go beyond the domains of technical expertise to identify and include social and environmental aspects of wind energy, including how they are intertwined with the politics of energy transitions.

3.7. Conclusion

Digital twins have emerged as a popular concept in different domains, including energy, public health and infrastructure, but the understanding of what a digital twin is and how twinning processes work has remained limited. We have explored digital twins as boundary object and through the prism of boundary work, illustrating that the process of their design is an active process of negotiated decision-making about how digital and physical aspects of reality should be aligned. Doing so, our study thus has helped to shed light on 'the becoming' and variable ontology (Callon, 1991a p. 140) of digital twins, relevant also to other (digital) technologies. Showing how these decisions in themselves constitute five acts of governance, this paper adds to the co-productionist stream in the literature asking questions of why and for whose benefit the different types of research and technological invention exist and how they relate to matters of societal concern (Jasanoff, 2016; Kirkegaard & Nyborg, 2020; Macnaghten et al., 2005; Owen et al., 2012).

In this paper, we showed that digital twins are boundary objects in that they coordinate work of different actors in wind energy who develop their own understanding of what a digital twin is and how the virtual reality should look like. We then unpacked twinning as boundary work that includes an active process of design. By unpacking decisions about who and what is included or excluded in twinning and evaluating the assumptions that are built into the twinning process, we showed that digital twins are not just objective representations of wind energy systems. They are instead an artefact of the choices made by experts about what can and what should be made virtual, and consequently on socio-material effects on society and the surrounding landscapes. We find that twinning produces 'situated' knowledge about wind energy infrastructures and their future, and that twinning re-produces and legitimises data-based decision-making and expert involvement in decisions about design, planning and management of wind energy infrastructures. Seen as such twinning does not only contribute knowledge for decision-making, but it is a governance process itself.

For digital twins to contribute to increasing sustainability of wind energy systems in a way that addresses complex, societal, spatial and environmental issues, twinning should deal with a wider diversity of concerns, stakeholders and practices relevant to wind energy infrastructure development. To do so, twinning requires a higher degree of inter- and transdisciplinary boundary work starting at the early stages of problem framing and network formation. We advocate for inclusion of a broader range of experts – in particular, from social science and ecology – to include their perspectives and data on the impacts and performance of wind energy in the social and natural environment. Finally, we also encourage reflection about possibilities for direct public engagement in design of digital twins such as such as citizen panels (Boogaard et al., 2008) or different kinds of technology assessments (Guston & Sarewitz, 2002; Joss, 2002; Rip & Te Kulve, 2008).

Twinning should therefore not only be about what is possible, (e.g. can the size of wind turbines be increased through twinning?) but also on the conditions allowing twinning to legitimately steer wind energy transformations. Drawing inspiration from co-production, future research could focus on the kinds of practices of engagement and deliberation that digital twins can foster, as well as the challenges of data ownership and data generation for twinning. It is also relevant to explore if and how the goals around inter- and transdisciplinary research and innovation (including the new Horizon Europe Framework) (Ingeborgrud et al., 2020) can incentivise twinners to meaningfully involve a broader range of stakeholders and to generate knowledge that addresses societal concerns.

CHAPTER 4

4

Wind energy and noise: Forecasting the future sounds of wind energy projects and facilitating Dutch community participation

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CHAPTER 4: Wind energy and noise: Forecasting the future sounds of wind energy projects and facilitating Dutch community participation

ABSTRACT

This paper presents a case of a digital device - a noise app – employed by a wind farm operator as a response to growing noise annoyance by residents living next to their wind farm in the Netherlands. This noise app communicates predicted sound levels to the residents and monitors their noise annoyance. We analyse the noise app as a digital framing device that governs concerns around wind turbine sound through three processes: *capturing, channelling and managing*. We show how in the process of *capturing*, the app uses a particular definition of 'the public' and construes 'noise' as a matter of concern. We use the term *channelling* to highlight who is involved in the interpretation of the data about annoyance, and how certain conclusions come to be seen as legitimate. Finally, we discuss how in the process of *managing,* specific kinds of solutions are proposed that fit with this problem definition. The framing process of the noise app also leads to unforeseen effects in the form of *overflows*. Particularly, we see that concerned residents develop an expectation to be more actively involved in decision-making around the wind farm, and that residents resort to alternative forms and channels for expressing existing and new concerns. We conclude by reflecting on the broader energy justice implications of digital framing and overflowing in terms of recognition justice, procedural justice, and distributional justice.

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4.1. Introduction

Wind energy takes up an increasing share in the energy system, but wind energy projects often meet local resistance. For residents living nearby a wind project, noise annoyance is one of the main negative and long-term impacts (Doolan, 2013; Haac et al., 2019; Pedersen & Waye, 2007). Concerns about noise may lead to opposition (Pohl et al., 2018), often already during the planning process of projects (Ogilvie & Rootes, 2015). For governments and professional actors involved in wind energy projects, tackling concerns linked to noise annoyance can therefore help to increase local acceptance of wind energy projects (Leiren et al., 2020). A challenge for these actors is how to manage noise annoyance in such a way that the concerns of local communities are recognised, that local communities experience their participation in processes as fair, and that the 'solutions' to noise annoyance are experienced as 'just' outcomes.

To define how much noise is 'acceptable' for communities living near wind turbines, national (and sometimes state or local) governments have established legal limits for wind turbine noise (Dällenbach & Wüstenhagen, 2022). An assumption underlying these limits is that the higher the level of sound in decibels, the more annoyance is reported by local communities (so called 'dose-response' rationale) (Pedersen & Waye, 2007). However, while noise exposure matters, the perception of wind turbine noise may also differ per person (Alamir et al., 2019). According to a study by Haac et al. (2019), noise annoyance is strongly correlated to "subjective factors of wind turbine appearance and self-reported noise sensitivity" (p.1124) rather than objective factors like wind turbine sound level. On top of that, wind turbine sound has been shown to be perceived as 'noisier' than other kinds of sound (Van den Berg, 2009), and the presence of tonal sounds can be experienced as very annoying by some people (Van den Berg, 2021). In general, concerns about wind turbine noise are often a subject of controversy, linked to disagreements within society around what and whose definitions, concerns, and knowledge should be recognised (Nieuwenhuizen & Köhl, 2015; Taylor & Klenk, 2019). In acknowledgement of the various concerns over wind turbine noise, and how they may differ among stakeholders, noise regulations may not be sufficient for tackling and preventing noise concerns.

To better manage noise annoyance, actors in the wind energy sector have started to experiment with participatory tools to communicate with residents about wind turbine sound (e.g. Gawlikowska et al., 2018). In this paper, we analyse a case of a so-called 'noise app' that can be installed on mobile phones. The noise app is deployed by a wind farm operator to manage wind turbine noise produced by a Dutch wind project. It communicates a sound forecast to the local community and enables residents to provide feedback on the level of noise annoyance they experience. The app thus enables real-time monitoring of perceived noise annoyance, which could provide the wind farm operator with a dynamic and contextual understanding of how residents experience wind turbine noise.

Our aim is to examine how the use of this digital device affects how, by whom and in what way concerns about wind turbine noise are governed. We use the term governance to refer to how different actors - experts as well as lay people - steer decisions about how and by whom wind turbine noise should be defined, and how and by whom noise annoyance should be measured and tackled. To understand the role of the app in the governance of noise concerns, we conceptualise the noise app as a 'framing' device (Callon, 1991b) that stabilises concerns by constructing a 'frame' around a specific problem (here wind turbine noise). We argue that the framing that arises from the noise app takes place through three processes: *capturing, channelling,* and *managing* concerns around noise. Through these processes, some (aspects of) noise concerns become part of the frame, while others are excluded. Excluded aspects become 'overflows', understood here as unforeseen (positive or negative) effects or 'externalities' (Callon, 1998). An example of a negative externality would be the emergence of new conflicts around the use of the noise app, while a positive externality would be unexpected benefits for local stakeholders. With this focus, we aim to reflect on the justice implications of using digital devices to govern concerns including, but also beyond, wind turbine noise. In doing so, we distinguish between recognition, procedural and distributional justice (Jenkins et al., 2021). More specifically, we focus on 1) recognition justice in terms of the perceived fairness of how the noise app includes and excludes concerned residents as the 'public' of the noise app; 2) procedural justice in terms of the perceived fairness of how and when residents can voice concerns about noise and participate in wind project operational management; and 3) distributive justice with respect to the perceived fairness of how the noise app redistributes the costs associated with wind turbine noise annoyance.

The paper is structured as follows: In section two, we explain how the theoretical lens of framing and overflowing can be used to examine the role of digital devices in governing (noise) concerns. In section three, we introduce the empirical case of the noise app and describe our methodology. Next, we examine the noise app by analysing the three processes of *capturing, channelling, and managing*, and the overflows that occur in this framing process. We conclude by reflecting on the justice implications of the noise app and describe conditions under which such digital devices can improve public engagement in understanding and managing noise concerns. Finally, we propose an agenda for future research.

4.2. Digital devices, framing and overflowing

To analyse the noise app as a framing device, we draw on Michel Callon's (1998) understanding of framing and overflowing. Framing is both cognitive and physical in nature (Callon, 1998 p. 249), establishing "a boundary [a frame against the outside world] within which interactions – the significance and content of which are self-evident to the protagonists – take place more or less independently of their surrounding context" (Goffman, 1971 in Callon, 1998 p. 249). Framings help to stabilise networks around matters of concern as they qualify which definitions and evidence count and which actors can legitimately participate (Breslau, 2013). Overflows are the unforeseen effects of all those things that could not be contained within the frame, as framing always involve inclusion and exclusion processes (Callon, 1998). In the context of energy projects, Pesch et al. (2017) have argued that with any energy project, framings will be contested and lead to overflows. As they argue, "overflowing is not a negative side-effect of energy projects, or […] evolves from bad management. Overflowing is inherent to decision-making on energy projects. Energy projects and systems involve a wide range of uncertainties that are not only technological, but also social and normative and that play out on different geographical, jurisdictional and temporal levels, as such increasing complexity and creating tensions" (p.832). In addition, a study on energy controversies by Cuppen (2020) shows that if the dominant framing solidifies a particular definition of an issue at stake, alternative interpretations might be marginalised and become overflows.

To the best of our knowledge, no framework has been developed yet for how digital devices in energy projects act as framing devices, and how this produces overflows. Because the use of digital devices shapes how problems are understood and governed (Kloppenburg et al., 2022), it is necessary to develop an analytically more precise understanding of the framing process. Doing so will in turn help to reveal the potential justice implications of framings and overflowing (Jenkins et al., 2021; Pesch et al., 2017). We conceptualise framing as an active process that involves decisions about how to translate a matter of concern into the digital realm, including which data to collect, how to analyse this (digital) data, and the type of solutions designed to address the problem at stake. We therefore dissect framing into three processes: *(1) capturing, (2) channelling* and *(3) managing*.

First, framing through digital devices includes *capturing* - an active process of setting boundaries around which aspects of socio-material reality to translate into digital data, and delimiting which actors can legitimately participate in this data collection. Specifically when concerns are translated into (digital) data, the choices about parameters for which data is generated, and how it is digitised often tend to be black-boxed (Rothe, 2017). Processes of capturing in the case of digital devices may thus allocate decision-making power in the hands of those who decide about what is being digitalised in the first place (Korenhof et al., 2021; Solman et al., 2022).

Second, digital devices act as framing devices through *channelling*, which we define as the active process of setting boundaries around how and by whom data is analysed, interpreted, and concluded upon. This process of setting boundaries may align with the interests of some actors more than with those of others. In the context of digital devices, scholars have shown how private actors increasingly own and manage digitalised data. As such, they steer the channelling processes and assign specific roles to other actors and stakeholders (Eubanks, 2018; Kloppenburg et al., 2022; Korenhof et al., 2021).

Third, we distinguish *managing* as an active process of creating data-driven interventions and solutions, and of allocating roles and responsibilities for interventions to specific actors. A key characteristic of this process of managing is the design of solutions that are based on a continuous flow of (real-time) digital data (Coglianese & Lehr, 2019). Such data-driven management therefore increasingly takes the form of real-time or anticipatory decision-making (as in smart grids, smart traffic management) (Bakker & Ritts, 2018; Sadowski & Bendor, 2019; Smale et al., 2019). Together, these three processes constitute the framing process of digital devices. The overflows that may occur are the unforeseen effects of things that cannot be contained in this frame.

4.3. Methods

In 2021, a noise app was implemented at a wind project in the Netherlands. There had been a long-standing conflict over the planning and implementation of this wind energy project and during the operational phase, many residents complained about wind turbine noise. The noise monitoring app was commissioned by and developed by a major consultancy firm in the Netherlands. The aim was to provide noise predictions to residents and collect their feedback on perceived noise annoyance. We (the authors) decided to investigate this case after finding online information about it, and had no stake in the wind farm project nor in the development of the app. To set up a study of this noise app, we contacted the noise app developer and the wind farm operator, as well as local networks and associations to ask if they were willing to participate. In this paper, we do not mention the names of individuals (nor their association) in order to assure that the statements are not directly attributed to specific individuals.

To gain in-depth understanding of the noise app as a framing device, we used a mix of qualitative research methods. We began with analysing documented information about how this app was designed, implemented and used. The key written resources included a webpage of the wind energy project, the app user interface, and additional secondary material including a podcast and a documentary. Next, the first author visited the area for observations and informal conversations, and identified relevant respondents for interviews, which was done via purposeful and snow-ball sampling (following Suri, 2011).

The first author of this paper conducted 25 interviews with stakeholders, including 10 residents of four villages located next to the wind project, one expert involved in the development of the noise monitoring app, two wind farm operators, three noise- and one digitalisation expert, one local journalist and seven representatives of various interest groups. The sampling strategy for respondents differed per stakeholder group. The experts (all the professional actors) were contacted directly by the first author with an interview invitation. To interview residents concerned about noise, the first author contacted a community representative who reached out to the concerned residents and asked if there were any who wanted to participate in this study. A few residents offered to participate and also suggested other residents. This sample of concerned residents was complimented with residents in the wind project area that the first author met randomly when visiting the area. This means that the focus in sampling was mainly on understanding the perceptions of concerned residents rather than those who are not annoyed by wind farm noise. Consequently, this leads to a limitation, since we were not able to account for how the residents who are not annoyed by wind turbine noise perceive the noise app and how they prefer the problem of noise annoyance to be tackled. We used semi-structured interviews with residents and professionals to at understand how the app was used to engage residents in the governance of noise concerns, and to also leave space for aspects that the respondents considered important.

The interviews were transcribed, or alternatively summarised in written form (if they were not recorded or - if recorded – included repetitive or irrelevant issues for the present study). Afterwards, interviews were coded inductively in the Atlas.ti software through open coding. As a next step, these open codes were grouped into themes and categories based on concepts from our theoretical framework (Gibbs, 2007), that is, the detected processes of capturing, channelling, and managing in framing and overflowing. The complete list of codes and themes can be found in the *Appendix 3*. This analysis was accompanied by simultaneous reflection on whether the information was relevant or if there was some information missing (Belotto, 2018). This analytical approach enabled internal validation of the data (Silva et al., 2014).

4.4. Empirical results: how a digital device captures, channels and manages noise annoyance

4.4.1. Capturing noise as a matter of concern

The noise app offers a novel approach to understanding residents' concerns about wind turbine noise. The app provides noise predictions and allows residents to rate how annoyed they are by the actual noise of the wind farm in their surroundings. In the Netherlands, the legal norm is 47 decibel Lden (a yearly average during the day, evening and night) and 41 decibel Lnight (average sound level during all nights of a given year). These noise limits determine how a wind farm is operated to control noise produced by wind turbines. As long as the wind turbines do not exceed these yearly norms, the noise is considered to be 'normal'. However, by implementing the noise app, the wind farm operator acknowledged that there was a possibility that wind turbine sounds can be annoying even when these norms are not exceeded. The wind farm operator explained that with the noise app, they went beyond what is expected from them based on the noise regulations: "*We did not implement the app because we had to, but because we wanted the best way for the local people.*"

The noise app provides sound forecasts tailored to individual addresses in the area. Based on variables such as local weather and background traffic noise, the app provides a 48-hour sound forecast. According to a noise expert involved in the development of the app, providing wind turbine sound forecasts may increase acceptance for the given wind project:

> *We try to show people what is really happening, because we see a lot of distrust (...) usually when people can hear the wind turbine better, they think the wind turbines are making more noise. But that's not always the case. Sometimes it's the atmosphere that causes that the noise can propagate more easily. So, they hear more noise, but the wind turbine itself makes the same noise. With the app we can now provide that insight, you'll also get insights into energy production. So, people understand also the benefit of the wind turbines. And if we give more insight, create more understanding, the social acceptance will grow. (App developer)*

The noise app provides a sound forecast expressed in A-weighted decibels (dB(A)) (i.e., which weights the sound as heard by the 'average' human ear). In addition to viewing these forecasts, residents can submit information about perceived annoyance on a 7-point scale of sound levels. Each level is represented by a bar. The bars range from dark green to red, starting with dark green indicating sound levels lower than 30 dB(A) and ending with red, which indicates sound levels between 46-48 dB(A). The residents can submit the feedback about noise annoyance in real-time by clicking on one of the seven bars, as well as through a written message. The wind farm operator and app developer contended that the noise app thereby provides a dynamic understanding of how residents' perceptions of wind turbine noise vary on different moments and may change over time.

