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Innovation systems for technology diffusion: An analytical framework and two case studies

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ABSTRACT

Existing theories on the diffusion of innovations fail to sufficiently account for contextual factors such as institutions, infrastructure, and supply-side dynamics. This paper presents a novel framework to analyse technology diffusion from a sociotechnical systems perspective, intended as an analytical tool to identify and assess drivers and barriers to diffusion that could be addressed through policy or business strategy. This framework, referred to as the *diffusion innovation system* (DIS) approach, is positioned within the innovation systems literature. The framework is applied to two empirical cases of renewable energy technology diffusion in Sweden: solar photovoltaics (PV) and wind power. The cases illustrate how key factors related to institutions, infrastructure, adopters, and supply co-develop over time as the technologies diffuse, hence demonstrating the merits of the framework. As these changes are both a reaction to and a cause of diffusion, the sociotechnical diffusion system develops through positive feedback loops. Although the systems' development is largely conducive of diffusion, some remaining and potential barriers are identified.

1. Introduction

The diffusion of innovations – i.e., the process through which a new technology is adopted by an increasing number of actors throughout society – is important for economic, social, and ecological sustainable development. For example, to mitigate climate change, renewable energy technology diffusion is needed. Understanding how different factors shape diffusion patterns is important as this helps policy makers and business leaders facilitate diffusion.

There is a broad and diverse literature on how innovations emerge and diffuse. First, sociotechnical systems approaches to technological transitions (Markard and Truffer, 2008; Weber and Rohracher, 2012) such as the multi-level perspective (e.g. Geels, 2010, 2002; Schot and Kanger, 2018; Smith et al., 2010) and different innovation system frameworks (e.g. Binz and Truffer, 2017; Carlsson and Stankiewicz, 1991; Edquist, 1997) emphasise factors beyond the diffusing technology itself and its adopters, including dynamic and complex relationships between institutions and actor networks. These approaches traditionally treat technology development, production, and diffusion as occurring together in one and the same system, typically not emphasising the diffusion part. While these approaches suit immature technologies struggling to diffuse beyond their earliest applications, they are not appropriate to analyse the diffusion of more mature technologies (Mignon and Bergek, 2016). For example, the technological innovation systems approach has been widely used as a hands-on analytical tool for informing policy on how to support e.g. renewable energy technologies and electric vehicles in early stages of these technologies' development. However, several sustainable technologies are now mature and (ready to) diffuse beyond their initial markets. Hence – as stated in recent calls for research in the sociotechnical transitions literature (Köhler et al., 2019; Mignon and Bergek, 2016; Palm, 2017a) – there is a need for a diffusion-focused system-oriented analytical tool.

There is also a comprehensive literature more exclusively focusing on diffusion, disregarding technology development and production (Dedehayir et al., 2017; Peres et al., 2010; Rogers, 2003). This literature, however, tends to emphasise the role of adopters and their social networks, and of the diffusing technology itself, rather than broader societal factors. Although it is known that various contextual factors shape diffusion, including cultural, economic, political, social, and geographical ones (Grübler, 1991; Peres et al., 2010; Wejnert, 2002), there is a lack of comprehensive theories on the role of such factors in diffusion, and established analytical frameworks and models (Bass, 1969; Fisher and Pry, 1971; Keller, 2004; Norton and Bass, 1987; Rogers, 2003; Utterback et al., 2018) fail to give them sufficient attention.

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Such ‘non-systemic’ diffusion approaches are appropriate for technologies whose diffusion patterns are not too dependent on the broader societal context, including for example various agricultural equipment and consumer durables (assuming that an electric grid is already in place). However, these approaches are insufficient for explaining the diffusion of technologies that depend on contextual factors beyond adopters and their social networks, including many technologies considered necessary for a sustainability transition. For example, clean energy and transportation technologies often require legislative, infrastructural, and entrepreneurial changes and activities to reach widespread adoption (Mignon and Bergek, 2016).

On those grounds, the present paper introduces a hands-on, analytical framework for analysing technology diffusion, taking the sociotechnical context into account. The framework is positioned within the innovation systems literature and draws on value chain literature and various case studies and reviews of innovation diffusion and technological change. The framework – referred to as the *diffusion innovation system* (DIS) approach – is demonstrated using two case studies of renewable energy technology diffusion.

The rest of the paper is structured as follows. In the next section, the innovation systems literature is briefly reviewed, and the need for and appropriateness of a diffusion-focused innovation system approach is justified. In Section 3, the novel DIS framework is presented. Section 4, demonstrating the merits of the framework, applies it to the two empirical cases. A synthesis of the cases' findings, together with overall conclusions, are presented in Section 5.

2. Innovation systems: space and value chains

2.1. Existing approaches

The innovation systems literature emerged in the 1990s, emphasising that innovation processes unfold through complex interrelations between various actors and institutions (Edquist, 1997). Over time, innovation system approaches became dominant in generating innovation policy recommendations (Weber and Rohracher, 2012). Various innovation system approaches have been presented, differing from one another in how they delimit the system under study. Established approaches include *national* (Lundvall, 2010; Sharif, 2006), *regional* (Cooke et al., 1997), *sectoral* (Malerba, 2002), and *technological* (Bergek et al., 2008; Carlsson and Stankiewicz, 1991) innovation systems. The latter differs from the others in that it is delimited to one single technology.

Common to these approaches is that they treat the development, production, and diffusion of new technologies as occurring together in one and the same sociotechnical system with uniform geographical boundaries for the whole system. Recent efforts have sought to nuance the understanding of innovation systems' relationships to space. For example, spatially coupled innovation systems have been conceptualised, in which two interdependent systems at different places together develop and diffuse a technology (Binz et al., 2012; Quitzow, 2015). Furthermore, the *global innovation systems* framework has been introduced for transnational, multi-locational, and multi-scalar innovation processes (Binz and Truffer, 2017). The global innovation systems literature emphasises that a technology can be developed and diffused jointly by local and global actors, and that value chain segments often differ from one another in how they relate to space as their respective activities pertain to different geographical areas and scales (Hipp and Binz, 2020; Rohe, 2020). This makes it inappropriate to apply the same geographical system boundaries to innovation systems that cover the entire value chain (Binz and Truffer, 2017).

A global innovation system contains *subsystems* of actor networks and institutions that contribute to the creation of certain system resources for the global innovation system, and whose boundaries may or may not correspond to political borders (Binz and Truffer, 2017). However, the conceptualisation of these subsystems remains rather crude. For example, it is unclear how different kinds of subsystems emerge and extend over space and value chains, and how their inner workings play out. The present paper introduces a hitherto unexplored kind of subsystem, namely that for the *diffusion* of innovations – i.e., the DIS. DIS's are here considered to contribute to the global innovation system by strengthening the system resource *market formation* (cf. Binz and Truffer, 2017). In the next subsection, the appropriateness of delimiting innovation systems for diffusion is justified.

2.2. The case for diffusion-focused innovation systems

In a systems approach, meaningful system boundaries should be defined (Kast and Rosenzweig, 1972; Sandén et al., 2008) so that elements within the boundaries interact much more among each other than with elements beyond the boundaries (Simon, 1991). Two critical dimensions for innovation system boundary setting are *space* and *value chain* (Sandén et al., 2008). As stated, however, uniform spatial system boundaries rarely suffice throughout a technology's value chain, making it challenging to set meaningful geographical system boundaries in conventional innovation system studies. However, the present paper argues that the *diffusion* of mature technologies tends to occur in sociotechnical systems – DISs – with meaningful system boundaries in space and value chains.

A DIS is delimited to a value chain's most downstream parts. The value chain literature discusses *modularity*, i.e. the tendency of value chains to split into segments (modules) with *break points* between them (Sturgeon, 2002). Between value chain modules, flows of information and artifacts are highly standardised (Gereffi et al., 2005). In the current global economy, technologies are often highly standardised and traded nearly as commodities on a global market, and there is a general and persistent trend towards increasingly globalised and modularised value chains in various sectors (Binz and Truffer, 2017; Gereffi et al., 2005; Hipp and Binz, 2020; Menzel and Adrian, 2018; Sturgeon, 2002; Sturgeon et al., 2009). Hence, technologies – also relatively complex ones – can be imported and deployed in new contexts regardless of where they are produced and without much producer involvement. This implies that there is often a natural value chain system boundary – a ‘break point’ – between production and diffusion.

As technologies mature, they attain a dominant design and get increasingly standardised (Grübler, 1991), meaning that a value chain break point (albeit differently pronounced for different technologies) forms between production and diffusion. Furthermore, mature technologies tend to diffuse simultaneously in multiple markets around the world, leaving each individual market less influential over the technology's upstream value chain, or its entire global innovation system (although several small markets together may have a large impact). Immature technologies, on the other hand, tend to show deep interdependencies between production and diffusion (Mignon and Bergek, 2016).

On the spatial dimension, the conditions affecting diffusion tend to be quite locally determined, and political borders (e.g. of a nation) can hence often serve as meaningful system boundaries for a DIS. Institutions shaping diffusion mainly reside on the national level (Wejnert, 2002), and actor networks engaged in technology deployment are often local (Neij et al., 2017). To take a trivial example, dishwasher installers naturally target local markets while manufacturers sell globally. Even within the relatively well-integrated European Union, national borders are significant barriers delimiting the activities of small and medium-sized enterprises (Leick, 2012). International firms engaging in deployment tend to establish local offices to cope with the peculiarities (language, culture, institutions, etc.) of each national market, at which native staff members are often critical for success (Birkinshaw et al., 1998; Fang et al., 2010). Hence, national system boundaries are, if not perfect, often meaningful as an analytical construct when studying diffusion.

3. Diffusion innovation systems: an analytical framework

This section identifies factors that, from a sociotechnical systems perspective, tend to affect the diffusion of innovations. These factors are packaged into an analytical framework – the DIS approach – consisting of four key processes that, when developing properly, tend to bring a technology towards widespread diffusion (although all four processes are not necessarily critical for all technologies or contexts). The framework is intended for relatively mature technologies that are non-trivial to deploy. While the DIS framework is here positioned in the innovation systems literature, it should be seen as part of the broader literature on technological transitions.

The idea of basing the framework on processes derives from the insight that the mechanisms behind diffusion are not uniform throughout the diffusion trajectory. What drives or hinders diffusion at an early stage might not be what matters later on (Grübler, 1991). Hence, a dynamic framework, highlighting *changes* along the trajectory, is adequate. This idea resembles that of the technological innovation system 'functions' (see Bergek et al., 2008). Just like these functions, the DIS processes serve to capture (actual or needed) change in the system over time, enabling the identification and assessment of barriers and drivers to the proliferation of new technology. Unlike the technological innovation system functions, nevertheless, the DIS processes focus on *diffusion*.

Below, the four key processes are introduced, including sets of subprocesses. The processes are derived through a categorisation of sociotechnical factors found by previous research to affect and co-evolve with diffusion. One key process relates to *institutions*, a second to *infrastructure*, while the other two relate to *actors* supplying or adopting the technology, respectively. These broad categories, which are intended to cover the most relevant sociotechnical factors interacting with diffusion, were derived from literature on innovation diffusion and technological change. While most diffusion studies do not consider all of these factors, scholars on the broader patterns of technology diffusion and technological change tend to agree that they are often crucial for diffusion (e.g. Freeman and Louçã, 2001; Grübler, 2003, 1991; Peres et al., 2010; Wejnert, 2002).

