# The innovation journey for sustainability:

## A reinterpretation of the Fireworks Model in the context of sustainability-oriented innovation unfolding in small and medium-sized enterprises

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# Overview of the articles included in this paper-based doctoral dissertation

This paper-based doctoral dissertation is composed of the framework paper and the following four papers (in annex) that have been or will be published. They meet the formal requirements of a paper-based dissertation according to §5 of the Leuphana Promotionsordnung, Faculty of Sustainability (8th July 2015). The papers are presented in order of publication year.

**Papers counting for the formal requirements of the paper-based dissertation**

[1] *Journal article, peer reviewed, published:*

Wicki, S. (2015): Diversification through green innovations: Lessons learned from a German engineering firm. Umweltwirtschaftsforum 23 (4), pp. 197–203. DOI: 10.1007/s00550-015-0370-7.

[2] *Journal article, double peer reviewed, published:*

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[3] *Journal article, double blind peer reviewed, published:*

Hansen, E. G.; Wicki, S. & Schaltegger, S. (2018): Structural ambidexterity, transition processes, and integration trade-offs: a longitudinal study of failed exploration, R&D Management, Vol. 28, No. 49, 484-508. DOI: https://doi.org/10.1111/radm.12339

[4] *Journal article, double blind peer reviewed, published:*

Wicki, S.; Hansen, E. G. (2019) Green technology innovation: Anatomy of exploration processes from a learning perspective, Business Strategy and the Environment, No. 28, 970-988, DOI: https://doi.org/10.1002/bse.2295

**Paper in further development**

[5] Hansen, E. G.; Wicki, S.; Schaltegger, S.: Ambidexterity management for diversification through green innovation: lessons learned from unsuccessful separation in SMEs.

*Status: first submitted to R&D Management Journal (peer reviewed; VHB JQ3: B; IF: 1,857), major revision, then withdrawn. Presented at ISPIM Conference: see paper [6].*

*Target Journal: Technological Forecasting and Social Change (peer reviewed, VHB JQ3: B, IF 3,129)*

**Supplementary material**

[6] Wicki, S. Hansen E.G. and Schaltegger, S. (2015) "Exploration of Green Technologies in SMEs: the Role of Ambidexterity, Domain Separation and Commercialization", XXVI ISPIM Innovation Conference, 14-17 June 2015, Budapest, Hungary.

The individual papers that compose this doctoral dissertation are provided in Annex.

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I was drawn to this research because after my Master's thesis I still had a huge open question: "How can a firm actually transform to become sustainable? How can it fundamentally transform, now?!" I am very grateful for the opportunity I received to work on this question in a PhD! It is the very inspiring people I met along these four years of doctoral research that made this personal journey possible, and actually so interesting. I am very grateful for having met so many who inspired, stimulated, moved, and supported me.

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*We are on this journey together.*

# Framework Paper

# The innovation journey for sustainability:

## A reinterpretation of the Fireworks Model in the context of sustainability-oriented innovation unfolding in small and medium-sized enterprises

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# Abstract

The importance of firms to participate in sustainable development has been widely discussed in the literature. Yet, progress is still slow in light of the size and the urgency of the challenge. In terms of sustainability management, the challenge is to engage firms in sustainable development. This includes all firms, also SMEs that represent globally about 70% of pollution but have so far received less attention.

Sustainability-oriented innovation (SOI) in the form of new products that lessen negative environmental impact, or even create a positive impact on the environment and positive value for society can play an important role, particularly at established SMEs who see business opportunities in sustainable development and consider possible diversifications into new sustainability markets. Whereas the extant literature discusses *what* SOIs are and *why* firms develop them, little is known about *how* they are developed. To enable firms to innovate for sustainability, it is essential to know more about how SOI are developed. This process is considered as a very difficult one, with many firms failing.

The aim of this doctoral research project is to examine how SOIs dynamically unfold at SMEs and how they can be managed. Innovation processes at established SMEs are analyzed with the Fireworks innovation process model. The SOI specific challenges allow advances in the model to be achieved for this context.

The findings reveal that SOI unfolds is an emergent, somewhat chaotic way, that duration and outcome are uncertain, that the overall journey is composed of multiple intertwined innovation paths, of which several will likely lead to setbacks. Four practices can help manage this process: first, the creation of a dedicated organization unit for exploration, second intelligent learning for efficient exploration, third in-depth investigation of the related technological innovation system, and fourth careful planning of the integration into the core business for commercialization.

This research contributes to the SOI literature by advancing the Fireworks model and thereby proposing a model of how SOIs dynamically unfold. The model is both holistic and detailed, which opens several avenues for future research. Furthermore, the research contributes to management practice by providing a heuristic to manage SOI development at SMEs.

**Keywords**

Eco-innovation, environmental innovation, sustainable innovation, green innovation, innovation processes, SME, ambidexterity, technological innovation system (TIS), Fireworks innovation process model, exploration and exploitation

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# 1. Introduction

We learn from the natural sciences that global environmental issues are accelerating (Rockström et al. 2009). The literature emphasizes that firms play a crucial role in sustainable development (Schaltegger & Burritt 2005), and that in light of the urgency of global sustainability challenges, more rapid and consequent action is needed (Whiteman et al. 2013). In terms of corporate sustainability, this means that firms must join the journey for sustainability, for instance by developing new green, or sustainable, products (Hart et al. 2003) that allow us to live in more sustainable ways.

Innovation plays an important role for corporate sustainability (Schaltegger & Wagner 2011). Sustainability-oriented innovations (SOI), colloquially called green innovation, have received important academic attention (Schiederig et al. 2012). They are new products that aim to significantly reduce negative impact – and even create a positive impact – on the environment and society, while generating revenues for the firm (Klewitz & Hansen 2014). Incremental product improvements are needed, but much can be expected from new sustainable products that allow a higher positive impact (Adams et al. 2016).

The extant literature discusses *what* SOI are and *why* firms should develop them (Hart et al. 2003; Hansen et al. 2009; Adams et al. 2016). But, much less is known about *how* firms develop SOIs; about the SOI process (Hall 2002; van Kleef & Roome 2007; Zollo et al. 2013). What we know is that developing SOIs is much more difficult than conventional innovations (Driessen et al. 2013) because they imply changes in many (if not all) parts of the business at the same time (Seebode et al. 2012).

Given our lack of knowledge and the importance of this topic, this research aims at exploring how SOI processes dynamically unfold at SMEs and how they can effectively be managed. To pursue this aim, an in-depth empirical research was conducted at a middle-sized German engineering firm. Its innovation process was initiated in the context of a diversification attempt, which lasted about 15 years, but ultimate failed (Paper 4, 5). The Fireworks innovation process model was used to analyze this journey as an innovation process that unfolds in an emergent, somewhat chaotic way (Cooper 1983; Van de Ven et al. 2000/1989). The model acknowledges the complexity involved and is therefore well adapted to study the challenges firms may face when developing SOIs (Fichter et al. 2007).

The focus in this research is on small and medium-sized enterprises (SMEs), who are responsible for an important share of business-related environmental impact (Spence 2007). It examines in particular established ones already successfully operating for many years, who have an intrinsic motivation for sustainability, and aim at developing new products to contribute to sustainable development by seizing new business opportunities (Noci & Verganti 1999; Hart et al. 2003; Klewitz & Hansen 2014). Archetypical for this kind of firm is the hidden champion (Simon 2009), which uses its strong core competences (Hamel & Prahalad 1994; Taylor & Helfat 2009) to contribute to sustainable development (Paper 5). This archetypical firm is very interesting to study, as implications can be drawn for many other SMEs who could adopt a similar approach to bring sustainability into the core of the business and its products (Paper 1).

The research contributes to the literature on SOI by advancing the Fireworks model. Based on the papers that comprise this dissertation, the model is advanced in four directions, each of which represents a key challenge for SMEs. First, it includes the notion of organizational separation to create a dedicated space for SOI. Second, organizational learning is added to better understand how firms learn along this journey. Third, the technological innovation system (TIS) perspective is also brought into play, as SOI are related to broader innovation dynamics towards sustainability. Fourth, integration mechanisms are built into the model, as the innovation needs to be re-integrated into the core business for commercialization. The resulting advanced Fireworks model reveals how SOIs dynamically unfold. It can be used as a meta-model to examine SOI development and provides several avenues for future research. To management practice, it contributes a heuristic that provides guidance for established SMEs to manage development of SOIs based on their specific challenges.

This framework paper is structured as follows: section 2 provides a literature review on SOI and is concluded with four important challenges that SMEs encounter when developing SOIs. Section 3 introduces the Fireworks model. The methodology is presented in section 4. Section 5 advances the model in four directions. It then explains the advanced Fireworks model as the main contribution of this research. Section 6 discusses this new model in light of the SOI and SME literature. Its contribution to management practice is presented, before outlining the mains limitations and the avenues for future research. Section 7 concludes the paper.

## 2. Literature Review

This section unravels the current knowledge about how SOIs unfold in the SME context and discusses the challenges SMEs may face when developing them.

### *2.1 Sustainability-Oriented Innovations*

Before framing SOI, it is important to have a common understanding of what the term innovation means. The first definition was probably coined by Schumpeter (1934), who explained that innovation is always related to something new. In the corporate context this can take the form a new product, new features in a product, a new production method, a new target market, new administrative processes, or a new organizational structure. As such, an innovation is more than a creative process leading to an invention as it includes commercialization (Crossan & Apaydin 2010).

The innovation literature is multifaceted and adopts many complementary perspectives on innovation (level of analysis, type of innovation, process or outcome). An overview can be found in Tidd & Bessant (2009) and Crossan & Apaydin (2010). There is extensive literature discussing innovation determinants, innovation outcomes (Díaz-García et al. 2015), innovation diffusion (Rogers 2003), drivers and barriers, (Tidd & Bessant 2009). The present research focuses on the innovation process perspective – *how* an innovation emerges – which is under-developed in the literature (Crossan & Apaydin 2010), also in the case of SOIs (Adams et al. 2016).

In the past years, concerns about how to advance corporate sustainability led to an increasing interest of innovation management scholars in SOI (Schiederig et al. 2012), not only in the context of large firms, but also SMEs (Klewitz & Hansen 2014). Several papers provide an in-depth review about this knowledge area: Schiederig et al. (2012) provide a meta-analysis of the literature and help identify the most active scholars, institutions and relevant publications; Klewitz & Hansen (2014) review the SOI literature in the SME context; Díaz-García et al. (2015) particularly focus on drivers for SOI; and Adams et al. (2016) review the empirical SOI literature and organize it into conceptual framework. These reviews reveal an important gap in our understanding about how SOI processes unfold and can be managed.

Alongside SOI, scholars use several other terms to refer to innovation in the context of sustainability. These terms influence each other and are often strongly overlapping (Klewitz & Hansen 2014). Other terms include green innovation, ecological innovation, environmental innovation, sustainable innovation, and sustainability-driven innovation (Schiederig et al. 2012). These authors discuss the differences between these terms and conclude that SOI, eco, environmental and green innovation show only minor conceptual differences. In this research study, the term sustainability-oriented innovations or "SOI" is preferred, which is defined as:

> an improvement (and/or introduction) of a product, technology, service, process, management technique, or business model which, in comparison to a prior version and based on a rigorous and traceable (comparative) analysis, has a positive net effect on the overall capital stock (economic, environmental, and social). (Klewitz & Hansen 2014, 3)

The SOI term stresses that in addition to a commercial goal, SOIs aim at reducing negative impacts on the environment and society, or even create a positive effect. With a focus on products, SOI resembles closely what Hart et al. (2003) refer to as a clean technology innovation, which involves developing a new product, radically different from existing product lines, in areas such as renewable energy. Following this line of reasoning, this paper discusses radical SOI development, and not the incremental improvement of sustainability performance such as introducing eco-efficiency measures as is typical in SMEs (Bos-Brouwers 2009).

SOI share many similarities with conventional innovation, but also strongly differ in many aspects. First, the most important difference is their purpose. On top of commercial success, SOI embraces the explicit double-aim of improving the firm's sustainability performance and contributing to solving societal issues (Hart et al. 2003; Hansen et al. 2009). This also means that the firm will explicitly search to move its innovation in a direction where it positively contributes to sustainability challenges. Second, SOI are characterized by very high uncertainties (Fichter & Paech 2003; Paech 2005) because they involve new and unknown sustainability-related technology and markets. It appears that the market dynamic is a particularly difficult factor for firms. SOI target markets are often unknown to established firms and are still emerging, therefore sometimes rapidly evolving and very volatile (Luethi 2010; Paper 2). Fourth, transdisciplinary knowledge is typically needed to understand the meaning of sustainability and its implications for firms and innovation (Schaltegger et al. 2013b). In this sense, SOI can be seen as a case of particularly complex innovation

(Noci & Verganti 1999).

In practice, SOI is in many cases motivated by seeking legitimacy in the face of changing political and regulatory environments, and increasing stakeholder pressure (Roome 1994). Next to these external incentives, firms are also developing SOIs as a result of new managerial mindsets (for intrinsic motivation for sustainability, see Hockerts 2008; McWilliams & Siegel 2001). In this research study, the focus lies particularly on intrinsically motivated firms who see business opportunities in sustainable development and therefore aim at seizing the opportunities that new sustainability markets can represent for them (Schaltegger & Wagner 2011; Schaltegger et al. 2012; Jenkins 2009).

*2.2 Small and Medium Sized Enterprises*

Even though SMEs have received less scholarly attention than large firms (Hammann et al. 2009; Klewitz & Hansen 2014), they are important for sustainability (EC 2010) as they represent by far the most common form of private business (Spence 2007), accounting for 99% percent of all enterprises in Europe (EC 2005) and responsible for 70% of pollution globally (Hillary 2004). This paper uses the European Commission's definition, which is widely used in the literature (Klewitz & Hansen 2014; Spence 2007). The term SME is defined as:

> a category of enterprises, which employ fewer than 250 persons, and has an annual turnover not exceeding €50 million, or annual balance sheet total below €43 million (EC 2005, 5).

In many ways SMEs are not "just little big businesses" (Welsh & White 1981; Tilley 1999; Bos-Brouwers 2009), and several SME particularities should be considered when it comes to innovation. First, the most discussed difference compared to large enterprises is that SMEs have fewer resources available (Lubatkin 2006). This implies that they are less able to develop fundamental innovation, such as inventing path-breaking new technologies (Baumann-Pauly et al. 2013). Second, having fewer resources is to some extent compensated for by their greater flexibility and adaptability in changing the firm's environment (Williams & Schaefer 2013). This greater adaptability is largely due to the short lines of command and flat hierarchies. Third, many SMEs are owner-managed, which provides greater decision-making freedom (Hammann et al. 2009). Overall, no innovatory advantage is associated with either large or small firms (Schumpeter 1934), the advantage of SMEs being mainly behavioral and the one of large firms material (Rothwell 1989; Nooteboom 1994).

Among the rather heterogeneous group of firms that SMEs represents (Jenkins 2009), this paper focuses on established entrepreneurial SMEs of a medium to large size. Indeed, start-ups or new ventures founded with sustainability as part of their founding mission (Hockerts & Wüstenhagen 2010; Kuckertz & Wagner 2010) will face different innovation challenges. This paper does not focuses on small SMEs (fewer than 10 employees) because in these firms sustainability management is largely about the environmental values and mindset of the owner-manager (Williams & Schaefer 2013). However, beyond established SMEs, this research is also applicable to internal ventures of larger industrial groups, which operate in an entrepreneurial way similar to SMEs (Fayolle 2007).

Thus, the implications of this paper are not limited in the strictest sense to SMEs, but rather extend to organizations or organizational units operating in an entrepreneurial way (Sarasvathy 2001; Schaltegger & Wagner 2011).

Common sense may suggest that SMEs only adopt reactive attitudes towards sustainability (innovating mainly in incremental steps in response to customer demand), but the literature suggests that they can be very proactive as well (Aragón-Correa et al. 2008; Zeyen & Beckmann 2017). In fact, early empirical investigations show that some SMEs are highly committed to green innovation (Noci & Verganti 1999). This pro-active sustainability strategy can materialize in the development of SOI (Hart et al. 2003; Schaltegger et al. 2012). Entering sustainability markets can also be interesting in the sense of the niche strategy that many SMEs pursue, because these markets are often too small to be interesting for large firms (Jenkins 2009). Finally, this strategy seems particularly appealing to SMEs, who are by nature more limited in conducting corporate sustainability activities in addition to their core business (Baumann-Pauly et al. 2013), and can thereby use innovation to bring sustainability into their core business (Jenkins 2009).

### *2.3 Challenges for Developing SOIs*

The literature reveals that established SMEs may encounter at least four challenges when developing SOIs. This section introduces these challenges, which will be used as input for advancing the Fireworks model and are used as a structuring element throughout this framework paper.

#### 2.3.1 Challenge 1: Dedicated exploration unit

The first challenge an established SME may face is the need to deal both with sustaining the "old" conventional business while at the same time developing the "new" sustainable business. Sometimes old and new may contradict or even cannibalize each other. Firms typically face a challenge known as the exploitation-exploration paradox (March 1991). Exploitation is associated with performance and the efficient utilization of known implemented technologies, and exploration aims at the discovery of new possibilities (March 1991; Raisch 2008; O'Reilly & Tushman 2013). The literature suggests that creating dual structures for innovation (one for exploitation, another for exploration) can help overcome this difficulty (Duncan 1976).

#### 2.3.2 Challenge 2: Intelligent learning for efficient exploration

The second challenge relates to the need to (re)develop the ability to explore unknown business areas. Firms will face difficulties to simply develop a new product for these markets (Chesbrough 2010) since these new markets and related technologies are so distant from the current business. New technologies need to be explored and unknown markets discovered (Foster & Green 2000). Therefore established firms will need to learn (again) – likely for the first time in a longer time period – how to explore unknown business areas, just as startups or new entrants do. While the literature discusses how exploration processes can unfold and be managed, little is known about how an established firm learns (again) to explore (Van de Ven et al. 2008), and learns intelligently so that this exploration is efficient and affordable.

#### 2.3.3 Challenge 3: TIS investigation

The third challenge is to take into account the complex firm-external innovation dynamics. Indeed, SOIs develop in the context of larger socio-technological changes (Geels 2002). These changes and their related dynamics are particularly difficult to investigate with emerging technologies for which no market has formed yet (Bergek et al. 2008). The development of each "local" SOI is embedded in a broader technological innovation system (TIS) (Markard & Truffer 2008), which strongly influences firm-level innovation processes (Pohl & Yarime 2012; Paper 2), and will ultimately also influence innovation success (or failure). Thus, the external TIS of each innovation must be investigated.

#### 2.3.4 Challenge 4: Innovation integration

The fourth challenge is that if a dedicated organizational unit was created the SOI must be re-integrated into the core business when mature (Gassmann et al. 2012). The SOI will need the "production machine" of the core business for its commercialization (Benner & Tushman 2002). In this sense, the exploration-exploitation paradox needs to be overcome once more, this time not for protecting SOI development, but for translating the newly born SOI into the production and commercial logic of the core business.

## 3. Fireworks Model as a Theoretical Framework

This section introduces the Fireworks model that is used as a basis in this framework paper. The model enables the study of innovation processes, i.e. the sequences of activities that lead to the birth of an innovation (Crossan & Apaydin 2010). So-called flow models are often used in innovation management and in design literature to represent innovation processes as an archetypical development in the form of a linear process (Verworn & Herstatt 2000). The stages are distinctively separated with "go – no-go" decision gates (Cooper 1990). Whereas this prescriptive view is of great use to visually represent an innovation process in a simple way and to communicate about it, it has a limited usefulness for empirical analysis. Indeed, in reality innovation processes are rather fuzzy: stages occur in parallel, often overlap and are iterative. Based on an in-depth qualitative study of 30 British industrial firms known to be active in R&D, Cooper concludes that:

> The new product process is not the sequential or series process so often portrayed in the literature. Rather, we see a more complex process, with many activities overlapping or undertaken in parallel. … The usual normative models, in contrast, propose a stagewise (series) set of activities for new product managers to follow. Such models are clearly unrealistic: product innovation simply does not occur that way, and normative guides that do not recognize either the differences in processes or the overlapping nature of activities will probably meet with little success. (1983, 12)

Few analytical models embrace the complexity of the innovation process described by Cooper (Verworn & Herstatt 2000). This explains why this research uses the Fireworks innovation process model. The model was already successfully used in German literature to examine SOI cases (Fichter et al. 2007). It is depicted in Figure 1 (Van de Ven et al. 2000/1989).

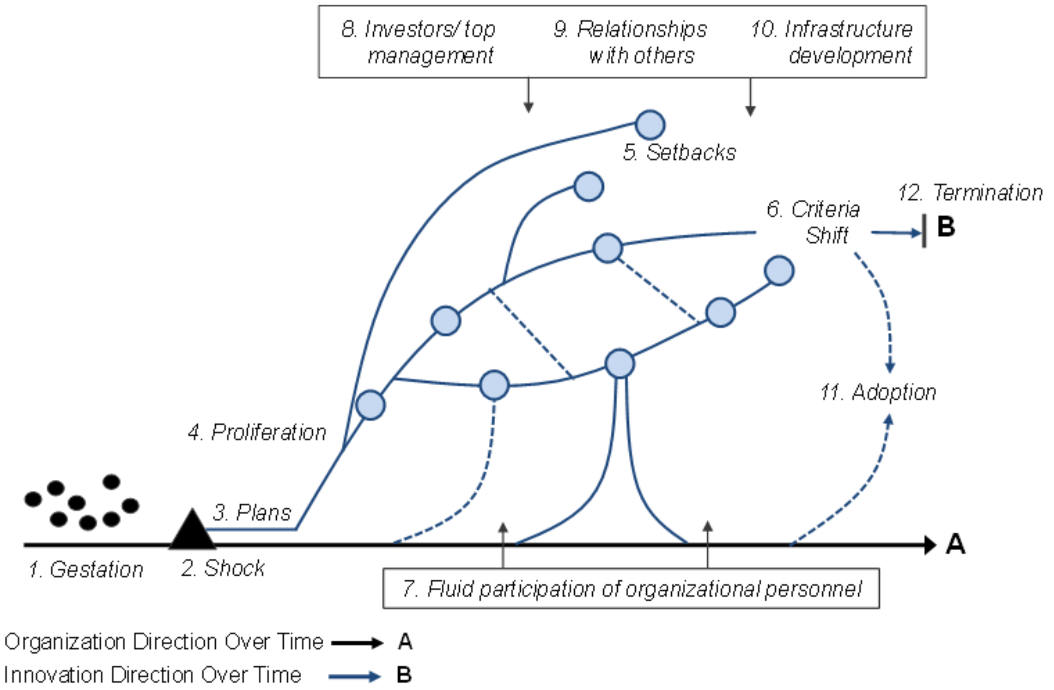


**Figure 1:** The Fireworks model (Van de Ven et al. 2000/1989)

The Fireworks model illustrates how multiple innovation paths emerge over time. It suggests that these innovation processes, taken together, form a journey that can be divided into four phases: initiation, development, implementation and termination. First, initiation is characterized by a long time period where ideas are in gestation and it is separated from the next phase by a shock. The shock signals to managers the urgency to develop (radical) innovations to guarantee the survival of the organization. The shock is followed by the second phase, development, characterized by the proliferation of new product ideas (different innovation paths). In the third phase, the innovation is adopted by the firm, in the best case leading to commercialization.

From a managerial perspective, the model captures

> the process of innovation [that] consists of motivating and coordinating people to develop and implement new ideas by engaging in transactions (or relationships) with others and making the adaptations needed to achieve desired outcomes within changing institutional and organizational contexts. (Van de Ven et al. 2000/1989, 9)

In the model, the paths (curved lines) represent the exploration of new business ideas. In the SOI case, each path typically relates to a new, different combination of technologies and markets. The paths are punctuated with activities that aim at exploring the viability of the innovation for the firm, and if viable, at developing a new product. Along each path, numerous small continuous changes happen (incremental innovations), whereas the emergence of a new path relates to a (radical) change in the exploration of technology-market area (Paper 4). In the most successful case, a path ends with the adoption of the innovation by the core business followed by its commercialization. However, as the literature indicates, by far not all paths lead to successes, which often alternate with failures (Van de Ven et al. 2000/1989; Maidique & Zirger 1985).

Even though this model already provides a detailed view that allows the complexity of innovation processes to be better understood, it does not enable the challenges that SMEs face when developing SOIs to be analyzed. Thus, an advancement of the model is needed, which was the goal of this PhD thesis. The next section will present the methodology used for developing the advanced Fireworks model.

## 4. Methodology

To advance the model, several papers were written that adopt different perspectives on the challenges that SMEs may face for developing SOIs. Table 1 provides an overview of the different papers and the challenges they address. The core findings of the individual papers are extracted and combined in light of the Fireworks model. As such, the approach is a meta-analysis of the key insights of the papers (Glass 1976) that were used to advance, complement, and enrich the original Fireworks model to better understand the SOI phenomenon. Thereby this research aims to answer the overarching research question of this PhD thesis.

**Table 1:** Overview of the papers used to develop the advanced Fireworks model

| Paper Nr. | Short title | Challenge for developing SOIs | Theoretical perspective |
|---|---|---|---|
| Paper 1 | Diversification through Green Innovations | Challenge 1: Dedicated exploration unit | Exploration & exploitation |
| Paper 2 | Clean Energy Storage Technology in the Making | Challenge 3: TIS investigation | TIS |
| Paper 3 | Structural Ambidexterity, Transition Processes, and Integration Trade-offs | Challenge 4: Innovation integration | Ambidexterity; focus on integration |
| Paper 4 | Green Technology Exploration: Anatomy of a Learning Journey | Challenge 2: Intelligent learning for efficient exploration | Organizational learning; Fireworks model |
| Paper 5 | Ambidexterity Management for Diversification through Green Innovation | Challenge 1: Dedicated exploration unit | Ambidexterity; focus on separation |
| Paper 6 | Exploration of Green Technologies in SMEs: the Role of Ambidexterity | Challenge 1: Dedicated exploration unit | Ambidexterity; focus on separation |

The individual papers feature case studies (Eisenhardt 1989; Yin 2014) that are centered on different aspects of the innovation process of a medium-sized entrepreneurial technology firm named TechLtd that set out to develop green technology innovation. Paper 1 (and supplementary papers 5 and 6) examines the innovation endeavor of TechLtd from an ambidexterity perspective, focusing on how a separation between old and new business can support innovation. Paper 4 features an embedded case of four innovation paths and examines the learning that took place on each path, as new paths were initiated and across all paths. Paper 2 examines the TIS related to the technology of one of the innovation paths: flywheel energy storage. Paper 3 examines the challenge of reintegrating an innovation into the core business for commercialization.

Papers 1, 3, 4, 5 and 6 are based on in-depth qualitative longitudinal process studies (Huber & Van de Ven 1995) of the innovation processes at TechLtd. An introduction to this firm and description of its innovation processes can be found in Papers 1 and 5. While Papers 1, 3, 5, and 6 study the overall innovation process, Paper 4 presents an embedded case study featuring four embedded case-studies corresponding to interrelated innovation paths focused on specific products and related technologies (fuel cells, small-wind turbines, flywheel energy storage and waste heat recovery).

For these papers, data was collected with a combination of retrospective and real-time approaches (Pettigrew 1990) covering a period of 15 years (2000-2015). The authors could observe the last three years (2013-2015) of the on-going innovation process, which allowed them to collect first hand insights into the process. Semi-structured interviews, focus group sessions, and internal documents were used to understand the innovation process and considerable research efforts were made to understand the external firm environment. Action research (Huxham & Vangen 2003) was also conducted and the author took the role of a facilitator in some of the innovation paths. For instance, a flywheel innovation workshop with current and potential partners of TechLtd was organized. The interview material was fully transcribed and data from site visits and participant observation was protocolled (Babbie 2013). The data was then analyzed and coded using software for qualitative data analysis (MAXQDA).

For Paper 2, a qualitative case study (Yin 2014) was developed using the theoretical lens of TIS (Bergek et al. 2008) to better understand how flywheel energy storage is developing and diffusing. Rich qualitative data was collected about the innovation system. A strategy of triangulation based on data from several sources was pursued (Babbie 2013), including semi-structured interviews, participant observation of a major industry workshop at the institute of the authors, various internal meetings with selected TIS actors (including TechLtd), and archival analysis. The data material was treated and analyzed with the same approach as the other papers.

Next section explains how these four advancements relate to the challenges for developing SOIs.

## 5. Advancement of the Fireworks model

This research advances the Fireworks model for the SOIs context with regard to four dimensions that relate to challenges 1-4 developed in section 2.3. Table 2 provides an overview of the four advancements and next sections explain them in detail: 1) how a dedicated organizational space for exploration is created and maintained over time, 2) how intelligent learning increases exploration efficiency, 3) how the TIS is investigated, and 4) how the innovation is reintegrated into the core business for commercialization. For each advancement, it is explained why it was necessary to advance the model in this direction, and how it was made, and the management challenges associated with these new, additional elements. The resulting advanced Fireworks model is then presented in section 5.5.

**Table 2:** Advancements of the Fireworks model in the context of green innovation

| Advancement characteristics | Fireworks model advancements | | | |
|---|---|---|---|---|
| | **1) Dedicated exploration unit** | **2) Intelligent learning for efficient exploration** | **3) Investigation of the technological innovation system (TIS)** | **4) Integration of the innovation into the core business** |
| Shortcomings in original model | Organizational structure is not considered | How the firm improves at exploration with organizational learning (OL) is not considered. | Relevant innovation processes in the firm environment are only considered in an abstract way. | Integration mechanisms supporting adoption by core business and adequate timing are only partly discussed. |
| Advancement description | Build in structural separation.<br>Organizational structures protect exploratory space from harmful core business influence (cross-contamination), while allowing it to draw resources from the core business (cross-fertilization).<br>Discuss the management of the exploration-exploitation interface over time to prevent it from becoming porous. | Add cognitive OL perspective<br>Reveals that firms become significantly better at exploration over time by moving from blind to intelligent trial-and-error exploration. | Build in the TIS perspective<br>TIS is used analyze the broader innovation dynamics with which the local innovation interacts. Helps firms identify and terminate unviable paths early on. | Build in integration mechanisms.<br>After organizational separation, innovation needs to be re-integrated into core business. Needed integration mechanisms, related trade-offs and integration timings are discussed. |
| Theory | Exploration and exploitation (March 1991); ambidexterity (O'Reilly & Tushman 2013) | Organizational learning (Argyris 1976; Crossan & Apaydin 2010) | TIS (Bergek et al. 2015) | Ambidexterity (integration perspective) (Gassmann et al. 2012 ; Paper 2) |
| SOI perspective | The strong difference in business logic between SOI and conventional core business calls for well managed organizational separation. | Rapid exploration is particularly important in sustainability markets, which are typically at early stage, have important political intervention, are rather volatile making them very dynamic and difficult to predict. | SOIs likely develop in the context of a TIS associated with large-scale socio-technical changes such as the energy transition. The dynamic of these TISs is complex and particularly difficult to predict , which calls for in-depth investigations. | Careful integration is particularly important for SOI because of their high cognitive distance to the core business, which increases the risks of core business rejection. |
| SME perspective | Challenging for SMEs because of resource constraints, multiple roles of managers, lack of management attention and ambidextrous mindset. | Essential for SMEs; developing an exploration proficiency allows resource-constrained SMEs to strengthen their behavioral advantage over larger firms. | Difficult to carry out because TIS investigations need important resources, but essential to strengthen SMEs' behavioral advantage. | SMEs may rush or neglect integration because of resource constraints and multiples roles of managers. |
| Time perspective | Beginning | During | During the journey; at the beginning of each innovation path | End |
| Management Implication | Setting up a dedicated, separated organizational unit can help protect exploratory innovation from the core business logic. The interface between old and new must be managed carefully over time. | Whereas it is unclear how to best manage exploration, increasing the return on learning can allow more rapid exploration, save resources, and ultimately increase the overall chances for future success. | Investigating the innovation processes taking place among firms and at the (nascent) industry level can help to understand if the innovation project is viable (and terminate early on if not) and how to make it successful. | Even though integration comes at the end, it must be carefully managed, as rushed and unplanned integration is an important source of innovation failure. Good timing and integration mechanisms can help manage integration. |

*5.1 Dedicated Exploration Unit*

The original Fireworks model considers innovation as emerging and proliferating from the core business without considering the organizational structure in which innovation happens. Organizational structures are important for innovation (Duncan 1976; Tushman & Nadler 1986) as they can be used to create a dedicated unit for exploration and thus provide it with independence, autonomy and, so to say, a safe space to unfold (Tushman & O'Reilly 1996). Based on a structural perspective on ambidexterity (Lavie et al. 2010), the original model is advanced by separating exploitation from exploration spaces.

Firms can create a dedicated exploration unit at the very beginning of the innovation journey (in Figure 2 : element Nr. 5 is added to the original model) (Paper 1). Whereas creating this space may appear simple, one difficulty resides in designing the interface between exploitation and exploration (Nr. 4). The interface needs to be permeable enough to allow for core business resources, competences and complementary assets to be used by the exploratory unit (cross-fertilization), while preventing harmful cognitive frames, worldviews and routines to cannibalize the exploratory space (cross-contamination; Nr. 17 and 18) (Paper 3). Overall, the two spaces need to complement each other in a value enhancing way (O'Reilly & Tushman 2008). Otherwise firms could simply decide to found an independent start-up with no connection at all to the existing business.

Once the unit is set up, the question is what organizational functions this unit should be equipped with (Nr. 6) (Paper 1). The short answer is that all functions needed for SOI development should be present. However, in many cases – and particularly in SMEs – resources may be constrained. Firms are therefore tempted to set up only a small unit, equipped with only the most necessary functions. Paper 1 argues that the chances for success increase when the size of the unit matches the scope of the exploration. The case study examined in this paper shows a firm that only equipped the new unit with an R&D function. This unit created blueprints for new products that were meant to be produced in the existing production facility and sold by the existing sales and marketing team. The lack of market exploration function in the unit strongly contributed to product failure. Indeed, the sales team tried to market the product using a maladapted marketing strategy, with the "old" knowledge on how to commercialize a product, whereas the product was actually for a new, unknown market. Given their scope, SOIs are more likely to need a large exploration space (with both R&D and S&M functions).

An important challenge for firms is to maintain the interface between the exploration and the exploitation unit over time, as discussed in Paper 5. Firms must maintain and carefully manage the interface over time (Nr. 4). This is particularly challenging for SMEs, who might be tempted to weaken the management of this interface and integrate the innovation too early into the core business (see also section 5.4) because maintaining the separation is very resource intensive (Paper 5). This separation drift (analyzed in Paper 5) is an important issue that can happen when the exploration-exploitation interface is not well-managed and is an important reason why structural separation may fail to protect exploration at some point of the innovation journey (O'Reilly & Tushman 2013). The case analyzed in Paper 5 explains that priorities shifted at the top management level, which forced the exploration manager to come up with a successful innovation before this was possible. Eventually, the product being developed was integrated into the core business with the belief that this would allow it to be brought to market and generate revenues, but in fact it stifled the innovation and contributed to its failure. The targeted use of linking mechanisms (Nr. 17) and their careful management can be a way to reduce erosion of the interface (see also section 5.4). Top management can for instance plan which employee will temporarily be switched to the exploration unit based on their understanding and support for SOI, instead of sending someone who is rather resistant to innovation (Paper 3).

For SOI, structural separation is particularly important because the cognitive distance (Taylor & Helfat 2009) between the old business and new SOI is high due the complexity that sustainability involves (Schaltegger et al. 2013a; Paper 3). Illustrative for this distance is that in some cases even a dedicated business model is developed (Boons & Lüdeke-Freund 2013) to bring the innovation to market, showing how strongly the business logic between the SOI and the existing core business may differ. Moreover, the mindset needed for SOI is quite different than what is common in more incrementally-based innovation at the core business (Hahn et al. 2016).

For SMEs, setting up dual structures for innovation can be very challenging, because they require more resources (Paper 1). In addition to the financial resources this involves, SMEs also often lack staff and are tempted to assign several roles to the same manager (Paper 6). This may be problematic if the same person has to manage tasks both in the explorative and the exploitative areas of the business. To be successful at this, the persons needs to develop an ambidextrous mindset (Gibson & Birkinshaw 2004). But experiences from practice show that this is not a skill that every manager has, hence also the challenge to find someone fitted to this task. Moreover, briefing these managers on their ambidextrous tasks requires significant top management attention, which is also very often scarce at SMEs.

### *5.2 Intelligent Learning for Efficient Exploration*

Based on the behavioral school of organizational learning (Cyert et al. 1963), the original Fireworks model takes a learning perspective that focuses on adaptation to new contexts (Van de Ven et al. 2008). Adaptation happens through trial-and-error learning. Knowing more about the nature of these learning processes may help to better manage the difficult innovation journey. With this objective in mind, the model was advanced with a cognitive learning perspective (Argyris & Schön 1978), allowing the study of single and double-loop learning processes. Beyond showing that firms learn many things about new technologies and markets (Nr. 8), this complementary perspective reveals two important learning processes.

First, the firm adjusts the size of the innovation space over time (Figure 2; Nr. 9) and becomes much better at estimating upfront if an innovation is viable or not. With each innovation path, a new combination of technology and market was explored (Paper 4). It is what the authors call the innovation space. What was observed in Paper 4 is that the case study firm started with a very ambitious green energy technology innovation that was far too big for the firm. Their innovation space was at first very large. The firm had the optimistic belief that almost every innovation was within their reach. Later, this space became much smaller, before finally adopting exactly the size that fitted the firm's (technical) competences, assets (such as the production facility), and resources. Discovering the real size of its innovation spaces – the range of possible innovations – took some time. Knowing this helped TechLtd to estimate quickly upfront if an innovation was realistic (Paper 4). This is very important as many exploration failures result from making the wrong decision: either in developing an innovation that is believed viable but in reality is not, causing an important loss of financial resources and time, or in not investing in a viable innovation, resulting in a missed opportunity (Van de Ven et al. 2000/1989).

In the SOI context, it is more difficult to make this estimation upfront. Indeed, the new technologies and markets that are explored are very different from what the firm is used to, hence the important of TIS investigation (Advancement 3). For instance, the TechLtd case shows phases of great enthusiasm and a strong belief in avant-garde technologies, even in very difficult market and regulatory contexts. In this phase, the innovation team was blinded by the general enthusiasm and did not realize that the innovation was too ambitious and would only yield financial returns in a distant timeframe (over 10 years).

Second, the cognitive learning perspective shows an evolution from a blind to intelligent trial-and-error exploration (Nr. 10) (Paper 4). The TechLtd case shows that the firm learned to explore a new innovation in fewer steps (from 12 to 5), with less time (from 8 to 4 years), and with significantly fewer financial resources (from about 3 million euros to half a million). In sum, it learned from this failure and learned to explore a new business idea with much less effort (Cannon & Edmondson 2005). This is very important as reducing the exploration duration also allows a saving of resources because an important part of the exploration costs is related to personnel. And, most importantly, being able to walk the innovation journey faster ultimately increases the chances for success. Being fast is especially important for SOIs characterized by significant uncertainty and unpredictable length. The unpredictable length may increase the risks that resources fade away towards the end of exploration, leaving no more resources for commercialization (Papers 4, 6). This finding shows that reducing the efforts needed for exploration through intelligent trial-and-error is essential to increase chances for success (Birkinshaw & Haas 2016). Thus along the innovation journey, achieving intelligent and efficient learning can be seen as important leverage in managing the development of SOIs.

Taken together, these two processes based on intelligent learning are important for understanding how exploration can be structured more efficiently. It appears that structuring the exploration process with smaller, distinct activities that are planned like experiments (Sitkin 1992; Weissbrod & Bocken 2017) to yield a high return on learning (Birkinshaw & Haas 2016) can be an important aspect of managing SOI processes and ultimately increasing the chances of success (Paper 4).

*5.3 TIS Investigation*

To analyze the broader firm-external innovation context, the original Fireworks model uses the social innovation framework (Van de Ven & Poole 1990), which covers essential aspects such as the institutional arrangement, resource endowment and market consumption but remains abstract on how these factors directly influence firm-internal innovation (Van de Ven et al. 2008, 126). To better account for the social system in which innovation is embedded (Granovetter 1985), the Fireworks model was advanced by including the technological innovation system (TIS) perspective (Bergek et al. 2008).