As the noise app was developed to better understand the peculiarities of noise annoyance at the local level, the wind farm operator needed to define the geographical area for which they wanted to provide predictions and collect feedback. They chose to limit the area to 2km around the wind project. One noise expert providing advice on wind farm operation found such spatial demarcation logical, explaining that "from a practical point of view, there should be a limit to where you assess effects" (Expert on wind turbine noise). Through collecting feedback from these local residents, the aim was to find out why and when wind turbine sounds are annoying (and hence when sound becomes constituted as 'noise'). The noise app would also help to understand complaints about low frequency noise, including a specific low frequency tone that respondents referred to as the 'hum'. According to a local noise expert, this low frequency tonal sound should not be occurring at all, as it is a sign that the wind turbine was not working properly. By enabling residents to provide feedback whenever they wanted, the idea was that the app would also help to get more insights into this 'hum'.

4.4.2. Channelling noise concerns by interpreting the feedback

In the next phase of the framing process, channelling, boundaries are set around who can analyse and access the data about noise annoyance. To enable analysis of the data, data handling protocols and agreements had to be developed. The consultancy firm that developed the app became responsible for running the data analysis by coupling the data on perceived annoyance with data such as respondents' location, wind direction, background sounds and sound forecasts. App users need to accept privacy policy, stating that the feedback data are processed and stored by the consultancy firm and the results are shared with wind farm operator, residents and other stakeholder. This privacy policy also stated that the feedback could not be traced back to individual users and would not be shared in raw form with others. In practice, this meant that the app developer regularly communicated the results in the form of (graphical and anonymised) reports and charts to the wind farm operator who in turn discusses the results with representatives of the local community. For some residents, however, using the app had generated the expectation that they would be involved in the interpretation of the data, and they expressed a desire to have more access to the data.

The results of the analysis were presented to various stakeholders, but in different ways. For the wind operator, a dashboard was developed that allowed them to monitor the sound levels and the feedback on annoyance in real time:

> *"[to communicate the results] we developed a dashboard for the wind farm operator, so that they can see the feedback from residents in real time. The dashboard presents results of automatic analysis. So, we give the wind farm operator insights into how the feedback from the residents relates to the distance of the wind farm, to the orientation of the wind farm, to the wind speed and direction and to the power production of the wind turbines". (App Developer)*

For the local residents, general insights were presented verbally in meetings with a few community representatives. The wind farm operator stressed that their intention was not to be secretive about the results; on the contrary, they explained they wanted to be open and to create a dialogue with the residents. At the same time, they considered a dashboard with restricted access the 'safe' option that would prevent misinterpretation of the results by the local community. This approach to data analysis, ownership and accessibility underscored the continuation of pre-existing conflict, negative sentiments towards collaboration and mutual lack of trust between some residents and professional actors involved in wind farm operation.

4.4.3. Managing concerns by findings solutions

How are these results about noise annoyance translated into wind farm operation and management strategies? The results from the data analysis showed that wind turbine noise, including the hum tone, was most annoying at night. On this basis, the wind farm operator decided to slow down rotation of the turbines during particular nights when weather conditions were expected to create high noise annoyance. Reducing the rotation at some nights was a voluntary initiative of the wind farm operator. In doing so, they went beyond the legislation-based approach that prescribes action only when the noise limits are exceeded. A while after this new management strategy had been implemented, the wind farm operator noticed a decrease in the amount of feedback submitted through the app. This led them to conclude that people were less annoyed by the sound of wind turbines. Interestingly, the wind farm operator said that at that point, they could identify those people who always complain:

> *"When we started off in, say, January, and then you see until April, we didn't pull the power back, then you see a lot of complaints, then we pulled the power back at night. And then you*

> *see you see that the complaints were getting down. And now you see only complaints from people who are complaining always. So, they can't accept that the wind turbines are there. So, I think it's about five people or something. So, you know, you can't satisfy everybody*". (Wind farm operator)

The operator concluded there is a need to accept that some people will always remain annoyed, regardless of interventions taken.

In this step of managing, responsibility for the problem of noise and for the solution was allocated to the wind farm operator and wind turbine manufacturer. According to the wind farm operator, the hum was a problem in the software of the wind turbines, and the wind turbine manufacturer in response updated this software. While decreasing the noise through a software update was one type of solution, another type was 'managing annoyance'. The wind farm operator viewed the app as a management solution on its own because they could use it to be a 'good' neighbour to the local community:

> *"When people are complaining, it's not okay, so together with a producer of wind turbines, we try to reduce all nuisance there is. That's why the app is so good, because you can continuously measure if people are satisfied or not".* (Wind farm operator)

For the app designer, the app was a tool for management of noise concerns because it engages residents on the issue of wind turbine noise and enables expectation management. Furthermore, while the wind turbine operator was satisfied with the amount of feedback they received through the app, they also noticed that some app users did not report any annoyance at all, and that there were people living within the geographical range of the app who had never installed the app. This group of residents was recognised by the wind farm operator as a 'silent majority' whose experience of noise annoyance was not captured but would be a valuable addition in understanding the problem.

4.4.4. Overflows: that which isn't captured, channelled and managed

Above, we have shown how the noise app produces a particular framing of noise-related concerns in the way those are captured, channelled and managed. In doing so, this framing is inevitably accompanied by overflowing in the sense that unforeseen effects occur.

4.4.4.1. Overflows in capturing

As residents started to make use of the app, it became clear that the app's definition of noise on a scale of different sound levels expressed in decibels (dB(A)) sometimes mismatched with their subjective experience of noise. In general, residents were most annoyed by the presence of the low frequency tone that we referred to above as the 'hum'. A common remark that residents made was that it was difficult to locate the source of the hum, which appeared to be omnipresent and stable. One respondent described the hum as "a heavy, industrial sound. As if you stand in a room with heavy machinery" (Resident [7]) and another said it sounded "as if there was a truck stationing next to your house, with a running engine" (Resident [10]). Because the rating scheme with the seven bars did not explicitly include the hum tone as a category, some app users were concerned that this specific experience was not recognised. A local noise expert explained that the assumption foregrounded in the noise app is that annoyance grows with the level of dB(A), but that this might not hold in case of the hum. This is because, he explained, at this specific wind farm, wind turbines produce most hum at lower wind speeds. While higher wind speeds make the turbine blades rotate faster, sound generated by the movement of blades is likely to be experienced as less annoying than the hum tone. Ultimately, this ambiguity around if and how the hum was included in the noise app became a subject of concern on its own.

Some residents asserted that the noise app did not take into account the inconveniences around providing feedback at night. That is, the app encouraged people to provide real-time feedback about annoyance, but many respondents found the wind turbine noise most annoying at night, when they are not willing to use the app:

> *"When I got it [the app], I checked it and it was written that you have to indicate when exactly you are annoyed by the noise. For me it is almost always at night. You don't think I will use this app at night?! (…) I sent an email, in which I said: this is a one-time message, in which I indicate that I suffer day and night and that I am not prepared to send feedback that I am annoyed every night. This bright screen would be one more disruption to my night rest".* (Resident [2])

Moreover, while the noise app captured noise annoyance as a concern, it did not recognise people's concerns about the impact of noise annoyance on health and well-being. We found that health impacts in particular worried the local community, and this also became a subject of controversy. To come up with evidence for health impacts, a group of residents established a noise group who consulted and hired their own noise experts to undertake noise measurements and to provide alternative evidence about the negative impacts of wind turbine noise on health. The noise experts that we interviewed, however, generally agreed that scientific evidence for the residents' concerns was lacking. One expert mentioned that concerns about wind turbine noise might be an expression of opposition by people who are fundamentally against wind energy:

> "*They are almost professional opponents of wind energy, they come up with all kinds of publications about how devastating their low frequency sound is. Because that's where they found something they can use in the opposition*". (Expert on wind turbine noise #1)

A final example of overflows is connected to the spatial demarcation of the area in which the app could be used. Only residents living within 2km distance of the wind farm were able to submit their feedback via the app, which means that potential complaints from outside this area were not captured. Several residents asserted that this meant the noise app failed to include everyone who could be affected by noise. Some people found other channels for submitting their complaints, for example per email or phone directly to one of the wind farm operators or to the municipality. Most commonly used and trusted by the residents was the email address of the local association of residents, which received complaints from both people within and beyond the 2km radius. According to one respondent, this provided proof that the impact of wind turbine sound was found far beyond the area that was recognised with the app. Hence, overflows linked to the active process of capturing by the noise app were found to occur because of the reliance on expert-based definitions and strict spatial demarcations, both of which were contested by alternative knowledge claims made by residents.

4.4.4.2. Overflows in channelling

The noise app channels the data analysis in such a way that conclusions about annoyance are drawn by one actor group in particular: the noise experts. As a result, the residents felt left out of this process. A representative of the local community explained this as follows:

> *"I am also wondering, how can I get some insights about the data that is gathered by the app, why don't they share the data? We do have people in the community who could interpret the data. I also do this for my work. I also wonder what they think about the data that they receive".* (Community Leader)

While the results of the analysis of app data were regularly shared with the wind farm operator and wind turbine manufacturer, some residents also wanted to be informed:

> *"It would be great if they could make a report in which they would describe what the status quo is around noise, how many complaints were submitted and what they have done with them [...] For example, if they send a flyer around the village twice a year with information about the app and its results, this will give us a much better feeling"*. (Resident [7])

Based on the analysis of data patterns over time, the wind farm operator concluded that noise annoyance had decreased. Some residents, however, came to a different conclusion: the decrease in feedback about noise annoyance meant that residents were simply tired of complaining and stopped providing feedback. While the wind turbine operator understood the data gathering and analysis as a long-term activity that would gradually increase their insights into noise annoyance, the residents expected a solution and actions in the short-term:

> *"Some people are willing to use the app, but they want to know when the problem will be fixed. The app gathers data and so there is an expectation for a solution. But it takes so long, and this worries me".* (Resident [7])

Overflows in relation to channelling thus include new concerns by residents over the lack of possibilities to be involved in drawing conclusions based on app data. For the residents, this feeds into pre-existing worries over how the wind farm operator approaches the problem of noise annoyance and seeks to solve it.

4.4.4.3. Overflows in management

When it came to the management solutions that followed from the noise app data analysis, the opinions of residents about who should be involved in designing and implementing these responses were split. Some residents were unhappy about the fact that the wind farm operator was taking decisions about wind farm operation on their own and stated that they as residents should be involved as well. This also led to a new concern about the noise app, namely that it was implemented to legitimize choices of the wind farm operator and was aimed at keeping the wind farm operational. A local journalist said that: "it is also a bit difficult to entrust this app in the hands of wind farm owner because it is in their interest to show that the noise problem is small" (Local Journalist). On the other hand, there were also residents who saw the wind farm operator as a 'problem owner' and thus they expected that a solution would also need to come from them.

A few local residents were concerned that the wind farm operator expected the residents to use the noise app as a tool that would help them to better live with the noise. In general, people had various coping strategies to deal with wind turbine noise, such as sleeping in a different room or house or even moving away. In practice, the role of the noise app in such adaptation practices was rather small as many residents relied on their prior experiences of when and how much noise could be expected under different weather conditions rather than on the sound forecast communicated by the app. Overall, the operator's emphasis on long-term monitoring with the help of the app was rather unsatisfying for the residents who wanted to have a clear timeline for when the problem of noise annoyance would come to an end.

Another matter of contestation was how the feedback gathered through the noise app would translate into specific operational decisions. While the wind farm operator decided to slow down the rotation of the blades at night, the representatives of local communities proposed different strategies. Some people wanted to have the wind farm completely switched off at night. Other people contended that in the absence of any evidence that (low-frequency) noise is unharmful to health, a precautionary approach should be taken in which exposure to wind turbine sounds would be minimised. Such more fundamentally different ideas about noise as a matter of concern directly affected ideas about what is safe, possible, or desirable in wind farm management. Overflows in management were thus found to consist of residents holding alternative visions for wind farm operation that included a much more active and co-managing role for residents. Table 3 summarises our findings of framing-overflowing dynamics in the capturing, channelling and managing of noise concerns.

Table 3: Summary of framing-overflowing in relation to capturing, channelling and managing

	Framing	Overflowing
Capturing	Defining sound levels through dB(A) metric Residents receive predicted sound levels for their location	Mismatch with experiential definition of wind turbine noise; residents focus on the 'hum' and on the impacts of wind turbine noise on health
	Noise concerns captured by gathering real-time feedback on the perceived sound levels; a feedback scale that assumes that the higher the perceived sounds levels, the more annoyance is experienced.	People's concerns about noise impact on health not captured, producing annoyance and uncertainty; Some residents do not want to use app during night-timej6
	Spatial demarcation (2km radius)	Email list that gathers complaints from area beyond 2 km
Channelling	Protocols for using data provided by the residents (privacy statement) and proprietary data agreement with wind turbine manufacturer	The local community felt they received too little information about the results and expected that the data would be shared
	Closing down and objectifying the process of analysis (automatic analysis and interpretation by wind farm operator and app developer)	Sparks 'citizen science' – noise group formed to research the impacts of wind turbine noise, commissioning own noise measurements, and consulting alternative noise experts
	Continuous, interactive process of analysis: the more data from the residents gathered in the future, the better understanding of noise annoyance	Residents expecting more immediate solution and a time-bounded strategy
	Possibility to see the results of feedback provided by the residents in real-time: how many complaints there are	It is not known why people provide or stop providing feedback
Management	Solutions are sought together with wind turbine manufacturer	Closes down the possibility for the residents to propose alternative ideas e.g. to stop wind farm operation at night
	The noise app enacts noise governance as an ongoing process that requires continuous feedback	Generates expectations about the creation of a timeline in which the problem will be solved
	App as a tool for informing and managing expectations	Leads to contestation of the information that is communicated by the app and how it should be used to manage expectations

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4.5. Discussion

While the existing literature on framing and overflows in energy projects often discusses how framings are constructed by social actors (e.g. Pesch et al., 2017; Ureta, 2017), our paper focuses on how digital devices mediate this process (also following Callon's (1998) focus on the role of technologies and other non-human actors). We argue that looking at framing through the three processes of capturing, channelling and managing enables us to understand how digital devices frame issues and create overflows. While the processes are analytically distinct, they need to be understood as entangled because they impact each other. *Capturing* will shape the process of *channelling* by defining what kind of concerns are relevant to analyse, and thereby whose expertise is deemed relevant for data interpretation. In turn, the outcome of the analysis in the channelling process will be acted upon in the *managing* phase, providing governance solutions tailored to the framed problems. In combination, the three processes - *capturing, channelling,* and *managing* - thereby construct both the 'problem' and its 'solution', and at the same time produce 'overflows'. Analysing the noise app from the perspective of framing and overflowing brings to the fore the justice implications of using digital devices for public engagement in the governance of (noise) concerns. Using Jenkins et al.,(2021) three tenets of energy justice, we can evaluate the *recognition, procedural, and distributional justice* of the noise app. Recognition justice is about who is ignored or misrecognised, procedural justice asks the question about fair processes and participation in decision-making, and distributive justice considers how and where the costs and benefits are distributed (ibid).