Once these categories had been identified, they were translated into processes. Various historical or contemporary cases (referred to in the subsections below) of how the abovementioned factors have co-evolved with technology diffusion were identified by exploring the literature. These cases informed the conceptualisation of the processes, which were labelled *institutional alignment*, *infrastructural buildout*, *market segment accumulation*, and *value chain module formation*.

See Fig. 1 for a schematic illustration of the framework. The main input to the DIS is standardised technical artifacts emanating from other subsystems of the focal technology's global innovation system. The outcome of the four key processes is diffusion of the focal technology within the DIS. It should be noted that significant interaction, for example by mutual reinforcement, should be expected between processes as they unfold.

It should also be noted that as a technology diffuses within a DIS, some degree of innovation (i.e. not only diffusion thereof) may occur within the system. For example, local innovation related to infrastructure, business models, or complementary equipment adapted for the local context may occur to facilitate diffusion.

As the framework focuses on the system's *development*, it does not (in its current form) emphasise factors that tend to be static or change independently of the technology's diffusion, such as climate, corruption, GDP, natural resources, or physical geography. Such factors could, nevertheless, be included in a DIS analysis by e.g. allocating them to one of the processes (e.g. to *value chain module formation* if they are considered important by entrepreneurs entering the value chain module).

Regarding limitations of the DIS framework, there are cases of diffusion where other theoretical approaches may be more adequate. First, very early stages of diffusion of an immature technology may be better analysed through the technological innovation systems approach, as diffusion tends to be deeply intertwined with technology development and production for immature technologies. Second, technologies whose diffusion depends mainly on the characteristics of adopters and their social networks, and only to a minor extent on broader societal factors, are better analysed through e.g. Rogers' (2003) framework.

3.1. The 'rules of the game': institutional alignment

Institutions are humanly devised rules for governing human behaviour, including legislation, technical standards, established procedures, and informal collective mind frames (North, 1994). Institutions not only constrain but also enable behaviour (Cardinale, 2017; Hodgson, 2006), and they are crucial for shaping technological change and economic development (e.g. Edquist and Johnson, 1997; North, 1994).

Institutions often affect technology diffusion (Fichter and Clausen, 2016; Freeman and Louçã, 2001; Wejnert, 2002), e.g. by reducing uncertainties, managing conflicts and cooperation, or providing incentives (Edquist and Johnson, 1997). They can obstruct as well as facilitate diffusion (Peres et al., 2010). For example, mobile phone diffusion has required both deregulation and the creation of new rules in various countries, including standards and operator licence allocation procedures (Botelho and Pinto, 2004; Gruber, 2001; Singh, 2008).

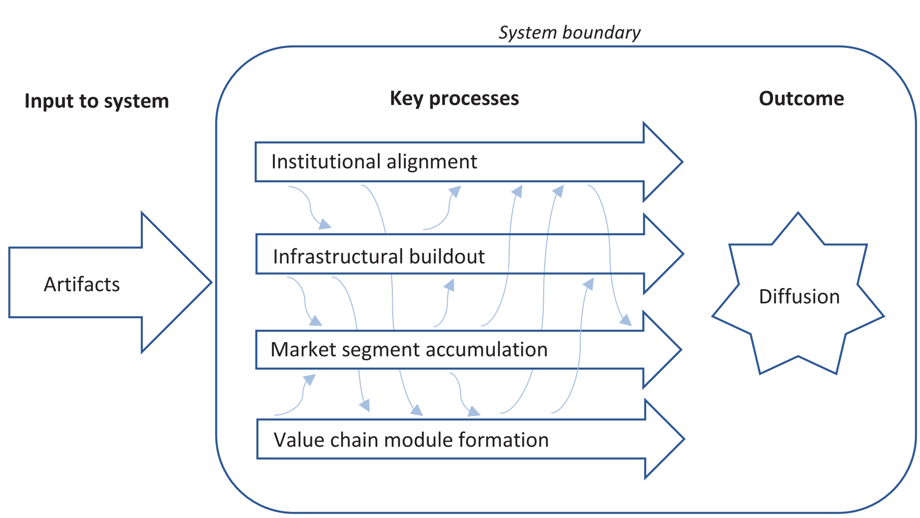

Fig. 1. Schematic illustration of the DIS framework. The thin arrows indicate that processes may influence each other.

Hence, for widespread diffusion to occur, institutions must often be altered, added, or removed. This process is here referred to as *institutional alignment*. In this process, institutions can be 'imported' from other countries (Fuenfschilling and Binz, 2018), often with some adaptation (e.g. Lundin, 2004), or designed from scratch. Institutional alignment is, nevertheless, often an arduous, time-consuming process (Edquist, 1997; Unruh, 2000). High legitimacy (alignment of an informal institution) for the technology facilitates the alignment of formal institutions as legitimacy makes policy makers more prone to implement supportive policies (Markard et al., 2016). Conversely, low legitimacy can impede the alignment process, which has for example been the case for genetically modified crops (Murphy et al., 2006).

The present paper distinguishes between four kinds of institutional alignment:

- *Enabling* the use of the technology. For example, in many countries autonomous vehicles will require rule changes to be allowed on public roads (Hansson, 2020).
- *Clarifying*, thus reducing uncertainties among adopters and suppliers. Existing rules may be difficult to interpret in relation to the new technology (Moses, 2003), and it may be difficult to predict how the ruleset will change. For example, regulatory unclarity has obstructed the diffusion of novel practices in the Dutch concrete industry (Vermeulen et al., 2007), smart food packaging in Europe (Heiskanen et al., 2007), drones in journalism and agriculture (Frankelius et al., 2019; Holton et al., 2015), and renewable energy technologies around the world (Painuly, 2001). Furthermore, a lack of technical standards can create confusion, hampering diffusion (Grübler, 2003).
- *Constraining* harmful use of the technology, thus protecting third parties (Jalonen, 2011) who could otherwise oppose and obstruct diffusion (Grübler, 2003). Constraining institutions can thus enhance the technology's legitimacy and reduce uncertainties. Once widely accepted restrictions are in place, suppliers and adopters can feel more confident about future institutional stability. For example, lacking regulation of Segways and electric scooters has been followed by sudden bans in some European cities while others have implemented more balanced constrains, thus creating a pathway for acceptable diffusion (Lipovsky, 2020; Varga, 2020). Furthermore, ethical concerns regarding drones have evoked much discussion on how they should be constrained (Culver, 2014).
- *Incentivising* adoption of the technology, which can be achieved through e.g. subsidies or other special treatment (Stoneman and Diederen, 1994). For instance, electric vehicles in Norway have been granted access to transit lanes and exemption from toll fees (Aasness and Odeck, 2015). As technologies tend to decrease in cost as they mature, subsidies may only be warranted in early stages of diffusion. Failure to reduce subsidies in due time can create adverse effects including escalating public spending, hence legitimacy problems (Aasness and Odeck, 2015; del Río and Mir-Artigues, 2012). Hence, 'alignment' can, depending on the stage of diffusion, mean both the introduction and phase-out of subsidies to keep incentives at an adequate level throughout the diffusion trajectory.

The distinction between constraining and enabling institutions is well established within institutional theory (Cardinale, 2017). The 'clarifying' subprocess was included in the DIS framework based on the established understanding in the literature on law and innovation that legislation is often hard to interpret in relation to new technologies (e.g. Moses, 2003). Finally, the 'incentivising' subprocess was included based on current trends of governmentally supporting the deployment of certain innovations related to e.g. climate change mitigation or socio-economic development.

3.2. Related technical systems: infrastructural buildout

Technology diffusion often depends on adequate infrastructure being available (Freeman and Louçã, 2001; Grübler, 1991; Mignon and Bergek, 2016; Negro et al., 2012; Painuly, 2001). This dependence has increased over time (Grübler, 2003, pp. 36–38). Hence, *infrastructural buildout* is often needed for diffusion to occur. For example, mobile phone diffusion presupposes the deployment of a base station network, and vehicles need roads and fuelling infrastructure. While some infrastructures, such as roads or electric grids, are of a general-purpose nature and have already reached a high coverage in many countries, the diffusion of innovations often requires the buildout of additional infrastructure. (It should be pointed out, though, that a *lack* of infrastructure can sometimes support diffusion; for example, mobile phone payments, while needing sophisticated telecom infrastructure, diffuse more rapidly where there are fewer banks and cash machines (Lashitew et al., 2019).)

This paper distinguishes between three kinds of infrastructural buildout:

- *Augmentation* means that an existing infrastructure, that has already reached a large coverage to cater for previous technologies, is enlarged or reinforced (without fundamentally changing its key features) to meet the needs of the new technology. For example, nuclear power diffusion often requires reinforcement and expansion of electric grids (Rashed et al., 2017).
- *Add-on* means that new features are added to existing infrastructure. For example, charging stations must be added to the electric grid to charge electric vehicles, and equipment must be added to gasoline stations to allow for the refuelling of biofuel cars.
- *Establishment* means that a new (for the focal DIS) kind of infrastructure network is built from scratch. For example, telephone diffusion required completely new wire networks.

The distinction between these three kinds of infrastructural buildout is, to the best knowledge of the author, novel, at least in the diffusion of innovations literature. They are derived through the author's own categorisation of different cases of infrastructure buildout or dependence related to technology use or diffusion identified in the literature.

3.3. The user side: market segment accumulation

For diffusion to occur, someone must start using (adopt) the technology. As some actors will be inclined to adopt earlier than others, and some ways of using the technology may proliferate before others, different market segments will emerge and expand at different times, adding to the cumulative diffusion. This process is here referred to as *market segment accumulation*.[1] The order in which segments gain traction may depend on, for example, differences in regulations or return on investment between sectors or applications.

Private individuals as adopters have received much attention in the diffusion literature. Among individuals, the earliest adopters are often driven by a fascination for the technology and may accept substantial hassle and high cost to adopt. By contrast, later private individual adopters tend to be more pragmatic and deterred by hassle (Dedehayir et al., 2017; Rogers, 2003).

Other adopter categories include organisations such as private enterprises or public entities. These have diverse motives and

[1] This concept resembles that of *niche accumulation*. However, niche accumulation is mainly associated with parallel processes of technology development and diffusion, emphasising immature technologies' gradual improvement as they reach new niche applications (Levinthal, 1998; Raven, 2007). *Market segment accumulation*, by contrast, was here chosen as a distinct term for mature technologies diffusing through (niche or mainstream) segments.

preconditions, and their earliness of adoption may depend on, for example, their capabilities, expected return investment, or whether they host a 'champion' advocating for adoption (Wisdom et al., 2014). They may also apply the technology in different ways.

Hence, this paper distinguishes between three parameters on which market segment accumulation can occur:

- *Innovativeness,* meaning that the propensity to quickly adopt innovations varies between individual actors within a certain actor category, such as private individuals (Rogers, 2003) or a certain kind of organization (Wisdom et al., 2014).
- *User categories*, meaning that a technology may diffuse earlier among certain actor categories or sectors than others. A technology may, for instance, diffuse among households before firms or vice versa. Another example is drones for the particular application of aerial footage diffusing earlier in agriculture than in journalism (Holton et al., 2015).
- *Applications,* meaning that some ways of using the technology occur before others. In fact, as a technology matures, "[a]lthough the number of radically different designs diminishes in favor of a few demonstrated alternatives, these continue to be modified and adapted for increasingly diverse and remote applications" (Grübler, 2003, p. 52). For example, subsequent to aerial footage, package delivery is expected to become a major application for drones (Stolaroff et al., 2018).