The TIS framework is mainly used to study the emergence of new technologies as a social process (Carlsson et al. 2002; Bergek et al. 2008; Foxon & Pearson 2008). Most of the time, a new technology is not developed by a single firm, but is the result of the interactions among a number of firms "running in packs" and multiple other actors (Mezias & Kuperman 2001). The TIS is composed of actors, networks, institutions and technologies that interact with each other (Carlsson & Stankiewicz 1991). Among these, important innovation processes are taking place that influence the course of the technology and its overall development dynamic. Research suggests that at least seven key processes (or functions) need to take place for a TIS to develop well (Carlsson et al. 2002; Bergek et al. 2008; Foxon & Pearson 2008). The TIS is a useful method where classical market analyses are not sufficient, that is to analyze early-stage SOI dynamics where market structure and rules are not yet in place (Paper 2).

TIS analysis is traditionally used to inform policy makers, but firms can also use it to investigate the dynamics of a new technology and assess its overall health (Figure 2; Nr. 15) (Paper 2). Each innovation path is related to a broader TIS. The firm needs to understand its dynamics in order to successfully develop innovation. Knowing the TIS dynamic can help in deciding whether to invest in an innovation or not. The TIS analysis should therefore be made early on in the innovation path before committing important resources. The analysis can for instance show that an innovation system is stagnant, as the flywheel energy storage system for the electricity grid that was stagnating because of several system weaknesses (Paper 2). In grid markets, flywheels were still far from commercialization even though the technology was almost mature. To TechLtd, this was seen as a warning signal that the innovation might not develop as rapidly as desired. On the other hand, a TIS with a positive dynamic driven by several motors of innovation (such as flywheels in the automotive sector) can indicate that the outlooks are good for investing in this innovation. In sum, investigating the TIS early on is important to understand the chances of innovation success and can reduce the risk of failure. Furthermore, it also provides very useful information on how to develop the innovation and what direction to give it (Paper 2), for instance by revealing product features demanded by the market or good marketing approaches.

Firm-level innovation processes can be related to the seven key functions of the TIS. At least two connections can be made (Nr. 15). First, the function "entrepreneurial experimentation" describes how firms that are part of a TIS experiment and gain practical knowledge about the technology. The firms examined in Paper 2 developed several different flywheels and tested their market response. Knowing that little experimentation has so far taken place, but that there are multiple possibilities to use this technology in several distinct markets, can indicate that there is still a lot of experimentation that needs to be done. Experimentation is related to high costs, which are particularly heavy for SMEs to bear. For TechLtd, this information was seen as warning signal that it would still take a lot of effort to successfully develop and commercialize a product. Furthermore, experimentation may show that a given innovation is not viable and that the path needs to be terminated (Nr. 13). Conversely, finding out that important collective TIS experimentation has taken place and that early markets are forming can be interpreted as a rather good signal. Indeed, in that case the firm will need to invest much less in finding a promising market since other actors have already done the work.

Second, the function “influence on the direction of search” relates to the exploration process of a new business. This function relates to the question whether new actors should enter the TIS and participate in technology development or not. Are they motivated to join in the collective development of this technology? What are the incentives or disincentives to do so? Or, are other competing technologies gaining so much traction that it is unlikely that the focal technology will develop at all? At the collective level, these questions are similar to the questions raised by a single firm.

For SOIs, investigating the dynamic of a TIS is very important. Indeed, they typically develop in volatile, early-stage market contexts. SOI such as the small-wind turbines analyzed in Paper 1 typically develop in emerging industries where the structure and rules are not yet formalized, which are rapidly evolving, and are subject to important (and sometime unpredictable) regulatory interventions (Negro et al. 2008; Luethi 2010). Moreover, the composition of these emerging industries can also be very volatile, with many firms joining and leaving the market (Paper 2). Furthermore, these developments often happen against the resistance of established industries, with incumbents actors that might oppose new actors aiming to develop products that might cannibalize their markets (Hockerts & Wüstenhagen 2010). These factors make the simple estimation of how attractive a new technology is much more difficult and thus justifies an in-depth analysis like the TIS investigation.

### *5.4 Innovation Integration*

When mature, the SOI needs to be integrated back into the core business for production and commercialization. Indeed, the exploratory unit is usually not equipped with the resources to commercialize an innovation (Durisin & Todorova 2012). The original Fireworks model considered that linking activities take place between the exploratory and exploitative spaces to gradually integrate the innovation and prepare for a smooth core business adoption (Schroeder et al. 2000/1989). Paper 3 reviews several new integration mechanisms that are discussed in the ambidexterity literature (Gassmann et al. 2012; Chen & Kannan-Narasimhan 2015) and brings them into a systematic integration framework. The Fireworks model is advanced by considering these other mechanisms used for integration, the associated management trade-offs, and the optimal timing for integration.

First**,** the literature discusses several new mechanisms that can support integration. Linking mechanisms can be set up early on (Figure 2; Nr. 17), as early as the creation of the exploratory unit. They can be used to manage the flow of information, routines, and assets that cross the exploration-exploitation interface (Nr. 4; section 5.1). Job rotation is an example of linking mechanisms that allows core business employees to carry out specific tasks in the exploration unit before returning to their initial job. Other mechanisms include social integration to increased informal connectedness between the units. A specific subset of linking mechanisms are complementary asset linking (Taylor & Helfat 2009) that allow the exploratory unit to access core business assets and competences. Next to linking mechanisms, integration mechanisms are used towards the end of the exploration phase. They include external validating, liaison channeling, showcasing innovation, and network building. For instance, Paper 6 shows that TechLtd's exploratory R&D manager presented its innovation at an important trade fair. He used the positive resonance to convince core business teams that this SOI will represent an important innovation for the future of the firm (showcasing innovation). Given the "radicalness" of SOIs, preparing the integration moment is very important to avoid core business teams being exposed too unexpectedly to a very new innovation as this could risk frustrating them, which could lead to core business rejection and innovation failure.

Second**,** these mechanisms are far from simple to implement because they necessarily involve a trade-off between increasing connectedness and decreasing autonomy of the exploration unit (Papers 3 and 5). These trade-offs must be carefully managed to avoid undesired effects that may jeopardize separation (and integration). Core complementary asset linking (Nr. 18) is a good example of trade-off management: while it can allow the exchange of competences between units, it bears the risk that harmful routines also migrate to the exploratory unit. Similarly, showcasing innovation can create legitimacy for the SOI, but as Paper 6 shows, if timed too early, it can also cause frustration in the core business team that was made enthusiastic about an innovation that turns out to be unviable. Another example is that using social connectedness early on can help core business employees to get used to SOIs and be less surprised when the actual integration happens. But, increased connectedness also bears the risks that the SOI never reaches maturity if the exploratory team feels too influenced by core business worldviews (cross-contamination). As Paper 3 shows, managing these mechanisms and the associated trade-offs can involve important top-management efforts as it must take time to brief (and possibly coach) involved employees about the necessity to work concurrently with two different business logics. For SMEs, managing these trade-offs is very challenging because of limited top management resources (Lubatkin 2006). Therefore, while integration is essential for success (Durisin & Todorova 2012), it always bears the risk of cross-contamination jeopardizing the pursuit of exploration and therefore must be carefully managed.

Third, the timing of the actual integration moment is very important. Premature integration (Nr. 20a) can significantly increase the risks that the core business rejects the innovation (Nr. 21b) (Paper 3). To prevent this, an innovation must first go through phases of incubation and acceleration. In the incubation phase, the SOI is matured into a business proposal, which is tested in the market with a prototype (O'Connor & DeMartino 2006). Subsequently, in a phase of acceleration the innovation is developed until "it can stand on its own" and some predictability in term of sales and operations becomes possible (O'Connor & DeMartino 2006, 491). Thus, to assure core business adoption (Nr. 21a), integration should only happen when the innovation is just about to become a mature product (Nr. 20b), i.e. just before sales increase. This means that integration happens at the critical moment of its lifecycle when it is gaining momentum. If it happens too early (premature integration; Nr. 20a), these two phases will happen in the core business, which may lead to the needed resources being denied because of lack of legitimacy, and thus may stifle the project. If it happens too late, or if core business integration is mismanaged, market introduction may be delayed, which can compromise its success too. This risk of premature integration is particularly high in SMEs because of the problem of resource scarcity, tempting them to integrate too early (see also separation drift under 5.1).

## *5.5 Overview of the Advanced Fireworks Model*

The advanced Fireworks model represents the emergence of multiple innovation paths over time and suggests that taken together they form a journey that is quite unpredictable, rather fuzzy and sometimes even chaotic. The model takes into account the latest knowledge on innovation process management. A detailed view is provided in Figure 2. This section presents the advanced model in a narrative of how the process of developing an SOI at an SME may be understood. The section is structured along the four SOI development challenges.

### 5.5.1 Challenge 1: Dedicated exploration unit

After the shock (Nr. 2 in Figure 2) and the more or less long orientation phase (Nr. 3), the firm may decide to create a new organization unit (Nr. 5) dedicated to developing radically different innovations from the core business (Papers 1, 5, 6). It can then equip this new unit with the necessary functions for developing innovations (Nr. 6), for instance an R&D lab and a marketing function. Once set up, several innovation paths (representing different new business ideas) may begin to proliferate (Nr. 7) and the innovation team develops the first innovations. At the same time, the team must carefully manage the interface with the core business (Nr. 4) to make sure that it effectively protects the emerging innovations and to avoid that it becomes porous or impermeable over time. Linking mechanisms (Nr. 17) are used to keep the new unit close to the core business, while preventing harmful routines from contaminating it. They are meant to facilitate cross-fertilization between the old and new units, but also bear the risk of cross-contamination. Therefore, managers must carefully weigh and manage the trade-offs they imply. To support innovation development, core business assets (Nr. 18) are made available to the new unit.

### 5.5.2 Challenge 2: Intelligent learning for efficient exploration

While these new paths are proliferating, important learning about new sustainable technologies and markets (Nr. 8) occurs (Paper 4). The firm also learns what a viable innovation means for its resource and competences bundle (Nr. 9). While some paths may inevitably fail (Nr. 11), other paths are initiated (Nr. 9). In this process, failures are considered as normal. In fact, they represent an important source of learning. Over time the firm gathers more experience that allows a very important type of learning: how to explore new business ideas as rapidly and as efficiently as possible (Nr. 10). This saves resources, reduces risks and increases overall chances for success. In sum, the firm develops some kind of a proficiency at exploration.

### 5.5.3 Challenge 3: TIS investigation

On top of managing the expectations of investors and top management (Nr. 14) and relationships with other stakeholders (Nr. 16), the innovation team examines the external innovation dynamic (TIS) related to each innovation (Nr. 15). Understanding the innovation system related to each local innovation (Paper 2) allows a firm to learn how to best develop this innovation – for instance to find out which product features are demanded in the market or what good commercialization approaches are – or terminate the innovation (Nr. 13) if the TIS dynamic seems unfavorable and thus the innovation unviable.

### 5.5.4 Challenge 4: Innovation integration

To prepare for integration in the core business for this new, very different innovation, several mechanisms are put in place (Nr. 19), for instance external validation or showcasing innovation (Paper 3). When the timing is right, the firm can integrate the innovation into the core business for production and commercialization. Integration should happen neither too early (Nr. 20a) nor too late. The innovation should be just mature (Nr. 20b), i.e. about when sales are picking up, to prevent the risk of core business rejection (Nr. 21b) and assure a smooth core business adoption (Nr. 21a). The exploration unit can then be either dissolved or, if further radical innovations are desired, maintained.

The next section discusses what this advanced Fireworks model means for our understanding of how SOI processes dynamically unfold at SMEs and how firms can effectively manage them.

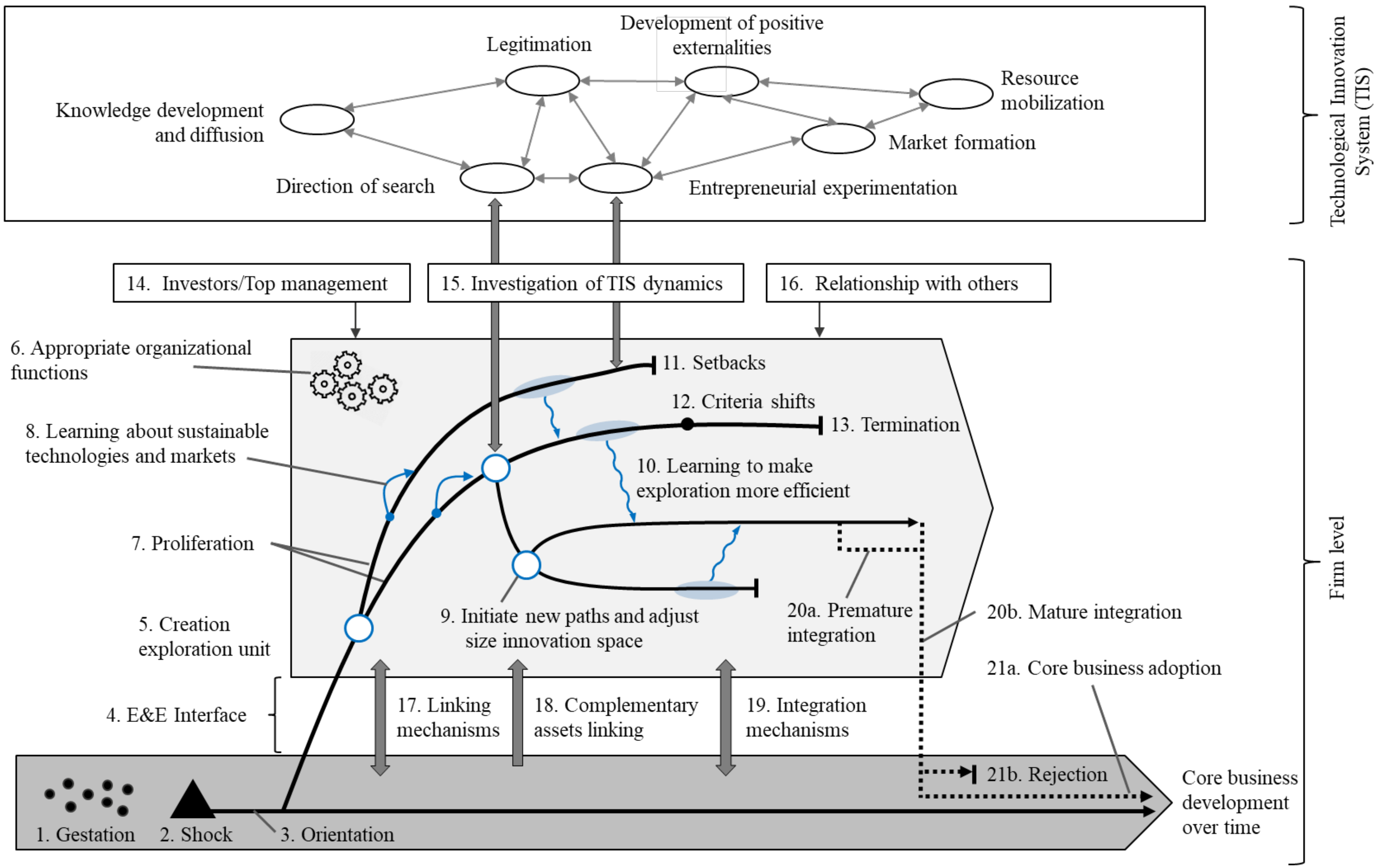


**Figure 2:** Detailed view of the advanced Fireworks model

# 6. Discussions and Contributions

*6.1 Conceptual SOI Development Model*

To show what the advanced Fireworks model means for SOI development at established firms, this section presents the conceptual SOI development model (Figure 3). This figure is an abstraction of the advanced Fireworks model (Figure 2) and the four challenges SMEs face (section 2.3). It suggests that SOI development happens alongside the core business. Once a dedicated organizational space is created, the Fireworks-like exploration of new sustainable business ideas happens. In the context of SOIs, the exploration of each new business idea relates to a TIS, which strongly influences innovation development. When the exploration leads to an innovation that becomes mature, it is reintegrated into the core business for commercialization. These four major dimensions of SOI development correspond to the four challenges introduced in section 2.3 and are discussed below.

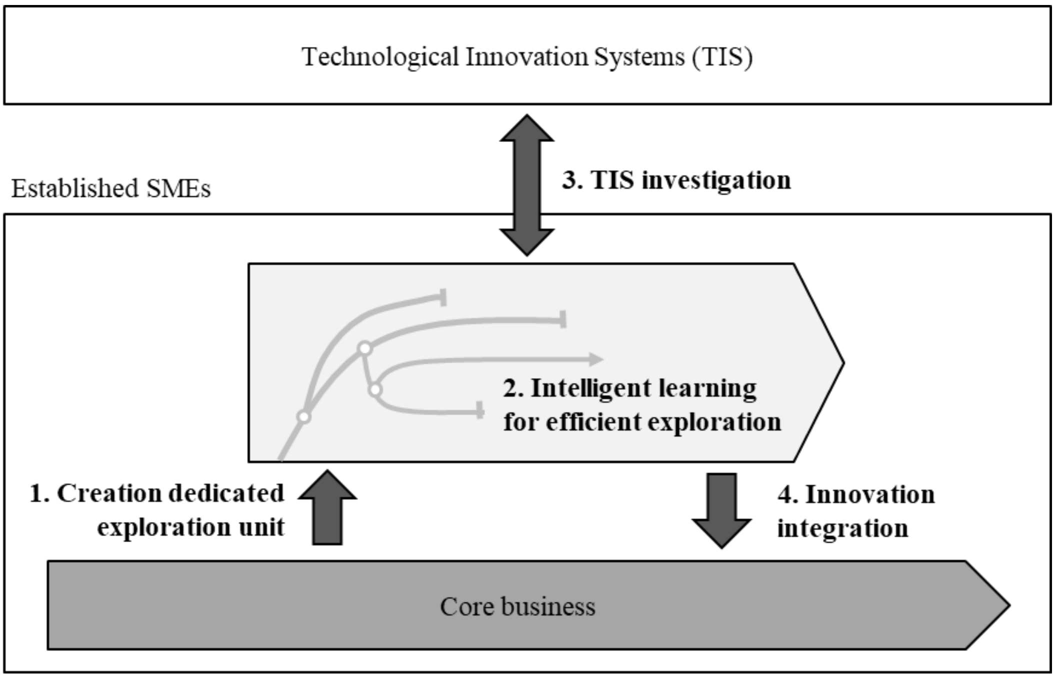


**Figure 3:** Conceptual SOI development model

### 6.1.1 First dimension: Creation of a dedicated exploration unit

To address the difficulty of both sustaining the "old" business while developing a "new" SOI, the model suggests that established firms may best locate SOI exploration in a dedicated organization unit. The advantage of separation is that it can protect the exploratory unit from harmful core business cognitive frames and routines (cross-contamination), while allowing it to draw resources from the core business (cross-fertilization). Once the dedicated unit is set up, the exploration of SOIs can "freely" take place in this new organizational space. After setting up the separated unit, the main challenge for the firm is to carefully manage the interface between old and new business units until the very end of the innovation journey, as it may erode over time and thus fail to protect the nascent innovation.

#### 6.1.2 Second dimension: Intelligent learning for efficient exploration

In this dedicated space, the Fireworks-like exploration of new business ideas is taking place. Since exploration involves an unpredictable trial-and-error process, some innovation paths will likely fail. Failed innovations are important and should not be considered as failures per se. Indeed, the learning outcomes generated allow improvement in exploration over time and hence develop an exploration proficiency that is crucial for navigating the innovation journey. Thus, while failed paths seem unavoidable, it is important for the management team to understand their value for the overall journey. Instead of seeing them as failures, management can accept them and focus on learning as intelligently as possible by designing exploration activities that yield a high return on learning. Intelligent learning can accelerate exploration, reduce costs, and ultimate increase chances for success.

#### 6.1.3 Third dimension: TIS investigation

Understanding the external innovation processes of emerging new technologies and markets is particularly difficult at an early stage because their evolution is highly dynamic and their course difficult to predict. This investigation is however very important for SOIs that are strongly influenced by the dynamic of the TIS they a part of. Firms benefit from investigating the TIS related to each local innovation early on the innovation path. Indeed, beyond gaining vital information, it also allows the firm to estimate how well the technology is developing and how healthy the overall innovation system is. Knowing this, allows firms to make investment decisions or to terminate unviable SOI projects early on and thus save valuable time and resources.

#### 6.1.4 Fourth dimension: Innovation integration

The mature innovation is integrated back into the core business for production and commercialization. Firms can use several mechanisms to facilitate integration. Integration mechanisms are particularly important for SOIs because of their high cognitive distance to the core business. While typically neglected because it comes at the end of the innovation journey, firms must pay close attention to preparing for and organizing the integration moment. If this moment is not well managed, the innovation risks rejection from the core business, which may deny it resources and jeopardize commercialization. Timing is very important, for instance as a rushed integration is typically a source of failure. Integration mechanisms can help, but they are associated with trade-offs, as they may also involuntarily facilitate cross-contamination. Therefore, firms must carefully manage these trade-offs.

*6.2 Contribution to Research*

This research contributes to the literature by explaining how SOIs are developed. Indeed, whereas the literature abundantly discusses *what* SOIs are and *why* firms develop them (Klewitz & Hansen 2014; Adams et al. 2016), much less is known about *how* firms develop SOIs (Hall 2002; van Kleef & Roome 2007; Zollo et al. 2013). This research does so in two ways: first by examining the extreme case of a very radical SOI that ultimately failed, and second, based on this case, by introducing a model to study SOI development in established firms.

First, the empirical case-study presented is centered on an established SME with a proactive sustainability strategy (Aragón-Correa et al. 2008) , using its core-competences to develop SOIs with new technologies for new emerging markets (Hart et al. 2003). This kind of innovation endeavor involves a very high degree of novelty for the firm and can therefore represents an extreme case (Yin 2014). A metaphor might illustrate the difficulty of such an endeavor. We could say that this firm invited a young and very ambitious green David to develop innovative green technologies in its house, where a powerful and successful Goliath lives (Hockerts & Wüstenhagen 2010), without having any prior experience in having such guests, with very few resources to accommodate him, and while trying to avoid peace being jeopardized in the house. In the case study, the endeavor unfortunately failed, but this provided an opportunity to study the hurdles along the journey. Such an analysis of a failed innovation case is unique in the extant literature, and of interest for illustrating the challenges firms may face, and for further theory building.

Second, the extreme case allowed an advancement of the Fireworks innovation process model developed by Van de Ven et al. (2008) in the context of SOIs. For several years this model has already strongly influenced the innovation research community, the model as such has not often been applied (Van de Ven 2016). The value of this model is that it allows a detailed study of how innovation processes emerge over time, without reducing their complexity, especially with regard to the multiple factors that influence the course of the innovation. It is the only innovation process model allowing this level of complexity, according to Verworn & Herstatt (2002). The original model allows the study of some aspects of SOI development. However, it was necessary to advance it in order to take SOI specificities into account. In particular, adding the TIS level is essential for understanding SOI development (Markard & Truffer 2008). For established firms an important aspect is to take into account that it may be the first time they are undertaking an exploration in many years. This aspect and the related (often lacking) exploration proficiency is important to understand why it is so difficult for established firms to develop SOIs (Adams et al. 2016). Finally, since the original model was developed, research has progressed significantly and the essential – now well-known – notion of ambidexterity was missing in the model (Hahn et al. 2016).

Beyond having a new model to study how SOIs dynamically unfold, the value of the advanced Fireworks model lies in its openness with regard to other innovation concepts. While very detailed, it still remains holistic in nature. In a way it is a “meta-model” that allows the combination and linking of other models and concepts (such as linking industry and firm-level innovation processes; Markard & Truffer 2008). This characteristic provides a common basis for studying SOI processes from a multitude of perspectives. Whereas this research advances the model in four directions, section 6.4 provides several other directions for further advancements. In conclusion, this model represents an important step forward in the SOI literature as it offers a common ground for studying how SOIs emerge.

The next subsections discuss the contribution of the advanced Fireworks model with a focus on the SOI and the SME literature.

### *6.2.1 SOI literature focus*

The advanced Fireworks model has several implications on the way SOIs are researched and studied. First, it shows the importance of time in studying how SOIs unfold. Time came up as an important additional parameter throughout the analysis. Even though it plays an important role, the time dimension is often neglected in the analysis of organizational phenomena (Ancona et al. 2001; Langley et al. 2013), also in the context of innovation processes (Garud et al. 2013). The advanced model shows that this dimension is also important for SOI processes. The idea of time zones (Nadkarni & Chen 2014) and synchronization (Halbesleben et al. 2003) between zones can help to illustrate the temporal complexity of SOIs processes. The TechLtd case shows that different time zones are involved in the process. They can be seen in Figure 3: the core business, the exploration unit, and the multiple TIS. These zones are associated with different time cultures, paces and rhythms (Sonnentag 2012). These different time zones represent an important challenge as time must be synchronized between them. For instance, one of the innovation paths examined in Papers 1 and 5 failed because market introduction occurred too late and the product was rejected by the market, even though the innovation team perceived the market launch as too early. From a temporal perspective, this market rejection can be explained by a lack of consideration of the two different time zones. The management did not pay sufficient attention to this dimension and failed to create entrainment between the exploration unit and the TIS. Thus, this research reveals the important role time plays in the development of SOIs and shows that it should be considered more explicitly in future research of SOI development.

Second, it shows that the SOI literature can be further enriched by drawing on the existing conventional innovation literature. Not only is the original model from the conventional literature, the theoretical elements used to advance it are as well. In the SOI literature, links to the conventional literature are not always made, and where they are, often not explicitly. In this sense, the advanced model can be helpful for future sustainability researchers to identify links to other disciplines. Specifically, the model brings knowledge of innovation processes, exploration and exploitation, ambidexterity, organizational learning, and technological innovation system together (see Table 2). While some authors follow this integrative approach – such as the recent publication by Hahn et al. (2016) that conceptually shows how essential for green innovation success it is for managers to have an ambidextrous mindset – this is rather rare in the extant SOI literature. Therefore, this research encourages other researchers to further explore the conventional innovation literature to find knowledge or theories helpful to explaining SOI phenomena.

Third, the advanced model can also be used to analyze the development of other type of SOIs. The literature review reveals that among SOIs several types can be distinguished: non-technological/technological, SOIs as products, services, organizational innovation and business models. The model can be used to study non-technological SOIs (i.e. where new technologies do not play a central role) as products. However, advancement 3 (investigation of the TIS) largely focuses on new technologies, and it encourages future research to first examine to what extent TIS could also be applied to non-technological innovations. Other non-technological innovation-system perspectives may be preferred (Carlsson et al. 2002). Similarly, the model can also be used to study SOIs as services, especially if they include a strong technological component, such as IT-related services. Then, the model can possibly also be used with new business models, in particular if related to new technologies. Indeed, the development of new business models in an existing firm will likely happen in a structurally separated space (advancements 1 and 4) and need important experimentation (advancement 2). However, the model is less adapted to study the improvement of existing processes and incremental adaptations of the business model.

### *6.2.2 SME literature focus*

This research shows that beyond top management commitment (Jenkins 2009; Bos-Brouwers 2010), top managers need a long-term vision and an ambidextrous mindset to successfully develop SOIs. Indeed, engaging in SOI is an important strategic decision that implies that top management fully understands the need of exploration for long-term survival. Whereas this may sound trivial, it is not. Many firms never enter explorative phases and ultimately fail because they did not adapt to evolutions in the firm environment (March 1991). I concur with Hahn et al. (2016), who discusses ambidexterity in the context of corporate social performance, that dual structures for innovation play an important role in successful SOIs. But here again, it is not a given that SME managers use the paradoxical thinking required for ambidexterity (Andriopoulos & Lewis 2010). Hence, the research suggests that the two conditions for successful SOI development at established SMEs are that top management thinks long-term and that it is capable of ambidextrous thinking.

To be effective, ambidexterity demands significant resources that are often scarce at SMEs (Welsh & White 1981). Papers 3 and 5 argue that this lack of resources can to some extent be compensated by a more sophisticated mode of ambidexterity (using a combination of modes of separation; Lavie et al. 2010). However, more sophisticated forms of ambidexterity increase the difficulty to manage the exploration and exploitation interface (O'Reilly & Tushman 2013) and thus requires more management attention. At SMEs, management attention is also a scarce resource, as their financial constraints prevent them from hiring additional managers (Nooteboom 1994). Therefore, while ambidexterity supports SOI development, the resources it demands to be effective are problematic for SMEs.

Following this observation, an important question is how this resource bottleneck can be overcome. Whereas this problem has been abundantly discussed in the literature (Welsh & White 1981), this research suggests two approaches to handle this bottleneck. First, the advanced model suggests that specialization on some innovation tasks and a division of tasks in networks may be a way forward. Several open innovation approaches (Gassmann 2006) are discussed in the literature: focusing on only one part of the innovation process (for instance outsourcing the first of three phases – discovery, incubation or acceleration – considered by O'Connor & DeMartino 2006), making use of an "informal network of external contractors to generate and develop wild ideas and inventions" (O'Connor & DeMartino 2006, 490), using partnerships to balance exploration and exploitation for instance by outsourcing R&D, or working with "communities" to develop new business, suggesting that entrepreneurs share exploration among several firms (Fichter 2009; Garud et al. 2013). However, Spithoven et al. (2013) warns that opening parts of the innovation process at SMEs does not necessarily solve the resource bottleneck, as it requires more networking, which is resource intensive too. Future research could examine extending such open innovation approaches are possibly helpful for developing SOIs at established firms. Even though it does not entirely solve the problem, this approach represents an interesting direction for further research.

Second, since specialization does not allow firms to overcome the resource bottleneck, a second approach could be to introduce proper techniques to manage this radical, exploratory innovation journey. Introducing management tools may help reduce the complexity of this exploration and thus increase the chances for success, even though so far few management tools exist for the early phases of an innovation journey (Gassmann & Schweitzer 2014). It will nevertheless be the role of top managers to handle the many underlying paradoxes (Andriopoulos & Lewis 2010; Paper 3), the overall uncertainty, and especially how to allocate their management attention. This situation cannot be removed from the shoulders of the manager. However, by using management techniques and building on their personal strengths, owners and managers can possibly help navigate SOI development and increase the chances for success.

Finally, the advanced model can also be used to analyze innovation development at other types of SMEs. As SMEs represent a very heterogeneous group of firms, it is worth discussing for what other kinds of SME it may apply. First, it applies to the group of SMEs with a pro-active sustainability strategy. Indeed, it was explicitly developed to study the emergence of radical SOIs that have sustainability at the core of the firm and therefore require top management commitment. These firms most probably already have sustainability values (Jenkins 2009; Seidel et al. 2018) and are possibly quite advanced on their sustainability journey (Boons 2009). Second, the advanced model applies to the group of established SMEs. Indeed, start-ups of firms founded with a green mission will likely be confronted with other challenges (Hockerts & Wüstenhagen 2010). However, it may also apply to a well-established entrepreneurial venture units of large firms that operate like SMEs. Third, when it comes to firm size, the model also applies to larger SMEs. Indeed, the literature suggests that in small firms sustainability is primarily embodied by the psychological characteristics of the entrepreneur or the owner-manager (Jenkins 2009).

*6.3 Contribution to Management Practice*

This research contributes to practice by providing a management heuristic for SOI development at established SMEs. When developing SOIs, most firms will encounter the challenges discussed throughout this paper. The management solutions presented in this research study allow the development of a management heuristic in four phases. The first aim of this heuristic is to raise the awareness of managers that these challenges will likely occur. Awareness is arguably the first step towards managing these challenges. The second aim is to tell managers that we have now some solutions to manage SOI development. Indeed, several management practices are available to manage SOI development and to provide an approach to handle the complexity involved. Therefore, the heuristic applies primarily to the development of radical or “complex” SOIs. It is not adapted to incremental innovation, which likely need less learning, investigation of unknown TIS, and structural separation.

The management heuristic is based on the four phases of the SOI development cycle and is illustrated in Figure 4. This cycle is started again every time a new SOI is developed. The four phases relate to the management challenges identified in section 2.3 and covers (chronologically) the good practices associated with the innovation dynamic studied. For each phase, a specific management focus and recommendations are provided. The focus is intended to attract the managers’ attention to the most important challenge of this phase. The recommendation provides a practical approach to managing the innovation dynamics at play and avoiding some of the known pitfalls. The phases are represented in a cycle and can overlap, particularly phases 2 and 3. Phase 3 is repeated at the beginning of each innovation explored in phase 2. Unlike stage gate models, the phases are not separated by gates. The passage from one phase to the next is signaled by the fact that either the task is completed, the innovation dynamic changes, or sufficient learning took place so that the focus can shift to the next phase.

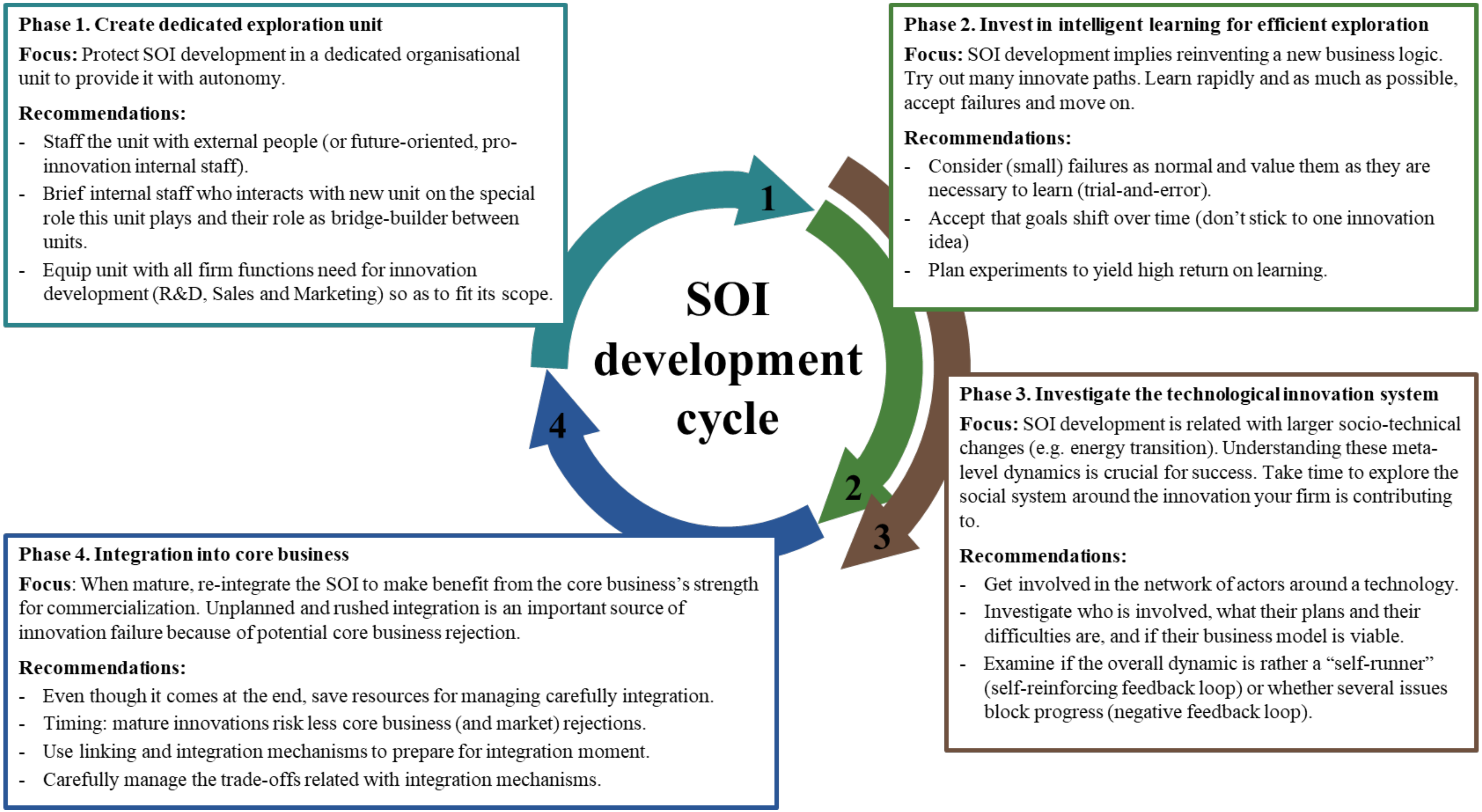


**Figure 4:** The SOI development cycle: a management heuristic for SOI development at SMEs

*6.4 Limitation and Future Research*

The main limitation of this research is that the advanced model is the result of an exploratory research process and needs further empirical testing. The model was developed thanks to four papers featuring the case of a single firm and one paper featuring a TIS analysis related to one innovation path at that firm. Even though abductive research methods were used for theory building (using rich empirical material and knowledge of the extant literature), this research is still exploratory and would need to be tested in a larger empirical analysis involving more firms. Beyond testing it with similar cases, the model should also be tested with other innovation types (non-technological, service, administrative or business model innovation) and other firms (larger, smaller, in other sectors).

Whereas in section 6.2 it is argued that the advanced model can be used as a meta-model for further researching how SOIs unfold, this model also has important weaknesses. Because it is very detailed and does not reduce complexity, it requires in-depth data about the innovation processes studied, which is sometimes difficult to obtain. Furthermore, using this model is relatively time consuming and therefore may be difficult to apply in many research settings.

The advanced model could be further developed in at least two directions. First, the literature stresses the importance of networks for the development of SOI (Clarke & Roome 1995; Adams et al. 2016). Networks are one way to access new information and learn about new technologies and markets (Jones & Macpherson 2006). Another reason why they are needed is to obtain support in the development of SOIs, for instance through intermediaries offering various support methods such as “handholding” processes with local authorities (Klewitz et al. 2012). Networking is part of the original Fireworks model (Figure 1 Nr. 9 “Relationship with others”), but remains vague and networking processes that are known to be supportive for SOI development (such as intermediaries) are not addressed. Furthermore, several networking activities overlap with the newly added process Nr. 14 “Investigation of the TIS”. Therefore, future research should focus more closely on the networking process, add networking processes known to be supportive for SOI, and clarify the distinction between networking and TIS investigation.

Second, a very promising avenue for future research is to combine the advanced Fireworks model with the TIS perspective. In this research study the TIS perspective was integrated in the model as a way to gain information. However, we know from the TIS literature that firms actively co-shape a TIS (Bergek et al. 2015). This means that firms not only learn from the TIS, but also influence it and shape its trajectory. The processes involved in co-shaping the TIS are not considered in this research. Links are only drawn between learning processes (internal perspective) and TIS functions, i.e. the direction of search and entrepreneurial experimentation. A possible way forward is to further explore the idea that each internal innovation path is associated with the trajectory of a TIS and systematically link firm-level innovation processes with TIS processes to understand how they influence each other. Given the important body of knowledge on TIS processes (Jacobsson & Bergek 2011), combining the two perspectives would further enrich our understanding of the role macro-level TIS dynamics play in firm-level innovation processes. Conversely, for TIS research it would increase our understanding of the role of firm-internal innovation processes in the emergence of TIS (see for instance Smink et al. 2015 or Pohl & Yarime 2012).

## 7. Concluding Remarks

Whereas research has already stressed the importance for firms to join efforts to reduce environmental impact (Whiteman et al. 2013), this PhD thesis explores how firms can embark on their own innovation journey for sustainability. It does so by featuring an extreme case of a radical SOI that unfolded at an SME over a period of almost 15 years and ultimately failed. The findings show that SOIs unfold in an emergent, somewhat chaotic way, that the duration and outcome of the process are uncertain. The overall journey is composed of multiple intertwined innovation paths, of which several will likely lead to setbacks. The findings have allowed an advancement of the Fireworks innovation process model in the SOI context and thus improve our understanding of how SOI processes dynamically unfold at SMEs and how they can be effectively managed. It was advanced in four directions: first by adding a separation between the core business and the exploration unit, second by showing that intelligent learning happens in this exploration unit that leads the firm over time to develop a proficiency for exploring unknown business areas, third by including the external innovation system into the model, and finally by adding integration mechanisms for the mature SOI into the core business for commercialization. This research contributes to the SOI literature by advancing the Fireworks model and thereby by proposing a first model of how SOIs dynamically unfold. The model is both holistic and detailed, which opens several avenues for future research. The research contributes to management practice by proposing a heuristic to manage SOI development at SMEs.

