How can pilot and demonstration plants drive market formation? Lessons from advanced biofuel development in Europe

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How can pilot and demonstration plants drive market formation? Lessons from advanced biofuel development in Europe

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ABSTRACT

This paper analyzes through what enabling mechanisms pilot and demonstration plants (PDPs) reduce supply and demand uncertainties, and thereby contributing to the market formation for novel sustainable technologies. The analysis builds on three case studies within the advanced biofuel development in Europe. For each case, we construct a narrative of the technology development and derive detailed insights into how technology actors use PDPs to drive market formation. We develop a comprehensive analytical framework, which highlights how PDPs contribute to supply uncertainty reduction through three main enabling mechanisms: building credibility for the technology, business ecosystem orchestration, and technology learning. The corresponding enabling mechanisms behind demand uncertainty reduction include technology standardization, constructing the narrative, and the creation of legitimacy for the technology. The paper also unfolds the composite activities of each mechanism, and outlines implications for technology developers, policymakers, as well as for the research community.

1. Introduction

The development of novel sustainable technologies is a complex process. Even if a certain technological pathway has been verified, markets may not exist or be greatly underdeveloped. For this reason, *market formation* is often a prerequisite for sustainability transitions to unfold (Boon et al., 2020; Hekkert et al., 2007). Market formation refers to the process of strengthening the factors that influence the development, diffusion, and use of a novel technology (Bergek et al., 2008a). Inherent in all efforts to market formation is uncertainty (Santos and Eisenhardt, 2009), in regards to both the demand and supply for the new technologies (Blind et al., 2017; te Kulve et al., 2018).[1] These uncertainties will prevail in many dimensions – i.e., technical, economic, institutional, and organizational. A key to reducing all these uncertainties is entrepreneurial experimentation, which implies probing into new technologies and applications (Bergek et al., 2008a). This paper addresses how technology actors use pilot and demonstration plants (PDPs) for catalyzing and facilitating such experimentation, thereby also contributing to the market formation for sustainable technologies. Technology actors are defined as "those who invest in, and carry technological development," (Schot and Rip, 1997: 256). These actors may therefore include technology suppliers, technology developers, and various entrepreneurial actors.

Novel technologies have to be verified, upscaled, and optimized to help establish a commercial market for them. In this context, PDPs represent the bridges between concept development and technological advances on the one hand, and industrial applications and commercial adoption on the other (Bossink, 2015; Fevolden et al., 2017; Hellsmark et al., 2016). Previous research has illustrated how the development activities taking place in and around various PDPs often go beyond coping with only technical uncertainties; these activities also contribute to reducing various organizational, institutional, policy, and market-related uncertainties (Bossink, 2017; Hellsmark et al., 2016; Hendry et al., 2010). In addition, PDPs are particularly important for the development of sustainable technologies, which address a global public good (e.g., climate change) but that do not have immediate market appeal (Brown and Hendry, 2009).

However, even though the literature has established that PDPs help bring new technologies to the market (see further Section 2.2), a more detailed understanding of how PDPs specifically drive market formation is lacking (Bossink, 2017; Hellsmark et al., 2016). This research gap involves several issues. For instance, some scholars have expressed

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[1] Uncertainty is often defined as the "difficulty firms have in predicting the future, which comes from incomplete knowledge," (Beckman et al., 2004: 260).

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concerns about the lack of work studying how various micro-level activities, such as entrepreneurial experimentation, could influence the innovation system (Hellsmark, 2010; Kukk et al., 2016). More research is needed to "understand what the main sources of uncertainty are, and what role experimental learning plays in handling these," (Bergek, 2019: 212). Bergek (2012b) also contends that it remains unclear what role PDPs could play in achieving uncertainty reduction to help evolve markets for new technologies (see also Bossink, 2015, 2017; Brown and Hendry, 2009).

The above research gaps become particularly evident in the case of PDPs that are used by technology actors to help develop large-scale and close-to-commercial technologies. Bossink (2017: 1354) remarks that such demonstration projects are underrepresented in the literature, which primarily highlights that these projects simply aim at identifying and exploring the market and sales opportunities for novel technologies. At the same time, however, some studies have illustrated how PDPs could contribute to various learning processes (e.g., Hellsmark et al., 2016; Nemet et al., 2018; Palage et al., 2019). Still, even these studies devote little attention to the mechanisms through which PDPs empower actors to contribute to uncertainty reduction, and thereby drive market formation. In other words, prior studies have mainly focused on the role of pilot and demonstration plants in overall technology development. Thus, the interface between the pilot and demonstration and the market formation phases of the technological development process has often not been the focal point in their analysis (Bossink, 2015, 2017). This implies in turn that existing research often addresses a few mechanisms related to market formation, but overall, they provide incomplete assessments of these mechanisms with respect also to the theoretical foundations and insights about the various types of activities that underlie these mechanisms (see Section 2). Since market formation has a strong bearing on the further development of the technologies and is critical for the evolution of new industry (Åhman et al., 2018), a more detailed understanding of how PDPs can catalyze market formation is called for.

The purpose of this paper is therefore to investigate through what enabling mechanisms PDP activities help reduce supply and demand uncertainty, and thereby drive market formation for novel sustainable technologies. This research could have important implications both for the technology actors who need to understand and assess the viable development activities and strategies in and around the plants, as well as for the policymakers who want to support system builders and foster market formation.

The analysis draws on key insights from the strategic niche management (SNM) literature (see further Section 2.3), and these are applied in the empirical context of three technologies for producing advanced biofuels that have been demonstrated at a close-to-commercial scale. The SNM approach recognizes that PDPs function as 'proto-markets', i.e., technological niches in which relationships with various market actors are established even if the technologies are still undeveloped (Bossink, 2015; Caniëls and Romijn, 2008). Here, the technology suppliers meet potential customers and other actors who could influence the articulation of demand (Hoogma et al., 2002; Schot and Geels, 2008). This is essential to in order to develop a market niche in which "the technology design and user demands have been stabilized," (Schot and Geels, 2008: 539). Caniëls and Romijn (2008) argue, though, that one gap in SNM research concerns the processes by which demonstration projects will evolve into viable market niches. Our analysis sheds light on this issue through novel insights on the main mechanisms through which PDPs can enable technological niches to evolve into market niches. Thus, while the SNM literature provides a key point of departure for this paper, our analysis also contributes to this same strand of research.

This study has been designed as a theory-elaboration study (cf. Ketokivi and Choi, 2014). Generally speaking, theory elaboration is the adapting of a general theory or pre-existing conceptual ideas to a specific empirical context to make it more applicable to said context. According to Ketokivi and Choi (2014), "successful theory elaboration hinges on the researcher's ability to investigate the general theory and the context simultaneously, in a balanced manner. Therefore, the aim of theory elaboration could be described as reconciliation of the general with the particular," (p. 236). Accordingly, one key contribution of our study is to explore the empirical context of pilot and demonstration plants in relation with market formation to elaborate on the salient effects of pilot and demonstration plants upon market formation.

We also employ a case study approach, which permits a context-rich empirical analysis that in turn enables us to construct narratives of the respective technology developments. The technologies for producing advanced biofuels[2] provide opportunities to gain an improved understanding of how the development activities in and around the associated PDPs have helped develop as well as sustain the technologies commercially in specific market segments. The choice of advanced biofuels is appropriate as the selected technologies are mainly now in a pre-commercial stage of development (Costantini et al., 2015). While several of the advanced biofuel technologies have been tested and proven on a laboratory-scale, they also need to demonstrate large-scale functionality before they can be implemented commercially (Palage et al., 2019). We analyze the development of three different advanced biofuel technologies that have been demonstrated on a commercial or near-commercial scale.

The paper proceeds as follows. Section 2 provides an overview of the literature, and thus further elaborates on the link between market formation, PDPs, and the SNM approach. The research methods are explained in Section 3, while Section 4 introduces the three case studies. Section 5 presents the empirical findings followed by a discussion of some of the most significant implications for research and policy in Section 6. The latter includes an analytical framework, which could serve as a key point of departure for further empirical work. Section 7 concludes the paper and outlines some important avenues for future research.

2. Lessons from the literature and analytical points of departure

This section provides a brief overview of the relevant strands of the literature, focusing on key lessons for investigating the role of PDPs in the market formation of novel technologies. The section ends by outlining the theoretical points of departure.

2.1. Market formation

Market formation refers to the opening up of an arena, or space, in which repeated structured exchanges take place between suppliers and customers (Bergek, 2019; Fligstein, 2002). Formal rules and informal norms govern these exchanges (Dewald and Truffer, 2011; Fligstein, 2002; Lee et al., 2018), and thereby facilitate trade, articulate demand, determine the use patterns and define the technology standards (Dewald and Truffer, 2012; Fligstein and Calder, 2015). Sarasvathy and Dew (2005) stress that in order to comprehend market formation, one has to address the formation of – and the interactions between – supply and demand.

In the context of market formation for novel technologies, both the supply of and the demand for the technologies are closely interrelated and contribute to shaping uncertainty in the market (Blind et al., 2017; te Kulve et al., 2018). Supply uncertainty is the (perceived or real) absence of suppliers of a new technology or product, or the perceived unpredictability of existing ways and capabilities to develop and commercialize these. Demand uncertainty in turn relates to the unpredictability of customer preferences and/or cognitive recognition of the value of a new technology or product. Market formation, therefore,

[2] Advanced biofuels refer to (second- and third-generation) biofuels that could be produced from cellulosic and lignocellulosic materials, such as agricultural and forestry residues, wastes, energy crops, or aquatic biomass.

involves actors seeking to mitigate such supply and demand uncertainties (Fligstein and Dauter, 2007; Lee et al., 2018).

Jacobsson and Bergek (2004) distinguish two phases in the evolution of a new technology, the formative phase and market expansion. The formative phase consists of pre-commercial R&D and demonstration, as well as early diffusion in niche markets, while market expansion is characterized by the diffusion on larger segments and subsequently on mass markets. In this context, market formation is part of the formative phase and involves exploring niches through some kind of 'nursing' markets, which provide the technology with space to develop (Bergek, 2012a; Bergek et al., 2008a). Such nursing markets help establish a constituency behind a new technology, and stimulate interactive learning processes and institutional alignment (Kemp et al., 1998). They also open up learning spaces in which entrepreneurial experimentation could be pursued (Jacobsson and Bergek, 2004). The entrepreneurial actors can prove the viability of products, processes, and business models in relation to customers and other stakeholders. As elaborated in Section 2.2, PDPs will typically play important roles in such experimentation.

The above implies that market formation concerns not only ways of addressing the technical uncertainties, but also the institutional, organizational, and market-related ones. Still, Moors et al. (2018) argue that detailed insights on how market formation exactly takes place are missing in the literature. Bergek (2019) concludes that previous research, e.g., technological innovation system analyses, tends to provide a rather simplified account of market formation. For instance, as noted above, it tends to focus primarily on sales and installation numbers and on descriptions of the public policies that have been in place. Moreover, prior studies have mainly investigated the market formation concerning various end-products (e.g., biogas). These products, though, could experience quite different dynamics compared to the corresponding formation of markets for new technologies, e.g., in terms of economies of scale as well as other sources of increasing returns to adoption (Ottosson et al., 2020). The present paper contributes to existing research by unpacking the mechanisms through which PDPs as entrepreneurial experimentations could catalyze market formation for new technologies.

2.2. Pilot and demonstration plants in the technology development process

From a market formation perspective, it is important to note that PDPs do not only aim at technical verification, optimization, and upscaling. Many plants support various other learning processes (i.e., learning-by-doing, learning-by-using, and learning-by-interacting), which help establish the necessary market niches for the novel technologies (Hellsmark et al., 2016; Palage et al., 2019; Söderholm et al., 2019).

In market niches, the main emphasis is on reducing production costs and various market-related uncertainties (e.g., Hendry et al., 2010). Specifically, PDPs can be considered 'technological niches' in which actors can nurture path-breaking technologies in protected spaces (Bergek et al., 2008a; Bossink, 2017; Hellsmark et al., 2016). By doing so, these niches become more robust and evolve into market niches through improvements in cost and performances, as well as through expansions in supporting socio-technical networks (Smith and Raven, 2012). New markets thus emerge in a process of co-evolution of markets and technologies (van der Laak et al., 2007). The market niches are often characterized by uncertainty and openness concerning technological design, and by the activities of pioneering entrepreneurs (Dewald and Truffer, 2011). PDPs allow technology actors to discover suitable market opportunities for the novel technologies and form industrial alliances and political networks through collaborative projects (e.g., Brown and

Table 1
Mechanisms through which PDPs can support market formation (previous studies).

