Knowledge types to progress the development of sustainable technologies: a case study of Swedish demonstration plants

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Abstract

Knowledge development and diffusion through demonstration plants are necessary to progress the development of sustainable technologies, yet current literature lacks detailed insights into which knowledge types are critical in facilitating this progress, and what the roles of different knowledge types are. We draw on knowledge-based theory and investigate four Swedish demonstration plants for advanced biofuels using case-study research. The findings underscore the need for and production of domain-specific, procedural and general knowledge to progress sustainable technology towards commercialization, with each type having a rather specific role and purpose. However, in the plants studied, there is a tendency to focus strongly on the generation of technical, domain-specific knowledge at the expense of procedural knowledge. This deficiency frequently creates problems since a lack of procedural knowledge on how to commoditize and commercialize technologies hinders efforts to move past the demonstration stage to large-scale commercialization. Based on these findings, the paper proposes novel approaches for dealing with these problems, and for managing knowledge more generally.

Keywords Demonstration project · Demonstration plant · Knowledge type · General knowledge · Domain-specific knowledge · Procedural knowledge · Technology development

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Introduction

A major societal challenge is to replace fossil-based technologies with increasingly ‘clean’ and sustainable ones, mitigating air pollution and lowering greenhouse gas emission levels. Therefore, climate and energy initiatives aimed at decreasing fossil dependence in the form of new products and applications from biomass take a high priority on political agendas. For example, the European Union has adopted a long-term target stating that by 2050 the carbon dioxide emissions will be reduced to around 80–95% below the levels of 1990 (European Commission 2011).

However, development and diffusion of such clean and sustainable technologies is difficult. For example, large-scale commercialization of advanced biofuels¹ is frequently hampered because underlying production technologies are still under development. While small-scale lab tests may produce favorable results, further development on an intermediate scale is necessary to sustain full-scale commercial production (Bäckström 2015). Consequently, building full-scale plants for commercial production is impossible based solely on lab- or bench-scale results (Nguyen et al. 1996; Rosenberg and Steinmueller 2013). When processes are scaled up, underlying process technologies tend to change, with new process properties added and existing ones lost (Frishammar et al. 2015). Consequently, intermediate environments for product and process upscaling, i.e. demonstration plants, are necessary in order to accelerate industrial deployment of advanced bioenergy and biofuels technology (Fevolden et al. 2017; Hellsmark et al. 2016a, b; Mossberg et al. 2017).

To add further to this complexity, demonstration plants are seldom the properties of a single company. Rather, they typically require significant public funding and may involve a diverse network of actors from universities, research institutes, various levels of government, and industrial companies (Hellsmark et al. 2016a, b). Although such networks allow the pooling of competencies and knowledge required to further develop emerging sustainable technologies, managing knowledge in this context in order to advance technological development is far from easy. In particular, it is important to identify the types of knowledge that a demonstration plant produces, and more specifically, the key knowledge-based challenges that hinder the further growth of sustainable technologies (Frishammar et al. 2018).

In prior literature, three types of knowledge – domain-specific, procedural, and general knowledge – have been identified as important during the process of technology development (Court 1997; Ramesh and Tiwana 1999), and their implications for innovation have been fleshed out (Hauschildt and Kirchmann 2001; Howell and Higgins 1990). However, their role and application in demonstration plants have gone largely unstudied. Arguably, in a demonstration context, there is a strong focus on experimentation and technical knowledge to enhance understanding of the evolving technology, i.e. in domain-specific knowledge. However, the way the experiments are performed and the methods used to evaluate them might draw more on procedural knowledge, seeking to improve the technology development process overall. Furthermore, general knowledge may also play a role, although such insights are lacking. All three knowledge types may well be important in facilitating

¹ Biofuels have not been free of controversy and the conventional first generation (derived from edible feedstock such as starch or sugar) has been accused of the crowding out of food production. To mitigate this and other problems, focus has increasingly turned to advanced biofuels with greater possibilities for reduction of greenhouse gas emissions and which are less land and water demanding compared to the conventional ones (Carriquiry et al. 2011; UNEP 2009; Scharlemann and Laurance 2008).

progression of the technology and ensuring the success of the plants, but most likely in different ways and with different purposes in mind.

Thus, an improved understanding of demonstration plants as tools for knowledge generation is a requisite, involving empirical study of the different types of knowledge that are developed in such plants. The purpose of this article, therefore, is to augment understanding of knowledge types used in demonstration plants. More specifically, the following two research questions are addressed:

- *Which types of knowledge are used in demonstration plants and what is the role and purpose of each type?*
- *What are the key knowledge-based challenges in demonstration plants so that technologies can progress towards commercialization?*

The remainder of this article is structured as follows: First, the theoretical background is outlined, and then the methodology and the cases under investigation are described. The next section presents the findings, followed by a discussion of the theoretical and managerial implications as well as the limitations of the study. The article concludes with a section on further research.

Theoretical background

The role of demonstration plants in technological development

New technology is an enabler consisting of both theoretical and practical skills, knowledge, and artifacts that can be used not only to develop products and services but also their accompanying production and delivery systems. In technology development, confidence is built through the use of prototypes, demonstration, and testing to assure the new technology can deliver the characteristics and functions sought (Högman and Johannesson 2013). Therefore, in this article, we view technology development as those activities aimed at developing new knowledge, skills and artifacts that will, in turn, facilitate subsequent product and/or process development. In process-based industries, demonstration plants are at the core of such efforts.

Attempts to commercialize technology directly from laboratories are uncommon, resulting typically in failure due to scaling problems and other technical difficulties, or a general lack of confidence in the technology in the marketplace. So, when a concept or invention needs to be further developed, improved and aligned to technical, market and economic requirements, additional upscaling is often organized by means of a ‘demonstration project’ or plant (Macey and Brown 1990). A demonstration plant connects research and development with marketing and deployment (Sagar and Gallagher 2004), thus providing the opportunity to build new social networks around the technology (Karlström and Sandén 2004) and to expand the set of actors engaged with the technology (Markusson et al. 2011) as it is further developed towards commercialization.