Although the precise term 'market segment accumulation' is novel, it is a well-established fact in the diffusion of innovations literature that different market segments tend to accumulate over time (e.g. Rogers, 2003). Rogers' *innovativeness* concept is perhaps the most established parameter on which this can occur. The distinction between the three parameters above is, nevertheless, not established in the literature but was developed for the DIS framework following a categorisation of different market segments found in the literature to often appear in sequence.

3.4. The supply side: value chain module formation

The deployment of technologies, even standardised ones, may call for the involvement of various entrepreneurs. Hence, a *value chain module* for deployment will form within the DIS, delimited from upstream value chain segments by a 'break point' through which standardised products are traded (cf. Gereffi et al., 2005), see Fig. 2. Tasks within this module may, depending on the technology's characteristics, include activities such as physical installation of artifacts, permit acquisition, project development, customer acquisition, O&M, or knowledge support. However, it takes time for entrepreneurs to learn and develop their businesses, and a lack of skilled entrepreneurs often impedes diffusion (Fabrizio and Hawn, 2013; Negro et al., 2012; Painuly, 2001).

Expectedly, the value chain module will first develop basic tasks needed to cater for the needs of the earliest adopters, such as sales and installation of artifacts without much support. To appeal to less innovative adopters, and for the technology to be feasible in subsequent applications or sectors, additional services and specialisation may be required. Hence, the value chain module over time will grow to incorporate a broader palette of activities. Local learning within the module can also contribute to price reductions over time (Strupeit and Neij, 2017).

Depending on the technology, different degrees of interaction with the DIS's environment (e.g. other subsystems of the global innovation system) can be expected. In a DIS with clear-cut system boundaries, the module's activities are almost exclusively carried out by actors based within the geographical boundaries of the DIS. However, for tasks with large complexities or economies of scale, large and resourceful actors may be substantially involved. This may require the involvement of external (international) actors, particularly at early stages of the DIS's development. Complex tasks may thus first be performed by external actors to later be taken over by local actors as they learn (e.g. through spillover from the external actor), or as the local market grows to support economies of scale. Hence, this paper distinguishes between two mechanisms through which the value chain module could materialise:

- *Local entrepreneurship*, where actors based within the DIS establish new businesses or diversify themselves to engage in deployment. Local entrepreneurs may 'copy' (with some level of adaptation to the local context) business models from lead markets, or develop their business through trial and error.
- *Seeding,* where firms based outside the DIS engage in deployment within it, establishing significant local presence in terms of e.g. offices and native staff. Over time, local actors may gradually take over certain tasks.

While the concept of value chain module is established in the value chain literature, it is not established (if it has ever occurred) in the diffusion of innovations literature. The above distinction between two ways in which a value chain module can form is not established but was derived by the author from generally accepted knowledge on economies of scale, spillover, and local learning.

4. Applying the DIS framework: renewable energy technology diffusion in Sweden

In this section, the DIS framework is demonstrated by being applied in two case studies: solar PV and wind power diffusion in Sweden. These cases each represent a DIS of its own, delimited by the Swedish national border. Below, the case selection rationale and the research methods are first outlined. Then, the empirical results are presented.

4.1. Case selection and research methods

The cases of wind power and PV in Sweden were selected for the following reasons. First, these technologies are rather mature and are diffusing in Sweden while being developed and produced in other

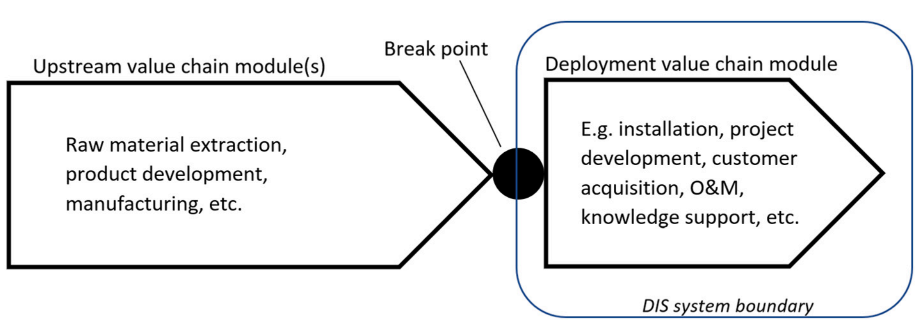

Fig. 2. A value chain module for deployment is formed within the DIS.

countries. Hence, these cases fit the scope of the DIS framework.

Second, PV and wind power – albeit both being renewable energy technologies – are fundamentally different regarding value chain and deployment logics (Binz and Truffer, 2017; Schmidt and Huenteler, 2016). These differences help illustrate the general validity of the framework. More skills and resources are needed for deploying and maintaining wind power than PV, inducing other actor types to engage in wind power than in PV deployment. Due to different physical properties (such as size) between wind turbines and PV modules, differences in institutional and infrastructural conditions can also be expected. Furthermore, wind turbines are less standardised, and their deployment requires more user-producer interaction than for PV modules (Malhotra et al., 2019). Hence, while PV has mainly diffused in regions where it is not produced (Binz et al., 2017), wind power production and diffusion have historically been more geographically interconnected (Garud and Karnøe, 2003; Schmidt and Huenteler, 2016), although increasing standardisation of wind turbines has entailed increasing spatial decoupling between production and diffusion (Rohe, 2020). Hence, both technologies' value chains have modularity 'break points' between manufacturing and deployment, although more pronouncedly so for PV.

A combination of research methods was used. For both cases, interviews and secondary data were important. Apart from academic articles, various non-academic reports issued by e.g. trade organisations or governmental bodies were used. For the PV case, an interview set performed for another study (Palm, 2015) was revisited. In addition, twelve complementary interviews, typically lasting 30–60 min, were performed in 2020 with actors in construction and building-integration, as these had recently become more involved in PV deployment. For the wind case, the need for interviews was smaller due to an abundance of industry reports. Seven interviews lasting 15–60 min were performed with experienced wind power project developers to resolve remaining issues after analysing the secondary data.

4.2. Results: solar PV

Sweden hosts a rapidly growing solar PV market, see Fig. 3. In 2020, solar electricity accounted for around 1 % of total Swedish electricity production, which is several times more than just a few years earlier. Below, the historical and present development of the Swedish DIS for solar PV is outlined.

4.2.1. Institutional alignment

Prospective Swedish PV adopters have often experienced substantial institutional uncertainties (Palm and Tengvard, 2011; Wallnér, 2015). For example, rules were previously lacking regarding whether, and at what charge, utilities should connect residential PV to the grid, and the process could be lengthy and end up expensive for adopters (Palm and Tengvard, 2011). In response to these issues, a game-changing *enabling* and *clarifying* legislative change was implemented in 2010 obliging utilities to connect residential PV to the grid at no charge under normal circumstances (Palm, 2015).

Permitting for PV deployment has largely been handled within the pre-existing institutional setup, which lacked clarity on how to deal with PV technology. Building permit processes have hence – particularly in the early stages of diffusion – caused uncertainty, delays, and fees (Sandén et al., 2008). However, municipalities gradually improved their processes as they learned how to deal with PV, and in 2018 *enabling* and *clarifying* national legislation was passed to abolish building permit requirements for rooftop PV that follows the roof's inclination and that is not installed on buildings of high cultural or historical value. For ground-mounted PV, the county administrative board must concede, considering societal interest such as farmland availability. This creates unpredictability as clear PV-specific guidelines are lacking, revealing a need for further *clarifying* alignment.

Tax rules have also been unclear. Pre-existing rules were sometimes interpreted so that even residential adopters had to register for value-added tax and pay energy tax on their self-consumed electricity. Apart from hassle and costs for adopters, the governmental administration of these practices was costly in relation to their revenues. In the mid-2010s, tax legislation was hence *clarified* so that residential adopters were normally exempt from these requirements.

Following new legislation in 2012, a (voluntary) certification scheme for installers was introduced. As prospective adopters have experienced uncertainties in finding trustworthy installers (Wallnér, 2015), this has a *clarifying* effect. For PV system components, international standards have been adopted in Sweden. In this regard, standards are an exception as institutional alignment has otherwise largely occurred independently of institutions in other countries.

There have also been subsidies *incentivising* PV adoption. Most importantly, an investment subsidy was introduced in 2005 in a rather ad-hoc manner. Although this was key to boost the market (Sandén et al., 2008), it had design flaws resulting in uncertainties and long waiting times for adopters (Palm, 2015; Wallnér, 2015). This subsidy will, however, together with other clean technology subsidies, be replaced by one common clean technology subsidy for private individuals. This new subsidy is intended to be more predictable and user-friendly, and will be aligned with established procedures for subsidies in other sectors (Ministry of Finance, 2020).

A remaining uncertainty concerns rules and guidelines for fire protection for building-sited PV. National rules are lacking, and local authorities have developed guidelines that are partly at odds with one another (Nordin, 2018), creating confusion and a need for *clarifying* alignment.

To summarise, important *enabling*, *clarifying*, and *incentivising*

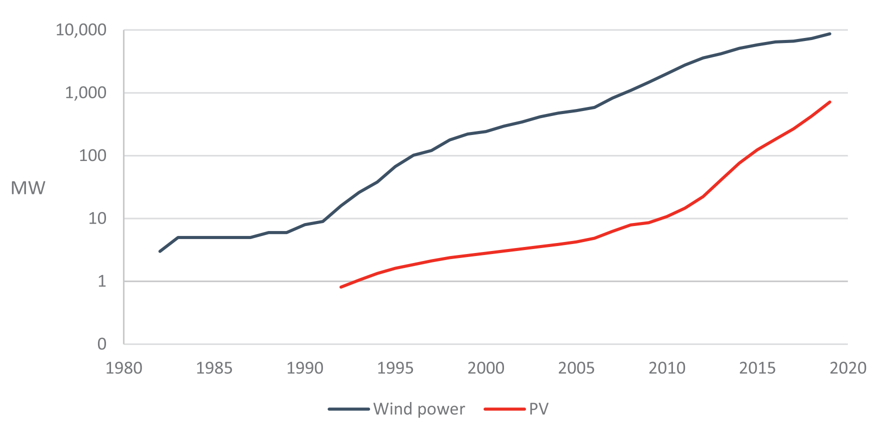

Fig. 3. Total (cumulative) installed PV and wind power capacity in Sweden over time. Based on Lindahl et al. (2020) (PV) and public data from Statistics Sweden (wind power). In 2020, wind and PV electricity constituted roughly 17 % and 1 %, respectively, of the total Swedish electricity production.

institutional alignment has occurred over the years, which has been critical for PV diffusion to occur. *Constraining* alignment has not been significant, likely due to the relative harmlessness of PV modules and an abundance of land. Overall, the institutional setup is now rather conducive of widespread PV diffusion, although further *clarifying* alignment would be desirable.