Authors (year)	Title of the study	Technology focus	Learning processes (mechanisms)
Harborne et al. (2007)	The development and diffusion of radical technological innovation: the role of bus demonstration projects in commercializing fuel cell technology.	Fuel cell technology	• Providing shared learning on technical and operational issues for a range of stakeholders • Building an infrastructure that can be used by the industry to test and develop product • Fostering collaboration across a range of stakeholders to facilitate learning by a wide audience
Harborne and Hendry (2009)	Pathways to commercial wind power in the US, Europe and Japan: the role of demonstration projects and field trials in the innovation process.	Wind power turbines	• Learning by using • Reducing operational costs • Stakeholder learning and building manufacturing capability • Technical development and the emergence of a dominant design
Brown and Hendry (2009)	Public demonstration projects and field trials: accelerating commercialisation of sustainable technology in solar photovoltaics.	Photovoltaic technology for electricity generation	• Reducing uncertainty through new information • Progressing towards a dominant design • Developing the socio-technical system
Hendry et al. (2010)	So what do innovating companies really get from publicly funded demonstration projects and trials? Innovation lessons from solar photovoltaics and wind.	Solar photovoltaics and wind turbines	• Coordinated programmes to develop technology, product and manufacturing • Subsidy, learning and unintended benefits • Capturing and spreading learning
Heiskanen et al. (2015)	Demonstration buildings as protected spaces for clean energy solutions- the case of solar building integration in Finland	Solar building demonstrations	• Building and deepening the networks • Encouraging different types of learning • Articulating the visions and expectations
Hellsmark et al. (2016)	The role of pilot and demonstration plants in technology development and innovation policy.	Bioenergy	• Creating awareness and legitimacy for a specific application, product, process, or service of the technology • Verifying technology by constructing a reference plant at a large but not necessarily optimal scale for a specific application • Improving performance and reducing costs by accumulating operational experience • Testing different value chains in practice, reducing product and organizational risks

Hendry, 2009). In this paper, niche creation constitutes an important point of departure, and the role of PDPs in niche creation is further elaborated in Section 2.3.

Even though the existing literature recognizes that technology actors typically use PDPs for different purposes through the different phases of technology development (Bossink, 2017; Hellsmark et al., 2016; Hendry et al., 2010; Karlström and Sandén, 2004; Brown and Hendry, 2009; Harborne et al., 2007; Hart, 2018), it does not scrutinize how the technology actors use these plants to facilitate the market formation for new technologies. In particular, there is a lack of empirical research on how technology actors use large scale-up demonstrations for creating a commercial market for the novel technologies. Bossink (2017) supports this conclusion and argues that future research should provide more fine-grained insights into how PDPs help to commercialize new technologies. This is motivated by the fact that the challenges associated with large-scale demonstration projects often may differ compared to smaller PDPs aiming at (primarily) technology verification. Large-scale demonstration is typically characterized by more complexity and higher risks (Åhman et al., 2018; Frishammar et al., 2015).

To further clarify the contribution of the paper, Table 1 outlines how previous key research has described the mechanisms through which pilot and demonstration influence market formation. Table 1 displays that a limited number of prior studies have focused on the interaction between PDP activities and market formation for novel sustainable technology. Although important, the focal point of previous studies has not been to identify market formation mechanisms, and they are most often only mentioned implicitly. In other words, previous research neither provides a comprehensive assessment of these mechanisms, nor does it report their theoretical foundations and the activities that the mechanisms involve.

Finally, a more in-depth understanding of the role of PDPs for market formation is also needed to provide more useful policy implications. Previous studies argue that policy support should be matched with the intended PDP outcomes (e.g., Hellsmark et al., 2016; Hendry et al., 2010; Mossberg et al., 2018). Indeed, PDPs are critical for proving the market-attractiveness of the technology, and failures to support the development at the market formation stage would imply a waste of resources applied earlier in the innovation cycle.

2.3. Niche creation and processes

As noted above, experimentation projects and PDPs constitute key spaces for nurturing path-breaking innovations and creating market niches. To further understand the processes of niche creation, we build on insights from the SNM literature (e.g., Schot and Geels, 2008). A key point of departure in the SNM approach is, as noted above, that the development of novel technologies can be facilitated in a technological niche. Early on, these niches are technological and are therefore not supported through actual market sales (Caniëls and Romijn, 2008). Still, technological niches – i.e., PDPs – enable actors to exchange knowledge and experience, learn about innovation in real-life circumstances, and develop a community with shared problem agendas concerning the new technology (Kemp et al., 1998). This actor collaboration involves experimentation with the co-evolution of technology and market (Caniëls and Romijn, 2008; Schot and Geels, 2008). If successful, the technological niche will evolve into a market niche. In the SNM literature, niche markets are also considered important for the further development of various socio-technical configurations (Hoogma et al., 2002; Smith and Raven, 2012).

For our purposes, it is useful to elaborate on three important processes, which enable the niche experiments to achieve their desired objectives (Kemp et al., 1998; Schot and Geels, 2008). These processes, it is argued, are vital for a technological niche to evolve into a viable market niche (Heiskanen et al., 2015).

The first process is the *articulation of expectations and visions*. Shared positive expectations legitimate the continuation of nurturing a niche, and provide orientation towards the future (e.g., Geels, 2005; Schot and Geels, 2008). This process is important for attracting attention and resources as well as new actors, not least when the technology is immature, and the market performance is still uncertain (van der Laak et al., 2007). Entrepreneurs, end-users, as well as policymakers will join the technology development based on such expectations.

Second, the *building of social networks* represents a process in which experimentation in niche markets can bring new actors together and make new social networks emerge (Schot and Geels, 2008). The SNM literature focuses on the endogenous steering enacted by a range of actors, including users and societal groups to establish niches through collective bottom-up processes rather than government orchestration (Schot and Geels, 2008). It is important that these actor-networks are heterogeneous, thus allowing the widening of cognitive frames (Heiskanen et al., 2015). The networks should also be 'deep' in that they mobilize the commitment and resources of the actors, and that alignment within the network is facilitated through regular interactions between the actors (van der Laak et al., 2007). Huguenin and Jeannerat (2017) contend that PDPs cannot be reduced to 'proto-market' instruments meant to incubate new niche solutions and diffuse exemplary practices; they are also societal experiments devoting attention to actors' roles and values (see also Mossberg et al., 2018).

The third niche process is *learning*. Learning processes enable adjustment of the technology and/or societal embedding to increase chances of successful diffusion (Geels, 2005; Schot and Geels, 2008). The SNM approach highlights that technology development is rooted in various learning processes, which are necessary for reducing risk (Hoogma et al., 2002), and, as noted above, PDPs are essential for such learning and risk reduction (e.g., Bossink, 2017; Hellsmark et al., 2016). In the case of configurational technologies, such as new energy technologies, where a key challenge is to get multiple components to work together, learning-by-doing in a project context becomes important (van der Laak et al., 2007). Learning processes are thought to contribute to niche development not only in terms of techno-economic optimization but also with respect to the evolution of cognitive frames and assumptions (Heiskanen et al., 2015).

In brief, the SNM approach is a useful conceptual point of departure for our study since it pinpoints how experiments, such as PDPs, could evolve into viable market niches. Doing this, we also contribute to the SNM literature by increasing knowledge about how PDP activities can culminate in viable market niches that ultimately will contribute to a regime shift (e.g., Caniëls and Romijn, 2008). In our empirical investigation, we map out activities and strategies of the actors in and around PDPs aiming at commercialization concerning the above niche processes. In other words, these three niche processes offer guidance in our search for the mechanisms through which PDPs empower technology actors to drive the market formation, not least by categorizing the first-order concepts derived from interviews (see further Section 3.3). We thus study how the technology actors' niche processes help reduce supply and demand uncertainties and thereby facilitate market formation for the new technologies.

3. Methods

3.1. Research design

The literature proposes that markets can be studied through the actors and their actions. Actors shape markets through their attempts to influence other actors (e.g., Kindström et al., 2018; Nenonen et al., 2019; Ottosson et al., 2020). In line with previous studies on market formation, which often have taken the perspective of the focal business firm (e.g., Jaworski et al., 2000; Kindström et al., 2018), we explore how technology actors engage in activities and develop strategies in and around PDPs that can pave the way for market formation.

Our choice to focus on the focal business firm, i.e., in this case the plant owner, gives us a good picture of what is done at the plant (e.g.,

Table 2
Short descriptions of the three advanced biofuel technologies.

Technology	Main actor	Short description of technologies for advanced biofuels
Fast Pyrolysis Technology	Valmet/Fortum - Finland	The integrated pyrolysis solution features a reactor constructed in connection with a fluidized bed, where wood is vaporized and condensed into bio-oil. The process is based on fast pyrolysis, whereby wood is decomposed in an oxygen-free atmosphere at high temperatures. The concept also allows integration of fast pyrolysis to existing industrial or district heating CHP plants. The combination allows lower investment costs when integrating into existing boilers. Even though bio-oil is not actually oil, it can be used to replace heavy fuel oil, for example, in power plants. In the future, it could potentially be further processed into transportation fuels and raw material for the chemicals industry.
Fast Pyrolysis Technology	BTG - the Netherlands	The fast pyrolysis process consists of a thermochemical decomposition of biomass through rapid heating, at a temperature of 450–600 °C in the absence of oxygen. The most distinctive asset of BTG's Fast Pyrolysis Technology is the Rotating Cone Reactor (RCR). It allows for intense mixing without the use of an inert carrier gas. The RCR design results in a remarkably small reactor, reduced system complexity and a minimal downstream equipment size, compared to other pyrolysis technologies. This fast pyrolysis technology converts biomass residues into a renewable bioliquid that can replace fossil fuels. The key features of BTG's technology – the exclusive use of biomass residues and the opportunity for local processing – make it a truly sustainable solution.
Sunliquid technology	Clariant-Germany	The sunliquid technology developed by Clariant meets all the requirements of a technically and economically efficient, innovative process for converting agricultural residues into cellulosic ethanol as a climate-friendly biofuel. The production of cellulosic ethanol is almost climate neutral. In this process, bioethanol made from material containing lignocellulose, such as agricultural residue (e.g., cereal straw, corn stover, bagasse) or energy crops (e.g., miscanthus, switchgrass). Using process-integrated enzyme production, optimized enzymes, simultaneous conversion of cellulose and hemicellulose into ethanol and an energy-efficient process design, it has been possible to overcome technological challenges and sufficiently reduce production costs to arrive at a commercially viable basis.

what problems are addressed). This is critical to our understanding of the role of PDPs in market formation, not least since the representatives of this firm could provide us with information about customer demand and regulatory challenges. Clearly, though, it is fair to argue that expanding the scope of the investigation to also address other actors, could influence the results. For instance, there may exist a trade-off between the expectations of the users of the technology and the focal firm's ability to live up to these in the daily operations of the plant. Some actors may wish to test a broad scope of solutions while other would preferably opt for a narrower scope in the tests conducted. Such differences in the goal functions of various actors are important avenues for future research, and we come back to this in the concluding section.

Replication logic is employed in order to investigate the development of three technologies for advanced biofuel production in three different European countries. This approach enables us to corroborate the findings and dissociate emerging patterns from the country- and company-specific circumstances (cf. Eisenhardt, 1989; Eisenhardt and Graebner, 2007). In this way, it is possible to generate more analytically valid findings across a certain type of case (Eisenhardt and Graebner, 2007; Yin, 2009). We implement a purposeful sampling to select information-rich cases that facilitate theoretical inferences (Eisenhardt, 1989; Patton, 2002).

The analysis focuses on the development of three technologies for advanced biofuels. These technology trajectories are thus the primary units of analysis, and include: (a) Valmet/Fortum's fast pyrolysis technology, Finland; (b) BTG's fast pyrolysis technology, the Netherlands; and (c) Clariant's Sunliquid technology, Germany (see further Section 4). Given the purpose of this paper, it is important to note that these trajectories have all been verified and tested, but there is a need to demonstrate large-scale functionality. The three advanced biofuel technologies are briefly described in Table 2.

3.2. Data collection

Ten semi-structured interviews with key informants of the technologies and related PDPs were, in combination with secondary sources, employed to reconstruct the history of each case. Most of the interviewees were identified based on the criteria of being involved in and/or having thorough knowledge about the construction and use of the respective PDPs in the selected technology development trajectories. The interviews took place from December 2018 up until November 2019. A list of all interviewees is presented in Table 3.

Table 3
List of interviewees.

Interviewee	Company	Main actor
Head of New Energy Concepts	Fortum	Valmet/Fortum - Finland
Manager of Bio-oil Business	Fortum	
R&D Program Manager, Environmental Systems	Valmet	
Managing Director	BTG-BTL	BTG - the Netherlands
Chief Technology Officer (CTO)	BTG	
Manager consultancy	BTG	
Chief Executive Officer (CEO)	BTG	
Head of Business Line Biofuels Derivatives[a]	Clariant	Clariant - Germany
Head of Public Affairs, Technology & Innovation	Clariant	

[a] The Head of Business Line Biofuels Derivatives at Clariant was interviewed twice, given the important role that this official played in the development of the Sunliquid technology.