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## Annex

# Paper 1

Diversification through green innovations: Lessons learned from a German engineering firm

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SCHWERPUNKTTHEMA

# Diversification through green innovations

## Lessons learned from a German engineering firm

**Samuel Wicki**



Samuel Wicki

**Abstract** Established conventional firms increasingly aim to seize business opportunities in emerging sustainability-related markets. They can do so by developing innovations based on their core competences, for instance in the context of a strategic diversification. While the development of green innovations can open new business opportunities, many firms struggle with seizing opportunities in unknown product-market domains. Yet little is known about how firms actually develop green innovations and what challenges they face. This paper presents the anatomy of a "failed" innovation process of a German engineering firm to shed light on the management challenges of developing green innovations in the context of diversification. The paper draws the attention to five major management challenges: (1) the adoption of an exploration strategy that matches the degree and scope of an innovation, (2) the set-up of appropriate organizational structures to separate old from new business, (3) the value of extensive networking and partnerships to access and acquire distant information, (4) the benefits of an entrepreneurial approach to uncertainty involving quick learning and (5) the advantages of business model innovation to widen the innovation space.

**Zusammenfassung** Vermehrt versuchen auch etablierte Unternehmen Chancen zu nutzen, die sich in entwickelnden Nachhaltigkeitsmärkten bieten. Unternehmen können diese unter anderem ergreifen, indem sie auf Basis ihrer Kernkompetenzen Innovationen zur strategischen Diversifizierung entwickeln. Obwohl die Entwicklung grüner Innovationen neue Geschäftschancen eröffnen kann, haben viele Unternehmen Schwierigkeiten die Chancen in unbekannten Produkt-Markt Umfeldern zu ergreifen. Jedoch ist bisher wenig über die Entwicklung und den Erfolg-, oder Misserfolg, solcher Explorationsvorhabens bekannt. Der vorliegende Artikel analysiert einen „gescheiterten" Innovationsprozess bei einem Unternehmen und präsentiert fünf zentrale Herausforderungen für das Management von nachhaltigkeitsorientierten Innovationen: 1) die Wahl einer Explorationsstrategie die dem des Innovationsgrades entspricht, damit die Innovation genügend Raum zur Entfaltung bekommt, 2) das Schaffen geeigneter Organisationsstrukturen, um Innovationsprozesse vom Kerngeschäft zu trennen, 3) die Bedeutung Netzwerke und Partnerschaften für neues Wissen aufzubauen, 4) die Nützlichkeit von unternehmerischem Denken und Handeln basierend auf schnellem Lernen, um Entscheidungen in Situationen der Unsicherheit zu treffen und 5) der Vorteil von Geschäftsmodellinnovationen, um den Innovationsspielraum zu erweitern.

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## Introduction

Established conventional firms increasingly aim to seize business opportunities in emerging sustainability-related markets, such as the one for renewable energy technologies (Schaltegger and Wagner 2011; Hockerts and Wüstenhagen 2010). They can do so by developing innovations based on their core competences, for instance in the context of a strategic diversification. Sustainability-oriented (also referred to as green) innovations are product, service, process and business model innovations that lead to environmental and/or social benefits (Hall and Martin 2005; Seebode et al. 2012; Klewitz and Hansen 2014; Schaltegger et al. 2012). Small and medium-sized enterprises (SME), standing out through their creativity, innovativeness and ability to swiftly adapt to new market contexts (Rothwell 1989; Nooteboom 1994), can likely benefit from a diversification through green innovations. Doing so, mature, well established firms can successfully combine competitive advantages with sustainable development (Delmas et al. 2011).

However, while the development of green innovations can open new business opportunities (Strebel 2009; Schaltegger et al. 2012), firms are typically seen to struggle with exploring new options and expanding their activities beyond the familiar product-market domain (Tushman and O'Reilly 1996). This is even more relevant for green innovations, which involve additional uncertainties (Fichter et al. 2005) and are therefore even more risky than conventional product-market innovations. Therefore, it might appear counter-intuitive to pursue a diversification strategy, which primarily intends firm growth and risk mitigation through product-market portfolio expansion (Ansoff 1957). However, firms are challenged to innovate for long-term survival (March 1991; O'Reilly and Tushman 2013). Furthermore, sustainability is increasingly seen as a driver for innovation and many sustainability-minded entrepreneurs are engaging in the development of green innovations (Seebode et al. 2012; Klewitz and Hansen 2014). Nevertheless, little is known about the way firms actually develop green innovations and navigate highly uncertain business environments. This paper therefore aims to increase our understanding of the management challenges a diversification through green innovations entails.

This paper presents the anatomy of an innovation process to shed light on the management challenges of developing green innovations in the context of diversification. It analyses the case of a German engineering firm in the industrial machine market, which decided to leverage its core competences by developing products for the emerging renewable energy technology market. Whereas many papers examine successful innovation processes, little deal with "failures". Drawing on such a case, this analysis provides insights into five essential management challenges that an innovator for sustainability might encounter.

The remainder of this paper is structured as follows: the next section briefly summarizes the extant literature. Section three presents the methodology applied. The case study is presented in Section four and Section five discusses the lessons learned. Section six concludes the paper.

## 1 Literature

A diversification strategy is pursued to achieve firm growth and to spread risks across the company's product-market portfolio (Sullivan and Sheffrin 2003). Diversification is thought of as a new product or market development. As product development, it involves the expansion of the product or service portfolio or as an integration of the value chain. As market development, it involves the search of new markets for existing products or services. A full diversification involves the development of both new products for new markets (Ansoff 1957). Diversification to enter an entirely new business area is called a full diversification.

In the context of emerging sustainability markets, firms could apply their core competences to develop new products and services to serve these. Innovations for these markets are referred to as green innovations and may include new processes, products, services, or business models. Additionally, they can either be technological, non-technological or both (Noci and Verganti 1999; Seebode et al. 2012; Klewitz and Hansen 2014). Since they aim to integrate all three dimensions of sustainability, such innovations not solely have a commercial purpose, but explicitly intend to reduce negative or increase positive impacts on the environment and society (Hansen et al. 2009). In contrast to conventional innovations, they are characterized by important uncertainties (Fichter and Paech 2003; Paech 2005), as they often embed new and unknown sustainability-related aspects in design and production. Additionally, their target market is new and mostly unknown to established firms. In general, emerging sustainability markets are often volatile, rapidly evolving, segmented little and commonly subject to state intervention (Luethi 2010). All these factors increase the uncertainty related to the pursuit of green innovations. However, as firms are seeking to secure legitimacy in the face of changing political and regulatory environments, growing stakeholder pressure or due to changed managerial mindsets, green innovations are gaining attention in research and in an increasing range of industries (Holmes and Smart 2009; Schiederig et al. 2012; Schaltegger and Hörisch 2015).

An important challenge that established firms face when developing green innovations is the need to deal both with sustaining the old, conventional business while at the same time developing the new, 'green' business. Sometimes old and new may contradict or even cannibalize each other (March 1991). They typically face a challenge known as the exploitation-exploration paradox. Exploitation is associated with performance and efficient utilization of known technologies and exploration aims at the discovery of new possibilities (Raisch 2008; O'Reilly and Tushman 2013). An illustrative example of this challenge is car sharing: the automobile company Daimler AG, renowned for producing and selling premium cars, created the company Car2Go for introducing an innovative and environmentally-friendly car sharing service, which contradicts the car sales business (Firnkorn and Müller 2011). Those firms are facing the challenge that the new green business may require a very different logic. Therefore, firms need to develop management approaches that can combine two possibly contradictory business logics without negatively affecting each other (Raisch 2008). Several approaches are discussed in the literature to separate the exploitative from the explorative business to create an innovation space within the firm that allows exploratory innovative processes to thrive. Those approaches primarily rely on forms of organizational or temporal separation (see Lavie et al. 2010 and O'Reilly and Tushman 2013 for an overview).

## 2 Research method

The innovation process approach was used to analyze in detail the development of the sustainability-oriented innovation process in the company, while the conventional core business continued (Huber and Van de Ven 1995; Van de Ven et al. 2008). The approach implies that an innovation is seen as a process that can be studied over time. The analysis covers several organizational levels (top management, business lines, and individuals), value chain functions (research & development, production and sales & marketing) and organizational boundaries (intra-organizational and inter-organizational through alliances). Data was collected with 17 semi-structured interviews (across organizational levels and boundaries) in 2013–2014 which were subsequently transcribed, coded, and analyzed (Yin 2014). Additional information was obtained through participant-observation of 16 top and middle management meetings. The trustworthiness of the analysis was assured by a triangulation of the data and informants, multiple investigators, rich description, consideration of alternative explanations and validation by top-management (Shenton 2004).

## 3 Anatomy of an innovation process

This paper examines a medium-sized German engineering firm (hereafter referred to as SteeringCo) that is operating in a business-to-business market. Over the past 50 years, it has accumulated extensive knowledge in the control and steering of high-speed engines and generators. Today, SteeringCo is a global market leader and is representative for the German 'Mittelstand'. Top-management, knowing that new, path-breaking technologies might disrupt in the near future its main market segment (representing 80 % of sales), recognized the urgency for strategic diversification. Inspired by their intrinsic motivation for sustainability, top-management searched for new applications for its core competence and found one in the emerging market for renewable energy technologies (RET). A new business line dedicated to the exploration and development technologies related to the feed-in of renewable energy into the power grid was created. The first new product was an electricity inverter transforming the electric output of small wind turbines to requirements of the grid. After several years of experimentation to sell the invert, the new product was eventually withdrawn from the market because sales numbers did not match top-management's expectations. In the following the innovation and market introduction will be examined in detail in four phases.

### 3.1 Phase 1: Technological exploration for new applications

Early 2003, top management employed an external engineer as head of the new feed-in business line. By searching for synergies with the existing core competences, the exploration aimed at finding applications in the area of 'rotation-based' renewable energy technologies, mostly different forms of turbines. Under the lead of the new unit head, several options were explored (Table 1). Among these networking activities, collaborations with universities were also initiated. In this context SteeringCo came to work with an engineering-minded university spin-off. Besides knowledge in decentralized energy production, this start-up (in the following referred to as 'WindEnergy') had gained knowledge about the small wind turbine technology and markets. However, it lacked production and commercial capabilities. Given their complementary expertise and assets, SteeringCo saw an opportunity to collaborate with WindEnergy. Negotiating the nature of possible collaborations, they eventually decided to jointly develop an inverter with a control system for small wind turbines, which seemed to be technically close to SteeringCo's core competences.

Early 2000, small wind turbines were an emerging niche market with globally around 300 manufacturers (BWE 2011; Gsänger 2013). At that time approximately 30 firms manufactured small wind turbines in Germany, with a typical turbine size below 100 kilowatt (BWE 2010). The total installed capacity represented less than 100 MW (Brück 2013). Even though the markets had been developing rather

**Tab. 1** Activities and knowledge development along the four innovation process phases

| Phase 1: Technological exploration for new applications (2003–2005) | Phase 2: Product design and development (2006–2008) | Phase 3: Market introduction (2009–2012) | Phase 4: Termination (2013) |
|---|---|---|---|
| • Top-management hire external head of the R&D<br>• R&D networking, new projects with universities and industry partners (e.g. air flow system, fuel cell inverter, induction system, feed-in technology)<br>• Decision to develop small wind inverter<br>• New partnership with university spin-off WindEnergy (partner for product development)<br>• Preliminary product design | • R&D manager leaves<br>• End of broader R&D exploration: refocuses unit activity on the small wind project<br>• Product development/design:<br>- Intense collaboration with WindEnergy<br>- Construction of prototypes<br>- Product tests<br>- Product improvement with pilot customers<br>• WindEnergy: market analysis for product design<br>• Client acquisition efforts result in many purchase intentions | • Blueprints transferred to production department<br>• Product improvement:<br>- Development version 2 and updates<br>- Cooperation with pilot users<br>• Market introduction<br>• Cooperation with manufacturers to troubleshoot poor quality turbines<br>• Top management sounds alarm as sales are not increasing<br>• International market research and increased sales efforts | • Reallocation R&D resources<br>• Final marketing attempt that yields no positive market response<br>• Project termination |

slowly, industry associations predicted very optimistic growth figures and forecasted global installed capacity of over one gigawatt by 2020 (Gsänger 2013). Many industry experts foresaw similar growth patterns as in the traditional wind (working with large scale turbines) and solar industries (Luethi 2010).

Motivated by the success of other start-ups active in this emerging industry and because the relatively small-sized market fitted its niche market strategy, SteeringCo signed a formal collaboration agreement with WindEnergy and jointly began to develop the inverter. To leverage each other's assets, SteeringCo was responsible for manufacturing and WindEnergy for bringing the product onto the market.

### 3.2 Phase 2: Product design and development

This phase is characterized by important product design and development efforts. While further exploration activities were maintained, from here on most efforts went into the inverter project and the intensive R&D collaboration with WindEnergy. The new product was customized to the needs of several turbine manufacturers, which were small firms and appeared to be typical for the industry. A second market study focusing on norms, regulations and feed-in tariffs was carried out. Final product design was rapidly determined based on the collaboration with the pilot customers and the market study. In the following years, several prototypes were developed until a product ready for production in small series was obtained.

This phase of pursuing multiple explorations ended in 2008 when top-management suddenly decided to end all but the small wind exploratory project. This decision was preceded by a change in SteeringCo's incentive system: the feed-in line head who was in charge of exploration was asked to work more performance-oriented and challenged to launch a product, which he was unable to deliver as his focus until then was the exploration of new applications for the core technology. When he was eventually replaced, top-management set the focus on an accelerated product design and re-staffed the position with an internal engineer, who brought extensive core business experience to the feed-in line. Moreover, a marketing manager joined the management of the business line. Before fully focusing on the new business line, he worked for both the core and the feed-in business lines, therefore also bringing important knowledge from the core business to the new business line. With this important organizational change, the feed-in business line was restructured into R&D and sales & marketing units and now fully integrated into the organization and its logic, with its new structure matching core business lines structure.

After creating a new sales & marketing unit, SteeringCo eventually also defined the sales strategy, mainly by applying the same approaches it had been using so far for its core business lines. It can be described as follows: senior engineers develop long-standing relationships with the largest clients in each international market. The main selling arguments were engineering excellence and, more specifically, customization to fit the needs of the different turbine manufacturers (thus allowing to improving turbine efficiency). Such customization and engineering excellence would provide strong sales arguments for manufacturers when selling the complete system to end-users.

### 3.3 Phase 3: Market introduction

Phase 3 started with a difficult transition time during which the teams had to get used to the new management and organizational structure. The R&D team continued to improve the product leading to new product versions and additional features, thereby fundamentally changing the initial design. The production department started production and the sales

& marketing team worked on market introduction. Sales gently took off but remained low.

By mid-2010, about one and a half years after market introduction, the first turbine users complained about the low energy yields and, as the yield in indicated on the inverters' display, blamed both the turbine and SteeringCo's product. To understand and solve the problems, SteeringCo further intensified collaboration with their various customers. SteeringCo' extensive knowledge in electrical engineering allowed to better trouble-shoot the turbines than the manufacturers themselves. In fact, SteeringCo's engineers realized that the manufacturers had developed turbines in a 'bricolage' style, meaning that they were doing all the work on their own, far less professionally than expected. To compensate for turbine weaknesses, SteeringCo decided to use its engineering skills to manage even more turbine functions with their inverter. This resulted in a more complex inverter design and in an increased degree of customization. SteeringCo did so because they saw the opportunity to develop an even better product and believed it could improve client relationships, and secure future competitive advantage, as it learned from the core business where customization was key for success.

Nonetheless, sales were not increasing as expected. The two partners came to realize that the market situation was more complex than they had anticipated and strongly different from the Market with which SteeringCo was familiar. First, given the early stage of the market, it was strongly fragmented: larger professional turbine manufacturers and smaller ones working in a much less professional way coexisted in the market and expressed very different needs. By increasing product customization, SteeringCo unintentionally oriented its product towards the needs of the latter segment. Second, the inverter market developed more rapidly than expected. Competitors, some from other industries such as the solar power industry, considerably improved their design and began producing inverters specifically for small wind turbines that partially imitated SteeringCo's design features. Given their success and economies of scale in the photovoltaic industry, their competitors could drastically reduce prices. Most importantly, by increasing product customization, SteeringCo narrowed its focus too early to the needs of one customer segment. It turned out that this segment was not representative of the global market. SteeringCo thereby strongly reduced the already small market size it could serve.

Understanding that the market situation was more complex than anticipated, SteeringCo's top-management came to realize that they had not sufficiently explored the market yet. Therefore they ordered further market research and strengthened their own sales team to intensify sales and customer acquisition.

### 3.4 Phase 4: Termination

The additional sales efforts did not bring significant increases in sales. As a result, top management eventually decided to end the production of the inverter and to reallocate R&D resources to other projects. Over 100 inverters were waiting to be sold and therefore the salesperson continued his work in the hope to sell the already manufactured inverters and thereby to minimize the losses that occurred with this project.

The innovation process was terminated in 2013, 10 years after its launch, when top-management officially decided to disinvest the project and end the collaboration with WindEnergy. Though the focal innovation failed, important knowledge was gained during the project, which provided input to further explorations—which are, however, not considered in this paper.

## 4 Lessons learned

The innovation journey at SteeringCo, a pioneering innovator for sustainability, provides a fertile ground for learning from and reflecting about the opportunities and challenges of a diversification strategy through green innovation. This section discusses five major lessons learned.

### 4.1 Awareness of the scope of innovation

The first lesson is that the scope of innovation needs to match the kind of diversification. At SteeringCo, top-management opted for a full diversification (with both new product and new market) strategy (Ansoff 1957) but allowed only for product (R&D) exploration. The alignment between the intended diversification strategy and the actual exploration (R&D or/and sales & marketing) is essential for success. Further, a lack of exploration in one domain might induce a misfit between the new product and the market it is intended to be sold in. The innovator should therefore be aware of the kind of diversification strategy he is pursuing and provide the innovation with sufficient space to unfold.

### 4.2 Organizational structures

The second lesson is that an organizational structure needs to be set up to protect the exploratory innovation space from the conventional core business (O'Reilly and Tushman 2008). A dedicated space is necessary for the exploratory innovation to unfold and reach maturity when the logic of the conventional business strongly differs from the new business, which is often the case by green innovations. Whereas in the former performance is essential, space for experimentation needs to be provided in the latter. Therefore, the two spaces need to be buffered from each other to avoid that possibly conflicting logics lead to an overall mitigated performance. This means that a form of separation needs to be implemented to avoid that world views, culture, cognitive representations, routines, and success metrics invade and cannibalize the new innovation space and compromise the success of the exploratory innovation.

### 4.3 Networking and partnerships

The third lesson is that innovations require knowledge that is new to the firm, even though managers might know the business very well. Engaging with so far unknown stakeholders allows to develop new ideas, sense new markets, learn about the needs of new customers and develop new products or possibly business model ideas (Prahalad and Hamel 1990). Furthermore, the discovery of distant knowledge is particular important in the context of green innovations, which is an area mostly unknown to conventional firms—in particularly when it comes to brining such innovations to the market (Holmes and Smart 2009). At SteeringCo, effective networking was done in R&D but not in the sales & marketing unit, which translated into the adoption of the old sales strategy that was not at all designed to bring the new product to the new and unknown market and therefore performed poorly. Further, partnerships are important and can be an effective way to leverage the knowledge, expertise and assets of another firm, therefore supporting learning, reducing the cost of developing new expertise and spreading risks.

### 4.4 Approach to uncertainty

The fourth lesson is that experimentation and trial-and-error learning are essential to make informed decisions in the exploration of highly uncertain business environments (McGrath 2001). Entrepreneurs are found to navigate the unknown in a way called "effectuation", which involves learning with a large number of small experiments to test the market and industry reaction (Sarasvathy 2001). By systematically trying out new ideas, effectuation allows to probe into the future. As many of those experiments—or perhaps most—will fail, it is important that they are designed to yield rapid and high learning while involving only limited (financial) resources. At SteeringCo, before abruptly narrowing down exploration, top management successfully investigated the renewable energy area by participating in several engineering projects with other firms and universities. This experimentation also allowed SteeringCo to learn aspects about its own core business (for instance that engineering consultancy was not an option as it did not fit its business model).

### 4.5 Business model innovation

As each business has its recipe, the last lesson is that a new business model can widen the innovation space and allow for more options when considered early in the innovation process (Amit and Zott 2010). Widening the space of possibilities is particularly relevant to successfully develop green innovations which are in many regards different from the core business and often follow different market logics. Furthermore, business models, when seen as a link or articulation between a commercial offer (the product) and the potential customers (the market), allow to create a better alignment between the offering and the demand, therefore also increasing the chances for market success of a new product or service (Boons and Lüdeke-Freund 2013). By adopting the core business' sales strategy for the new innovation, SteeringCo demonstrated that it was not prepared to innovate on the market side of its business model. This considerably limited the spectrum of possible innovations and prevented the firm to find a good market fit for its product.

## Conclusion

The pursuit of diversification is primarily intended to yield growth and reduce risk by expanding the product-market portfolio. Its overall goal is therefore securing future competiveness and risk mitigation. However, initiating an innovation process is far from a 'risk-averse' decision. As this innovation process analysis shows, many hurdles can punctuate the development of innovations. The paradox is that neglecting innovation is not a way out of the dilemma as in a competitive, dynamic market context this decision would in most cases endanger long-term firm survival. Therefore, the question is how the risks involved with the development of innovations can be best managed. Based on the experience of a pioneering innovator for sustainability, this paper draws the attention to five major management challenges: (1) the awareness of the scope of innovation to allow for sufficient space for exploration, (2) the setup of appropriate organizational structures to separate old from new business, (3) the value of extensive networking and partnerships to access and acquire distant information, (4) the benefits of an entrepreneurial approach to decision-making to navigating uncertainty and (5) the advantages of business model innovation to widen the innovation space. Dealing with those challenges in an appropriate way may increase the success of green innovations and allow established firms to seize business opportunities in new emerging markets in the context of the green economy.

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## Paper 2

Clean Energy Storage Technology in the Making: An Innovation Systems Perspective on Flywheel Energy Storage

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# Clean energy storage technology in the making: An innovation systems perspective on flywheel energy storage

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A B S T R A C T

The emergence and diffusion of green and sustainable technologies is full of obstacles and has therefore become an important area of research. We are interested in further understanding the dynamics between entrepreneurial experimentation, market formation, and institutional contexts, together playing a decisive role for successful diffusion of such technologies. Accordingly, we study these processes by adopting a technological innovation system perspective focusing on actors, networks, and institutions as well as the functions provided by them. Using a qualitative case study research design, we focus on the high-speed flywheel energy storage technology. As flywheels are based on a rotating mass allowing short-term storage of energy in kinetic form, they represent an environmentally-friendly alternative to electrochemical batteries and therefore can play an important role in sustainable energy transitions. Our contribution is threefold: *First*, regarding the flywheel energy storage technology, our findings reveal two subsystems and related markets in which development took different courses. In the automotive sector, flywheels are developing well as a braking energy recovery technology under the influence of two motors of innovation. In the electricity sector, they are stagnating at the stage of demonstration projects because of two important system weaknesses that counteract demand for storage. *Second*, we contribute to the theory of technological innovation systems by better understanding the internal dynamics between different functions of an innovation system as well as between the innovation system and its (external) contextual structures. Our *third* contribution is methodological. According to our best knowledge, we are the first to use system dynamics to (qualitatively) analyze and visualize dynamics between the diverse functions of innovation systems with the aim of enabling a better understanding of complex and iterative system processes. The paper also derives important implications for energy scholars, flywheel practitioners, and policymakers.



## 1. Introduction

Energy storage has recently come to the foreground of discussions in the context of the energy transition away from fossil fuels (Akinyele and Rayudu, 2014). Among storage technologies, electrochemical batteries are leading the competition and in some areas are moving into a phase of large-scale diffusion (Köhler et al., 2013). But batteries also have a number of environmental issues that are only marginally discussed, such as their hazardous chemical content and "grey" energy (Longo et al., 2014). Environmentally-friendlier alternatives exist at least for some applications (Akinyele and Rayudu, 2014). However, we know little how they develop, what drives or hinders their development, and why they are almost absent from discussions about energy storage. Against this backdrop, we are empirically analyzing the development of a promising clean short-term storage technology: flywheel energy storage (FES). Its operation principle is simple: flywheels store energy in kinetic form in a rotating mass. While low-speed flywheels have been used for years for uninterrupted power system, modern high-speed flywheels (HSF) promise a range of new applications, including the recovery of automobile braking energy and the stabilization of grid operations in the context of higher penetration of renewable energies. FES can represent a clean

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substitution technology for conventional chemical-based and potentially hazardous batteries in short-term storage applications, as it does not involve hazardous materials, has a very long operational lifetime (millions of full-depth discharge cycles), and has a limited impact during production, operation, and disposal (Hadjipaschalis et al., 2009).

We use innovation systems theory to shed light on the development of FES. This approach emphasizes the role of non-technical aspects to understand technology development (Edquist, 1997), which is seen as complex processes that unfold over time and are influenced by the interaction of a multitude of social, political, institutional, and technological factors (Carlsson and Stankiewicz, 1991). Assuming that a number of key processes need to be fulfilled for innovation system build-up, growth, and maturation (Hekkert and Negro, 2009), we adopt the technological innovation systems (TIS) approach (Carlsson et al., 2002) to capture these processes and draw links to influential contextual elements (Bergek et al., 2015). Positive self-reinforcing dynamics – motors of innovation – need to overcome system weaknesses for TIS growth and maturation (Jacobsson and Bergek, 2011).

We conducted an explanatory case study (Yin, 2014) providing insights into FES development geographically centered in German-speaking Europe, but also tracing links beyond this region's borders. The findings reveal that modern FES are emerging with very different dynamics in two different sectors. First, in the automotive sector FES is developing well as a braking energy recovery technology and is close to introduction in medium-sized markets in mass transportation. Development was driven by two important motors of innovation: the incubation, and in a latter phase the market motor. Second, in the electricity sector FES is developing in various grid-related applications but is currently stagnant because of two important system weaknesses that counteract the demand for storage. First because of an institutional weakness related with the unclear role FES could play in the transition to a sustainable grid, and second an actor weakness in the form of lacking entrepreneurial and commercial capabilities.

We contribute to two different literature. First, we address the cleaner production and sustainable energy technology literature by providing insights into the development of a storage technology that is more environmentally-friendly than conventional batteries and could possibly serve as a substitute in short-term storage applications. Second, we also contribute to TIS literature. We discuss the determining influence of two contextual structures: industry sectors and competing TIS. And we introduce a new methodological component to the TIS literature by using system dynamics representations to visualize complex TIS dynamics. Finally, we provide strategic insights for practitioners and policymakers.

The paper is structured as follows: Chapter 2 reviews the literature on FES and TIS. The research method and the case study are introduced in Chapter 3. Chapter 4 analyses the structural elements and the seven key functions of the innovation system. The analysis is deepened in Chapter 5 using system dynamics to explain how the innovation system develops. Chapter 6 concludes the paper and draws implications for researchers, practitioners, and policymakers. A schematic overview of the research is provided in Fig. 2 in the method section.

## 2. Literature review

### 2.1. Flywheel energy storage technology overview

Energy storage is of great importance for the sustainability-oriented transformation of electricity systems (Wainstein and Bumpus, 2016), transport systems (Doucette and McCulloch, 2011), and households as it supports the expansion of renewable energies and ensures the stability of a grid fed with multiple intermittent energy sources (Purvins et al., 2011). Batteries increasingly dominate discourses on energy storage (Akinyele and Rayudu, 2014), but their environmental impact is only marginally discussed (Matheys et al., 2007; Zackrisson et al., 2010). Other promising technologies exist, but, to our knowledge, little is known about how well they are developing. Neglected short-term storage technologies include compressed air, hydrogen, super-capacitors, and FES (Hadjipaschalis et al., 2009; Mahlia et al., 2014). Among these, FES represents an environmentally-friendly option as it is made of non-hazardous basic metals and carbon fibers (although some rare earth elements can appear in the motor-generator). Its operational lifetime of several[1] million full depth of discharge cycles (Mahlia et al., 2014) and up to 20 years operational time (Hadjipaschalis et al., 2009) is very long. For short-term storage applications FES is a clean substitution technology for batteries (Liu and Jiang, 2007). In extension of the term "clean technology", we consider FES to be a clean energy storage technology.

Compared to batteries, FES typically have a higher power output (watt), but store less energy (watt-hours) over a short period of time (currently only a couple of hours). With several million discharge cycles, FES have a much longer service life and are significantly lighter, have a smaller size, and occupy less floor space (Piller, 2015). Also, their lifecycle cost is lower than for batteries (Zakeri and Syri, 2015). In some cases, FES can be complementary to batteries, as an FES is more effective at storing and delivering large amounts of energy (watt) over a short-time period. Moreover, when used in combination, they can increase battery lifetime (Dhand and Pullen, 2013). FES also compete with super-capacitors for very short-term storage application (in the seconds to minutes range (Doucette and McCulloch, 2011).

In the literature, three main types of flywheels are distinguished: low-speed, high-speed, and micro-high-speed flywheels. Table 1 captures their main characteristics and differences. First, low-speed flywheels (LSF) are typically made of a steel mass using roll bearings and rotating at speeds varying from 1000 to 10,000 revolutions per minute. They have been commercially available for over 30 years and are a conventional solution when low cost is important but floor space is not. Second, high-speed flywheels (HSF) – a kind of modern "big brother" of LSF (Fig. 1) – are equipped with a rotor made of composite materials and/or steel and low friction bearings. They typically rely on an advanced magnetic system to reduce friction.[2] Low friction bearings mean lower inertia losses (therefore higher efficiency) and longer storage duration, up to one day (Wasserman and Schulz, 2011) – with only a fraction of the LSF size (Schaede et al., 2015). In sum, HSF allow the storage of larger amounts of energy in a smaller space and over a longer time. Third, micro-HSF – the "little brother" of the HSF – are used as kinetic energy recovery systems (KERS). They were first developed to recover the braking energy of race cars and then buses. They are light, compact, and store relatively little energy, but have a high power output. Compared to their larger counterparts, they are safer but less efficient. Given the bumpy conditions of the road environment in which micro-HSF operate, less advanced but more shock-resistant roller bearings are used, which decreases efficiency, but this is a minor issue as braking energy abounds in vehicles.

[1] Over 8 million full depth discharge cycles according to industry sources (IHS Automotive (2014)).

[2] See Bolund et al. (2007) and Mahlia et al. (2014) for details on the magnetic bearings used in FES.

**Table 1**
Typical characteristics of flywheels.

| Characteristics | Low-speed flywheel (LSF) | High-speed flywheel (HSF) | Micro high-speed flywheel (micro-HSF) |
|---|---|---|---|
| Operating speed | <10,000 rpm | >10,000 rpm | >10,000 rpm |
| Rotor composition | Steel | Carbon fiber composite | Carbon fiber composite |
| Bearing type | Conventional | Low friction | Conventional |
| Typical specific energy | ~5 Wh/kg | Up to 100 Wh/kg | ~10 Wh/kg |
| Typical weight | n/a (stationary equipment) | n/a (stationary equipment) | 15–60 kg |
| Expected (full depth) discharge cycles | $10^5$–$10^7$ | $10^5$–$10^7$ | $10^5$–$10^7$ |
| Expected lifetime | ~20 years | ~20 years | ~20 years |

Sources: based on Bolund et al. (2007), Hadjipaschalis et al. (2009), Doucette and McCulloch (2011), Dhand and Pullen (2013), Akinyele and Rayudu (2014), and Mahlia et al. (2014).

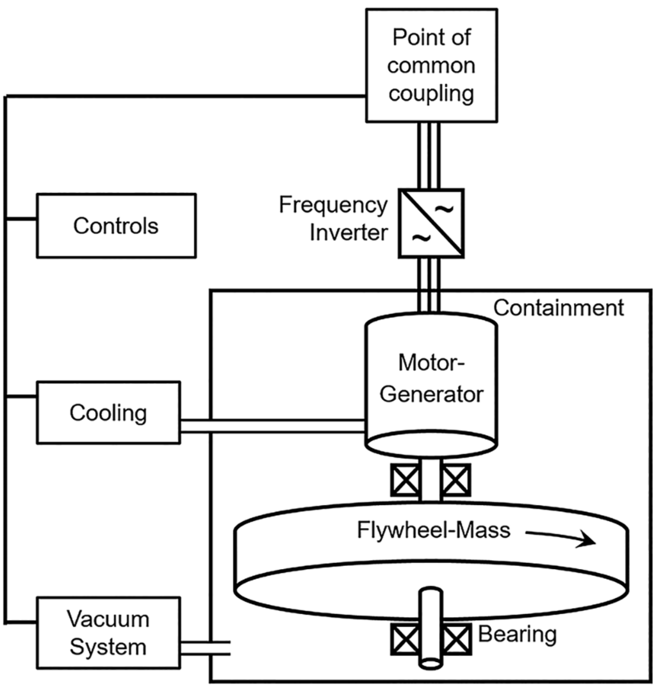


**Fig. 1.** Diagram of a high-speed flywheel (Schaede, 2015).

In addition to specialized applications e.g. in the International Space Station or in physics research institutes (Bolund et al., 2007), we can distinguish two broad fields of applications (Liu and Jiang, 2007) related to specific sectors (Bergek et al., 2015). First, in the automotive sector, micro-HSF can be used to store recovered braking energy (Doucette and McCulloch, 2011) and to either provide extra power (mainly in race car applications) or to decrease fuel consumption. They can be mechanically coupled to the powertrain and thereby also equip conventional vehicles powered by an internal combustion engine (ICE) (see Dhand and Pullen, 2013 for a review of mechanical coupling in flywheels). Furthermore, they can be coupled to the electric system of hybrid vehicles and/or used as a range-extender for battery-powered electric vehicles (Doucette and McCulloch, 2011). Second, HSF are intended for stationary applications related to the electricity grid. In these contexts FES are used to stabilize grid operations, to increase power grid security (Boroojeni et al., 2016), and to facilitate the expansion of renewable energies (Akinyele and Rayudu, 2014). Indeed, past a certain level, embedding intermittent renewable energy sources poses grid balancing issues (Hadjipaschalis et al., 2009). Short-term storage could allow an increase in the renewable energy share of 25–70% depending on the grid configuration and location (Lund et al., 2015).

FES have been developed for several years and are being commercialized – though at different speeds – in several markets. Overall, commercialization and diffusion seem to be below its potential. Extant literature does not provide indications on how the technology developed and why its diffusion is low. Therefore, we empirically analyze how it is developing and diffusing using the TIS approach. Based on this analytical framework, we discuss its development potential to better understand the role they can play in the energy transition. As conventional LSF has been a mature technology and commercially available for a very long time, the empirical analysis focuses on HSF and micro-HSF. We only consider LSF when it contributes to the understanding of the development of the flywheel types in focus.

### *2.2. Technological innovation systems*

Systems approaches to policymaking appeared in the 1970–1980s as a reaction to the perceived inadequacies of neoclassical market-based climate policies, which rest on R&D subsidies and market-based economic incentives (Bergek et al., 2008a; Jacobsson and Bergek, 2011). In this context, scholars argued that adopting a systems approach can lead to a better understanding of holistic, complex, “wicked” problems to inform interventionist climate change policies. In the past years, several innovation system approaches emerged, including national innovation systems (NIS), regional innovation systems (RIS), sectorial innovation systems (SIS) and technological innovation systems (TIS) (Chang and Chen, 2004). They are all rooted in evolutionary economics (Nelson and Winter, 1982), but they differ in focus. TIS is used to study the emergence of new technologies as an individual and collective social process (Carlsson et al., 2002). A TIS can defined as a “network(s) of agents interacting in a specific technology area under a particular institutional infrastructure for the purpose of generating, diffusing, and utilizing technology” (Carlsson and Stankiewicz, 1991: 21). It is intended to inform policymaking on how to manage, influence, and accelerate technology evolution (Foxon and Pearson, 2008). In academia, it gained popularity with the desire to understand the emergence of renewable energies (Jacobsson and Johnson, 2000) and, more recently, clean-tech in general, also in developing countries (Gosens et al., 2015).

An innovation system is composed of several structural elements (Table 2): actors in the whole supply chain, networks, institutions, and – in the case of TIS – also technology (Bergek et al., 2008a; Carlsson et al., 2002). Being embedded in a wider socio-technical environment (Granovetter, 1985), the innovation system interacts with wider contextual structures (Jacobsson and Bergek,

**Table 2**
Structural elements of the technological innovation system.

| Structural elements | Description |
|---|---|
| Actors | Actors and their competences shape the development of a technology. They can be part of a value chain (when the system becomes commercially organized), or they can be policy actors, researchers, funding organizations, etc. Actors possess competences that can be used to support the development of the innovation system (Carlsson et al., 2002). |
| Networks | Networks emerge when actors organize themselves to achieve common goals. Networks are seen as important ways to exchange knowledge and transfer technology. Networks have different purposes and include developing academic knowledge and transferring technology between academia and industry, as well as collaboration among industry actors (consortia) and between users and suppliers (Jacobsson and Bergek, 2011). |
| Institutions | Institutions form the regulatory and socio-cultural contexts in which a technology is embedded. They cover elements such as the laws and regulations that govern the innovation system. But institutions can also include less tangible elements such a culture, mental frames or cognitive representations (Tripsas and Gavetti, 2000), dominant world views, and typical ways of thinking about a problem (e.g. how the energy storage problem ought to be solved). Actors compete over markets but also over shaping the institutional context to their advantage, sometimes in lobby or policy networks (Smink et al., 2015). |
| Technology | Technology is understood as a field of knowledge, typically centered on one primary knowledge area, but also composed of complementary areas needed for its functioning. This knowledge is materialized in the form of technological artifacts, which are applied in products (for instance, a flywheel in a storage device) (Jacobsson and Bergek, 2011). |

2011; Markard and Truffer, 2008). Recent research suggests considering four types of contextual structures depending on the intensity of the interactions Bergek et al. (2015). First, the focal TIS may coevolve with other TIS, which could influence their reciprocal dynamics. Second, TIS can be related to the structures and dynamics of the sector(s) of which it is a part. Third, a TIS is always localized somewhere and, while the analytical focus is on technology, geographical aspects may also be relevant. Fourth, political contexts can play an important role, for instance in the availability of public resources and societal legitimacy.

#### 2.2.1. Innovation system functions

To understand innovation system dynamics involving these structural elements, scholars have reviewed a broad literature (including evolutionary economics, political science, institutional economics, sociology of technology, and population ecology) and identified several key processes that play a determining role for their formation and growth (Bergek et al., 2008a; Hekkert et al., 2007). Research shows that these functions need to perform well for TIS build-up, growth, and maturation (Hekkert and Negro, 2009). These processes can influence each other and form positive or negative feedback loops (Jacobsson and Bergek, 2011). When the effect of several positive loops cumulate, a self-reinforcing dynamic can materialize that is referred to as a “motor of innovation”. The term suggests that such motors bring momentum in growth and development (Suurs et al., 2010). Conversely, negative self-reinforcing dynamics can also appear when several factors cumulate that prevent the system from growing. These dynamics are referred to as system weaknesses (Jacobsson and Bergek, 2011). The identification of these weaknesses can inform policymakers about the type of policy intervention needed to promote the system's development.

For the empirical analysis, we follow the approach described by Bergek et al. (2008a). An overview of the seven functions used, their description, and the event types associated is given in Table 3. The full description of the functions of innovation systems (FIS) can be found in Bergek et al. (2008a) and Jacobsson and Bergek (2011), and an application of the framework in Bergek et al. (2005).

The FIS framework has been applied to numerous renewable energy technologies and allowed the identification of several common motors of innovation and system weaknesses, which have been used to inform policymaking. Jacobsson and Bergek (2011) provide an overview of recent FIS literature and its implications for practice. We review in Table 4 a number of illustrative FIS studies that illustrate the use of this analytical approach for policymakers and practitioners.