As an activity, demonstration is part of a social process of knowledge production and technology development. In process industries, it is an integral part of the innovation process (Markusson et al. 2011) focusing on building support and arriving at a consensus on technology properties (Shapin 1984). Demonstration plants are places for learnings

used to progress technology and reduce the risks involved in development work and commercialization (Bossink 2015; Brown and Hendry 2009; Harborne et al. 2007). They may be used to enhance existing processes and products as well as contribute to bringing new technological and organizational inventions to the market (Frishammar et al. 2015).

However, not all demonstration plants are the same. Previous work (Hellsmark et al. 2016b) has suggested that four main types of plant exist within the technology development process – namely, high-profile PDPs, verification PDPs, deployment PDPs and permanent test centers. The interfaces between the different types overlap due to the iterative nature of technology development. However, the plants are commonly used as knowledge generators and diffusors aimed at reducing different kinds of uncertainty when bringing new inventions to the market.

In this study, we look upon a demonstration plant as a tool for knowledge generation and diffusion. At its core lies technical development, but it serves additional purposes as well. For example, it could be used to attain the efficient organization, design and management of (future) commercial facilities at a lower risk to stakeholders (Frishammar et al. 2015). When demonstration plants are perceived in this way, it follows that the types of knowledge that can be produced need to be categorized. Consequently, an overview of different knowledge types in development work that might support demonstration activities is provided in the section that follows.

Knowledge types in demonstration plants

The more an organization knows, the more it can learn, since knowledge opens up new opportunities and strengthens an organization's ability to exploit those opportunities (Cohen and Levinthal 1990; Kogut and Zander 1992). In the constantly changing business environments of today, with the diffusion of IT and other technologies, in addition to industry conditions and tangible resources, knowledge can rightly be considered as a crucial resource for achieving as well as maintaining a firm's long-term competitive advantage (Kallmuenzer and Scholl-Grissemann 2017). Furthermore, innovation is many times viewed as a social process involving diverse actors (Adamides and Karacapilidis 2006) where knowledgeable people share knowledge (Anderson and Hardwick 2017). Knowledge is therefore critical to any organization and especially when working with development activities and demonstration plants.

Acquiring and sharing knowledge is a prerequisite for innovation (Ritala et al. 2015) and in order to exploit new opportunities and succeed in technological development, there are several types of knowledge that an organization requires. First of all there is the notation of *explicit* knowledge that easily can be shaped and documented in contrast to *tacit* knowledge that resides in the minds of people (Lee and Choi 2003). An organization also needs to agree on defined labels, distinctions and classifications to make sense of the world (Roos and Von Krogh 2016), which is considered as their *declarative* knowledge (Zack 2001).

However, when considering the developmental nature of demonstration activities, they are believed to benefit from general knowledge, domain-specific knowledge and procedural knowledge since these types have been shown as important for the development of new technology and products (Court 1997; Ramesh and Tiwana 1999) and also crucial for the innovation process to succeed (Hauschildt and Kirchmann 2001; Howell and Higgins 1990).

The knowledge gained through everyday experience and general education is called *general knowledge* (Court 1997). Typically, updates of such knowledge are done

without much reflection on the specific domain in which the work is performed and with information known to most people. With regard to demonstration activities, this general knowledge about the external environment might consist of insights into the role of governmental activities such as rules and regulations.

Knowledge about something that is gained by means of experiments, study and experience *within* the specific technical domain in which the work is performed is called *domain-specific knowledge* (Ramesh and Tiwana 1999) or simply *domain knowledge* (Yayavaram et al. 2018). Presumably, in a demonstration plant context, this type of knowledge is at the core of the evolving technology, such as process or product specifications. Domain-specific knowledge in a demonstration plant can also relate to underlying chemical processes, and the level of output from the demonstration plant when altering the feedstock into the plant.

Third, how to undertake work and engage in collaboration is a necessary facet. How ordered sequences of events are to be performed in order to achieve some task can be thought of as *procedural knowledge*, often rooted in a combination of domain-specific and general knowledge, although it is a distinct knowledge type (Court 1997). For example, procedural knowledge is frequently gained from previous experience of performing technical or chemical tasks, such as design-concept creation, specifications, theoretical guidelines, and various practical considerations as well as more tacit features that are said by Davenport and Prusak (1998) to “reside in the minds of people”. In a demonstration plant, this procedural knowledge might consist of working processes such as how to perform experiments, what steps to follow, and how to engage in inter-organizational work for the purposes of demonstration and commercialization.

Finally, demonstration plants by their very nature gather together a network of actors with vested interests. The plants, therefore, engage multiple participants with many different points of view. Although there have been shown difficulties with working interdisciplinary (Borge and Bröring 2017; Roy et al. 2013; Yegros-Yegros et al. 2015) and inter-organizationally (Dingler and Enkel 2016; Easterby-Smith et al. 2008) it is from these interactions among collaborating members that synergies emerge, new ideas are born, knowledge needs are specified, and technology is advanced (Jassawalla and Sashittal 1998). These interactions among actors underscore the importance of organizing and utilizing a knowledge-based perspective (Court 1997). We therefore expect these types of knowledge to be important in a demonstration context, but the specific ways in which they impact are as yet unknown, as are the challenges facing knowledge production in demonstration plants.

This view of demonstration plants as tools for knowledge generation and diffusion also implies that there is a challenge in balancing the knowledge production that is taking place in order to best support further progression of the technologies to the market. When knowledge-processing requirements exceed the capabilities, overload occurs and performance is degraded (Zack 2001). It is clear, then, that an infinite amount of knowledge cannot be produced, and that there may be a trade-off among the three types. Furthermore, humans are constrained by bounded rationality (Gigerenzer and Selten 2001; Selten 1990; Simon 1982), meaning that humans have limited capacities for processing knowledge. This also underscores the trade-offs in the production of new knowledge and signals the difficulties in sustaining adequate knowledge levels.

Method

Research design

Prior literature regarding knowledge production in demonstration plants is nascent. Therefore, we adopted an exploratory multiple-case-study approach (Eisenhardt 1989; Yin 2014). Although guided by previous literature, the empirical analysis was performed with an openness towards the data, continuously adjusting initial assumptions as well as deriving ideas from the data.