We asked the key informants about the history of the technology development, and the role of PDP activities, particularly in relation to market formation. The interviews also addressed the main challenges and problems encountered in technological development, and how these have been dealt with, particularly in relation to PDP activities. To further develop the narrative, triangulation with different secondary sources of data (cf. Denzin and Lincoln, 2007) was used. These include public interviews, reports of the companies, company presentations, companies' press releases and websites, news about the technologies, information on PDP activities in professional journals and whitepapers, and PDP project partners archival data. Table 4 provides an overview of all data sources for each case technology. All interviews were transcribed and consolidated with the other material in a database. We then used the NVivo software to compile all gathered data and build a case

Table 4
Data sources for each case.

Main actor	Case	Data sources (number of sources)
Valmet/Fortum - Finland	Fast Pyrolysis Technology	- Interview (3) - Public interview (4) - Secondary data (Articles and whitepapers) (4) - Company presentation& Technology brochure (6) - Press release & company website (29) - News about the project (18) - Patent (1) - Project partners archival data[a] (11)
BTG - the Netherlands	Fast Pyrolysis Technology	- Interview (4) - Public interview (7) - Secondary data (Articles and whitepapers) (5) - Company presentation& Technology brochure (12) - Press release & company website (23) - News about the project (37) - Patent (1) - Project partners archival data (25)
Clariant - Germany	Sunliquid Technology	- Interview (3) - Public interview (6) - Secondary data (Articles and whitepapers) (4) - Company presentation& Technology brochure (11) - Press release & company website (31) - News about the project (50) - Patent (1) - Project partners archival data (21)

[a] Archival data: public interviews, website, press release, and news.

study database for each technology. Based on this, we could establish a chain of evidence from raw data to findings (Yin, 2009).

3.3. Data analysis

For analyzing the data, we began by writing individual case histories and narratives to trace important events (cf. Langley, 1999), and with a focus on the evolution of the technologies and the role of PDPs. In a second step, we adopted an abductive approach to code the data from the narratives based on in-vivo informant terms, so-called "open coding" (Strauss and Corbin, 1990). The resulting first-order concepts are presented in Tables A1 and A2 in the Appendix; these stem from the interviews and were triangulated with the secondary data.

In a third step, adopting insights from SNM research (Schot and Geels, 2008), we employed 'axial coding' to come up with categories among the first-order concepts, i.e., the second-order themes. The first-order concepts were coded and categorized in the context of the three niche processes: articulation of expectations and visions, building social networks, and learning. The analysis was also guided by cross-case replication logic (Eisenhardt and Graebner, 2007); this step helps elicit the key themes of niche processes (see also Glaser and Strauss, 1967).

Fourth, we assessed the semantic relationships among the niche processes, i.e., the second-order themes, and their interaction within and outside of the niche community to categorize them into the enabling mechanisms that underlie market formation for the novel technologies. Some significant first-order data in support of the explanatory mechanisms are provided in the supplementary material to this article. Finally, we aggregated the enabling mechanisms into two market formation subprocesses; i.e., supply uncertainty reduction and demand uncertainty reduction. In this way, we identified the mechanisms through which PDPs allow technology actors to reduce uncertainties with respect to supply and demand, and thereby facilitate market formation for the new technologies. Fig. 1 illustrates the result of this data structuration and analysis process (with all first-order concepts outlined in Tables A1 and A2 in the Appendix).

4. Background to the case technologies

In this section, we provide a brief introduction to the three technologies for advanced biofuel production, and with particular emphasis on key events regarding their development.

4.1. Fast pyrolysis: Valmet/Fortum (Finland)

Fig. 2 presents the key events regarding the development of Valmet/Fortum's fast pyrolysis technology. The research on pyrolysis technology in Finland took off in the 1980s as the VTT Technical Research Centre of Finland initiated the first laboratory studies. In the 1990s, VTT launched several R&D projects and constructed a lab-scale process development unit (PDU) aimed at producing different types of bio-oils from various feedstocks. In 1996, to address the challenge of lowering production costs, VTT invented the technology concept integrating the pyrolysis reactor and the fluidized-bed boiler. Today, this is widely used in combined-heat-and-power (CHP) production. The first patent on integrated fast pyrolysis was granted to VTT in 2006.

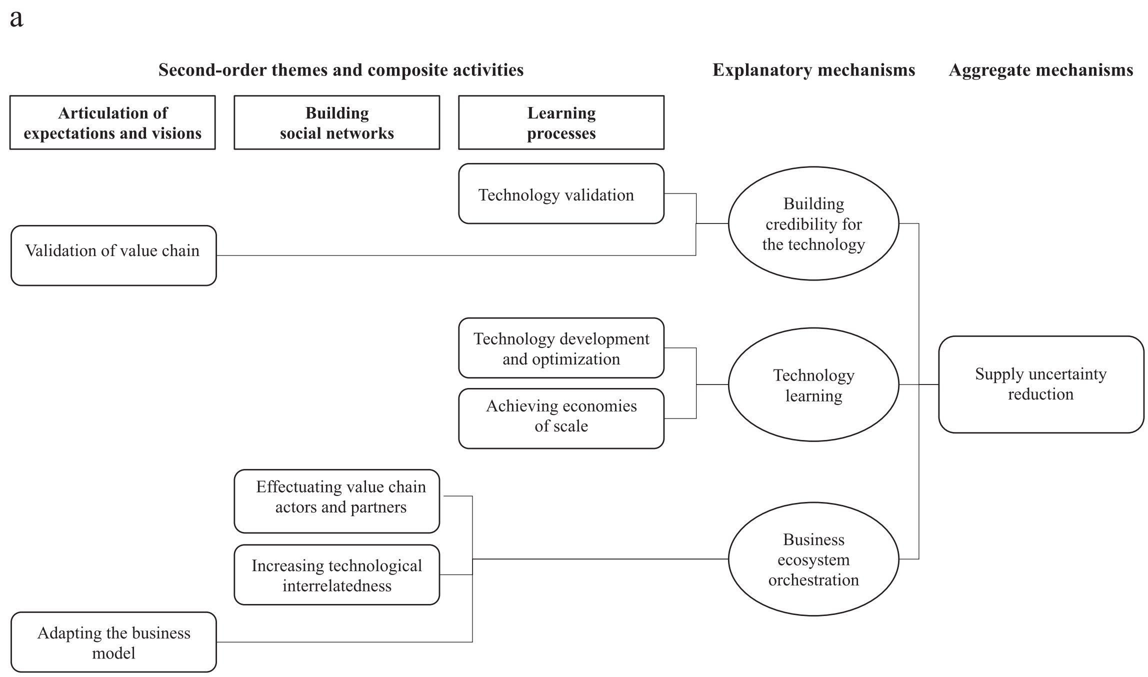
In parallel with VTT, Fortum, an energy company, was also developing the technology for its own purposes. In 1999, Fortum decided to up-scale the pyrolysis technology to commercial size. It built the first pyrolysis (stand-alone) pilot plant in close cooperation with VTT. In 2002, Fortum together with Oilon, a burner manufacturer, verified the pyrolysis technology concept, and demonstrated that it is feasible to convert forest residues into a liquid that can be combusted in boilers and thereby replace oil. Fortum probed the market but found that the business case for the technology was quite poor at the time. Still, due to the continuous rise of fossil energy prices as well as increased concerns about global warming, the technology development efforts were brought up again.

In 2007, a consortium of private Finnish companies – Valmet and UPM along with VTT – was established to develop an industrial application for the integrated fast pyrolysis process. This effort was based on the basic R&D and patents of VTT, and it received research funding from TEKES, the Finnish Funding Agency for Technology and Innovation. The market outlook had improved, and the consortium went ahead to develop an industrial-scale pilot plant at Valmet's R&D Center to further verify the integrated technology concept.

Fortum joined the consortium (in 2009) to bring end-product user expertise to the project. The aim was to develop the process so that it could be integrated into existing industrial or district heating CHP plants. Successful scale-up of the technology was achieved by 2010, and Fortum built the first commercial-scale demonstration plant for integrated fast pyrolysis technology. In 2018, the consortium engaged in a joint venture with the Swedish refinery Preem to produce advanced lignocellulosic fuels.

4.2. Fast pyrolysis: BTG biomass technology group (the Netherlands)

Fig. 3 represents the key events regarding BTG's fast pyrolysis technology development in the Netherlands. This development took off in 1989 at the University of Twente, and resulted in one prototype reactor. In 1993, BTG took over the patent rights of the pyrolysis technology, and has since then improved and optimized the concept. R&D support from the European Commission and the Netherlands Enterprise Agency enabled BTG to build its own pilot plant in Enschede, generate



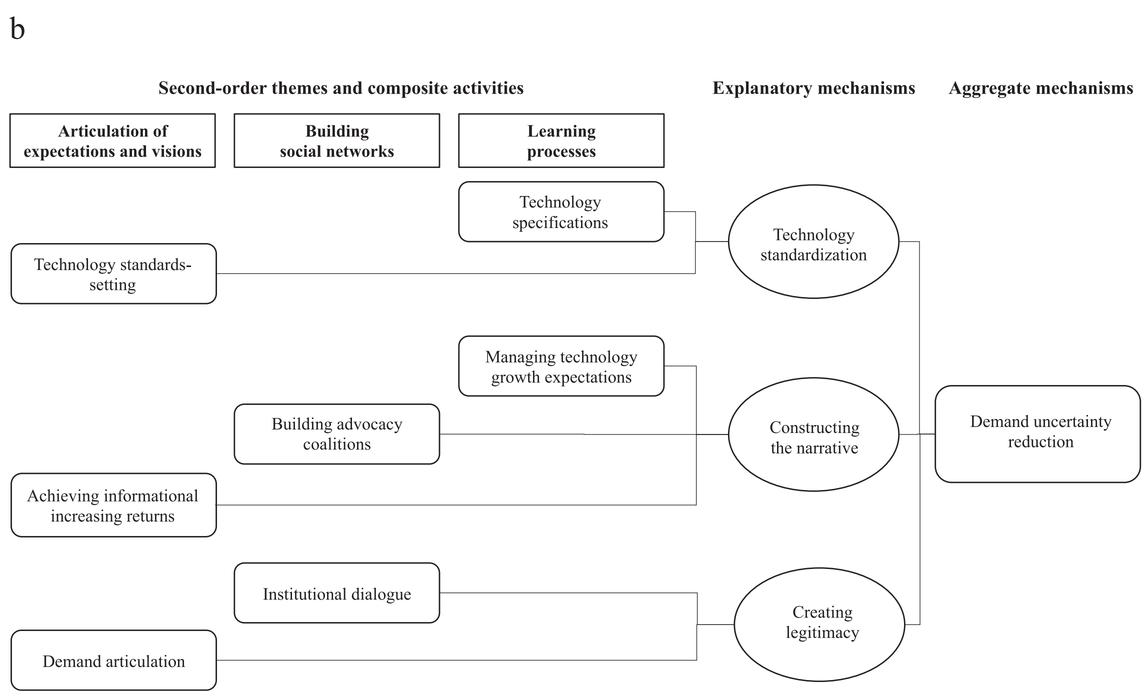


Fig. 1. (a): Data structure: supply uncertainty reduction.
(b): Data structure: demand uncertainty reduction.

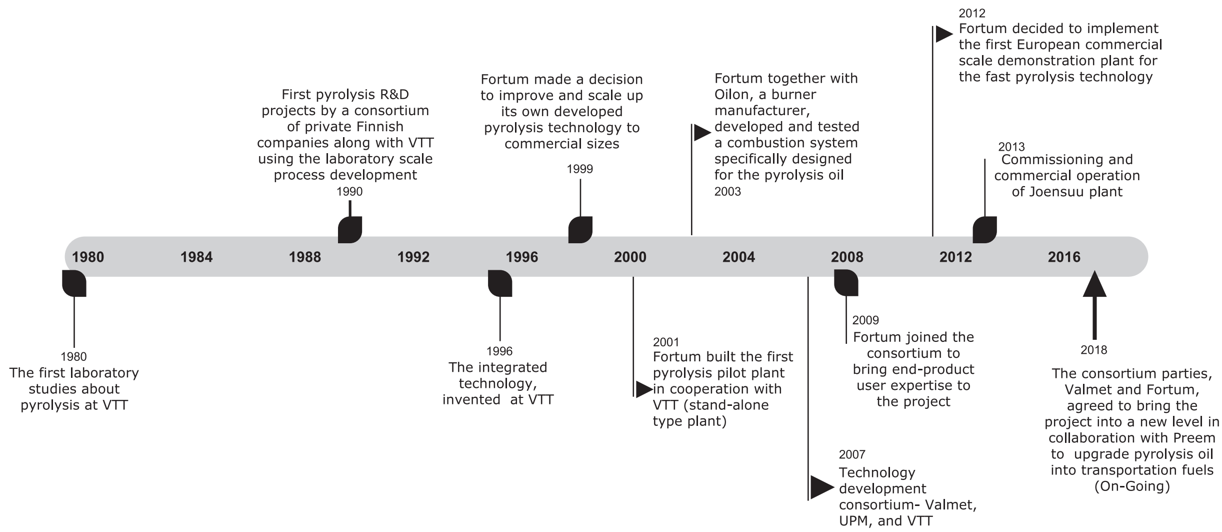


Fig. 2. The Fast Pyrolysis Technology Development of Valmet/Fortum: key events.

