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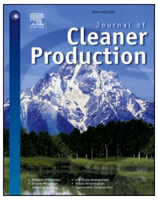

Developing and (not) implementing radical energy efficiency innovations: A case study of R&D projects in the Norwegian manufacturing industry

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ABSTRACT

The prospect of enabling more sustainable industries through energy efficiency innovations has received increased attention in policy and research. In Norway, previous studies have identified a techno-economic potential of 12 TWh reduction in direct energy use and an additional 10 TWh utilization of surplus heat, in industries. However, the novelty and complexity of energy efficient technologies can make their adoption, and hence utilizing this potential, difficult. This paper explores the development and implementation of two high-temperature heat pumps and one heat recovery concept in three R&D projects in the Norwegian manufacturing industry. Our qualitative research finds and explores three *implementation paradoxes*: 1) While the novelty of innovations partly explains why they are difficult to implement, novelty is also a motivator for firms' technology development strategies. 2) Both innovations close to core production technologies, as well as seemingly incremental innovations, can have system-wide consequences in the organizations, making them difficult to implement. 3) While implementation windows (changes to organizations and technical systems) positively affect firms' motivation, ability, and opportunity to develop and adopt innovations, these situations introduce time constraints, putting pressure on less mature technical solutions and R&D processes. Through unpacking these seemingly opposing dynamics, we find that the same factors can both promote and inhibit adoption of technologies during different stages of innovation processes. We discuss the managerial implications on how firms can align R&D collaborations with implementation opportunities, to enhance adoption of radical energy efficiency innovations. In conclusion, we discuss how these contributions can translate into future quantitative research.

1. Introduction

Improved industrial energy efficiency is pivotal in climate change mitigation and the transition to more sustainable production. The possibilities of reducing energy consumption through the adoption of energy efficiency measures have been widely recognized in both the industry (Sorrell et al., 2011) and residential sector (Ma et al., 2020). Developing and implementing innovative technologies is seen as a key strategy to promote a low carbon transition (Chen et al., 2020). While much of the focus has been on incremental improvements, i.e. 'low-hanging fruits', more attention is being paid to technologies with high potential for energy reductions, such as industrial heat pumps (Kosmadakis, 2019) and energy recovery systems (Papapetrou et al., 2018). However, these technologies have larger implications for industrial plants, making them more difficult to implement (they are 'high-hanging', to complete the fruit metaphor).

Such technologies are increasingly being labeled as *energy efficiency innovations* (EEIs) (Solnørdal and Thyholdt, 2019). This not only contains a semantical difference to that of *measures*,[1] but also directs attention to the degree of novelty for the firms involved (Rennings et al., 2013) and the complexity of implementing cleaner technologies (Dieperink et al., 2004). Distinctions are often made between incremental innovations (i.e. continuous improvements of existing technological systems) and radical innovations (i.e. discontinuous processes) (Rennings et al., 2013). Implementing radical innovations can be difficult,

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[1] While there is significant overlap in how studies label energy efficiency *measures* and *innovations*, we apply the latter from here on to highlight the novelty of the technologies for the firms involved.

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Abbreviations

EEI	Energy efficiency innovation
FP	Firm partner
MOA	Motivation, ability and opportunity
RP	Research partner
R&D	Research & development

since this often depends on other changes to organizations or production systems (Fleiter et al., 2012). Therefore, expert knowledge and innovation processes are necessary in order to develop and align these EEIs with industrial production systems (Svensson and Paramonova, 2017). However, there is limited research on how such innovation processes can facilitate development of EEIs, and particularly how firms can address implementation challenges with radical innovations. There is also a need for more in-depth case studies to explain the dynamics that occur in companies when deciding whether to adopt EEIs (Chai and Baudelaire, 2015).

To address these research gaps, this paper investigates how radical EEIs are developed in R&D projects and the dynamics influencing whether they are implemented in firms. By adding to the in-depth studies on EEIs, we contribute with new insights to the literature and practice field on how to improve energy efficiency in industries. Table 1 summarizes key findings from relevant cases and prior research on factors hindering adoption of radical innovations, and how the present study extend on, and contributes to, this literature.

We conducted a qualitative study of three R&D projects in Norwegian industry aiming to develop and implement radical EEIs within firms. Building on literature on the adoption of energy efficiency technologies, we mainly draw on system frameworks, as these allow us to investigate adoption of radical innovations, where implementation entails significant organizational and technical changes for the firms involved (Chai and Yeo, 2012). These frameworks are dynamic in the sense that they describe interactions between *factors* that can both promote and inhibit implementation, rather than formulating them as either barriers or drivers per se (Svensson and Paramonova, 2017). This makes them suitable for investigating innovation processes over time. While the study applies a developed system framework (Chai and Baudelaire, 2015), the novelty of this work lies in investigating the interrelations between system dimensions. Through this, we find dynamics that stand out as *implementation paradoxes*, as they can both hinder and promote development and adoption of technologies, during different stages of the innovation process. With this, the paper contributes with new analytical methods, empirical examples, and knowledge on implementation challenges of radical EEIs, and how these can be mitigated through long-term and close collaborations between researchers and firms.

We structure the paper as follows. In section 2, we elaborate on barriers to and drivers for energy efficiency, EEI characteristics, and system frameworks. Section 3 describes our methodological and analytical approach. Section 4 provides case descriptions, a crosscutting analysis and analytical model, and addresses the research gaps through discussing three implementation paradoxes. Section 5 discusses implications for practice, limitations of this study, and proposes areas for further research.

2. Literature background

Within previous studies on adoption of EEIs, a common perception is that the implementation rate is considerably lower than the potential for utilizing available cost-effective technologies (Sorrell et al., 2011). This apparent *energy efficiency gap* (Hirst and Brown, 1990) has puzzled researchers and policymakers for decades, as money is presumably 'left on

Table 1
Overview of previous research on radical innovations and contribution from the present study.