Research setting and data collection

Data were gathered through interviews with respondents engaged in four Swedish demonstration plants developing biorefinery technologies. Two of the plants, GoBiGas and LignoDemo, are considered reference plants used for the verification of new technologies, i.e. they are industrial-scale verification demonstration plants. The other two plants, the Biorefinery plant and LTU Green Fuels, are considered permanent test centers (Hellsmark et al. 2016b). The cases diverge with regard to specific production technologies, regional settings, and types of technology for development (e.g. biochemical or thermochemical). A summary of the four different cases are presented in Table 1.

A total of 20 interviews were undertaken, lasting from 22 to 97 min, with an average of 60 min. Both face-to-face and telephone interviews were conducted from the autumn of 2015 to the winter of 2018 (see Table 2). The respondents were mainly managers and academics who were deeply involved in each case. The interviews from 2015 and 2016 were recorded and transcriptions were handed out to respondents to confirm what they had stated, whereas the interviews from 2018 were simply summarized. To complement the insights from the plants, two interviews were held at the Swedish Energy Agency, the governmental body responsible for the lion's share of public finance to these plants.

Data analysis

We relied on thematic analysis to process the data (Braun and Clarke 2006). The coding was theory guided, i.e. deductive as well as general, domain-specific, and procedural knowledge were used as sensitizing concepts (see Table 3). This assisted the analysis by suggesting directions in which to search for patterns in the data (Blumer 1954). That said, the analysis was kept open to ideas revealed in the data but not reflected in the literature. The analysis was performed in three major steps, notwithstanding the fact that there was constant toing and froing between the data and the literature.

Becoming familiar with the data

In order to become acquainted with the data and improve the contextual knowledge of the demonstration plants, the data was read thoroughly and reflected upon prior to launching the formal coding. This led to an enhanced understanding of knowledge development in the demonstration plants and also provided input regarding interesting aspects of the challenges in knowledge production.

Table 1 Presentation of the cases

Demonstration plant	Classification*	Short description
GoBiGas	Industrial-scale verification, still in technology verification stage	The municipal energy company, Göteborg Energi, is the owner of the GoBiGas Demonstration Plant located in the industrial area, Rya Harbour, in Gothenburg, Sweden. The plant demonstrates indirect gasification of biomass for the production of biogas (synthetic natural gas quality, SNG). The gas from the plant is injected into the existing natural gas grid and can be used for a number of different purposes (transportation, feedstock in the chemical industry, production of power and heat, etc.). In early 2014, the plant was established with the initial intention of working as a phase 1 demonstration. So far, the plant has verified gasification of pellets and is presently being converted to manage more diverse feedstock such as forest residues.
LignoDemo	Industrial-scale verification PDP developing towards a permanent test center	The LignoDemo Demonstration Plant was established in 2007 and is located close to the Nordic Paper pulp mill in Bäckhammar, Sweden. The owner of the plant is LignoBoost Demo AB, a subsidiary of the research institute RISE. The LignoBoost process, extracting lignin from the chemical pulping process, was verified in this plant, which is currently in the process of transforming into a permanent test center as part of an initiative called LignoCity, focusing on evaluation and verification of new processing concepts for lignin. Extracted lignin has a wide range of possible uses from bulk applications such as fuel for boilers to high-value applications such as carbon fibers. The technology can also be used to unburden the recovery boiler and, by so doing, facilitate higher production capacity without investment in additional boiler recovery capacity.
LTU Green Fuels	Permanent test center, but presently in a mothballed state	The LTU Green Fuels Demonstration Plant is owned and managed by Luleå University of Technology and works on the gasification of biomass, mainly black liquor but also co-gasification of pyrolysis oil. The gasification plant was set up in 2005 and was supplemented with a unit for dimethyl ether (DME) production in 2010. The facilities are located next to the Smurfit Kappa pulp and paper mill in Piteå, in close proximity to ETC, which hosts a laboratory and a number of pilot plants. DME and methanol produced in the plant have been used in demonstrations of downstream auxiliary technologies, e.g. fleet trials of DME trucks. In late 2016, the decision was taken to mothball the plant in 2017, and this was duly implemented.
Biorefinery Demo Plant (BDP)	Permanent test center	The Biorefinery Demo Plant (BDP) is part of a biorefinery initiative located in Örnsköldsvik, Sweden. The plant was inaugurated in 2004 and is today co-owned by Luleå University of Technology, Umeå University and the technology developer, Sekab (minority share), but it is managed by RISE. The plant initially focused on the development of technology for ethanol production based on lignocellulosic feedstock (for use as transport fuel or as a chemical) but has over time developed into a broader biorefinery plant based on the so-called sugar platform (i.e. the transformation of lignocellulosic raw materials into sugars and thence into a range of products). Since late 2013, the plant has been operated as an open test center.

Analysis based upon sensitizing concepts

The sensitizing concepts referring to the type of knowledge were used to create a better understanding of the production of different types of knowledge in demonstration plants. This meant documenting initial patterns by listing quotes that exemplified usage of these knowledge types under each sensitizing concept. All types were present in the data. Furthermore, in order to keep the analysis open to the data, other interesting quotations and ideas, e.g. challenges for knowledge production, were also identified. Quotations identified were subsequently reviewed in order to establish whether they represented the sensitizing concepts.

Reviewing codes

In the process of further reviewing and comparing the quotations, codes gradually emerged providing a view on how different knowledge types were used in demonstration plants and what challenges in knowledge production existed. When no further beneficial ideas were forthcoming, the coding process was terminated. A schematic view of the analysis showing the quotations, codes and sensitizing concepts as well as other interesting knowledge-based aspects is presented in Fig. 1.