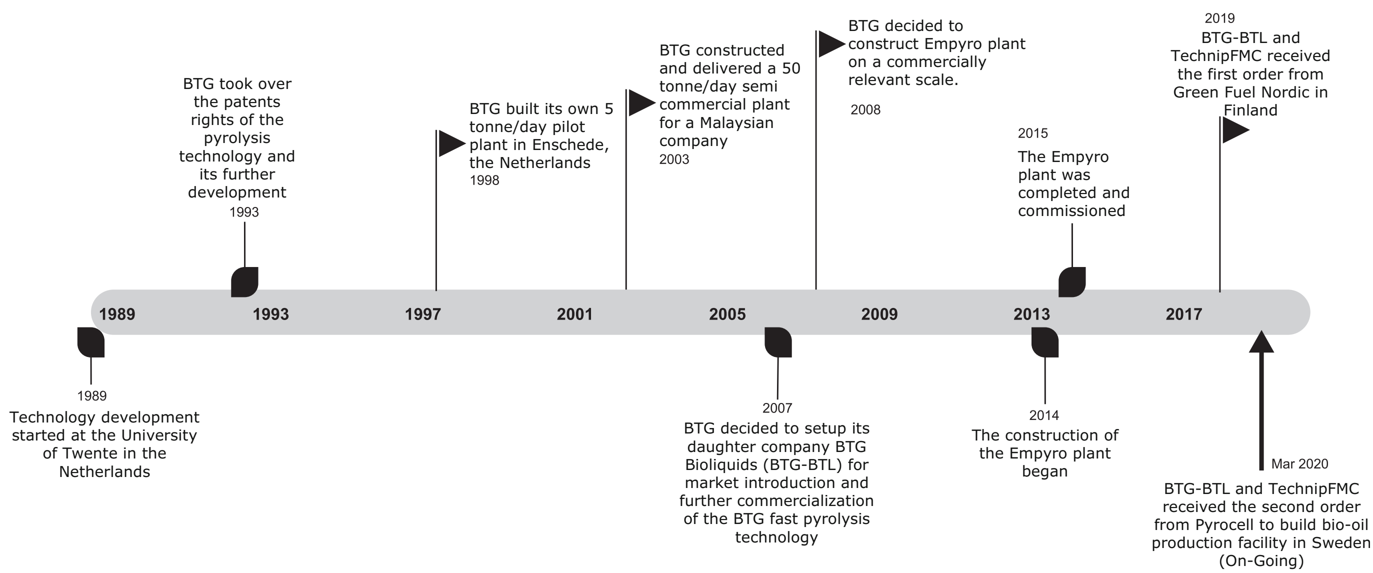


Fig. 3. The Fast Pyrolysis Technology Development of BTG: key events.

more engineering data, and produce larger quantities of pyrolysis oil. This plant is still in operation, and it serves as a backup plant for the technology development.

In 2003, BTG constructed a semi-commercial plant for a Malaysian company to convert empty fruit bunches into pyrolysis oil. The company tried to sell this pyrolysis oil in the Netherlands, but the existing subsidy for pyrolysis oil was removed by the Dutch government. A few years later, the company decided to set-up a daughter company, BTG Bioliquids (BTG-BTL), for market introduction and further commercialization of the technology. The business model of BTG-BTL was to supply the core components of the pyrolysis unit.

A bottleneck for the development, though, was that the pyrolysis plant was located in far-away Malaysia. Hence, the availability of the plant for visits by potential customers was limited, and the produced pyrolysis oil was not freely available for further development. For this reason, BTG decided to build its own plant. The so-called Empyro pyrolysis plant was inaugurated in 2015, and BTG-BTL now collaborates with TechnipFMC, an Engineering, Procurement and Construction (EPC) contractor, on further rolling out the new technology.

4.3. *The Sunliquid technology: Clariant (Germany)*

Fig. 4 presents the key events regarding the development of Clariant's Sunliquid technology in Germany. This development took off in 2006 when the company restructured its R&D to focus more on energy and resource efficiency and the production of bio-based chemicals and biofuels. Using its expertise in biocatalysts and bioprocessing and its know-how in downstream processing and process design, Clariant has developed the Sunliquid process for the conversion of lignocellulose to cellulosic ethanol, primarily based on agricultural residues such as wheat straw, corn stover, and sugarcane bagasse.

In 2009, Clariant commissioned a first pilot plant at its research center in Munich, Germany. At this plant, the company successfully tested the technology for over 15 different feedstocks. Additional

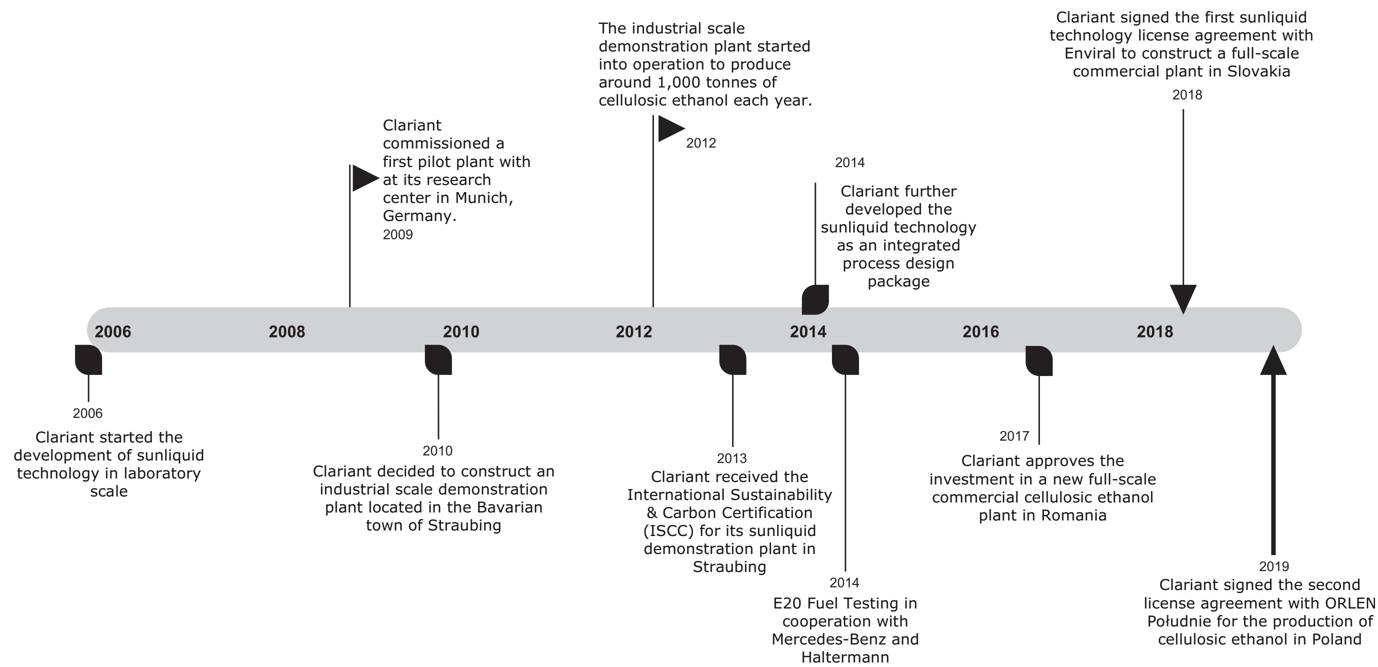


Fig. 4. The Sunliquid Technology Development of Clariant: key events.

improvements and process optimizations were identified to be implemented at the plant or included in additional R&D efforts. In 2010, Clariant constructed an industrial-scale demonstration plant in the Bavarian town of Straubing. The next step in commercializing this technology was the construction of the first commercial production facility (in Romania), and Clariant has begun to issue licenses for the construction of commercial Sunliquid plants, as well as providing the technology needed for their successful implementation.

5. Findings

In this section, we present our empirical findings concerning the enabling mechanisms through which PDPs have contributed to the market formation for three advanced biofuel technologies.

The data structure in Fig. 1 is used as the basic framework for describing and analyzing these mechanisms. Specifically, for each aggregated mechanism of supply and demand uncertainty reduction, the analysis identifies three explanatory mechanisms that facilitated and supported the market formation for the new technologies.

In all three cases, the organizational risks and the market-related risks have been the biggest motivators behind the various technology actors' decisions to construct industrial scale PDPs. Organizational risks such as realizing a stable value chain for the technology or its products, and market-related risks such as market demand for the new technology or its product market risks have been the main sources of uncertainties for technology actors. We also find that the main aims of constructing and operating these plants have been to reach a stable operation and performance of the technologies, to achieve economies of scale, to create the initial supply of the technology products, and to show the application of the technology and its products. These aims have enabled technology actors to persuade and facilitate investment decision-making for technology actors, potential customers, and other actors along the value chain to join and create supply-demand networks around the new technologies.

5.1. Supply uncertainty reduction

5.1.1. Building credibility for the technology

The first enabling mechanism for supply uncertainty reduction, i.e., building credibility for the technology, consists of two composite activities: (a) *technology validation*, which is the process in which technology developers, customers, and other stakeholders learn about the technology; and (b) *value chain validation*, which represents the process in which expectations and visions are articulated. Credibility is the extent to which a project or technology is believable, and the technology developer has the knowledge and ability to live up to its claims (Featherman et al., 2021).

Our three case studies illustrate that the technologies have been validated for advanced biofuel production on several scales, this to create authoritative information on the adequacy of the processes. The experiences of Fortum following the construction of the first commercial-scale demonstration plant for fast pyrolysis technology offer an apt illustration. The Head of New Energy Concepts at Fortum explained the technology-validation role of this plant:

> I think this demonstration plant is the crucial thing […] You need the first one; maybe you need "a couple of more first of its kind" to convince people and the market that this is a continuing alternative for them.

An additional objective of Fortum and Valmet has been to demonstrate the use of pyrolysis oil in a medium-sized boiler installation, thus gaining insights into the long-term effects of firing pyrolysis oil on boiler corrosion and demonstrating that the applicable emission requirements are met. The R&D Program Manager, Environmental Systems, at Valmet explained:

> If you want to convince somebody of a technology, you need to show long-term operational data, and preferably to have customer feedback that you can rely on.

BTG decided to construct the Empyro plant on a commercially relevant scale as a reference pyrolysis plant close to its base in Enschede to demonstrate that it is not only technically feasible to produce oil from sawdust but that it is also a commercially viable proposition. The Managing Director at BTG-BTL explained the role of the Empyro plant as a demonstration plant in the commercialization of the technology:

> Empyro [plant] was the first example of commercialization. What you need is to prove that the technology is working because people will not buy from you if you do not prove it. That is why we proved it

> ourselves. Customers are coming into Empyro saying that I want to have that plant, exactly the same one.

In a similar vein, representatives of Clariant argued that their industrial-scale plant helps prove the maturity of their technology. Through the validation of its biocatalysts and bioethanol production, the plant results have provided input for the planning and construction of the first commercial production plants. The Head of Business lines Biofuels & Derivatives at Clariant expressed:

> Customers do not like to buy a product that the seller of the product has not demonstrated. Demonstrating our technology on a commercial scale generated a lot of additional expertise and know-how. […] When you change from the pilot to a pre-commercial demonstration, you start to run the plant more like a production plant. It is designed as – and it works along with the principles of – a commercial plant. In the lab environment, the stability of the process or repeatability is often not your focus area. But in a demonstration plant, your focus is to do it in a stable manner.

Technology actors have also used large-scale demonstration plants to verify the entire value chain, from the feedstock to end-users. Based on these plants, sales can be realized, and these can pave the way for more advanced applications. For instance, Fortum uses its own heat plants to verify that bio-oil can replace heavy and light fuel oil in such plants. According to Fortum, the use of bio-oil has significant positive environmental impacts because energy produced with bio-oil reduces carbon dioxide emissions by as much as 90 % or more compared to fossil fuels. Fortum aimed for continuous development and growth of the business in CO2-free energy production. The company has also delivered batches of bio-oil for combustion to other energy generators in Sweden and Finland. Experiences have also been gained about the supply and storage of the pyrolysis oil.

With regards to the Empyro plant, the Chief Technology Officer at BTG explained that at this plant, it has not been enough to demonstrate the company's own technology. It also needs to engage with its customers to identify future business opportunities.