First, the use of the app has implications for who is *recognised* as bearing the burdens of wind energy projects, and whose concerns are considered legitimate. In line with Felt and Fochler (2010), we argue that experts who design tools and processes of participation affect whose voice and stake is recognised. By introducing the app, the wind farm operator and developer recognise that residents can experience noise annoyance even when the noise limits are not exceeded. At the same time, specific groups and individuals that are unable or unwilling to use digital devices are not recognised. In addition, the noise app can only capture feedback about noise annoyance within a 2km area around the wind farm. It thereby fails to acknowledge experiences of noise annoyance beyond this restricted area. In the channelling phase, the app allows to categorise residents according to their user-behaviour with labels such as 'people who always complain', 'the silent majority' or 'serious app users'. While the term 'the silent majority' is more commonly used by policymakers and researchers to refer to people who do not report any annoyance to wind turbine sound (Haac et al., 2019), the other two terms are new and specific to the noise app. Referring to specific groups as 'people who always complain' is an example of misrecognition of the concerns of these people, categorising these people as unwilling to collaborate with the wind farm operator and app developer.

Second, the noise app affects procedural justice through changing how and when residents can provide input to and participate in decision-making about wind turbine noise. The app in general fosters participation of local communities in wind energy projects because it creates a new channel for information exchange between the wind farm operator and local residents. By voluntarily disclosing information about the negative impacts of wind turbines (that is, providing sound forecasts), the operator can be said to improve procedural justice in the operation of wind farms. Ultimately, however, we argue that this digital device organises participation around a scientific and expert-based definition of noise, rather than opens up alternative ways for residents to express their own interpretations of 'the problem' at stake. Moreover, the app does not provide space for residents to voice a more diverse set of concerns such as impacts on health, which is then manifested in overflows. While the residents had an active role in providing feedback via the app, they did not get an active role in the analysis of the data or in proposing solutions. A lack of participation in the management decisions tends to lead to more opposition and to make residents search for new ways to adopt or resist these decisions. For instance, the introduction of sensor-based obstruction lights in Denmark has caused residents to find strategies to adapt to the technology-based solutions rather than to collaboratively develop solutions (Rudolph et al., 2017). At the same time, the app – deployed as a management solution – assigns the public with the responsibility to provide feedback in order for the operator and developer to listen to the public's concerns. The noise app did help the developer to go beyond what is legally required from them based on the Dutch noise limits, and thus was an attempt to overcome structural injustices (Elmallah & Rand, 2022). Yet, in practice, the implementation of the noise app generated new concerns about fairness and engagement in the process of data interpretation and operational decisions.

Third, in terms of distributive justice, the implementation and use of the noise app diminished the local burdens associated with wind energy projects to some extent, as the operator adjusted its operation in response to annoyance. Traditionally in governance of noise concerns, intervention is only expected and enforced if noise limits are exceeded in a given area (Dällenbach & Wüstenhagen, 2022). Meanwhile, the digital device created expectations among its users for more responsive operation of wind turbines. Some residents hoped that wind turbines would be switched off entirely when high levels of noise annoyance are reported, for example at night, or called for a precautionary approach. The specific siting of wind energy projects by definition makes the distribution of burdens of wind energy projects unequal, disproportionally affecting people who live in the surroundings. Our case shows that adaptive operation of wind turbines can contribute to a sense of justice, but that the use of the app could also lead to new distributional justice claims from local communities.

How can digital devices for public engagement be used to create more just processes and outcomes in the governance of burdens of the low-carbon energy transition? We argue that by not pre-defining the solutions, and opening up to alternative views of the local community on the issue at stake there is a better chance for increasing the different kinds of justice (Jenkins et al., 2021) in the future. When local communities choose to continue resisting both wind energy projects as well as the solutions offered to address their concerns (such as the noise app), it is important to examine the role of framing processes in shaping the problem definition, and thereby also the types of solutions that can be envisioned. Thus, framing may lie at the root of many of today's controversies over renewable energy developments. More research into these underlying reasons for opposition is needed to better govern the energy transition in a 'just' way and to deal with situations of conflict (see also Cuppen, 2018; Cuppen & Pesch, 2021).

One of the ways to deal with ubiquitous overflowing is to acknowledge its existence and to discuss it openly with local communities. Doing so, we argue, can create an open and fair space for the governance of concerns and for developing and facilitating alternative forms of engaging residents. As argued in research on citizen science projects (Freitag & Pfeffer, 2013), the end-product and goal of digital tools such as the noise app should not be the making of a dataset, but rather the very 'process' of collecting data and engaging citizens. In the case of the noise app, this could include engaging small groups of residents in discussions– about noise annoyance and acceptable solutions to this problem in various phases, from the development of the app to the interpretation of monitoring data. Following Ferrero et al. (2018), a role play – in which the roles of different residents, app developer and wind farm operator are enacted by residents - could help to reveal the tensions and understand various positions. This may help to increase empathy amongst different stakeholders and as such help to improve decision-making in case of complex problems. In this way, digital devices can be used to improve participation in decision-making about wind energy projects by providing a starting point to gather and discuss different experiences and understandings of both problems and solutions.

4.6. Conclusions

This paper analysed how a noise app was used to manage noise annoyance experienced by residents living next to a wind farm. We approached the noise app as a digital framing device that shapes the governance of noise concerns through three framing processes - *capturing, channelling, and managing*. Through these processes, concerns are translated into the 'digital domain' in which digital data are used to demarcate and define 'the problem' and to 'solve' it. In this process, boundaries are set around the definition of the problem, the solution and around the roles and responsibilities of different actors such as noise experts, the app developer, wind energy actors, and residents. Because digital framing devices affect which and whose matters of concern or knowledge are being recognised as relevant, or which are dismissed, their use in energy projects has important justice implications. Building on this study, future research could focus on how the quantification of issues may perform a particular valuation of what counts as legitimate concerns. For example, does the use of digital devices (and their workings through algorithms) prioritise easily quantifiable over less easily quantifiable concerns? If so, how can digital devices better recognise concerns that are complex and include lay-people knowledge?

Our paper also showed that this active process of *capturing, channelling and managing* inevitably leads to overflowing, in the sense that unintended side effects occur. Decision-makers need to be aware that overflows are inevitable, and that from a perspective of justice, it is important to recognise what kind of concerns are overflowing. Future research could look into the ways in which overflowing, and in particular alternative forms of engagement such as citizen science, could be used to inform or even reform spatial planning procedures and environmental legislation around wind turbine noise.

Finally, we suggest two areas for future research and policy around the use of digital devices in wind energy projects. First, as prior research (Mulvaney et al., 2013) has shown that acceptance tends to be linked to perceptions of how and whether operational turbines produce financial benefits to the community (e.g. lower energy bills, funds for local development, co-ownership), future research could examine how residents respond to information about power production in addition to the information about sound levels. Second, we suggest exploring ways in which digital devices such as apps could further open up opportunities for local communities around energy projects to voice concerns and to be involved. This could include transdisciplinary research or practices of co-design that support societal actors in posing research or design questions linked to their matters of concern. Further, such research should invite the concerned public to actively participate in decisions about how and where such digital devices are implemented. Wind farm operators who implement these devices could explore or experiment with how such devices can facilitate alternative ways for citizens to engage with their concerns and participate in decision-making, thus doing digitally-enabled governance otherwise.

CHAPTER 5

5

Can acceptance for wind farms be predicted with the help of digital twinning? A case study of the UPWARDS research and innovation project

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ABSTRACT

One of the key priorities in the Research and Innovation Policy of the European Union is to develop green and digital technologies. A growing number of Research and Innovation projects (R&I) projects contributes to design of digital technologies, in particular to tackle challenges in the upscaling of renewable energy. As means to speed up energy transition, digital technologies are designed to address a range of technical, social and environmental challenges in the design and implementation of renewable energy such as wind energy. Despite this important role that digital technologies have in solving challenges of the energy transition, little is known about how these challenges are approached through the design and implementation of digital technologies within R&I projects. To shine light on how design of digital technologies affects governance of social challenges in energy transition, such as the challenge of societal acceptance, this chapter focuses on a case of one such EU-funded R&I project. It presents the case of UPWARDS project to show how experts involved in this projects affect how societal acceptance is digitalised and with what consequences for the governance of the wind energy sector. These insights are relevant for fostering a more just way of addressing concerns voiced by communities about wind energy projects, as well as other kinds of renewable energy, or for other environmental problems for which digital technologies are developed.

5.1. Introduction

How to make Europe greener and more digital are the twin challenges for our generation, and our success in meeting them will define our future.

European Commission (2022)

This statement defines the ambitions of the EU to fund research and innovation projects (R&I) to explore how the digitalisation of energy systems can make energy production greener, more efficient and socially robust (European Commission, 2022). A growing number of such R&I projects contribute to the design of digital technologies (CORDIS, 2022a) and, more broadly, to exploring their potential to tackle challenges in the upscaling of renewable energy (Barber et al., 2022). For example, digital technologies are developed to present different scenarios for the energy transition (Deckert et al., 2020), to enable collaboration on the design of renewable energy systems (Barbierato et al., 2022) or to address a range of technical, social and environmental challenges in the design and implementation of renewable energy such as wind energy (Solman et al., 2022). Despite this important role that digital technologies have in solving challenges of the energy transition, little is known about how these challenges are approached through the design and implementation of digital technologies within R&I projects.

One of the key challenges related to upscaling renewable energy is the challenge of lack of community 'acceptance' (Rhodes, 2020). Commonly, community acceptance is defined as an expression of support from residents and stakeholders for proposed renewable energy projects (Wüstenhagen et al., 2007). However, while community support is crucial in assuring a just and sustainable transition towards renewable energy, it is increasingly acknowledged that lack of acceptance should not be framed as a problem and that achieving acceptance should not be a goal on its own (Jasanoff, 2018; Jenkins et al., 2021). This is why the notion of acceptance is increasingly being redefined as one of the possible ways in which societal actors relate to or choose to engage with renewable energy technologies (Verhoeven et al., 2022). The new definitions of community acceptance acknowledge that resistance is a legitimate response (Cuppen & Pesch, 2021; Mouffe, 2002) and that individuals and communities form their opinions within a certain historical, cultural and political context (Cuppen et al., 2020). Overall, the majority of the academic work on acceptance indicates that the way in which different publics are likely to respond to renewable energy projects is a function of interrelated factors rather than a single issue.

Wind energy projects are one of the most contested renewable energy developments, and there is a prolific body of evidence on the reasons for the lack of acceptance of wind energy (e.g. Rand & Hoen, 2017). The lack of community acceptance for wind energy is often related to residents' concerns about possible, negative impacts of wind turbines, which include but are not limited to bird strikes (Dohm & Drake, 2019), shadow flicker (Hirsh & Sovacool, 2013), noise annoyance (Klæboe & Sundfør, 2016) and the aesthetics of wind farm designs (Oosterlaken, 2014). Community acceptance is also linked to the scale of wind energy projects, opportunities for participation and community ownership (Kirch Kirkegaard et al., 2020; Toke et al., 2008). The extent to which these concerns are addressed through research and innovation is therefore likely to increase the (likelihood) of community acceptance, and in the long-term, determine the ability of the sector to upscale sustainably.

A recent proliferation of digital technologies indicates novel opportunities for addressing concerns voiced by communities and for increasing the acceptance of wind energy projects. For example, a study by Aaen et al. (2022) suggested that demand-based obstruction lights (which are lights on top of wind turbine blades and/or tower lights that switch on and off only when planes pass by) cause less annoyance than regular obstruction lights (which are on all the time). However, the way in which digital technologies might capture and tackle the problem of lack of acceptance is likely different from the traditional and analogue ways (e.g., establishing a dialogue between wind turbine producers, wind turbine owners and residents of the wind farm area (Karnøe & Garud, 2012)). This is because the digitalisation of any object or idea requires technical expertise, quantitative definitions and pinning down how 'things work' (based on Gillespie, 2014; Machen & Nost, 2021). This means that the design and use of digital technologies might both open up and close down (new) ways for increasing community acceptance.

To better understand how digital technologies affect how the problem of lack of acceptance is addressed and approached, there is a need to determine how experts who design digital technologies define and use the concept of acceptance. With these insights, it would then be possible to improve the justice of how digital technologies are designed and used and to minimise the chance for encoded bias (Eubanks, 2018). These insights are relevant for fostering a more just way of addressing concerns voiced by communities about wind energy projects, as well as other kinds of renewable energy, or for other environmental problems for which digital technologies are developed.

To gain these insights, I focus on the ways in which experts involved in R&I projects affect how the concept of acceptance is digitalised and with what consequences for the governance of the wind energy sector. My analysis is based on a case study of one R&I project called UPWARDS that is funded under the Horizon 2020 framework. UPWARDS stands for Understanding the Physics of Wind Turbine And Rotor Dynamics through an integrated Simulation framework. The goal of the UPWARDS project is to design a digital twin that improves the understanding of how wind turbines (including a new model of a 15-MW wind turbine) interact with their environment. This digital twin can help to, for example, optimise the design of a wind farm by taking into account concerns that affect community acceptance. My role in this project as a PhD candidate was to conduct research on the 'social and environmental aspects of wind energy' and to contribute to the design of UPWARDS digital simulations, referred to as digital twins (used synonymously in this chapter).

This chapter is structured as follows. In section two, I present the framework used in this chapter for unpacking the process of translation into digital space. In section three, I outline the methodology, and section four presents the findings about the translation of acceptance. In section five, I make a conceptual contribution to understanding the process of translation into the digital as an act of governance by experts. Finally, I conclude the chapter in the final section, provide recommendations for future research and innovation projects and propose how such projects could be facilitated with future EU funding schemes.

5.2. Analysing the translation of acceptance into the digital

To analyse the meaning and uses of acceptance in the design of digital technologies, I focus on how acceptance is translated through an active process of design. In doing so, I consider the design of digital technologies as an act of governance, that is, of steering how, when and by whom decisions are taken. Following Klerx et al. (2012), design is an act of governance because experts who design digital technologies draw boundaries in designs and figuratively by defining concepts. In this chapter, I focus on how experts affect whose knowledge and which aspects and understandings of acceptance are included or excluded in the design of digital technologies.

I unpack the process of translation as an act of governance by experts in three steps: 1) 'defining': an active process of negotiating and describing what acceptance for wind energy means in the context of digital technologies, 2) 'digitalising': a process of deciding how acceptance should be digitalised and 3) 'interpreting': a process of drawing conclusions about acceptance after it was digitalised.

The first step in the process of translation is 'defining' the concept of acceptance in the context of digital technologies. This involves an active process in which experts who participate in research and innovation projects build a collective definition of acceptance. This definition often needs to include an explanation that is as simple as possible (Luna-Reyes et al., 2019) so that it is easy to understand how acceptance will be achieved in the context of a given project. At the same time, because the existing definitions of acceptance tend to be blurry, experts might need to choose from multiple explanations of what it means to accept and how acceptance should be used as a concept in research and innovation projects (Ingeborgrud et al., 2020). As shown by Korenhof (2021), in the process of digitalisation, experts tend to quantify objects or ideas that are digitalised. In the case of acceptance, this could require that acceptance is being narrowed down to a reduced (set) of parameters rather than a whole range of possible factors (as done by Woo et al., 2019).

Second, 'digitalising' acceptance involves an active process of representing the defined concept of acceptance in the digital realm. In this process of digitalisation, boundaries are likely to be drawn around what aspects can be translated into the digital domain (Luna-Reyes et al., 2019). Central to this process of drawing boundaries is decision-making over what aspects can be made digital and which cannot (Eubanks, 2018; Gillespie, 2014; Korenhof et al., 2021), so that they can be excluded or simplified from digital representations. Digital technologies such as digital twins are often seen to mirror reality; however, in practice, any digital representation is a subject of an active design process (Korenhof et al., 2021; Tomko & Winter, 2019). This means that experts who develop digital technologies need to make choices regarding data, regulation and alignment of different models as well agree which concerns are digitalised (Solman et al., 2022). How acceptance is digitalised, therefore, inherently includes decision-making over what concerns and aspects of wind energy technology are relevant and to whom.