	Previous research on radical innovations and energy efficiency innovations (EEIs)	Findings from this study (case studies on developing and implementing EEIs in the Norwegian context)
How does *novelty* of EEIs affect development and implementation?	Novelty can be a barrier towards adoption of EEIs: Technological uncertainty is an important barrier for implementing radical innovations (Rennings et al., 2013) Expert knowledge and innovation processes needed to align novel EEIs with production systems (Svensson and Paramonova, 2017)	Novelty of innovations can *both* be a barrier and driver in different stages of innovation processes: While the novelty of innovations partly explains why they are difficult to implement, novelty is also a motivator/driver for firms' technology development strategies.
How does implementation *complexity* affect adoption of EEIs?	Complexity of innovations can be a barrier towards adopting EEIs: Complexity of technologies affect opportunity for implementation (Trianni et al., 2014) Complex technologies diffuse slowly (Kemp and Volpi, 2008) Implementing radical innovations can be difficult, since this often depends on other changes to organizations or production system (Fleiter et al., 2012) The difficulty of adopting innovations is related to whether integration and adjustment with the production process is required (Dieperink et al., 2004) Risks and costs of disruption are barriers towards implementation (Thollander and Ottosson, 2008)	Complexity is also a product of implementation context. Thus, incremental innovations too, can entail complexity: Both innovations close to core production technologies, and seemingly incremental innovations, can have system-wide consequences in the organizations, making them difficult to implement.
How does changes to the organizational and technical systems (*implementation windows*) affect development and implementation of EEIs?	Implementation windows provides opportunity for developing and adopting EEIs: Implementation opportunities arises during equipment retirement and investment (Worrell and Biermans, 2005) Retrofit projects or equipment changes, can create a window for implementing EEIs (Chai and Yeo, 2012) Without implementation windows, firms are less likely to pursue energy efficiency (Chai and Baudelaire, 2015)	Implementation windows entails *both* drivers and barriers at different stages during the innovation process: While implementation windows (changes to organizations and technical systems) positively affect firms' motivation, ability, and opportunity to develop and adopt innovations, these situations introduce time constraints, putting pressure on less mature technical solutions and R&D processes.

the floor' (Sorrell et al., 2004, p. 6). The desire to address this paradox has led to multiple research efforts to identify *non-technical barriers* (Weber, 1997), defined as a "postulated mechanism that inhibits a decision or behavior that appears to be both energy efficient and economically efficient" (Sorrell et al., 2004, p. 4). For example, several studies draw upon transaction costs and behavioral economics to articulate barriers that hinder the adoption of technologies, including risk, imperfect information, hidden costs, access to capital, split incentives, and bounded rationality (Sorrell et al., 2011). The objective of these studies is to formulate policy responses to effectively overcome these barriers (Cagno et al., 2013). Other studies have focused on *drivers* of adoption, defined as "factors facilitating the adoption of energy efficient technologies and practices, thus going beyond the view of investments and including the promotion of an energy efficient culture and awareness" (Cagno and Trianni, 2013, p. 277). Here, the focus is on firms' motivation, ability, and absorptive capacity to develop and implement technologies (Solnørdal and Thyholdt, 2019).

Utilizing this literature to investigate the dynamics influencing adoption of radical EEIs requires making some theoretical choices, since studies within this field draw on different research strands grounded in diverse assumptions of human behavior and rationality (Sorrell et al., 2011). For example, there are several literature reviews proposing different theoretical frameworks and taxonomies (e.g., Sorrell et al., 2011; Trianni et al., 2017). Furthermore, there are country specific and sectoral differences, for example between manufacturing industries (Solnørdal and Thyholdt, 2019) and that of the building sector (Ma et al., 2019), which actualize quite different implementation challenges. In order to investigate the particular issue of radical EEIs, we limit our focus to studies of EEI characteristics and system frameworks to understand the factors influencing their adoption.

2.1. Characteristics of energy efficiency innovations

Most of the energy efficiency literature has tended to treat EEIs homogeneously, by classifying technologies by their energy end-use (e.g., lighting, space heating) or on a more aggregated level (e.g., motor systems, thermal systems) (Fleiter et al., 2012). Such a conceptualization does not account for how different characteristics of technologies affect implementation. A few studies have investigated the impact of characteristics, such as novelty, required knowledge, complexity, distance from core production technologies, and system-wide consequences (Dieperink et al., 2004). Fleiter et al. (2012) provide a framework to categorize EEIs according to three dimensions: *relative advantage, technical context,* and *information context*. Relative advantage includes characteristics such as the internal rate of return, payback period, initial expenditure, and non-energy benefits. The technical context of EEIs includes the distance to core processes (close, distant), type of modification (technology substitution, add-on, or organizational measures), scope of impact (system-wide effects vs. local effects), and lifetime for replacement. Finally, Fleiter et al. (2012) conceptualize the information context of EEIs as transaction costs, knowledge required for planning and implementation, diffusion progress, and sectoral applicability. Here, diffusion progress relates to the maturity of the EEI, while the latter concerns whether the technology is process-related or has a wider sectoral applicability.

An important insight from these studies is how characteristics, such as complexity, affect the prospects for being implemented (Trianni et al., 2014). Prior studies have found that expensive and complex technologies tend to diffuse more slowly (Kemp and Volpi, 2008), as they require more know-how and skills and are associated with higher risks (Fleiter et al., 2012). For example, Fleiter et al. (2012) found that EEIs close to core processes with system-wide effects are less likely to be adopted than those applied to ancillary processes. The difficulty of adopting innovations in general is related to whether integration and adjustment with the production process is required (Dieperink et al., 2004). Similarly, research on energy intensive industries finds that the risks and costs of production disruption are significant barriers (Thollander and Ottosson, 2008). However, these characteristics are often neglected in studies of diffusion of EEIs (Fleiter et al., 2012), and there is a need for more knowledge on how novelty and complexity of innovations affect development and implementation processes.

2.2. System perspectives on EEI implementation

To study the underlying dynamics that influence the implementation of EEIs, we draw on system perspectives. System frameworks highlight that barriers to and drivers of energy efficiency cannot be properly understood by looking at them in isolation (Chai and Baudelaire, 2015). Here, organizations are viewed as social systems influenced by objectives, routines, and structures with different power relations (Thollander and Palm, 2012). For example, Svensson and Paramonova (2017) studied implementation complexity, in a qualitative case study of three companies in Sweden, by addressing the relationship between an EEI and the wider organizational system. This line of research represents a shift from viewing complexity as a characteristic of technology, to observing the emerging connections with the organizational system within which it is implemented. Similarly, based on a survey among companies in Singapore, Chai and Baudelaire (2015) draw on system theory to develop a framework, comprising motivation, ability, and opportunity (MOA), for adopting EEIs. The MOA framework allows assessment of the interrelations between influencing factors and the study of their impact under different circumstances (Chai and Baudelaire, 2015, p. 225).