4.2.2. Infrastructural buildout

For rooftop PV, the Swedish distribution grid is generally strong enough to support widespread diffusion (Widén, 2010). However, *augmentation* through the addition of conventional cables or transformers with larger capacity is sometimes needed even for the residential segment (Johansson et al., 2020; Thomas, 2017).

Ground-mounted solar parks, by contrast, often require substantial augmentation. The electric utility must be involved to add any cables outside the park, and the utility charges the adopter for this service. Existing cables may also need to be upgraded to larger-capacity ones. Proximity to a grid of sufficient capacity is thus important in solar park site selection as costs for infrastructural buildout may otherwise be prohibitive.

Infrastructural *add-on* of new features is required for rooftop PV. To allow adopters to sell temporary surpluses, the electric utility must install meters that can handle electricity flows in both directions, which were uncommon until recently. For residential adopters, the expenses for new meters and any necessary grid reinforcement are normally (as stipulated in the legislation) covered by the utility.

Sometimes, homeowners wish to install PV on an adjacent building or on the ground (for example if their home's roof is shaded). However, general electric grid legislation prevents them from adding cables outside buildings to connect PV, which sometimes hinders adoption, illustrating how institutions and infrastructure are often intimately intertwined.

To summarise, although PV diffusion can to a large extent rely on the pre-existing electric grid, *augmentation* and *add-on* have been crucial to support diffusion. However, the *establishment* of completely new infrastructure networks has not been necessary. Overall, infrastructural buildout is on a satisfying trend for widespread PV diffusion, although imposing a limitation in the siting of solar parks.

4.2.3. Market segment accumulation

Over time, there has been a clear shift in *innovativeness* among Swedish PV adopters. Interviews with homeowners suggest that the earliest PV adopters were primarily driven by environmental concern and technophilia, while later adopters were primarily driven by economic gains (Palm, 2018). Quantitative research confirms that later adopters are less environmentally concerned than earlier ones (Palm, 2020). Hence, residential PV adoption in Sweden seems to, in accordance with established theories on diffusion of innovations (cf. Rogers, 2003), have shifted towards mainstream consumers.

An obvious explanation for this shift is price reductions. Improved availability of services and information has likely contributed as well, facilitating adoption for mainstream consumer. For example, in the mid-2010s a survey ranked the blog of a private individual as the most important of all information sources (Wallnér, 2015), which illustrates the lack of more formal information channels. By contrast, by the late 2010s the Swedish Energy Agency had implemented an information portal and launched nationwide information campaigns (Palm and Lantz, 2020). An increasing number of local actors have also launched 'solar maps' over the years, through which homeowners can easily estimate their roof's solar potential. Peer effects, through which early adopters influence and help others adopt, have contributed as well (Palm, 2017b). *Value chain module formation* has also contributed as supply-side development has addressed new market segments (see next subsection).

Shifts have also occurred in *user categories* and *applications*. In the 1990s and early 2000s, off-grid PV for remote cabins, campers, and caravans dominated the market (Malm et al., 2003), likely due to high costs of PV systems and lacking institutional support for connecting PV to the grid. By the late 2000s, public and non-profit organisations installing on-grid PV dominated the demand, much thanks to the new subsidies. During the 2010s, the relative importance of public and non-profit actors decreased dramatically. Instead, homeowners (which had now strengthened legal support for grid connection) became one of the most important user categories, and small businesses – particularly farmers (Palm, 2015; Wallnerström et al., 2019) – became increasingly important. Ground-mounted solar parks are a more recent application in the DIS, accounting for about 5–10 % of the yearly installed capacity since 2012. Solar park electricity is economically worth less than rooftop PV per kWh for the adopter as it does not replace bought (taxed) electricity, which can explain why solar parks emerged later and account for a small market share given their potential. Investors in solar parks have almost exclusively been Swedish actors.

Building-integrated PV accounts for a very small share of installations. According to the interviewees, slow PV diffusion in this application depends to a large extent on lack of knowledge about PV integration in the construction industry, lack of coordination between actors in construction projects, and lack of compatibility (e.g. regarding size) between PV system components and other construction elements. Hence, learning and management in the construction industry could facilitate diffusion. The technical compatibility issues illustrate the downsides of relying on imported standardised products. By contrast, building-integrated PV has flourished in Japan much due to its domestic PV industry, which could swiftly customize PV modules for Japanese construction firms (Strupeit and Palm, 2016).

To summarise, market segment accumulation has occurred on the parameters *innovativeness*, *user categories*, and *applications*, leading to increasing overall diffusion. Some potentially important applications, such as solar parks and building-integrated PV, have yet to flourish. Fig. 4 displays the development of important segments and applications over time.

4.2.4. Value chain module formation

In the early stages of Swedish PV diffusion, supply was mainly catered for by companies selling equipment without installation or other services attached. Before 2010, residential adopters were typically expected to install the PV systems themselves (Palm and Tengvard, 2011). For larger installations, the Finnish company Naps, which established an office in Stockholm, was the first to offer turnkey PV (Sandén et al., 2008). A consultancy firm, founded by previous PV researchers, was also important to get the market going (Sandén et al., 2008).

As subsidies increased the demand in the late 2000s, more actors engaged in supply. By 2013, around 70 turnkey suppliers existed, typically staffed by one or a few persons (Palm, 2015) and targeting both residential and larger customers. They typically both sold and installed PV systems, and were often devoted to other tasks as well, such as installation of other technical equipment (Palm, 2015). Hence, specialisation remained low. During this period, prices of turnkey PV decreased dramatically, even compared to PV module price reductions (Lindahl et al., 2020). Hence, 'soft cost' reductions emanating from suppliers' local learning occurred (cf. Strupeit and Neij, 2017). Another example of local learning is that quality issues decreased over time as installers became more skilled (Kovacs, 2019).

Over time, specialisation increased. Market growth allowed for more installers to exclusively dedicate themselves to PV or to target certain market segments. A specialised provider of third-party ownership (cf. Strupeit and Palm, 2016) has been active and growing since 2013, specifically targeting large companies seeking low-hassle PV adoption.

Electric utilities have increasingly engaged in providing turnkey PV. Around 2010, some local utilities started selling PV systems (Palm, 2016). Subsequently, several utilities – including the largest ones – have followed. Utilities specialise in sales while outsourcing the installation work (Altunay et al., 2021). Other incumbent actors recently engaging

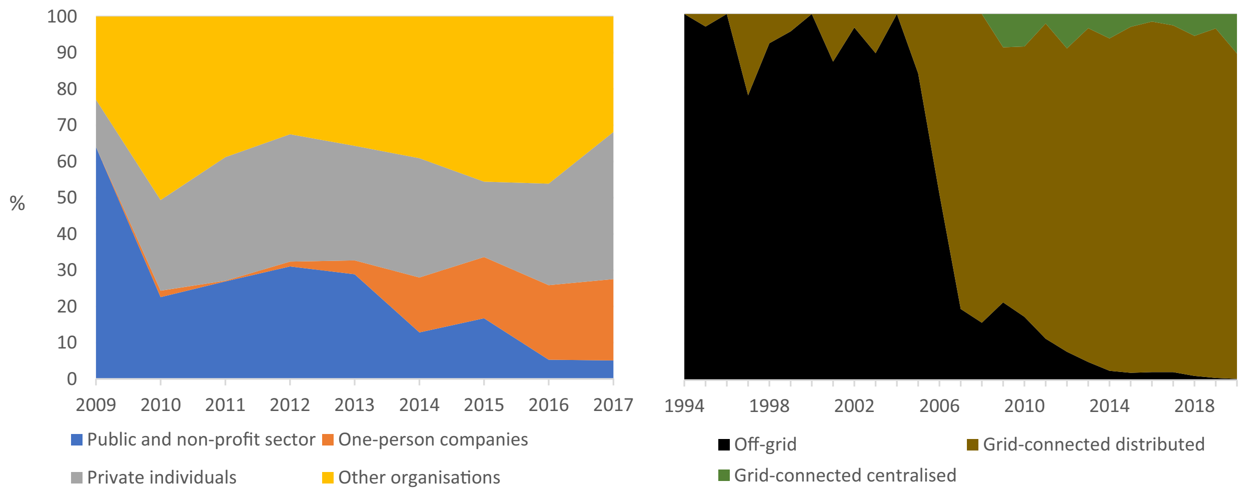

Fig. 4. Yearly PV adoptions among different user categories (left) and in different applications (right) as shares of the total estimated PV market. Based on data for the investment subsidy (user categories) and Lindahl et al. (2020) (applications).

in PV deployment include large construction firms offering PV with their buildings.

There are few providers of building-integrated PV, of which a couple (which were interviewed for this paper) have developed their own roof and mounting solutions specifically adapted for the Swedish or Nordic construction sector. They mainly use imported thin-film modules with no or moderate customisation, although one firm produces its own thin-film cells and modules (also for export). Their novel roofing solutions illustrate how innovation can occur in a DIS to make standardised products fit the local context.

Furthermore, various supporting services for PV deployment have emerged. For example, consultants and online platforms facilitate adoption through 'intermediation' (cf. Aspeteg and Mignon, 2019), interconnecting adopters and installers.

While the smallest suppliers are restricted to the sub-national level, larger firms operate the whole country while (to avoid extra administration) not targeting neighbouring countries. This suggests that the national system boundary is meaningful.

Until the early 2010s, when succumbing to competition from Asia, there was significant PV module production in Sweden. However, Swedish modules were mainly exported, while modules deployed in Sweden were mainly imported. Swedish thin film production, aimed at international niche markets, has persisted on a small scale. Overall, PV diffusion in Sweden has been almost completely disconnected from the Swedish PV industry (Andersson et al., 2021).

To summarise, a value chain module for PV deployment has gradually emerged mainly through *local entrepreneurship*. Only to a minor extent were foreign actors involved. Actors within the module have become increasingly specialised, and the module has offered an increasing diversity of services to adopters, facilitating adoption for new market segments.

4.3. Results: wind power

Since the early 1990s, wind power has grown from a fringe technology in the Swedish context to account for around 17 % of the country's electricity production in 2020, see Fig. 3. Below, the historical and present development of the Swedish wind power DIS is outlined.

4.3.1. Institutional alignment

The first wind power specific Swedish legislation appeared in the 1980s after the first turbines had been deployed. For several years, diffusion nevertheless remained predominantly governed by general rules for environmental protection and construction that did not explicitly mention wind power, creating large uncertainties and openness to interpretation (Carlman, 1990). For example, it was unclear whether wind turbines should be regarded as buildings or machines, which had implications for tax rates (through *clarifying* alignment, this issue was resolved by the Tax Agency in 2005).

Furthermore, as the Swedish electricity system was traditionally based on centralised large-scale generation, utilities' procedures for grid-connection and reimbursement for small-scale producers (such as owners of stand-alone wind turbines) were underdeveloped, creating difficulties for adopters (for this reason, temporary electricity surpluses from the first commercial turbine installed in 1983 was used to heat water locally rather than being fed into the grid). Over time, utilities became increasingly aware that commercial turbines fulfilled the requirements for grid connection, and they got less reluctant towards connecting turbines to their grids (this is an example of *enabling* alignment of collective mind frames and procedures). Furthermore, the deregulation of the general Swedish electricity market in the 1990s facilitated adopters' sales of wind electricity.