## 3. Research method

Investigating both structures (actors, networks, institutions) and dynamics (functions), this study presents a qualitative explanatory case study (Yin, 2014) using the theoretical lens of TIS for better understanding the strengths and weaknesses as well as the drivers and barriers linked to the diffusion of FES. The empirical research process is captured in Fig. 2. The first step clarifies the boundaries of the technology innovation system in focus (and will be explained in detail in the subsequent section 3.1). Steps 2 to 4 represent the empirical analysis based on the structures, functions, and dynamics of the innovation system (as will be presented in section 4). Step 5 shows the aim for using the analysis to derive policy implications (see section 6). The case employs multiple units of analysis covering both individual economic actors and industry network-level entities and activities. According to Yin (2014), single case studies can be used not only for further developing emerging theoretical fields but also for in-depth examination of a contemporary topic. This approach has been used by other authors including Jacobsson et al. (2004), van Alphen et al. (2008), and Pohl and Yarime (2012) to demonstrate the emerging character of the research field.

### 3.1. Case selection

The FES innovation system was delineated along three dimensions based on recommendations by Bergek et al. (2008a). First, we distinguish between a field of knowledge and a product. We view FES as a field of knowledge that is increasingly embodied in a group of artifacts used in mobile and stationary applications. Although we also consider these products (the storage devices) and the end products in which the storage devices are built, products and end-products are not at the core of our analysis (Carlsson et al., 2002). For instance, FES are used in buses, but we do not study the innovation system of public transportation. The second dimension is the breath of the study. Whereas we focus on a narrow technology (flywheels as energy storage systems), we adopt a broad perspective when it comes to its applications and consider all applications that promise market development. We only excluded highly specialized applications such as power boosters in nuclear research facilities (e.g. CERN or Max Planck Institute) or space applications (e.g. for NASA) (Bolund et al., 2007). Third, for the choice of the spatial domain, we followed the logic of conceptual delineation, according to which system boundaries are drawn so that “the interaction among the components within the system are more intense than the interactions between the system and its environment” (Markard and Truffer, 2008: 601). We explored the

**Table 3**
Functions of the technological innovation system.

| No. | Name | Description | Associated event types |
|---|---|---|---|
| F1 | Knowledge development and diffusion | The depth and breadth of the research and practice-based knowledge, and how actors develop, diffuse, and combine knowledge in the system. | Academic research, consortia, alliances, workshops, technology literacy of entrepreneurs |
| F2 | Influence on the direction of search | The extent to which actors are induced to enter the TIS by directing their research and investments in this technology. This function includes actors' visions, expectations, and beliefs about growth potential (also due to TIS in other countries), changes in the TIS landscape as well as incentives and disincentives to participate. | Vision, promises, expectations, technological competition, beliefs in growth, policy targets |
| F3 | Entrepreneurial experimentation | Knowledge development of a more tacit, explorative, and/or applied nature. How new knowledge is turned into concrete entrepreneurial activities (experiments) to generate, discover, or create new commercial opportunities. | Demonstration or commercial projects |
| F4 | Market formation | Articulation of demand and market development in terms of demonstration projects, nursing markets (or niche markets), bridging markets and, eventually, mass markets (large-scale diffusion). | Expectation, areas of application generating common interest, market regulations |
| F5 | Legitimation | The socio-political process of legitimacy formation through actions by various organizations and individuals. Central features are the formation of expectations and visions as well as regulative alignment, including issues such as market regulations, tax policies, or the direction of science and technology policy. | Mental frames, lobbying, advocacy coalitions |
| F6 | Resource mobilization | The extent to which the TIS is able to mobilize human and financial capital as well as complementary assets. | Subsidies, investments |
| F7 | Development of positive externalities | The collective dimension of the innovation and diffusion process, i.e. how investments by one firm may provide free-rider benefits for other firms. It also an indicator for overall dynamics of the system since externalities magnify the strength of all the other functions. | Interest of new actors in joining TIS, quality of the other functions |

Sources: based on Bergek et al. (2008a) and Jacobsson and Bergek (2011).

**Table 4**
Selection of empirical functions of innovation system literature.

| Reference | Innovation system | Results |
|---|---|---|
| Negro et al. (2008) | Biomass gasification in the Netherlands | Biomass gasification has not yet emerged in the Netherlands because of a structural misalignment between the institutional framework (of the electricity grid) and the technical requirements of gasification. Furthermore, TIS actors did not join forces when it came to developing a vision, shaping expectations, and advocating the technology. |
| Negro and Hekkert (2008) | Biomass digestion in Germany | Successful development of biomass digestion in Germany was due to a well-functioning system (all seven functions) and the role of the government as a system builder, not only as fund provider. |
| Pohl and Yarime (2012) | All-electric and hybrid electric vehicles in Japan | Successful development of all-electric and hybrid electric vehicles was carried out in-house by automakers as a result of a specific type of competition in the domestic market, without support of national policy. |
| Alkemade and Suurs (2012) | Alternative transport fuels in the Netherlands | In the development of alternative transport fuels (biofuels, hydrogen, and natural gas), early phases of competition are often based on actors' expectations rather than on technological performance. |
| Andreasen and Sovacool (2015) | Hydrogen fuel in Denmark and the USA | The two countries have similar strategies (aiming at ultimately replacing incumbent fossil-fueled power plants and vehicles) but widely different pathways. However, neither system achieved important commercialization because of important vested interests. |

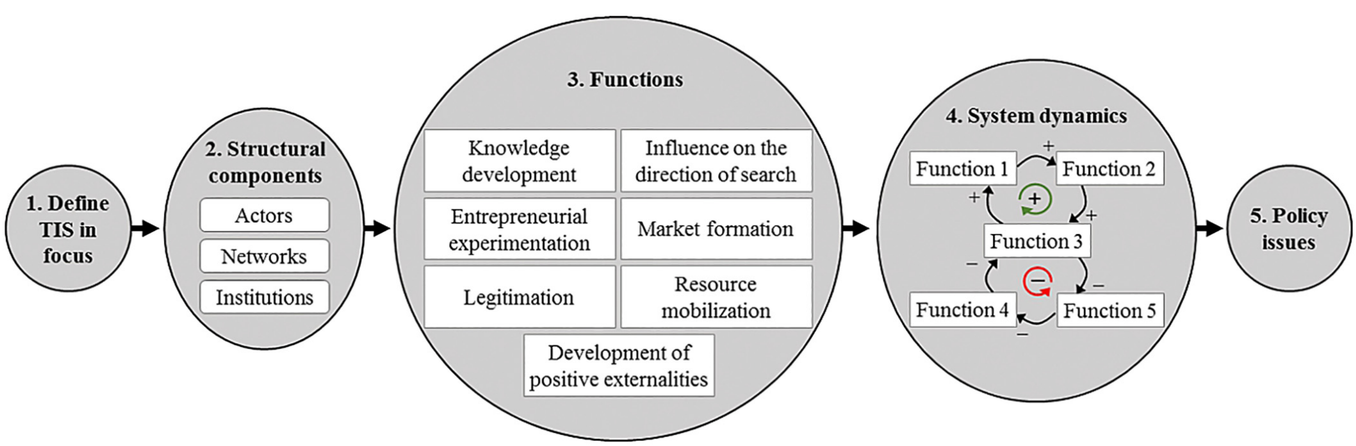


**Fig. 2.** Research process using TIS approach (based on Bergek et al., 2008a).

TIS with a geographical center on German speaking Europe with ties to the Netherlands, Sweden, the UK, and the US. Indeed, empirical investigations show that TIS actors do seem to be influenced by developments within this geographical space. Links to external structures are discussed when relevant (Bergek et al., 2015) (see for instance Function 2 in Section 4.2).

In line with theoretical sampling criteria (Eisenhardt, 1989), the case was chosen for being representative and revelatory (Yin,

**Table 5**
Data collection methods.

| Data type | Sources | Documentation |
|---|---|---|
| Semi-structured interviews | 15 interviews with important TIS members | Transcripts |
| Participant observation | 13 internal meetings with important TIS members<br>1 major industry workshop at the first authors' institute | Protocols |
| Informal interviews | 15 telephone interviews with workshop participants | Protocols |
| Document analysis | 110 publicly available documents (e.g. industry reports, market analyses, newspaper and industry magazine articles, and websites of industry actors) | – |

2014). The case is representative for the development of energy technologies that are not considered "mainstream" solutions by industry actors or policymakers in Germany's energy transition policy. The case is also revelatory because the researchers had in-depth, intimate access to the actors in the TIS and were therefore able to collect rich data about the underlying processes, system dynamics, as well as possible technology applications and related markets. Following the philosophy of engaged scholarship (Van de Ven, 2007), access was partly enabled by trust-building measures in the industry. Central to gaining access was the organization of a major international workshop on the market opportunities of FES, targeting scientists, industry experts, technology developers, system builders, and end-users. For approximately three years, we also worked closely together with a member of the innovation system, a medium-sized electrical engineering firm.

### 3.2. Data collection and analysis

Data collection followed a qualitative research paradigm with the triangulation of several sources (Babbie, 2013), including semi-structured interviews, participatory observation of a major industry workshop at the institute of the authors, various internal meetings with selected TIS actors, and archival analysis (Table 5). The formal interviews were fully transcribed and data from informal interviews and participatory observation were protocolled according to the methods described in Babbie (2013). The data was then coded and analyzed using the MAXQDA software for qualitative data analysis.

Data analysis was guided by the step-by-step scheme described in Bergek et al. (2008a), an application of which can be found in Bergek et al. (2005). It guides the researcher in the analysis of innovation systems along six iterative steps: 1) defining the TIS in focus, 2) identifying and analyzing structural components (actors, networks, and institutions), 3) mapping the functional patterns, 4) assessing the functionality of the TIS and setting process goals, 5) identifying inducing and blocking mechanisms, and 6) specifying key policy issues.

To deepen our analysis in step 5, we used system dynamics (Forrester, 1961; Sterman, 2000) to illustrate the relationship between TIS elements, functions, and contextual elements. The resulting models are representations that are not to be confused with deterministic or "hard" mathematical models aimed at making predictions about future system development (Featherston et al., 2012; Lane, 2000). They are not computational models or algorithms run by computers. They are instead used as representations for explaining and (visually) communicating complex sociotechnical systems in a simple way (Coyle, 1999). A limitation is that they do not account well for hierarchy and time in the system (Featherston et al., 2012; Lane, 2000). We built these representations following Sterman (2000) and use them for visually communication about the FES technological innovation system.

## 4. Analysis of the flywheel innovation system

### 4.1. TIS structure

As explained in the literature review, any TIS can be structured into actors, networks, and institutions. In terms of actors, the FES landscape is composed of approximately fifteen engineering firms (see Table 6). The automotive-related group is composed of fewer but larger firms. Leading actors have recently merged with larger industrial groups to develop commercial products – for instance, GKN's acquisition of Williams Hybrid Power (Clancy, 2014) in the UK. The grid-related group is more volatile with many firms having entered and left over the past decades. Firms are rather small and focus primarily on engineering tasks. Some lack marketing experience, while others are subject to financial difficulties.

Knowledge is exchanged in academic, industry-academic, and user-supplier networks (Jacobsson and Bergek, 2011). In purely academic networks, four universities are conducting basic research. Second, actors participate in industry-academic networks, which often take the form of publicly funded R&D projects. An example is the network around the Long Term Storage Flywheel project at TU Wien (Wasserman and Schulz, 2011). Third, user-supplier networks are found in the automotive subsystem, for instance in the UK involving FES, powertrain, vehicle manufacturers, and public transport companies. However, industry FES actors are not members of industry associations. The only example of a cross-consortia industry network is the Lüneburg flywheel workshop, which was organized at the authors' institute in mid-2014 with the aim of identifying potential markets.

Concerning institutions, there are important differences between the automotive and the electricity sectors. In the first, vehicle-mounted micro-HSF are subject to road (and railway) regulations, including stringent safety requirements and emission regulations (EC, 2007). FES has the potential to significantly improve the environmental performance of vehicles, but it is not aligned with the dominant discourses on clean mobility, in which hybrid or battery-powered vehicles are favored (see for instance massive investment in battery research, ZSW (2015). However, in light of the growing regulatory pressure on emissions, several automotive manufacturers are now interested in FES to complement conventional ICE.

Second, in the electricity sector, storage generally receives political and public support as it enables the expansion of renewable energies and is needed for smart grids (Boroojeni et al., 2016). However, there are controversial discussions on the need for storage. While some voices, such as the Berliner energy transition think tank Agora Energiewende (Agora, 2014), argue against storage, renewable and storage lobbies strongly favor it (BDEW, 2016). Critics argue that energy storage is only needed when renewable energy generation exceeds about 60% of total supply (currently around 30%) and that below this level grid expansion is sufficient (Agora, 2014). In terms of regulations, the German electricity sector

**Table 6**
Actors involved in research, engineering, and manufacturing of FES in the German-speaking technological innovation system (non-exhaustive list).

| Type of actor | Name | Country | Mission and target applications |
|---|---|---|---|
| Research institutions | TU Braunschweig | DE | Historical role in the development of the stationary low-speed flywheel |
| | Energie Forschungszentrum Niedersachsen (EFZN) | DE | Examine possible role for HSF in the German energy transition and provide funding for research. |
| | TU Darmstadt | DE | Increase energy density and reduce size of stationary flywheel |
| | TU Vienna | AT | Increase viable storage time of stationary flywheels |
| | TU Graz | AT | Optimal designs of mobile flywheels |
| | Fraunhofer IVI | DE | Test micro-HSF as storage in an innovative large bus (Autotram project) |
| Manu-facturers | ABB | CH | Commercial LSF-based UPS system |
| | Adaptive Balancing Power | DE | Develop HSF for grid applications (to compensate for the intermittency of renewable energies) |
| | Asper | CH | R&D of HSF |
| | Centre for Concepts in Mechatronics | NL | Develop HSF for large transportation systems, mobile cranes, and industry specific applications (participated in the Fraunhofer Autotram project) |
| | Compact Dynamics/Bosch | DE | Developed a micro-HSF for race cars, which was never used in a race. Technology sold to Bosch, unknown future projects |
| | Enercon | DE | Offered a commercial flywheel to level the output of a wind turbine. |
| | Flybrid/Torotrak | UK | Micro-HSF for race cars, mass transportation markets, and cars |
| | GKN | UK | Commercial micro-HSF for mass transportation markets (currently mainly buses). Markets for off-highway machinery and cars are also targeted. |
| | Piller | DE | Commercial LSF-based UPS |
| | Ricardo UK Limited | UK | Commercial micro-HSF for mass transportation and cars. |
| | Rosseta Technik | DE | Produced HSF that were mainly used to balance the private grid of public transport firms. |
| | Rotokinetik UG | DE | Work on an innovative LSF for frequency regulation. |
| | Sieb & Meyer | DE | Supply electronic control system to HSF |
| | Socomec | FR | Commercial flywheel based UPS |
| | Stornetic | DE | Work on an HSF for grid balancing. |
| | Williams Engineering | UK | Work on HSF for the stabilization of island grids. |
| Others | Achmed Khammas | DE | Provide public information about (renewable) energies |
| | Johann Klimpfinger, Eurosolar | AT | Lobby for the use of clean storage technologies (in particular HSF for home storage of photovoltaics) |

is subject to the Energy Industry Law (EnWG) and renewable energies to the Renewable Energies Law (Luethi, 2010). In the past years, energy markets have been liberalized and power generation, power distribution, and grid balancing were separated (Jacobsson and Johnson, 2000), creating a market for storage, the regulatory framework of which is currently being shaped by several powerful industry lobbies.

The next subsections analyze the seven innovation system functions (see Table 7 for an overview).

### 4.2. Function 1: knowledge development and diffusion

In the automotive sector, knowledge development started decades ago (Dhand and Pullen, 2013) but dramatically accelerated when the use of kinetic energy recovery systems (KERS) was allowed in Formula One races in 2007 (FIA, 2014). Leading firms worked in consortia involving multiple technology specialists and customers (powertrain and vehicle manufacturers). Examples include Flybrid Automotive, who with Torotrak developed demonstrators for customers such as Honda Racing F1, Hope Racing, and Dyson Racing and later worked on commercial offerings for

**Table 7**
Overview of FES innovation system functions.

| | Functions | Automotive sector | Electricity sector |
|---|---|---|---|
| 1 | Knowledge development and diffusion | Knowledge development began decades ago, but motorsports consortia suddenly and dramatically accelerated it. | Basic research at universities but slow diffusion to industry. |
| 2 | Influence on the direction of search | Strong vision of clean energy storage and large potential in several markets. Demand most strongly articulated in the automotive sector, where the first flywheels are already being used in buses to reduce fuel consumption and ease compliance with EURO-X emission norms. | Demand not articulated yet. Unfavorable regulatory frameworks in the electricity sector and unclear business case for storage explain low interest of new actors and investors to participate in FES development. |
| 3 | Entrepreneurial experimentation | Strong experimentation thanks to motorsports. | Limited technical experimentation. Many applications are discussed but overall market experimentation remains weak. |
| 4 | Market formation | Motorsports acted as a nursing market. Public transport (buses) is currently developing as a bridging market. Market for passenger cars discussed as largest consumer market in this sector. | While markets for LSF exist, few signs of market formation for HSF are observed. Several promising potential markets are discussed: control reserve, stabilization of island grid, uninterrupted power supply (UPS), home storage of renewable energies, etc. |
| 5 | Legitimation | Good legitimacy thanks to demand for onboard storage, fit between mental frames and mechanical core competences of the incumbents (rotation, high-speed, and kinetic energy). | Low legitimacy: no demand for clean energy storage, misalignment with current institutional and regulatory frameworks, misalignment with mainstream view of storage (as a chemical battery, not a rotating device). Concerns about the technology because of safety issues. |
| 6 | Resource mobilization | Good access to financial resources for larger firms (thanks to motorsports, government subsidies, and co-development with customers). | Good access to financial resources for larger firms (government subsidies and co-development with customers). Small firms struggle to fund demonstrators and access to qualified human resources. |
| 7 | Development of positive externalities | Important positive externalities observed first when motorsports adopted micro-HSF and later when automotive incumbents joined the innovation system, translating into an acceleration of technology development. | Few positive externalities observed because of volatile TIS participation and several weakly performing system functions leading to overall stagnant situation. |

**Table 8**
Incentives and disincentives for manufacturing firms to join the innovation system.

| Factors | Incentives | Disincentives |
|---|---|---|
| Firm environment | + Storage increasingly needed for energy transition<br>+ Need to reduce fuel costs[a]<br>+ Stringent air quality regulations[a]<br>+ Fit between engineering-oriented core competencies and institutional frameworks (better than for electric vehicles)[a] | – Important technological competition (with battery technology)<br>– Strong path dependency (of conventional ICE and powertrain design,[a] of grid stabilization through large power plants[b])<br>– Complex and unfavorable regulation[b]<br>– No business case for storage[b]<br>– No demand for clean storage[b]<br>– Current regulatory developments favor chemical batteries (both in vehicles and large-scale grid storage) |
| Firm-level | + Strong belief in the technology's superiority<br>+ Good economic appropriability of the technology<br>+ Potentially large global markets | – Large R&D investments<br>– High degree of uncertainty about future developments |

[a] Factors specific to the automotive sector.
[b] Specific to the grid sector.

passenger cars with Volvo, Jaguar, and Porsche (IHS Automotive, 2014). Competitors Williams F1 and Ricardo followed similar paths (Ricardo, 2009; Williams, 2014). Therefore, motorsports worked as a catalyzer for knowledge development.

Conversely, in the grid sector, universities played an important role by conducting basic research on the physics, mechanics, and electronics of HSF. Knowledge was also exchanged between the engineering firms in several academic-industry networks, such as between TU Braunschweig and Piller in Germany (EFZN, 2007) and TU Wien, Austria with regional industrial actors (Wasserman and Schulz, 2011).

However, beyond these networks we observed little knowledge exchange among firms. For example, our triangulation of data from the industry workshop and interviews shows that some actors did not reveal their experiments to other players. A heavy-duty vehicle manufacturer even positioned itself publicly against micro-HSF, while at the same time being involved with internal testing. Triangulation of our data also shows that incumbents spread false market outlooks, possibly to mislead competitors. In general, knowledge absorption appears to be slow, particularly for market knowledge. Finally, to a limited extent knowledge is also being diffused to the broader public with a regularly updated website reviewing FES developments (Khammas, 2007) and a science documentary (ZDF, 2013).

### 4.3. *Function 2: influence on the direction of search*

The factors influencing the search process and thus the incentives and disincentives to participate in the TIS are shown in Table 8. We discuss here only the most important ones. First, against the backdrop of the German energy transition policy and the increasing need for storage, the vision of a sophisticated and clean storage technology is animating many TIS members. Positive developments in the US-based TIS have fueled this enthusiasm. Indeed, several members have visited Beacon Power's 2 MW storage station in Stephentown (NY), which has been in operation since 2011 (Beacon Power, 2016). While some were more skeptical, many actors interpret this as a positive signal for the European TIS and believe that the technology is about to gain traction massively. This strong vision is reinforced by strong commercial prospects and good economic appropriability of the technology. However, it should be noted that interviews revealed that other TIS members were more skeptical as they realized that the US grid storage business case is vastly different from the German one and that initial reports by the firm about its profitability were misleading.

The energy storage landscape is rapidly changing under the influence of a leading substitution technology: lithium-ion batteries. Storage discussions are dominated by this technology, which receives support from important lobbies, such as the German Energy Storage Association (BVES) in Germany. This discourse aims to turn the battery into a synonym for storage, casting a shadow on alternative environmentally-friendlier technologies. This situation can also be observed in the automotive sector where battery-based hybrid or all-electric cars are in the spotlight.

The articulation of demand is stronger in the automotive sector, where micro-HSF can be used to reduce fuel consumption (especially, as interviews reveal, for large fleet operators) and comply with emission regulations (for vehicle manufacturers). Therefore, automotive manufacturers are interested in this technology, as the recent acquisitions of Williams Hybrid Power by GKN, and Flybrid by Torotrak show (see Section 4.1). In the grid sector, demand for storage is not yet well articulated, and there is virtually no demand for clean storage, which would however be the main advantage of micro-HSF over substitution technologies.

The influence of regulatory frameworks differs between the automotive and the grid sectors. In the first, emission regulations regarding gaseous and particle emissions – EURO-X Norms (European Commission, 2007) at the EU level and in many European cities (STVA, 2016) – are becoming more stringent. These regulations may create markets for clean vehicle technologies, including micro-HSF. In the grid industry, controversial discussions about the disputed need for storage (see Section 4.1) create important uncertainties that hinder HSF development.

### 4.4. *Function 3: entrepreneurial experimentation*

Engineering firms and universities are experimenting along technology and market dimensions. In technology, companies are experimenting with different design options, such as construction types (inner-rotor inner-mass, disc-shaped, inner-rotor outer-mass, and outer-rotor), rotation speed, rotor material (steel or composite material) and bearing types (roller bearings, active and passive magnet bearings) (Dhand and Pullen, 2013; Schaede et al., 2015). Related to micro-HSF, firms are also experimenting with different ways to couple the storage device to the vehicle transmission: mechanical coupling with flywheel integration in the axle or in the gearbox (IHS Automotive, 2014) and electrical coupling, as in the case of GKN's Gyrodrive (Williams, 2014), with the electric system powering the motor.

In the market dimension, firms are experimenting with numerous applications in the broad automotive and grid-related fields already introduced. A non-exhaustive list of experiments with estimates of development stage is given in Table 9, showing that experiments in the automotive sector are often more advanced than in the grid sector, where markets experiments are often only at the planning stage.

**Table 9**
Market-related experiments.

| Subsystem | Experiments | Status[a] | Known involved actors[b] |
|---|---|---|---|
| Automotive sector | Light-weight trains | E | Ricardo UK Limited, Alstom (F) |
| | Trams | E | Centre for Concepts in Mechatronix (NL), GKN plc (UK) |
| | Urban buses | C | GKN plc (UK), Ricardo UK Limited, Torotrak plc (UK) |
| | Passenger cars | E | GKN plc (UK), Jaguar XF (UK), Porsche (D), Ricardo UK Limited, Renault (F), Torotrak plc (UK), Volvo (SE), |
| | Off-highway machinery (mobile cranes, construction machinery) | E | Centre for Concepts in Mechatronix (NL), GKN plc (UK), KAMAG Transporttechnik (D), Vycon (USA) |
| | Refuse collection vehicles | E | Non-disclosure |
| Electricity grid sector | Grid balancing (control reserve market) | E/C | Stornetic (D), Williams Advanced Engineering (UK), Beacon Power (USA), Boeing (USA), Calnetix (USA), Kinetic Traction Systems, LLC. (USA), Aspes (CH), Rotokinetik UG (D)[c] |
| | Balancing of island grids | E/C | Williams Advanced Engineering (UK), Piller (D)[c] |
| | Balancing of private grids (i.e. large industrial plants or public transport grids) | C | Rosseta Technik (D), Piller (D)[c] |
| | Stabilization of critical nodes in the electricity grid | P/E | Non-disclosure |
| | Decentralized home storage of renewable energies | P | Klimpfinger (AT) |
| | Output leveling of single wind turbines | P/E | Enercon (D), Rotokinetik UG (D)[c] |
| | Output leveling of solar or wind parks (in Austria) | P | Non-disclosure |
| | Energy for storage for remote telecommunication station | P | Non-disclosure |
| | Uninterrupted power supply (including cold start for emergency power systems) | C | Socomec (F), Kinetic Traction Systems LLC (USA), Calnetix Technologies LLC (USA), Piller (D)[c] |
| | Balancing fluctuations in industrial applications (e.g. elevators or machines requiring important short-term power) | E | Rotokinetik UG (D), Piller (D)[c] |
| | Provide power boost for experimental research (e.g. particle accelerators) | C | Piller (D)[c] |
| | Fast charging stations for electric vehicles | P | Non-disclosure |
| | Energy storage for spatial applications | P | Non-disclosure |

[a] We distinguish between planned (P), ongoing experiments (E), and successful experiments (commercialized) (C).
[b] We provided company names whenever disclosure was allowed. See also Khammas (2007) and Dhand and Pullen (2013) for a chronological review.
[c] Low-speed flywheels.

### 4.5. Function 4: market formation

Though at a very early stage, several markets for micro-HSF are emerging (see Table 10). We distinguish nursing markets providing learning spaces that support TIS growth and bridging markets that allow volumes to increase (Bergek et al., 2007). First, motorsports has served crucially as a small nursing market where several manufacturers have developed, refined, and tested micro-HSF. Second, a medium-sized bridging market for buses in metropolitan mass transportation is currently the most advanced market development, with GKN implementing micro-HSF in over 500 buses in London (GKN, 2014). Other medium-sized markets – though only at a nursing stage – are emerging for heavy and light-duty vehicles, trams, urban trains, and off-highway machinery. Finally, at least theoretically the largest potential market for micro-HSF is passenger cars. As these three markets offer complementarities in terms of technological requirements and volume, several firms are planning to move progressively into this third market. Market breakthrough for passenger cars strongly depends on original equipment manufacturers adopting the technology, which is a major barrier to be overcome. For instance, the car manufacturer Volvo decided to abandon the technology even though tests were successful (Clancy, 2014). Another major market entry barrier is compliance with safety regulations involving very expensive crash tests.

In the grid sector (Table 11) LSF have been available for over 30 years for uninterrupted power supply (UPS), for providing power boost (e.g. physics research institutes), for stabilizing large private industry and public transportation grids (e.g. grid for trams and trolley buses in Braunschweig, Hamburg, Hannover or Freiburg in Germany). Next to LSF, some HSF were produced for this purpose too and are successfully operating (e.g. Rosseta, 2011). Therefore, LSF are established in these markets with HSF being occasionally used too. In addition to these established markets, signs of market formation are observed in at least five areas (Table 11), which however remain at an early-stage.

### 4.6. Function 5: legitimation

Legitimation differs not only between automotive and grid-related sectors, but also within these sectors. While in the automotive sector, technologies to increase vehicle fuel efficiency are welcomed and social acceptance is high, we find mixed results regarding the micro-HSF itself. In the area of utility vehicles, public transportation operators are among the first companies that gained interest in micro-HSF as they need to mitigate the risk of fuel price volatility. Furthermore, flywheels fit the mental frames and mechanical core competencies of the traditional automotive sector. However, we also found serious concerns by a heavy-duty vehicle manufacturer who considered the potential for accidents was too high for micro-HSF and chose to use super-capacitors instead. However, as their adoption in mass transportation demonstrates, safety is hardly discussed in automotive markets, as micro-HSF passed crash tests and so far no accidents have been reported.

In the grid sector, legitimacy is much lower. This can be explained by several important factors. First, there is currently no specific demand for clean energy storage. Second, when storage is discussed, HSF is absent from discussions dominated by batteries. Third, the emerging regulatory framework for grid balancing is significantly shaped by the battery lobby and is therefore tailored to the specificities of batteries and is unfavorable to HSF. Fourth, the government support program for decentralized storage claims that it is technologically neutral; however, the term “battery systems” in the title indicates its aim to support more narrowly batteries (KfW,

**Table 10**
Potential markets in the automotive sector.

| Potential markets | Market description | Market outlook |
|---|---|---|
| Motorsports | This is a niche market where HSF are used to supplement the ICE for additional power. This particular market environment (characterized by important R&D resources and pre-established sales deals) allowed several firms to develop, test, and refine the technology. As such, it functioned as a technology incubator. | HSF are well established in this market. Market growth could take place if this technology is allowed in new races, but growth potential appears insignificant as the market is saturated. |
| Buses | In this bridging market, HSF are used to recover braking energy of buses operating with stop-and-go driving cycles. HSF allow a strong increase in fuel efficiency (25–35%) and therefore a reduction of emissions. Furthermore, the additional power source can allow a downsizing of the ICE. | Compared to batteries and super capacitors, the long operational lifetime, the ability to absorb harsh charge-discharge cycles (innumerable full depth of discharge cycles), their relatively small size and light weight are considerable advantages of HSF. Several manufacturers target the market for buses with plans to roll out the technology in London (GKN, 2014). Future developments strongly depend on technology adoption by vehicle manufacturers. |
| Heavy and light-duty vehicles, trams and light-weight trains and off-highway machinery | Similar to buses, HSF are used to recover braking energy of stop-and-go driving cycles and of duty cycles in machinery (e.g. frequent on-and-off cycles). Furthermore, in some applications HSF are used to stabilize the onboard electricity grid, for instance in the case of light-duty vehicles equipped with additional machines such as in waste collection vehicles. | These markets are still in their infancy and to our knowledge no firm can at present rely on them for commercial success. As for buses, future market developments strongly depend on technology adoption by OEM manufacturers. |
| Cars | HSF can be used to dramatically improve the fuel efficiency of conventional internal engine powered cars (with fuel savings of 25–35%), particularly in urban environments (IHS Automotive, 2014). As such, micro-HSF represents a workable medium-term solution to comply with stringent emission regulations. In electric cars, they can be used to increase battery life-time and as a range extender. | In this market, HSF compete with battery-powered electric cars. This market has the largest potential market, but future developments strongly depend on the technological choices of car manufacturers (so far typically favoring battery-based solutions) and a related decrease in costs, the development of the oil price, and the demand for clean cars. Given the large-scale global investments in battery production and related significant decreases in production costs, it is unlikely that flywheels can compete in the mid and long-term. Another barrier is the safety issues related to production use, leading to high development costs because of mandatory crash tests. |

2013). Fifth, FES does not fit the dominant mental frames about storage. Unlike in the automotive sector, actors are less familiar with kinetic storage than with batteries or large infrastructures such as pumped-storage hydropower. Finally, several accidents marked the development of HSF, for example, at Beacon Power in the USA (Flint, 2011) or the explosion of a Piller LSF (Göttinger Tageblatt, 2014). These accidents led to public distrust that still persists. In contrast, leading scientists argue that HSF are not more problematic than batteries (Bolund et al., 2007; Recheis, personal communication). Hence, this issue also seems to be purposefully instrumentalized by incumbents (Smink et al., 2015) precisely to reduce HSF acceptance.

Even though low legitimacy is a central issue, only few legitimation activities were observed. FES manufacturers are not even part of a lobby or industry association. In addition to achieving legitimacy among experts, the technology also needs to gain the trust of the broader public. Unfortunately, this technology seems too specialized to receive media attention, as even more mainstream storage technologies receive little media attention, with the exception of a single German television documentary (ZDF, 2013).

### 4.7. Function 6: resource mobilization

Leading manufacturers in the automotive sector benefited from funding by motorsports. In just two years Flybrid/Torotrak developed a micro-HSF prototype that was able to pass a Formula One crash test (Khammas, 2007). This extremely short development time shows the important accelerator role that motorsports played. Furthermore, several firms were successful in obtaining government subsidies for technology development – such as Flybrid/Torotrak (Innovate UK, 2015), GKN (2014), and Piller (EFZN, 2007). As the demand for micro-HSF had already been articulated, other firms co-developed it with customers (who also participated in funding). Still other firms such as Stornetic (2015) and CCM (2011) developed HSF through internal cross-funding from other engineering activities. It is mainly the smaller firms in the electricity grid area that experienced funding difficulties, in particular when it comes to the demonstration projects necessary to showcase their technology. Some of them also experienced difficulties hiring qualified engineers with the interdisciplinary knowledge needed. Hence, resource mobilization is not only a question of money, but also of competences.

### 4.8. Function 7: development of positive externalities

In the automotive sector, positive externalities emerged when the technology was adopted by motorsports and several new entrants joined the innovation system. The entrance of new actors brought in important knowledge, competences, and resources (strengthening Functions 1 and 6), resolved uncertainty about technology development (F2), demonstrated its safe use as onboard storage, and overall increased legitimacy (F5). In a more recent phase, the positive externalities were further strengthened with the entrance of two large UK automotive players, which further supported technology development, and demonstrated the market potential of micro-HSF (F4), and safety (F5).

The situation in quite different in the grid sector, where actor participation in the TIS is more volatile, with many firms entering but also leaving in the past years. We could at the moment of the analysis not observe any positive externalities for existing or new actors. Indeed, uncertainty about the technology and its application is high (weakening F2 and F5), knowledge development and

**Table 11**
Potential markets in the electricity sector.

| Potential markets | Market description | Market outlook |
| --- | --- | --- |
| Control Reserves | A very important development is the emergence of a market for control reserves, where stored short-term energy can be made available to stabilize the grid (Regelleistung.net, 2016), which is an essential element of power security (Boroojeni et al., 2016). This market is currently dominated by fossil power plants that ensure the functioning of grid balancing through large synchronal generators. In the context of the German electricity market liberalization, this function is being progressively decoupled from power plants, allowing new market entrants to offer balancing services. Liberalization of grid balancing created a market for control reserves[a] (Bundesnetzagentur (2011), in which HSF could participate. However, the regulatory framework underpinning this market is being shaped by political interests and important lobbies, and is currently evolving in an unfavorable direction for HSF. | Experts argue that the regulatory framework is strongly being shaped by political interests and important lobbies (including the battery lobby). The current regulatory framework is rather unfavorable to the features of HSF (Regelleistung.net, 2016) (hence the importance of R&D for high performance HSF). Furthermore, conventional LSF might suffice. Therefore, while the market for control reserve is being defined by politics in Germany, technological competition appears tremendously high and the unfavorable regulatory framework creates important uncertainties. |
| Island network stabilization | In island networks (in the insular context or in locations without grid connection, e.g. tests on islands in Alaska, the UK, and Greece), integration of intermittent renewable energy poses an additional difficulty (Schaede et al., 2015). In this context, storage is used to compensate for the fluctuation of intermittent renewable energy sources when those exceed about 30–40%. Below that level, diesel generators suffice to stabilize the island grid. Storage can thus allow an increase in the penetration of renewables in such grids, which is particularly interesting for remote grids where diesel supply is costly. | This market is potentially very large, considering the number of island networks. However, a difficulty might be that each island grid has different characteristics and therefore sales can only be done on a case-by-case basis, which significantly increases marketing costs and, unless a standard solution is found, reduces its commercial attractiveness. |
| Uninterrupted power supply (UPS) | The global UPS market is mature but still expected to grow strongly (Lauwigi and Vogt, 2013). It is dominated by a handful of international firms, among which one player uses LSF as cold-start for diesel generators to provide uninterrupted power to critical infrastructures, such as data centers, hospitals, or airports. In addition to critical infrastructures, UPS are also used in countries where grid quality is poor. | This still growing market is estimated to be worth over five billion euros (Lauwigi and Vogt, 2013). Here, HSF could have an advantage compared to LSF in applications where size matters. Next to size, another advantage is the very long lifecycle of HSF and the possibility to know the exact energy content of the device, two criteria where batteries show weaknesses but that are essential for this application. Therefore, the UPS market represents a large, promising consumer market that is less dependent on uncertain electricity grid regulations. Finally, this market could be interesting as it is independent of complex and rapidly changing energy politics. |
| Renewable energy home storage | Renewable energy home storage is currently emerging in Germany and Austria thanks to a government subsidy program (BSW, 2015; KfW, 2013). A growing number of energy autarchic households (currently 15,000) reportedly use only home produced wind and solar energy, relying on storage to compensate for intermittency. Home storage also has the advantage of reducing the energy bill by reducing the power purchased from the grid (BSW, 2015). | While this market appears to be a very promising consumer market, batteries are strong competition for HSF, especially the growing availability of second-hand batteries from electric vehicles. A support program was launched in Germany (BSW, 2015), which however seems to favor batteries. Furthermore, very few households expressed the desire to work with clean storage technologies. Therefore, the demand for HSF is still unclear and competition on price very high. |
| Leveling of solar/wind parks | In Austria, where the maximum output power of solar and wind parks is regulated, a need to level production peaks, and therefore storage at the park level, is emerging. Production levelling would allow an increase of overall generation capacity by shifting peak power to off-peak hours. | Future developments strongly depend on national regulations. At present, this market seems specific to the Austrian context and is uncertain as the regulatory framework is still developing. |

[a] Procurement takes place in a competitive tendering process. Based on response time, availability, and amount of energy, three types of reserves are distinguished: primary, secondary, and tertiary control reserves Regelleistung.net (2016). Characteristics of the three reserve types: primary reserves: 30 s activation time and 1 MW available for at least 15 min; secondary reserve: 5 min activation time and 5 MW for 15–60 min; tertiary reserves: 15 min activation time and 5 MW for a minimum 15 min. Given their technical characteristics, FES could provide primary and possibly also secondary control reserves. But given the size of the bids, tendering is only accessible for large storage facilities, such as the flywheel storage plants built by Beacon Power (2016) in the US.

diffusion slow (F1), and advocacy coalitions weak (F5). That said, this is rather typical of early-stage innovation systems characterized by long stagnant development periods (Suurs et al., 2010) and could rapidly change with the entrance of new actors.

## 5. Dynamics of the flywheel innovation system

The analysis revealed differences between the functional patterns and dynamics (interplay between structural elements, functions, as well as external inducing and blocking mechanisms) in the automotive and electricity FES subsystems. These dynamics and the influence of contextual structures are further analyzed in the next subsections.