The *motivation* dimension includes cost-driven motivation, corporate social responsibility (CSR), objectives, and legal compliance (Chai and Baudelaire, 2015). In addition, improving energy efficiency can lead to 'multiple' or 'non-energy' benefits (IEA, 2014), such as improved work environments and production systems (e.g., productivity, quality, process control) and reduced production costs, waste, and emissions (Rasmussen, 2017). Nehler and Rasmussen (2016) observed that despite high levels of awareness of non-energy benefits, such as improved maintenance and work environments, profitability, and payback periods remain the most critical factors for whether or not an energy efficiency investment will be made.

The *ability* dimension relates to 'know-what' (the firm's understanding and specification of EEIs) and 'know-how' (the technical skills and proficiencies required to implement them) (Chai and Baudelaire, 2015, p. 225). As such, Walton et al. (2020) argue the importance of developing firm-level competencies and intangible resources in order to implement eco-innovations, such as energy efficiency. Chai and Baudelaire (2015) emphasize that the ability of firms to implement EEIs also depends on external knowledge flows. Consequently, a combination of internal R&D and external knowledge flows has lower perceived barriers to efficiency improvements, thereby increasing firms' ability to adopt technologies (Cagno et al., 2015). Similarly, Solnørdal and Thyholdt (2019) find a positive relationship between firms' absorptive capacity and their adoption of EEIs. These insights have directed attention towards the importance of transdisciplinary- (Miah et al., 2015), inter-organizational projects (Thollander et al., 2007) and industrial energy efficiency networks (Backman, 2018) for increasing external knowledge flows. However, such endeavors are, simultaneously, prone to collaboration barriers, such as communication issues (Ankrah and Al-Tabbaa, 2015), and rely on informal networks, trust, and mutual understanding to be effective (Al-Tabbaa and Ankrah, 2016; Steinmo and Rasmussen, 2018). Thus, the ability dimension pays attention to how firms apprehend the problem at hand and combine internal and external knowledge and the dynamics of these R&D processes.

The *opportunity* dimension includes internal buy-in from the firm (the extent of firms' production and quality departments' commitment to energy efficiency projects) and the ease of energy efficiency implementation (Chai and Baudelaire, 2015, p. 225). Studies have pointed to how a lack of managerial commitment is a barrier to adoption

(Johansson and Thollander, 2018). Furthermore, Chai and Baudelaire (2015, p. 227) found that easy-to-stop systems in firms and the absence of physical constraints result in easier technical implementation. Conversely, Chai and Yeo (2012, p. 468) contend, based on a multi-case study, that due to interrelations between technological and organizational barriers in product operations, firms will be reluctant to provide a 'window' to implement energy efficiency improvements for fear of disrupting firms' production. However, changes in technical systems, such as retrofit projects or equipment changes, can create a window for implementing EEIs (Chai and Yeo, 2012). Worrell and Biermans (2005) also note that there may be periods of more intense equipment retirement and investment, and whether efficient equipment options are available and affordable during that window of opportunity is important for the implementation of energy efficiency improvements. Without such implementation windows, firms are less likely to pursue energy efficiency (Chai and Baudelaire, 2015, p. 227).

2.3. *Research gaps and questions*

Although existing literature provides relevant insights into how firms develop and adopt EEIs, there is a call for more in-depth studies to understand the drivers (Solnørdal and Foss, 2018), as well as the dynamics affecting whether firms implement energy efficient technologies (Chai and Baudelaire, 2015). Perspectives incorporating system-oriented theory, such as the MOA framework, are useful for assessing how specific circumstances affect implementation. However, these studies do not account for how firms can align R&D activities with such implementation windows to enable adoption of technologies. Further, although there are studies on EEI characteristics and recognition that radical innovations are difficult to implement, this is often a neglected dimension, which needs more attention as different technologies bring about different implementation challenges (Fleiter et al., 2012). As such, the novelty of this study lies in investigating the *interrelations* between factors that affect firms' decisions to implement radical EEIs. With this, the paper addresses the identified knowledge gaps through three research questions:

RQ1 How does *novelty* of EEIs affect development and implementation?
RQ2 How does implementation *complexity* affect adoption of EEIs?
RQ3 How does changes to the organizational and technical systems (*implementation windows*) affect development and implementation of EEIs?

3. Methods

To achieve an in-depth understanding on innovation processes to develop and implement EEIs, this study has adopted a qualitative multiple case study design (Yin, 2009). This allows for studying the diverse nature of energy efficiency projects while also contributing with generalizable and robust results.

3.1. *Context and case selection*

While this paper focuses on three specific cases of EEI implementation in Norwegian industry, an understanding of the wider context is useful to situate findings and enable comparisons. A previous study covering 95% (76 TWh) of the energy used by shore-based industry in Norway identified a techno-economic potential of a 12 TWh reduction in direct energy use and a 10 TWh utilization of surplus heat compared to a reference scenario without measures (Enova, 2009). Strategies to unleash this potential include government incentive programs (Enova, 2020), regulations, and voluntary agreements for energy intensive industries (Cornelis, 2019), and importantly, university-industry research centers, with the objectives of increasing knowledge and innovation diffusion. This study is a result of a long-term multifaceted collaborative engagement in one of these research centers on industrial energy efficiency, which began in 2017. The center includes firms (user-partners and technology developers), universities, and research institutes. While most activities of the center focus on basic and fundamental research, one area concentrates on applied research and technologies defined as 'close-to-implementation.' Here, researchers and firm partners collaborate on smaller *firm projects* to develop EEIs. The objective of these projects is to develop innovative technologies, and ultimately, obtain implementation within the firms.

We selected three firm projects, involving different firms and research partners (Table 2). The selection was based on theoretical sampling (Corbin and Strauss, 1990), with the purpose of exploring the varied conditions of firm implementation. The projects focus on internal utilization of surplus heat, which involves applying waste heat recovery technologies to reduce the consumption of primary energy (e.g., Huang et al., 2017). More specifically, the EEIs under development are two high-temperature heat pumps and a heat recovery and transfer concept. The projects included different industry sectors and specific technologies for surplus heat utilization, which provided contextual variety (Yin, 2009). The projects had been completed, and decisions had been made as to whether to implement the EEIs, making it possible to conduct a systematic qualitative comparison (Eisenhardt, 1989). Through an empirical investigation of these innovation processes, involving firm representatives and technical researchers, we identified dynamics explaining whether the projects lead to implementation.