> How could the pyrolysis oil be a solution for you as a customer? We needed the Empyro [plant] to show that we can make it in large volumes, but now it's not the focus anymore. The focus is now on how to use the oil. In this phase of the technology development, we have to help customers with the pyrolysis oil part. In a mature market, I can focus on technology sales. Now I have to find a kind of compromise; I have to help my customers by implementing the pyrolysis oil.

For Clariant, it has also been critical to address the entire value chain, from feedstock, handling by-products to selling off the finished product, to showcase to the customers how the value chain may come to work in practice. The Head of Business lines Biofuels & Derivatives at Clariant, stated:

> In the early technology stages, you check feedstock availability in the market, like grass availability in each region, whatever you can check in terms of the price level, also on the products. You do all this stuff, developing it very concretely, closing contracts on supply, and the selling of the products; that usually only happens with the first-of-its-kind commercial plant.

The customer has to buy like a quarter of a million tons of feedstock on the market and has to sell the product on the market. The customer has to deal with all of the by-products. Hence, what do you do with them? What do you use for energy generation? Are there other markets to use them? Thus, the inside know-how that we generated in the development of the commercial plant of the first-of-its-kind plant in Romania, is also very helpful for the project development of customers.

5.1.2. Technology learning

Technology learning refers to the processes taking place within a technology development or industry, and that leads to the improvement in performance and the progressive reduction in costs of a specific technology (cf. Ek and Söderholm, 2010; Grafström and Lindman, 2017). Various PDP activities are important for such technology learning processes. For our purposes, it is useful to distinguish between two composite activities related to technology learning: (a) technology development and optimization; and (b) achieving economies of scale.

By building and operating PDPs, technology actors have tested, developed, and optimized advanced biofuel technologies for integration in large-scale power plants. In all our three cases, it is emphasized that some challenges only emerge when the technology is used in full-scale. The Valmet/Fortum case is an apt illustration of the need for technology learning at the demonstration plant level. Even if bio-oil can replace light and heavy fuel oils, it differs from fossil fuels in terms of composition and properties. Bio-oil is acidic, and not all materials are compatible with this. For this reason, process optimization and quality control throughout the value chain have been critical. In the commissioning phase, technology suppliers developed and optimized the process as well as tested different raw material and process parameters.

The manager consultant at BTG reflected on this issue, and emphasized the importance of continuous testing to be able to offer their product to customers with certain warranties.

> If you have to build a full-scale plant, you always encounter problems that you would not expect. I mean that you know that you will get problems, but you do not know where. That's also why it is necessary to build a plant and operate it 24/7 to tackle the problems. It gives you a lot of experience and helps you improve the technology in a way that you can offer future plants with certain guarantees.

All three companies have worked strategically to attain such a set-up. The Head of Business lines Biofuels & Derivatives at Clariant explained the key role of a pre-commercial plant for technology learning and the time it takes to pursue testing:

> We have spent five to six years in the demonstration plant to sort out these problems, to test different process schemes, different means to transport products, and to create a stable performance. Only then have we decided to pursue with an investment into a commercial-scale plant.

Technology learning also concerns highly practical things, such as how to ensure a good plant layout. The Head of New Energy Concepts at Fortum explained.

> Of course, we noticed some [technical] bottlenecks in the process, [but] there were also some boundary conditions that we were able to take into consideration. One of them was the plant layout, which we need to address more in detail. The plant layout was one of the items that came as a surprise to us. It is not all about the process.

These large demonstration facilities will continue to play a role in technology learning also as the technology matures. For instance, feedstocks differ based on the region where the customer resides; even for the same feedstock, there can be quality variations. For this reason, continuous adaptations are needed.

We now turn to another important component of technology learning – achieving economies of scale. Following pilot trials in the laboratory, the main challenge for the technology actors is to strike a balance between demonstrating the technology at an industrial scale and the first-of-its-kind commercial-scale production plant. Although an industrial-scale plant is typically significantly smaller than a commercial-scale plant, the cost of operating the former is still often significant while the potential income from the production can be negligible. The Head of New Energy Concepts at Fortum reflected on this:

> The thing is that when you have a laboratory scale, the running costs are very high from a health and safety point of view. This is very important for both Valmet and Fortum. We have very tight policies. You have to manage it as a huge power plant. One running week is very expensive. […] You get some cubic meters of oil from that. You do not sell anything, though everything is a cost on that scale. The other issue is that even if the Tampere [plant] was a megawatt-scale boiler and it was a miniature boiler, you need different equipment when you upscale it. You have the equipment on a smaller scale, but you should test them in practice. But you don't run it for thousands of hours because you cannot afford to do that.

BTG decided on another approach with their Empyro plant. The company opted for a first full-scale commercial fast pyrolysis plant. The difference is that it can be run 24/7, but the scale is 25 times bigger than the previous pilot plant and twice as big as their plant in Malaysia. The CEO at BTG commented on this decision:

> We decided to build up at a scale, which would be commercially feasible in the Netherlands because we did not want to build another monument. In the past, many monuments have been built, e.g., in the field of gasification. They cost lots of money, tens of millions of Euros, and they were never able to run on a commercial basis because they did not have sufficient scale.

In the case of Clariant, the company constructed pre-commercial plants. Although these plants have been costly to operate, the intermediate step has been important for solving technical problems, but also to demonstrate how cellulose ethanol can be produced economically. The Head of Business lines Biofuels & Derivatives at Clariant explained the role of the large-scale demonstration plants for achieving economies of scale:

> In a commercial-scale plant, the challenges are more on construction cost or investment. For the lab and the pilot, it is rather small figures and people do not care too much about cost-efficiency. However, that grows stronger in a pre-commercial plant. When you go then finally into a commercial, in a first-of-its-kind plant, there you have to control costs.

5.1.3. Business ecosystem orchestration

Business ecosystem orchestration refers to establishing a supporting inter-organizational and multi-stakeholder infrastructure as well as championing the value chain across complementary contributions to surround, permeate, and shape a market for the technology (cf. Moore, 2006; Williamson and De Meyer, 2012). In our context, this consists of three composite activities where the first two activities are related to establishing actor networks, and the third one is about the articulation of expectations and visions.

First, technology actors use PDPs as a platform to effectuate the value chain actors and the committed partners. For example, the development of integrated fast pyrolysis in Finland has been conducted in collaboration between the VTT Technical Research Centre, Valmet, UPM, and Fortum. Techno-economic assessments and market studies have motivated the partners to effectuate and demonstrate the entire value chain from feedstock procurement and pretreatment to bio-oil production, transportation, storage, and end-use. In this collaboration, Valmet has overseen the technological development of the pyrolysis process integrated into the fluidized bed boiler. UPM, being a forest products company, has added expertise on the raw material. Fortum has brought the perspective of an operator and end-product user to the project. This collaboration has covered experimental runs enabling the study of the pyrolysis of industrially relevant feedstocks, recovery of bio-oil, properties, handling, and quality improvement.

The development efforts at the Empyro plant in the Netherlands indicate a similar experience where the plant itself has been instrumental for BTG-BTL in effectuating the full value chain from biomass to end product and use. BTG's strategy has been to seek cooperation with other companies to gather complementing expertise, this for both the construction of the plant and the development of pyrolysis applications. The Managing Director at BTG-BTL commented:

> Developing technology is the art of cooperation, and not do everything yourself. That's extremely important! For example, with Zeton, we worked already with them for the Malaysian project. […] Stork supplied the pyrolysis oil burner. I have a background in Stork.

With regards to the Sunliquid development, Clariant has managed to establish a collaboration between actors along the entire value chain, i.e., from co-product utilization and valorization to advanced bio-ethanol production, product, as well as technology distribution. Under the coordination of Clariant, companies and research institutes from Germany, Austria, Romania, and Hungary participated. The actors supplying the feedstock have been particularly important. The Head of Public Affairs at Clariant commented on the challenges involved in creating an effectuation that includes the biomass suppliers:

> You should be able to mobilize enough biomass for your biorefinery. It is one thing that there is biomass available in the area, but then to get that biomass actually to your plant is another question. Then obviously it depends very much on the regions where you operate, and how the farming sector is being established there.

Second, one important aspect of the establishment of effective actor collaborations along the value chain concerns increasing technological interrelatedness. In the demonstration plants, technology suppliers have adopted complementary technologies to decrease uncertainty. For example, the Fortum bio-oil plant is unique in that it is integrated with the company's CHP plant. Scaling up the technology, Fortum and Valmet have proved the considerable potential for the deployment of fast pyrolysis in industries with established infrastructures. The Head of Power business line at Valmet commented on the compatibility of the new technology with the dominant technological regime:

> The demonstration of pyrolysis technology is an indication of our company's strategy of offering energy solutions in which technologies related to fuel refining have been brought about alongside traditional combustion.

BTG-BTL has addressed technological interrelatedness by partnering with TechnipFMC. The ambition has been to receive EPC services for the modular pyrolysis plants; this partnership has allowed BTG-BTL to launch its global roll-out of turnkey pyrolysis plants and services to industrial companies. The CEO at BTG stressed the advantage of this partnership:

> Technip is a big EPC Contractor. They can deliver turnkey plants to clients. BTG-BTL is only delivering the core part of the plant on pyrolysis, and we still do it together with Zeton. But the whole thing around it, also the guarantees, and financial guarantees, all is done by Technip. This is also a big advantage for a bank as there is a big company behind it.

Similar to BTG, Clariant has identified commercialization partners out of an existing contact when it launched its pre-commercial plant. The company has teamed up with these based on the complementary competencies that are required along the entire value chain. In these efforts, Clariant has focused on using standard process equipment from other industries, e.g., the pulp and paper sector, to reduce the risks of technology upscaling. For instance, Clariant has applied Valmet's pretreatment system in its pre-commercial plant, and has cooperated with Valmet to verify and optimize this system. The Head of Business lines Biofuels & Derivatives at Clariant elaborated on this:

> How did that network around the technology develop? It is more about identifying partners out of an existing contact. We started to develop that a long time before we even thought about doing the

> investment in Romania. Thus, developing that network started […] when we opened our pre-commercial plant for the first product to the market. That is when you get into contact with the customers, commercial partners in the supply chain, and then at some point, you make a decision for one or the other of them for that specific project.

Third, and finally, business ecosystem orchestration also concerns the adaption of the business model, and PDPs have helped facilitate this process. The original business model of Fortum was to develop the new pyrolysis plant for itself, run it, employ the pyrolysis oil in its CHP plants and sell the oil to potential customers. So far, though, it has proved difficult to convince potential CHP companies to make the investments needed for burning the bio-oil, in part due to low fossil fuel prices. In 2018, Fortum changed its business model. Together with Valmet, they agreed on joint development with the Swedish refinery Preem, and in this way, the value chain could be extended from bio-oils for CHP production to biofuels for the transport sector. According to the Head of New Energy Concepts at Fortum, instead of acquiring customers, the company has invested in the development process to create a new business out of the bio-oil on a long-term basis:

> We have established another consortium, including an oil refining company [Preem], to bring the technology to the next step. First, we wanted to use the bio-oil as the heating fuel, if the market works, then we invest more in it. That is our business. However, we also looked in parallel to the further development because the updated EU legislation was coming. We think there will be a lot of future demand for transportation biofuels.

The BTG case differs from Fortum in the sense that BTG has never aimed at becoming a main producer of bio-oil. Instead, they wanted to market the technology, i.e., engineering hours. Due to a lack of customers, however, they have been forced to change their business model and set up a production company, which owns and operates the Empyro pyrolysis plant. In 2018, BTG sold the plant, and the company could then revert to its focus on being an engineering company. The Managing Director at BTG-BTL explained how the company managed to align its business model with the evolving ecosystem:

> The reason why we built the Empyro was not that we wanted to produce oil, because the role of the BTG-BTL is to sell the technology. We needed the Empyro to demonstrate to the world that it's working. We have now sold the Empyro plant to Twence [a Dutch energy company], which is the neighborhood of the Empyro. It is a big success for us.

Finally, the business model of Clariant has involved issuing license packages for the process. However, also in this case the business model had to be adapted since the market was immature, and Clariant was forced to take on a much larger role in developing the first commercial plant in Romania. The entire offtake was contracted with a multi-year agreement to Shell, a leading global energy company. Shell aims to be a material, profitable supplier of sustainable advanced low-carbon fuels as part of its wider work to become a net-zero emissions energy business by 2050. It was only after successful implementation (in 2018) that Clariant signed a license agreement with Enviral, the largest bioethanol producer in Slovakia. In 2019, another license agreement was signed, now with ORLEN Południe, to produce cellulosic ethanol in Poland based on the Sunliquid technology.

5.2. *Demand uncertainty reduction*

5.2.1. *Technology standardization*

Technology standardization consists of two composite activities, which relate to the formation and diffusion processes of technology standards (e.g., Jiang et al., 2018). These include: (a) an ongoing learning process in which technology actors commit resources to the technology specification and the associated products; and (b) the articulation of expectations and visions concerning the technology standards-setting.