Over time, additional wind power specific rules emerged, *constraining* harmful deployment and *clarifying* where and how turbines could be deployed. However, laws were sometimes changed without sufficient consideration of the legislation as a whole, creating an unnecessarily complicated and unpredictable legislative framework (Åstrand and Neij, 2006; Söderholm et al., 2007). This development mainly occurred in the onshore segment, where permitting requirements became stricter than for offshore wind power (Söderholm and Pettersson, 2011). In 2009, an overhaul of the legislation was performed to make permitting simpler and more predictable without compromising environmental or other concerns, resulting in further *clarifying* alignment through the streamlining of previously overlapping regulations.

Municipalities, being responsible for general land-use planning, have handled important parts of the permitting process since the earliest days of wind power diffusion. Municipalities may deny or withdraw permits at their will, creating local differences and unpredictability which discourages adoption (Dolff, 2019; Söderholm et al., 2007). Municipalities, often influenced by local opposition ('nimbyism'), have sometimes stopped wind power projects at a late stage in the planning process or changed a previous approval to a rejection. To resolve these issues, the national government in 2020 appointed an enquiry to investigate the possibilities of increasing the predictability in municipal permitting, hence aiming for further *clarifying* alignment.

Constraining rules have also emerged to protect the interests of aviation. By 2010, wind power specific regulation for aircraft warning lights had emerged (despite the international character of aviation, these rules differed substantially from those of other countries (Jansson, 2016)). In 2010, the military declared wind power bans in substantial areas around the country to protect air force exercising (Engström, 2015). In 2013, an agreement was reached for the distancing of wind turbines from airports to protect private air traffic (Engström, 2015). Furthermore, the National Board of Housing has developed recommendations limiting turbines' shading on private residences, and case law has emerged for noise (Engström, 2015).

Incentivising alignment has occurred in tax rules and through subsidies. Before 2005, there was a general property tax on power plants of 0.5 % of their appraised value, which was determined by their peak capacity. As wind turbines have a relatively low load factor, the property tax per produced kilowatt-hour disadvantaged wind power compared to conventional electricity sources. Accordingly, after lobbying from the Swedish Wind Power Association, the property tax on wind turbines was reduced to 0.2 % to level the playing field.

Various subsidies have been present (Åstrand and Neij, 2006). Following different short-term subsidies in the 1990s, a more long-sighted tradable green certificates scheme was introduced in 2003. This subsidy was common for several renewable energy technologies and replaced various existing subsidies for different technologies, hence simplifying (*clarifying*) the overall policy framework. As wind power and other renewables are increasingly profitable without subsidies, the scheme is currently phased out over several years in a transparent manner.

A remaining uncertainty experienced by developers is large, unpredictable, and non-transparent grid connection fees. The Swedish Wind Energy Association lobbies for *clarifying* rules in this regard.

The Swedish institutional setup for wind power has developed rather differently from institutions in other countries both in the onshore and offshore segments (Pettersson, 2008; Söderholm and Pettersson, 2011). This suggests that the national system boundary is meaningful.

To summarise, crucial *enabling*, *clarifying*, *constraining*, and *incentivising* institutional alignment has occurred. Although this process has not always been straightforward, the overall long-term pattern has led to a more predictable institutional setup that supports diffusion while protecting other interests. There is, nevertheless, a need for additional *clarifying* alignment related to permitting and grid tariffs.

4.3.2. Infrastructural buildout

Wind power diffusion depends on infrastructure in different ways. First, an appropriate electric grid is needed. Vast wind power deployment in northern Sweden requires *augmentation* through high-capacity transmission line buildout to the south. Although wind power diffusion has been a substantial driver of transmission capacity buildout (Svenska kraftnät, 2017), trade organisations and others have frequently raised the issue of insufficient grid capacity as a barrier to further diffusion. Distribution grids must often be augmented too.

Second, the transportation of turbine components requires appropriate infrastructure. Blades and tower segments are large, and Swedish roads must sometimes be *augmented* when wind power is deployed in areas where roads are not adapted to heavy or bulky loads (Nilsson, 2010). Access to adequate ports is another issue, and some Swedish ports have specialised themselves towards wind power transports. Although authorities have previously deemed the pre-existing Swedish port capacity sufficient for substantial onshore wind power diffusion (Nilsson, 2010), several Swedish ports have recently been upgraded to meet the increasing demand for turbine transportation. This includes *augmentation* (e.g. larger cranes and storage facilities) and *add-on* (machinery adapted specifically for turbine parts).

Future offshore wind power diffusion could require substantial port buildout, although ports in nearby countries could also be used (Jacobsson et al., 2013; Swedish Energy Agency, 2017). Furthermore, offshore wind power requires *add-on* of high-performing non-conventional cables and transformers to withstand the harsh environment at sea (Swedish Energy Agency, 2017).

To summarise, *augmentation* of basic infrastructure such as electric grids, ports, and roads has been crucial for wind power diffusion. *Add-on* of new features to ports, and to connect offshore wind power to the onshore electric grid, has also been important, while the *establishment* of completely new infrastructure networks has not been needed. A potential future bottleneck is insufficient electric grid *augmentation*.

4.3.3. Market segment accumulation

Regarding *user categories*, there has been a clear process of accumulation. Before 1990, a narrow set of actors dominated the demand for wind power in Sweden. Typical adopters were local electric utilities and private individuals dedicated to farming (Åstrand and Neij, 2006; Swedish Wind Power Association, 2016). During the 1990s, small companies and cooperatives specialised in wind power ownership became important adopters in the growing market (Åstrand and Neij, 2006; Engström, 2015).

After the turn of the millennium, a more diverse set of users adopted wind power (Bergek et al., 2013). Large companies within or outside the energy sector became an increasingly important user category (Darmani et al., 2017; Engström, 2015; Wizelius, 2014). During the 2010s, purely financial actors who were mainly based outside Sweden increased their investments relative to other actors, revealing that the geographical system boundary is not impermeable. These actors, seeking low-risk, long-term (but not necessarily high-return) investments had by the late 2010s come to dominate new investments in wind turbines in Sweden (Dolff, 2018; Swedish Energy Agency, 2018; Swedish Wind Power Association, 2016). These actors should not be seen as adopters in the traditional sense, but rather as investors in a financial asset.

To an increasing extent, wind electricity has recently been sold through power purchase agreements (PPAs) rather than on the spot market. By the late 2010s, PPAs dominated electricity sales for new wind farms (Dolff, 2019). The IT sector (mainly large data centres) and the production industry are the most important buyers of these PPAs (Dolff, 2019). PPAs reduce risk for turbine adopters and electricity consumers as they fix the electricity price for an extended period, which has attracted new risk-averse investors. Furthermore, PPAs offer a way to 'adopt' wind power without owning turbines, inviting new user categories.

There has also been accumulation of *applications*. While stand-alone turbines dominated in the early years, wind farms later came to dominate (Wizelius, 2014). Offshore wind power is another application that has emerged, although it accounts for a minor share of installations.

Regarding *innovativeness*, the earliest adopters are typically described as enthusiasts fascinated by the technology and by changing society for the better (Engström, 2015; Swedish Wind Power Association, 2016; Wizelius, 2014), while later adopters have mainly pursued financial gains (Wizelius, 2014), increasingly appreciating low risks. This suggests that accumulation has occurred also on this parameter (cf. Rogers, 2003).

To summarise, new and distinct market segments have successively emerged over time. This accumulation has occurred on the parameters *user categories*, *applications*, and *innovativeness*. Through this process, large and established sectors of society are now adopting or investing in wind turbines, or purchase wind electricity through PPAs (thus 'adopting' wind power in a broader sense). Hence, *market segment accumulation* has transformed wind power from a fringe to a mainstream phenomenon.

4.3.4. Value chain module formation

The first wind turbines deployed in Sweden were do-it-yourself projects built by enthusiasts or prototypes built by large Swedish engineering firms. The first commercial turbines, which were imported, appeared in the early 1980s when a small Swedish firm dedicated to farming equipment sales started taking orders from the Danish turbine producer Vestas. While Vestas installed and maintained the turbines, the Swedish firm offered related services such as helping adopters acquiring permits and engaging other entrepreneurs. The Swedish firm's owner shortly thereafter became Vestas' first representative in Sweden. Before the mid-1990s, banks were unwilling to finance wind power, and adopters paid for turbines upfront due to difficulties in acquiring funding (Wizelius, 2014).

In the early 1990s, specialised so-called wind power developers emerged (Åstrand and Neij, 2006; Swedish Wind Power Association, 2016). These companies initiated and owned wind power deployment projects, either to own the installed turbines themselves or to sell them to other adopters. Over time, these firms became larger and more sophisticated. Their core tasks include identifying suitable sites, negotiating with landowners, and acquiring permits. Hence, they facilitate adoption for other actors (Aspeteg and Bergek, 2020). Developers procure various subcontractors needed for wind farm construction. While certain specialised skills cannot be found locally, developers prefer local entrepreneurs for general construction tasks such as groundwork. Using local labour is not only a matter of economic efficiency, but also of gaining local support (Aspeteg and Bergek, 2020), which is particularly important given municipalities' tendencies to interrupt projects.

Swedish developers have also refined their financial strategies and competences over time. By primarily seeking external funding for their projects, they could make their own capital available for other purposes. Thus, attracting funding became one of their core competencies (thus supporting *market segment accumulation* by attracting new investors).

The interviewees unanimously agreed that developers benefit strongly from being based in Sweden and using Swedish staff. Language fluency, knowledge about institutions and culture, and trustworthiness in the eyes of residents and landowners were stressed as crucial aspects for successful project development. In addition to Sweden-based developers, international ones have been present (Åstrand and Neij, 2006), although they tend to establish permanent Swedish offices staffed by native Swedes.

Over time, new and increasingly sophisticated turbine ownership models emerged. These were tailored for different adopter categories (Wizelius, 2014), hence facilitating market segment accumulation through business model innovation.

The erection of turbines is mainly performed by international labour on behalf of turbine producers, revealing that the national system boundary is not perfect. This includes Swedish staff that also works abroad, travelling between projects. Vestas, the leading provider of turbines in Sweden, has had a Swedish office since the 1990s and partly uses native staff for installation and O&M. Cranes for turbine erection are expensive, and their operation requires advanced skills. In response to the growing Swedish market (economies of scale), Swedish actors have lately invested in cranes, and skilled domestic crane operators have emerged, suggesting that the Swedish value chain module is increasingly undertaking work related to turbine erection.

While O&M was traditionally performed by turbine manufacturers, an increasing share of the Swedish O&M market has been taken over by Swedish actors, including large utilities and specialised O&M firms (Andersson et al., 2018; Dolff, 2019). Although the number of Swedish O&M workers has increased dramatically, the workforce has not kept pace with wind power diffusion, resulting in a lack of skilled labour (e.g. Stenman, 2018). As O&M is more efficiently done through local labour, the lack of personnel is perceived as an important problem within the trade.

Transportation of turbine components is another key task. Transports have become increasingly complicated as turbines have become larger. While transports were previously largely performed by international actors, Swedish hauliers have recently acquired the necessary skills and equipment. Compared to international hauliers, domestic ones benefit from knowledge about institutions, infrastructure, and obstacles in the physical environment.