3.2. *Data collection and analysis*

The data material consisted of interviews, documents, and workshops (see Appendix). The primary data for this study included 14 (16)[2] in-depth interviews with firm and research partners who were involved in the three cases. The information was obtained through semi-structured interviews, conducted face-to-face and over the phone during 2018 and 2019. The purpose was to achieve a case narrative and identify the trajectory concerning the implementation of EEIs. We avoided using analytical terms, such as 'barriers' and 'drivers,' to ensure that the informants were not steered towards a specific theoretical perspective. The interviews were transcribed verbatim shortly after they occurred. In order to ensure a contextual understanding of the cases, we complemented the primary data with 29 additional interviews with

Table 2
Overview of case studies and innovation characteristics.

	Case I	Case II	Case III
Industry sector	Food and beverage	Metal and processing	Food and beverage
Energy intensive	No	Yes	No
EEI characteristics	Novel heat pumps utilizing internal surplus heat	Pre-heating of input factors by utilizing internal surplus heat	Novel heat pumps utilizing internal surplus heat for steam production
Distance from core process	Close to core process	Distant (Ancillary process)	Close to core process
Scope of impact	System wide	System wide	System wide
Sectoral applicability	Crosscutting	Process related	Crosscutting
Implemented	Yes	No, but project considered a success and an option in the future	No, alternative EEIs were implemented in the same period
Data collection	2018–2019	2018–2019	2019

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[2] We interviewed two of the key informants twice at different stages in the process.

research center management, research area managers, and firm partners, and with contextual interviews for Case III. Furthermore, our project group arranged three workshops with researchers, firm partners, and policymakers to discuss the topic of surplus heat utilization. We also obtained information through documents, such as project descriptions, reports, and presentations, as well as research notes from discussions in joint industry-research workshops. Lastly, as a research partner in the center, our experience in this multi-organizational field over time provided an ethnographic account, contributing to our contextual understanding. This methodological triangulation with primary and secondary data (Yin, 2009) gave us a comprehensive understanding of the innovation processes leading up to (non-) implementation.

To achieve an in-depth understanding of the dynamics influencing implementation of the EEIs, we conducted two initial analysis sessions, discussing the main findings to lay the basis for further analysis. In this phase, we noted that the prominent crosscutting themes were different implementation paradoxes. Next, we utilized NVivo to code the data. Here, we identified 36 empirical first order codes. At this point, we revisited the literature on energy efficiency and narrowed our focus to innovation and system theory perspectives. We then coded the empirical constructs into second order codes according to the MOA framework (Chai and Baudelaire, 2015 p. 225), expanding its initial categories to include multiple benefits, R&D process, and implementation windows (Fig. 1).

Furthermore, we systematically reviewed the data in order to reconstruct the case narratives. In this way, we sought to avoid missing the forest (main issues and implementation paradoxes in cases) for trees (empirical constructs). We developed an analytical model encompassing the interrelations between influencing factors. This further expanded our understanding of the empirical constructs through viewing their interrelations from a system perspective. Thus, while our analytical point of departure was inspired by a grounded theory approach (Glaser and Strauss, 1968), we relied on and sought to expand the understanding of existing analytical concepts.

4. Results and discussion

We present the cases as empirical narratives to provide an overview of their development, R&D processes, and results. Then, we provide a crosscutting model, highlighting the interrelations between EEIs and influencing factors affecting implementation. Based on this, we elaborate on how the findings address the three research gaps.

4.1. Case narratives

4.1.1. Case I - Implementing integrated heat pumps in a food and beverage company

Case I includes a large firm that produces food and beverages sold in stores around the country. The firm has a strategic long-term objective: "*to become carbon neutral within 2025 and 2030 for production" (FP1)*. To ensure carbon neutral production, the firm engages in long-term collaborations with universities in order to develop technologies for more efficient energy use. The firm and research partner had collaborated over time to develop and demonstrate the viability of an integrated high-temperature heat pump for the firm's production process: "*We developed that technology a lot in the last five-six years before the [center] started. Therefore, we had a head start, which paved the way for us to offer customers a solution that is already close to industry implementation" (RP1)*. Hence, the firm's motivation was to further investigate and develop use cases for a specific heat-pump technology. While "*cost is a big part of it,*" as argued by the firm informant, the objective was also to optimize the production process and to "*retrieve as much [surplus heat] as possible" (FP1)*. In addition, the firm was in the process of planning a new factory, which provided an opportunity, as well as a necessity, for implementing novel technologies: "*One of the reasons that we wanted to participate in the center was to have a case where we studied a specific solution with high-temperature heat pumps [...], then the new factory presented an excellent opportunity for testing it" (FP1)*.

The decision to build the industry plant also put pressure on the research partners by introducing time constraints. As one of the researchers explained: *"A decision is made centrally, it happens quickly, and then, you have to deliver quickly too" (RP1)*. This meant that the firm and researchers needed to establish a project quickly. They established a project to evaluate novel heat-pump solutions for implementation in the new factory and to answer the question: "*How do we make this the most energy efficient?" (FP1)*. The principal idea was to reuse surplus heat from the internal sub-processes at the factory and raise it to the required temperature levels using heat pumps. The research partner evaluated different heat-pump solutions for minimizing energy consumption at the industrial plant. Hence, the collaboration between the researchers and the firm revolved around searching for the best possible solution concerning thermodynamic, technical, and economic aspects.

The firm partner experienced that the prior collaboration was important for scoping out and developing the project: *"In a way, they have the background knowledge. They understand how our processes work" (FP1)*. During the project, the firm partner contributed with knowledge about the industry processes and operational requirements: "*We discussed a bit, back and forth, the practical feasibility of some of their cases. Mainly, they studied what was the optimal solution, and then our job was to 'reality check'" (FP1)*. The strong mutual involvement helped the research partner in assessing which of the solutions were the most technical and economically feasible: "*We received input along the way of 'we do not want this,' 'this is more relevant' "(RP1)*. This resulted in the evaluation and modeling of five heat-pump technologies, and the firm decided to move forward with one of the solutions. Rather than just replacing a traditional steam boiler with heat pumps, the EEI entailed a fully integrated system close to the core production at the plant. As argued by the firm partner: "*The complexity of heat pumps is significantly higher [than conventional technologies] in that respect" (FP1)*. Thus, the proposed EEI meant system-wide implications for the other processes at the plant. This also induced risks since "*The systems cannot stop. So we have back-up systems in order to contain the risk" (FP1)*.