### 5.1. Dynamics in the automotive subsystem

Micro-HSF development was facilitated two important motors for innovation (Suurs et al., 2010), as illustrated in Fig. 3. The figure illustrates how motors of innovation emerge as result of a number of positive interactions between functions – sometimes forming

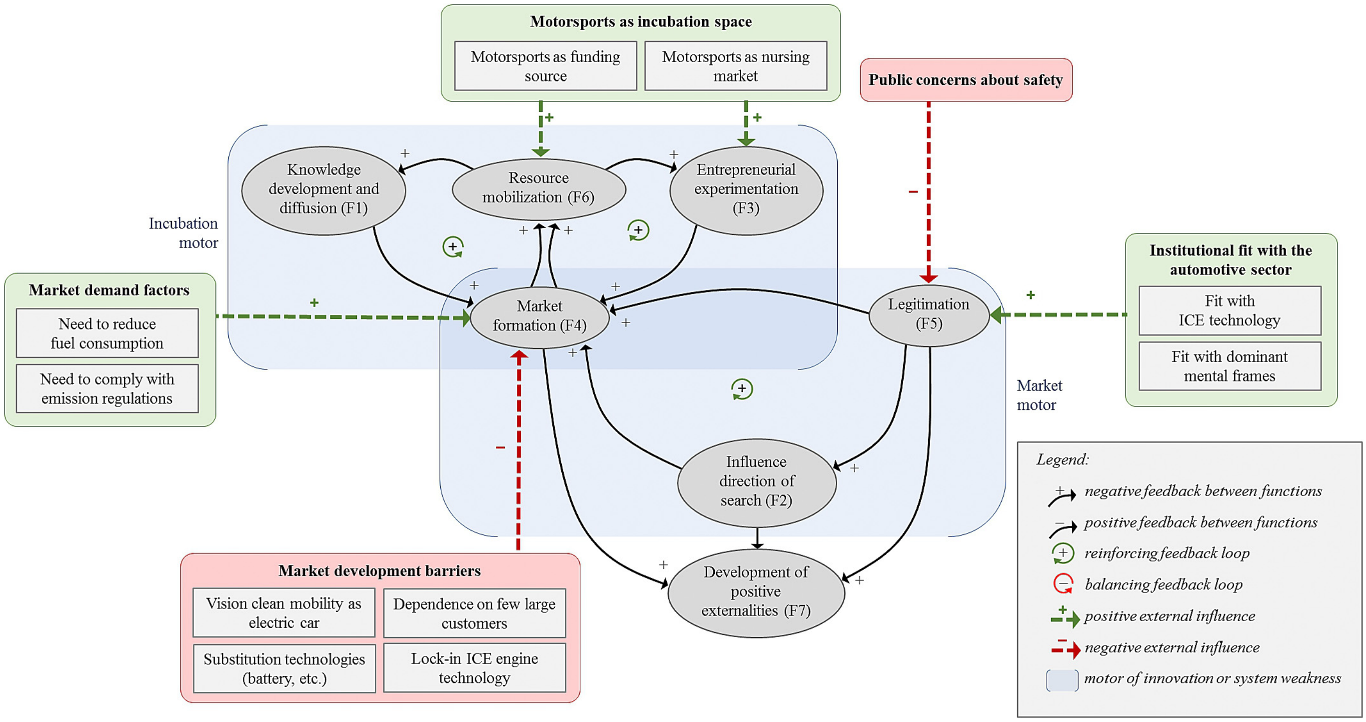


**Fig. 3.** Innovation dynamics in the automotive subsystem (system dynamics representation based on Sterman, 2000).

feedback loops – as well as the positive and negative influence of external factors. The first motor, the incubation motor, provided an experimentation space and important funding in the early market formation phase. It was fueled by the presence of motorsports, which allowed the mobilization of financial resources (F6) for the development of knowledge (F1) and for testing the technology in real-life applications (F3). Furthermore, motorsports acted as a nursing market (F4), which some firms successfully used to develop other markets.

The second motor of innovation, the market motor, was later induced by two external factors. The first relates to the favorable market demand arising from vehicle manufacturers' need to reduce fuel consumption and comply with tighter emission standards, which provided a window of opportunity for clean vehicle technologies. Indeed, engineering firms were already developing micro-HSF when vehicle manufacturers began to search for solutions to comply with emission regulations and when some large fleet operators became interested in reducing volatile fuel expenses. A market opportunity emerged (F4) and some engineering firms successfully positioned micro-HSF as a mid-term solution in the transition to the all-electric car. This market opportunity strengthened the motivation of other actors to support the innovation system (F2), aided market formation (F4), increased legitimacy (F5) as customers articulated a demand for the technology, eased access to resources (F6), both through co-development with customers and by means of government subsidies, and eventually strongly contributed to developing positive externalities (F7). The second factor relates to the good institutional fit with the automotive sector and in particular the similar underlying physical and mechanical principles of the flywheel and the ICE technologies. Indeed, flywheels fit the mental frames and the competences of automotive players, who rapidly came to understand their benefits. This proximity made the technology more interesting for new actors to join the TIS (F2) and supported its legitimacy (F5).

However, hindering factors in the form of market entry barriers and safety issues work against micro-HSF development. First, the vision of the battery-powered electric car as the ultimate clean vehicle dominates discussions on clean mobility. Second, in line with this vision, several leading automakers are working to develop the battery technology, which is the main competitor of micro-HSF. Third, other less innovative automakers are still pursuing incremental improvements in the ICE and consequently are becoming interested in complementary, mid-term solutions to improve its efficiency, such as micro-HSF. Therefore, while flywheels are becoming established in the mid-term solution niche market, paradoxically, this positioning might well confine it there, making it less suitable to diffuse to mass markets. Fifth, and perhaps most importantly, automotive markets are problematic as they are dominated by a few large firms controlling market access. Thus, diffusion depends on these firms adopting the technology (F5). Finally, safety issues still reduce its legitimacy, which may prevent some actors from adopting it. TIS actors will need to overcome these factors to become established in automotive markets.

### 5.2. Dynamics in the electricity subsystem

In the electricity sector subsystem, the dynamic is influenced by one main positive external influence: the political demand and technical need for storage to stabilize the grid for greater penetration by renewable energies (see Fig. 4). This demand supports market formation (F4), influences corporate R&D programs (F2) and legitimates HSF development (F5).

Two important system weaknesses (Jacobsson and Bergek, 2011) counteract the clear demand for storage and explain the overall stagnation. Fig. 4 illustrates these weaknesses as a number of negative interactions between functions that form negative feedback loops and culminate in system weaknesses. The first is an institutional weakness caused by two external factors. The first is the unfavorable institutional environment and the little attention that HSF receive. Indeed, there is simply no demand for

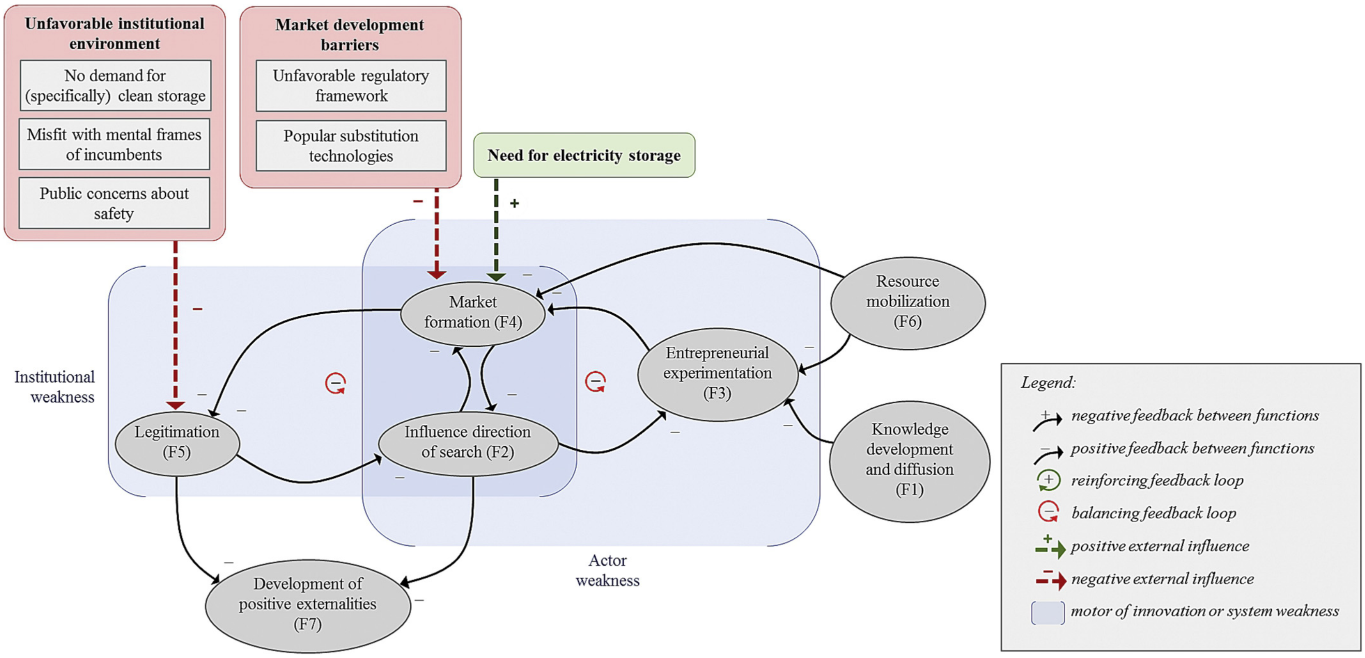


**Fig. 4.** Innovation dynamics in the electricity subsystem (system dynamics representation based on Sterman, 2000).

environmentally-friendly storage (negatively influencing F5), which is however the main advantage of HSF. As the environmental performance of mainstream storage technologies has escaped scrutiny, actors are guided away from clean storage (F2). Consequently, HSF is not seen as creating benefits for other actors (F7). Then, HSF do not fit the mental frames of the incumbents (or the public), who expect a battery (i.e. a chemical, non-rotational device) for storage. Finally, safety issues, negatively affect FES legitimacy (F5). End-users are reportedly afraid of fast-rotating flywheels, a fact which seems to have been purposefully instrumentalized by incumbents (Smink et al., 2015) to reduce HSF acceptance. The second external factor relates to market development barriers. The regulatory framework of the emerging storage market is unfavorable to HSF, providing a possible explanation for why there is so far no market for HSF in this sector (negatively influencing F4). Then, there is the fact that batteries represent a very popular and affordable substitution technology, are currently technologically more advanced, and as a result receive a much greater share of subsidies (thus also negatively influencing F4).

A second system weakness explains that HSF are also not performing well in markets less dependent on this institutional context (such as the market for UPS). This second weakness relates to actors (Jacobsson and Bergek, 2011) and their poor organizational capabilities. It is fueled by four internal factors (see also section 4). First, several actors focus on the engineering and put commercial matters in the background, negatively affecting market-related experimentation (F3). Second, partly because of their strong focus on engineering, many actors have only a weak knowledge about possible applications and related markets (F4). Also, they are not organized in an association or in lobbies, which hinders knowledge exchange among them (F1), preventing the collective organization of legitimation activities (F5), and preventing them from organizing effectively as an industry branch in competition with substitution technologies (F2). Finally, firms are often small and less professional, which can explain their difficulties to mobilize resources (in particular access to public funding) (F6). Finally, there is no vibrant community with clear business objectives that would attract new actors (F2) or create positive externalities (F7). Taken together, these factors create a strong system weakness centered on the negative feedback loop between direction of search (F2), entrepreneurial experimentation (F3) and market development (F4) but ultimately involving most TIS functions: slow diffusion of knowledge (F1), reduced ability to experiment (F3), to penetrate (or develop) markets (F4), to advertise and lobby to increase legitimacy (F5), and to mobilize resources (F6).

### 5.3. *Influence of contextual structures*

This analysis of innovation system dynamics reveals the influence of two types of contextual structures (Bergek et al., 2015): relevant industry sectors and competing TIS. The interaction of the TIS with these external structures is discussed in the following subsections and is illustrated in Fig. 5.

#### 5.3.1. *Industry sectors*

The interactions of the focal TIS with the automotive and the electricity sectors (interactions I1 and I2 respectively in Fig. 5) is so strong that two subsystems emerged that are coupled to these industry sectors. Indeed, the sectors are so different that this situation brought the actors of the focal TIS to specialize in the one or the other sector. These differences are located at two levels. First, the two sectors have different technological needs: the automotive sectors a relatively small (in watt-hours), compact, and shock-resistant FES whereas the grid needs large (in watt-hours) and scalable FES with minimum inertial losses to store energy over longer time periods (see also Section 2.1). These diverging needs imply that actors would need to develop different products for the different sectors (and their related markets), which can explain their choice of specialization for the one or the other.

Second, the institutional contexts of the two sectors are very different. This difference strongly influences the actors' strategies (Kishna et al., 2011) in promoting the technology and overcoming path dependencies. In the automotive sector, path dependency relates to the use of the ICE as a propulsion system and the related infrastructure, mental frames, and competences. Here, actors appear to meet the need for less emission intense vehicles. On the

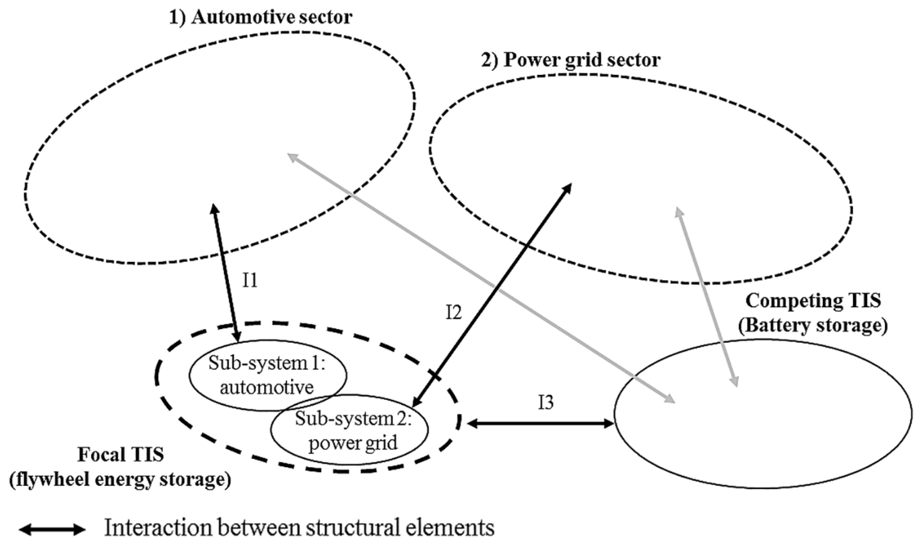


**Fig. 5.** Interactions between the focal TIS and contextual structures (based on Markard and Truffer, 2008).

other hand, in the electricity sector path dependency relates to the paradigm of the large centralized power generation system. In this sector, actors for instance try to play a role in balancing power markets. In addition to the different technologies needed, promoting the FES in these two sectors involves different strategies. Thus, the strongly differing institutional settings may further explain that actors specialize in one sector, as competing in both sectors would be too resource intensive.

#### 5.3.2. Competing TIS

The focal TIS is also influenced by developments in competing TIS. First and most important, the focal TIS is influenced by the rapidly growing battery TIS (interaction I3 in Fig. 5). Batteries are a more mature technology and represent a substitution technology (Norton and Bass, 1987) to FES. Therefore, in most applications, batteries and FES compete for the same function of short-term storage. Both TIS also compete for attention in public and political discussions about storage, but batteries are currently leading the technological competition (Eggers, 2012), and are therefore not threatened by developments in the FES innovation system. The two TIS are coupled in the grid sector in shaping the emerging regulatory framework on grid storage. In some cases, the battery TIS also positively influences the focal TIS. It supports the electricity subsystem of the focal TIS by advancing political and public discussions on grid storage, which also increases the legitimacy of FES. Furthermore, batteries act as a bridging technology (Sandén and Hillman, 2011), paving the way to alternative storage technologies. Finally, batteries create funding opportunities for storage in general, which FES may benefit as well. In the automotive subsystem, competition with batteries is also strong, primarily because batteries shape the vision of the ultimate clean car, one that is battery-powered. However, to some extent batteries also support micro-HSF by creating this clean car vision. Indeed, some manufacturers have become interested in less radical clean vehicle solutions and are searching for a mid-term solution. This creates a market in which some micro-HSF manufacturers are positioning themselves.

A second less influential TIS-TIS interaction is observed between the German and the US-based FES innovation system. The main influence observed is that the US-based TIS contributes to legitimize the focal TIS and positively influences its search direction (see also Section 4.2). Thus, the US-based TIS plays a supporting role.

## 6. Discussion

Our qualitative case study results draw attention to nontechnological factors related to the development of clean storage technologies, in particular the importance of institutional fit with the targeted industry sectors. Moreover, the case provides insights into the reasons why this clean technology is almost completely ignored, amongst others for political and national competitiveness reasons (in the context of large scale efforts to develop the battery as a core technology in the German energy transition). The next sections discuss the implications for researchers, practitioners, and policymakers.

### 6.1. Implications for researchers

Our research contributes to TIS literature in two ways: first, we innovate in the way TIS dynamics can be communicated and, second, we contribute to the current discussion on contextual structures.

First, we use system dynamics representation (Sterman, 2000) to illustrate TIS dynamics. In our view, a weakness in the TIS literature lies in the lack of visual tools to communicate the dynamics within the TIS – specifically, between system functions and contextual elements. While some authors have used static models (Alkemade et al., 2007; Bergek et al., 2007; van Alphen et al., 2008), others have used system dynamics models (Negro and Hekkert, 2008; Negro et al., 2008; Suurs et al., 2009), but only for theoretical purposes and without applying it to their findings or including contextual elements. While system dynamics enables a relatively simple visualization of TIS dynamics, we struggled with properly representing the hierarchy of the system, that is, the relationship of different system components to each other (Featherston et al., 2012). To keep the illustrations simple, we decided to represent only the most important relationships. Consensus about which relationships to represent was based on an iterative dialogue process between the two co-authors, knowledgeable colleagues, and feedback obtained at conferences.

The second contribution relates to the recent critique that TIS analysis is too focused on internal processes and dynamics (Jacobsson and Bergek, 2011; Markard and Truffer, 2008), thus neglecting contextual elements, which are merely treated as external factors, with the risk that influential processes external to the focal TIS are not fully captured. To better account for these, Bergek et al. (2015) proposes that four contextual structures should be considered: technological, sectorial, geographical, and political. Our case shows the role two of these structures plays (sectors and competing TIS) and contributes to better understanding their influence on the focal TIS. First, with regard to sectors, we show that specialized subsystems can emerge within the focal TIS when it is closely coupled to industrial sectors with strong differences in technological needs and/or institutional settings. Specialization is particularly likely to occur in a TIS in the formative stage (Bergek et al., 2008b; Suurs et al., 2010), which means that technology specialization is still low and thus the number of possible applications is high. We argue that a typical bottleneck at this stage is that entrepreneurial experimentation is too weak in relation with the many possible future markets in which the technology could be established. To overcome this bottleneck, TIS actors may benefit from focusing their activities on one industry sector – the one with the best institutional fit – in order to avoid their efforts being fragmented in the pursuit of too many uncertain directions. Therefore, the emergence of specialized subsystems may be the result of actors specializing on one sector when the TIS is closely coupled with several. Second, with regard to competing TIS, we concur with Bergek et al. (2015) that the relationship can be not only competitive, but also supportive or even symbiotic (Sandén and Hillman, 2011). We show that supportive and symbiotic relationships, which have been less well researched, can play an important role as well, for example when the competing TIS helps bring the storage topic into political discussions. In fewer cases, symbiotic interactions were observed as well, for example when the focal technology complements the competing one. Our case study thus provides evidence for the importance of these two contextual structures to understand TIS development.

Future research should further examine the influence of contextual structures on the direction of TIS development, particularly the role that coupling with multiple sectors plays on the direction of search of TIS at the formative stage. In this context, the role of actor strategies should also be further investigated, both of incumbents who may support or resist TIS development and how TIS members react to this. Another avenue for future research is to examine how competing TIS at different stages of maturity (such as batteries and flywheels) co-evolve and influence each other in the energy transition. Understanding how they interact – in ways other than competition – could help further improve innovation support policies, particularly to avoid lock-in situations of rapidly emerging but suboptimal technologies.

### 6.2. Implications for practitioners

This research demonstrates the importance of non-technical aspects in technology development, as FES development was shown to be very different in the automotive and the grid-related sectors. Given that the electricity grid subsystem is developing less well, we also provide insights for practitioners working in this context. First, our findings show that individual actors likely have only a limited influence on the current institutional development as powerful lobbies are shaping the future regulation of grid storage. Practitioners would benefit from developing applications less dependent on electricity grid regulations, such as in the growing global market for UPS or for island grid stabilization, where regulatory pressure is lower as is pressure on prices.

Second, practitioners may be able to decrease the actors' weaknesses (Section 5.2). The innovation system is composed of many smaller actors that share similar commercial objectives. They could benefit from joining forces in some areas while remaining in competition in others. In the early pre-competitive stage of industry development, such "co-opetition" could foster valuable synergies. For instance, forming professional networks could improve the image of this nascent industry, contribute to increase its legitimacy and visibility, and thereby possibly attract new actors. Further, partnerships with larger industrial groups could ease access to financial resources and to various competences (such as marketing). Finally, a clearer commercial perspective, instead of focusing solely on engineering tasks, would help target R&D efforts to specific markets and understand how technical knowledge can be turned into a commercial product. Beyond suggesting practitioners to reduce their actor weaknesses, this research also shows that TIS dynamics significantly influence innovation practices at firm level (Pohl and Yarime, 2012). Hence firms benefit of adjusting their (internal) innovation management to the specific TIS context and, particularly in pre-competitive stages, coordinating it with other actors.

### 6.3. Implications for policymakers

The most alarming finding for policy makers is that environmental criteria for storage technologies have hardly been considered to date in the context of the energy transition. The rapid diffusion of hazardous batteries might create important rebound effects, at the latest when they need to be disposed of. Therefore, policymakers are strongly advised to consider the environmental impact not only of energy generation but also of storage technologies.

Policy support for storage has so far been technology neutral, which is a minimum condition for FES development but not sufficient, according to Jacobsson and Bergek (2011). The flywheel case shows that technology-specific support is also needed. Indeed, the policy framework is being successfully shaped by the leading technology (battery) actors. In the early development phases, competition is more about actor expectations and political power than about technological performance (Alkemade and Suurs, 2012), with the risk of being locked-in into a suboptimal technology that prevents better technologies from diffusing. Therefore, less well organized TIS are disadvantaged, unless a technology-specific support for a range of alternative technologies is provided.

### 6.4. Limitations

The most important limitation of this paper relates to the delineation of the innovation system boundary. The analysis would benefit from a more systematic study of the processes and dynamics taking place a) in the two industry sectors the flywheel TIS plays a role in, b) in the competing battery TIS, and c) in the US-based FES innovation system. Another limitation is the use of system dynamics representations to communicate TIS dynamics. Indeed, a known weakness of these representations is the poor depiction of system hierarchy and temporal dimension (Featherston et al., 2012).

## 7. Conclusion

The paper shows that FES is almost a fully mature technology that is being commercialized – though at different speeds – in several markets. Through its low environmental impact and high efficiency, FES could play a beneficial role for the energy transition in many short-term storage applications. However, its diffusion is below its potential. The findings of the qualitative case study explain this situation and reveal how modern FES are emerging in the automotive and the electricity grid sectors.

In the automotive sector, micro-HSF is developing well as a braking energy recovery technology and is close to introduction in mass transportation markets. Development was fueled by two motors of innovation. First motorsports provided an important technology and market incubation space. Second, development was favored by market demand and a good institutional fit with the automotive industry. Further development is uncertain because it strongly depends on technology adoption by major incumbents.

In the electricity sector, HSF is developing in various markets but stagnating at the stage of demonstration projects because of two system weaknesses. The first, an institutional weakness, relates to the absence of a clear role for HSF in the energy transition. Indeed, environmentally-friendly storage is not demanded, which is HSF's most important advantage. HSF does not fit dominant mental frames about storage, and the emerging markets are strongly shaped by more popular substitution technologies (batteries). The second is an actor weakness that relates to their weak organizational capabilities. Many actors lack a clear market perspective and are weakly organized, which prevents them to establish as an industry.

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**Paper 3**

Structural ambidexterity, transition processes, and integration trade-offs: a longitudinal study of failed exploration

R&D MANAGEMENT

# Structural ambidexterity, transition processes, and integration trade-offs: a longitudinal study of failed exploration

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**In order to overcome the exploration–exploitation paradox, structural ambidexterity literature suggests establishing differentiated units for exploitation and exploration with a carefully managed exploration–exploitation interface supporting cross-fertilization without cross-contamination. Recent research demonstrates the crucial role of integration mechanisms (i.e. how knowledge exchange between exploratory and exploitative units can be organized) and related transition modes (i.e. how exploratory innovations can ultimately be transferred back into the exploitative structures of core business) to deal with this challenge. However, a systematic account of the diverse tensions, risks, and trade-offs associated with integration which may ultimately cause exploration failure is missing, so far. This paper presents a longitudinal process study uncovering the anatomy of an unsuccessful exploration of (green) technologies by a medium-sized entrepreneurial firm. We investigated their transition processes to understand how the managers dynamically configured and reconfigured the exploration–exploitation interface over time. Our theoretical contribution lies in providing a framework of six integration trade-offs (Exploratory-complementary linking vs. contamination; Seeking legitimacy early on vs. frustration at discontinuation of innovation; Boundary spanning through job rotation vs. carrying over of old culture; Early vs. premature transfer; Reorganization vs. capability mutation; and Improved access to core business resources vs. resource starvation) linked to three phases in the transition process (before, at, and after transfer). We also highlight mechanism, pulling-forward, and streamlining-related failures linked to integration trade-offs in resource-constrained contexts. Our implication for R&D and top management is that the use of integration mechanisms for structural ambidexterity bears the risk of cross-contamination between the exploitative and exploratory structures and are therefore inevitably linked to trade-offs. To minimize negative side effects and prevent exploration**

Correction added on 24 November 2018, after first online publication: an error in the affiliation details of the first author has been corrected

**failure, organizations have to consciously select, schedule, operationalize, and manage (re)integration mechanisms along the transition process. Our framework of integration trade-offs systematically supports managers in their organizational design choices for integration mechanisms in the transition processes.**

## 1. Introduction

In uncertain, volatile, and rapidly evolving industries, the simultaneous orchestration and balancing of exploration and exploitation is necessary for long-term survival (Cesaroni et al., 2005; O'Reilly and Tushman, 2008). Firms with this capability are called ambidextrous organizations. To facilitate cross-fertilization between exploitative and exploratory structures without cross-contamination (O'Reilly and Tushman, 2004), following the call for research by Raisch (2008), Lavie et al. (2010), Gassmann et al. (2012), and O'Reilly and Tushman (2013), recent research in ambidexterity has focused on the management of the exploration–exploitation interface. Of particular interest are integration mechanisms (or tactics) to loosely couple exploitation and exploration (Jansen et al., 2009) as well as related transition modes for ultimately reintegrating radical innovations back into the core business (Gassmann et al., 2012; Chen and Kannan-Narasimhan, 2015).

While current literature mostly considers the integration of differentiated units as key to tapping into the 'energizing potential' of the exploration–exploitation paradox (Andriopoulos and Lewis, 2009), some scholars emphasize the tensions, risks, and dysfunctional effects involved in bridging differentiated units (e.g. Raisch, 2008) and in reintegrating exploratory units back into the core business (Durisin and Todorova, 2012). It therefore seems that while integration mechanisms are crucial to dealing with the exploration–exploitation paradox, they are also linked to drawbacks and potential failure, together representing trade-off situations.

In the resource-constrained contexts often observed in small and medium-sized enterprises (SMEs), these tensions increase because maintaining differentiated units for exploration and exploitation is more difficult (Voss and Voss, 2013) and core business involvement is expected earlier in the transition process (Chen and Kannan-Narasimhan, 2015). Against this background, our overarching research question is: *What role do integration mechanisms play in exploration failure, particularly in resource-constrained contexts*? To answer this question, we ask: *What* integration trade-offs exist? *When* in the transition process are they relevant? And *how* do they lead to exploration failure?

To inform these research questions, we integrate previously scattered literatures on formal and informal integration mechanisms (Jansen et al., 2009; Chen and Kannan-Narasimhan, 2015), organizational linkages (Taylor and Helfat, 2009), cross-functional ambidexterity across product and market domains (Voss and Voss, 2013), transition modes (Gassmann et al., 2012), radical innovation capability (O'Connor and DeMartino, 2006), and capability mutation (Durisin and Todorova, 2012). Based on this interdisciplinary approach, we aim at studying structural ambidexterity and its related integration processes as dynamic phenomena unfolding over time. We follow methodological suggestions by Simsek et al. (2009) and answer the research questions using an in-depth longitudinal case study. In contrast to current studies using longitudinal research designs in large firm contexts (Gassmann et al., 2012; Zimmermann et al., 2015; Raisch and Tushman, 2016) or design consultancies (Andriopoulos and Lewis, 2009), we studied a medium-sized technology firm. Also, the focus of prior longitudinal studies was on success patterns in using integration mechanisms or tackled only individual trade-offs (Durisin and Todorova, 2012), while our aim is to systemize existing tensions and trade-offs. Investigating a period of 13 years enabled us to cover a full exploration and transition process, while other studies cover only part of the transition process (Zimmermann et al., 2015).

The results of this study enable us to contribute to theory in the following way: To the best of the authors' knowledge, our article is the first to give a systematic account of the tensions associated with using various integration mechanisms. More specifically, we develop a framework for analyzing integration trade-offs in the transition process. This gives insights into the dynamics of exploration–exploitation interfaces over time (Gassmann et al., 2012; Chen and Kannan-Narasimhan, 2015) at the 'ground level' (O'Reilly and Tushman, 2013, p. 327). Finally, we also contribute to the growing research on the exploration–exploitation interface in resource-constrained contexts (e.g. Lubatkin et al., 2006; Voss and Voss, 2013) and show that greater streamlining of integration processes leads to higher risks of cross-contamination.

## 2. Literature review

Pursuing exploration and exploitation simultaneously in a value-enhancing way is considered a challenge of managing paradoxes because these activities represent 'synergistic and interwoven polarities' (Smith and Tushman, 2005; Andriopoulos and Lewis, 2009; Raisch et al., 2009; Zimmermann et al., 2015). One way to managing the tensions linked to these paradoxes is to pursue both types of innovation in structurally distinct units while at the same time addressing the need for cross-fertilization (O'Reilly and Tushman, 2004) by bridging them through integration mechanisms (Andriopoulos and Lewis, 2009; Jansen et al., 2009; Gassmann et al., 2012). This paradoxical relationship is expressed as, for instance, interdependence between seeming opposites (Andriopoulos and Lewis, 2009), differentiated subunits with clearly defined interfaces (O'Reilly and Tushman, 2013), or separate units which are purposefully interdependent (Simsek et al., 2009).

According to O'Reilly and Tushman (2008, p. 191), the main leadership task is not to create structurally independent units but 'the processes by which these units are integrated in a value enhancing way' (cf. Jansen et al., 2009), which then represents a dynamic capability (Raisch et al., 2009). Indeed, integration is largely represented as the holy grail of managing the exploration–exploitation paradox successfully (Jansen et al., 2009; Gassmann et al., 2012; Chen and Kannan-Narasimhan, 2015). In the following, we engage in a critical review covering, on the one hand, how integration is pursued using overarching transition processes and individual integration mechanisms and, on the other, which new tensions emerge due to such integration measures.

### *2.1. Transition processes and resource-constrained contexts*

In our longitudinal study, we focus on the time dimension and in particular transitions as the overarching context for integration. Transition processes begin after the initial ambidexterity structure has been put in place (see Zimmermann et al., 2015 for the charter definition process prior to implementation), and can be described as the phase in which innovations develop from the purely exploratory to the purely exploitative space (Raisch and Tushman, 2016). Particularly in technology-oriented contexts, when once strongly separate exploratory units enter later stages of the innovation life cycle, they may be switched to more integrated structures (Durisin and Todorova, 2012; O'Reilly and Tushman, 2013), following a natural sequence from discovery to commercialization (Simsek et al., 2009). In the transition process, research increasingly focuses on the time dimensions by shifting toward analyzing *when* and *how* to pursue a *re*integration from exploratory into exploitative spaces (Durisin and Todorova, 2012; Chen and Kannan-Narasimhan, 2015). We will refer to the overall process of reintegration as the transition process, while we refer to the actual switch of an exploratory innovation project into the institutionalized processes of the core business as the actual 'transfer'. O'Connor and DeMartino (2006) differentiate three sub-phases necessary before actual transfer: the generation of radical new ideas ('discovery'), new business models ('incubation'), and an adequate sales volume ('acceleration').

Though others have argued that exploration and exploitation are characterized by a parallel (i.e. both can be pursued simultaneously) rather than orthogonal (i.e. competing) relationship (O'Reilly and Tushman, 2008), on the organizational level both ultimately compete for scarce resources and require trade-offs (March, 1991; Lavie et al., 2010). Given that studies on transition processes have predominantly focused on large multinational corporations, this may have played a minor role. These companies usually pursue organizational ambidexterity with a *permanent* radical innovation unit producing a continuous stream of exploratory projects, which are then considered for reintegration (Gassmann et al., 2012; Chen and Kannan-Narasimhan, 2015; Raisch and Tushman, 2016). In contrast, competition for resources across exploitation and exploration is a significant challenge for SMEs (Cao et al., 2009). SMEs have in general fewer resources and specifically often lack slack resources (Chang and Hughes, 2012). SMEs are therefore much more constrained in managing and staffing physically and culturally separate units for exploration and exploitation as these parallel structures require more resources and increase internal complexity (Voss and Voss, 2013). SMEs are therefore particularly likely to pursue *temporary* ambidexterity because it is relatively resource efficient (Raisch, 2008). Temporal or sequential ambidexterity is defined by periodic switches between exploitation and exploration phases (Lavie et al., 2010), in which the separate temporary exploration units (not only the individual projects) are ultimately reintegrated into the institutionalized processes of the core organization (Siggelkow and Levinthal, 2003; Durisin and Todorova, 2012).

Whether exploratory units are designed as permanent or temporary, recent longitudinal case research on transition processes (Gassmann et al., 2012; Chen and Kannan-Narasimhan, 2015) has unpacked the integration mechanisms involved and how they are dynamically orchestrated.

## 2.2. Integration mechanisms

Initially, integration was considered rather narrowly as the responsibility of the senior management team (O'Reilly and Tushman, 2004). However, in an early contribution by Jansen et al. (2009), integration is considered at various hierarchical levels, most importantly senior management and middle management. On these levels, both informal mechanisms (e.g. social integration, connectedness) and formal (e.g. cross-functional interfaces, rewards) coexist. Jansen et al. stress that while informal integration is necessary, more formal organizational integration mechanisms – which our paper focuses on – are required for ambidexterity. Following Jansen, more recently many scholars have focused explicitly on how the exploration–exploitation interface is improved by various formal and informal integration mechanisms (e.g. Durisin and Todorova, 2012; Gassmann et al., 2012; Chen and Kannan-Narasimhan, 2015; cf. O'Connor and DeMartino, 2006).

Most of the integration mechanisms used in early phases of the transition are based on loose coupling. They aim at deepening knowledge flows across differentiated units yet they retain contradictory processes and a time orientation (Jansen et al., 2009). In the context of this paper, we will refer to these loose coupling mechanisms as *linking* mechanisms. For example, Gassmann et al. (2012) show how 'integrative innovation planning' uses cross-functional boards (including representatives from exploratory and exploitative units) during the transition to involve core business management into radical innovation projects (still) hosted in the exploratory unit (Gassmann et al., 2012).

While linking mechanisms operate across exploitative and exploratory innovation spaces, the later phases of the transition process require a *reintegration* mechanism. Reintegration occurs when the exploratory innovation is transferred back into the exploitative space to benefit from core business strengths in commercialization. This transfer is considered key to successful strategy execution (Durisin and Todorova, 2012, p. 71) because otherwise innovation projects risk never finding their way out of the R&D-focused exploration unit.

## 2.3. Integration trade-offs as a source of failure

While integration mechanisms and the orchestration of transition processes are certainly important to dealing with the tensions linked to the exploration–exploitation paradox (Andriopoulos and Lewis, 2009; Andriopoulos and Lewis, 2010), it is unlikely to be resolved because 'at the heart of any theory that solves a paradox, is another, different paradox' (Poole and van de Ven, 1989). Comparably, in their theorizing on paradox, Smith and Lewis (2011) find that one source of paradox is the dialectic process in which contradictory and interrelated elements are temporarily integrated via synthesis, only to disintegrate later because a fundamental duality persisted.

Against this background, we argue that while integration and the use of integration mechanisms help to resolve the exploration–exploitation paradox on a higher level, they represent new paradoxes on lower levels. As Durisin and Todorova state,

> *there is little direct evidence on how organizational units for incremental and discontinuous innovation can be kept simultaneously separated to prevent cross-contamination and integrated to allow cross-fertilization. (*2012*, p. 69)*

Moreover, there are many risks linked to integration mechanisms and they have so far not been systematically taken into account in the current literature. First, integration always bears the risk of cross-contamination, as the case study analyzed by O'Connor and DeMartino (2006) shows. For example, a strong involvement of core business into decision-making processes concerned with the radical innovation constrains the degree of radicalness (Gassmann et al., 2012) and can weaken the ambition of sustainability innovations (Hahn et al., 2016). Job rotation can lead to contamination of the culture in exploratory units by exploitative mindsets (Durisin and Todorova, 2012). Second, if transfer from exploration to exploitative units is not carefully timed – taking into the account discovery, incubation, and acceleration phases – it risks failure (O'Connor and DeMartino, 2006). In fact, the majority of new business ventures are perceived as immature and are therefore not accepted for transfer

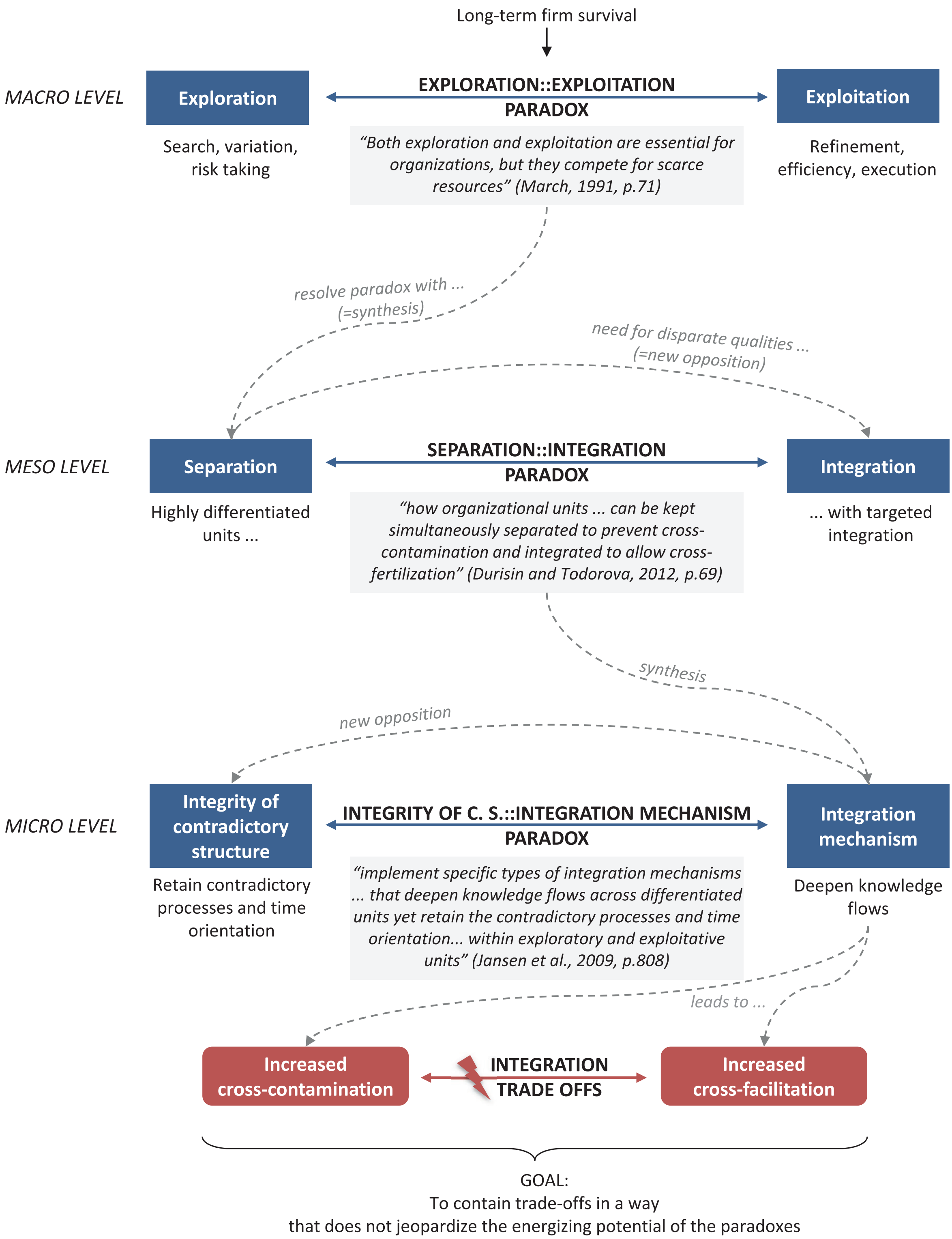


Figure 1. Nested challenges of exploration–exploitation paradox and integration trade-offs: based on a dialectical process following Smith and Lewis's (2011) theory of paradox. Note: C.S. = Contradictory Structure. [Colour figure can be viewed at wileyonlinelibrary.com]

 

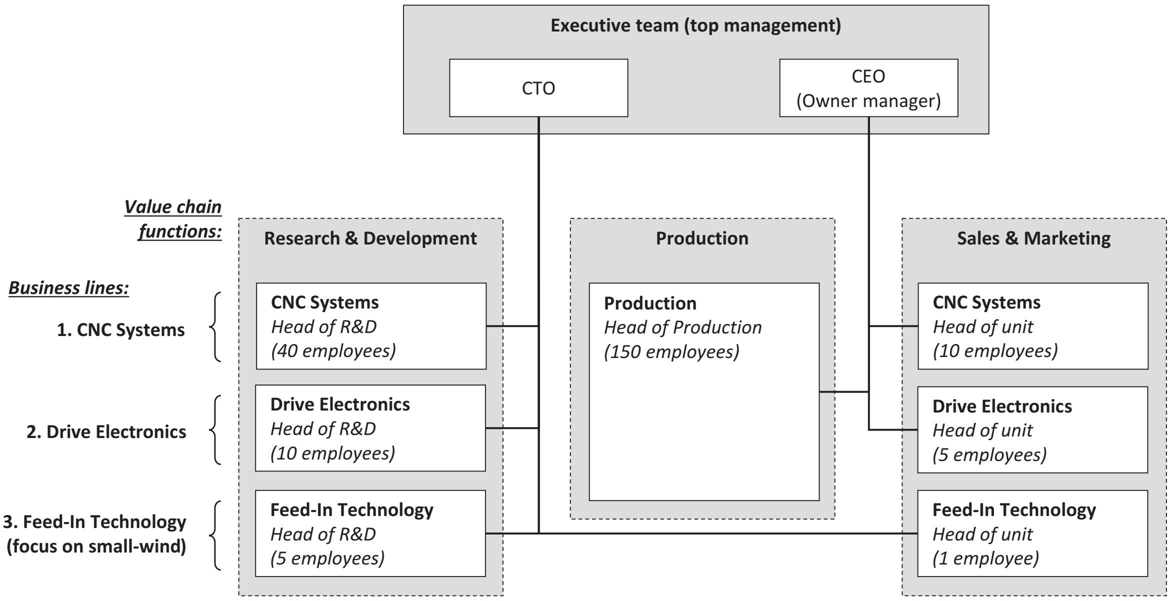


Figure 2. Organizational chart of TechLtd (based on Wicki et al., 2015, p. 8).

by the core business or are discontinued shortly thereafter (Gassmann et al., 2012; Chen and Kannan-Narasimhan, 2015). Therefore, it may be necessary to defend unit independency (Raisch and Tushman, 2016). Third, Durisin and Todorova (2012, p. 70) note that the actual 'reintegration of the new unit [into the core business] may have strong dysfunctional effects' leading to 'capability mutations'. All these examples show that obtaining the benefits of integration mechanisms is linked to some form of cross-contamination. This very well describes a trade-off 'meaning compromise situations when a sacrifice is made in one area to obtain benefits in another' (Byggeth and Hochschorner, 2006, p. 1420). If these trade-off situations are not consciously tackled by R&D and senior managers, they potentially lead to exploration failure.