Swedish turbine production has not been important for Swedish diffusion. Domestically produced turbines have been limited to do-it-yourself projects, prototypes, and micro turbines. Production of commercial mainstream turbines has never existed within the country. There is, nevertheless, a thriving Swedish production of upstream components for the global wind turbine industry (e.g. Åstrand and Neij, 2006). The emergence of this industry benefitted from geographical proximity to Danish and German turbine producers rather than from Swedish diffusion (Takeuchi, 2003).

Icing of the turbines' wings can severely affect electricity production in cold climates, and there has been a lack of feasible anti-icing solutions on the market as turbine producers used to pay limited attention to this niche. Hence, there have been entrepreneurial attempts at developing add-on anti-icing systems within the Swedish DIS. While these attempts at local innovation have not reached significant commercial success, turbine manufacturers have lately developed better anti-icing solutions for markets in cold climates.

To summarise, a growing number of increasingly specialised entrepreneurs have engaged in Swedish wind power deployment. Both *local entrepreneurship* and *seeding* have been important as Swedish and international firms have been involved (foreign-based firms have had a strong local presence through local offices and native staff). Hence, a value chain module for deployment has gradually formed within the country, although this module is not as clearly delimited geographically and from upstream value chain segments as in the PV case. A lack of skilled domestic technical labour is a barrier that could be alleviated through education.

5. Synthesis and conclusions

The two case studies illustrate that the DIS framework is appropriate for analysing the diffusion of innovations from a sociotechnical systems perspective. The cases reveal that, as the technologies have diffused, much development has occurred through the DIS framework's four key processes. This development has been crucial to facilitate diffusion, although some barriers to diffusion remain. The processes both induced and responded to diffusion, and they developed symbiotically fuelling one another. Hence, positive feedback mechanisms were important for the system's development. Overall, the national system boundary made sense for the two cases as the processes' development was – besides the import of standardised artifacts – largely determined by factors within the system. Although the system boundaries were by no means perfect, they proved good enough to serve as analytical constructs.

Regarding *institutional alignment*, the cases demonstrate how existing institutions were insufficient to govern the new technologies, and how an increasingly appropriate institutional setup gradually emerged. Before diffusion took off, technology-specific rules were lacking. Instead, pre-existing, general rules were applied, causing confusion and barriers to diffusion as these rules were not adapted to the new technologies. Over time, specific rules were added or general rules adapted. Although these processes were not always straightforward, the overall trends were towards institutional setups that supported diffusion in a predictable and acceptable way. *Enabling*, *clarifying*, and *incentivising* alignment were important in both cases, while *constraining* alignment was only important for wind power due to the physical properties of turbines.

The cases also illustrate the importance of different kinds of *infrastructural buildout*. Electric grids, roads, and ports had to be *augmented*, and *add-on* to existing infrastructure was needed, including smart meters for building-sited PV and new cable and transformer types for offshore wind power. *Establishment* of completely new infrastructure networks was not needed in the studied cases, although this is known to be necessary for other technologies. As demonstrated by the cases, infrastructure buildout is often dependent on institutions – for example, new legislation forcing utilities to add meters to homes was critical for PV diffusion.

Furthermore, the cases show how *market segment accumulation* can occur on the parameters *innovativeness*, *applications*, and *user categories*, bringing the technologies towards increased overall diffusion. How this process unfolded depended on differences in utility and financial returns that the technologies provided in different market segments, and on differences in characteristics between user categories (e.g. risk aversion). In short, adoption occurred first in market segments where the technologies provided large value (financial or emotional) in relation to their cost (including administration, risk etc.). The other key processes affected this process as institutions, infrastructure, and supply-side development sometimes favoured adoption in certain segments over others.

The cases also demonstrate how *value chain module formation* can occur in DISs. Through this process, entrepreneurs undertook increasingly advanced and specialised tasks related to technology deployment. Some innovation (development of complementary technology or business models) or attempts thereof also occurred to make the technologies fit the local context. Increasing demand for the technologies induced development in the value chain module, which in turn induced further diffusion by meeting the needs of later market segments. As later adopters have different needs than earlier ones, supply changed not only in amount but also in character. The mechanisms behind this process differed, however, between the cases. For PV, the value chain module developed mainly from within the DIS through *local entrepreneurship* with little input from other countries (besides import of standardised artifacts). Only in the earliest stages was *seeding* significant (which may, nevertheless, have had a long-term impact by initiating diffusion and inspiring Swedish entrepreneurship). For wind power, on the other hand, substantial *seeding* occurred as international actors engaged in Swedish deployment. This difference should come as no surprise – while PV modules are highly standardised and can be installed using relatively low-skilled labour, wind turbine installation requires substantial skills and resources. Hence, the system boundaries were less distinct in the wind power case. However, the need for international suppliers to establish offices specifically for the Swedish market suggests that the national system boundaries were not meaningless.

Despite substantial diffusion-fostering development along the four key DIS processes, the studied cases have some remaining and potential barriers to further diffusion which could be addressed by policy makers or business leaders. These include lack of clarifying institutional alignment, insufficient electric grid buildout, lack of organisational learning in the construction sector, and lack of skilled labour. It should also be noted that future, larger shares of intermittent electricity sources (including PV and wind power) may, to handle the fluctuating electricity generation, require substantial buildout of electricity storage capacity, plannable (as opposed to weather-dependent) power generation capacity (e.g. gas turbines), or cables for international electricity trade. Such needs for infrastructural buildout may form significant barriers to PV and wind power diffusion further along their diffusion trajectory.

A matter for future research is to apply the DIS framework to additional cases to test its general validity. For example, the diffusion of maturing and sustainable technologies for energy production, transportation, water supply, or food production is of societal and academic relevance. How the DIS processes interact with each other and the system's environment is another matter for further investigation. Another potential area of further investigation is how complementary innovations emerge in DISs in relation to the imported technology, and (related to the global innovation systems literature) how such innovations may potentially travel to other DISs or even upstream the value chain past the 'break point'. Furthermore, future research may propose alternative ways of structuring a DIS framework by e.g. reconfiguring or adding processes or system components; while the present paper illustrates the merits of the proposed framework, alternative configurations may be viable as well. For example, sub-processes could be added or removed, or knowledge creation and dissemination (here treated individually for each process) could be assigned a key process of its own. Whether or not the framework proposed in this paper gets acknowledged in its current form, a sociotechnical systems approach focused on technology diffusion is needed.

CRediT authorship contribution statement

Alvar Palm: Conceptualization, Methodology, Investigation, Writing - Original Draft, Writing - Review & Editing; Visualization.

Declaration of competing interest

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References

Aasness, M.A., Odeck, J., 2015. The increase of electric vehicle usage in Norway—incentives and adverse effects. Eur. Transp. Res. Rev. 7, 34. https://doi.org/10.1007/s12544-015-0182-4.

Altunay, M., Bergek, A., Palm, A., 2021. Solar business model adoption by energy incumbents: the importance of strategic fit. Environ. Innov. Soc. Transit. 40, 501–520. https://doi.org/10.1016/j.eist.2021.10.013.

Andersson, C., Tellström, S., Bondesson, T., 2018. Fördjupad studie Drift och underhåll.

Andersson, J., Hellsmark, H., Sandén, B., 2021. Photovoltaics in Sweden – success or failure? Renew. Sust. Energ. Rev. 143, 110894 https://doi.org/10.1016/j.rser.2021.110894.

Aspeteg, J., Bergek, A., 2020. The value creation of diffusion intermediaries: brokering mechanisms and trade-offs in solar and wind power in Sweden. J. Clean. Prod. 251, 119640 https://doi.org/10.1016/j.jclepro.2019.119640.

Aspeteg, J., Mignon, I., 2019. Intermediation services and adopter expectations and demands during the implementation of renewable electricity innovation – match or mismatch? J. Clean. Prod. 214, 837–847. https://doi.org/10.1016/j.jclepro.2019.01.034.

Åstrand, K., Neij, L., 2006. An assessment of governmental wind power programmes in Sweden—using a systems approach. In: Energy Policy, Renewable Energy Policies in the European Union, 34, pp. 277–296. https://doi.org/10.1016/j.enpol.2004.08.036.

Bass, F.M., 1969. A new product growth for model consumer durables. Manag. Sci. 15, 215–227.

Bergek, A., Jacobsson, S., Carlsson, B., Lindmark, S., Rickne, A., 2008. Analyzing the functional dynamics of technological innovation systems: a scheme of analysis. Res. Policy 37, 407–429. https://doi.org/10.1016/j.respol.2007.12.003.

Bergek, A., Mignon, I., Sundberg, G., 2013. Who invests in renewable electricity production? Empirical evidence and suggestions for further research. Energy Policy 56, 568–581. https://doi.org/10.1016/j.enpol.2013.01.038.

Binz, C., Tang, T., Huenteler, J., 2017. Spatial lifecycles of cleantech industries – the global development history of solar photovoltaics. Energy Policy 101, 386–402. https://doi.org/10.1016/j.enpol.2016.10.034.

Binz, C., Truffer, B., 2017. Global innovation Systems—A conceptual framework for innovation dynamics in transnational contexts. Res. Policy 46, 1284–1298. https://doi.org/10.1016/j.respol.2017.05.012.

Binz, C., Truffer, B., Li, L., Shi, Y., Lu, Y., 2012. Conceptualizing leapfrogging with spatially coupled innovation systems: the case of onsite wastewater treatment in China. Technol. Forecast. Soc. Chang. 79, 155–171. https://doi.org/10.1016/j.techfore.2011.08.016.

Birkinshaw, J., Hood, N., Jonsson, S., 1998. Building firm-specific advantages in multinational corporations: the role of subsidiary initiative. Strateg. Manag. J. 19, 221–242. https://doi.org/10.1002/(SICI)1097-0266(199803)19:3<221::AID-SMJ948>3.0.CO;2-P.

Botelho, A., Pinto, L.C., 2004. The diffusion of cellular phones in Portugal. Telecommun. Policy 28, 427–437. https://doi.org/10.1016/j.telpol.2003.11.006.

Cardinale, I., 2017. Beyond constraining and enabling: toward new microfoundations for institutional theory. Acad. Manag. Rev. 43, 132–155. https://doi.org/10.5465/amr.2015.0020.

Carlman, I., 1990. Blåsningen: svensk vindkraft 1973 till 1990, Geografiska regionstudier / utgivna av Kulturgeografiska institutionen vid Uppsala universitet. S. Academiae Ubsaliensis : Distribution, Kulturgeografiska institutionen. Uppsala universitet, Uppsala.

Carlsson, B., Stankiewicz, R., 1991. On the nature, function and composition of technological systems. J. Evol. Econ. 1, 93–118. https://doi.org/10.1007/BF01224915.

Cooke, P., Gomez Uranga, M., Etxebarria, G., 1997. Regional innovation systems: institutional and organisational dimensions. Res. Policy 26, 475–491. https://doi.org/10.1016/S0048-7333(97)00025-5.

Culver, K.B., 2014. From battlefield to newsroom: ethical implications of drone technology in journalism. J. Mass Media Ethics 29, 52–64. https://doi.org/10.1080/08900523.2013.829679.