Implementing the EEI also depended on achieving government funding to cover the additional costs compared to conventional technologies. With the help of its research partner, the firm developed an application for funding grants for a full-scale pilot: "*One of the principles was that it had to be innovative, moving beyond the best-available technology. Therefore, we had to describe how the chosen technology was better, or more innovative, than other available technologies"* (FP1). Demonstrating the *novelty* of the EEI was essential in order to achieve funding from the agency, which made its implementation economically viable. Based on the assessment from the researchers and technology developers, the firm decided to implement the heat-pump concept.

4.1.2. Case II - Assessing the viability of pre-heating metal with surplus heat

Case II includes a Norwegian metal and processing plant, which is part of a large multinational company. The plant produces metal that goes into different products and has significant energy consumption. The firm has an explicit objective: *"Reduce our carbon footprint and energy consumption" (FP3)*. The firm had an established strategy of continuously searching for incremental energy efficiency improvements since energy consumption was one of the largest expense items: "*We do it in order to strengthen our company in the long term, either in the form of a new product or improved processes. All these things increase our earnings" (FP3)*. Moreover, representing an industry characterized as energy intensive, the firm had to comply with existing and position itself for future environmental requirements: "*We get stricter and stricter requirements and expectations" (FP2)*. Engaging with research institutions and universities in energy efficiency projects was key to the firm's strategy of attaining these objectives and provided other benefits, such as "*increased competence, recruitment, public relations, or corporate relations, which improve our standing in the local community*" (*FP3*). Thus, the

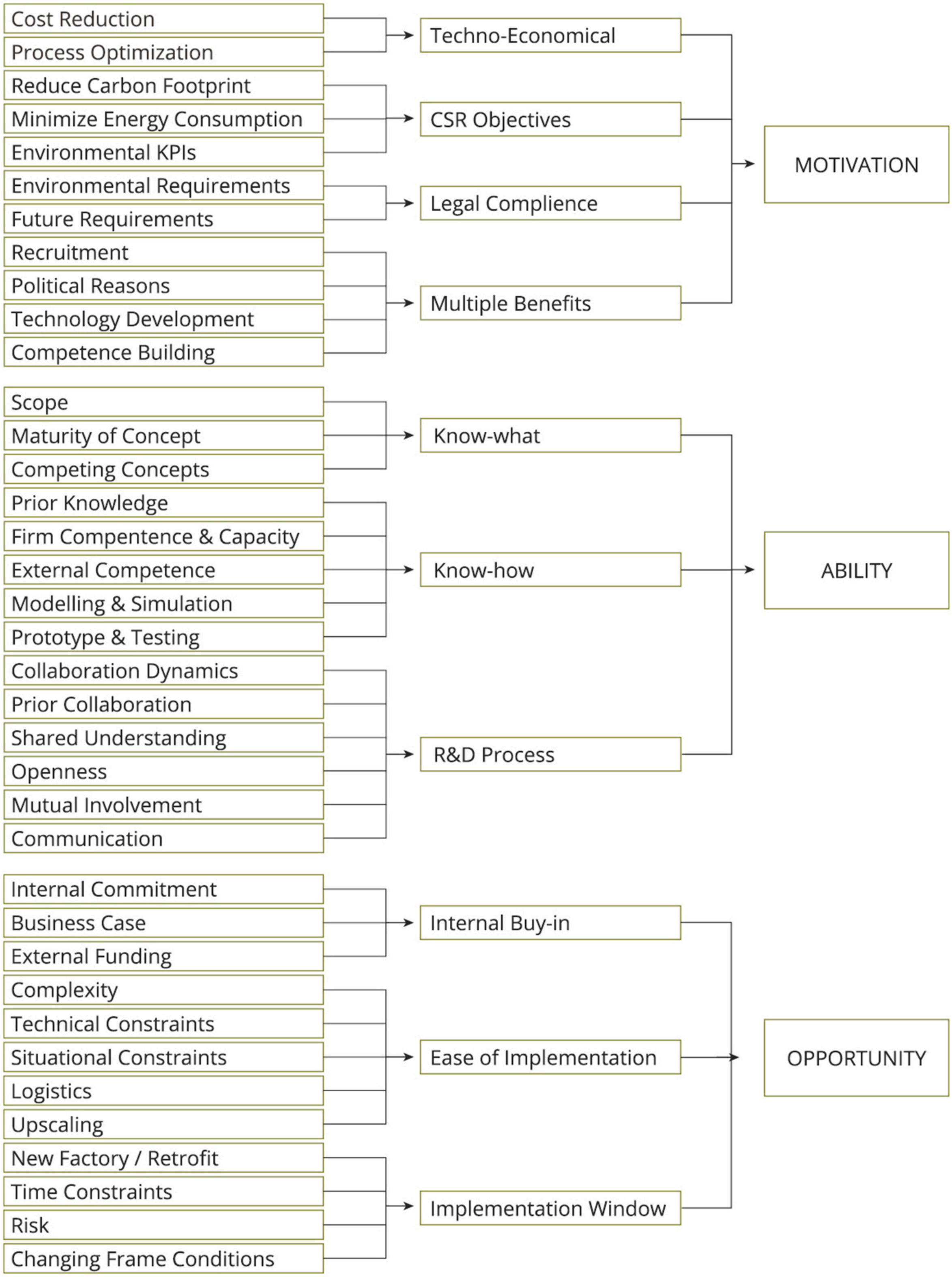

Fig. 1. First order and second order coding of empirical data in case studies organized in the motivation, ability and opportunity (MOA) framework.

firm aimed to initiate projects to address its energy consumption: "*We need projects that are relevant for our energy efficiency potential, which is obviously huge but not so easy to grasp. If it were, we would have done it a long time ago" (FP2)*.

The partners formed a project with the principle of pre-heating raw materials, to reduce the time required before initiating metal production. In the original production process, raw materials with ambient temperatures were inserted into a fully heated oven. This discrepancy in temperatures delays the start of metal production. The firm had earlier hypothesized that production could be initiated faster by pre-heating the material before inserting it into the oven, but it did not have the capacity to test it, as stated by several informants: "*We have* *had some wild ideas over the years*" (*FP2*). "*I have the impression that employees there have had similar thoughts before, and they think it is fun to finally test them" (RP4)*. To systematically investigate possible solutions and establish a proof of concept, the firm engaged a student from the research center. The aim was to verify the viability of pre-heating: "*The results will confirm whether it works or not. If it doesn't, then at least we know*" (*FP2*). With help from management and process operators in the firm, the research partner became familiar with the firm's production process by joining work shifts. During this time, the idea matured into utilizing the surplus heat from materials removed from the oven to preheat the new materials before inserting them: "*We actually had a different idea on how to do the pre-heating. Then we thought, 'why not just place them next to each other?'" (RP7)*. The set-up for testing was based on a "*do-it-yourself solution*", using existing metal boxes to place the old and new materials next to each other and covering them to optimize heat transfer. As a firm representative stated: "*That is how we do it here. We call it a Reodor Felgen crash test method.*[3] *If we have something similar available, then we use it" (FP2)*. The firm provided access to an oven with testing equipment to assess the energy-saving potential. The researchers designed a research concept, simulations, and test procedures to verify the results of the EEI in practice.