Third, 'interpreting' is an act of explaining the outcomes of digitalisation (here of the digital twin) to the 'users'/the 'audience' of digital technologies. In some cases, digital technologies offer solutions and explanations that seemingly 'remove' human agency from the process of interpretation (Hassan & De Filippi, 2017). However, Eubanks (2018) argues that this process of interpretation involves experts and therefore is inherently human and may embed biases or even mistakes. The act of interpreting likely requires technical literacy (Venturini et al., 2015), which means that in order for the results of simulations to be useful for policy or practice, they need to be made 'explainable'. To achieve that, experts tend to focus on transferring scientific 'facts' to the broader public or decision-makers (Maas et al., 2022). However, the process of interpreting can also be done in a more participatory approach (e.g. as discussed by Whitfield, 2013), i.e., one that involves not only experts but also lay people and stakeholders in drawing conclusions about the outcomes of digital research and innovation. In sum, the process of interpreting the outcomes of digital technologies can take different forms and involve different constellations of experts and societal actors.

5.3. Methodology

In this chapter, I employ a case study of the UPWARDS project, which is one of 42 projects on research and innovation related to both wind energy and acceptance; it is funded under the H2020 programme (Cordis, 2022b). I participated in this project as a PhD candidate through a social science work package. The proposal itself was written by a core team of project partners in the consortium prior to my involvement. In addition to two social scientists (including myself), the UPWARDS project involves six other project partners in the field of wind energy science, two industrial partners (wind turbine manufacturer and software developer) and a consultancy organisation that organised dissemination and stakeholder engagement. Thanks to my involvement in this project, I had a unique opportunity to observe and participate in how acceptance was gradually being translated over the course of 4.5 years in which the project has run (from April 2018- Sept 2022). My involvement as a PhD candidate in the UPWARDS project therefore enabled me to reflect on the concept of acceptance both an 'insider' and 'outsider' (involvement that resembels a participatory action research approach by Katz & Solomon, 2008). I could take the 'outsider's' perspective, as I did not participate in the writing of the project proposal that predetermined a focus on acceptance and indicated how it should be approached in the context of the UPWARDS digital twin. I was also able to gain an insider's perspective on acceptance by participating in how the concept was operationalised, digitalised and interpreted. I worked under supervision of a work package (WP) leader; and for four months, we worked with a student assistant. Because of this dual role, I became a critical observer of how research and innovation projects work in practice, but my direct engagement in the project has also likely shaped the way in which I perceived this process.

This chapter's methodological approach was informed by my conceptual focus on analysing the process of translation as defining, digitalising and interpreting. This methodological approach involved a mix of qualitative research methods that enables to explore how different experts involved in the UPWARDS project define acceptance, how they digitalise it and how they draw conclusions about it with the help of digital twin technology.

The first source of data was the project proposal that refers to and frames the concept of acceptance in the context of the UPWARDS project. The project proposal was studied with a focus on how acceptance was defined as a concept and in relation to the project's goals and impact. To do this, I extracted all the mentions of 'acceptance' in the project proposal and then analysed its function within the project. This resulted in the identification of several themes that describe acceptance and how it can be simulated within the UPWARDS project. I combined this analysis with a reflection on my involvement in the UPWARDS project with a focus on the work that relates to the digitalisation of acceptance.

Second, I organised two workshops during project consortium meetings. One was organised halfway through the project, and it invited project partners to reflect on how their work on the UPWARDS digital twin touches upon different concerns around wind energy technologies, landscapes and how it relates to the public. The second workshop was organised towards the end of the project for the purpose of gathering insights about experts' understanding of acceptance. This second workshop started with a presentation of my personal reflection about how acceptance as a concept was defined and included in the UPWARDS digital twin. Afterwards, I openly discussed with project partners about acceptance as a challenge in research and innovation, our choices in how to include it in the UPWARDS digital twin, the limitations we faced in translating acceptance and finally, how the uses and users of the UPWARDS digital twin are imagined. The results of both workshops were summarised in writing and analysed into themes that cover how acceptance is understood as a concept, ideas and arguments for how it should or should not be digitalised, and how the concept of acceptance relates to the technical research and innovation of other partners.

Third, I wrote a reflection that summarised my own role, experiences and process of developing ideas about the acceptance and design of digital technologies. I started to intentionally reflect on this process at the end of the project for the purpose of this chapter. I discussed my reflection with the leader of social science work package on which we worked together. His reflection was then added to mine to provide a retrospective account of the process of our involvement in the UPWARDS project, the challenges we faced when contributing to deliverables and to the development of the UPWARDS digital twin. Reflection is a valuable source of information for better understanding experts' views on certain topics and for shedding light on how research and innovation on acceptance is done. Inspired by Jones et al. (2016), I reflected on my own engagement as an expert working with the concept of acceptance. Furthermore, I followed Godden (2017) in reflecting on how my own role as a researcher affected actions by and the role of other experts or societal actors. Finally, I built on Robbins (2007) by reflecting on what it means to be a reflexive scientist in terms of how experts relate to the knowledge and technology that they generate.

I used the reflection piece by following Hickson's work (based on Fook and Gardner's approach) that recommends focusing on the "different assumptions, relationships and influences embedded within it and how it affects our practice" (2011 p. 829). More specifically, I used reflection to identify themes in the personal experience throughout the course of the project.

Collectively, the analysis of the proposal and my personal reflection, verified with project partners, informed the results that I present in the next section. Together, these different sources of data helped me to collect information about the different steps of defining, digitalising and interpreting acceptance. Furthermore, by using different sources of information, I was able to triangulate the results, which helps to assure the internal validity of the findings (Grix, 2018).

5.4. Results

5.4.1. Defining acceptance

To design the UPWARDS digital twin, the concept of acceptance needed to be first defined by the consortium partners, alongside other technical aspects of wind energy systems, so that they could be digitalised. This definition of acceptance was shaped by how the UPWARDS project's proposal predefined acceptance as a focus for the digital twin on the one hand and how the social science work package defined acceptance on the other hand.

On the most general level, the project's proposal predefined acceptance as a sociotechnical challenge in which a lack of acceptance is a barrier between wind energy technologies and society. This challenge was to be approached through interdisciplinary research and innovation for 'better' wind turbine designs, simulated within the UPWARDS project. I found that there were different kinds of acceptance discussed in the proposal, each accompanied by a specific goal for the project to accomplish and with different understandings of which 'mechanisms' help to increase acceptance.

First, in the proposal, there was a specific focus on how acceptance is defined by the European Union experts, namely, as a societal-technical challenge for upscaling wind energy infrastructure in the transition to renewable energy. For example, the proposal referred to the following definition by the Joint Research Centre (JRC) report (Ellis & Ferraro, 2017) in which social acceptance is "a key challenge for the deployment of wind energy (...) [that] could limit the overall wind resource we are able to exploit to meet climate change targets" (p.2). In relation to this framing of acceptance, the proposal had a specific focus on increasing and improving acceptance or easing the lack of acceptance to ensure the uptake of wind energy.

The proposal promised that the UPWARDS digital twin would help to improve community acceptance by offering a platform for decision-making over new or existing wind turbine or wind farms. By integrating data about wind turbine(s) in real time, the UPWARDS digital twin would, for example, help professional stakeholders anticipate and manage better design, planning and management options. As this digital twin technology was deemed to require a certain level of 'technical' literacy, the proposal imagined that wind energy experts would use it to act in the interest of improving the safety, reliability or efficiency of wind energy infrastructure, which is beneficial for both wind farm operators and local communities. The idea for the UPWARDS digital twin was to anticipate issues that lower levels of acceptance and then to proactively account for them to minimise opposition.

Second, the UPWARDS proposal discussed acceptance as a concept within social science and humanities (SSH) fields and referred to three possible kinds of acceptance: socio-political, market and community acceptance (Wüstenhagen et al., 2007). Based on this broad definition of acceptance, the proposal continued to focus only on community acceptance, which relates to the degree to which local communities support wind energy projects (Wüstenhagen et al., 2007). The proposal also preidentified key 'technical' issues that are likely to play a role in community acceptance. These issues were noise annoyance, shadow flicker and safety. While the proposal predefined these issues, it left open whether they related to onshore or offshore wind farms. A wind farm location for the UPWARDS digital twin was therefore to be determined at the later stage of the project.

Following this understanding of acceptance as a concept within SSH, the proposal mentioned that the UPWARDS project would generate new social scientific knowledge about factors of community acceptance for wind energy in Europe. This information was needed, as the proposal identified, as such comprehensive review of the factors that affect acceptance had previously been published only for the North American context (Rand & Hoen, 2017). While reflecting with the PI of the social science work package on why this was the first task for us to carry out, he shared that it seemed a logical step to learn first about what the social science literature reports regarding acceptance and then to build on this knowledge.

The synthesised SSH knowledge about the acceptance of wind energy in Europe became a base from which key factors of acceptance could be chosen, investigated in depth, and then included in the UPWARDS digital twin.

5.4.2. Digitalising acceptance

After acceptance was defined as a concept in the context and for the purpose of the UPWARDS project, the second step was to digitalise acceptance so that it could be included in the UPWARDS digital twin.

The findings of the literature review (Solman & Smits, 2018) showed that there are many aspects that influence acceptance and that these aspects tend to vary across different wind energy projects. Through this review, I confirmed that noise annoyance is indeed one of the leading concerns and reasons to oppose wind energy; however, the literature also argued that procedural and distributional justice is likely to play a large role in the degree to which residents accept wind turbine noise. In addition to the variables mentioned in the proposal (noise annoyance, shadow flicker and safety), I also found that there is a range of other factors that are also likely to influence acceptance. These factors include, for example, concerns about bird strikes, visual aspects (e.g., height of the wind turbines) or sustainability of wind turbine materials. Furthermore, I also found that acceptance of wind energy needs to be seen in the context of residents' preferences for other renewable energy sources or their alternative ideas about transitioning away from a fossil fuel-based economy. Based on this review, I learned that there are technical factors related to acceptance that can be proactively accounted for. I also concluded that it is inevitable that UPWARDS simulation will not be able to account for all the other societal aspects in a way that creates a complete representation of community acceptance inside virtual reality.

For the UPWARDS digital twin, there was a need to pick at least one factor that explained acceptance; to do so, all the project partners needed to agree on a key factor for which data could be gathered/models created. While choosing only one factor was the minimal input, the consortium partners agreed that this choice made the project feasible. Based on internal discussions during project meetings, a decision was made to pick annoyance to wind turbine noise as a key factor of acceptance and hence as a proxy for acceptance by neighbouring communities. This decision was based mainly on the need to select a variable that can be integrated in a quantitative way that can be parametrised and described by quantitative datasets. Another requirement was to select a variable for which expertise and knowledge were present within the consortium.

This method of digitalising acceptance was meant to better understand under what conditions acceptance is likely to be granted and to understand how the design of wind turbines/wind farms can be optimised for noise annoyance as a proxy for acceptance. This approach was also seen to be a novel way of including societal concerns in the early stage of design and innovation for wind energy technologies. However, picking only one factor was a limitation because different factors in combination, rather than noise annoyance individually, are likely to shape people's response to wind energy at the local level.

After agreeing that the digitalisation of acceptance would be mainly focused on simulating noise annoyance as a proxy for acceptance, the next step in digitalisation of acceptance was to define how noise annoyance can be parametrised and supported by data. This was achieved in a deliverable (which task was to: "Collect stakeholder data on noise, shadow flicker, risk and other social and environmental issues" (Solman, Smits, Struthoff, et al., 2021)) that connected the social knowledge about noise annoyance with the acoustic models, atmospheric models and wind turbine technology inside the simulation framework.

To include noise as a proxy for acceptance, first, UPWARDS experts needed to define at what levels noise annoyance is likely to be experienced and how noise levels are regulated by national or regional regulations. For both aspects, secondary data were gathered to define how much noise is acceptable and at what levels it is likely to cause annoyance. The first determinant of what is acceptable was based on the review of European legislation for wind turbine noise (mainly for the sound of blades but also of tonal sounds when included in legislation). Next, the social science work package selected key publications with underlying case studies on noise annoyance and aggregated these results to define the threshold of annoyance. This process resulted in a scale at which noise annoyance can be experienced, in which noise levels span from 30 dB(A), i.e., where little to no annoyance can be expected, to >45 dB(A), i.e., where over half of the residents can be expected to report annoyance. This scale of noise annoyance and the summarised regulation could be digitalised to determine when the sound levels are acceptable.

While digitalising acceptance through a focus on noise annoyance was mainly a quantitative approach, the social science work package also carved out a space for qualitative explanations of how acceptance of wind turbine noise is dynamic and connected to different societal concerns. This qualitative knowledge was, however, not directly included in the digital twin but rather embedded as a thick description of the social-scientific 'model' of acceptance.

5.4.3. Interpreting the simulation results

After acceptance was digitalised—that is, noise annoyance was incorporated into the UPWARDS digital twin—the simulations were run on a case study of an onshore wind farm, and conclusions could be drawn with respect to effects on acceptance. The case study in point was a HogJaeren wind farm in Norway, for which noise annoyance was simulated alongside the technical wind farm performance.

In the interpretation of the outcomes of the HogJaeren case study, it was the task of the social science work package contributors (myself and the work package leader), noise experts and simulation experts to draw conclusions about how wind farm operation could be optimised for noise reduction and power production. This meant that we searched for points (suggested by machine learning) at which a better position for the yaw mechanism[1] was possible. It was concluded that by changing the yaw angle (by 4 degrees), it was possible to arrive at a better annoyance/power production ratio. This conclusion showed how the UPWARDS digital twin could help wind farm operators decrease the overall noise levels at a given wind farm without causing financial losses due to the lower rotation speed. The next step was to describe and interpret what can be learned about acceptance from the UPWARDS digital twin and how this information can be used for improved decision-making over wind energy infrastructure.

The first level of the qualitative interpretation of the simulations on the HogJaeren case was that the outcomes provide a possible explanation of how noise annoyance is likely to affect acceptance of this given wind farm. More specifically, UPWARDS digital twins help to understand how audible levels of wind turbine noise affect residents living within 2 km of a wind farm and help to identify how different levels of sound interact with power production. Then, on a substantive level, there was the need for an interpretation of how the predicted noise annoyance could be a result of existing concerns and the landscape characteristics at this given wind farm. In doing so, this qualitative interpretation also focused on explaining how the change in seasons and thus in the vegetation and residents' daily routines might affect their perceptions of noise. For example, this interpretation highlighted the importance of concerns about low-frequency sound, and noise annoyance is related to other societal and environmental concerns, such as wind farm visibility. This interpretation, therefore, went beyond the simulation outcomes, contextualising the simulation results and considering other aspects connected to acceptance. Overall, this qualitative interpretation of the noise and annoyance simulations nuanced the otherwise quantitative explanation about when residents might be annoyed.

Then, another level of interpretation focused on the general use and relevance of UPWARDS digital twins as platforms for decision-making over the design, planning or management of any wind farm. In this interpretation, we focused on the use of UPWARDS twin for different stakeholders. We argued that by using the UPWARDS digital twin before wind farms are panned, it is possible to proactively account for possible resistance and to inform decision-making accordingly (e.g., identifying areas where possibly high levels of acceptance can be found). In this generic interpretation, we also mentioned the limitations of using the UPWARDS digital twin for realistically

[1] The wind turbine yaw mechanism is used to turn the wind turbine rotor against the wind. The wind turbine is said to have a yaw error if the rotor is not perpendicular to the wind. A yaw error implies that a lower share of the energy in the wind will be running through the rotor area. Source: http://xn--drmstrre-64ad.dk/wp-econtent/wind/miller/windpower%20web/en/tour/wtrb/yaw.htm

predicting acceptance. More specifically, two limitations were identified: 1) the use of units of dB(A) neglects subjective and context-dependent perceptions of noise, and 2) acceptance depends on social, environmental and financial factors other than noise annoyance alone. This interpretation also emphasised that the UPWARDS digital twin should not be expected to produce evidence about acceptance or to prioritise noise concerns only. The overall conclusion of the interpretation was that any simulations of acceptance, even those that are promising high levels of support, cannot and should not replace residents' participation.

5.5. Discussion

The reflections presented above hold relevance for understanding the practical and conceptual implications of digital technologies on wind energy governance. More specifically, they enable the identification of implications for the use of digital technologies in 'governing' the acceptance of wind energy.