Technology specification involves detailed descriptions of technical requirements, usually with specific acceptance criteria, stated in forms suitable to form the basis for a production process. PDPs can contribute to such specifications. As noted above, Fortum's plant has been integrated into an existing CHP plant; the demonstration efforts have validated this type of integration, and that the pyrolysis bio-oil can be used as a fuel oil. This added knowledge has helped the technical specification for potential customers, illustrating that specific minor additions to existing boiler plant equipment are needed when integrating the pyrolysis unit.[3] The PDPs have also enabled technology actors to recognize the technology specifications of the end-users. The R&D Program Manager at Valmet discussed this:

> We prefer, at least at this phase of the technology development, to work together with our potential customers. […] You can build a so much stronger case. That it is viable also from a market point of view and the daily operations point of view. We were able to take their views and considerations into account on how to integrate a fluid burn boiler and pyrolysis system.

The experiences from the BTG case also illustrate how the PDP activities could contribute to technology specifications. Since the company's first pyrolysis plant was built in Malaysia, there were limited opportunities for customers to learn about technology specifications. The pyrolysis bio-oil was not freely available for further research to help specify its properties. Lessons in relation to technology specifications instead emerged from BTG's more recent plants. This learning has been an illustration of poly-generation of three products (e.g., bio-oil, steam, and electricity), and their applications involving different customers (e.g., AkzoNobel and the dairy company FrieslandCampina). Besides technical performance, demonstrating the technology at full scale also enabled BTG to specify environmental, health, and safety aspects, staff requirements and skills for operation, maintenance, capital and operating costs, and plant variability in relation to product demands.

Learning about technology requirements and specifications is closely related to the formation of future technology standards. According to interviewees representing both Fortum and BTG, pyrolysis bio-oil differ in their technical specification from conventional liquid fuels, and it is essential to find a common standard to promote its acceptance. As a result, collaborative efforts between the equipment suppliers, producers, and end-users have been pursued to define such standards. Standardization work under CEN, the European Standardization body, and REACH registration has also been initiated.[4] The R&D Manager at Fortum explained more about the ongoing collaboration concerning the standardization of pyrolysis technology:

> We have been cooperating on the standardization of the product. This was a big effort because there was so little evidence about the end-use and what kind of and where you should put those specifications. Valmet was involved as well as BTG from the Netherlands. We saw that there is a competition between them as the technology supplier. However, if we do not get this market working, what's the point? There are other guys also who took the same risk and invested their money on this. For instance, this EU chemical substances

[3] Even though it was verified that pyrolysis bio-oil can be used as a replacement for heavy fuel oil, the bio-oil is shown to be different from fossil fuels in terms of composition and certain properties, such as a low heating value and high acidity. Interviewees argued that one reason why the pyrolysis technology has not penetrated the market more quickly partly originates from these properties.

[4] REACH is short for Regulation for Registration, Evaluation, Authorization and Restriction of Chemicals, and refers to EU legislation, which aims to improve the protection of human health and the environment through better and earlier identification of the intrinsic properties of chemical substances.

> legislation REACH is a very heavy process and very expensive. I think when we started the REACH, we tried to find everybody interested in getting approval for the REACH.
> Typically, the data that you have from full-scale plants are not available in the pilot plants. [...] The risk is that if you rely on pilot data, maybe you make the margins too tight, and then at the end, you have the standards that you cannot fulfill. Now, we can argue that our experience and our data for the technology and the bio-oil have been produced in full scale. That is the relevant data!

This illustrates the importance of large-scale demonstration plants for detailed specification and future technology standards; these plants provide the relevant data, and can thereby ensure that a realistic set of specifications are determined.

Clariant has been involved in similar processes, in their case also at the plant level. In 2013, the company received the International Sustainability & Carbon Certification (ISCC) for its demonstration plant in Straubing. This certificate confirms that the cellulosic ethanol based on agricultural residues is compliant with the sustainability criteria in the European Renewable Energy Directive (RED). The Head of Business lines Biofuels & Derivatives at Clariant explained the role of the ISCC in promoting a market for the Sunliquid technology:

> The ISCC certificate allows the company to demonstrate even more clearly to potential partners the efficiency of its technology and quality of products from the Straubing plant. The biofuel produced in Straubing fulfills and exceeds the sustainability criteria defined in the RED, and can be counted towards the climate policy targets – this is an important prerequisite for establishing the process in the European market.

5.2.2. *Constructing the narrative*

Constructing the narrative refers to activities, which are intended to shape and raise other actors' expectations concerning a novel technology (Kern et al., 2015; Ottosson et al., 2020). Through this enabling mechanism, the technology developers make the novel technology comprehensible, plausible, and attractive enough to persuade actors to establish advocacy coalitions in support of the technology. This mechanism consists of three various activities: (a) managing technology growth expectations; (b) building advocacy coalitions; and (c) achieving informational increasing returns.

To manage technology growth expectations, technology actors have often followed a stepwise market introduction to shape the expectations about the technology. This involves discovering what can be achieved with the technology as well as providing a compelling vision for potential customers. According to interviewees from Fortum and BTG, this stepwise scale-up has been essential for managing risk. For instance, Fortum demonstrated that the integration of fast pyrolysis and CHP plants was technically viable, and once the entire value chain from biomass to fast pyrolysis plant to heat utilization was proven, the more demanding uses of the bio-oil could be introduced. The R&D Manager at Fortum argued that this has constituted a way of making the risks involved more manageable:

> We thought this is a part of the risk management if the market does not work, then we can utilize the pyrolysis bio-oil by ourselves.

If there was no pyrolysis bio-oil, it would have been difficult to justify further R&D efforts on using the pyrolysis bio-oil for other applications. For example, the CTO at BTG described how the Empyro Plant has contributed to shaping the vision and the expectations of the value chain actors:

> I think since the late 1990s, the vision has been to develop pyrolysis technology. To some extent, you also have to create a market for it. [...] It's not only for this kind of product, but also for transportation fuel or small-scale heat and power. You can go to different bio-based products but it's just a whole range. That is what you would like to show and that it would become more commodity and that people would like to produce pyrolysis oil because they can sell it in the market and make money.

Similarly, Clariant has adopted a stepwise market introduction. As noted by interviewees, this approach has allowed the company to manage regulatory and market risks. It has also, though, put pressure on Clariant to launch "flagship" projects that can attract customers' attention. The Head of Business lines Biofuels & Derivatives at Clariant described this:

> When these projects are in the energy sector, they have a specific exposure to regulation. Any investment decision will go through a very formalized process to check the value chain. I always say that everybody wants to be first with a second plant, justifying that additional investment into the first plant. That is why I would say public support grants are essential and the public-private partnership is helpful to deal with those risks and uncertainties.
> The vision that also lies behind a project like the Sunliquid plant is that you should build a flagship plant, a first-of-its-kind target, but that should not be a one-off. It should be the first in a row. That is the idea; what do we need to be able to not only build the first-of-its-kind plant but how can we replicate the technology and contribute to energy demand?

An important activity for constructing a narrative concerns the building of advocacy coalitions, i.e., essentially a group of actors that share certain ideas and coordinate themselves to influence the government decision-making process. Our empirical material illustrates that the PDPs have played key roles in forming such coalitions, and in creating a narrative around the technology. For instance, the PDP activities of Fortum have been quite effective in joining different actors' forces to create a constituency behind the technology. In addition, BTG's Empyro plant has attracted the attention of different actors in the ecosystem, i.e., technology developers, potential customers and policymakers. The manager consultancy at BTG confirmed how the plant has helped create an important community of advocates, which also includes existing competitors working on the same type of technology.

> We see other people that are also developing this technology such as our competitors like Fortum, Dynamotive, and Ensyn [...]. They are also our colleagues in the sense that they are working on the pyrolysis, and they also help to develop the market for it. If their projects failed, it also harms us. If they have success, we also have success!

The interviewees confirmed that since regulatory and market uncertainties for advanced biofuel technologies are significant, there is a need to establish market niches in which the technologies can be nurtured. In this context, building an advocacy coalition is important to bring together different groups having similar visions. The Head of Public Affairs, Technology & Innovation at Clariant explained how the building of advocacy coalitions around the technologies for advanced biofuels has contributed to market formation:

> The political activities are typical for all advocacy work companies or even associations around the new technologies. Usually, you team up with your competitors to a certain extent because they share the same interests. That's where the competition eventually comes from. We are also working on a political level with companies that are interested in our technology as potential clients, but also with companies that have different technology offerings and that would eventually compete for the same potential customers. But the idea behind this whole advocacy effort, especially with regards to advanced biofuels, is that we first need to bake a cake and once the cake is baked, we can cut it into slices, and then everybody can have some of it.

The final composite activity when it comes to constructing a narrative for the technology is achieving informational increasing returns.

Informational increasing returns occur because the adoption of a technology means that it receives greater attention, which in turn stimulates other users to adopt it. According to our interviewees, the PDPs have contributed to this, not least by reducing uncertainty about future market demand. Technology suppliers have communicated and disseminated the results of PDP activities through field-configuring events and market priming activities. For instance, Valmet's integrated commercial-scale bio-oil plant showed that this technology is ready for scale-up. The R&D Program Manager at Valmet explained the role of this plant as a reference plant in terms of infusing knowledge about the progress of the technology.

> At that time, and still, we need large-scale demonstration plants as references to generate confidence in the technology and the product. Without any product, there is no market! Without that demonstration plant, there is no business for us either. Typically, customers do not want to buy the first plants; they want to buy the second or third plant where the problems or the challenges from the first plant have been corrected.

Also, in the BTG and the Clariant cases, the PDP development has served as a reference case for potential customers and the public. The interviewees expressed that the Empyro plant was "an expensive brochure" that displayed to potential customers what the company sells, and that this has been necessary for selling the technology. BTG-BTL also needed the Empyro plant to be confident enough to offer the technology with certain price guarantees.

5.2.3. Creating legitimacy

The creation of legitimacy for a new technology refers to the mechanisms that can intensify and persuade actors to engage in the development and use of the novel technology (cf. Geels and Verhees, 2011; Suchman, 1995). It also includes mechanisms that determine what choices actors can make within the technological field, e.g., in terms of applications for the technology, market segment, and business models. Our findings indicate that two composite activities have proved to be important in this case: (a) institutional dialogue; and (b) demand articulation.

Institutional dialogues involve influencing potential actors to enter novel technological fields and fund risky projects, but it is also about gaining legitimacy and becoming eligible for various government funding schemes. Valmet pursued the possibility of investment support from the Finnish government, which, as a result, became more interested in investing in the company's industrial-scale demonstration plant. As noted by the R&D Manager at Fortum:

> There are great risks when you scale up the technology from 1.5 MW to 50 MW. Thus, we started talking with the Ministry of Employment and the Economy in Finland to get funding for this kind of initiative. […] It was quite a long process.

BTG has attempted to select and combine public funds and subsidies at the EU, national and regional levels in combination with private equity. This involved lobbying efforts to get access to funding and to make sure that the pyrolysis technology was included in existing and planned funding programs. One result of this was a production subsidy from the Dutch government, the so-called Stimulation of Sustainable Energy Production (SDE) program.[5] This enabled BTG to produce pyrolysis bio-oil, deliver the heat to AkzoNobel, and the main product to the customer FrieslandCampina. According to the Manager Consultancy at BTG, dialogues with the Dutch government were important for including the use of pyrolysis oil in the SDE program:

> The moment we started, liquid biomass was not included in the SDE. SDE was only for solid biomass. Therefore, I started to lobby to get this financing. This operation subsidy is much more than the investment subsidy. Various projects were defined to show the Dutch government that there is a real potential for pyrolysis oil. By sending them a lot of calculations, and also letters from the people that wanted to start with pyrolysis oil, [..], the Dutch government confirmed that it was going to include the pyrolysis oil in the SDE subsidy.

Our interviews show that a key role of institutional dialogues is also to reduce uncertainty concerning the long-term "rules of the game" in a specific technological field. The Head of Business Project Biofuels & Derivatives at Clariant elaborated on this:

> For the market development, we have taken important steps. Is that finished? No, and it's never going to be finished because changing the energy markets into a more sustainable direction is a continued development. We have taken important decisions; one of them is RED II. What we currently need is that RED II is transposed into the national law of the EU Member States. There are still uncertainties in how the RED II framework ends up in national legislation in the member states. There is still market uncertainty.

Finally, demand articulation is a highly iterative process in which various stakeholders attempt to address what they perceive as important characteristics and try to unravel preferences for an emerging innovation. In the Fortum case, the PDPs have helped generate an initial supply and validate the production of bio-oil. Still, as the technology performed well and the bio-oil quality fulfilled specifications, Fortum and Valmet, in collaboration with Preem, became eager to also pursue new applications. The R&D Manager at Fortum discussed this.