Darmani, A., Niesten, E.M.M.I., Hekkert, M.P., 2017. Characteristics of investors in onshore wind power in Sweden. Environ. Innov. Soc. Transit. 24, 67–82. https://doi.org/10.1016/j.eist.2016.10.005.
Dedehayir, O., Ortt, R.J., Riverola, C., Miralles, F., 2017. Innovators and early adopters in the diffusion of innovations: a literature review. Int. J. Innov. Manag. 21, 1740010. https://doi.org/10.1142/S1363919617400102.
del Río, P., Mir-Artigues, P., 2012. Support for solar PV deployment in Spain: some policy lessons. Renew. Sust. Energ. Rev. 16, 5557–5566. https://doi.org/10.1016/j.rser.2012.05.011.
Dolff, F., 2019. Marknadsanalys av vindkraften i Sverige Under 2018.
Dolff, F., 2018. Marknadsanalys av vindkraften i Sverige 2017.
Edquist, C., 1997. Systems of innovation approaches - their emergence and characteristics, in. In: Edquist, C. (Ed.), Systems of Innovation: Technologies, Institutions and Organizations. Pinter Publishers, London.
Edquist, C., Johnson, B., 1997. Institutions and organizations in systems of innovation. In: Edquist, C. (Ed.), Systems of Innovation: Technologies, Institutions and Organizations. Pinter Publishers, London, pp. 41–63.
Engström, S., 2015. Historien om den svenska vindkraften: hur det började, läget idag, framtid. Ägir konsult AB, Stockholm, Sweden.
Fabrizio, K.R., Hawn, O., 2013. Enabling diffusion: how complementary inputs moderate the response to environmental policy. Res. Policy 42, 1099–1111. https://doi.org/10.1016/j.respol.2013.02.003.
Fang, Y., Jiang, G.-L.F., Makino, S., Beamish, P.W., 2010. Multinational firm knowledge, use of expatriates, and foreign subsidiary performance. J. Manag. Stud. 47, 27–54. https://doi.org/10.1111/j.1467-6486.2009.00850.x.
Fichter, K., Clausen, J., 2016. Diffusion dynamics of sustainable innovation - insights on diffusion patterns based on the analysis of 100 sustainable product and service innovations. J. Innov. Manag. 4, 30–67. https://doi.org/10.24840/2183-0606_004.002_0004.
Fisher, J.C., Pry, R.H., 1971. A simple substitution model of technological change. Technol. Forecast. Soc. Chang. 3, 75–88. https://doi.org/10.20801/jsrpim.3.4_540_2.
Frankelius, P., Norrman, C., Johansen, K., 2019. Agricultural innovation and the role of institutions: lessons from the game of drones. J. Agric. Environ. Ethics 32, 681–707. https://doi.org/10.1007/s10806-017-9703-6.
Freeman, C., Louçã, F., 2001. As Time Goes by: From the Industrial Revolutions to the Information Revolution. Oxford University Press.
Fuenfschilling, L., Binz, C., 2018. Global socio-technical regimes. Res. Policy 47, 735–749. https://doi.org/10.1016/j.respol.2018.02.003.
Garud, R., Karnøe, P., 2003. Bricolage versus breakthrough: distributed and embedded agency in technology entrepreneurship. Res. Policy 32, 277–300. https://doi.org/10.1016/S0048-7333(02)00100-2.
Geels, F.W., 2010. Ontologies, socio-technical transitions (to sustainability), and the multi-level perspective. Res. Policy 39, 495–510. https://doi.org/10.1016/j.respol.2010.01.022. Special Section on Innovation and Sustainability Transitions.
Geels, F.W., 2002. Technological transitions as evolutionary reconfiguration processes: a multi-level perspective and a case-study. Res. Policy 31, 1257–1274. https://doi.org/10.1016/S0048-7333(02)00062-8.
Gereffi, G., Humphrey, J., Sturgeon, T., 2005. The governance of global value chains. Rev. Int. Polit. Econ. 12, 78–104. https://doi.org/10.1080/09692290500049805.
Gruber, H., 2001. Competition and innovation: the diffusion of mobile telecommunications in central and Eastern Europe. Inf. Econ. Policy 13, 19–34. https://doi.org/10.1016/S0167-6245(00)00028-7.
Grübler, A., 2003. Technology and Global Change. Cambridge University Press.
Grübler, A., 1991. Diffusion: long-term patterns and discontinuities. In: Nakićenović, N., Grübler, A. (Eds.), Diffusion of Technologies and Social Behavior. Springer, Berlin, Heidelberg, pp. 451–482. https://doi.org/10.1007/978-3-662-02700-4_18.
Hansson, L., 2020. Regulatory governance in emerging technologies: the case of autonomous vehicles in Sweden and Norway. Res. Transp. Econ., 100967 https://doi.org/10.1016/j.retrec.2020.100967. Thredbo 16 conference 83.
Heiskanen, E., Hyvönen, K., Niva, M., Pantzar, M., Timonen, P., Varjonen, J., 2007. User involvement in radical innovation: are consumers conservative? Eur. J. Innov. Manag. 10, 489–509. https://doi.org/10.1108/14601060710828790.
Hipp, A., Binz, C., 2020. Firm survival in complex value chains and global innovation systems: evidence from solar photovoltaics. Res. Policy 49, 103876. https://doi.org/10.1016/j.respol.2019.103876.
Hodgson, G.M., 2006. What are institutions? J. Econ. Issues 40, 1–25.
Holton, A.E., Lawson, S., Love, C., 2015. Unmanned aerial vehicles. Journal. Pract. 9, 634–650. https://doi.org/10.1080/17512786.2014.980596.
Jacobsson, S., Dolff, F., Karltorp, K., 2013. Bidrag till en handlingsplan för havsbaserad vindkraft i Sverige: För säkrad eltillförsel, stabilt klimat och industriell utveckling. New approaches for transitions to low fossil carbon societies: promoting opportunities for effective development, diffusion and implementation of technologies, policies and strategies.
Jalonen, H., 2011. The uncertainty of innovation: a systematic review of the literature. J. Manag. Res. 4 https://doi.org/10.5296/jmr.v4i1.1039.
Jansson, A., 2016. Investigating Dimming of Obstruction Lights in a Swedish Wind Farm. Uppsala University, Sweden.
Johansson, P., Vendel, M., Nuur, C., 2020. Integrating distributed energy resources in electricity distribution systems: an explorative study of challenges facing DSOs in Sweden. Util. Policy 67, 101117. https://doi.org/10.1016/j.jup.2020.101117.
Kast, F.E., Rosenzweig, J.E., 1972. General systems theory: applications for organization and management. Acad. Manag. J. 15, 447–465. https://doi.org/10.5465/255141.
Keller, W., 2004. International technology diffusion. J. Econ. Lit. 42, 752–782. https://doi.org/10.1257/0022051042177685.
Köhler, J., Geels, F.W., Kern, F., Markard, J., Onsongo, E., Wieczorek, A., Alkemade, F., Avelino, F., Bergek, A., Boons, F., Fünfschilling, L., Hess, D., Holtz, G., Hyysalo, S., Jenkins, K., Kivimaa, P., Martiskainen, M., McMeekin, A., Mühlemeier, M.S., Nykvist, B., Pel, B., Raven, R., Rohracher, H., Sandén, B., Schot, J., Sovacool, B., Turnheim, B., Welch, D., Wells, P., 2019. An agenda for sustainability transitions research: state of the art and future directions. Environ. Innov. Soc. Transit. 31, 1–32. https://doi.org/10.1016/j.eist.2019.01.004.
Kovacs, P., 2019. Besiktningar av mindre solcellsanläggningar i drift. Report No. 9P04225-04.
Lashitew, A.A., van Tulder, R., Liasse, Y., 2019. Mobile phones for financial inclusion: what explains the diffusion of mobile money innovations? Res. Policy 48, 1201–1215. https://doi.org/10.1016/j.respol.2018.12.010.
Leick, B., 2012. Business networks in the cross-border regions of the enlarged EU: what do we know in the post-enlargement era? J. Borderl. Stud. 27, 299–314. https://doi.org/10.1080/08865655.2012.750952.
Levinthal, D.A., 1998. The slow pace of rapid technological change: gradualism and punctuation in technological change. Ind. Corp. Chang. 7, 217–247. https://doi.org/10.1093/icc/7.2.217.
Lindahl, J., Dahlberg Rosell, M., Oller Westerberg, A., 2020. National Survey Report of PV Power Applications in Sweden 2019.
Lipovsky, C., 2020. Free-floating electric scooters: representation in french mainstream media. Int. J. Sustain. Transp. 1–10. https://doi.org/10.1080/15568318.2020.1809752.
Lundin, P., 2004. American numbers copied! Shaping the swedish postwar car society. Comp. Technol. Transf. Soc. 2, 303–334. https://doi.org/10.1353/ctt.2005.0005.
Lundvall, B.-Å., 2010. National Systems of Innovation: Toward a Theory of Innovation and Interactive Learning. Anthem Press.
Malerba, F., 2002. Sectoral systems of innovation and production. Res. Policy, Innov. Syst. 31, 247–264. https://doi.org/10.1016/S0048-7333(01)00139-1.
Malhotra, A., Schmidt, T.S., Huenteler, J., 2019. The role of inter-sectoral learning in knowledge development and diffusion: case studies on three clean energy technologies. Technol. Forecast. Soc. Chang. 146, 464–487. https://doi.org/10.1016/j.techfore.2019.04.018.
Malm, U., Lundberg, O., Stolt, L., 2003. National Survey Report of PV Power Applications in Sweden 2002.
Markard, J., Truffer, B., 2008. Technological innovation systems and the multi-level perspective: towards an integrated framework. Res. Policy 37, 596–615. https://doi.org/10.1016/j.respol.2008.01.004.
Markard, J., Wirth, S., Truffer, B., 2016. Institutional dynamics and technology legitimacy – a framework and a case study on biogas technology. Res. Policy 45, 330–344. https://doi.org/10.1016/j.respol.2015.10.009.
Menzel, M.-P., Adrian, J.M., 2018. Modularisation and spatial dynamics in the wind turbine industry: the example of firm relocations to Hamburg. Camb. J. Reg. Econ. Soc. 11, 297–315. https://doi.org/10.1093/cjres/rsy014.
Mignon, I., Bergek, A., 2016. System- and actor-level challenges for diffusion of renewable electricity technologies: an international comparison. J. Clean. Prod. 128, 105–115. https://doi.org/10.1016/j.jclepro.2015.09.048. New approaches for transitions to low fossil carbon societies: promoting opportunities for effective development, diffusion and implementation of technologies, policies and strategies.
Ministry of Finance, 2020. Lagrådsremiss: Skattereduktion för installation av grön teknik. Stockholm, Sweden.
Moses, L.B., 2003. Adapting the law to technological change: a comparison of common law and legislation. Univ. New South Wales Law J. 26, 394.
Murphy, J., Levidow, L., Carr, S., 2006. Regulatory standards for environmental risks: understanding the US-European Union conflict over genetically modified crops. Soc. Stud. Sci. 36, 133–160. https://doi.org/10.1177/0306312705054591.
Negro, S.O., Alkemade, F., Hekkert, M.P., 2012. Why does renewable energy diffuse so slowly? A review of innovation system problems. Renew. Sust. Energ. Rev. 16, 3836–3846. https://doi.org/10.1016/j.rser.2012.03.043.
Neij, L., Heiskanen, E., Strupeit, L., 2017. The deployment of new energy technologies and the need for local learning. Energy Policy 101, 274–283. https://doi.org/10.1016/j.enpol.2016.11.029.
Nilsson, M., 2010. Transporter till vindkraftsparker - en handbok.
Nordin, L., 2018. Mindre aktörer i energilandskapet – förslag med effekt. Final Report of the Public Enquiry "Utredningen om mindre aktörer i ett energilandskap i förändring" (SOU 2018:76). Swedish Government Official Reports, Stockholm, Sweden.
North, D.C., 1994. Economic performance through time. Am. Econ. Rev. 84, 359–368.
Norton, J.A., Bass, F.M., 1987. A diffusion theory model of adoption and substitution for successive generations of high-technology products. Manag. Sci. 33, 1069–1086. https://doi.org/10.1287/mnsc.33.9.1069.
Painuly, J.P., 2001. Barriers to renewable energy penetration; a framework for analysis. Renew. Energy 24, 73–89. https://doi.org/10.1016/S0960-1481(00)00186-5.
Palm, A., 2020. Early adopters and their motives: differences between earlier and later adopters of residential solar photovoltaics. Renew. Sust. Energ. Rev. 133, 110142 https://doi.org/10.1016/j.rser.2020.110142.
Palm, A., 2016. Local factors driving the diffusion of solar photovoltaics in Sweden: a case study of five municipalities in an early market. Energy Res. Soc. Sci. 14, 1–12. https://doi.org/10.1016/j.erss.2015.12.027.
Palm, A., 2015. An emerging innovation system for deployment of building-sited solar photovoltaics in Sweden. Environ. Innov. Soc. Transit. 15, 140–157. https://doi.org/10.1016/j.eist.2014.10.004.
Palm, A., Lantz, B., 2020. Information dissemination and residential solar PV adoption rates: the effect of an information campaign in Sweden. Energy Policy 142, 111540. https://doi.org/10.1016/j.enpol.2020.111540.