The case of the UPWARDS project shows that acceptance as a concept has a useful role in mediating multidisciplinary work around the design of digital twins. By focusing on acceptance, project partners found a common goal and were able to connect their different kinds of expertise on wind energy to contribute to addressing the challenge of lack of acceptance. However, as also argued by Batel (2018), a focus on acceptance might marginalise other possible responses to wind energy projects. This can be problematic with regard to fairly relating to resistance, as lack of acceptance might emerge for many different reasons, and acceptance can change over time (Toke et al., 2008). The results of this chapter indicate that when acceptance is digitalised, it needs to be quantified, and that the qualitative dimensions of acceptance are often excluded or considered to be part of a broader context. As the case of UPWARDS indicated, this may lead to digital technologies emphasising what is known and measurable (such as annoyance to wind turbine sound) rather than exploring the unknowns (new emerging concerns around wind power). While analogue ways of framing challenges such as acceptance might simplify how such challenges emerge and are solved in practice (Diedrich et al., 2011), this work and prior works (Eubanks, 2018; O'neil, 2017) show that digital representations tend to exclude the uncertainties and complexities that cannot be easily quantified. In sum, while using digital technologies to understand acceptance is useful, it also leads to simplifications and (therefore) limitations.

Governance implications stemmed from lessons learned in the UPWARDS projects that foregrounded lack of acceptance as a problem of noise annoyance and noise reduction, as well as digital twin technology on its own, as solutions for increasing community acceptance. This approach to acceptance can, however, lead to narrow conclusions about how acceptance works and how it should be approached. For example, according to van den Berg (2021), the expert definition of noise tends to marginalise residents' concerns about noise. Another approach, and one that is perhaps more agnostic of the outcomes, would be to focus on a more inclusive concept such as societal engagement as opposed to societal acceptance. Building on Owen et al. (2012), a focus on societal engagement would turn the logic of anticipation of concerns into a logic of public engagement in the design of (digital) technologies and in shaping the agenda for (digital) research and innovation.

The translation of acceptance into digital technologies occurs through the inclusion and exclusion of matters of concern into virtual representations that make up digital technologies. Shining light on the three steps in the translation process—defining, digitalising and interpreting—I show that translation into digital is an active process of inclusion and exclusion of factors related to concepts such as acceptance. Emerging through this translation process, digital technologies such as the UPWARDS digital twin should be seen as a political arena populated by wind energy experts who decide which opinions, needs and concerns count (Felt et al., 2016; Felt et al., 2012; Irwin, 2001, 2006; Rommetveit & Wynne, 2017). In doing so, experts who design and implement digital technologies, such as a UPWARDS digital twin, affect how and by whom wind energy is developed and managed. Based on this observation, I argue that digital technologies strengthen the role of experts in shaping the pathways for energy transition.

This way of unpacking the process of translation into the digital and as an act of design is also likely to be applicable to other sectors for which digital technologies are designed and used to tackle societal challenges and concerns. In contrast to Dirk Messner (TEDxTalks, 2012), who argues that designing digital technologies for industrial applications is likely not as political as designing digital technologies for applications within civil society, I argue that the design of all digital technologies is an inherently political activity. Therefore, there is a need to reveal how experts and other actors involved in the design of digital technologies decide what digital technologies should do and for whom. Being open about the design of digital technologies will likely help to involve concerned publics and encourage debate about the societal or environmental goals they should serve, with acceptance or not, rather than seeing them as goals on their own. R&I projects could therefore be reformed by changing the way in which digital technologies are designed. To do so, the design of digital technologies needs to become an issue in debate among experts, stakeholders of wind energy and concerned publics (Pesch, 2021). This debate could entail inclusive decision-making over what needs to be both included and excluded from digital representations of the social and environmental challenges and how these challenges should be addressed.

Finally, this chapter shows that personal reflection can be a very useful source of information for exploring the active role of experts involved in research and innovation projects. By combining personal reflection with insights from the proposal and workshops with UPWARDS experts, this work provides a nuanced picture of how this research and innovation project used the concept of acceptance in designing a digital twin. My own reflection proved to be useful for retrospectively identifying and critically assessing the different assumptions, relationships and influences that shaped how acceptance was defined, digitalised and interpreted within the UPWARDS project. Based on this research experience, I suggest that to strengthen the internal validity of personal reflections, it is worthwhile to not only rely on one's own memories and experiences but also to verify them with others who participated in the same research activity. Overall, I suggest that personal reflection by experts is useful for accessing insights about research and innovation projects that would otherwise not be brought into light.

5.6. Conclusions

This chapter is positioned within broader scientific and sociopolitical debates about the role of digital technologies in addressing the pressing challenges in renewable energy. Zooming in on a societal challenge of acceptance for wind energy, this chapter discusses how the design and use of digital twin technology can affect what it means to accept wind energy and how acceptance can be gained. This is shown in a case study of the UPWARDS project, which exemplifies how experts affect the translation of concepts such as acceptance into the digital domain in three steps, namely, by defining, digitalising and interpreting.

The findings of this chapter add to the extant critical social science scholarship on the acceptance of renewable energy technologies in the analogue context (Batel & Rudolph, 2021; Rudolph et al., 2018). The key finding of the UPWARDS case study was that to be digitalised, acceptance needed to be narrowed down to a focus on noise annoyance. By shining a light on the three steps of the translation process, I have shown that wind energy experts need to make choices regarding what to include and what to exclude. I have argued that this process of translating acceptance tends to lead to simplifications of what acceptance means and how acceptance can be increased. By focusing only on what is known and measurable, it becomes difficult to carve out space for managing concerns and aspects that might not be easily quantifiable. This includes, for example, a lack of trust between community and wind farm owners (Walker et al., 2010) or emotions such as place attachment (Devine-Wright, 2009), all of which are difficult to digitalise but can be important factors in how people relate to wind energy.

To move beyond the limitations of how digital technologies can be used to understand and increase acceptance for renewable energy, I suggest that it is desirable to change the focus of future R&I project acceptance as a goal on its own and instead to view acceptance as one of the possible outcomes of R&I for wind energy. EU calls could fund projects where the focus is on using digital technologies to understand resistance, understand emerging concerns or foster collective learning. Moreover, funding is also needed to support R&I activities that enable reflection and to possibly adapt the projects' focus. Such funding may help to ensure that the R&I projects do not continue simply because certain outcomes around the design of digital technologies for acceptance were promised in proposals. Instead, such reflexive use of the concept of acceptance can help to develop R&I projects that enable learning and adjusting the course of innovation so that the outcomes are 'allowed to be' even significantly different from what proposals initially envision. This needs to involve the possibility that innovation and research can take (more) time and that there might be no technological solutions at all. Ultimately, opening up the design of digital technologies to public input and to be a subject of deliberation on its own is likely to make digital innovations socially robust – not in anticipating and proactively removing resistance but by internalising concerns into the design phase. This deliberative approach to design in research and innovation projects could benefit not only the wind energy sector but also other sectors of the economy, such as smart agriculture (Klerkx, 2021; Kruk et al., 2021), digital urban governance (Nochta et al., 2019) and, more broadly, environmental governance (Coeckelbergh, 2021; Kloppenburg et al., 2022). In the long term, this would help to ensure that research and innovation projects develop more sustainable technologies that engage societal actors in transitioning towards a green and digital economy.

CHAPTER 6

Discussion and conclusions

CHAPTER 6: Discussion and conclusions

6.1. Introduction

The energy transition is one of the key governance challenges of our times, and the upscaling of wind energy is globally considered necessary to achieve this transition. However, the expansion of wind energy infrastructure is being halted by various related concerns about the increasing scale of wind farms (Bjärstig et al., 2022), wind turbine noise and the impacts of wind turbines on landscapes (Klæboe & Sundfør, 2016). Therefore, the sustainable upscaling of wind energy requires technical developments in wind turbine technology as well as the involvement of different publics to ensure socially robust, just and environmentally sound wind energy projects. While sustainable wind energy growth is desirable in light of global energy transition goals, its upscaling should not override local concerns and voices of resistance (Devine-Wright, 2011). As this thesis has addressed, digital technologies have been proposed as a means for overcoming these concerns, but the sociological understanding of how digitalisation affects wind energy governance has thus far been lacking.

The interest in understanding the effects of digitalisation on wind energy governance has mainly been from a technical perspective. This technical view assumes that digitalisation is an act of mirroring reality and that digital technologies provide revolutionary means to design, plan and manage wind energy technologies and their infrastructure (Clifton et al., 2022). However, although digital technologies are also being increasingly used to facilitate innovative forms of public participation (for example, through immersion experiences) (Barber et al., 2022; Clifton et al., 2022; Desholm et al., 2006; Gawlikowska et al., 2018; Haghshenas, 2022), little empirical work has examined the role of the experts who shape the processes of digitalisation.

This thesis has explored the ways in which experts' actions affect governance, and its insights provide a new way of understanding digitalisation as an act of governance. Based on this idea, it is possible to explore what modes of governance are possible beyond an expert-driven governance of wind energy. How digitalisation affects different modes of governance is relevant not only for wind energy governance but also for other domains of environmental governance, such as sectors of the renewable energy economy, nature conservation or climate governance. This desire for a deeper understanding of digitalisation as an act of governance led to the main research question in this thesis:

What are the implications of digitalisation for wind energy governance?

This question has been addressed through the formulation of three subquestions. First, how do the experts who design and/or use digital technologies translate concerns, knowledge and expertise related to wind energy into digital technologies? Second, to what extent do these experts enable different publics to engage in decisions on wind energy technologies and landscapes? Third, in what ways do these experts influence the ways wind energy landscapes are defined and interacted with?

Answering these questions while building a sociological understanding of digitalisation, this concluding chapter is structured as follows: In Section 2, I first draw conclusions on the key research findings and answer the three sub-questions. Building on these findings in Section 3, I answer the main research question. This third section includes a new perspective on digitalisation in environmental governance that first identifies and characterises the acts of digital wind energy governance and then builds on them, defining three possible modes of digital governance. Section 4 looks ahead and concludes this thesis by proposing an agenda for future research and innovation on digitalisation in wind energy governance and beyond.

6.2. Synthesis of findings

6.2.1. Translation of concerns, knowledge, and expertise into the digital

The first sub-question concerns how the experts who design and use digital technologies translate concerns, knowledge and expertise into digital technology. Based on the insights in the four research chapters, I argue that a range of disparate experts involved in the process of translation, shape the design and use of digital technologies. Doing so, I argue, they construct the digital framing of problems and solutions in wind energy governance. This overall finding reveals that while wind energy experts tend to believe that the design of digital technologies is an objective act of mirroring the 'real world', the translation of concerns, knowledge and expertise is affected by experts' choices in what to digitalise and how, as Tomko and Winter (2019) argue. Below, I synthesise the results on which experts are involved in translation, how they make choices on the design and use of digital technologies, and thus how they construct the digital framing of problems and solutions in wind energy governance.

First, the results shed light on the range of expertise among the academic and industrial wind energy and digitalisation experts involved in the design of digital technologies and how this affects whose concerns, knowledge and expertise impact the process of translation. I have found that the experts who are involved with digital technologies are much more diverse than is often assumed (Clifton et al., 2022; Jones et al., 2020). Chapters 3, 4 and 5 have addressed the different kinds of expertise that are provided by all the professional actors who design, commission and manage digital technologies. These experts tend to work across different domains of applied wind energy science (e.g., acoustics, wind turbine/blade technology, solid/fluid mechanics interaction, meteorology) and digitalisation (e.g., data analysts, experts in high-performance computing and machine learning), across various domains of social and environmental science, and in the wind energy industry (e.g., wind farm developers, wind turbine manufacturers). While the combinations of these different types of expertise tend to vary across different digitalisation projects, as also shown by Whitfield (2013) in the case of crop modelling, this thesis has shown that while technical expertise is always considered necessary, social and environmental expertise on wind energy tends to be considered optional. Digital technologies play an important, new role in bringing together these different kinds of expertise and by doing so, offer a multidisciplinary but often not an all-encompassing understanding of how the various parts of a given wind energy system interact.

Second, I have found that the use of a range of collectively recognised concepts helps develop inclusion and exclusion mechanisms in the translation of concerns, knowledge and expertise. In Chapter 5, acceptance is a concept that helps operationalise societal concerns, needs and preferences for wind energy. Chapter 3 discusses how the concept of digital twins acts as a boundary object, enabling different kinds of knowledge and expertise to come together in the digital realm. While these concepts make the digitalisation of concerns, knowledge and expertise across different domains of wind energy science possible, I have found that experts often need to define these concepts in a quantitative way. More specifically, Chapter 5 has shown that when designing digital simulations, the case wind energy experts needed to narrow the concept of acceptance to a proxy of noise annoyance. A similar observation has been made by Korenhof et al., (2021) who, by using an example of digital twins in the domain of agriculture, show that experts ‘steer’ digital representations by choosing what aspects of a given food system deserve attention and how these are measured and represented. Adding to this work, this thesis has shown that when making choices on how to measure and represent 'analogue’ aspects digitally, experts tend to prioritise quantitative over qualitative knowledge, concerns and expertise. Most experts do so out of a conviction that while quantitative aspects can be more easily or more objectively mirrored, qualitative aspects are more complex and more difficult to represent digitally. While attempts to quantify the impacts of energy projects, especially in environmental impact assessments (Taebi et al., 2016), are an already established controversy, I show that in the development of digital technologies, the quantification of concerns and impacts becomes even more dominant and sometimes controversial.

Third, I have found that the translation of concerns, knowledge and expertise into digital technologies tends to affect how experts solve different problems related to wind energy. This is a novel finding in terms of the wind energy literature, which has thus far mainly discussed the potential of digital technologies to solve problems in wind energy on their own, not how digital technologies might affect existing or spark new concerns at the wind farm level. In addition, while it has already been argued by Firestone (2019) that more technology is not necessarily the right answer for the societal and environmental challenges in wind energy, I have found that there is often little room for identifying and implementing nontechnological solutions in cases where digital technologies are applied. Instead, as shown in Chapters 3, 4 and 5 by translating concerns, knowledge and expertise, wind energy experts tend to predetermine what kinds of solutions are possible through digital technologies. For example, in Chapter 4's discussion of the noise monitoring app, I show that proposed solutions based on digital technologies tend to rely on monitoring and measuring the parts of 'the wind energy system' that are digitalised, which in turn are used to anticipate a relatively narrow set of impacts. As noted by Hassan and de Filippi (2017), digital ways of problem solving can reproduce biases, such as the preference for economically feasible solutions—as noted elsewhere in the wind energy sector (Kirch Kirkegaard et al., 2020) and for other domains of environmental governance, such as climate (Machen & Nost, 2021). Overall, this means that by designing digital technologies, wind energy experts play a leading role in defining and legitimising decisions related to the design, planning and management of wind energy, and by doing so, they become the de facto governors of wind energy.

6.2.2. Virtual participation and virtual publics

The second sub-question explores how the experts who design and use digital technologies enable different publics to be engaged in decisions on the design and management of wind energy technologies and landscapes. The key findings, presented below, focus on how experts define 'the public' in the context of digital technologies and wind energy and how they enable or constrain public engagement.

First, the chapters in this thesis demonstrate how the experts involved in the design and implementation of digital technologies define the public in a relatively narrow way, as they focus on nearby residents and often overlook other residents or stakeholder networks. While these two different types of publics have been recognised (Pesch, 2019), the focus has tended to be on individuals rather than on communities or networks of interest, neglecting the importance of how people form relationships and opinions around wind energy in collective settings (Hindmarsh, 2010). However, as shown in Chapter 4, new labels are created in the design of digital technologies for the different kinds of users of these digital technologies, such as 'serious' users (who use digital technologies regularly and provide their 'unbiased' input), users who are 'outliers' (those who provide exaggerated feedback) and the 'silent majority' of nonusers. While such labelling of the public based on user behaviours is common across different forms of online participation (Barrios-O'Neill & Schuitema, 2016), Hatuka and Zur (2020) argue that it is important not to dismiss nonusers. The ways in which the publics are defined by experts in the context of digital technologies thus influences not only which societal actors have a say in wind energy governance but also whose voices are (not) digitally represented.

Second, the wind energy experts who design or use digital technologies affect the modes of involvement and the degree of decision-making power that different publics have in the design, planning or management of wind energy technologies and landscapes. With respect to public engagement in the design of digital and wind energy technologies, wind energy experts tend to consider direct forms of public participation difficult (if not impossible). This has been shown in the case of digital twins, for which public involvement is often seen by experts as 'out of scope'. Furthermore, Chapter 5, regarding the UPWARDS project, shows that when designing the focal digital twin technology, the experts focused on noise annoyance, as a proxy for acceptance, and considered the perceptions of the broader public via existing datasets, which may not match the actual opinions of residents at the wind farm level. Sovacool and Enevoldsen (2015) argue that the design of wind turbines continues to be an expert-driven process that is characterised by a closed style of innovation and high competitiveness among wind turbine manufacturers. Building on this argument, I conclude that the choice to exclude publics from the design of digital technologies also excludes them from providing input in the design of wind turbines.