In summary, the current literature on structural ambidexterity can be described using a dialectical process following Smith and Lewis's (2011) theory of paradox (see Figure 1): the competing demands of exploration–exploitation (*macro*-level) are synthesized by means of structural separation. However, separation leads to a new need for integration, described as a new separation-integration paradox (*meso*-level). Synthesizing these contradictory demands is the aim of integration mechanisms. However, new opposition occurs as the implementation of integration mechanisms also jeopardizes the integrity of contradictory structures (*micro*-level). Ultimately, this micro-level paradox is linked to integration trade-offs because the use of integration mechanisms for cross-fertilization also leads to a risk of cross-contamination. It is the task of the senior management team to carefully design the individual mechanisms within the larger transition process to contain that risk and prevent jeopardizing exploration success. With this understanding, we also contribute to the integration of contradictory perspectives – paradox vs. trade-offs – on the exploration–exploitation challenge (e.g. Andriopoulos and Lewis, 2009).

We now aim at better understanding the individual and cumulative effects of integration trade-offs in the transition process and how this relates to exploration failure through a longitudinal case study.

## 3. Method

### 3.1. Research design

Studying ambidexterity as a dynamic, unfolding phenomenon dictates a longitudinal focus typically involving qualitative research (Simsek et al., 2009; Khanagha et al., 2014). We undertook a longitudinal process study (Huber and van de Ven, 1995) in a medium-sized entrepreneurial high-tech firm (here referred to as 'TechLtd'). Such process studies of single organizations are important to unravelling the underlying dynamics of a phenomenon (Siggelkow, 2007), particularly in the case of *un*successful innovation projects (van Oorschot et al., 2013).

 

## 3.2. Case selection

We followed theoretical sampling (Eisenhardt, 1989, p. 537) with the aim of extending ambidexterity theory. We chose TechLtd as an entrepreneurial SME employing about 220 employees in Germany. The family business, founded in 1962, is owner-managed in the second generation and is a typical representative of a 'hidden champion' (Simon, 2009). It develops and produces electronic components they sell to system integrators. TechLtd has a flat hierarchy, with top management playing key roles in balancing exploration and exploitation (Figure 2).

The case of TechLtd is critical for our goal of theory development (Yin, 2014, p. 41): (i) TechLtd has engaged in exploration and a transition process using various integration mechanisms with an ultimate transfer back into their core business. Hence, while most qualitative ambidexterity studies focus on separation (O'Reilly and Tushman, 2013), our case focuses on reintegration. (ii) While most innovation studies are subject to a pro-innovation bias, our case presents an example of unsuccessful exploration. (iii) As a medium-sized company, TechLtd is a good representative for radical innovation in resource-constrained contexts.

Usually, it is relatively difficult to get (longitudinal) access to an unfolding innovation process, particularly when unsuccessful. We developed a close relationship via engaged scholarship (van de Ven, 2007) and gained intimate access to the organization – making the case also *revelatory* (Yin, 2014).

## 3.3. Data collection

We utilized a combination of retrospective data and real-time observations of the innovation process 'in the making' (Pettigrew, 1990; van de Ven and Poole, 1990; Rogers, 2003, p. 112), together covering a period of approx. 13 years (2002–2015). We were able to observe the last three years of the ongoing innovation process. To assure construct validity and to overcome bias involved in partially retrospective accounts, we used various data sources including semi-structured interviews, participatory observation, focus groups, and desk research (Table 1). We used these multiple sources to collect complementary evidence and, where necessary, triangulate the findings (Babbie, 2013). We covered top and middle management involved in the exploration, including former employees. Semi-structured interviews served to retrace events characterizing the innovation process. The triangulation of interview accounts from current and past organizational managers was particularly important for getting a holistic perspective on managerial decisions and failure and to rule out impression management, political action, and related interviewee tactics (Alvesson, 2003). Focus group sessions were used to understand the motivation of strategic and operational choices as well as to develop a deep understanding of the top management's cognitive representations as they evolved over time. We regularly presented timelines to the interviewees and participants in order to facilitate arrangement of new data, revising their order, or simply seek approval. The interviews were transcribed and other data (e.g. site visits, participant observation) was protocolled (Babbie, 2013).

## 3.4. Data analysis

Our analysis followed three steps. First, in line with the recommendations for longitudinal case

Table 1. Data collection methods

| | Sources | | |
|---|---|---|---|
| Data types | Internal: Top and middle management | External: Business partners and value chain actors | Total |
| Semi-structured interviews | 8 interviews[1] | 10 interviews | 18 |
| Participant observation | 13 meetings | 2 industry events | 15 |
| Focus group sessions | 7 sessions | n.a. | 7 |
| Documents | 25 internal documents (e.g. market studies, technical design descriptions, sales statistics, customer lists) | 70 publicly available documents (e.g. industry reports, market analysis, newspaper and magazine articles and websites of industry actors) | 95 |

[1]Includes interviews with former managers.

 

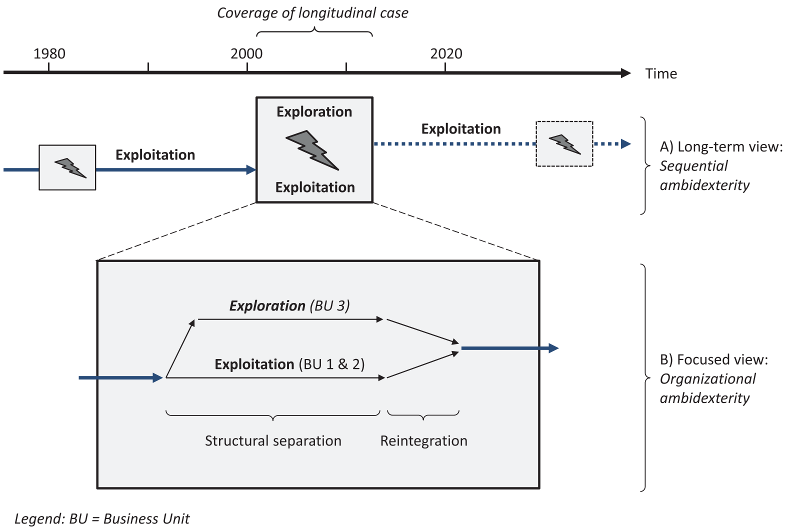


Figure 3. Sequential and organizational ambidexterity over time at case company. [Colour figure can be viewed at wileyonlinelibrary.com]

studies (van de Ven and Poole, 1990; Huber and van de Ven, 1995; Yin, 2014), we started the analysis by reconstructing the timeline of the innovation process. At TechLtd, there are two core business lines, one selling controllers for computerized numerical control (CNC) systems and one producing drive electronics. After a long period of exploitation, TechLtd decided to balance risks, particularly considering the core business was subject to high volatility and competitive pressure. Therefore, they engaged in a period of exploration with the ultimate goal of diversifying and founding a third business line, 'feed-in technology' (Figure 3). The aim of this new business line was to explore how the company could use its engineering competencies for renewable energy technology markets. With a new product for new markets, this third business line represented an ambitious diversification strategy for the company (Ansoff, 1957).

In a second step, we focused on the exploration phase and referred to the fireworks model for longitudinal analysis (Poole and van de Ven, 2000/1989) because it allows for a rich analysis of complex, non-linear exploration processes on the micro-level. Originally, we covered innovation projects targeting fuel cells, small wind turbines, flywheel energy storage, and waste heat recovery (Wicki and Hansen, 2016; see also: Wicki and Hansen, 2017). We analyzed (temporal) events along the innovation trajectory such as setbacks, changes in the search direction, fluid participation of personnel, involvement of top management, evolution in success metrics, cognitive representations, and routines based on tracking ideas, people, transactions, contextual events, and outcomes (Van de Ven and Poole, 1990). We then focused on the most important technology in the exploration process: the feed-in system for small-wind inverters. The exploration process led to a new product, which was transitioned back into the core business but was eventually terminated because of low sales (Figure 4; see also Wicki, 2015).

In the third step, we analyzed the exploration process with the focus on the integration trade-offs. We followed the 'Gioia methodology' (Gioia et al., 2013) by transitioning from inductive to abductive analysis in an iterative process between analysis of data and current literature. To link our emergent concepts with current theory, we used both open and a-priori coding for deriving the trade-offs and their components. Ultimately, we aggregated these codes to a longitudinal dimension representing the phases of the transition process (Figure 5; exemplary quotes in 2).

We employed measures to ensure the trustworthiness of our data (Lincoln and Guba, 1985; Shenton, 2004). To ensure credibility and objectivity, we used *triangulation* and reflexive interpretation (cf. Alvesson, 2003) for integrating diverse and partly contradictory perspectives from various informants. *Multiple investigators* were involved, each taking specific roles allowing for *peer scrutiny*. The first lead researcher was most deeply immersed in the empirical field and prepared the field notes, transcripts, and descriptive case report (Eisenhardt, 1989). The second lead researcher focused on the iterative process of data analysis and theory-building. At major milestones, in-depth discussions between the two lead researchers continued until consensus over the

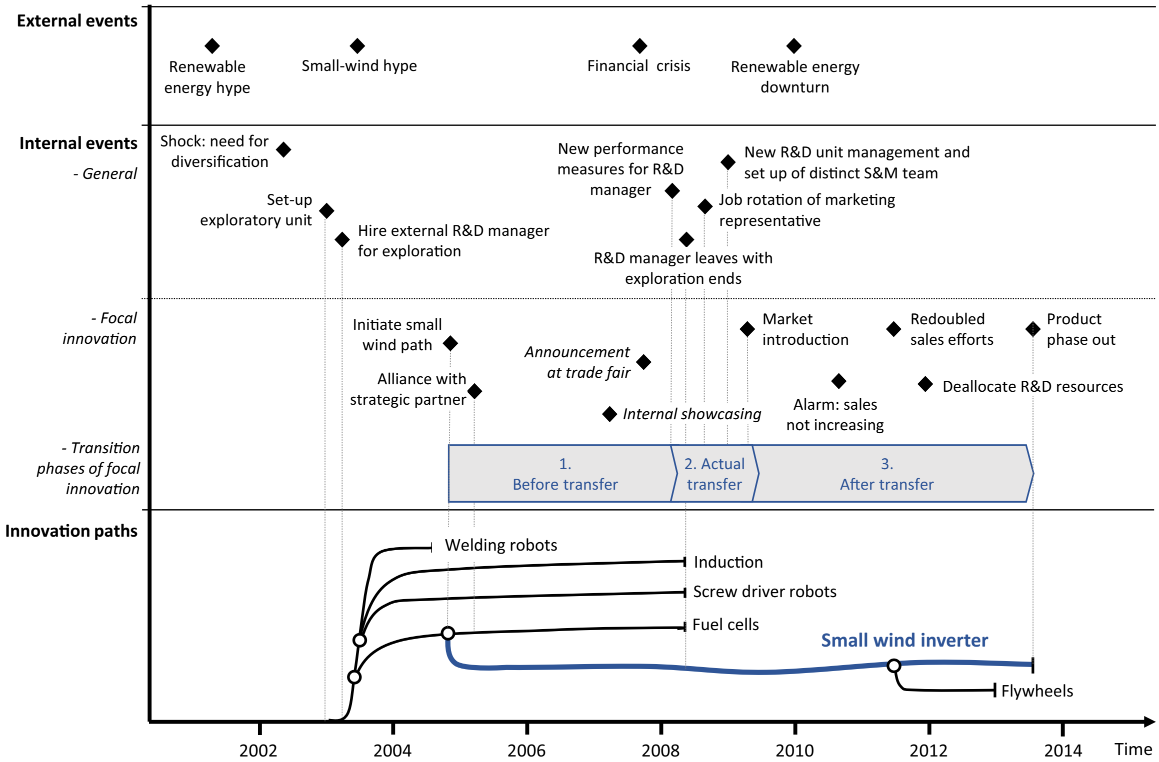


Figure 4. Visualization of the innovation process over time based on innovation phases, innovation paths, internal and external events. [Colour figure can be viewed at wileyonlinelibrary.com]

interpretations was achieved. A third researcher served as a 'critical friend', pointing out theoretical inconsistencies and providing fresh perspectives. *Member checks* were conducted with all management levels.

## 4. Findings

Our analysis of the unsuccessful radical innovation process results in a set of six integration trade-offs (benefits of integration vs. related risks) during various phases of the transition process (see Figure 6 and Table 3). A transition process from originally separate innovation spaces to a reintegrated innovation in the core business covers a considerable time period from (a) linkages in early phases *before transfer*, (b) the *actual transfer* from the exploratory unit to the receiving core business unit to (c) the reorganization and related activities necessary *after transfer*. It should be mentioned that integration trade-offs are not empirically distinct but overlapping and are sometimes causally dependent (e.g. premature integration increases the risk of resource denial by the core business). Each of the resulting integration trade-offs is further elaborated.

### 4.1. *Before transfer*

We identified three risks linked to integration mechanisms used before transfer: exploratory–complementary contamination when complementary assets are used, frustration with (failed) discontinued innovations when external validating or internal legitimacy-building activities were previously involved, and carrying over of the old culture through job rotation.

#### 4.1.1. *Exploratory-complementary linking vs. contamination (T1)*

*Benefits sought through exploratory–complementary linking.* Exploratory units usually follow a mix of developing distinct capabilities and leveraging existing capabilities from established units (Raisch and Tushman, 2016), which we generally refer to as 'exploratory-complementary linking'. This term is derived from Taylor and Helfat's (2009) more specific term of 'core-complementary linking', which describes the use of complementary assets (e.g. marketing, production, financing) in the exploration of new core technologies. This linking intensifies communication across exploratory and

 

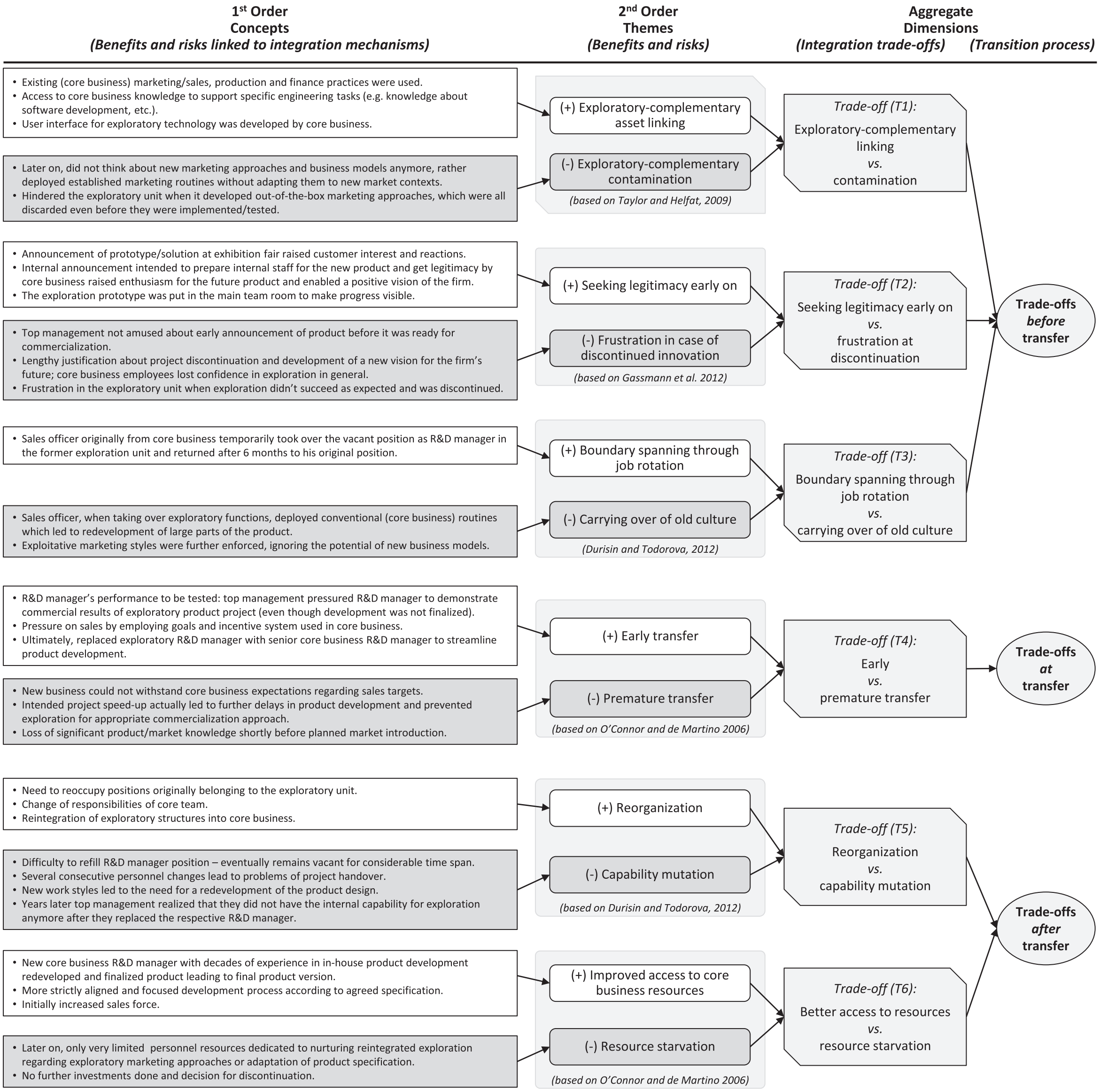


Figure 5. Data structure according to the Gioia Methodology: Integration trade-offs.

exploitative units and aims at increasing the successful commercialization of exploratory projects. This approach is also likely to leverage resource efficiency potential: resource-intense exploration is only done in one function and not in others (in our case, in R&D but not in marketing/sales), an approach also referred to as 'within-functional separation' (Voss and Voss, 2013) or, more generally, 'function domain separation' (Lavie et al., 2010).

At TechLtd, radical innovation in the domain of green energy technology was initially developed in a newly founded separate business unit dedicated to exploration. Therein, exploration initially involved both R&D and marketing activities. Later more and more responsibility for the commercialization of the product exploration shifted to the existing sales and marketing units:

*I had a shared responsibility. Partly I have continued my responsibility for marketing and sales of our current products. With the rest of my time, I dealt with marketing and sales for the new small-wind project. (Head of Sales and Marketing)*

Hence, while R&D exploration was done in the separate unit, commercialization was steered from within the core business structure, thus leveraging existing complementary assets.

*The risk of exploratory–complementary contamination.* While the tight coupling of the new exploratory R&D unit with existing complementary

 



Table 2. Interview data on integration trade-offs

| Transition phase | Integration trade-offs | Quotations | |
|---|---|---|---|
| | Name | (+) Benefits sought through integration mechanisms | (-) Integration risks |
| Before transfer | Exploratory–complementary linking vs. contamination (T1) | CTO: 'At the beginning, for instance, the user interface of the new small-wind inverter was made by the drive electronics people of the core business'.<br>Head of Sales & Marketing: 'In these newly emerging markets [which we explored in the radical innovation unit], we do not have the capacity needed to do effective sales and marketing. We also don't have the team of say five people who can only focus on doing this task … I had a shared responsibility. Partly I have continued my responsibility for marketing and sales of our current products. With the rest of my time, I supported the new small wind project with my knowledge about sales marketing'. | Head of Sales & Marketing: 'Regarding our sales approach, we only do business with OEMs, who then sell to the end-users. In fact, we very rarely have a direct contact with the end-user. We don't like to do that'. [The CEO later stated that a different approach would have been needed]<br>CTO: 'We are used to delivering components to system integrators, but we didn't know much about final customers [of the system] and so we aren't used to delivering full products that satisfy the needs of final customers'.<br>CTO: 'Since in our existing businesses – which were based on close [B2B] customer relationships with rather established and professional firms – we trusted in [end] market information from our immediate customers, such as sales forecasts. However, the information given by these rather new and unestablished customers in immature markets often turned out to be misleading'.<br>CEO: 'It's a good question, in retrospect, whether we shouldn't be dealing more strongly with the final customers, rather than only with our immediate customers as we are used to doing'. |
| | Seeking early legitimacy vs. frustration at discontinuation (T2) | CEO: 'He [the externally hired R&D manager] sold the project very well to the employees as a project paving the way for the future. As a result, the employees were very enthusiastic about it and stuck very much to it'.<br>CTO: 'We placed a prototype of the Aeocon [name of the product] in the staff meeting room so that people could see what it looked like and become familiar with the new product'.<br>CEO: 'The externally hired R&D manager showed the product publicly at industry fairs. Potential customers were interested and even expressed intentions to purchase'. | CEO: 'We were dissatisfied with the R&D manager because he launched our prototype in the marketplace far too early, before we knew about the schedule for the final product design and its commercialization'.<br>CEO: 'It [the discontinuation of radical innovation project] is an important leadership challenge to know how to handle the emotions or disappointments of the people involved [in discontinued radical innovation projects], both in the exploratory units as well as in the core business'. |
| | Boundary spanning through job rotation vs. carrying over of old culture (T3) | CEO: 'Sending the internal sales manager to the small-wind team who already had experience in the exploration allowed for further intensifying the sales and marketing competences in this team and, without the need to hire an additional person, represented a quick solution'.<br>Sales Manager (working temporarily in R&D): 'Then I moved for about half a year to the new business unit. At that time I was the technical manager … With my team I dealt only with the technical development part'. | CEO: 'Since TechLtd makes money by selling products [physical artifacts, not services], no one questioned that we [the new unit] needed to develop a product as well. This logic was also strongly pushed by the sales manager. He believed that an [R&D] idea is only profitable if it can be turned into a product'.<br>Sales Manager (working temporarily in R&D): 'I am to some extent also biased. I only see how we [in the core business sales & marketing department] work and I've been here for 16 years now. Maybe the big industry players like Siemens work differently, but in the drive electronics area where I come from, this is the usual way [to set up a new product development project]'. |

(*Continued*)

Table 2. Continued

| Transition phase | Integration trade-offs | Quotations | |
|---|---|---|---|
| | Name | (+) Benefits sought through integration mechanisms | (-) Integration risks |
| Actual transfer | Early vs. premature transfer (T4) | CEO: 'In an important meeting, which my father [the retired founder] also attended, he argued that each business unit needed to be profitable from the beginning … This gave the impulse that a specific product needed to be developed [and commercialized] as rapidly as possible. Therefore we changed the performance metrics of the R&D Manager from innovation-related to actual sales targets, which forced him to commercialize the product'.<br>CEO: 'It is not that we ran out of money but still the amount spent was relatively large and it seemed too large to justify continuing exploration on a similar scale'. | CEO: [In retrospect] 'The changes in performance indicators in the feed-in business unit came in a very abrupt way and much too early! This change put the [externally hired] R&D manager under huge pressures to quickly generate positive sales figures'. |
| After transfer | Reorganization vs. capability mutation (T5) | CEO: 'We suddenly had the thought: why the hell are we developing a product twice? We need to bundle these products better! Our expertise lies in power electronics … In the end, feed-in is just a part of that, nothing else. Having realized the technological proximity between the feed-in and the drive electronics unit, we began to better integrate them into one business line'. | Sales Manager (small wind project): 'We never really made it to serial production. We only produced about 100 units'.<br>CEO: 'We were unsatisfied with the R&D manager's performance regarding product development and commercialization. But actually, by firing the R&D manager, we lost the capability to explore further – he was really driving that. Afterwards, the exploration unit never worked again in the way it was founded – in fact we lost it'.<br>CEO: 'If we had this vision today [of an ambidextrous organization] and knew the risks [of exploration failure], the externally hired R&D manager would still be in the company today! It was a mistake to fire him'. |
| | Improved access to core business resources vs. resource starvation (T6) | CEO: 'After the externally hired R&D manager left [after integration], the technical development was led by a senior product developer, an internal guy. He already knew the topic because he built a similar device in the past. He brought 40 years of product development experience with him'.<br>CEO: 'I see us as high-speed control provider. Whether that is in the PCB board market or elsewhere, this is and will also be our brand image in the future … In sum, in the feed-in business unit, we also provide high-speed control and that's why we could easily merge it with the drive electronics unit. In the end, we take a high-speed inverter, buy the feed-in component, assemble them and sell them as one product [in renewable energy markets, in a way we do the same as we do in our other markets]'. | CTO: 'But as I said, we didn't find a market for the small-wind inverter. And then, by the end of 2012, we were already starting to slow down a bit on the staff side and finally in 2013 we slammed on the brakes [and definitely closed the feed-in unit]'. |

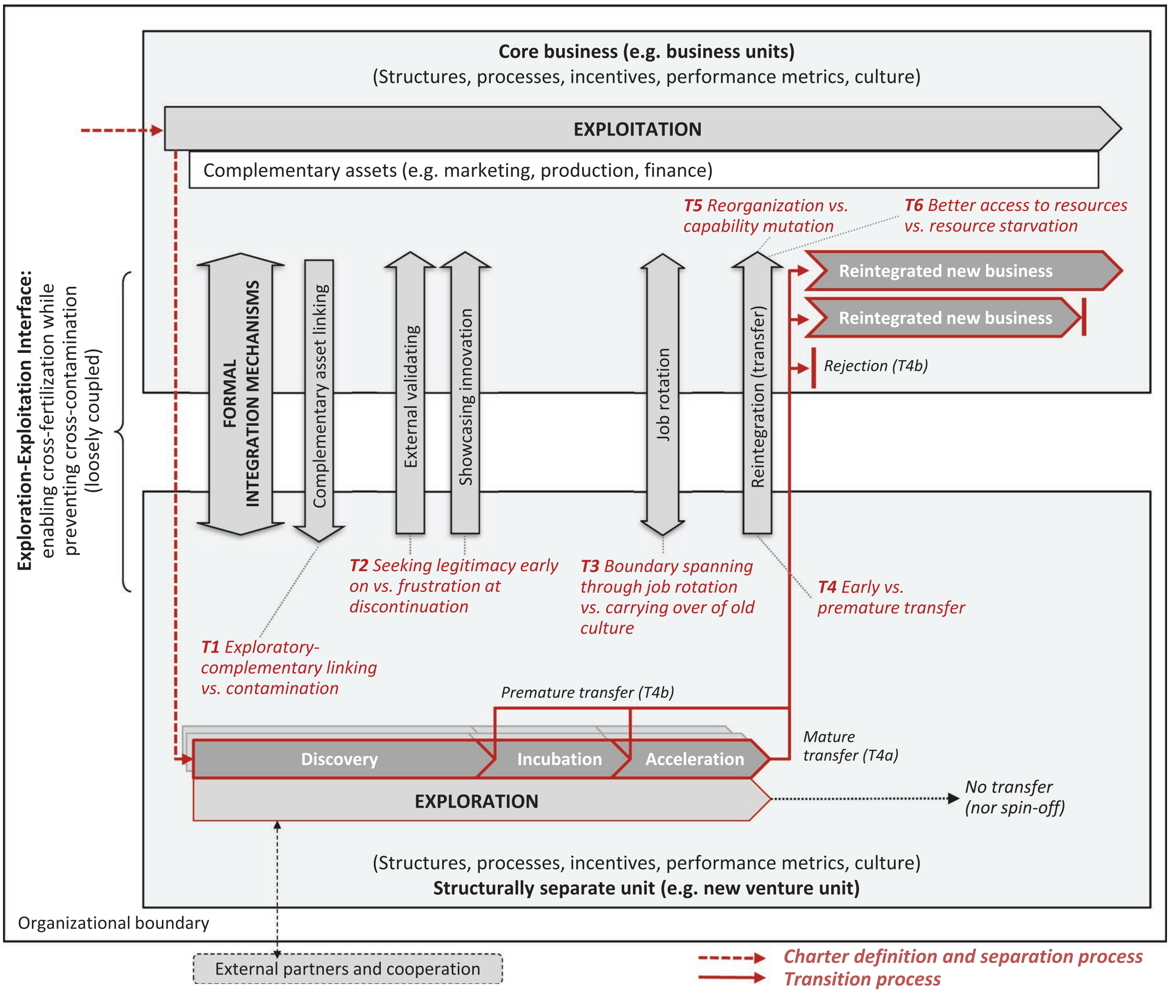


Figure 6. Integration trade-offs in the transition process. [Colour figure can be viewed at wileyonlinelibrary.com]

assets in the exploitative marketing unit through exploratory–complementary linking provided potential for cross-fertilization by increasing communication and coordination and leveraging resource efficiencies, it also risked (exploratory-complementary) contamination of the exploratory space with the exploitative culture. At TechLtd, even though the new markets entered were fundamentally different to the known ones (Table 4), they trusted in their core marketing competences and experience. They also focused on traditional product sales as used in the established business units. As the CEO put it:

*TechLtd makes money by selling products [physical artifacts, not services], no one questioned that we [the new unit] needed to develop a product as well. This logic was also strongly pushed by the sales manager. He believed that an [R&D] idea is only profitable if it can be turned into a [physical] product.*

While initially successful with the acquisition of a limited number of new customers, the marketing unit's assumptions about the new market proved to be wrong. It became clear that if they wanted to have any prospects at all in the premature market, they would need to question their traditional role in the value chain and its related business model and offer full service packages directed at end users by bundling technology with various services which had so far been offered separately in the market. For example, the CTO stated,

*we are used to delivering components to system integrators, but we did not know much about final customers [of the system] and so we aren't used to delivering full products that satisfy the needs of final customers.*

 

Table 3. Integration trade-offs along the transition process

| Transition phase | Integration trade-offs | | | | |
|---|---|---|---|---|---|
| | Name | Related integration mechanism | Benefits | Risks | Further risks due to streamlining in resource-constrained contexts |
| Before transfer | Exploratory–complementary linking vs. contamination (T1) | Exploratory–complementary asset linking | Use of complementary assets from core business (e.g. marketing, production, finance) by new business creates synergies and prevents double asset structures | Cross-contamination (particularly marketing) by increased cross-functional interaction;<br>Use of exploitative core complementary assets prevent exploration and development of new approaches (particularly marketing) eventually needed for developing and commercializing a truly radical innovation | For resource efficiency reasons, organizations may strongly rely on core complementary assets in disregard of the type of exploration project. While effective in conventional product development, this may be ineffective for pure explorations usually requiring dedicated marketing exploration skills. |
| | Seeking legitimacy early on vs. frustration at discontinuation of innovation (T2) | External validating; internal showcasing | Internal showcasing allows the core business to become acquainted with radical innovations early on.<br>External validating presents product idea to lead customers and clarifies market needs. Together, the legitimacy of radical innovation is increased in the organization. | In (likely) case of failure of a specific exploration project, internal showcasing makes it more difficult to unlink emotional bonds; frustration of core business members can follow, possibly hindering future exploration projects<br>External validating raises customer expectations, which need to be managed in case of failure. | Organizations need to demonstrate commercial results quickly and, therefore, may be more prone to communicate early on about exploration results externally with customers or internally with core business staff. This increases likelihood of tying expectations to innovation projects, which are still linked to considerable uncertainty and potential failure. |
| | Boundary spanning through job rotation vs. carrying over of old culture (T3) | Job rotation | Competencies can be rotated between exploitation and exploration units and personnel develop ambidextrous mindset. Once back in the exploitation unit, job rotators are ideal for working on reintegrated innovation projects. | Cross-contamination by carrying over of old culture, particularly from exploitative to explorative units. | Organizations may use job rotation primarily for efficiency potential, for example, using existing personnel (instead of external hiring), thus accelerating the set-up of the exploratory unit.<br>Streamlining may also lead to overuse of dual responsibility positions in exploitative and exploratory units. This makes development of an exploration-oriented culture impossible in the first place, despite a separate unit. |

| Transition phase | Integration trade-offs | | | | |
|---|---|---|---|---|---|
| | Name | Related integration mechanism | Benefits | Risks | Further risks due to streamlining in resource-constrained contexts |
| Actual transfer | Early vs. premature transfer (T4) | Reintegration (transfer from exploratory to exploitative unit) | Early reintegration saves resources and enables the early use of established structures and capabilities often necessary for scaling up and commercialization | Phases of incubation and acceleration – necessary for innovative product to reach maturity – are either skipped or moved through too rapidly, leading to premature reintegration and ultimately to rejection or resource denial by core business | Reduction of resource spending in exploration project or unit and high pressure to shorten exploration increases risk of premature transfer and rejection. |
| After transfer | Reorganization vs. capability mutation (T5) | Reintegration (after transfer) | Once exploratory innovations (or the entire unit) are reintegrated into the core business, redefining structures, processes, and responsibilities becomes necessary and bears the potential for synergies. | Reintegration generally leads to capability mutation (i.e. loss of groups and processes in exploratory and exploitative units) requiring further investments for capability (re)building. Hence, reintegration can lead to losing money, time, and competencies. | Organizations may underestimate efforts and resources required for reorganization. Moreover, these contexts increase risk for premature reintegration (see T4), which leads to stronger capability mutations. |
| | Improved access to core business resources vs. resource starvation (T6) | Reintegration (accommodation within core business) | After reintegration, accommodation within core business saves resources and enables the use of established structures and capabilities needed for commercialization | In comparison to established core business activities, unaligned or premature innovation projects are not considered interesting enough, leading to resource denial, starvation, and ultimate phase out. Also, additional budgets for remaining or additional exploration activities are much more difficult to obtain in core business. | Given tighter budgets in resource-constrained contexts, core business will be a more hostile environment for unaligned, premature, or otherwise needy innovation. |

Table 4. Comparison between old and new markets

| Market criteria | Market of main business line (CNC systems) | Market of new business line (feed-in technology for small-wind turbines) |
|---|---|---|
| Maturity | High | Low |
| Volatility | Low | High |
| Dominant design | Available | Not available |
| Customer-specific development | Important (made-to-order) | Less important |
| Nature of customers | Large companies | Mostly micro-companies; few medium/large companies |
| No. of customers | 20-30 international buyers (medium to large international companies) | 300 very diverse international buyers (micro, small and medium-sized companies alike) |
| Regulatory complexity | Low | High (diverse national regulatory environments for renewable energies increase complexity) |

Overall, two integration drawbacks were faced at TechLtd: First, the attempt to benefit from resource-saving complementary asset reuse, particularly the shared use of sales and marketing staff, led to cross-contamination in that tactics from the core business were reproduced although they were not necessarily appropriate for the new market. The commercialization challenge was ultimately underestimated. Hence, TechLtd followed a 'cross-functional exploration' strategy, although the attention of new markets required 'pure exploration' including both R&D and marketing (Voss and Voss, 2013).

Second, the sales officer divided his time across tasks in both the core and the new businesses, leading to severe time constraints and an opportunistic use of exploitative approaches learned from the core business. Hence, the use of exploitative marketing and commercialization approaches can stem from the dual demands of exploitation and exploration put on individuals – a severe challenge, as research in contextual ambidexterity discusses (Gibson and Birkinshaw, 2004; O'Reilly and Tushman, 2013). Indeed, initially the externally appointed R&D manager of the radical innovation unit also engaged in the exploration of new marketing and sales approaches. But later, when the exploratory–complementary linking was strengthened, this was considerably constrained – not without resistance and disappointment from the R&D manager.

#### *4.1.2. Seeking legitimacy early on vs. frustration at discontinuation (T2)*

*Benefits sought through external and internal legitimacy seeking.* We also identified a trade-off linked to integration mechanisms used in early phases in order to inform, inspire, and prepare the core business with the exploration results and legitimatize the existence of the exploratory activities. Gassmann et al. (2012) identified two mechanisms coined 'internal showcasing' and 'external validating'. Internal showcasing was used by TechLtd, for example, when the prototype of the new small-wind inverter was placed in the company's main conference room. According to the top management, this enabled core business employees to get in touch early on with the innovation. As the CEO recalls the R&D manager's actions:

> *He sold the project very well to the employees as a project paving the way for the future. As a result, the employees were very enthusiastic about it and stuck very much to it.*

Indeed, the exploratory technology became the subject of frequent discussions among the employees. External validating was also pursued: the R&D manager of the exploratory unit involved potential customers early on at trade fairs by announcing commercialization of a superior new technology, trying to create market pull and legitimize the exploration efforts internally.

*The risk of frustration at discontinuation of the exploratory project.* Internal and external showcasing at TechLtd also led to unintended side effects. Technology exploration was no longer perceived as merely trial and error (without a guarantee for success), but rather expectations emerged which were tied to the innovation. This peaked when the prospects of the new technology were exaggerated and it was promoted internally as the successor to the declining core business technologies – so that core business workers developed strong emotional bonds to the innovation and were desperately looking forward to the new technology. Once, however, top management felt more uncertain about its success, they had difficulties detaching core business expectations from the exploration. As the CEO recalls:

*It is an important leadership challenge to know how to handle the emotions of the people involved, both in the exploratory units as well as in the core business.*

This also constrained or delayed decision-making regarding the discontinuation of technology exploration, thus wasting exploration resources.

This process was further intensified by the attempts for early *external validating* by the R&D manager because 'going public' with the premature technology sent additional signals of hope to internal constituencies, which later went unmet. Also customer demand was raised although the company could not immediately satisfy this demand nor give details about the technology's positioning (e.g. pricing). When top management became aware of the independent external validating activities, they held back the R&D manager and installed a more restrictive policy for external communication, as used in their traditional business culture. This shows that integration mechanisms must also fit organizational culture, particularly when the exploratory unit is supervised by top management with ultimate responsibility for integration (Jansen et al., 2009).