Palm, A., 2017a. Residential solar photovoltaics deployment: barriers and drivers in space. International Institute for Industrial Environmental Economics (IIIEE), Lund University, Lund, Sweden.
Palm, A., 2017b. Peer effects in residential solar photovoltaics adoption—a mixed methods study of Swedish users. Energy Res. Soc. Sci. 26, 1–10. https://doi.org/10.1016/j.erss.2017.01.008.
Palm, J., 2018. Household installation of solar panels – motives and barriers in a 10-year perspective. Energy Policy 113, 1–8. https://doi.org/10.1016/j.enpol.2017.10.047.
Palm, J., Tengvard, M., 2011. Motives for and barriers to household adoption of small-scale production of electricity: examples from Sweden. Sustain. Sci. Pract. Policy 7, 6–15. https://doi.org/10.1080/15487733.2011.11908061.
Peres, R., Muller, E., Mahajan, V., 2010. Innovation diffusion and new product growth models: a critical review and research directions. Int. J. Res. Mark. 27, 91–106. https://doi.org/10.1016/j.ijresmar.2009.12.012.
Pettersson, M., 2008. Renewable Energy Development and the Function of Law: A Comparative Study of Legal Rules Related to the Planning, Installation and Operation of Windmills. Luleå University of Technology, Sweden (Doctoral Thesis).
Quitzow, R., 2015. Dynamics of a policy-driven market: the co-evolution of technological innovation systems for solar photovoltaics in China and Germany. Environ. Innov. Soc. Transit. 17, 126–148. https://doi.org/10.1016/j.eist.2014.12.002.
Rashed, M.R.H., Zaman, M., Mobassear-Ul-Islam, Raihan, M.F., 2017. An analysis on the required reinforcement for embedding a nuclear power plant in a generic power system. In: 2017 4th International Conference on Advances in Electrical Engineering (ICAEE). Presented at the 2017 4th International Conference on Advances in Electrical Engineering (ICAEE), pp. 597–600. https://doi.org/10.1109/ICAEE.2017.8255427.
Raven, R., 2007. Niche accumulation and hybridisation strategies in transition processes towards a sustainable energy system: an assessment of differences and pitfalls. Energy Policy 35, 2390–2400. https://doi.org/10.1016/j.enpol.2006.09.003.
Rogers, E.M., 2003. Diffusion of Innovations, 5th ed. Free press, New York. cop. 2003.
Rohe, S., 2020. The regional facet of a global innovation system: exploring the spatiality of resource formation in the value chain for onshore wind energy. Environ. Innov. Soc. Transit. 36, 331–344. https://doi.org/10.1016/j.eist.2020.02.002.
Sandén, B., Jacobsson, S., Palmblad, L., Porsö, J., 2008. Assessment of the impact of a market formation programme on the Swedish PV innovation system. In: Presented at the DIME International Conference "Innovation, sustainability and policy" 11-13 September, Bordeaux, France.
Schmidt, T.S., Huenteler, J., 2016. Anticipating industry localization effects of clean technology deployment policies in developing countries. Glob. Environ. Chang. 38, 8–20. https://doi.org/10.1016/j.gloenvcha.2016.02.005.
Schot, J., Kanger, L., 2018. Deep transitions: emergence, acceleration, stabilization and directionality. Res. Policy 47, 1045–1059. https://doi.org/10.1016/j.respol.2018.03.009.
Sharif, N., 2006. Emergence and development of the National Innovation Systems concept. Res. Policy 35, 745–766. https://doi.org/10.1016/j.respol.2006.04.001.
Simon, H.A., 1991. The architecture of complexity. In: Klir, G.J. (Ed.), Facets of Systems Science, International Federation for Systems Research International Series on Systems Science and Engineering. Springer US, Boston, MA, pp. 457–476. https://doi.org/10.1007/978-1-4899-0718-9_31.
Singh, S.K., 2008. The diffusion of mobile phones in India. Telecommun. Policy 32, 642–651. https://doi.org/10.1016/j.telpol.2008.07.005.
Smith, A., Voß, J.-P., Grin, J., 2010. Innovation studies and sustainability transitions: the allure of the multi-level perspective and its challenges. Res. Policy 39, 435–448. https://doi.org/10.1016/j.respol.2010.01.023. Special Section on Innovation and Sustainability Transitions.
Söderholm, P., Ek, K., Pettersson, M., 2007. Wind power development in Sweden: global policies and local obstacles. Renew. Sust. Energ. Rev. 11, 365–400. https://doi.org/10.1016/j.rser.2005.03.001.
Söderholm, P., Pettersson, M., 2011. Offshore wind power policy and planning in Sweden. Energy Policy 39, 518–525. https://doi.org/10.1016/j.enpol.2010.05.065. Special Section on Offshore wind power planning, economics and environment.
Stenman, S., 2018. Ny väg till vindkraftstekniker. En förstudie i samarbete med Region Norrbotten.
Stolaroff, J.K., Samaras, C., O'Neill, E.R., Lubers, A., Mitchell, A.S., Ceperley, D., 2018. Energy use and life cycle greenhouse gas emissions of drones for commercial package delivery. Nat. Commun. 9, 409. https://doi.org/10.1038/s41467-017-02411-5.
Stoneman, P., Diederen, P., 1994. Technology diffusion and public policy. Econ. J. 104, 918–930. https://doi.org/10.2307/2234987.
Strupeit, L., Neij, L., 2017. Cost dynamics in the deployment of photovoltaics: insights from the german market for building-sited systems. Renew. Sust. Energ. Rev. 69, 948–960. https://doi.org/10.1016/j.rser.2016.11.095.
Strupeit, L., Palm, A., 2016. Overcoming barriers to renewable energy diffusion: business models for customer-sited solar photovoltaics in Japan, Germany and the United States. J. Clean. Prod. 123, 124–136. https://doi.org/10.1016/j.jclepro.2015.06.120. Advancing Sustainable Solutions: An Interdisciplinary and Collaborative Research Agenda.
Sturgeon, T.J., 2002. Modular production networks: a new American model of industrial organization. Ind. Corp. Chang. 11, 451–496. https://doi.org/10.1093/icc/11.3.451.
Sturgeon, T.J., Memedovic, O., Van Biesebroeck, J., Gereffi, G., 2009. Globalisation of the automotive industry: main features and trends. Int. J. Technol. Learn. Innov. Dev. 2, 7–24. https://doi.org/10.1504/IJTLID.2009.021954.
Svenska kraftnät, 2017. Systemutvecklingsplan 2020–2029 – En statusuppdatering om läget i kraftsystemet.
Swedish Energy Agency, 2018. In: Vindkraftsstatistik 2017. Nationell-, länsvis- och kommunal statistik. ER 2018, p. 13.
Swedish Energy Agency, 2017. In: Havsbaserad vindkraft: En analys av samhällsekonomi och marknadspotential. Report No. 2017, p. 03.
Swedish Wind Power Association, 2016. In: Svensk vindkraftförening fyller 30 år. Swed. Wind. Mag, p. 21.
Takeuchi, L., 2003. Subcontractors and Component Suppliers in the Swedish Wind Power Industry (No. 42). Department of Environmental and Energy Systems Studies, Lund University, Lund, Sweden.
Thomas, L., 2017. The Impact of Photovoltaic Systems on Rural Grid. Umeå University, Sweden, Sweden (Master of Science Thesis).
Unruh, G.C., 2000. Understanding carbon lock-in. Energy Policy 28, 817–830. https://doi.org/10.1016/S0301-4215(00)00070-7.
Utterback, J.M., Pistorius, C., Yilmaz, E., 2018. The Dynamics of Competition and of the Diffusion of Innovations (Working Paper).
Varga, G., 2020. Conflicting economic and social interests in the use of urban commons: Segways and electric scooters in public spaces. A case study from Budapest, Hungary. Espaço E Econ. Rev. Bras. Geogr. Econômica. https://doi.org/10.4000/espacoeconomia.17212.
Vermeulen, P., Büch, R., Greenwood, R., Vermeulen, P., Büch, R., Greenwood, R., 2007. The impact of governmental policies in institutional fields: the case of innovation in the dutch concrete industry. Organ. Stud. 28, 515–540. https://doi.org/10.1177/0170840606067927.
Wallnér, E., 2015. Aiding Households to Invest in Domestic Photovoltaics – An Adopter-centric Analysis.
Wallnerström, C.J., Dalheim, M., Seratelius, M., 2019. Leveranssäkerhet i Sveriges elnät 2018 - Statistik och analys av elavbrott.
Weber, K.M., Rohracher, H., 2012. Legitimizing research, technology and innovation policies for transformative change. Res. Policy 41, 1037–1047. https://doi.org/10.1016/j.respol.2011.10.015.
Wejnert, B., 2002. Integrating models of diffusion of innovations: a conceptual framework. Annu. Rev. Sociol. 28, 297–326. https://doi.org/10.1146/annurev.soc.28.110601.141051.
Widén, J., 2010. System Studies and Simulations of Distributed Photovoltaics in Sweden. Uppsala University, Sweden (Doctoral Thesis).
Wisdom, J.P., Chor, K.H.B., Hoagwood, K.E., Horwitz, S.M., 2014. Innovation adoption: a review of theories and constructs. Adm. Policy Ment. Health Ment. Health Serv. Res. 41, 480–502. https://doi.org/10.1007/s10488-013-0486-4.
Wizelius, T., 2014. Windpower Ownership in Sweden: Business Models and Motives. Routledge, Taylor & Francis Group, New York, NY.

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