Table 2 Summary of the interviews

NR	Respondent	Plant	Date	Duration (h:m:s)	Words transcribed
1	Professor	LignoDemo Demo Plant	151,008	52:39	6076
2	Manager	LignoDemo Demo Plant	151,015	51:28	7481
3	Industrial manager	LignoDemo Demo Plant	151,125	58:28	6687
4	Industrial manager	GoBiGas	150,908	45:24	5334
5	Industrial manager	GoBiGas	150,910	1:17:43	10827
6	Industrial manager	GoBiGas	151,008	1:06:26	6207
7	Professor	GoBiGas	151,010	46:06	5088
8	Manager	LTU Green Fuels	150,611	1:07:05	8300
9	Industrial manager	LTU Green Fuels	151,002	1:37:02	11757
10	Senior advisor	LTU Green Fuels	160,212	32:46	3550
11	Professor	LTU Green Fuels	180,208	33:36	–
12	Industrial manager	LTU Green Fuels	180,209	22:30	–
13	Manager	Biorefinery Demo Plant	150,922	1:22:01	9927
14	Senior advisor	Biorefinery Demo Plant	151,013	40:48	4289
15	Industrial manager	Biorefinery Demo Plant	151,013	54:18	8400
16	Industrial manager	Biorefinery Demo Plant	151,013	41:23	5888
17	Professor	Biorefinery Demo Plant	180,123	30:29	–
18	Manager	Biorefinery Demo Plant	180,123	35:53	–
19	Administrative official	Swedish Energy Agency	160,209	52:20	5753
20	Administrative official	Swedish Energy Agency	151,202	56:54	–

Table 3 Sensitizing concepts during the thematic analysis

Sensitizing concept	Definition	What we looked for in the data
General knowledge	<i>Knowledge of a broad range of facts about various subjects, available to everyone.</i> <i>General knowledge is gained through day-to-day experiences and general education without regard to any specific domain. (Court 1997).</i>	Knowledge about the surroundings; business intelligence. Societal trends.
Procedural knowledge	<i>Knowledge about how to do something, exercised in the performance of some task.</i> <i>Knowledge on how to do something gained from the experience of undertaking a task within the domain. (Ramesh and Tiwana 1999).</i> <i>Ordered sequences of events, such as everyday operations and routines (Zack 2001)</i>	Know-how about the technological development from ideation to commercialization. How to organize the development work. What to do when, how to do it and by whom. Ways of working; how are different types of collaboration executed, how are experiments performed, what inter-organizational forms of working are there and how are they organized etc.
Domain-specific knowledge	<i>Knowledge about something, gained through study and experience within a specific domain. (Ramesh and Tiwana 1999; Yayavaram et al. 2018).</i>	Results from development, causal knowledge about how things work. Technological progress: What works and what does not work. Technical experiments. Biorefinery activities.

Findings

The findings highlight examples of all the knowledge types reviewed in the theoretical background and a cross-case comparison is provided in Table 4 and further explained in detail in the following three sections. The data analysis also resulted in knowledge-based challenges presented in the last section of the chapter.

The role and use of general knowledge

General knowledge is gained from day-to-day experiences without any particular regard to a specific domain (Court 1997). Our findings showcase two key examples of the use of general knowledge in a demonstration plant context. The first is about securing funding for demonstration activities. One example, expressed by virtually all the respondents, was the problem of getting funding approved given the European Union's exacting state-aid regulations. Knowing the rules and legislation concerning funding, and having an appreciation of

Table 4 Examples of the different knowledge types, how they are used and their role in demonstration plants

Plant	GoBiGas	LTU green fuels	Biorefinery demo plant	LignoDemo
Usage of...				
General knowledge				
To secure funding	X	X	X	X
To facilitate business opportunity recognition	N/A	X	X	X
Domain specific knowledge				
Prerequisite to bring about a demonstration plant	X	X	X	X
The base for technology development	X	X	X	X
Used for troubleshooting	X	X	X	X
Used for flexible management of permanent test centers	N/A	X	X	
Contributes to business opportunity recognition	N/A	X	X	X
Procedural knowledge				
To manage legal issues	N/A	X	X	X
Creation of a demonstration plant	X	X	X	X
Management of inter-organizational teams	X	X	X	X
Patenting		X	X	X
How to operate a permanent test center	N/A	X	X	

N/A: Not applicable, i.e. dependent on the settings of GoBiGas some areas are not applicable, while an empty spot means that no empirical evidence was found for that usage

means to deal with issues that surface along the way so that demonstration activities are not put on hold was one example of the use of general knowledge. Needless to say, a corresponding logic existed for rules, and legislative

Fig. 1 Schematic view of the relations between sensitizing concepts, codes and quotations as well as between knowledge bases challenges, codes and quotations

lag at the national level, e.g. concerning public funding from governmental bodies. For example, EU support cannot be overly directed to commercial companies. Consequently, this places restrictions on the constellation of actors working with demonstration plants, and the intensity of the contributions of some actors. There is the additional problem of a protracted decision-making process governing the approval of finance, which lowers the incentive for commercial companies to engage in such projects. Commensurate use of general knowledge can help mitigate this problem. The following example comes from a manager in the LignoDemo demonstration plant talking about a commercial actor who disengaged before public financing was finally approved:

A commercial company cannot wait two years for these things, it is completely wrong. They [the commercial company] had gone further with other installations that had received this money [that the company originally had assigned for the project that sought public financing]– so it was a failure.

Another example of general knowledge used in a demonstration context concerns how to recognize a business opportunity. In this case, it was possible to purchase facilities for the LignoDemo demonstration plant given the fortunate timing, even though proficient business intelligence also played its part:

These things depend on beneficial circumstances; I mean you have to have luck. As with the facilities in Bäckhammar, it was very fortunate that Borregaard decided not to proceed with their business and sell out to another company.

However, luck is not sufficient. Business intelligence (i.e. environmental scanning of opportunities and threats) and domain-specific knowledge (e.g. possible areas for technology applications) contribute to technological development by helping to identify business opportunities. For example, the selling of the LignoBoost patents to Valmet was possible because of i) the business intelligence of the professor involved in the LignoDemo demonstration plant who carried out the screening of possible buyers and ii) the domain-specific knowledge concerning filtering and soda boilers of the professor and the managers at Valmet (at that time called Metso), leading to the creation of the business opportunity. Finally, the findings do not explicitly demonstrate an intended use of general knowledge in demonstration plants, such as the systematization of business intelligence handling.