Third, the wind energy experts who design and use digital technologies also create opportunities for proactively accounting for concerns of broader publics and for improving the understanding of how their concerns may change over time. Hence, the experts designing or using digital technologies enable new forms of public participation in the stage of planning and management. Chapter four illustrates, with the case of the noise monitoring app, how digital technologies can help involve residents in managing their concerns, disseminate information and gather feedback from residents over a longer period of time. However, in line with Rouvroy et al. (2013), I argue that providing new opportunities for involvement does not automatically free users to codecide on the issues at hand (Rouvroy et al., 2013). Different forms of (digital) device-enabled participation have already been discussed in the context of using domestic energy technologies, such as smart metres, as new 'energy practices' (Naus, 2017; Smale et al., 2019) or as emerging forms of 'material participation' in energy transitions (Marres, 2016; Ryghaug et al., 2018). In contrast to this literature, the case of wind energy has revealed that it is more difficult to meaningfully connect people to wind energy infrastructure, as it is only rarely mediated by domestic technology devices (such as noise apps). Moreover, while their proximity to a wind farm might not always explain why people choose to use digital devices to participate in wind energy governance (which is also the case for analogue participation, as described by Wolsink (2000)), concerns about the visibility and audibility of wind energy projects are likely to affect if and why residents choose or do not choose to participate digitally.

6.2.3. Digital spatial ontologies

The third sub-question addressed in this thesis explores the ways the experts designing and deploying digital technologies steer how wind energy landscapes are defined and interacted with. The key finding is that by making and interacting with digital representations of wind energy landscapes, these wind energy experts can affect decisions on the future siting of wind energy projects, how wind turbines are designed, and how and by whom wind farms are managed.

First, the wind energy experts who design and use digital technologies steer digital representations of wind energy landscapes by making design choices about how to digitally capture or imagine the biophysical and social aspects of these landscapes. In regard to representing existing wind farms digitally, wind energy experts generate 'realistic' digital representations of wind energy landscapes, but in practice, they often need to exclude some aspects of the social and ecological complexity of these landscapes. The analyses of the noise monitoring app (Chapter 4) and the UPWARDS digital simulations (Chapter 5) have shown that experts tend to digitalise a radius of two kilometres around wind turbines. This Cartesian way of digitally demarcating wind energy landscapes tends to be at odds with 'how far' the concerns with wind farms are being voiced (Dällenbach & Wüstenhagen, 2022; Labussière & Nadaï, 2014; Simcock, 2014). This means that instead of being contained within a digitalised area, concerns with wind farms are also found beyond the 'borders' drawn by planners or wind farm owners. When these spatial borders are represented by digital technologies, their spatial demarcations are reinforced or formalised and might become a base for the spatial exclusion of both the people and ecosystems outside their digitalised area.

Second, with respect to digitally representing the possible configurations of wind turbines on landscapes, experts often need to decide where to locate virtual wind turbines and what biophysical and social aspects of landscapes should be included. Chapter three shows that when designing digital twins for wind energy innovation, experts tend to assume a 'universal' type of landscape, such as an offshore landscape. The case of digital twinning shows that prioritising landscape typology or characteristics over the socio-political context of landscapes obscures how people relate to and use wind energy landscapes. For example, Chapter 5 shows how the simulations of a given wind farm have excluded the broader context of its place's history and other cultural and recreational functions, as well as how landscapes might change with the weather, seasons (and connected to them, changes in fauna and flora) and time of the day.

Third, wind energy experts affect how different actors relate to the digital representations of wind energy landscapes. For example, Chapter 3 shows how wind energy experts aim for that digital representations of wind energy landscapes convey information about how wind turbines interact with each other and their spatial and atmospheric conditions, which in turn can be used as inputs for the optimisation of wind farm performance. Residents located near wind farms that are represented in digital technologies tend to, however, find such digital representations less relatable, as they perceive wind energy landscapes through their everyday experiences. A similar conclusion has been reached by Phadke (2010a), who argues that while digital representations of landscapes, such as Google Earth, "may enable distant viewers to 'witness' change; [they] may add limited value to how local citizens experience their own topographies" (p. 267). This means that while digital representations of wind energy landscapes tend to appear neutral or objective, in practice, they might become a subject of controversy on their own because people do not reconcile their digital and analogue experiences of landscapes.

6.3. Digitalisation as an act of governance

6.3.1. Towards a sociological definition of digitalisation

When understood through the three dimensions described above, it becomes clear that digitalisation is an act of governance that can be defined as enacted decisions on wind energy technologies and landscapes. In summary, wind energy experts play an active role in (1) translating concerns, knowledge and expertise into the digital, (2) enabling public engagement and (3) steering how digital representations of wind energy landscapes are defined and interacted with. Through these three dimensions of digitalisation, these experts also connect different stages in governance: the design of digital technologies, the planning and implementation of physical technologies and their management on landscapes. Moreover, digital technologies connect different actors, places and decision-making moments, which in turn reveal new ways of designing, planning and managing physical objects or technologies on landscapes.

Understanding that digitalisation is an act of governance by experts enables a more precise sociological understanding of how digitalised objects reflect the human choices, concerns and visions for what the future of a sector such as wind energy should be. This active process of translation challenges the conventional definitions of digitalisation as an act mirroring the 'real' world in the virtual domain (as also argued by Tomko & Winter, 2019 for digital twins). Instead of a passive process of mirroring, the results of this thesis indicate that digitalisation is an active process of deciding what is and what is not digitalised. As argued by Rouvroy (2013), failing to acknowledge the 'human factor' involved in digitalisation can "contribute to (re)producing and multiplying this immanent normativity (….), albeit by obscuring social normativities, silencing these as far as possible because they cannot be translated digitally" (p. 163). Furthermore, an understanding of any digitalisation process should take into account that what is excluded from digitalisation might not be relevant but is difficult to represent with existing digital methods of observation, recording and communication. Seeing digitalisation as an act of governance can therefore enable a better understanding of such potential biases in the design of digital technologies and the socio-political contexts in which this design occurs.

6.3.2. Digitalised acts of governance

The definition of digitalisation as an act of governance outlined above allows a new way of identifying and describing how digitalisation forces us to rethink how governance processes are performed. Based on the findings in the previous chapters, it is possible to identify at least four acts of digital wind energy governance: (1) digitalising design, (2) digitalising landscape management, (3) virtual public engagement, and (4) digitally enabled learning. The figure below visualises how digitalisation can be defined through its three analytical dimensions; when viewed in this way, it is possible to characterise how governance processes are affected (see Figure 4).

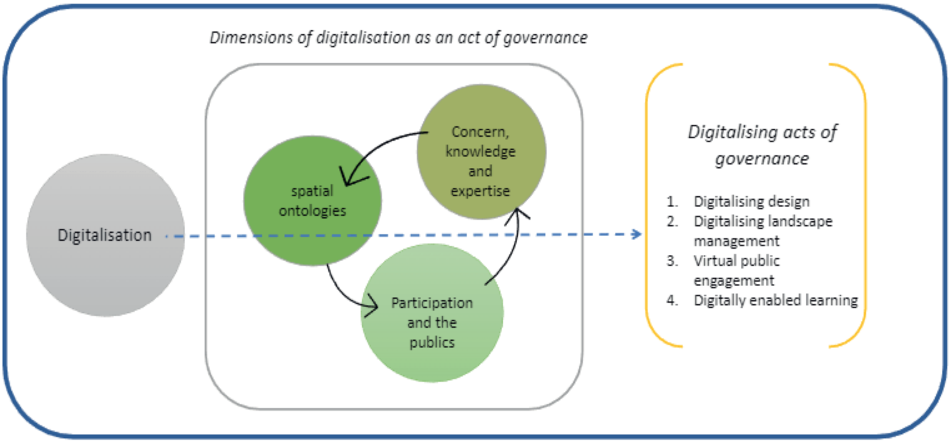

Figure 4: Digitalisation as an act of governance.

The first act of identified governance is the digitalisation of design, through which actors can directly shape the design of wind turbines. How wind turbines are digitally designed is a function of experts' choices in the three dimensions of digitalisation. For example, the design of digital technologies can (and often does) prioritise experts' concerns, knowledge and expertise and their spatial ontologies. While the digital way of designing wind turbines is novel for the sector, the role of experts in driving its design priorities has been increasing in recent years (Kirch Kirkegaard et al., 2020). More specifically, large wind turbine manufacturers tend to prefer a closed and in-house style of research and innovation for the design of wind energy technologies (as shown by Sovacool & Enevoldsen, 2015). However, digital technologies can help integrate information from the planning and management phase into the design phase and in turn improve the design of wind turbines. Digitalising design is, then, an act of responding to the emerging concerns and changing circumstances that digital technologies monitor.

The second act of governance identified in this thesis is digitalising landscape management. By translating concerns, knowledge and expertise into the digital, by virtually involving and defining the public, and by understanding space through the prism of digital ontologies, landscapes are managed digitally. Digitalising landscape management entails both decision-making that is supported by the outputs of digital technologies and landscape management through interaction with virtual landscapes. For example, as shown in Chapter 3 in this thesis, digitalising landscape management can include decisions on how to optimise wind farm designs for efficiency or other social or environmental criteria. This act of governance is both similar to and different from the analogue methods of managing wind energy landscapes. It is similar to the analogue methods because the digital representations of landscapes tend to reproduce conventional ideas about how landscapes should be demarcated on maps and in spatial plans or how they can be visualised in their environment (see Phadke, 2010b). Therefore, in both digital and analogue landscape management, experts rely on legal and scientific criteria that define wind farms, which generally tend to be within a diameter of 2 km around a wind turbine/wind farm (as seen in Chapters 4 and 5 in this thesis and noted by Dällenbach and Wüstenhagen (2022)). This spatial definition, then, tends to be a basis on which participation and the publics are defined, and there is little possibility for redefining these digital demarcations through participation. However, this thesis has shown that digital landscape management is also distinct because spatial demarcations might be changed depending on whose spatial ontologies are included in digitalisation; it is possible that digital landscape management can zoom in or out on landscapes in a way that fits the preferences of the observer. Last, the difference between analogue and digital landscape management concerns the ways in which landscapes are visualised. As mentioned in Chapter 5, digital representations become increasingly dynamic and interactive in terms of how different elements of landscapes are combined.

The third act of governance is virtual public engagement. Public engagement in the context of renewable energy technologies can take many forms, both formal and informal (Chilvers & Longhurst, 2016), and can be a means to express different opinions, including resistance (Mouffe, 2014). By translating concerns, knowledge and expertise into the digital, by virtually involving and defining the public, and by understanding space through the prism of digital ontologies, a virtual mode of engagement becomes a dominant mode of participation. This thesis and the work of Skjølsvold et al. (2017) both indicate that the engagement through digital technologies—here coined virtual engagement—is an act of governance, as it can enable the publics to make choices and provide feedback that affects the governance of larger societal challenges, such as energy transition. Hence, virtual engagement can allow the voices of different residents to be heard without the bias that tends to exist, for example, in a workshop setting (as discussed by Stirling, 2007). However, this thesis has shown that virtual public engagement often requires wind farm residents to devote themselves to regularly using digital technologies, which might be difficult to achieve in practice. Moreover, if local concerns, knowledge and expertise are marginalised in digital representations and publics are narrowly defined, virtual engagement can also constrain participation among the publics who cannot or do not use digital technologies.

The fourth act of governance is digitally enabled learning. With digital technologies, learning no longer depends on the capacity of individuals, groups of people or analogue technologies to document and memorise past experiences. Digital technologies can help decision-makers learn from data by applying a range of statistical and deep learning methods that identify patterns and suggest optimal solutions that could otherwise be missed. Because of this, digitally enabled learning is coined 'smart' (Kitchin, 2014). However, as shown in Chapters 4 and 5, such digitally enabled learning also requires skills related to interpreting outcomes and reflecting on their limitations. Learning from digital technologies often entails understanding possible effects on any aspects that are digitally represented, which in turn means that it is difficult to learn about any aspects that are not digitalised (as, for example, in the case of the noise monitoring app). Ultimately, this may mean that digitally enabled learning requires creativity, imagination and broader 'system' knowledge to assess outcomes from a bird's eye view. If these skills are missing, learning from digital technologies might only help verify and legitimise what is already known.

These acts of governance apply to wind energy, but it is also likely that similar governance transformations might occur in other sectors of digital environmental governance. For example, Kruk et al. (2021) demonstrates, in the context of digital food sustainability initiatives, how digitalisation can either predefine or enable the co-construction of digital identities of the users of these digital technologies. This in turn is connected to the degree of decision-making power that they have in governance (Kruk et al., 2021). Moreover, Kloppenburg et al. (2022) argue that different sectors of environmental governance are likely to undergo transformations as a result of digitalisation. Ultimately, a deeper understanding of how the expert-driven processes of digitalisation affect the ability of different actors to participate in governance is needed. The next section thus focuses on what modes of digital governance can emerge across different domains of environmental governance.

6.4. Potential modes of digital governance

Examining the relationship between digitalisation and wind energy governance demonstrates that these four acts of governance, which are currently performed by experts, might lead to different ways of governing with distinct outcomes in sectors such as wind energy. These 'modes', involving more or less expert involvement, public autonomy, state involvement and reflexivity (Gritsenko & Wood, 2020), are a function of who is acting in the design of digital technologies, digital landscape management, virtual public engagement, and digitally enabled learning. In short, acts of digital governance can affect how, where and by whom digitalised systems such as wind energy are designed, planned and managed over time. More specifically, the possible modes of governance depend on whether the decision-making power rests with experts or with the public or whether it is shared among the different actors. To illustrate the kinds of outcomes that can emerge as a result of different actor constellations, the following sections distinguish three ideal modes of digital governance: 1) citizens in digital control, 2) digital expert systems, and 3) digital deliberation. While these modes may exist on their own in practice, they might also coexist, evolve or split into new modes of governance. Nevertheless, they offer a starting point for reflecting on the possibilities of moving digital governance beyond its current dominant mode, which is the expert-driven system.

The first mode of governance is labelled ‘citizens in digital control’. This mode addresses decision-making at a local level for governing at least one specific matter of concern and meaningfully involve residents. Here, residents participate through digital technologies and as a result of an intrinsic concern (Marres, 2013; Skjølsvold et al., 2017) that motivates them to codecide the design, planning and management of digitalised objects or systems. Central to this mode of engagement is a high degree of decision-making power in digitalised design. This means that the public, and their subjective perceptions of landscapes and wind energy technologies, determine how matters of concern are digitally represented and how objects and landscapes are represented through digital design. In terms of virtual public engagement, continuous and meaningful participation through digital technologies is central in governing digitalised objects and systems on the bases of individuals’ preferences, needs and concerns. In this mode, residents engage individually with digital technologies via a user-oriented interface, such as a mobile phone app (Lember et al., 2019). Another important part of this mode is learning from digital technologies, both in real time and over a long period of time (van Winden & de Carvalho, 2017). When citizens are in control, these users of digital technologies define the rules for when interventions need to be taken (Johnston & Hansen, 2015). Ultimately, this mode of governance demonstrates a high degree of responsiveness to emerging concerns and relies on a commitment of residents to provide feedback over time.

The second mode of governance is labelled ‘digital expert systems’. This mode of digital governance involves the experts at the centre of decision-making on the digital design of technologies or technological systems. This mode is diametrically opposed to the first mode because here, experts lead any decisions on how, where and by whom technologies are digitally designed, developed and managed over time. In this mode, environmental governance tends to be centralised and to take place within a digital expert system that is based on the knowledge of an expert group (such as expert groups on geo-engeneering described by Bellamy et al., 2012; Gupta & Möller, 2019)—a space in which direct forms of virtual public participation are not considered possible. These experts define the priorities for governance, and other actors—e.g., planners or the public—are considered the recipients of the outcomes of digital products (Kügler et al., 2018). Here, the public is often imagined as a ‘society at large’ with standardised and objectified sets of concerns and preferences (Felt & Fochler, 2010). Furthermore, in this mode of expert governance, when digitally managed, landscapes are likely to be objectified and standardised from either a technical or economic perspective that focuses on their material (biophysical) and measurable elements and is connected to different market segments. Central in making this mode of governance possible are expert digital technologies, such as digital twins that allow a multidisciplinary expertise to provide inputs for system-level decision-making. In this mode of governance, big data becomes a very important tool in learning from digital technologies what works and what does not work in terms of improving the design, planning and management of digitalised and physical objects (Kitchin, 2014). Consequently, this mode of digital governance concerns the use of scientific knowledge for decision-making regarding wind energy.

