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Published in:
Environmental Science and Policy

Link to article, DOI:
10.1016/j.envsci.2021.10.027

Publication date:
2022

Document Version
Publisher's PDF, also known as Version of record

Link back to DTU Orbit

Citation (APA):
Solman, H., Kirkegaard, J. K., Smits, M., Van Vliet, B., & Bush, S. (2022). Digital twinning as an act of governance in the wind energy sector. *Environmental Science and Policy*, *127*, 272-279. https://doi.org/10.1016/j.envsci.2021.10.027

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Environmental Science and Policy 127 (2022) 272–279

Contents lists available at ScienceDirect

Environmental Science and Policy

journal homepage: www.elsevier.com/locate/envsci

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

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ARTICLE INFO

Keywords:
Digital twins
Wind energy
Co-production
Governance by design
Boundary work

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.

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 (Dembski et al., 2020; Nochta et al., 2020; Bauer et al., 2021). 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 and 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 and 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).

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https://doi.org/10.1016/j.envsci.2021.10.027
Received 30 March 2021; Received in revised form 18 September 2021; Accepted 22 October 2021
Available online 8 November 2021
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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 et al., 2021). For example, the increasing concern about the impacts of wind turbines on landscapes (Stremke, 2010), wildlife (Arnett and 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 (building on Latour, 2004, Jasanoff, 2016, Harbers, 2005); 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.

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, 1991); 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. Fig. 1 (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.

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 (Leigh Star, 2010) in how boundary objects coordinate work of the different actors, despite and sometimes because of the

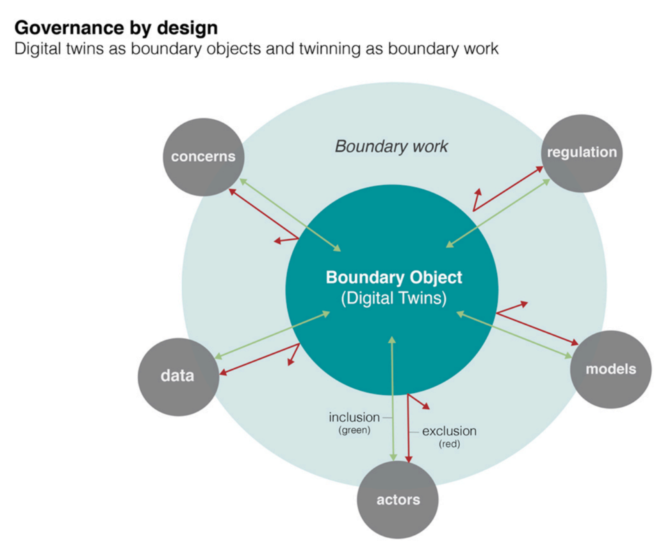

Fig. 1. Twinning as an act of governance: the emergence of digital twins as boundary objects through boundary work.

difference in meanings (see Tharchen et al., 2020). Following this line of 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 (Rundstrom, 1995; Howe, 1988). In this way, the making of boundaries holds consequences for whose matters of concern are incorporated and which are not (Funtowicz and 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 (ispired by Toonen and Bush, 2020, Judson et al., 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 (Nochta et al., 2020; Bauer et al., 2021).

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 (summarised in Appendix A). 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 A). 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 15 MW 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.

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.

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.

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.

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.

Table 1
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'

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 and 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 (Wagg et al., 2020; Jones 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 and 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'.

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 and Rosner, 2017 p. 998). 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 and 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 (Labussière and Nadaï, 2014; Kirch Kirkegaard et al., 2020). 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, 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.

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, 1991 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; Macnaghten et al., 2005; Owen et al., 2012; Kirkegaard and Nyborg, 2020).

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 (Rip and Te Kulve, 2008; Guston and Sarewitz, 2002; Joss, 2002).

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.

Funding

This work was supported by the European Union's Horizon 2020 Research and Innovation programme [grant numbers 763990, 2018].

CRediT authorship contribution statement

Helena Solman- CRediT roles: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Visualization; Writing - original draft; Writing - review & editing, Julia Kirch Kirkegaard- CRediT roles: Conceptualization, Visualization, Methodology, Writing - original draft; Writing - review & editing, Mattijs Smits- CRediT roles: Conceptualization, Funding acquisition, Methodology, Project administration, Supervision, Visualization, Writing - original draft; Writing - review & editing, Bas van Vliet- CRediT roles: Conceptualization, Methodology, Supervision, Visualization, Writing - original draft; Writing - review & editing, Simon Bush- CRediT roles: Conceptualization, Methodology, Supervision, Visualization, Writing - original draft; Writing - review & editing.

Declaration of Competing Interest

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

Acknowledgements

Many thanks to Tom Cronin for sharing his expertise on wind energy technologies, to Emily Liang for her support in science communication and in visualisation, to Iryna Lunevich for help in organising the workshop and to Jaap Toet for personal coaching. Thank you all for your genuine support.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.envsci.2021.10.027.

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