The role and use of domain-specific knowledge

Domain-specific knowledge is said to develop through the experiences gained and the studies undertaken within a specific domain (Court 1997); the empirical findings reveal multiple examples of the role of this knowledge. First and foremost, domain-specific knowledge in a demonstration context is found to be the basis for technological development and is used as a prerequisite for getting plants up and running, for troubleshooting and for running plants, such as type IV permanent test centers, on a day-to-day basis. In order to establish a

demonstration plant, domain-specific knowledge is a key prerequisite since it entails knowledge about the technology and the plant itself, i.e. different pieces of equipment and their functionality, and how they are connected to each other. Domain-specific knowledge is crucial in the startup phase of a demonstration plant; it is regarded by all respondents as a strength, exemplified here by a professor working in the LignoDemo demonstration plant when talking about the startup phase:

Most of the problems concerned the pumps, and there were no real surprises...we had done our homework and knew how it would be connected. Then it worked out pretty well, great fun actually, once we started.

In order to develop a technology and verify its functionality, there are invariably many technical problems to solve, which emphasizes the need for domain-specific knowledge. To expedite development and to get the demonstration plant up and running, a so-called ‘task force’ involving participants from the owner of the GoBiGas demonstration plant, university representatives, and the contractors was created; its discussions and the results that flowed from its work is yet another example of domain-specific knowledge in a demonstration context. The following quotation by the former project manager of the plant is an example of how such ‘task force’ discussions can prove beneficial:

Why do we get so much tar; that is not the case at the reference plant, which has been up and running for 10 years. Why don't they get a lot of tar? Because they have more ash, it has to be something to do with the ash.

The work of the task force can also be seen as a way of learning-by-doing that takes place in demonstration plants.

When using a demonstration plant as a type IV, permanent test center, domain-specific knowledge provides crucial input in managing the increased flexibility in facility usage. The use of domain-specific knowledge when operating as a permanent test center is exemplified by the collaboration in the Biorefinery demonstration plant that led to the development of a new technology for a customer:

One example that is really good is this fish food that they created a technology for, where they cooperate with Sekab during pretreatment and, using this Sekab pretreatment technique, make a solution for growing proteins from which you can make fish food.

When it comes to identifying business opportunities, data analysis shows that domain-specific knowledge is useful for both the technology developers and the commercial companies. This is exemplified by a manager at a commercial company:

A very important goal that we saw right from the beginning was to unburden the soda boiler: We are suppliers of soda boilers, we build and rebuild soda boilers, and there is considerable value in being one of the few in the world, not so many are doing this. There is absolutely no doubt that we saw the potential for this.

The role and use of procedural knowledge

Procedural knowledge concerns how to do something and is gained from the experience of performing tasks within some specific domain (Court 1997; Ramesh and Tiwana 1999). The knowledge acquired from the experience of performing tasks in demonstration plants can be exemplified in several ways. An example of procedural knowledge, expressed by all respondents except GoBiGas, was initially creating a legal form for organizing the demonstration work, such as a separate subsidiary or entity for the demonstration activities. This was put forward as a way of managing legal issues and of more easily commercializing the technology. The example below comes from a manager commissioning the LignoDemo demonstration plant:

We put the patents in a subsidiary of Innventia, LignoBoost AB. The operations of the demo plant became LignoBoost Demo AB, of which we still owned 100%. So, the idea was that, by putting patents in LignoBoost AB, we would have a commercial, saleable asset.

Another example of procedural knowledge is how to establish a demonstration plant. Respondents from GoBiGas provided the principal reflections on this since, at the time of the interviews, some project work from the initial construction of the plant was still ongoing; consequently, memories were still very fresh. One of the interviewees reflected on the difficulties over cooperation and finding suitable mechanisms to undertake the project work so that the construction of the demonstration plant could be expedited. A former project manager of GoBiGas expressed it thus:

You then buy a design and a license to use this design, then you have to find someone to implement the project in detail, someone who can buy, someone that can keep the assembling process running smoothly. It is a completely different logic concerning how work should be carried out, and that skill set is largely unknown in the energy business.

Another example of procedural knowledge in a demonstration plant context is the management of inter-organizational and cross-functional teams. This way of working was identified as a success factor in getting the plant up and running and in facilitating technological development. A former project manager from GoBiGas explained:

When we started this task force with Chalmers, we were able to find correlations and then with Metso, they had also been involved, the right people from Metso, there are really skillful people there who took on real responsibility and generated action to make things happen.

The management of patenting provides another example of procedural knowledge, featured in all demonstration plants in this study, which influences the advancement and dissemination of technology. A manager of a commercial

company connected to the LignoDemo demonstration plant exemplifies the point:

It is also a matter of keeping and sustaining patents, so one alternative to not taking patents is to allow the knowledge to enter the public domain, to publish it because no one else can then take out patents on it. The knowledge and strategies of the patenting team ensure proper control and exploitation of our intellectual property.

However, managing confidentiality appears not only to be an issue in patenting but also in the utilization of demonstration plants. Procedural knowledge on how to operate a type IV plant is also a topic of reflection by interviewees from those types of plant (with the exception of GoBiGas). However, a manager involved in LignoDemo reflected upon possible future operations in a permanent test center since, at the time of the interviews, the demonstration plant was not yet operating as the permanent test center that had been envisaged and to which the company was still committed. The handling of neutrality when running permanent test centers was given considerable attention since it was held to be crucial in a facility where customers may well have competing interests. A manager working as the mandator for the SP Biorefinery demonstration plant provided an example of how type IV operations function:

A customer either comes to us, or we search really hard to find a client. We create the research design, work out the design together with our own or hired development engineers, and then the operational organization performs the experiment on our behalf. Sekab is not in direct contact with the customer. This is regulated; we have a number of agreements, non-disclosure agreements. In principle, a competitor of Sekab could enter this way and carry out experiments in the plant.

The findings of this study show that procedural knowledge used in demonstration plants can be of varying kinds, focusing on how to organize development work, how to handle confidentiality and patenting, and how to operate permanent test centers. From this study, the examples of procedural knowledge supplied by respondents barely touch on the idea of how to bring a new technology to market.

Knowledge-based challenges in demonstration plants

The findings have revealed not only a variety of examples of knowledge types used in demonstration work but also the particular challenges that were encountered. In reflecting on why the new technologies under development experienced difficulties with commercialization, respondents perceived lack of clarity, such as ambiguous political decisions, as likely obstacles. A project manager at the GoBiGas demonstration plant referenced low prices for fossil-based products, making it impossible to compete on price. Responsive political decisions were, therefore, crucial for the advancement of bio-based alternatives:

We do not know what political instruments will materialize on the way. It is extremely crucial.