The third mode of governance is labelled 'digital deliberation'. This mode of digital governance involves the use of digital technologies to enable shared decision-making amongst the experts, societal actors, and stakeholders in digitalised projects as well as decision-makers across different levels of planning and policy-making. In this mode, the direct and active involvement of different experts and professional actors alongside the active virtual engagement of the publics in the design of digital technologies leads to deliberation over how the materiality of digitalised objects and landscapes should be affected by digital technologies (Linders, 2012). This deliberation could be organised virtually, but it might also rely on a hybrid of online and in-person interactions where decisions are reached. Finally, in this mode of digital deliberation, both experts and the concerned publics should be involved in the digital design of technologies (e.g. through open web-based innovation as discussed by Lee et al., 2018) and in the digital management of landscapes (e.g. through differnt forms of e-participation in spatial planning as described by Anaafo & Appiah Takyi, 2021). This means that in this mode of governance, digitally enabled learning relies on the shared responsibility for identifying any emerging concerns and on the inclusivity of different kinds of knowledge and expertise that can be applied to draw conclusions from digital technologies. To strike the right balance in sharing responsibility, this mode is likely to continuously negotiate the different needs and priorities and might require that some of these needs and priorities are compromised.

These three modes of digital governance empower different actors to act and thus determine their agenda and directions for digital governance. Depending on the socio-political context and the scale and type of technological or environmental change that is being governed through digital technologies, a specific mode of digital governance or a combination of these modes might be preferred. For example, when there is an established and active community around a wind farm with a clear interest in and the resources to digitally govern wind energy projects, it might be possible and desirable to move towards the 'citizens in digital control' mode of governance. This might be possible for (wind) energy cooperatives, as they tend to design and manage wind energy projects on their own (Hufen & Koppenjan, 2015). By enrolling in digital modes of governance, energy cooperatives could increase the frequency and the content with which the involvement of the different members of a given cooperative is made possible. While such a high level of empowerment might also be beneficial for other kinds of wind energy projects, as well as other problems in environmental governance (e.g., deforestation, climate engineering or smart agriculture), in most situations, 'digital deliberation' might prove to be the preferred mode of governance. This is because many environmental problems are complex and span disparate environmental scales and areas of expertise (Buizer et al., 2011), which means that the involvement of both experts and nonexperts from different places is likely to allow addressing problems in a more integrated and inclusive way. Furthermore, as technical expertise tends to be necessary for designing and deploying digital technologies, combining this technical expertise with different kinds of expert and lay knowledge might open possibilities for the codesign of sustainability technologies and new possibilities for their comanagement (Skjølsvold et al., 2017; Verran & Christie, 2007). Ultimately, the choice from the different modes of digital governance is likely to follow a pre-existing political context, but it might also become a subject of deliberation on its own.

6.5. Proposed further research agenda on digitalisation in the domain of environmental governance

Based on the insights of my thesis concerning digitalisation as an act of governance, here, I discuss the relevance of this new way of understanding digitalisation for other fields of sustainability science and environmental governance and propose an agenda for future research.

Acknowledging that digitalisation is an act of governance in the wind energy sector opens new possibilities for reforming how and by whom 'problems' are defined. Understanding digitalisation as an act of governance can also help decision-makers observe and select solutions that include both digital and analogue interventions. Such a broader range of solutions helps prevent digitalisation from being seen as an external force that inevitably shapes governance. Instead, a digitalisation process understood through the prism of the four acts of governance and their possible governance combinations in the three different modes of governance opens the possibility for reforming these acts of governance and altering the available choices for achieving desired governance outcomes. In particular, by opening a debate about 'who' is acting in the four acts of governance, it is possible to arrive at a more balanced representation of different kinds of knowledge and expertise and to make digitalisation processes more inclusive for different publics.

These governance implications indicate a need for further research on the different kinds of digital technologies, from those that are expert-based to individual ones. Such future research could examine the implications of proliferation for different domains of environmental governance. This leads to three lines of future research on digital environmental governance that account for the four acts of governance and how they might lead to the three modes of digital governance.

First, I propose a line of research on digital design that investigates the range of emerging digital technologies in environmental governance. This thesis has contributed insights regarding digitalisation as an act of governance in the context of wind energy design, which likely also offers relevant insights for recent research on solar energy (Oudes & Stremke, 2021) or airborne wind power (Schmidt et al., 2022). First, the findings on digitally enabled design could be further verified in the context of other sectors of the renewable energy economy. In particular, little is known about how societal actors can engage in the design of digital technologies in the governance of environmental matters of concern. While there is a growing line of research on smart grids (e.g. Naus et al., 2014; Smale et al., 2019) and smart cities (Dembski et al., 2020; Di Dio et al., 2018; Nochta et al., 2019) and environmental conservation (e.g. Büscher, 2020), little attention has been given to how these technologies are designed and whether prospective users could be involved in the codesign of (participatory) digital technologies.

Second, I propose a line of research on virtual public engagement in the governance of sustainability technologies that explores the emerging sociotechnical challenges for which digital technologies can be used. For example, in the case of wind power, research has been published on improving the environmental sustainability of wind farms through smart sensors for birds (Hadipour et al., 2017), but little is known about how residents or the broader public could become engaged with such digital technologies, contributing their (local) knowledge and communicating concerns. Similar questions on possibilities for virtual public participation in the design of sustainability innovations could be posed of controversial sustainability technologies, such as geoengineering technologies (as a follow up on Gupta & Möller, 2019). Such research could include citizen science or collaborative projects that design or use digital technologies as a means to answer questions posed by citizens and to achieve their goals. An innovative example of such research has been recently published by Barber et al. (2022), who showcase how a digital platform can help collate expertise from different domains of wind energy science to address technical challenges in wind energy. Future research could examine how such digitally enabled collaboration could be further expanded to different domains of social and environmental science and to public engagement.

Third, there is a need to research experts' and decision-makers' ability to learn from digital technologies to capture the nature and scope of environmental problems in a just way and to identify fair solutions. This requires research on the needs for interdisciplinary education among the next generation of reflexive experts. In particular, future research should focus on the science-policy interface in the context of digital environmental governance. While the science-policy interface in the context of environmental governance has already identified the challenges of incorporating expert knowledge into environmental policies (Maas et al., 2022), future research that builds on this could also explore what kinds of mediation or interventions are needed at the science-policy interface to move beyond an expert-based system in digital environmental governance.

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Thesis summary

Thesis summary

The transition to renewable energy sources is necessary to assure a sustainable future for current and future generations and ecosystems on our planet. But while there is growing recognition (if not consensus) on the need for these alternative sources of energy, there is an ongoing debate amongst experts and societal actors on how, where and by whom renewable energy systems should be designed, planned and managed. Wind energy is a case in point. Perhaps one of the most controversial forms of renewable energy, due to the perceived visual and ecological impacts of turbines of land and seascapes, debate centres around how and by whom both problems around wind energy are defined and implemented through design, planning and management. This means that the challenge of energy transitions is not merely an issue of developing and deploying renewable energy technologies, but a fundamentally social challenge of aligning what is technically possible with what is 'acceptable' to diverse and often increasingly polarised societies. Yet despite the recognition given to incorporating both expert and societal perspectives into the design and management of wind energy, much of the debate remains highly technical in nature.

The question of enabling more inclusive forms of wind energy governance, to ensure both just and sustainable energy transitions across landscapes, is of great contemporary importance. Nevertheless, this question is not new. Participation in wind energy governance has long been a major focus of scholarship, policy and practice. However, much of this literature has focused on the planned participation of local communities in the siting of wind parks. In doing so, the researchers have tended to narrow diverse community concerns to technical issues, such as wind turbine noise or the visual impact of wind farms. Once narrowed, these concerns have become sites of debate and innovation that are dominated by a narrow set of technical expertise and knowledge.

Despite all the attempts to involve the public in wind energy decisions, technical experts remain the key determining how, where and by whom wind energy technologies are designed, implemented and managed over time. By lending their expert knowledge to the design of new technologies, such as wind turbines, they become the de facto governors of the environmental problems at stake. However, while various kinds of professional expertise clearly have important stakes in wind energy governance, the role of experts tends to be underplayed and, in turn, poorly understood in terms of the challenges and dilemmas that these actors experience in wind energy decision-making.

The advent of digital technologies in the wind energy sector offers an opportunity to rethink participation in wind energy governance. Digital technologies are used to address public concerns

about wind energy, most notably in planning of wind energy projects. As a result of these advances, upscaling wind energy is increasingly linked to a large-scale adoption of digital technologies. The proliferation of digital technologies is often referred to as a process of digitalisation. Given this importance of digital technologies, a better understanding of digitalisation and its effects on how the different concerns about wind energy are governed is needed. However, digitalisation is mainly defined from a technical perspective that focuses on digital technologies themselves rather than on the expert and their role in digitalisation processes. This lack of a social-scientific understanding of digitalisation in turn obscures the need for deliberation on which digital technologies should be designed and for which purposes in the wind energy sector. To carve out such a space for digital governance deliberation, this thesis explores the social and environmental aspects of digitalisation and its implications for wind energy governance.

Given this objective, the research question in this thesis is as follows:

What are the implications of digitalisation for wind energy governance?

To answer this question, this thesis explores how digitalisation affects the choices, actions, preferences and opinions of experts and different publics concerning wind energy are shaped by the design and use of digital technologies. These insights in turn inform how digitalisation affects the participation of different experts and diverse publics, by shaping whose knowledge impacts the design, planning and management of wind energy technologies and landscapes. To answer the main research question, the research is divided to answer three sub-questions:

How do experts translate concerns, knowledge and expertise related to wind energy into digital technologies?

To what extent do experts who design and deploy digital technologies enable different publics to engage in decisions about the design and management of wind energy technologies and landscapes?

In what ways do the experts who design and deploy digital technologies steer how wind energy landscapes are defined and interacted with?

The effects of digitalisation on governance have been addressed in this thesis through a focus on three analytical dimensions that unpack digitalisation: 1) the translation of concerns, knowledge and expertise; (2) the effects on the participation of different publics; and (3) the representation of diverse spatial ontologies.

This thesis includes four chapters that present the results of my research on wind energy governance in the digital era. Chapter 5 aside, chapters 2, 3, 4 have been published in peer reviewed journals. All these chapters are building blocks for a new way of understanding digitalisation as an act of governance in the context of wind energy. They interrogate this topic of digitalisation in the context of wind energy governance from different angles as follows:

Chapter 2 presents a systematic literature review on public engagement beyond the invited forms of participation, including virtual forms of engagement as well as local and collective modes of public engagement, conceptualised as three modes of co-production. This review creates the base from which this thesis further examines how emerging digital wind energy technologies are designed and used to govern wind energy.

Then, building on the results of this review, I explore expert-focused digital technologies in the stage of their design. I do this in Chapter 3, by shedding light on how the wind energy experts involved in EU-funded projects for the design of digital twins, innovate wind turbine technology and thereby affect how and where the wind energy sector is being upscaled. In this chapter I unpack how the experts who design digital twins explain what digital twins are, what they can do and how they can help solve problems in wind energy governance. Presenting cases of recent or ongoing digital twinning projects funded by the Horizon 2020 framework to innovate wind turbines, this chapter shows that 'twinning'- is an act of governance on its own. The chapter concludes that twinning involves design choices for including and excluding different aspects of wind energy systems and their socio-spatial context in the digital domain.

Moving from the case of digital twins, Chapter 4 analyses a mobile phone app, a case of a digital technology that aims to involve wind farm residents and address their concerns with wind turbine noise. By focusing on how this noise app was designed and implemented, this case study highlights the differences among experts and residents in terms of their framing of 'the problem' and what solutions they think should be implemented. This chapter reveals the practical difficulties in assuring a just representation of the different ways in which concerns are voiced and of involving residents via the noise app in management of concerns and of wind farms.

Finally, building on the insights derived from the different digital twin projects, Chapter 5 focuses on one of these projects to reveal how digital twins are designed to tackle challenges around upscaling wind energy. In this chapter, I focus on how the experts involved in the UPWARDS project, an EU funded project on research and innovation in which I participated myself, have translated the concept of wind energy acceptance into digital twin simulations. Exploring this case, I reflect on how wind energy acceptance is approached as a problem of noise annoyance and the consequences of this for decision-making concerning wind energy design and planning. With this focus, the chapter provides lessons for how the design of digital technologies can be improved and how concepts such as acceptance should (not) be digitalised and used in wind energy governance.

The final chapter synthesises the findings from Chapters 2-5 and concludes the thesis by presenting a new perspective on digitalisation as an act of governance and by providing an agenda for future research. Specifically, this concluding chapter discusses how digitalisation is an inherently social process, as it relies on the ideas and choices of societal actors, and experts in particular. Based on the findings in the previous chapters, it is possible to identify at least four acts of digital wind energy governance: (1) digitalising design, (2) digitalising landscape management, (3) virtual public engagement, and (4) digitally enabled learning. Whose choices and ideas are included in digitalisation processes is a function of how decision-making power is concentrated or distributed among experts and the publics.

These four acts of governance, which are currently performed by experts, might lead to different ways of governing with distinct outcomes in sectors such as wind energy. These 'modes', involving more or less expert involvement, public autonomy, state involvement and reflexivity, are a function of who is acting in the design of digital technologies, digital landscape management, virtual public engagement, and digitally enabled learning. In short, acts of digital governance can affect how, where and by whom digitalised systems such as wind energy are designed, planned and managed over time. More specifically, the possible modes of governance depend on whether the decision-making power rests with experts or with the public or whether it is shared among the different actors. This thesis distinguishes three ideal modes of digital governance: 1) citizens in digital control, 2) digital expert systems, and 3) digital deliberation. While these modes may exist on their own in practice, they might also coexist, evolve or split into new modes of governance. Nevertheless, they offer a starting point for reflecting on the possibilities of moving digital governance beyond its current dominant mode, which is the expert-driven system. These three modes of digital governance empower different actors to act and thus determine their agenda and directions for digital governance, depending on the socio-political context, the scale and type of technological or environmental change that is being governed through digital technologies.