> We would like to call this technology a pyrolysis platform in a way that the technology is based on pyrolysis. […] It is about different applications of pyrolysis oil. This is a heavy fuel. You can refine it either to the end drop in fuel or you can produce some sort of green crude oil to be used in conventional refineries. It seems that now, at least in some parts of the world, the focus is on traffic decarbonization. We see this as an opportunity!

BTG-BTL approached a mix of potential clients to identify the best customer for the company's pyrolysis bio-oil, and, in the end, the company signed a contract with FrieslandCampina. FrieslandCampina aimed to improve sustainability in own value chain by using a renewable energy source such as pyrolysis oil. The Manager Consultancy at BTG stressed the importance of having a committed customer in the technology development:

> We wanted to go to a real demonstration project, it's not just an EU project where you research and report on that! Our real goal was to make a working plant! In the end, it has to be feasible. The investment was nearly 20 million Euros. If we wanted to succeed, we simply needed an economically feasible project, not only that year, but also for 12 years. Thus, that was the main reason why we needed a customer like FrieslandCampina that could pay a real and good price for the oil, and could also give a guarantee for 12 years the offtake contact.

Similar to Fortum, BTG-BTL has attempted to find alternative applications for the pyrolysis bio-oil to stimulate demand articulation. In 2019, BTG and the biofuel developer GoodFuels set up a new technology company that can convert crude pyrolysis bio-oil into diesel fuel for the maritime sector. The Managing Director at BTG-BTL confirmed the importance of this strategy, and the key role of the Empyro demonstration plant in this process.

> The Empyro plant has played an important role in creating a demand for the technology. If we did not have this first step of making the oil, people would say we do not believe you. First, make the bio-oil; this

[5] Stimulation of Sustainable Energy Production (SDE) is an operating subsidy in the Netherlands. Companies can receive financial compensation for the renewable energy they generate and use.

Table 5
Mechanisms through which pilot and demonstration plants enable market formation.

Pilot and demonstration plants contribute to market formation through…					
…**Supply uncertainty reduction**, which is enabled through the following mechanisms:			…**Demand uncertainty reduction**, which is enabled through the following mechanisms:		
Building credibility for the technology, consisting of…	**Technology learning**, consisting of…	**Business system orchestration**, consisting of…	**Technology standardization**, consisting of…	**Constructing the narrative** consisting of…	**Creating legitimacy** consisting of…
• Technology validation • Validation of the entire value chain	• Technology development and optimization • Achieving economies of scale	• Effectuating value chain actors and committed partners • Increasing technological interrelatedness • Adapting business model to evolving ecosystem	• Technology specifications • Technology standards-setting	• Managing technology growth expectations • Building advocacy coalitions • Achieving informational increasing returns	• Institutional dialogue • Demand articulation

is what we have now proof for it. The entry barrier is extremely high. I think in marketing terms, it is called a suicide corner because we are developing the technology and a market at the same time. Therefore, we try to reduce our risk by working together with others.

Similar examples can be found in the Clariant case, and in their efforts to commercialize the Sunliquid technology. For instance, Clariant has decided to set up a new business line (biofuels) that is responsible for further commercializing biofuels. Following this strategic segmentation, Clariant has used the initial supply of cellulosic ethanol from the pre-commercial plant to find alternative applications for the technology or to articulate demand for cellulosic ethanol. Moreover, in another endeavor, Clariant, in cooperation with Werner & Mertz (a producer of cleaning agents), launched a project that expanded the possible applications of the Sunliquid bioethanol made from agricultural residues to detergents, cleansers, and cleaning agents.

6. Discussion

Our study has aimed to improve the knowledge about the specific mechanisms through which PDPs contribute to the market formation for novel sustainable technologies. To this end, we identify six such mechanisms, which enable supply or demand uncertainty reduction. Table 5 provides an analytical framework, and summarizes these mechanisms as well as the associated activities pursued by the actor networks surrounding the PDPs.

The empirical findings suggest that PDPs contribute to supply uncertainty reduction through three enabling mechanisms: building credibility for the technology, technology learning, and business ecosystem orchestration. These mechanisms enable technology actors to mitigate the perceived unpredictability of existing ways and capabilities to develop a novel technology in a new market segment. Using PDPs, technology actors could reduce demand uncertainty through the following three mechanisms: technology standardization, constructing the narrative, and creation of legitimacy for the new technology. These mechanisms enable technology actors to instead mitigate the unpredictability of customer preferences and/or the cognitive recognition of a novel technology or a by-product's value in a new market segment.

Applying the framework (Table 5) in full would be a different paper, but to demonstrate its value it is useful to illustrate to what extent some of these mechanisms are (un)observed in a less successful (discontinued) case. For this purpose, the case of Chemrec (2004–2018) can be highlighted (see Hellsmark et al., 2016; Hellsmark and Hansen, 2020). The small Swedish firm Chemrec managed to establish a novel consortium of companies that could demonstrate the entire value chain from black liquor (a byproduct from the pulp and paper production) to a new transportation fuel (biobased DME), as well as a small test fleet of DME-trucks supplied from Volvo that could run on the new fuel. However, Chemrec failed to move towards large-scale and integrated biorefineries that are dependent on the active participation of incumbents in the forest industry and/or the oil industry. The incumbents in these industries did not take an active and committed role in the development of the technology since they did not blend or integrate this business opportunity into their current business activities.

This implies that Chemrec failed to orchestrate the business system around its technology by effectuating committed partners, increasing its technological interrelatedness, and adapting the business model of the company to the evolving ecosystem. Chemrec could also not create legitimacy for the technology to drive market formation. Demonstrations were abandoned as there was little confidence that the temporary exemption from the Swedish carbon dioxide tax (on which the entire profitability was based) constituted a stable framework for an investment with a payback time of 10–15 years. None of the incumbent actors had significant motivation and abilities to really question the Swedish carbon tax policy or to make efforts to suggest a more stable policy alternative. Chemrec potentially could have seen the problem but may have recognized it too late and did not have the resources and ability to lobby for a change.

Hence, although the various mechanisms identified in previous research are sometimes labelled differently, they can easily be understood in the context of our proposed framework. We could also stress our contribution in terms of a more comprehensive and systematic assessment of the mechanisms compared to previous studies. Our analytical framework provides a more thorough insight into the mechanisms through which PDPs enable actors to achieve systematic progress from technology to market compared to previous studies (e.g., Hellsmark et al., 2016; Hendry et al., 2010). It could therefore help companies and policy makers to further consider the more comprehensive mechanisms as the coordinated and structured steps and activities in and around PDPs.

In the remainder of this section, we address some important implications of our findings, both for the research community as well as in terms of practical implications for both technology developers and policymakers.

6.1. Research implications

An important contribution of this paper has been the systematic unfolding of the mechanisms through which PDPs enable market formation of novel sustainable technologies. In achieving this, we have mainly focused on large-scale demonstration plants aiming at commercialization, but also, to some extent, on the up-scaling processes leading up to these installations and the activities taking place in and around the plants. Even if the existing literature recognizes that when the scale of the plant is large and the technology thus is close to market readiness, these activities become particularly complex and risky (Åhman et al., 2018; Frishammar et al., 2015), previous work has not provided fine-grained insights into link between such demonstration projects and market formation (Bossink, 2017). This also goes for various contributions to the SNM literature, which so far mainly have addressed the success and failure of demonstration projects (e.g., Heiskanen et al., 2015; van der Laak et al., 2007). Thus, also in these works, there is a lack of attention devoted to the specific sub-processes, mechanisms, through which such projects can be turned into viable market niches (e.g., Caniëls and Romijn, 2008; Schot and Geels, 2008). This study has therefore been more purposeful to identify the agency role, and to understand the affordance role of PDPs in market niche formation.

For instance, earlier studies have emphasized the overall roles played by various types of PDPs, including how these can support different learning processes (e.g., learning-by-doing, learning-by-using, etc.) (e.g., Hellsmark et al., 2016; Harborne and Hendry, 2009). Our paper has gone beyond this and scrutinized the mechanisms through which PDPs can set in motion concurrent cycles of supply-push and demand-pull of technology development. Our findings, summarized in Table 5, lead us to view market formation by PDP activities as a long-term strategy that to be successful needs to focus on supply and demand uncertainty reduction simultaneously.

This paper – and the analytical framework presented in Table 5 – is in many ways a response to Bossink's (2015, 2017, 2020) plea for additional research on the role of demonstration projects in the market formation phase of technological development. Bossink's own work includes three systematic review studies of sustainable energy demonstration projects over the past 40 years. He concludes that the demonstration project is an effective organizational routine to create market (niches) for new sustainable energy technologies. However, he remarks that previous research has not asked and answered the questions when and in what ways these projects contribute to market formation.

Furthermore, although the SNM literature is the theoretical departure point of our study, the Technological Innovation Systems (TIS) literature (e.g., Bergek et al., 2008a), in line with the SNM literature, also argues that technological development is rooted in different learning processes that are necessary for reducing risk. To this end, successful demonstration projects, as entrepreneurial experimentation functions, are believed to be of critical importance to uncertainty reduction and TIS development (e.g., Harborne and Hendry, 2012; Hellsmark et al., 2016). Our study highlights the interaction among functions of TIS, particularly between entrepreneurial experimentation and market formation, by bringing forward these functions as the effects or the outcomes of the identified mechanisms.

The step-by-step construction and use of PDPs at different scales enable technology developers to display that the new technology is valid, trustworthy, and mature from a technical and value chain perspective. Such a controlled scale-up can be seen as a low-risk approach to technology development, and manage not only technical but also institutional and market-related risks (see also Hellsmark et al., 2016). For large-scale demonstration plants, it is also essential to verify the entire value chain, and (occasionally) pave the way for alternative applications of the end product. This signals that the technology is mature and that the developers are committed to its commercialization. Hellsmark et al. (2016) described the above upscaling process as achieving systemic progress from technology to market.

Our findings confirm that some challenges associated with technological development only arise in large-scale production. One prominent example is that these plants provide appropriate settings for technology standardization (see also Jiang et al., 2018). Specifically, the large-scale demonstration plants provide long-term and reliable operational data that ensure that a realistic set of specifications are determined. At a general level, of course, these plants are necessary to ensure that the production is both operationally stable and economically feasible.

PDPs are instrumental for technology actors to pro-actively build business ecosystems around the new technologies. These ecosystems need to be initiated through an effectual commitment that sets in motion different actors of the value chain, i.e., build on their resources and expertise to create value for potential customers. Consistent with this finding, Bossink (2020) reported that not least the large-scale demonstrations stimulate the dissemination of knowledge and interactive learning in the supply-demand actor network. Our case studies have shown that the interactions with end-users and potential customers are key aspects of such interactive learning. Related to this is also the role that PDPs play for the construction of a narrative, something that is important for actors in the new ecosystem to acquire political power (Bergek et al., 2008b; Boon et al., 2008). In other words, PDP activities are often instrumental in gathering advocates in support of the new technologies in the form of both public acceptance and policy support.

6.2. Practical implications

Our findings concerning the mechanisms through which PDPs could contribute to market formation also bear important practical implications for decision-making, both on the part of technology developers and policymakers.

PDPs allow entrepreneurial actors to develop the technology and the market in tandem; as the technology actors build larger-scale demonstrations and explore alternative applications, the market learns about – and expects more from – the new technology. Although not aiming to be predictive, our results help identify under what circumstances market formation is more likely to be achieved. We here see benefits from a bricolage strategy and a stepwise approach to up-scaling. Although such an approach is relatively slow and involves incremental steps, PDPs at different scales help support different learning processes (see also Hellsmark et al., 2016) and enable technology developers to gain legitimacy for the technology and construct a narrative for it. There is overall a need for the technology actors to become realistic and flexible in the articulation of expectations and visions for their technologies, by adjusting visions to the maturity level of the new technology. This implies that the narrative can evolve from its initial focus, and also highlight different directions and possibilities.

Moreover, the entrepreneurial actors need to prioritize customers and partners that can form part of a mutual learning process, and perceive the benefits of the technology beyond the initial investment. Thus, the technology actors need to develop new capabilities that enable them to motivate other ecosystem actors to join the demonstration projects.

A more comprehensive understanding of the mechanisms through which PDPs can contribute to the market formation for new sustainable technologies is also important for policymakers. One aspect concerns the construction of the narrative and the possibly changing nature of the narrative. The construction and operation of PDPs at different scales allow the technology actors to influence the ecosystem stakeholders' expectations concerning future promises of the technology. This approach also enables the technology actors to continuously explore different opportunities and update policy makers and potential customers with the latest information, options, and possibilities of the technologies.

Policymakers should work closely with the technology actors, while at the same time not ruling out any competing technology narratives. Even though there is likely a trade-off in terms of regulatory capture, the participation of technology actors in the policy process will often be essential to overcome informational constraints on part of the government authorities (i.e., in terms of the future potential of new technologies), and enable policy learning (Rodrik, 2014).