In a similar vein, the manager of LTU Green Fuels talked about the constant struggle to keep the plant up and running and how the operation of facilities for demonstration are very dependent upon rules and regulations:

Because there were no clear tax reliefs, rules of the game, they then realized that there has to be another owner, otherwise they will have to close down the business.

Unclear political agendas with short-term rules and regulations have made it difficult to maintain an interest in the market for bio-based alternatives, according to a manager of a commercial company involved in LTU Green Fuels:

Meanwhile the market has diminished, the prerequisites that were there in 2012 are not the same today and...the interest from these big companies that we really would have liked to have as stakeholders in BioGreen has cooled off, not because of the project...but in general terms.

Our findings also show that respondents felt that the problem with commercialization was less to do with the technology itself, or a lack of technological know-how. Typically, they expressed confidence with the technological demonstration but they were less confident regarding the means to bring the technologies to the market. This uncertainty is exemplified by a manager involved in LTU Green Fuels and a manager of a commercial company involved in the Biorefinery demonstration plant:

In the absence of a market this is what the reality looks like, nothing happens; it has great potential, the technology is demonstrated and it has shown good functionality, performance, availability but nothing happens.

It is a very great deficiency, things just grind to a halt...you've got great research reports but then you need half of a billion to take it to the next stage, and unfortunately it is not easy to get the risk capitalists involved.

In addition to unclear regulations, and scant knowledge of their implications, the senior advisor and a manager of a commercial company involved in the Biorefinery demonstration plant expressed a lack of competence in marketing and selling this kind of technology. The senior advisor asserted the need to engage a larger number of people internally who “could spread the word”, while the manager spoke of difficulties in balancing diffusion as a marketing activity with retaining technological knowledge internally.

It has a lot to do with marketing, we have been wondering, “how do we do that?” We have sort of embarked on it, we have to engage as many people as possible internally and there are many who talk about the BDP when they are outside, but it is an area where we could do better.

If it is a future customer and he is here and collects a lot of information, then it is obvious that if we get him as an ‘internal salesperson’, then we have “the wind blowing our way”. Instead of avoiding giving him information and then him thinking that this technology is no good. It is not everyone that understands this and thinks that it should be shared; in that case nobody would know what we are doing, it is a balancing act between marketing and not giving information out, it is subtle and a learning process.

This example, and several of the earlier ones, can be seen as a lack of procedural knowledge on how to progress the technology further from demonstration to commercialization. Not only was the lack of knowledge on how to commercialize technologies perceived as problematic but also the resources available for doing so, exemplified by a manager of the mandator of the Biorefinery demo plant:

Well, we have a process, we are some personnel that work with this, we have reconciliation meetings regularly when we discuss customer contacts and plan some shorter meetings, so we have like a process for it. But we do not have a person that devotes half his time to the process or... but there are a few of us who split up the task and then it works okay...sometimes it is really intense.

The challenges facing knowledge production identified by this study reflect a constant financial struggle to keep demonstration plants running in conjunction with uncertainty over the political agendas and a lack of procedural knowledge on how to work with commercialization and the requisite competencies needed to implement it.

To summarize, the technology development process tends to unfold in a stepwise manner, e.g. basic R&D with small-scale lab tests, pilot tests, demonstrations, followed by tests in full-scale operational plants, with iterations back and forth between the stages (Fevolden et al. 2017). As presented in Fig. 2, our study centered on the demonstration step and, in particular, on the types of knowledge that are used in demonstration plants and on the key knowledge-based challenges involved in progressing technologies towards commercialization.

Discussion

Replacing fossil-based technologies with ‘clean’ and more sustainable ones is perhaps the greatest challenge of our times. However, development and diffusion of such technologies is not done in a jiffy. The development process is lengthy and full of technical-, market- and institutional uncertainties (Hellsmark et al. 2016b). While small-scale trial-and-error based experiments are critical to progress technology beyond the concept stage, full-scale demonstration plants for close-to-commercial production is eventually needed to demonstrate technology viability (Fevolden et al. 2017; Nguyen et al. 1996; Rosenberg and Steinmueller 2013). And different types of knowledge is what propels such demonstration plants.

While previous literature has elaborated three types of knowledge (domain-specific, procedural, and general knowledge) (Court 1997; Ramesh and Tiwana 1999) and underscored their implications for innovation in general (Hauschildt and Kirchmann

Fig. 2 The steps in the technology development process are shown in the boxes, and our key focus (demonstration) is highlighted in black. The figure also summarizes the different knowledge types together with key knowledge-based challenges. The dotted arrow indicates the possibility that some demonstration plants will be run as permanent test-centers

2001; Howell and Higgins 1990), their role and application in demonstration plants has remained largely unstudied. Managing knowledge also give rise to a couple of important knowledge-based challenges that needs to be addressed so that new technologies can progress towards commercialization. Our research addresses these two shortcomings on which prior literature on demonstration so far has remained largely tacit (Fevolden et al. 2017; Frishammar et al. 2015; Hellsmark et al. 2016b).

Theoretical contributions

On an overall level, our findings reveal that all three knowledge types matter but have different roles. This augments previous research into demonstration plants which has hitherto tended to focus strongly on the pure technical aspects of these plants, and/or appropriate policy responses to stimulate technology development (Frishammar et al. 2015). The paper contributes to the emerging literature on demonstration projects in three different ways.

First, the importance of domain-specific knowledge is critical in a biofuel demonstration context. There is (and should be) a strong focus on experimentation and technical knowledge to enhance understanding of the evolving technology. The results in this paper suggest that domain-specific knowledge is crucial if development activities are to be embarked on successfully. For instance, getting a demonstration plant up and running requires the codifiable expertise knowledge and technological capabilities that initiates innovative collaborations (c.f. Anderson and Hardwick 2017). In contrast to

general knowledge, domain-specific knowledge appears to evolve throughout the entire technology development process. For example, results from the lab-scale tests provides the starting point for the establishment of a demonstration plant and evolved further through the troubleshooting and development taking place there. Furthermore, when operating demonstration plants as permanent test-centers, domain-specific knowledge is needed if the increased flexibility of the plant is to be effectively managed and new opportunities for businesses recognized. This augments the current view on domain-specific knowledge in a demonstration setting by better describing its role and use.