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Appendices

Appendices

Appendix 1: Supplementary Materials for Chapter 2

Table A1.1 List of codes and their groups

Code	Code Groups
‘communities of interest’ and ‘communities of place'	local co-production collective co-production
aesthetics of wind turbines	co-production of wind energy technologies
agent and network	collective co-production
alternative wind turbine designs	co-production of wind energy technologies
beyond invited stakeholder participation	invited stakeholder participation and beyond
co-creation of designs	collective co-production co-production of wind energy technologies
collaboration	collective co-production
collective engagement (definition)	collective co-production
collective publics	collective co-production
community benefits	overlap: local and collective co-production
community wind/ civic wind parks	overlap: local and collective co-production
co-production (approach)	overlap: local and collective co-production
co-production of wind turbine technology	co-production of wind energy technologies
critique of NIMBY	invited stakeholder participation and beyond
defining publics	invited stakeholder participation and beyond
digital tools for co-production	virtual co-production co-production of wind energy technologies
distant publics	collective co-production
distribution of costs and benefits	local co-production collective co-production
energy citizenship	local co-production collective co-production
engagement in large scale projects	local co-production
engagement with landscape	co-production of wind energy landscapes
engagement with technology	co-production of wind energy technologies
engaging communities	invited stakeholder participation and beyond
environmental skepticism	Other
financial participation in collectives	collective co-production
forms of virtual engagement	virtual co-production
globalized production/standardization of design	co-production of wind energy technologies

Green consumerism	virtual co-production
historical perspective on the wind energy sector	Other
infrastructure for wind energy	co-production of wind energy technologies
invited stakeholder participation	local co-production
issue-oriented publics	collective co-production virtual co-production
landscapes for wind energy	co-production of wind energy landscapes
large scale wind energy and the publics	local co-production
limitations of invited stakeholder participation	invited stakeholder participation and beyond
Local control	local co-production
local engagement	local co-production
local energy consumption	local co-production
local opposition	local co-production
local publics	local co-production
nature and wind energy	co-production of wind energy landscapes
Noise impacts	local co-production co-production of wind energy landscapes
offshore wind power and public engagement	local co-production
non-local opposition	collective co-production virtual co-production
proximity	local co-production
psychological mechanisms in making sustainable choices (related to wind energy)	Other
public authorities	collective co-production
public concern	Other
public participation in national scale projects	local co-production
publics and decisions about technical aspects of wind energy	co-production of wind energy technologies
research and design	collective co-production
residents	local co-production
stage of design	co-production of wind energy technologies stages of co-production
stage of implementation	stages of co-production
stage of long-term management	stages of co-production
stages	stages of co-production
territorial focus	local co-production
tourism, leisure and recreation	local co-production
transmission lines	co-production of wind energy technologies
upscaling wind turbines	co-production of wind energy technologies

urban and semi urban wind	local co-production
use of visualisation tools	virtual co-production co-production of wind energy landscapes
virtual energy markets and the publics	virtual co-production
virtual engagement	virtual co-production
wind energy cooperatives	collective co-production
wind farm developers	collective co-production
wind turbine users	co-production of wind energy technologies

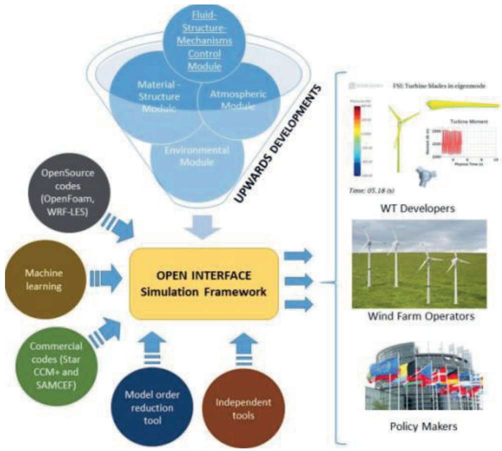
Table A1.2 Categorized sampled articles

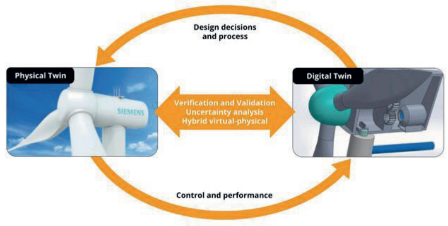
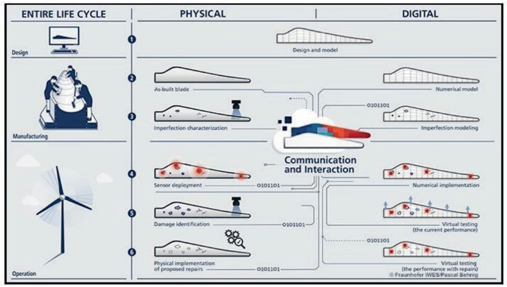
	# Articles	% of Total	% of Mode of co-production
Collective	**40**	**17%**	
collaborative networks	22		55%
investment collectives	16		40%
resistance	2		5%
Local	**158**	**69%**	
local publics engagement	31		19%
local resistance	28		18%
publics and offshore wind	35		22%
publics of implemented wind farms	22		14%
tourists and 2ndhome owners	6		4%
invited stakeholder participation	36		23%
Overlap	**10**	**4%**	
Community wind:	10		100%
Virtual	**22**	**10%**	
digital visualisation	13		59%
online resistance	2		9%
virtual energy market	7		32%
Total	**230**	**100%**	

Appendix 2: Supplementary Materials for Chapter 3

Table A2.1 Sampled Twinning Projects

The description of twinning approach as well as the graphical explanation of twinning process/outcomes were retrieved in 2021 from the websites of projects listed below.

Project short name	Project full name	Project website /source of information	Twinning approach	Graphical explanation of twinning process/outcomes
UPWARDS	Understanding of the Physics of Wind Turbine and Rotor Dynamics through an Integrated Simulation Framework	https://www.upwards-wind.eu/	“The goal of UPWARDS project is to develop a simulation framework, which will incorporate a more complete description of the wind field, turbine, the support structure, and their interaction in order to better understand the physics of the entire system. The complex wind field will be calculated adding interactions from nearby turbines, waves, terrain, etc. By using high-performance computing (HPC), the simulation framework will yield more accurate prediction of the forces acting in the system and thus the energy captured by the turbine. In addition, it will better predict acoustic phenomena, and materials' issues related to the turbine blades, etc.”	

DigiTwin	Digital Twin for improved Dynamic Design	https://digitwin.ac.uk/	“This project will empower industry with the ability to create digital twins as predictive tools for real-world problems that (i) improve design methodology leading to significant cost savings, and (ii) transform uncertainty management of key industrial assets, enabling a step change reduction in the associated operation and management costs. Ultimately, we envisage that the scientific advancements proposed here will revolutionise the engineering design-to-decommission cycle for a wide range of engineering applications of value to the UK”.	
ReliaBlade	Improving Blade Reliability through Application of Digital Twins over Entire Life Cycle	https://www.reliablade.com/	“ReliaBlade develops and demonstrates techniques to create Digital Twins for wind turbine blades with their unique defects and imperfections. The digital twin can track not only the current state of the blade but also predict the future state - as damages initiate and grow through its entire life cycle”.	

Appendix 3: Supplementary Materials for Chapter 4

A3.1. Analysis: themes, sub-themes and codes

Theme: Knowledge, expertise and uncertainty related to WT noise

Code: 'Official' Expertise on noise
Code: Noise measurements
Code: Knowledge claims related to noise and LFN
Code: Citizen science of noise (also overflowing)

Theme: Management of WT noise and digitalisation
Code: Definition of digitalisation
Code: Digital technologies and centralised vs distributed modes of governance
Code: Governments and digitalisation
Code: Data ownership (also overflowing)
Code: Data quality (also overflowing)
Code: Cyber security (also overflowing)
Code: Private companies and digitalisation

Theme: virtual engagement through the app
Sub-theme: Data
Code: Noise annoyance data gathered by the app
Code: Data shared by the app (noise predictions, weather, wind, who controls the kind of info that is shared)
Sub-theme: Networked actors
Code: The role of Dorpsraad and other interest groups
Code: Relationship towards WT manufacturer
Code: Sub-theme: Digital technologies
Code: Opinion about the noise app
Code: Considerations about the app as a tool for participation
Code: Decision-making based on data output
Code: Experts
Code: Prior experience of participation
Code: How people use the app

Theme: overflows/controversies

Sub-theme: Noise as a matter of concern
Code: Definition of noise (legal)
Code: Concern about the impacts of low-frequency sound (mainly health)
Code: Experience of low-frequency sound
Code: hum/'brom' tone
Code: Noise by blades

Code: ‘lasten, niet de lusten’
Code: Adapting/living with noise in everyday life
Code: Spatio-temporal context
Code: Wind turbine technology/design (importance or management of)
Code: Prior expectations for noise

Sub-theme: Demarcations and decision-making
Code: 2 km distance
Code: Legislative context
Code: Communication about noise
Code: Finding solution and taking responsibility for noise
Code: Fairness of solutions
Code: Socio-economic context
Code: Connected concerns
Code: Stakeholder networks

A3.2. Description of codes

Themes: Knowledge, expertise and uncertainty related to noise

Code: ‘official’ expertise on noise: this includes the scientific knowledge on noise, the statements brought by RIVM, noise consultancy and official noise data/noise measurements

Code: Noise measurements: mentions about all kinds of noise measurements that have taken place at the wind farm or on residents’ properties, or in the wind farm area.

Code: Knowledge claims related to noise and LFN: information gathered or used by opposition groups or residents related to wind turbine noise, including LFN and its impacts on health

Code: Citizen science of noise: all the action taken by the residents to prove (measure) LFN and outline its impacts on health (often experienced as a pressure to provide evidence for their matters of concern related to noise); trust in noise measurements

Theme: Management of WT noise and digitalisation

Code: Definition of digitalization: how different actors discuss the trend of digitalization in wind energy and in their everyday life

Code: Digital technologies and centralised vs distributed modes of governance: ideas about how digital devices and technologies allow to distribute the decision-making power form centralised to distributed forms of decision-making

Code: Governments and digitalisation mentions of how governments try to keep up on the increasing use of digital tools in governance of (wind) energy infrastructures

Code: Data ownership: mentions about who owns the app data, wind turbine data, noise data etc.

Code: Data quality: opinions around the quality of data that is being digitalised

Code: Cyber security: concerns about the cybersecurity in online domain

Code: Private companies and digitalisation: ideas about the role of private actors in (wind) energy when implementing digital tools for assets management, citizen participation etc.

Theme: Virtual Engagement with the app

Sub-theme: Data

Code: Data included by the app: explanation about what kind of information the noise app includes and how it is shared with residents.

Code: Data excluded by the app/limitations: mentions of what kind of information was not possible to include, what were the limitations

Code: Experts motivation: motivation for why wind farm operator and app designer developed

the noise app and included certain functions in it

Code: Noise annoyance data gathered by the app: this includes the kind of feedback that people provide about noise and how the wind farm operator and app designer perceive it

Code: Data shared by the app: perceptions of people on the usefulness of noise predictions, weather; Residents' understanding of who controls the kind of information that is shared

Sub-theme: Networked actors (this includes residents, experts, media, developer, manufacturer

Code: The role of Dorpsraad and other interest groups (how they are mediating, communicating concerns, the role as an alternative point for residents' complaints)

Code: relationship towards WT manufacturer mentions related to the process of communication or a lack thereof and possibilities for engagement with WT

Sub-theme: Digital technologies

Code: Opinion about the noise app: different opinions about the noise app, ideas about how trust matters for the overall opinion about the noise app, how the opinion changed over time (e.g. if people 'gave up 'on it over time or change their mind based on the user experience)

Code: Drawing conclusions from app data: how results about what is annoying about wind turbine noise and under what conditions are drawn based on the app

Theme: overflows/controversies

Sub-Theme: Noise as a matter of concern

Code: Definitions of noise: ways in which different respondents explain what wind turbine noise means and what kinds of noise exists and are annoying

Code: Concern about the impacts of low-frequency sound: this includes mainly health-related concerns for humans such as brain damage, stress, hearing problems, heart disease, but also impacts on animals (cows, wildlife)

Code: Experience of low-frequency sound: this includes stories of people bodily experiences of LFS: people experience it as a sort of vibration, amplified by their house, people explain it as long sound waves that can travel through the ground for long distances, some people make a distinction between LFS and 'brom' tone, others do not.

Code: 'brom' tone: the ways in which residents experience it

Code: Noise by blades: how respondents characterise it and compare to other kinds of WT noise

Code: ‘lasten, niet de lusten’: this code represents the negative sentiment towards noise as an externality- that residents hear wind turbine operate but do not receive any benefits form them developers/landowners do- this gives the wind turbine sound a negative association

Code: Adapting/living with noise in everyday life this code includes collection of information about how residents adopt to the presence of WTN/ LFN/brom tone and deal with noise annoyance. For the people who are very annoyed this includes changes to lifestyle such as new patters of recreation and relaxation (both inside and outside home), changes to the bedtime routine and sleep time, altered perceptions of comfort and safety at home.

Code: *Spatio-temporal context:* this include information about the effect of landscape and vegetation on perceived noise annoyance and when during day/night it is experienced. For example, vegetation is very important in shielding them form noise or that the ‘brom tone’ is most annoying at night, and why (no other environmental noises that would mask the ‘brom’ tone and sound of blades.)

Code: *Wind turbine technology/design:* residents own ideas about how design/ selection of wind turbines or how the design could be improved, concerns about malfunctioning turbine or about a wrong choice in the WT model

Code: management of wind farms/ smart operation*:* this includes the information that residents shared about their expectations for what noise modes will be implemented, how wind farm will operate, the promises that were made about the noise levels

Sub-theme: Demarcations and decision-making

Code: 2 km distance: how people make sense of the 2 km demarcation for the app- ideas about whether noise can be heard outside of 2km but, presence of LFS or the hum tone

Code: *Legislative context:* opinions the current Dutch legislation for noise - especially the contestations of the rule that the noise limits are based on a yearly average rather than an absolute daily maximum and the fact that there is no legislation for LFS/tonality

Code: *Communication about noise* opinions about the process of receiving information, searching for information about the noise app, and potential misinformation about the noise

Code: *Finding solution and taking responsibility for noise:* perceptions about of collective/ individuals’ ideas about who should be responsible for providing data about noise annoyance, to solve the issue or to adapt to and how to manage the wind farm

Code: *Fairness of solutions*: perceptions about the fairness of proposed solutions, also in relation to financial compensation

Code: *Socio-economic context;* ideas about how the issue of noise relates to other wind energy projects in the Netherlands and to the trends in governance of wind energy developments (how the needs of local communities are accounted for/ or not)

Code: *Connected concerns:* this includes shadow flicker (minor concern), obstruction lights (major concern)

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The SENSE Research School declares that **Helena Maria Solman** has successfully fulfilled all requirements of the educational PhD programme of SENSE with a

work load of 44.7 EC, including the following activities:

SENSE PhD Courses

- Environmental research in context (2018)
- Data quality and data visualisation in sustainability science, PBL & SENSE (2018)
- Research in context activity: 'Video Pitch of My PhD Research and UPWARDS project' (2020)

Other PhD and Advanced MSc Courses

- Data quality and data visualisation in sustainability science, PBL & SENSE (2018)
- Advanced Sociological Theory, Wageningen University (2018)
- Scientific writing, Wageningen Graduate Schools (2018)
- Writing retreat, ENP & WIMEK (2018)
- Expertise at stake: technoscience and public participation in the post-truth age, STS Italia (2019)
- Writing retreat, Energy Geographies Research Group, UK (2019)
- Sociology and political science of environmental transformations, ENP (Wageningen University; 2020)

Selection Management and Didactic Skills Training

- PhD Representative at ENP and PhD representative to the cluster (2019-2021)
- Member of WUR Energy Alliance (2021-2022)
- PhD wellbeing committee (2021-2022)
- ETIP wind steering committee (2022)
- Supervising BSc student (2019-2020) and two internship students (2019-2021)
- Assisting in the BSc course 'Sustainable Solutions to Environmental Problems' (2019), MSc course Environment and Development (2020), MSc course 'Theories on Politics and Governance' and the MSc course 'Academic Consultancy Training'(2021)

Oral Presentations

- *Public engagement in design of wind turbines- the premises and the limits of user- centred design of sustainability technologies and their landscapes*. 4S Conference, 18-21 August 2020, online
- *Digitalisation in wind farm management: what are we sensing?* Digital geographies Critical perspectives on the platform economy, 28-29 October 2021, online
- Panel discussion "*Science without Jargon*" COP26 11th November 2021, Glasgow, United Kingdom

SENSE coordinator PhD education

Dr. ir. Peter Vermeulen

About the author

Helena was born in 1993 in Poznan, Poland. In 2012, Helena moved to the Netherlands, where she got a Bachelor of Science in Tourism, a joint degree of Breda University and Wageningen University & Research. After the Bachelor, she continued with a master's degree in Landscape Architecture and Spatial Planning.

After her studies, Helena worked for a year as a consultant, helping to establish a Food Council for Amsterdam Metropolitan Region. In 2019 she started a PhD at the Environmental Policy Group (ENP) at Wageningen University & Research. Her research was part of an EU funded project called UPWARDS- a multidisciplinary consortium focused on wind turbine innovation.

Helena participates in several networks focused on wind energy and digitalisation, including a current membership in the ETIP Wind- a European Technology Platform on Wind Energy in which she advises on priorities for research and innovation in wind energy in the EU.

During her PhD Helena visited the STS group in Graz, where she spent a month working intensively on her third paper. She also visited the SMP group at the Danish Technical University in Denmark, where she worked with Julia Kirch Kirkegaard and Tom Cronin. Together with other researchers at DTU, David Rudolph, Sophie Nyborg and with Elisabeth Gill at NRL in USA, they wrote a paper titled "Grand Challenges in Wind energy Research"- the Social Science response.

In 2022 Helena finished writing her thesis and left to travel around South America. In May 2023 she started a Postdoc position at ENP.

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