#### 4.1.3. Boundary spanning through job rotation vs. carrying over of old culture (T3)

*Benefits sought through job rotation.* One important integration mechanism involves transferring personnel (in contrast to shared use, as in exploratory–complementary *linking* described in T1) through job rotation, enabling boundary spanning between exploitative and exploratory spaces (Durisin and Todorova, 2012; Gassmann et al., 2012). Job rotation can also help save time and resources. This is particularly valuable for SMEs, which often have difficulties to effectively staff and manage multiple differentiated subunits (Voss and Voss, 2013). Job rotation can be used already at the beginning of a transition processes to partially staff the new exploratory unit with core business personnel. But such mechanisms also play important roles later in the transition process. Independent of the timing of the job rotation, employees from the core business can temporarily take over responsibilities in radical innovation projects and then return to the core business, better equipped with an ambidextrous mindset (Gibson and Birkinshaw, 2004). In such a 'liaison channeling', they remain inactive until the transfer of a radical innovation is undertaken in order to bypass the NIH syndrome (Gassmann et al., 2012).

At TechLtd job rotation occurred in the intermediate stage of the transition process, closely linked to the transfer from exploration to exploitation. In this process, top management decided that the sales manager already involved in the exploration (see T1) should fully enter the exploration team. This yielded much knowledge and experience in technology marketing to the explorative unit and strengthened the identification of the core business team with the innovation, but also changed the nature of the exploration process.

*The risk of carrying over of old culture.* With the job rotation put in place at TechLtd, the gradual process from exploratory to *more exploitative* orientation intensified, particularly in the marketing domain. Despite exploratory–complementary linking, some marketing exploration still took place in the exploration unit. However, when the sales manager from the core business temporarily took over complete responsibility for marketing in the exploration unit, a further crowding out of the more exploratory marketing activities could be observed and finally came to an end. The rotated sales manager's approach was to focus on scaling up the current sales strategy and multiplying sales contacts to drive sales volume.

Since employees often tend to retain their values, mental frames, and routines, job rotation bears the risk of carrying over the culture from the core business to the exploratory unit, which can lead to cross-contamination (cf. T1). Consequently, the culture of the old business is replicated, making it difficult to stimulate entrepreneurial behavior (Durisin and Todorova, 2012). Hence, switching successfully between exploration and exploitation needs much more than workforce flexibility (Simsek et al., 2009).

### 4.2. Actual transfer

Further trade-offs exist during the time in which exploration results are actually *transferred back* into the core business.

 

*4.2.1. Early vs. premature transfer (T4)*

*Benefits sought through early transfer.* Generally, it is in the best interest of any firm to transition innovations into its core business as soon as they are mature (i.e. early) and it has received first positive market signals. Particularly for SMEs, a timely reintegration into the core business can be critical, as there are usually few slack resources and at some point in time resources spent in exploration are missing for necessary investments to maintain the core business. At the same time, defending unit autonomy may be important to successfully scale up exploratory business (Raisch and Tushman, 2016) and maintain its orientation (Hahn et al., 2016).

At TechLtd, after five years of exploration and discoveries within the new exploratory structure, the top management reassessed its reintegration strategy. They realized that they had spent considerable resources for exploration and, while this had yielded many discoveries, there was still no viable product. The small-wind inverter was in the process of being incubated, a first generation prototype existed, and market experience through first attempts of commercialization had been gathered. It is not that they were unable to invest more, as top management clarified, but the amount invested was relatively large and it seemed too large to justify continuing exploration on a similar scale.

A full transfer of the temporary exploration unit to the core business was intended from the beginning (Siggelkow and Levinthal, 2003), but it was then initiated much earlier than planned. In a critical executive board meeting showing dissatisfaction with the exploration process, top management decided to bring exploration under tighter control to speed up commercialization. In a first step, they introduced performance targets (i.e. sales-related targets). Also, the exploratory activities were refocused on the main project (small-wind inverter). When performance failed to increase, they replaced the exploratory R&D manager with another employee from within the company. Together modifications in staff responsibilities and performance metrics demonstrate the actual shift from exploration to exploitation and from a clearly demarcated radical innovation unit to a rather conventional R&D project managed in core business fashion.

*The risk of premature transfer.* Before shifting toward exploitation, the small-wind inverter was technologically mature, but not fine-tuned to the multiple customer needs. The innovation team had not spent sufficient resources for the incubation, necessary for exploring alternative business models to successfully commercialize the technology – therefore representing a premature transfer. The CEO later recalled that the meeting central to the initiation of the switch toward exploitation as follows:

> *The changes in performance indicators in the feed-in business unit came in a very abrupt way and much too early! This change put the R&D manager [of the exploratory unit] under huge pressures to quickly generate positive sales figures.*

After the new business unit had become subject to performance expectations derived from the core business, more units of the product were sold, but commercial expectations remained unfulfilled. Not meeting the new sales targets made the R&D manager suddenly look bad. His work, hitherto characterized by experiments in both R&D and marketing domains, was considerably constrained. Moreover, his past success in leading the firm into a complex exploration of new technologies and markets became quickly irrelevant and he was ultimately dismissed.

As will be described in detail in the next section, this premature transfer also contributed negatively to subsequent phases of the transition, which met with a disruption of the organizational structures (see T5) as well as starvation and discontinuation (see T6). This is because a premature shift to exploitation can jeopardize support for exploratory innovations and cause resistance to folding them back into the core business (O'Connor and Maslyn, 2004; Chen and Kannan-Narasimhan, 2015).

Determining the right point in time to achieve an *early* but not *premature* reintegration can be difficult. But it seems more likely that a new business will survive and thrive when enough time for incubation and acceleration is provided (O'Connor and DeMartino, 2006): incubation involves developing a business model to profit from the new technology (cf. Siggelkow and Levinthal, 2003); acceleration involves implementing repeatable processes (e.g. manufacturing), a set of qualified customers, and predictable sales forecasts. If any of the latter elements is not fully achieved, nurturing such premature businesses in transitional business units may serve as a temporary solution before actual transfer to the core business (Chen and Kannan-Narasimhan, 2015). This strategy, however, was not pursued at TechLtd. Overall, while streamlining incubation and acceleration phases can save resources in the short-term, this advantage can be easily offset by integration failure in the mid to long-term.

## 4.3. After transfer

The process of reintegration into the core business does not end with the formal transfer from one space to the other. Instead, considerable follow-up activities are necessary for ensuring its ultimate success, which come along with additional trade-offs.

### 4.3.1. Reorganization vs. capability mutation (T5)

*Benefits sought through reorganization.* Reintegrating a new innovation from the exploratory unit into established structures requires diverse measures of reorganization (Durisin and Todorova, 2012), such as changes in formal structure, routines, leadership styles, systems of reward and control, and resource allocation (Simsek et al., 2009). The receiving unit takes over teams and management positions while other now unnecessary positions are terminated. At TechLtd, top management's decision for reintegration provided potential for synergies and was followed by a complete reorganization with considerable change in organizational structures, staffing, and innovation trajectory. The new technology was ultimately integrated with the existing business line in drive electronics, with which it had the most technological similarities.

*The risk of capability mutation.* At TechLtd, we witnessed two main negative consequences: complex staff replacement processes and the partial loss of the exploration structures and related capabilities. The first negative consequence relates to staff hiring and the related reorganization of work and innovation processes, leading to instability, additional expenses, and considerable delays – much the opposite as intended. The position of the fired R&D manager needed to be filled – but remained vacant for some time and was re-staffed twice before an experienced internal manager was put in position. Also, many R&D tasks were delayed not only because the handover between successors was done in a rush, but also because the new internal R&D manager preferred a different approach toward product design. As a result, while the switch to reintegration into the core business was intended to speed up the commercialization, it took several years after the reorganization to move from prototype to final product and commercialization.

Such lost or damaged structures, processes, and teams – and their re-cultivation – are considered by Durisin and Todorova (2012) as inevitable capability mutation in reintegration processes. Capability mutation is also linked to other integration risks: mutation is higher in the case of premature transfer (see T4) and capability mutation increases the risk of subsequent resource denial by the core business (see T6).

A second and even greater damage linked to reintegration at TechLtd is the partial loss of exploration capability. Consistent with their objective of temporary exploration, reintegration led to the discontinuation of the separate exploration unit. Still, this was also linked to 'unintended consequences' and hence capability mutation (Durisin and Todorova, 2012). In a retrospective attempt, the CEO reflects:

> *If we had this vision today [of an ambidextrous organization] and knew the risks [of exploration failure], the externally hired R&D manager would still be in the company today! It was a serious mistake to fire him.*

Hence, only when the single project prioritized in the transition process had ultimately failed did top management realize that they no longer had a dedicated unit and the related capability to pursue alternative exploratory pathways in the same way and intensity as before. In retrospect, top management understood that they also lost key personnel and thereby intellectual capital and networking competencies for exploration. It is not unusual for SMEs to follow sequential ambidexterity using temporary exploration units with the ultimate aim of reintegration (Siggelkow and Levinthal, 2003) following a natural sequence from technology discovery to commercialization (Simsek et al., 2009). However, given the high failure rates of exploration, it is quite unreasonable to close down the (temporary) exploration *unit* before a single exploration *project* has ultimately succeeded toward commercialization. The timing for switching from exploration to exploitation is therefore crucial.

### 4.3.2. Better access to resources vs. resource starvation (T6)

*Benefits sought through core business accommodation.* It is largely established that radical innovation units are not able to commercialize an innovation on their own (Gassmann et al., 2012) and mainstream business often provides the complementary assets necessary for commercialization (Taylor and Helfat, 2009). While complementary asset linking is pursued before transfer, the completion of transfer allows the radical innovation to become accommodated in and an actual part of core business structures and thus benefit directly from resource richness and professionalization – all objectives for final commercialization and the related market diffusion.

Similarly, at TechLtd, based on the reorganization (see T5), the small-wind inverter entered the more established product development process, thus benefiting from core business expertise and resources. Professional product development routines were used to finalize the product, which led to the first commercially available product version. Given the limited sales success in the domestic market, the sales team carried out an international market study and was strengthened with additional employees to intensify customer acquisition.

*The risk of resource starvation and termination.* Once transferred to the core business and when their professional marketing efforts did not yield expected sales, TechLtd focused on selling the current product version in newly identified international markets, but prevented more investment in further product exploration or on-going exploration of innovative ways to market the product. As top management also recognized in retrospect, the company retained a rather reactive stance toward new business proposals, which could have however increased commercialization success (O'Connor and DeMartino, 2006). In general, it can be observed that while on the surface a new business may seem to be integrated, there are tendencies to, 'starve nascent business of resources and talent' (O'Connor and DeMartino, 2006, p.493) and terminate results when success does not immediately follow transfer (Chen and Kannan-Narasimhan, 2015).

At TechLtd, after reintegration without a fully functioning business proposal, further resources needed to explore a viable business model which could potentially increase sales were denied by the top management. They allowed the sales manager to continue for a limited time of another six months, without however providing resources to adjust the sales approach or explore other business models. The CTO recalls the phasing out as follows:

*We didn't find a market for the small-wind inverter. And then, by the end of 2012, we were already starting to slow down a bit on the staff side and finally in 2013 we slammed on the brakes.*

As a result, top management decided in favor of market withdrawal and closed the feed-in exploration unit.

## 5. Discussion

With this fine-grained process study of the failed integration of a radical innovation project – involving a carefully planned separation, followed by cross-contaminating linking mechanisms, and ultimately rushed reintegration leading to capability mutation – we shed light on the existence, character, and timing of integration trade-offs in transition processes. Next we discuss integration trade-offs in general and within resource-constrained contexts. Finally, we discuss limitations and managerial implications.

### 5.1. Integration trade-offs in the transition process

Given that managing the exploration–exploitation interface involves trade-offs and that they occur during the entire transition process, our main contribution is a *framework of integration trade-offs in transition processes*. With our focus on the entire transition process, our framework gives insights into the *dynamics* of the exploration–exploitation interface *over time* and also considers the cumulative effects of trade-offs which may lead to failure. We further deepen the research on processes of *how and when separation and integration occurs* (Gassmann et al., 2012; Chen and Kannan-Narasimhan, 2015) and thereby contribute to the time dimension in organizational research (Ancona et al., 2001). This also reflects the conclusion of Simsek et al. that 'little is known about what drives a unit to shift between episodes of exploration and exploitation, or precisely how this shift takes place' (2009, p. 888). Last but not least, with the focus on trade-offs leading to failure, we also overcome the pro-innovation bias and contribute to the rather thin body of literature analyzing *innovation failure* (Khanna et al., 2016). The existence of trade-offs does not necessarily lead to failure per se. Instead, these trade-offs should be carefully analyzed and contained so that they do not jeopardize the 'energizing potential' of the overarching exploration–exploitation paradox.

While we have identified a significant set of integration trade-offs, given the context of a single organization, they are surely not complete. For example, while cross-functional decision making is also likely to be part of an integration trade-off, because it bears the risk of lowering the degree of radicalness (Gassmann et al., 2012), it was not relevant in our case context and therefore not included. Hence, future studies should extend our framework by complementing it with other relevant trade-offs or further developing existing ones. Moreover, we suggest further analyses of the conscious or unconscious combination, customization, and scheduling of integration mechanisms by top and middle management and the effects on trade-offs. Last but not least, the present study's context of renewable energy technology also indicates another fruitful research avenue: to focus on the context of green technology and broader sustainability-oriented innovation (Hansen et al., 2009; Schaltegger and Wagner, 2011; Schiederig et al., 2012), with its relevance for ambidexterity (Seebode et al., 2012). Studying the role of integration mechanisms and trade-offs in this context seems important because the tensions between exploitation and exploration are stronger. In addition to integrating radical and incremental innovation perspectives, ambidextrous organizations embarking on the sustainability journey also have to bridge conventional technology innovation directed at customer and business growth with innovations generating broader societal benefits. This puts new demands on individual integration mechanisms and their orchestration.

## 5.2. Integration trade-offs in resource-constrained contexts as a source of failure

Our research confirms that in resource-constrained contexts organizations may have difficulties to fund an independent exploratory unit so that it remains independent for longer time spans, making early or mid-stage involvement of the core business likely (Chen and Kannan-Narasimhan, 2015). Resource-constrained organizations must pursue ambidexterity more efficiently, making trade-offs between exploration and exploitation a necessity (Cao et al., 2009). Against this background, and independently of the phase-specific trade-offs and risks presented in our framework of the transition process, we see three generic sources of failure when integration mechanisms become subject to resource-efficiency considerations:

1. *Mechanism-related (inherent) failure:* The implementation of integration mechanisms may itself become a vehicle for (resource-saving) synergies between exploitation and exploration (e.g. linking the exploratory unit with complementary assets in core business enables reuse of existing resources; job rotation allows the reuse of existing personnel). Such a misuse of integration mechanisms is particularly prone to weaken separation and lead to cross-contamination. It may even contradict the intended separation strategy (e.g. strong exploratory-complementary linking in the domain of marketing when in fact a pure exploration was intended).
2. *Pulling-forward-related failure:* Integration mechanisms are pulled forward in the transition to accelerate the process, which may backfire. For example, while cutting incubation and acceleration saves resources in the short term, the premature transfer of exploration projects back into the core business ultimately leads to failed commercialization.
3. *Streamlining-related failure*: Integration mechanisms are implemented in a simplified or partial way, however, to an extent that their functioning can no longer be assured (e.g. job rotation scheme poorly integrated in the overall ambidexterity strategy).

Overall, we find that the more integration processes are streamlined, the higher are the respective risks of cross-contamination and ultimate exploration failure. It is therefore important to carefully weigh both benefits and risks related to streamlining transition and related integration processes. Future research should further examine and potentially expand these modes of failure in resource-constrained contexts.

## 5.3. Limitations

Our study is limited in three ways. First, while our longitudinal study investigates processes leading to failed innovation, we do not know whether the trade-offs observed in the integration processes were the only causes of failure. The difficult characteristics of an immature market may have also constrained innovation success. Second, we experienced the well-known challenge of building analytically distinct concepts to achieve conceptual clarity despite empirical overlap. For example, there is an overlap among our early vs. premature transfer trade-off (T4) and the subsequent trade-offs. We dealt with this limitation as far as possible by detailing the linkages among the trade-offs.

### *5.4. Managerial implications*

Our results are crucial for top management, R&D managers, and other middle managers (e.g. marketing) involved in the innovation process who want to prevent exploration failure, whether in resource-constrained contexts or in large organizations. Structural ambidexterity has been the preferred approach for managing the dual challenges of exploration and exploitation successfully. This suggests that both types of activities should be undertaken in separate units while engaging in targeted integration. Integration can be achieved by a broad set of mechanisms such as use of complementary assets from the core business, cross-functional decision-making structures, job rotation, external and internal legitimacy seeking, and the actual transfer back into and accommodation within established structures of the core business organization. Integration mechanisms always bear the risk of cross-contamination, which could damage the separate exploration and exploitation structures – thus, they are inevitably linked to trade-offs. This does not mean that integration mechanisms should not be implemented; they are a necessary element in managing the tensions involved in the exploration–exploitation paradox. Rather, organizations have to consciously design and schedule (re)integration mechanisms along the transition process in order to minimize potential negative side-effects.

Finally, each integration mechanism also bears the potential for saving resources, which makes it particularly prone to resource-thin contexts such as SMEs. However, a motive of resource savings when applying integration mechanisms may backfire in the form of mechanism, pulling-forward, and streamlining-related failure. Managers should carefully weigh the benefits of resource savings with the increased risks of exploration failure.

## 6. Conclusion

Integration mechanisms have been presented as a panacea for managing the exploration–exploitation paradox. We agree that they are certainly relevant, and may in fact be the most important elements of an organizational design for ambidexterity. However, while integration mechanisms are implemented in pursuit of cross-fertilization, they simultaneously hold the risk for cross-contamination – two sides of the same coin. It is therefore crucial for organizations to carefully choose, customize, and time – that is, orchestrate – the integration mechanisms along the transition process.

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## Paper 4

Green technology innovation: Anatomy of exploration processes from a learning perspective

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RESEARCH ARTICLE

WILEY Business Strategy and the Environment

# Green technology innovation: Anatomy of exploration processes from a learning perspective

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**Abstract**
This paper examines how established firms use their core competences to diversify their business by exploring and ultimately developing green technologies. In contrast to start-ups dedicated to a green mission, diversifying into green markets by developing new products based on existing core competences has proven to be challenging. This is because the exploration processes to find a match between green technology opportunities and internal competences is complex and new to most established firms. This paper gains insights into exploration processes for green technologies and the learning modes and outcomes linked to these processes. We examined exploration processes at the microlevel in an embedded case study of an engineering firm using a combination of the "fireworks" innovation process model and organizational learning theory. First, we found that developing green technologies involves a long-term exploratory process without guarantee of (quick) success and likely involves many exploration failures. Second, as exploration unfolds along multiple technology trajectories, learning occurs in individual exploration paths (on-path), when new paths are pursued (path-initiation), and when knowledge from one path is spilled over to subsequent paths (across-paths). Third, to increase their chances for success, firms can increase the efficiency of exploration by fostering a failure-friendly organizational culture, deliberately experimenting, and purposefully learning from failures.

KEYWORDS
core competences, eco-innovation, green innovation, green technology, innovation process, organizational failure, radical innovation, sustainability-oriented innovation

## 1 | INTRODUCTION

Despite important literature on why firms become more sustainable and what it means for a firm to be sustainable, there is still limited literature on how firms transform themselves in order to become more sustainable (Zollo, Cennamo, & Neumann, 2013). Relatedly, the literature on eco, green, or sustainability-oriented innovations has grown considerably (Hansen et al. 2009; Schiederig, Tietze, & Herstatt, 2012), but the innovation processes of how organizations are "going green" is still only marginally understood (Klewitz & Hansen, 2014). This is particularly the case for established firms previously offering conventional product portfolios that then aim to diversify into green markets—in contrast to entrepreneurial firms founded with a green mission. We are therefore interested in how established firms search for sustainability-related business opportunities, develop green technologies, and exploit niche markets (Hart, Milstein, & Caggiano, 2003; Jenkins, 2009; Schaltegger, Lüdeke-Freund, & Hansen, 2012). For established firms, green technology innovations are often radical as they significantly differ from their current business in terms of technology and markets, and involve large unknowns (Driessen, Hillebrand, Kok, & Verhallen, 2013).

As green innovation processes are new to many established firms, adapting to green technology as well as product and market contexts requires important learning efforts (Siebenhüner & Arnold, 2007), a process that is presently not well understood but is thought to be hindered by past beliefs about business success. What is also often neglected is the role of trial and error as well as failures in innovation processes (Cannon & Edmondson, 2005; Khanna, Guler, & Nerkar, 2016; Sitkin, 1992). Therefore, this paper aims at understanding how green technology innovation processes unfold in established organizations, and what the role of learning from failures plays. To do so, we investigated microlevel learning processes in a business-to-business engineering firm previously operating solely in conventional markets, but later also engaging in radical innovation targeted at green markets, particularly sustainable energy technologies (SETs). Focusing on the early phases of the innovation process and less on product development and diffusion, we examined how the firm explored green technology and related markets. We analyzed these outcomes from an organizational learning perspective (Crossan, Maurer, & White, 2011; Lozano, 2014) with a focus on learning from failures (Cannon & Edmondson, 2005; Khanna et al., 2016; Sitkin, 1992).

We contribute to the literature on green innovation in three ways: (a) by developing a path-based learning framework for green technology innovation involving multiple paths, emerging branches, and dead ends. (b) By showing that learning occurs at three points in time: during an existing path (on-path), when new path branches are opened (path-initiation), and finally when the experience of multiple paths is considered (across-paths). The path-based view also shows the inherent complexity of green technology innovation. (c) By discussing two key innovation practices—deliberate failures and intelligent trial and error—that can be managed to increase chances for success.

The remainder of this paper is structured as follows: Chapter 2 reviews the literature on green innovation and organizational learning. Chapter 3 presents the methodology and introduces the embedded case study. Chapter 4 analyses the learning outcomes, and Chapter 5 concludes the paper by discussing how a conventional firm can explore green technologies and markets and how this exploration can be managed.

## 2 | LITERATURE REVIEW

### 2.1 | Green technology innovation processes

Green innovations include new technologies, products, services, or business models that have positive impacts on the environment and society (Adams, Jeanrenaud, Bessant, Denyer, & Overy, 2016; Foster & Green, 2000; Seebode, Jeanrenaud, & Bessant, 2012) or fulfil the needs of customers with lesser harmful impacts than the alternatives (Goodman, Korsunova, & Halme, 2017). Compared with conventional innovations, they share many similarities but differ strongly in purpose, complexity, direction of search, and uncertainty (Bos-Brouwers, 2009; Klewitz & Hansen, 2014; Noci & Verganti, 1999; see also Dangelico, 2016 for a review of green product innovation). Indeed, in addition to commercial success, green innovation embraces the explicit dual aim of improving the firm's sustainability performance and contributing to solving societal problems (Hansen, Große-Dunker, & Reichwald, 2009; Hart et al., 2003), thus helping firms to become sustainable development agents (Scheyvens, Banks, & Hughes, 2016). Firms need to search for innovation in a specific direction to assure that the outcomes will have positive impacts on sustainability.

A common way for established firms who aim to develop green technologies is to engage in a diversification process. Diversification allows existing business to be complemented with green technologies, following what Hart (1997) calls a clean technology strategy (see also Jenkins, 2009, on competitive advantage through green product innovation and unserved markets). We focus on resource-based (Ansoff, 1957; Montgomery, 1994) diversification, which involves using the existing resources and core competences (Prahalad & Hamel, 1990) a firm already has to enter new green (niche) markets.

There is important literature on the determinants of innovation and innovation outcomes (Díaz-García, González-Moreno, & Sáez-Martínez, 2015; Kiefer, Del Río González, & Carrillo-Hermosilla, 2018), for instance, discussing the importance of innovation for long-term survival (March, 1991) and drivers and barriers to developing innovations (Tidd & Bessant 2009), also in the context of Sustainability-oriented Innovation (SOI) (Álvarez Jaramillo, Zartha Sossa, & Orozco Mendoza, 2018; Bos-Brouwers, 2009). However, the innovation process perspective is underdeveloped in the literature (Crossan & Apaydin 2010), and even more so in the SOI context. This process perspective can be further developed based on several existing innovation process models (Verworn & Herstatt 2002).

The fireworks model allows to study innovation processes, which refer to sequences of activities that lead to the birth of an innovation (Crossan & Apaydin 2010). So called flow-models are often used to study innovation processes (Verworn & Herstatt 2000). Frequently used in innovation management and in the design literature, these models represent the archetypical development of an innovation in the form of a linear process that ranges from the idea to the launch of the new product (Verworn & Herstatt 2000). This prescriptive view yields limited usefulness for empirical analysis. Indeed, in reality, innovation processes are often complex and rather chaotic, particularly in early phases or in radical innovations (Koen et al., 2002). Based on an in-depth qualitative study of 30 British industrial firms known to be active in research and development, Cooper (1983, 12) concludes that

> *[T]he new product process is not the sequential or series process so often portrayed in the literature. Rather, we see a more complex process, with many activities overlapping or undertaken in parallel. Indeed there*

*appear to be certain efficiencies in adopting this parallel approach. The usual normative models, in contrast, propose a stagewise (series) set of activities for new product managers to follow. Such models are clearly unrealistic: product innovation simply does not occur that way, and normative guides that do not recognize either the differences in processes or the overlapping nature of activities will probably meet with little success.*

Few analytical models embrace the complexity of the innovation process described by Cooper. This explains why this research uses the fireworks innovation process model which allows to study green technology innovation processes without reducing their complexity. The model was already successfully used in German literature to examine cases of sustainability innovation (Fichter et al. 2007). It is depicted in Figure 1 (Van de Ven et al. 2000/1989). A full description can be found in Van de Ven, Polley, Garud, and Venkataraman (2008).

The fireworks model suggests that these innovation processes, taken together, form an innovation journey that typically begins with a long time period where ideas are in gestation. The actual journey begins with a shock that signals the urgency to develop innovations to guarantee the survival of the organization (March, 1991). After the shock, new product ideas start proliferating as different innovation paths (curved lines). In the case of green technology, each path typically relates with a different combination of technology and market and has many activities to explore if this combination can lead to a commercially successful new product. However, as the literature indicates, by far, not all paths lead to success, which often alternate with failures (Van de Ven et al., 2000/1989; Maidique & Zirger, 1985).

## 2.2 | Organizational learning and learning from failures

The organizational learning literature discusses how firms learn to adapt to new business environments and develop new innovations (see reviews by Dodgson, 1993; Crossan et al., 2011; also in the context of green technology innovation, Siebenhüner & Arnold, 2007). Organizational learning can take various forms and involve multiple processes. Many authors use the well-established behavioral psychology concepts of single and double-loop learning (Argyris & Schön, 1978). In single-loop learning, a mistake is corrected by using a different action to attain the same goal. Although the set of actions changes, the goal remains the same. Double-loop learning is a more complex process in which the mistake is corrected by rethinking the original goal. A person in the process of learning will not only reflect on and change their actions to attain the goal, but also change the goal itself. The new set of actions will therefore be aligned with the reevaluated goal. Double-loop learning also involves an organization questioning its underlying norms, mental frames, world-views, sets of beliefs, routines, and assumptions about success (Tripsas & Gavetti, 2000).

Although the literature rarely indicates whether learning is induced by successes or failures (Khanna et al., 2016), as exploration is typically punctuated by failures, we pay particular attention to the latter. Learning from failures has received much less attention (Cannon & Edmondson, 2005), but several authors argue it is important as failures provide more valuable feedback (Sitkin, 1992). These authors maintain that small failures are essential prerequisites for effective organizational learning and encourage deliberate experimentation to trigger learning from failures (Khanna et al., 2016).

Overall, our understanding of green technology innovation processes, nonlinear innovation processes (taken from the fireworks innovation model with its emphasis on trial and error), and organizational learning are used to build our preliminary conceptual framework (see Figure 2). In this framework, the innovation paths (curved black lines) represent a specific exploration of a new product idea intended for a new market. In each path, the organization (further) develops green technologies or their components — with more or less distance to its existing core technologies — with the aim to commercialize them as new products for new markets. This exploration generates learning outcomes for green innovation (Hoffmann, 2007) that may be useful on subsequent innovation paths (symbolized by blue arrows).

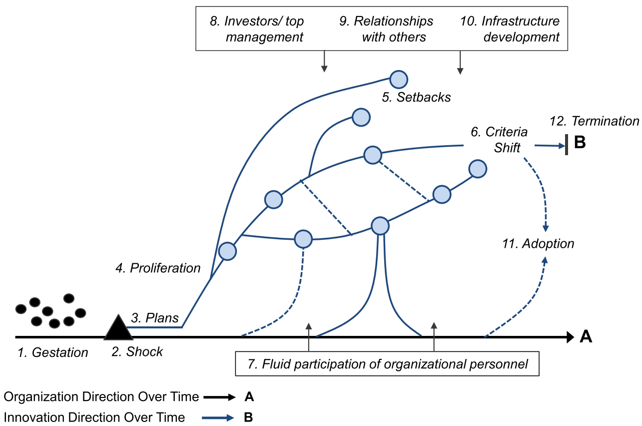


**FIGURE 1** The innovation journey and its key components (Van de Ven et al., 2008) [Colour figure can be viewed at wileyonlinelibrary.com]

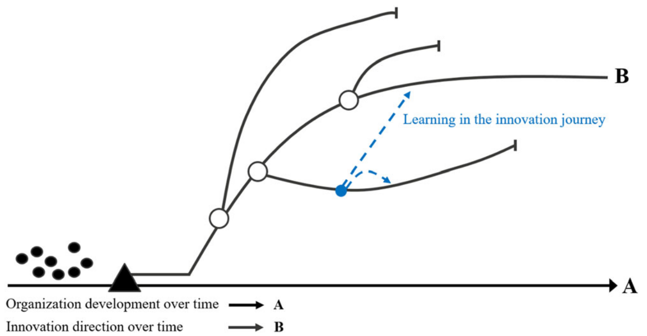


**FIGURE 2** Preliminary conceptual framework: the fireworks innovation process model (Van de Ven et al., 2008) combined with organizational learning [Colour figure can be viewed at wileyonlinelibrary.com]

## 3 | METHODOLOGY

### 3.1 | Research design

The aim of this paper is to investigate how green technology innovation processes unfold in organizations and what can be learned from exploration failures. To address this goal, we undertook an in-depth longitudinal and embedded case study (Yin, 2014) in a well-established German engineering firm successfully operating in the electronics industry. We specifically focus on the learning outcomes that occurred within a new business line dedicated to the exploration of SETs. Although we are interested in understanding the overall innovation process, to obtain deep insights into the process, the research features four embedded cases corresponding to innovation paths focused on specific products and related technologies. We follow other innovation scholars who adopt this method and focus on several embedded cases of unsuccessful innovation (for example, Cannon & Edmondson, 2005; Khanna et al., 2016; Tripsas & Gavetti, 2000).

### 3.2 | Case selection

#### 3.2.1 | Overview

We conducted theoretical sampling (Eisenhardt, 1989, 537) with the aim of extending the literature on green technology innovation. The exploratory case chosen is critical for expanding this body of knowledge (Yin, 2014, 41) in four directions as follows:

1. First, instead of a company founded with a green mission (Schaltegger & Wagner, 2011), we searched for an established firm with conventional product portfolios that was developing innovations in unknown green markets—hence, representing “green diversification.” This phenomenon has not been examined yet (Jenkins, 2009; Klewitz & Hansen, 2014).
2. Second, although learning from failures has been recently receiving more attention in the organizational learning literature (Baumard & Starbuck, 2005; Cannon & Edmondson, 2005; Khanna et al., 2016), empirical studies about failures are still sparse. Furthermore, to our knowledge, the case of a firm learning from failures in innovation processes for radical innovation has not been researched yet, even though failures are frequent in this context.
3. Third, fine-grained studies of innovation dynamics at the microlevel have seldom been reported in the green technology innovation literature (Schiederig et al., 2012; Zollo et al., 2013).
4. Finally, TechLtd as a small and medium-sized enterprise (SME) is a good representative for radical innovation in resource-constrained contexts. In their systematic literature review, Klewitz and Hansen (2014) found that some SMEs have very proactive approaches toward sustainability. Proactive SMEs are more inclined to develop radical innovations and search to solve sustainability problems in an entrepreneurial way (Aragón-Correa, Hurtado-Torres, Sharma, & Garcia-Morales, 2008), even those operating in a resource constrained environment (Halme & Korpela, 2014). The results are likely also applicable to larger more resourceful entrepreneurial firms.

The case is revelatory (Yin, 2014) because it is difficult to obtain (longitudinal) access to unfolding innovation processes, particularly at an early stage. Indeed, early stage processes are difficult to identify and study as they do not always lead to successful innovation outcomes. This is even more true for unsuccessful innovation paths, which potentially weaken an organization's (or individual manager's) reputation as a “successful innovator.” In fact, this study was only possible through an engaged scholarship approach involving the development of close ties with the organization's top management prior to the research project (van de Ven, 2007).

#### 3.2.2 | Introducing TechLtd

This paper examines TechLtd, a medium-sized German engineering firm operating in business-to-business markets in the electronics industry. The family business, founded in 1962 and owner-managed in the second generation, employs about 200 people. Over the past 50 years, it has accumulated extensive knowledge in control systems for high-speed engines and generators, and has become a global leader with a market share of about 40% in its main market, machine-tools for circuit-board drilling. It has the typical characteristics of a “hidden champion” (Simon, 2009).

TechLtd develops and produces electronic components (computerized numerical control system and control systems for high-speed motors and generators) that are sold to manufacturers of machine tools (its primary market), turbines, or various other industrial machine manufacturers. Product development typically takes several months and is characterized by intensive research and development collaboration with customers and trust-based, long-term relationships. Production is typically done in small batches and is, contrary to industry trends, fully located in Germany. Sales offices exist in Europe, the United States, and Asia. Top management, knowing that new path-breaking technologies might weaken its main market segment (representing 80% of sales) sometime in the future, recognized the urgency for exploring new product and market areas. Inspired by their intrinsic motivation for sustainability (Baumard & Starbuck, 2005), top management sought new applications for the core technologies that underlie in their existing products (Taylor & Helfat, 2009) and found several in emerging SET markets. After a long gestation period, a new business line dedicated to the exploration and development of SET-related technologies and markets was created.

The focus of this paper is on this new business line, called feed-in technology, which is characterized by an exploration rationale. It was formally created in 2003 to explore how the company could use its engineering competences (and related core technologies) to develop new applications for the market of renewable energy technologies (particularly small wind turbines; see Wicki, 2015). An engineer was hired externally to lead the exploration and began to search for synergies between these existing core competences and applications in the area of rotation-based SET, mostly different forms of turbines. Exploration led to the four main innovation paths (P1–P4), illustrated in Figure 3 and described in Table 1 : fuel cells (P1), small wind turbines (P2), flywheel energy storage (P3), and waste heat recovery (P4). An overview of the paths and an analysis of their individual learning outcomes can be found in Section 4.

## 3.3 | Data collection

We utilized a combination of retrospective and real-time approaches (Pettigrew, 1990) covering a period of 15 years (2000–2015), of which we were able to observe the last three as an on-going process (2013–2015). To assure construct validity (Babbie, 2013), we triangulated various data sources (Table 2) including formal semistructured interviews with top management, middle management, and value network actors; informal and unstructured interviews (e.g., informal conversations in the target company), participatory observation, and focus groups at top-management meetings; observation of industry workshops; and extensive desk research. We also conducted action research (Huxham & Vangen, 2003) and took the role of a facilitator in some of the innovation paths. For instance, we organized a flywheel innovation workshop with current and potential partners of the focal company. The interviews were transcribed, other data (e.g., site visits, participant observation, focus groups) were protocolled (Babbie, 2013), and both were coded using software for qualitative data analysis (MAXQDA).

## 3.4 | Data analysis

In line with recommendations for longitudinal case studies (Huber & van de Ven, 1995; Van de Ven & Poole, 1990a; Yin, 2014), we started the analysis by reconstructing the timeline of the innovation process (Wicki 2015; Wicki, Hansen, & Schaltegger, 2015). Specifically, we analyzed (temporal) events along the innovation trajectory such as setbacks, changes in search direction, fluid participation of personnel, involvement of top management, evolution in success metrics, cognitive representations, beliefs, world-views, and routines. These events were observed by tracking ideas, people, transactions, contextual events, and outcomes, following the fireworks innovation process model (van de Ven & Poole, 1990a). We referred to the fireworks model for longitudinal analysis (Poole & van de Ven, 1989) because it allows rich analysis of complex nonlinear processes on the microlevel. The analytical process involved three iterative coding steps, comparable with the recommendation of Gioia, Corley, and Hamilton (2012) for inductive research. First, our empirical data was coded into first-order concepts (detailed learning outcomes, see Table A1) for each innovation path. Second, the data was aggregated into second-order themes (learning outcomes Learning 1–6). Third, we distilled the themes into aggregated dimensions (path-based learning types T1–T3). Figure 4 provides a graphical overview of the data structure, with the detailed learnings of the small wind turbines path (for consistency reasons). Table A1 provides the full range of learnings as they related to all four innovation paths (P1–P4).

We assured "trustworthiness" (Shenton, 2004) by addressing the criteria of credibility (internal validity), transferability (external validity), dependability (reliability), and confirmability (objectivity) with various research strategies such as triangulation of data types and informants, multiple investigators, transparency of the methodological approach, rich description of the phenomena and context, as well as consideration of alternative explanations.