Second, domain-specific knowledge is not enough. What is considered general knowledge in a demonstration plant has been the least prominent of the knowledge types investigated. That said, it may nevertheless play an important role. The examples given in this study show the great importance of having general knowledge about the environment in which the plants operate, given the importance of recognizing business opportunities and securing public and private funding to establish and maintain demonstration plants. In part, this lack of general knowledge may be due to its general nature, its close relationship to common sense, or the prospect that engineers and scientists running the plants may be more comfortable focusing on knowledge within their own domain of expertise. Still, the relative shortage of general knowledge may help explain why demonstration projects often struggle to sustain over time (Hellsmark et al. 2016b).

Third, our findings also revealed an awareness among respondents of the lack of procedural knowledge, in particular concerning improved ways of working with marketing and commercialization activities. Procedural knowledge was also needed to create a demonstration plant, and to manage legal issues, such as patenting, so that the technology can be commercialized. Both competence and resources for such procedures were generally lacking, which could be the result of a strong focus on engineering and technology issues per se (c.f. Frishammar et al. 2015). In addition, the nature of demonstration activities, which incorporates a high degree of novelty in technological aspects in combination with new ways of working in inter-organizational constellations (Hellsmark et al. 2016b) may signal a lack of experience on which to build procedural knowledge.

However, there may also be an opportunity cost based explanation, i.e. an imbalance in the production of different types of knowledge. Human decision making operates under conditions of bounded rationality (Gigerenzer and Selten 2001; Selten 1990; Simon 1982). In a demonstration plant, where reducing uncertainties by means of process upscaling is critical, the ‘production’ of technical domain-specific knowledge may be favored over other types of knowledge perceived to be more distant from the core technology. There may thus be a trade-off in which a certain type of knowledge is favored over others (Zack 2001). This finding adds to recent research into pilot and demonstration plants (Fevolden et al. 2017; Hellsmark et al. 2016b; Sagar and Gallagher 2004), which mostly highlights the role of domain-specific knowledge in reducing various forms of technical, market, and institutional uncertainties. In summary, our findings put a spotlight on the imbalance in the production of different types of knowledge, which further exacerbates the problem of technologies being unable to progress beyond demonstration, even though the technologies themselves have demonstrated their feasibility unequivocally (Sagar and Gallagher 2004).

Limitations and future research

In order to capture a broad view of knowledge production in demonstration plants, the respondents in this study were drawn from a range of different types of organization. Therefore, some views on commercialization might be less well-defined than those working primarily in commercial enterprises. This paper is also limited by the fact that interviews were the primary data source, with the consequent biases and shortcomings that potentially operate in qualitative data analysis. Future research could target the specific roles of each knowledge type, and the particular challenges in ensuring that a sufficient quality of each is attained. In a similar vein, it would be of interest to examine in detail the actor network surrounding a demonstration plant, so as to earmark the contribution of each type of actor (e.g. research institute, industry, university). Another idea for future research is to research the decision-making process and the motives for investing in each type of knowledge production activity, given that such decisions are largely influenced by conditions of bounded rationality.

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References

- Adamides, E. D., & Karacapilidis, N. (2006). Information technology support for the knowledge and social processes of innovation management. *Technovation*, 26(1), 50–59.
- Anderson, A. R., & Hardwick, J. (2017). Collaborating for innovation: The socialised management of knowledge. *International Entrepreneurship and Management Journal*, 13(4), 1181–1197.
- Bäckström, K. (2015). What are the Innovation Effects of Pilot and Demonstration Plants?: The Case of Advanced Biofuels in the Transport Sector. In *European Biomass Conference and Exhibition: 01/06/2015–04/06/2015*.
- Blumer, H. (1954). What is wrong with social theory. *American Sociological Review*, 18, 3–10.
- Borge, L., & Bröring, S. (2017). Exploring effectiveness of technology transfer in interdisciplinary settings: The case of the bioeconomy. *Creativity and Innovation Management*, 26(3), 311–322.
- Bossink, B. A. (2015). Demonstration projects for diffusion of clean technological innovation: A review. *Clean Technologies and Environmental Policy*, 17(6), 1409–1427.
- Braun, V., & Clarke, V. (2006). Using thematic analysis in psychology. *Qualitative Research in Psychology*, 3(2), 77–101.
- Brown, J., & Hendry, C. (2009). Public demonstration projects and field trials: Accelerating commercialisation of sustainable technology into solar photovoltaics. *Energy Policy*, 37, 2560–2573.
- Carriquiry, M. A., Du, X., & Timilsina, G. R. (2011). Second generation biofuels: Economics and policies. *Energy Policy*, 39(7), 4222–4234.
- Cohen, W. M., & Levinthal, D. A. (1990). Absorptive capacity: A new perspective on learning and innovation. *Administrative Science Quarterly*, 35, 128–152.
- Court, A. W. (1997). The relationship between information and personal knowledge in new product development. *International Journal of Information Management*, 17(2), 123–138.
- Davenport, T. H., & Prusak, L. (1998). Working knowledge: How organizations manage what they know. Harvard Business Press.
- Dingler, A., & Enkel, E. (2016). Socialization and innovation: Insights from collaboration across industry boundaries. *Technological Forecasting and Social Change*, 109, 50–60.
- Easterby-Smith, M., Lyles, M. A., & Tsang, E. W. K. (2008). Inter-organizational knowledge transfer: Current themes and future prospects. *Journal of Management Studies*, 45(4), 677–690.