The results from the project showed significant improvements when inserting pre-heated materials compared to materials with ambient temperatures: "*The results are surprisingly good. We did not think the difference would be zero, but not that it would be this good either" (FP2)*. In addition, pre-heating raw materials optimized other parts of the production process. However, the partners identified several factors that hindered implementation. Upscaling the concept to the full plant would involve significant complexity to fit the interdependencies and internal logistics, as explained by the manager: "*There are technical barriers [...], we do not have sufficient automation to control them. It will be a lot of extra work, and it is difficult to obtain the benefits" (FP2)*. As such, "*There is no apparent way towards innovation. Because the biggest challenge is not energy, but logistics" (FP2)*. Changing internal logistics implies a significant retrofit project. Even so, the manager argued that implementing EEI could be viable at a later stage: "*There might be other reasons that force us to change [equipment], when it is expired or if we need to improve how we handle emissions. So, other factors can push us in a direction where this could be viable" (FP2)*. While the implementation of the EEI is on hold until it can be aligned with larger changes at the plant, both the researchers and firm partner agreed that the study was a satisfactory proof of concept and regarded the project as having been successful.

4.1.3. Case III - Novel energy efficiency solutions in a food-processing plant

Case III also involves a large firm in the food and beverage industry. Similar to Case I, the firm was about to build a new food-processing factory when it became engaged with the research center. Accordingly, its motivation was to develop and implement EEIs to construct the "*most environmentally friendly food-processing plant in the world" (FP6)*, operationalized in indicators, such as "*kilowatt hours divided by produced [products]*" *(FP4)*. While the firm representatives agreed that this objective was ambitious, they argued that this was useful "*as a management tool"* to guide the choice of technologies: "*If we are to become the best in the world, can we do it like this?" (FP4)*. Furthermore, management and project leaders at the firm were open to new technologies to reach their ambitious sustainability targets.

The firm partner proposed a project to identify novel heating and cooling solutions for the factory. However, the plant's specification and location were not decided at this time. Therefore, the project entailed an open-ended approach to assessing solutions for minimizing energy consumption. As noted by one of the research partners, this proved difficult to align with the otherwise strict timelines imposed by the parallel planning of the new factory: "*We were contacted at short notice, and the case was not clearly defined"* and *"It was not possible to work in peace and provide a thorough concept" (RP1)*. The firm also acknowledged the difficulties of aligning the R&D process with these time constraints: *"It is not so easy to develop concrete ideas according to cost guidelines within the time period we have" (FP4)*. Another researcher also recognized challenges imposed by cost constraints: "*When you meet the firm, you have to 'calculate it home' from day one, and [the solution] should be economically viable without external* funding *from the government" (RP6)*.

The researchers proposed investigating a novel integrated high-temperature heat-pump concept that utilized surplus heat to produce steam. While they argued that this concept could fit the firm's techno-economic demands, it also introduced complexity: *"You have high temperatures, you are producing steam with heat pumps. That is completely new, [...] and if everything is to be integrated, this is quite difficult" (RP6)*. The concept was "*sort of groundbreaking*" *(RP6)* since no similar concepts were in operation, making its implementation a challenge for first adopters: "*If you are number four, it is a completely different story than if you are number one" (RP6)*. Furthermore, the proposed EEI was not a commercial off-the-shelf solution and required more development, which further complicated the collaboration: *"There was a mismatch between what was industrially available and what was actually under development. This also created expectations" (RP1)*. The lack of shared understanding was arguably due to "*a lot of actors involved, with different agendas,*" as well as communication barriers: *"When it came to the technology readiness level, we spoke two different languages" (RP1)*. A firm representative also pointed out these communication issues: "*The information we first got was that this existed and that we could do it. When we started to investigate, things were not ready" (FP6)*. Thus, the project experienced multiple challenges, essentially due to the low maturity of the EEI, which were intensified by scoping issues and a lack of shared understanding in the R&D process. Furthermore, the frame conditions changed along the way when the firm decided on the final location for the industrial plant: *"The decision to move there and become part of a future industry cluster probably led to a drift in the choice of technology" (RP6)*. At this point, competing concepts for utilizing available external heat sources emerged: *"After a while, it became clear that there were other parallel projects with neighboring firms that investigated a 'cluster alternative'" (RP6)*. According to a firm representative, the technology focus drifted while the overall ambition was maintained: "*In the beginning, we had an overarching concept that we thought we would go for, but it has changed. Eventually, we sat down and asked 'What are we actually going to have?' and then it evolved. But, the overall idea of phasing out fossil fuel [remains]"* (FP4). As another firm representative argued, the new solution, which eventually became district heating, would integrate better with the regional energy system: *"The story is best if we do it like this; it will also be the best option from a wider socio-economic perspective" (FP6)*. The initial researchers agreed that "*When you eventually calculate emissions and energy efficiency, it will be positive when you consider the frame conditions, energy system, neighbors, and connections. I think it is ok" (RP6)*. As such, the partners agreed to end the heat-pump case, and the firm continued with the district heating solution.

4.2. Interrelations between influencing factors

As seen here, the EEI in Case I is a radical technology for the firm, and especially for the industrial plant. The EEI, which is close to the core processes and has a system-wide impact, is dependent on alignment with an implementation window, which, in this case, was the planning of a new industrial plant. Here, collaboration between the partners and the technology had matured over the years, and the project group was able to align the remaining development with the time constraints of planning the new factory. This opportunity for implementation also affected

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[3] A reference meaning a 'creative inventor,' which became common in the Norwegian language after the stop-motion animated feature film 'The Pinchcliffe Grand Prix' from 1975, where a bicycle repairman 'Reodor Felgen' builds a racing car, using only available spare parts from the mountain where he resides.

positively the firm's motivation for establishing the project in the first place.