Another important implication is that policy instruments should support the construction and use of PDPs at different scales, enable technology actors to present various kinds of evidence that the new technology is valid, trustworthy, and mature from a technical and value chain perspective. Supporting this type of development and market introduction of the technology enables the technology actors to construct the narrative of achieving systematic progress from technology to market. Hence, an effective policy for the construction and use of PDPs requires clarity about the purpose of policies and instruments and the progressive focus of PDPs in the objectives. In this way, policymakers could help facilitate the commercialization of novel technologies more timely and effectively.

Previous studies have also argued that policy instruments should be matched with the intended PDP outcomes (e.g., Hellsmark et al., 2016; Hendry et al., 2010; Mossberg et al., 2018; Palage et al., 2019), thus recognizing whether the plants are mainly aimed at generating technical, economic, and/or commercial information. Our findings confirm that some challenges and problems of technological change only arise in the large-scale production. Large-scale, market demonstration plants would enable technology actors to run and show that their technologies are operationally stable and economically feasible.

Our findings also add to this notion, particularly in the context of large-scale demonstration plants, and one important implication is that policy should facilitate ecosystem orchestration and stimulate the development of the value chain around the PDPs, particularly for the large-scale, market demonstration plants. It is thus important that the entire value chain is included in the incentive programs and supportive regulations as various value chain actors typically have different motivations for joining the actor networks surrounding the plants. This also includes specific measures that help strengthen these networks, e.g., by activating new actors and/or developing clear visions for the network collaborations (see Söderholm et al. (2019) on the role of so-called network management in the innovation policy mix).

Supporting measures that include the business ecosystems around novel technologies should be formed to strengthen the effectual commitments since these can set in motion different actors of the value chain to bring together complementary resources and expertise to create a value for potential and committed customers. Specifically, the focus of such supporting policies of the ecosystem could be the establishment of effective actor collaborations along the value chain by including the existing infrastructures, competencies, and underlying motives of the incumbent actors. For instance, in the context of biofuel development, it is useful to activate incumbent actors in the form of the pulp and paper sector and/or the oil refinery sector since reducing the costs and complexity of novel technologies hinges on successful integration into existing infrastructures and the development of complementary resources and competencies. A key factor for joining forces and for successful collaboration is profit-sharing schemes that enable value chain actors to profit from joint development throughout the value chain.

Based on our study, another key policy action to stimulate PDP ecosystem development is to articulate the demand for the novel technology and to open up new market segments for the products coming out of the PDPs. The creation of the initial supply is a prerequisite to this step, Hence, in addition to supporting technology actors to build large scale plants, it is important to articulate demand for and to motivate early customer of the initial supply. An important policy implication is thus to create market conditions in favor of the products coming out of the demonstrations. It can be added that long-term secure and stable political conditions are also important requirements for demonstration projects to achieve their full potential. For example, it is argued that if a private investor does not have the confidence that the regulatory system still allows marketing the product in five years or ten years from now, nobody would choose to build a plant.

Finally, we also recognize that biofuel development is not only about achieving climate policy objectives. It concerns industrial policy, and offers an opportunity for innovation and for strengthening the long-term competitiveness of various industrial sectors. It means that an effective policy for the construction and use of PDPs needs a comprehensive and general coordination policy among different policy domains.

7. Concluding remarks and avenues for future research

The purpose of this study was to investigate through what enabling mechanisms PDP activities help reduce supply and demand uncertainty and thereby contribute to the market formation for novel sustainable technologies. We build on lessons from the SNM literature, and investigate three case technologies for advanced biofuel production. The empirical findings suggest that PDPs contribute to supply uncertainty reduction through three enabling mechanisms: building credibility, technology learning, and business ecosystem orchestration. The corresponding mechanisms through which PDPs can enable demand uncertainty reduction include technology standardization, constructing the narrative, and creation of legitimacy for the new technology. The case studies also helped gain a better understanding of technology actors' development activities with respect to PDPs, not least in the context of large-scale demonstration plants with the objective of commercial use.

Clearly, there are limitations in our research endeavor, which in turn should provide scope for additional research. One limitation is that our findings are, at least in part, context-specific, and may not be entirely generalizable to other technology domains. For this reason, verification of the findings of this study in other domains is called for. Another limitation is the retrospective design of the study; it relies on existing data and the memories of interviewees. Even though we adopted measures to limit any retrospective bias – e.g., using extensive secondary sources and interviews – future research should also benefit from real-time, longitudinal case studies. In this way, it ought to be possible to provide a better understanding of the complexity and the variety of the enabling mechanisms through which PDPs drive market formation.

There is also a limitation related to our choice to focus on the focal business firm, i.e., in this case the plant owner. As noted above, it is probably fair to argue that expanding the scope of the investigation to also address other actors, could influence the results. For instance, there may exist a trade-off between the expectations of the users of the technology, and the focal firm's ability to live up to these in the daily operations of the plant. Some actors may wish to test a broad scope of solutions while other would preferably opt for a narrower scope in the tests conducted. Such differences in the goal functions of various actors are important avenues for future research.

The next limitation is related to the previous one, and is that the findings and insights derived from this study might be valid for comparable cases from a focal business firm perspective as a technology actor, but there is no guarantee that this will be the case if several companies work on a similar and competing technology. Results drawn from this study might therefore not include whole, all-encompassing mechanisms of market formation. This is due to the research design, which was based on the focal business firm perspective. To this end, further multiple-case study research from the perspective of actor networks around PDPs as the main unit of analysis is necessary.

Finally, in this paper, we have also identified co-dependencies among the various enabling mechanisms. For example, by authenticating their novel technologies in other actors' minds and demonstrating the functionality of the technologies through PDP activities, technology actors have gained credibility to lobby with government in different levels to get funding and investment subsidy for larger scale plants. The technology learning mechanism consisting of technology development and optimization and achieving economies of scale is also critical for technology standardization mechanism. The technology learning mechanism also enables the technology actors to build credibility for the technology and create legitimacy in the market. As another example, constructing the narrative of the technology starting from research and development activities in the lab to commercial scale plants plays an important role in business system orchestration. The mechanisms of creating legitimacy and technology standardization could also contribute to further orchestrate business system and to facilitate the construction of technology narrative. One avenue for future research would be to scrutinize these interactions in more detail, including the sequence and timing of their appearance in catalyzing the market formation in a longitudinal study. Such an approach could shed more light on the process of market formation.

CRediT authorship contribution statement

Seyedesmaeil Mousavi: Conceptualization, Investigation, Writing – original draft, Writing – review & editing. **Hans Hellsmark:** Conceptualization, Supervision, Funding acquisition, Writing – review & editing. **Patrik Söderholm:** Conceptualization, Supervision, Funding acquisition, Writing – review & editing.

Data availability

Data will be made available on request.

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Supplementary material

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Appendix A

Table A1
The first-order concepts in support of the second-order themes in Fig. 1(a).

Second-order themes	First-order concepts
Technology validation	• Pilot plants prove the technology concept • Developing and validating the scale-up design • Technical validation of the technology and its stability in the large-scale plants • Testing the technology in the operational environment • PDPs are built, run, and owned by the technology supplier/consortium
Validation of the entire value chain	• Creation of initial supply • Demonstrate the viability of the value chain • Testing customers' feedstock in PDPs • Demonstrating the compatibility of the technology with different raw materials (different feedstocks) • Deliver the product to the potential customers • Identifying the business opportunities and promising paths of the technology • Learning what government policies and regulations is required to make the technology viable
Technology development and optimization	• Demonstration plant to reduce technical risk • Learning from continuous operation of the plant • A feedback loop between pilot and demonstration plants • Learning by doing • Learning by using • Technology design specification and its optimization with respect to the different scales • The commissioning phase aimed to ensure the process runs as designed • Spatial proximity between PDPs and technology supplier/consortium • Feedback loop with potential customers • Learning how to build and run a large-scale plant of the technology economically
Achieving economies of scale	• Learning and experience curve effects • Cost efficiency become important in large scale plants compared to pilot plants • Demonstration plants should be built on sufficient scale to run economically • Reducing the costs and stabilizing the performance of the technology in the industrial and commercial-scale plants (price/performance improvement)
Effectuating the value chain actors and committed partners	• Getting the most relevant actors of the value chain involved in the PDPs activities • Integrating partners with complementary resources and competencies into the network • Effectuating and combining public fund at different levels of the government for PDP activities • Looking for committed partners (mainly committed off-take partner) • Building network based on the proximity of the partners • Finding partners based on existing network (mainly from previous stages of the technology development) • Building trust-based collaboration in the network • Defining clear role and responsibilities for the partners • Having mainly the development partners near to the PDPs
Increasing technological interrelatedness	• Cospecialize complementary technologies • Using established process equipment and components from other industries • Developing or modifying complementary technologies • Team up with partners based on complementary competencies

(continued on next page)

Table A1 (*continued*)

Second-order themes	First-order concepts
	• Leveraging a network of specialized partners • Forming symbiotic relationship • Partnering with the key entities of other industries or incumbent companies • Developing and using the new technology in connection with the current business model of the company • Implementing and using the new technology in connection with available infrastructure • Expanding the network in line with the scale-up and further development of the technology • Changing and modifying network structure and partners in the course of the progress and scale-up of the technology • Expanding the network of development partners to involve commercial partners particularly for large scale demonstrations • Differentiate development partners from commercial partners
Adapting the business model to the evolving ecosystem	• Supporting licensing as the business model of the technology suppliers • Markets and technologies need to be built hand in hand • Demonstrating how the technology could support the business of the value chain actors • Demonstrate the benefits of the technology to potential value chain actors • Partners have different motivations and expectations from the collaboration • Motivating other actors to join the network by the first-mover advantage

Table A2
The first-order concepts in support of the second-order themes in Fig. 1(b).

Second-order themes	First-order concepts
Technology specifications	• Specification of the technology (with respect to technological, economic, and social aspects) • The modular design of the technology enables a rapid deployment • Learning about the environmental benefits expected from the technology • Assessing the requirements and needs of potential customers • Engaging potential customers and end-users in the technology development from early on, particularly for industrial and commercial-scale plants • Adapting the technology to customers' specific needs • Dialogue closely with customers to adapt the technology in line with what customers want and are willing to pay for it
Technology standards-setting	• Standardization must be developed for the successful market introduction of new technology • The demonstration plants contribute to the standardization of the technology • Setting standards for the new technology and its by-products • Collaborative work in defining standards and specifications of the technology • Getting standards and certifications for the technology and its by-products
Managing technology growth expectations	• Introducing new technology into the market is not going to happen easily • A stepwise development and market introduction of the technology was adopted – from laboratory scale to commercial-scale plants • Risk management • Phased construction of biofuel production capacity • Know-how and experience of the technology in several scales • Developing the market in conjunction with technology development • Learning about the market pressure and uncertainty which the new technology will encounter
Building advocacy coalitions	• Communication with a wider public that is not actively involved in the PDP activities (with outsiders) • Collaborating with technology competitors • Engaging all potential customers that are interested in the technology on a political level • There is still a market uncertainty for biofuel technologies • Disseminate and communicate the vision and expectation from the technology • Communication and dissemination of the results of PDP activities • Field configuring events or market priming activities • Marketing in conjunction with technology development
Achieving informational increasing returns	• Demonstrating the effectiveness and efficiency of the technology in the production environment • Demonstrating technology is commercially available • Demonstrating the technical feasibility and competitiveness of the technology • Demonstration as a market introduction facilitate the adoption of market pull strategies and policies • Demonstration plant as a reference plant • Demonstration plant as an initial market introduction (Technology showcase) • Demonstrating the stable performance of the technology • Raising awareness among the public on the advantages of the technology • Receiving technology awards
Institutional dialogue	• Coordination of policy domain in favor of the technology • Effectuation approach to select and combine public fund at different levels of the government • Collaboration with the government to adapt legislation or changing norms • Feedback loop to the Institutions • Lobbying with the government at different levels to put the new technology in the incentive and funding program • Looking for the public fund at different levels of the government (EU, National, and Regional)

(*continued on next page*)

Table A2 (*continued*)

Second-order themes	First-order concepts
	• Technology developers are lobbying for Market pull policies- such as RED2 and Feed-in-Tariff • Technology developers actively participate and lobby with the policymakers ahead of the technology development • Technology developers communicate with Funding agencies on progress, deviation, and other technical issues of the demonstration plant and the technology
Demand articulation	• Demonstrating the commitment to the technology and customers • Finding alternative applications for the technology and its by-products (Economies of scope) • Technology developers are lobbying for Market pull policies- such as RED2 and Feed-in-Tariff • Interactions between technology suppliers and potential customers • Public funds create legitimacy for the technology developer • Marketing in conjunction with technology development • Looking for committed customers • Creation of initial supply

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