- Eisenhardt, K. M. (1989). Building theories from case study research. *Academy of Management Review*, 14(4), 532–550.
- European Commission. (2011). In European Commission (Ed.), *Energy roadmap 2050, COM(2011)/885 final*. Brussels.
- Fevolden, A. M., Coenen, L., Hansen, T., & Klitkou, A. (2017). The role of trials and demonstration projects in the development of a sustainable bioeconomy. *Sustainability*, 9(3), 419.
- Frishammar, J., Söderholm, P., Bäckström, K., Hellsmark, H., & Ylinenpää, H. (2015). The role of pilot and demonstration plants in technological development: Synthesis and directions for future research. *Technology Analysis & Strategic Management*, 27(1), 1–18.
- Frishammar, J., Söderholm, P., Hellsmark, H., & Mossberg, J. (2018). A knowledge-based perspective on system weaknesses in technological innovation systems. *Science and Public Policy* in press.
- Gigerenzer, G., & Selten, R. (2001). Rethinking rationality. *Bounded rationality: The adaptive toolbox*, 1, 12.
- Harborne, P., Hendry, C., & Brown, J. (2007). The development and diffusion of radical technological innovation: The role of bus demonstration projects in commercializing fuel cell technology. *Technology Analysis & Strategic Management*, 19, 167–187.
- Hauschildt, J., & Kirchmann, E. (2001). Teamwork for innovation—the ‘troika’ of promoters. *R&D Management*, 31(1), 41–49.
- Hellsmark, H., Mossberg, J., Söderholm, P., & Frishammar, J. (2016a). Innovation system strengths and weaknesses in progressing sustainable technology: The case of Swedish biorefinery development. *Journal of Cleaner Production*, 131, 702–715.
- Hellsmark, H., Frishammar, J., Söderholm, P., & Ylinenpää, H. (2016b). The role of pilot and demonstration plants in technology development and innovation policy. *Research Policy*, 45(9), 1743–1761.
- Högmán, U., & Johannesson, H. (2013). Applying stage-gate processes to technology development—Experience from six hardware-oriented companies. *Journal of Engineering and Technology Management*, 30, 264–287. <https://doi.org/10.1016/j.jengtecman.2013.05.002>, 30, 264.
- Howell, J. M., & Higgins, C. A. (1990). Champions of technological innovation. *Administrative Science Quarterly*, 35, 317–341.
- Jassawalla, A. R., & Sashittal, H. C. (1998). An examination of collaboration in high-technology new product development processes. *Journal of product innovation management*, 15(3), 237–254.
- Kallmuenzer, A., & Scholl-Grissemann, U. (2017). Disentangling antecedents and performance effects of family SME innovation: A knowledge-based perspective. *International Entrepreneurship and Management Journal*, 13(4), 1117–1138.
- Karlström, M., & Sandén, B. A. (2004). Selecting and assessing demonstration projects for technology assessment: The cases of fuel cells and hydrogen systems in Sweden. *Innovation*, 6(2), 286–293.
- Kogut, B., & Zander, U. (1992). Knowledge of the firm, combinative capabilities, and the replication of technology. *Organization science*, 3(3), 383–397.
- Lee, H., & Choi, B. (2003). Knowledge management enablers, processes, and organizational performance: An integrative view and empirical examination. *Journal of Management Information Systems*, 20(1), 179–228.
- Macey, S. M., & Brown, M. A. (1990). Demonstrations as a policy instrument with energy technology examples. *Knowledge*, 11(3), 219–236.
- Markusson, N., Ishii, A., & Stephens, J. C. (2011). The social and political complexities of learning in carbon capture and storage demonstration projects. *Global Environmental Change*, 21(2), 293–302.
- Mossberg, J., Söderholm, P., Hellsmark, H., & Nordqvist, S. (2017). Crossing the biorefinery valley of death? A role-based typology for understanding actor networks’ ability to overcome barriers in sustainability transitions. *Environmental innovation and societal transitions*.
- Nguyen, Q. A., Dickow, J. H., Duff, B. W., Farmer, J. D., Glassner, D. A., Ibsen, K. N., Ruth, M. F., Schell, D. J., Thompson, I. B., & Tucker, M. P. (1996). NREL/DOE ethanol plant: Current status and capabilities. *BioTechnology*, 58, 189–196.
- Ramesh, B., & Tiwana, A. (1999). Supporting collaborative process knowledge management in new product development teams. *Decision Support Systems*, 27(1), 213–235.
- Ritala, P., Olander, H., Michailova, S., & Husted, K. (2015). Knowledge sharing, knowledge leaking and relative innovation performance: An empirical study. *Technovation*, 35, 22–31.
- Roos, J., & Von Krogh, G. (2016). *Organizational epistemology*. Springer.
- Rosenberg, N., & Steinmueller, W. E. (2013). Engineering knowledge. *Industrial and Corporate Change*, 22, 1129–1158.
- Roy, E. D., Morzillo, A. T., Seijo, F., Reddy, S. M., Rhemtulla, J. M., Milder, J. C., et al. (2013). The elusive pursuit of interdisciplinarity at the human—Environment interface. *BioScience*, 63(9), 745–753.

- Sagar, A., & Gallagher, K. S. (2004). Energy technology demonstration and deployment. *Ending the Energy Stalemate: A Bipartisan Strategy to Meet America's Energy Challenges*, 117.
- Scharlemann, J. P., & Laurance, W. F. (2008). How green are biofuels? *Science*, 319(5859), 43–44.
- Selten, R. (1990). Bounded rationality. *Journal of Institutional and Theoretical Economics (JITE)/Zeitschrift für die gesamte Staatswissenschaft*, 146(4), 649–658.
- Shapin, S. (1984). Pump and circumstance: Robert Boyle's literary technology. *Social Studies of Science*, 14(4), 481–520.
- Simon, H. A. (1982). *Models of bounded rationality: Empirically grounded economic reason* (Vol. 3). MIT press.
- United Nations Environment Programme. Biofuels Working Group, & United Nations Environment Programme. International Panel for Sustainable Resource Management. (2009). Towards sustainable production and use of resources: Assessing biofuels. UNEP/Earthprint.
- Yayavaram, S., Srivastava, M. K., & Sarkar, M. B. (2018). Role of search for domain knowledge and architectural knowledge in Alliance partner selection. *Strategic Management Journal*, 39, 2277–2302.
- Yegros-Yegros, A., Rafols, I., & D'Este, P. (2015). Does interdisciplinary research lead to higher citation impact? The different effect of proximal and distal interdisciplinarity. *PLoS One*, 10(8), e0135095.
- Yin, R. K. (2014). *Case study research (5th Ed.)*. U.S.A: Sage.
- Zack, M. H. (2001). If managing knowledge is the solution, then what's the problem? In *Knowledge management and business model innovation* (pp. 16–36). IGI Global.