Case II, on the other hand, illustrates how an apparent incremental concept for pre-heating materials outside core production systems becomes radical if scaled up to the full industrial plant. While the EEI was techno-economically viable, implementation required alignment with the wider industrial system and essentially a change in plant logistics. Thus, adoption depended on an implementation window where other technologies were replaced and the EEI could 'tag along.' In this case, such an opportunity remains several years away.

Case III shows how the novelty of the proposed EEI made it difficult to align with the planning and development of a new factory. The time constraints imposed by the new factory made it difficult for the research group to conduct open-ended research. This further actualized collaboration issues in the R&D processes, such as a lack of shared understanding regarding the maturity and specification of the solution. The open-ended approach, combined with a strict time plan for implementation, proved to be difficult to align with the slower temporal trajectory of research.

Essentially, all the cases highlight the broader characteristics of *novelty* and *system-wide consequences*. While the EEIs have different maturity levels, their implementation would still introduce 'something new' for the firms involved. Furthermore, the EEIs are radical in the sense that they all require reconfigurations of the organizations and wider technical systems. These findings highlight the systemic effects and interrelations between influencing factors and EEI characteristics, which we discuss in the next section.

4.3. Implementation paradoxes

Our study provides qualitative insights into how EEIs are developed in R&D projects and sought implemented in firms. In particular, these dynamics stand out as *implementation paradoxes*, as novelty, complexity, and implementation windows seem to both promote and inhibit implementation of radical EEIs during different stages of the development processes. We provide an analytical model (Fig. 2) to encompass these findings, which answers the three research questions (Section 2.3). The framework directs attention towards dynamics visible at the intersection between dimensions, explaining the (non-) implementation of EEIs.

Our findings show that the novelty of EEIs (*RQ1*) affect development and implementation in quite different ways. Innovations that are new for the firms involved actualizes the need for mutual involvement in the R&D process, shared understanding, and the specification of the concept (know-what), as well as the need to align the development of the innovations with operational requirements (know-how). However, we also find that the novelty of an EEI serves as an enabling factor. Our study shows that developing and implementing novel energy efficient technologies are important motivators for firms, in order to demonstrate that they contribute to sustainability. Furthermore, in order to be eligible for public funding for energy efficiency projects, applications must demonstrate novelty beyond the state of the art. These are important findings as they show that downgrading the innovation aspect will not necessarily make them easier to implement. While characteristics such as novelty partially explain the difficulty of adopting EEIs in firms, our findings indicate that the novelty characteristic also enables the implementation of EEIs. The novelty of EEIs, and innovations in general, is often considered to be a barrier to implementation (Kemp and Volpi, 2008), and these findings recalibrate this picture. Thus, we formulate this as a paradox of novelty:

P1a. The novelty of EEIs can lead to technical and collaborative challenges, making implementation more difficult.

P1b. The novelty of EEIs can motivate technology development processes and ease possibilities for external funding, which positively affects implementation.

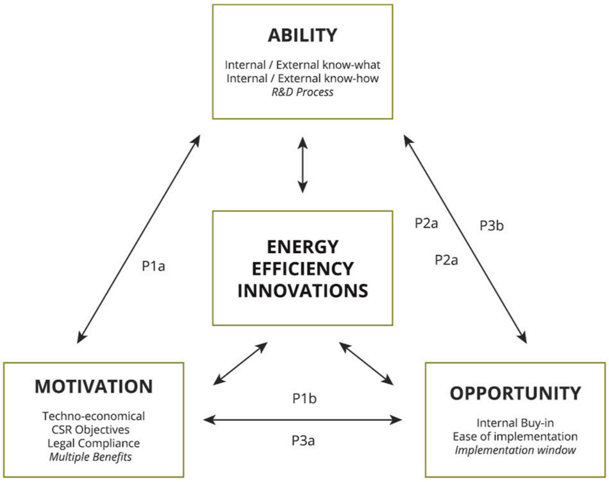

Fig. 2. Analytical model highlighting implementation paradoxes affecting the (non-) implementation of energy efficiency innovations (EEIs).

Our findings also provide novel insights into how implementation complexity affects adoption (*RQ2*). EEIs close to core production technologies and with system-wide consequences are found to be more difficult to implement than those applied to ancillary processes (Fleiter et al., 2012), since they influence the entire production process (Dieperink et al., 2004). Our study corroborates these findings, by showing that such systemic effects necessitate alignment with larger changes to organizations. Therefore, complexity is not necessarily an embedded characteristic of the EEI but emerges from the relationship with the implementation context. In addition, our findings show that EEIs can be radical in the sense that they provoke, or depend on, larger changes in organizations and technical systems. Thus, while some EEIs are considered *low-hanging fruits* or stand-alone technologies, our findings suggest that implementing these EEIs in tightly coupled systems certainly requires climbing to the top of the tree. Thus, we suggest this as a paradox of complexity:

P2a. EEIs close to core production technologies actualize implementation challenges and the need for larger changes in organizations and technical systems.

P2b. EEIs that seem to be incremental can have system-wide consequences when implemented in tightly coupled systems, actualizing technical and situational constraints.

Furthermore, our study provides knowledge on the importance, and emerging challenges, of aligning innovations with implementation windows (*RQ3*). Our findings show that building new industrial plants or retrofit projects can create opportunities to implement EEIs. Conversely, the lack of larger changes to organizations can also delay implementation. Even EEIs considered to be economically viable may be put on hold until they can 'tag along' with a larger retrofit project. These findings extend on previous research on how 'technical openings', such as equipment retirement and investment, make it easier to implement EEIs (Worrell and Biermans, 2005). In these events, influencing factors, such as the fear of disrupting production, are minimized (Chai and Baudelaire, 2015). However, we find that implementation windows not only remove technical barriers to implementing new technologies, but also provide an *opportunity* to push organizations towards developing and implementing EEIs, by affecting firms' *motivation* and *ability*. Implementation windows can affect firms' motivation for engaging with research partners to increase know-what and expertise and search for suitable EEIs. This, in turn, can contribute to firms' ability and knowledge flows with regards to assessing opportunities for energy efficiency and forming applicable projects with better possibilities of implementation. Furthermore, larger investments in new industrial plants enable the incorporation of capital investments in EEIs. Thus, the impact of implementation windows transcends the phases of EEI adoption. However, implementation windows can also make adoption difficult. The most notable in our findings is how the planning of new factories imposed time constraints, which put pressure on less mature technical concepts, as well as on collaboration. This illustrates a paradox of opportunity. While implementation windows provide an opening for adopting technologies, they also put increasing pressure on the R&D process since the EEIs must be ready to be implemented within the given time window. Hence, we suggest there is a paradox of opportunity:

> P3a**.** Implementation windows can increase firms' motivation and ability to develop and implement EEIs.
>
> P3b**.** Implementation windows induce time constraints, putting pressure on the R&D process, and actualize potential collaboration issues, which can make the adoption of EEIs more difficult.

5. Conclusion and implications

This paper provides knowledge on how radical EEIs can be developed in R&D projects and implemented in practice. By studying dynamics that occur in companies in-depth, as called for by Chai and Baudelaire (2015), we extend on the energy efficiency literature by addressing research gaps on how novelty (RQ1), complexity (RQ2) and implementation windows (RQ3) affect development and adoption of EEIs. We find that these dimensions stand out as implementation paradoxes, which can both enable and inhibit adoption during different stages of the projects. First, while novelty of innovations partly explains why they are difficult to implement, novelty is also a motivator for firms' technology development strategies and a requirement for attracting government funding. Second, innovations can have system-wide impact and implementing them depends on other changes to organizations and technical systems. Third, while implementation windows positively affect firms' motivation, ability, and opportunity to develop and adopt innovations, these situations introduce time constraints, putting pressure on less mature technical solutions and R&D processes. Taken together, these findings indicate that moving from the development to implementation phase requires different forms of alignment. Technologies must be aligned with the technical and organizational systems they are to be implemented within, and innovation processes need to be aligned in time with implementation windows for this to succeed. These findings show the usefulness of moving beyond dichotomies, such as 'implemented/not implemented' framings of EEIs and 'push/pull' framings of influencing factors, when assessing whether radical EEIs are implemented. Thus, this study contributes to theory by demonstrating the viability of system perspectives to explain why some EEIs are implemented, while others strand during the innovation process. While the cases in this study are indeed context dependent, the findings and the narrative framing can provide learning to firms and researchers occupying similar roles in R&D projects.

5.1. Implications for practice

These findings have implications for firms and researchers that engage in R&D projects to improve industrial energy efficiency. In particular, implications can be drawn from the identified collaboration and project dynamics, which can carry relevance also for other countries and industries (however, see Chapter 5.2 for limitations). First, our study suggest that while radical innovations can indeed be difficult to implement, leveraging the knowledge and competence in research institutions through participation in R&D collaborations can ease these processes. In addition, actively building informal networks and trust to enable mutual involvement in projects appear to be imperative for developing radical EEIs.

Second, our study highlights the importance of involving operating personnel within the firms in these projects. As shown, radical innovations require close alignment with technical and organizational systems. Involving operating personnel in R&D processes can both improve the specification of the problem, and contribute to align the solutions with practical issues and complexities at the industrial plants. Thus, bridging external knowledge flows with internal operational and managerial competence in energy efficiency projects can potentially increase chances of adoption.

Third, this paper illustrates the benefits of engaging in *long-term* industry-research centers on energy efficiency. Participating in networks, or sequential projects, over time is important to accumulate knowledge and mature technologies. Furthermore, a longer time span and exposure to R&D environments improves the probability that implementation windows occur simultaneously. However, when these opportunities arise, time is of the essence. Our findings suggest that aligning research processes with implementation windows is necessary to ensure that radical EEIs become adopted. This calls for flexibility from the project or center management, to adjust research activities in order to utilize such opportunities. Firms participating in R&D projects should also seek to align innovation processes with implementation windows outside the project level. This could potentially increase the chances for successful implementation of radical EEIs.

5.2. Limitations and future research

Our study has certain limitations. Since our paper is based on three in-depth case studies, the findings should be interpreted with caution. Qualitative approaches are inherently context dependent and there is a need to investigate these issues across different sectors and countries. For example, the particularities of the Norwegian industry and policy context differ from other countries and industries. However, by making these particularities explicit in this study, our findings can provide a basis for comparative and quantitative studies in the future. Empirical evidence from the Norwegian context is under-represented in the energy efficiency literature, and by comparing and extending on findings from previous cases in other countries, this paper provides a comparative contribution to this end. Future research could apply statistical methods to utilize the analytical model proposed in this paper or test the findings quantitatively. This could yield insights into how novelty and complexity of innovations and implementation windows affect adoption of EEIs over a wider population. While this paper shows how factors influencing adoption change over time, this could be further investigated through quantitative time-series studies. Future studies could also investigate how firms and researchers work proactively in projects to align R&D activities with implementation windows. Applying dynamic perspectives and system frameworks can yield novel insights on the implementation of radical energy efficiency innovations and is a promising avenue for future research.

CRediT authorship contribution statement

Jens Petter Johansen: Conceptualization, Methodology, Validation, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Irina Isaeva:** Conceptualization, Methodology, Validation, Investigation, Writing – original draft, Writing – review & editing.

Declaration of competing interest

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

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Appendix

Primary data sources

No.	Informant Code	Case I	Case II	Case III	Who	Field/Position
1	RP1	x		x	Researcher, responsible for Cases I and III (two interviews)	Chemical engineering
2	RP2		x		Researcher	Physics, mathematics
3	RP3		x		Researcher, master student	Process engineer
4	RP4		x		Researcher	Materials and chemistry
5	RP5	x	x	x	Researcher, in charge of firm projects	Master of science
6	RP6			x	Researcher, industry contact	Energy and processing
7	RP7		x		Researcher responsible for Case II	Materials and processing
8	FP1	x			Firm representative	Project leader
9	FP2		x		Firm representative	Project leader
10	FP3		x		Firm representative	Engineering
11	FP4			x	Firm representative	Environmental manager
12	FP5			x	Firm representative	Energy planning
13	FP6			x	Firm representative (two interviews)	Project leader
14	FP7			x	Firm representative	DH network leader
Secondary data sources						
15–31	Contextual interviews (Research center)	x	x	x	Interviews on collaboration dynamics and innovation from the research center	
32–42	Contextual interviews (Case III)			x	Interviews and workshops with industry cluster, which Case III is a part of	
43–45	Contextual workshops (Firm representatives, researchers and policymakers)	x	x	x	3 workshops with firms, researchers, and policymakers, discussing barriers and drivers for surplus heat utilization	
46	Analysis of written documents	x	x	x	Project reports, deliverables, technical research articles, and media articles describing case studies and center activities	
47	Ethnography in center	x	x	x	Participation in the research center over time allowed for informal conversations with industry and research partners, contributing to contextual insights	

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