# 4 | RESULTS

Given the longitudinal character of our research, the study design with a long time frame, and our emphasis on learning from failures, this section analyses the learning outcomes as they relate to the four innovation paths (Figure 5; Table 3; Table A1). The results shows innovation paths that represent green technology exploration processes of new products, new markets, or a new combination of product and market (i.e. a "pure exploration" according to Voss & Voss, 2013). The

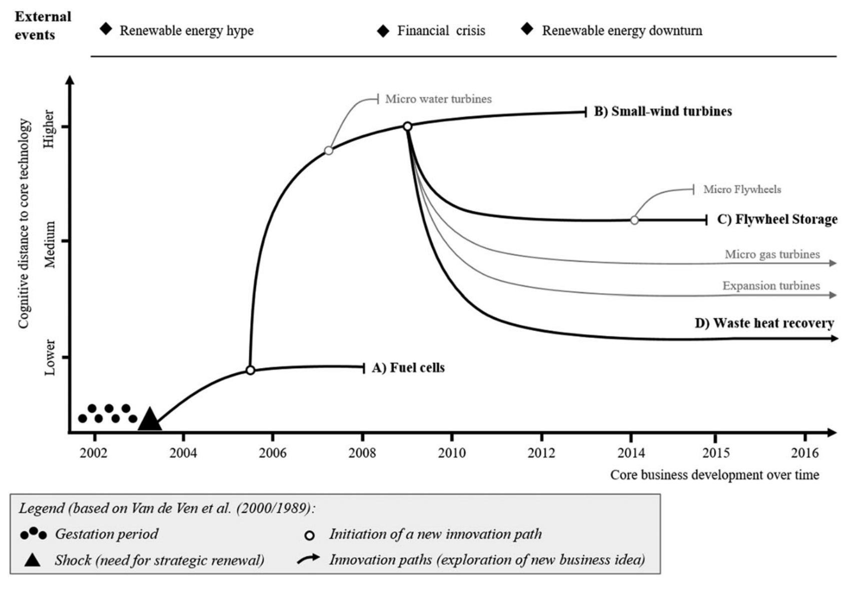


**FIGURE 3** Innovation paths representing the exploration of new business ideas at TechLtd

**TABLE 1** Descriptive overview of the innovation paths

| Path characteristics | P1: Fuel cells (FC) | P2: Small wind turbines (SWTs) | P3: Flywheel storage (FS) | P4: Waste heart recovery (WHR) |
|---|---|---|---|---|
| Overview | Used core technology to develop control system for high-speed turbines supplying FCs with combustion gases. Technology development with a large automaker that was control system customer | Developed controller for SWTs with partner firm with knowledge about and access to small wind market (met on Path P1). Relied on existing core technology and new components from previous path. | Explored high-speed flywheels (kinetic energy storage devices). Flywheel controller based on the SWT controller, without turbine management functions, and customized to flywheel application. Many technological components reused. | Used controller in ORCs turbines for the recovery of low temperature heat. Controller based on SWT controller and adapted to needs of gas turbines. |
| Related energy technology | FCs | SWTs | High-speed FS (energy storage) | Industrial WHR |
| Product (component) description | Controller for turbine supplying combustion air to FCs. Controller equipped with inverter for grid feed-in of generated electricity. | Controller for SWT (<10 kW), turbine management, and grid feed-in of generated electricity | Controller for high-speed flywheels storing kinetic energy over short time periods (<1 day). | Controller for gas turbines in WHR based on the ORC principle. |
| Duration | 5 years (2003–2008) | 8 years (2005–2013) | 4 years (2010–2014) | Ongoing (2010 onwards) |
| Staff expenses | <0.5 million euros | 3–4 million euros | <0.5 million euros | <0.5 million euros |
| Technology | High-speed (HS) drive electronics (core business), grid feed-in technology | HS drive electronics, grid feed-in, and turbine management | HS drive electronics and grid feed-in | HS drive electronics and grid feed-in |
| Market description | Automotive market (cars), FC for decentralized electricity production | Decentralized energy production to increase energy autarky and reduce energy costs in households, agriculture, and industry | Short-term electricity storage for grid stabilization, control power, Uninterrupted power supply (UPS) and home storage. Flywheels can be used to recover braking energy in vehicles. | Heat recovery from low temperature sources such as (industrial) waste heat and geothermal sources. |
| Upfront market exploration | Very limited (outsourced to main customer) | Medium (relied on business partner);<br>Exploration toward the end only | Important | Important |
| Exploration steps and related activities | 1. Discovers FC thanks to R&D project of large automaker<br>2. Adapts existing controller to FC turbines and produces 20 prototypes<br>3. Terminates path | 1. Discovers SWT thanks to university spin-off met on P1 and discusses potential to develop inverter<br>2. Begins partnership with spin-off<br>3. Market analysis focusing national grid feed-in requirements and regulations<br>4. Builds several prototypes<br>5. Tests prototypes with potential customers<br>6. Builds a product and engineers an improved version (V2)<br>7. Advertises product at trade fairs and in industry press<br>8. Begins small series production<br>9. Launches product<br>10. Market analysis of other countries to understand why sales not increasing<br>11. Strengthens team for final sales effort<br>12. Terminates path and exits market | 1. Discovers FS thanks to previous partnership with university<br>2. Builds prototype based on product developed in P2 (removes some components and adapts to FS)<br>3. Searches for other potential customers than the university<br>4. Approaches end user to initiate joint product-development project.<br>5. Approaches market leader in the United States to study its business model<br>6. Attends industry workshop<br>7. Terminates path due to negative market outlook | 1. Discovers controller can be also be used for WHR applications<br>2. Studies regulatory context<br>3. Based on prototypes of P2 and P3, builds product for WHR applications<br>4. Searches for potential customers and sells them custom-made product<br>5. Adopts wait-and-see approach, given uncertain market outlooks |

(Continues)

**TABLE 1** (Continued)

| Path characteristics | P1: Fuel cells (FC) | P2: Small wind turbines (SWTs) | P3: Flywheel storage (FS) | P4: Waste heart recovery (WHR) |
|---|---|---|---|---|
| Rationale for path initiation | Promising future technology with immense market potential<br>Automotive market seen as strategically important<br>Very high importance for sustainability (new high-efficiency renewable energy generation technology) | Niche markets fits existing production capability<br>Challenging engineering tasks.<br>Secure large market shares through mastery of HS technology and gain unique competitive advantage<br>Large contribution to sustainability by facilitating diffusion of SWTs | Minor R&D development costs (largely same technology as SWT)<br>Niche markets fits production capacity<br>Relevance for sustainability (energy storage) | Minor R&D development costs (largely same technology as SWT)<br>Niche markets fits production capacity<br>Relevance for sustainability (increase energy efficiency) |
| Rationale for continuing or path termination | Terminated as FC technology not mature for commercial applications<br>Market size of consumer cars does not fit niche strategy | Terminated due to poor sales | Wait-and-see as technology not mature for commercial applications<br>End-user business model not financially viable | No termination, but wait and see because markets still emerging and unpredictable |
| Sustainability ambition | High: new generation of high-efficiency energy conversion technology | High: new energy conversion technology. Provision of missing piece in technology diffusion: the energy inverter | Medium: short-term storage to increase system efficiency and support renewable energy diffusion. Energy efficiency increases of up to 35% | Low: limited system efficiency increase, mainly due to energy recovery in industrial processes |

*Note*. FC: fuel cell; HS: high-speed; ORC: organic Rankine cycle; SWT: small wind turbine; R&D: research and development; UPS: uninterrupted power supply; WHR: waste heat recovery.

**TABLE 2** Data collection methods

| Data types | Sources | | |
|---|---|---|---|
| | Internal: top and middle management | External: business partners and value chain actors | Total |
| Semistructured interviews | 8 interviews | 21 interviews | 29 |
| Informal unstructured interviews | 3 interviews | 18 interviews | 21 |
| Focus group sessions | 3 sessions | n/a | 3 |
| Participant observation | 3 meetings | 2 industry events | 5 |
| Action research | Seven AR events | 3 AR events, including one major industry event organized (flywheel workshop) | 10 |
| Document analysis | 25 internal documents (e.g., market studies, sales statistics, and customer lists) | Over 300 publicly available documents (e.g., industry reports, market analyses, newspaper and magazine articles, and websites of industry actors) | 300+ |

vertical axis indicates the cognitive distance to the original core technology (Li, Vanhaverbeke, & Schoenmakers, 2008). The innovation paths are punctuated by exploration activities that aim at determining whether the new technology market area is interesting for the firm, whether commercial viable products can be developed, and, if they can, how the new product can be developed and commercialized. Each path consists of numerous small continuous changes (incremental innovations), whereas the emergence of a new path results from a (discontinuous) change in the technology-market idea. In the most successful case, a path ends with the commercialization of a new product.

The analysis reveals that (single and double) loop learning outcomes relate to the innovation paths in three ways (Table 3): first, as outcomes on the path that are directly useful for the innovation processes in this same path (T1); second, as outcomes that initiate new paths (T2); third, as outcomes that improve overall innovation performance at a metalevel across paths (T3). The subsections below discuss these three innovation types (T1–T3) and the related learning outcomes (Learning 1–6).

## 4.1 | On-path learning (T1)

### 4.1.1 | Knowledge about new technologies and markets (Learning 1)

Even though not all innovation paths led to successful commercialization, they generated important knowledge about new green technologies and markets. As will be later analyzed in detail, it is this on-path learning which also becomes useful to exploration of subsequent innovation paths (see T2). First, the firm added new technologies to its technological repertoire. On path P1, it discovered the feed-in technology that allowed it to transform renewable energy to fit grid characteristics (Table 1). This component proved to be useful for all paths.

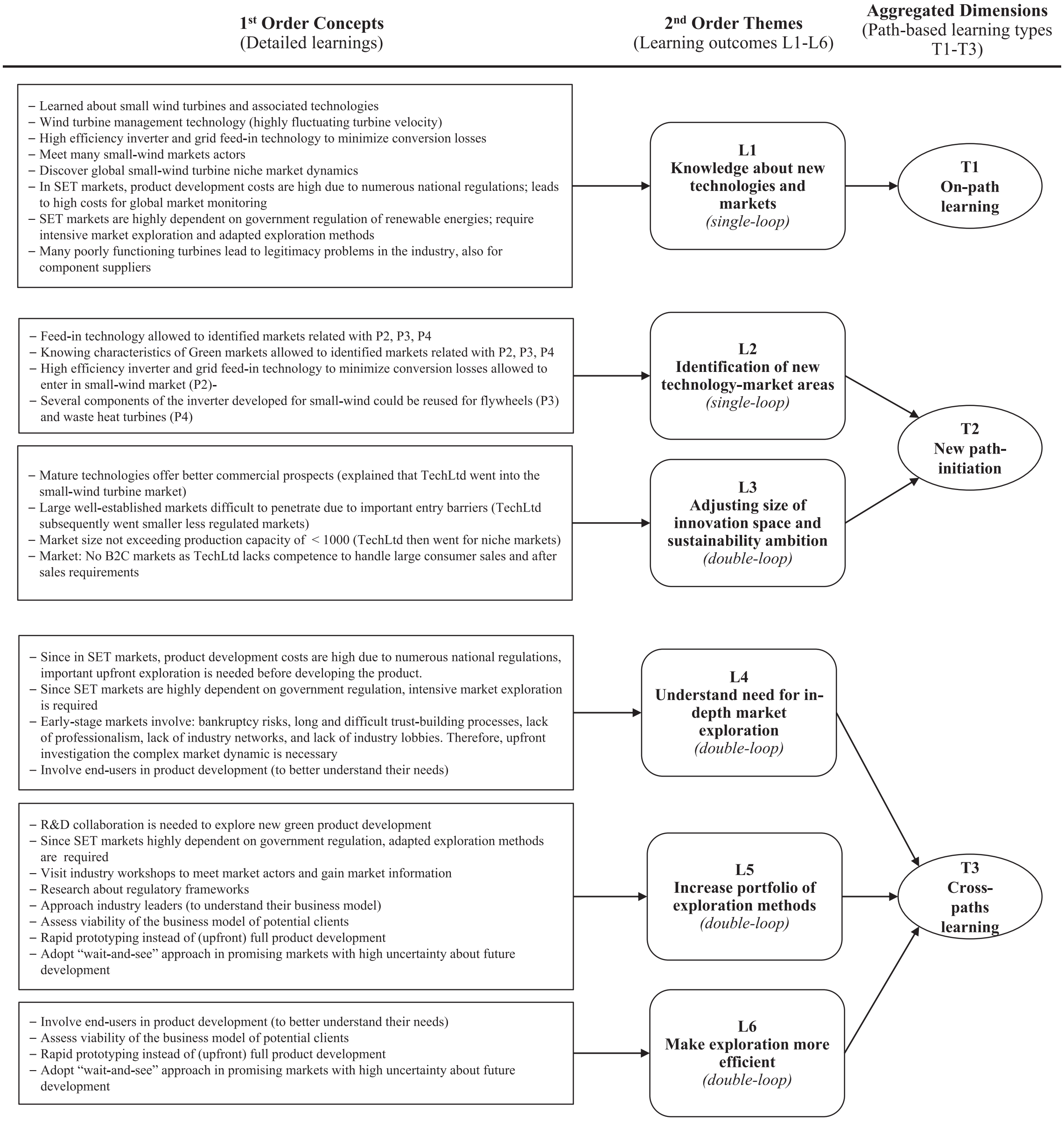


**FIGURE 4** Data structure based on the Gioia methodology: path-based learning types

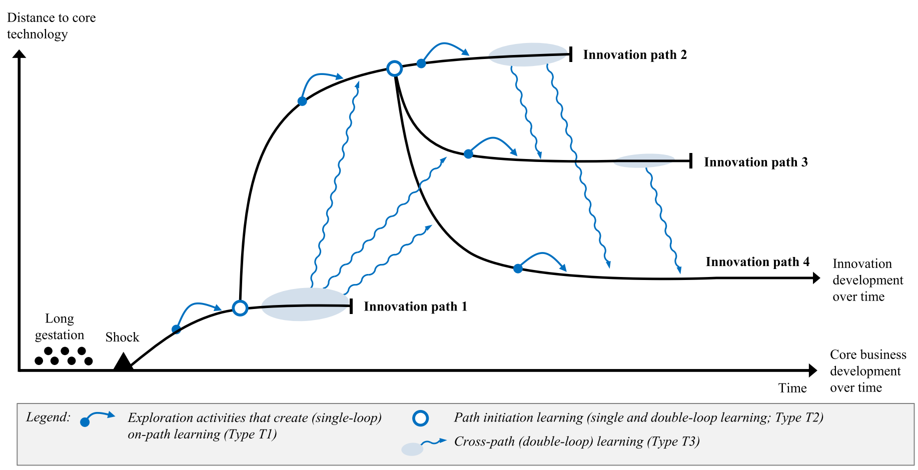


**FIGURE 5** A path-based learning framework for green technology innovation (based on (Van de Ven et al., 2008) [Colour figure can be viewed at wileyonlinelibrary.com]

**TABLE 3** A path-based learning framework for green technology innovation

| Learning dimensions | Learning types and their relation to innovation paths | | |
|---|---|---|---|
| | T1: on-path learning | T2: path-initiation learning | T3: cross-paths learning |
| Timing | Early | Middle; during process | Overall; toward process end |
| Learning mode | Single-loop | Single and double-loop | Double-loop |
| Learning outcomes | Learning 1: Knowledge about new technologies and markets | Learning 2: Identification of new technology-market areas (single-loop)<br>Learning 3: Adjusting size of innovation space and sustainability ambition (double-loop) | Learning 4: Understand need for in-depth market exploration<br>Learning 5: Increase portfolio of exploration methods<br>Learning 6: Make exploration more efficient |
| Sustainability aspects | Specific characteristics of green technologies and related markets; importance of the firm's core competence for sustainability | Identify related green technologies, contributing to the market area<br>Trade-off between wide innovation space and high sustainability ambition<br>Gain more realistic perspective on potential (technological) contributions, also for commercialization | Learn to explore green markets (with complex dynamics) and cope with high cognitive distance between existing conventional and new green market areas |

TechLtd also met new actors. For instance, the partner of the small wind turbine controller (on path P2) was initially met on the first path P1. Furthermore, it discovered how it could best make use of its core competences in these green markets. Top management had a “eureka moment” when it realized that its high-speed generator control competences could be used to solve an important problem in the emerging small wind turbine industry: the absence of an (efficient) inverter customized to small wind applications (Wicki, 2015).

Second, on each path, the firm also learned about new market environments (Table 1): the automotive fuel cell on Path P1, the small wind turbine on P2, the flywheel on P3, and finally waste heat recovery on P4. In addition to discovering new markets, it learned about the specific characteristics of green markets, which at an early stage, typically have very different dynamics than the mature markets with which TechLtd was familiar. Most of the market-related learning occurred toward the end of Path P2, when TechLtd began to actively explore the small wind market itself. This market is illustrative of an emergent green market as participation is very volatile, with many small wind turbine manufacturers entering and leaving the market or going bankrupt, often due to a lack of professionalism. At the market level, the lack of an industry association, producer networks, or lobbying organizations revealed a low level of market formalization.

## 4.2 | Path-initiation learning (T2)

Learning outcomes allowed the firm to set out on new innovation paths that would not have been considered if they had not explored previous paths. In this regard, two learning outcomes played an important role: first, the identification of new technology-market areas; (Learning 2) and second, the adjustment of the size of the innovation space (Learning 3).

### 4.2.1 | Identification of new technology-market areas (Learning 2)

One of the most striking findings is that the exploration of a technology-market area allows the firm to identify other—different but still related—green technology-market areas and can thus open subsequent innovation paths. It appears that the discovery of new areas is path-dependent on the technology and market knowledge gathered on the earlier paths (Learning 1). Consequently, even if a path leads to a setback, the discoveries made can allow a firm to identify new and promising paths. For instance, discovering how the automotive market (P1) works (for example, the stringent safety requirements) allowed TechLtd to recognize the market opportunity of flywheels as onboard storage in heavy-duty vehicles (P3). In fact, as explained in Learning 1, the feed-in technology discovered on Path P1 allowed the firm to enter other SET markets. Exploration on all subsequent paths was thus conditional on having embarked on path P1 (Table 1).

### 4.2.2 | Adjusting the size of the innovation space (Learning 3)

The size of the innovation space—the area in which a firm search for new innovation opportunities—adjusts over time as the firm learns more about which green technology-market area fits its assets, competences, and resource base. As it became progressively less constrained by its old business model—and related cognitive frames—the firm developed a better sense of what innovations were feasible and realistic. This is important for two reasons: first, better knowing what is feasible reduces the risks of initiating an innovation path that appears promising at first sight but is not realistic; second, it prevents missing out on viable innovation opportunities that the firm would not see because it had considered them as unrealistic. The data shows how this space was both widened and narrowed over time (Table 1), and how eventually a trade-off between a wide innovation space and high sustainability ambition was found (see also Wicki et al. 2015).

Sustainability guided TechLtd to technology-market areas that they had not previously considered. In this sense, sustainability widened the innovation space. At the beginning, top management hoped to have a very high positive impact and was consequently only interested in highly innovative energy generation technologies such as fuel cells. Following this rationale, it aimed to contribute to what it perceived as high impact technologies: at first, fuel cells (P1) and later small wind turbines (P2). This selection significantly narrowed down the innovation space. When it experienced difficulties penetrating these markets, TechLtd again widened the space from alternative energy generation (P1 and P2) to energy storage (P3), and finally even more broadly to energy-efficient technologies (P4). Although the innovation space was widened in this second phase, the decision to develop components that merely increased the efficiency of existing technologies (rather than engaging with high-impact innovative technologies) implies that TechLtd's initial ambition to develop sustainable technologies strongly decreased, and hence its potential sustainability impact. Thus, over time, the firm became more realistic with regard to its level of sustainability ambition.

### 4.3 | Cross-path learning (T3)

In addition to learning how to initiate new paths, double-loop learning also allowed the firm to reflect how exploration is done and draw important lessons for future innovation management practice. This reflection at the metalevel involved three learning outcomes. First, the firm came to understand the need for in-depth market exploration (Learning 4). Second, it increased its portfolio of exploration methods and became proficient at selecting the appropriate one (Learning 5). Third, it learned to make exploration more efficient (Learning 6).

#### 4.3.1 | Understanding the need for in-depth market exploration (Learning 4)

The firm learned across paths about the importance of market exploration—including end users—in assessing the validity of new business ideas before significantly committing resources. In-depth market exploration is particularly important in the context of emerging technologies with poorly established markets, a situation typical in the renewable energy context (see also Learning 1). Indeed, the dynamics of early-stage markets are more complex (Suurs, Hekkert, Kieboom, & Smits, 2010) and thus require in-depth exploration.

The findings show progressive learning about the importance of market exploration across the four innovation paths (see Table 1). On the first path (P1), TechLtd simply delegated market exploration to its main OEM customer in the belief that this major automotive player would be familiar with industry trends, trusting its interpretation and simply waiting until its own order book would fill up. Following this rationale, TechLtd did not seek to acquire any market information on its own. On path P2, exploration was largely delegated to a business partner with prior knowledge of the small wind market. In fact, its market knowledge was a major reason for initiating the joint venture. TechLtd began exploring the market with maladapted core business methods only toward the end of the path when sales did not increase. It is only when TechLtd had come to realize the importance of market exploration and when it no longer trusted the assumptions of its business partner that they began to carry out its own in-depth market exploration. An important change happened from path P3 onwards: it systematically began to explore markets before committing important resources to product development and terminated paths that were not perceived as promising (Table 1).

#### 4.3.2 | Increasing the portfolio of exploration methods (Learning 5)

Learning across paths allowed TechLtd to expand its portfolio of available exploration methods (Table 1) and to become more proficient at selecting an appropriate one. A firm that has focused for years on exploitative business strategies will likely lack the exploration methods needed to acquire knowledge about unknown green technologies and markets. These methods go beyond conventional market analysis by including networking activities (such as visiting industry workshops or approaching end users). Conventional market analysis tools typically do not allow a firm to understand the dynamics of emerging green technologies.

On the first path, P1, virtually no market exploration was undertaken and thus no methods were used. On path P2, realizing that relying only on the OEM did not provide them with enough market information, TechLtd initiated a strategic alliance to pursue market exploration. This partnership can be seen as its first new exploration method. Most new exploration methods were introduced on Path P3 after TechLtd realized how important exploration was (see previous section). On Path P3, TechLtd sought for the first time to (a) actively find new customers on its own, (b) attended a workshop to sense the pulse of the emerging industry, and (c) approached leading end users (not customers) with the aim of understanding their needs and so the viability of end-user business models in a highly volatile the market (see also Table 1). TechLtd learned to carry out in-depth market analysis before committing important resources to product development. Even though it carried out in-depth market exploration, path P3 was also eventually terminated because the flywheel markets were not mature enough to yield profits over the short term (see also Wicki & Hansen, 2017). On path P4, some of these methods were discarded because this market was more mature than those on paths P1, P2, or P3. New methods were also introduced, such as the "wait-and-see" approach, which consisted of analyzing whether a technology market area is theoretically promising and then waiting to see if it fulfills that potential. Without having made upfront investments, TechLtd periodically surveyed the market for positive signals.

#### 4.3.3 | Making exploration more efficient (Learning 6)

Given the high uncertainty that each path involves, it is essential to make exploration more efficient by terminating unviable paths early on and thus saving important resources (in terms of time, personnel, and investment). Improving exploration efficiency allows a firm to increase its overall chances of success, as it is able to "walk down" more paths, increasing the chances that one will lead to success. The findings show an evolution from a random to a more intelligent trial-and-error approach, with exploration activities yielding better learning outcomes. This evolution is most visible from Paths P2 to P4 with regard to three elements.

First, the findings show that the effort needed to assess a new business idea decreased in terms of the number of exploration activities needed, the duration of the exploration, and the financial resources involved (Table 1). For instance, Path P3 was terminated after only 5 years, five exploration activities, and about half a million euros, whereas it took top management over 8 years, 11 activities, and three–four million euros to terminate path P2. For Path P4, top management took about 2 years (five activities and also three–four million euros) to adopt a wait-and-see approach.

Second, the firm improved at selecting the appropriate exploration methods, making it more efficient at exploration. Indeed, across paths, the use of exploration methods became more targeted and yielded more accurate information. The proficiency at selecting the appropriate method increased along path P3. Fewer methods were used, but they brought exactly the information needed to understand the market dynamics. As the market was not mature, top management terminated this path early on without significant investment (Table 1). TechLtd further improved its ability to select the right method on Path P4, where methods that were only adapted to early-stage markets were dropped, because they were not useful in this more mature market. The firm's increased proficiency at selecting the right methods also shows that it developed a much better understanding of what information was needed to assess the viability of a new business idea and learned to search for it in a very focused way.

Third, the decision whether or not to pursue an innovation path came earlier and was more pragmatic (Table 1). Interesting but not promising paths—those that might yield commercial success only in a distant and uncertain future—were given less attention. This evolution is visible in the rationales of path termination. On Path P1, the project was continued based on the explicit signal of the main customer who trusted the market. It was only terminated when TechLtd realized it could not protect its intellectual property and thus not capture the value of its innovation. Path P2 was terminated very late, only when it became obvious that there was another way to market the product, which by then was maladapted to market needs. Path P3 was terminated as soon as top management realized that the business model of its end users was not viable. Finally, on Path P4, the wait-and-see approach was adopted (instead terminating the project) as soon as TechLtd realized that the market was still too young to be reasonably predicable. From then on, it only invested periodically in market screening. With the exception of the first path (which was relatively simple as the signal came from the customer), it is striking to see how these decisions were taken much earlier on the fourth path compared with the previous two.

## 5 | DISCUSSION AND CONCLUSION

### 5.1 | Green innovation as path-based learning processes

This paper empirically examines how green (technology) innovation processes unfold at established firms aiming to seize new business opportunities emerging with sustainable development (Hart et al., 2003). Our findings provide a path-based learning framework and a fine-grained longitudinal view of underlying exploration processes (Table 3; Figure 5) and of a typical green innovation journey. Opening up the black box reveals a very different process from the incremental innovation typically observed in established firms with focus on performance (Benner & Tushman, 2003). Far from a planned one-time action, our research reveals a more complex and nonlinear process that is unfolding over time. It is emergent, with several paths coevolving in parallel, influencing each other, sometimes overlapping, very often intertwined, iterative, and of an unpredictable length. It is an often long—over a decade in the case study, messy, sometimes surprising, discovery process toward an entirely new and unknown business area—much like the entrepreneurial action of starting up a new firm. Our findings corroborate previous research on radical innovation in the nonsustainability context, which found very similar process patterns (Cooper, 1983; Van de Ven et al., 2008).

The findings also reveal that failures play an important role. The unfolding innovation process involves many trials and errors. For the many new things that are learned, numerous mistakes were also made. Failures can therefore not be disassociated from this process; they are a necessary element. Hence, a new perspective on failures is needed, one that considers failures as learning opportunities that are inherent to any creative process where someone discovers and start to learn something new.

The path-based learning framework offers a new view on green technology innovation processes. It reveals that three types of learning happen along the paths. First, learning happens on-path, second as path-initiation learning, and third as cross-path learning.

#### 5.1.1 | On-path learning

First, a part of the journey is simply to learn an important amount of new things. It is the hard learning work that the firms need to do on each path. At this level, the firm learns about the specificity of green technology and market environments as well as how to use its core competences in emerging environments. It learns what sustainability really means for the firm. As the learning effort required is tremendous and there are probably no shortcuts, firms expect to team up with other actors that do have some of this knowledge (Lavie & Rosenkopf, 2006). The failures at this level relate to learning things that are not needed for the innovation at hand.

#### 5.1.2 | Path-initiation learning

Second, the knowledge generated on each path allows the firm to identify new paths that were not previously accessible. In this process, the size of the innovation space is progressively adjusted and the firm learns to make trade-offs between a high ambition for sustainability and a more realistic view of what is possible. Related to this learning type, failure consists of investing in an innovation path that is not viable, i.e. walking down a path leading to a dead-end. However, we concur with previous research that this kind of failure is simply part of an exploratory journey (Van de Ven et al., 2008). Dead-ends are normal in a trial-and-error processes. In fact they even allow new paths to be opened up. Indeed, it is unlikely that a firm would discover new business areas without first exploring one or two unsuccessful ones. Therefore, dead-ends (and opening up new paths) are simply part of the unfolding journey and should not be seen as failures.

Since dead-ends are normal and likely more frequent than successful innovations, innovation researchers should further examine the role of this kind of failures in green innovation. For instance, a practical way to better understand their role in this process is to examine if there are typical failures or traps (van Oorschot, Akkermans, Sengupta, & Van Wassenhove, 2013). This research shows at least one trap: The case study firm first aimed at a high impact innovation, before realizing it was too ambitious and eventually finding innovations that better fitted their competences. Knowing more about typical traps may tell us more about the journey toward greater sustainability and help firms speed up their processes.

### 5.1.3 | Cross-path learning

Third, cross-path learning allows the firm to evolve from a rather simple and blind approach to a more intelligent form of exploration. The firm becomes faster and more effective at exploration over time, as it comes to understand the need for in-depth exploration before committing important resources. Moreover, it learns how to better use exploration methods, which allows exploration to be more effective and efficient, increasing the return on exploration (Birkinshaw & Haas, 2016). This evolution is located at the level of believes, cognitive frames, and routines (Tripsas & Gavetti, 2000). It involves abandoning old habits of thought that become limiting for innovation and developing new ones. Turning new thoughts into organizational reality implies creating new routines, which is a tremendous challenge as routines are hard wired into the organization and are thus an important source of inertia (Leonard-Barton, 1992). New practices that favor a more intelligent exploration may include involving innovation intermediaries (Klewitz, Zeyen, & Hansen, 2012), participating in networks (Halme & Korpela, 2014), or relying on open innovation (Arnold, 2011). It is this evolution that allowed the case study firm to become over time better equipped for exploring emerging business areas.

Related to cross-path learning, three kinds of failures can be found. First, firms may underestimate the need for upfront exploration, for instance, by believing that there is no need to learn much about a new area. Second, they may use inappropriate exploration methods that do not provide the information needed to pursue or terminate a path. Third, they may not draw the important lessons of previous failures and thus be inefficient at exploration. Efficient exploration processes allow new business areas to be explored quickly, and to decrease the exploration costs of each path. This in turn also allows firms to decrease the high financial risks involved with walking into a dead-end. As each path costs less, more paths can be explored, thus increasing the ultimate chances for success. It also saves time, which is essential to achieve competitive advantage when other firms are racing for the same emerging markets (Eggers, 2012). Although the failures related with the first two types of learning seem unavoidable, firms can work on this last type of failures.

To be successful at developing green technology, we suggest that firms need to significantly invest in learning "how to explore intelligently." This appears to be the most important leverage point for firms to successfully navigate the innovation journey. However, learning how to explore more intelligently is an ability that established firms typically lose as they mature and focus on productivity (Benner & Tushman, 2003), and become less entrepreneurial. Therefore, it needs to be continually redeveloped. Even though this is so important, we so far know relatively little about how firms actually develop again the ability to explore intelligently after a long period of exploitation. Hence the ability to do so is perhaps the fundament of what some authors refer to as the green innovation capability (Assink, 2006; Chen, 2008). This seems to be a very interesting avenue for further research.

## 5.2 | The complexity of green innovation

The path-based learning framework also provides empirical insights into the complexity involved with green technology innovation. In the literature, it has often been argued that green technology innovation is more complex than conventional innovation (Seebode et al., 2012; NBS, 2012; Adams et al., 2016). However, the literature features little evidence to support this claim. The fireworks model allowed the study of this unfolding innovation without reducing its complexity and reveals complexity at least at two levels: overall and on each path. First, developing green technology innovation is complex overall because it likely requires several paths to be walked down before one innovation is successfully developed. In one innovation endeavor several individual innovations are embedded, each being very different from the other and bringing their own complexity with it, thus strongly increasing overall complexity.

Second, each path has its own complexity. Our findings show complexity at three levels: First, sustainability markets are more prone to regulatory interventions (Luethi, 2010), at least in the renewable energy context. Regulations change unpredictably, making market evolution more uncertain. This uncertainty increases the difficulty for firms to invest in these markets. Thus, although governmental interventions aim to support market development (Kemp, Schot, & Hoogma, 1998), unpredictable regulation increases entrepreneurial risk and can lead firms to shy away from investment. Second, sustainable technology markets are often still at an early stage of development and typically function differently than mature markets (Suurs et al., 2010). These younger markets are often more volatile, their dynamics less stable, and their evolution less certain. Hence, they are more difficult to analyze. Thus, established firms must first develop appropriate exploration methods to understand the complex dynamics of these markets before entering them. Third, due to the "directional risk", a green technology innovation idea that was initially considered as having the potential to have a strong sustainability impact may turn out to have less impact in the use phase (Hansen et al. 2009; Paech, 2007). This means that an innovation's sustainability performance needs to be periodically reassessed along the innovation journey. If the firm does not want to compromise its sustainability ambition, this may decrease the size of the innovation space. This would also mean that a number of paths will be terminated because the impact is too low, which may increase the overall costs of the innovation journey.

## 5.3 | Management implications

The findings raise important questions about how to successfully manage green technology innovation processes at established firms and make them as ressource efficient and fast as possible. Likely, the failures related with exploring the wrong technologies or markets (relating with T1 and T2) cannot really be avoided. However, the failures related with T3 represent an important leverage point to improve the effectiveness of this process. We therefore focus on two significant ways to improve exploration: first, by fostering an organizational culture that values failures, and second, by developing exploration skills that yield a high return on learning.

First, a safe exploration space can be created within the organization (Raisch, Birkinshaw, Probst, & Tushman, 2009). In this space, exploration failures are not only tolerated but are even valued so as to enrich the exploration process and make it more efficient. Indeed, even though errors are a natural part of trial-and-error learning, firms do not necessarily understand their value. In fact, risk and failure adverse organizational cultures are very common (Khanna et al., 2016), possibly because traditional management textbooks emphasize failure avoidance. However, learning from failures is often hampered by important barriers embedded in the social system that are related to adverse psychological reactions to failure (Cannon & Edmondson, 2005). Furthermore, as most firms reward success and punish failure, managers have an additional incentive to disassociate themselves from failure. Therefore, a prerequisite for effective learning from failure is a failure-friendly organizational space, which according to Sitkin (1992), can be promoted by removing procedural constraints on natural experimentation and by legitimizing “intelligent” failures.

Second, the return on learning from each exploration activity can be increased (Birkinshaw & Haas, 2016). Our findings show a movement from blind to more intelligent trial-and-error processes, which progressively yield a higher return from learning. Exploration activities can be purposefully designed as small experiments to yield as much learning as possible (Cannon & Edmondson, 2005; Sitkin, 1992). When an experiment is well-defined in terms of its expected knowledge gain, it is easier to design further small-scale experiments to build up, step by step, the knowledge needed for exploration. Another advantage of such a deliberate experiment design is that it allows exploration to be split up into smaller discreet activities. These are easier to manage, also in case of failure. Finally, with numerous small instead of a few large-scale experiments, the firm can more rapidly assess the viability of a new business idea.

A failure-friendly space and intelligent trial-and-error learning can help overcome the additional complexity that green technology innovation involves and thus represents a good basis for building green exploration capabilities. Given how new and different this is from managing the core business, hiring an external, qualified person to facilitate this exploration is possibly a very good investment for firms aiming to navigate the innovation journey.

## 5.4 | Future research

An interesting question for future research is how a firm orients its initial search direction. Noci and Verganti (1999) suggest that firms can use the concept of sustainability as an orientation point in the context of strategic change, and Hart et al. (2003) explain that firms can use green technologies to seize new business opportunities. Our paper shows how exploration might work, but we still know little about how a firm chooses its initial direction of search. Why does a firm develop small wind turbines instead of (green) nanotechnologies? This paper shows that firms may use their core competences as a starting point in their search to create sustainable value in emerging green markets. In this sense, our findings corroborate with insights of the literature on strategic management (Ansoff, 1957) and exploration strategies (Voss & Voss, 2013), which suggest that firms use their core competences to orient their exploration direction. Hence, we suggest that established firms leverage their existing core competences (or assets) to obtain profits in emerging green markets (Kiefer et al., 2018; Shah, Arjoon, & Rambocas, 2016). This approach appears particularly interesting to technology-driven firms who possess strong core technologies (Kiefer et al., 2018; Taylor & Helfat, 2009), but it is not limited to the technology area. Future research could examine what can trigger such a process. We have, for instance, little clarity whether intrinsic top management motivation—or a set of values (Baumgartner, 2009; Dangelico, 2016; Jenkins, 2009)—is a necessary precondition for engaging in a green technology innovation journey. Or can more conventional (nonsustainability minded) top management teams initiate similar processes? Furthermore, future research could also explore whether firms can also leverage their market position (instead of core competences) for green exploration.

## 5.5 | Limitations

The main limitation of this research relates to its research design. We studied a single firm and our results are therefore not simply generalizable. Nevertheless, they are transferable (Guba, 1981) as the learning processes and related outcomes are assumed to be typical of many entrepreneurial SMEs and other organizations (including large ones) in resource-constrained contexts.

Although we did include external actors in our analysis, a second limitation comes from the firm internal perspective on the learning process. Future research could adopt a broader focus that approaches the innovation process from a network perspective, for instance, using the notion of action-learning networks (Clarke & Roome, 1999). This complementary perspective would allow a better understanding of the role other actors play in the innovation process. This is particularly relevant in the SME context, where collaboration and networking play a crucial role (Adams et al., 2016). Furthermore, this perspective could also help us better understand how intermediaries—local governments, innovation process facilitators, or consultants—could support a firm on its path of innovating for sustainability (Goodman et al., 2017; Klewitz et al., 2012).

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## APPENDIX A

**TABLE A1** Empirical data: path origin of detailed learnings in relation to their impact on innovation paths

| | Impact on Path 1—FCs | Impact on Path 2—SWTs | Impact on Path 3—FS | Impact on Path 4—WHR |
|---|---|---|---|---|
| Detailed learnings 1–14 from Path 1 (FCs) | ***T1: On-path learning***<br>1. TechLtd learns about FC technology → L1<br>2. Size of controller needs to be small to fit vehicle applications → L1<br>3. Strict compliance with many safety standards is needed in the car industry → L1<br>4. Learns about feed-in technology (how electricity generated by FCs needs to be transformed to be grid compatible) → L1<br>5. Discovers characteristics of green markets (numerous small niche markets with different regulations, some are at very early stage or still in formations and thus difficult to predict) → L1<br>6. Discovers automotive supplier markets → L1<br>7. Meet actors knowledgeable about feed-in technology and green markets → L1<br>8. Norms in car industry (product quality and compliance, need for dedicated department) → L1<br>9. Automotive markets have high entry barriers due to long supplier selection processed. High risk of important upfront investment → L1<br>10. High-volume automotive markets exceed TechLtd's current manufacturing capacity → L1 | ***T2: Path-initiation learning***<br>4 → L2<br>5 → L2<br>7 → L2<br>11. Mature technologies offer better commercial prospects, unlike those still in emerging as in path P1 → L3<br>12. Large well-established markets difficult to penetrate due to important, formalized entry barriers (such as strict norms and supplier selection standards) → L3<br>13. Market size should not exceed TechLtd's production capacity of <1000 pieces/year → L3<br><br>***T3: Cross-path learning***<br>14. R&D collaboration is very helpful for new product development (to share costs and risks) → L5 | ***T2: Path-initiation learning***<br>2 → L2<br>3 → L2<br>4 → L2<br>5 → L2<br>6 → L2<br>7 → L2<br>8 → L2<br>11 → L3<br>13 → L3<br><br>***T3: Cross-path learning***<br>14 → L5 | ***T2: Path-initiation learning***<br>4 → L2<br>5 → L2<br>7 → L2<br>11 → L3<br>12 → L3<br>13 → L3<br><br>***T3: Cross-path learning***<br>14 → L5 |
| Detailed learnings 15–31 from P2 (SWTs) | n/a | ***T1: On-path learning***<br>15. Learns about SWTs and associated technologies → L1<br>16. Wind turbine management technology (manage highly fluctuating turbine velocity) → L1<br>17. High efficiency inverter and grid feed-in technology to minimize conversion losses → L1<br>18. Meet many SWT market actors → L1<br>19. Discover global SWT niche market dynamics, and the difference among countries → L1<br>20. SET markets often come with high product development costs due to national regulation; high costs for market monitoring → L1 | ***T2: Path-initiation learning***<br>17 → L2<br>24. Most inverter and feed-in components developed for SWT can be reused for FS and WHR → L2<br>25. Do not go into B2C markets as TechLtd lacks competence to handle large consumer sales and after sales requirements → L3<br><br>***T3: Cross-path learning***<br>20 → L4<br>21 → L4, L5<br>22 → L4<br>26. Industry workshops are good to rapidly meet many market actors and gain market information → L5 | ***T2: Path-initiation learning***<br>17 → L2<br>24 → L2<br>25 → L3<br><br>***T3: Cross-path learning***<br>20 → L4<br>21 → L4<br>26 → L5<br>27 → L5<br>29 → L4, L6 |

(Continues)

**TABLE A1** (Continued)

| | Impact on Path 1—FCs | Impact on Path 2—SWTs | Impact on Path 3—FS | Impact on Path 4—WHR |
|---|---|---|---|---|
| | | 21. SET markets are highly dependent on government regulation of renewable energies; require intensive market exploration and adapted exploration methods → L1<br>22. Early-stage markets typically involve → L1<br>– bankruptcy risks<br>– long and difficult trust-building<br>– lack of professionalism<br>– lack of industry networks<br>– lack of industry lobbies<br>23. In the SWT market, many poorly functioning turbines create legitimacy problems (that can even impact reputation for component suppliers) → L1 | 27. In SET markets, upfront research is needed about the numerous regulatory frameworks (for instance related with the different feed-in tariffs in Europe) → L5<br>28. Approach industry leaders (to understand their business model) allows to rapid have an idea of the market dynamic at play → L5<br>29. Involve end users in product development (to better understand their needs) → L4, L6<br>30. Assess viability of the business model of potential clients. Sometimes it even allows to estimate if the overall market is viable; the business model of a waste truck manufacturer showed that flywheels are not ready for automotive applications → L5, L6<br>31. Rapid prototyping instead of (upfront) full product development → L5, L6 | |
| Detailed learnings 32–39 from P3 (FS) | n/a | n/a | ***T1: On-path learning***<br>32. Learns about FS technology → L1<br>33. Two main application areas: vehicles and electricity grid → L1<br>34. Learns to developed and emergency shutdown module in case of electricity cut → L1<br>35. High complexity as FS can be used for multiple applications in several still emerging markets → L1<br>36. Large FS fit electricity-grid, micro FS rather automotive applications → L1<br>37. FS diffusion dependent on government feed-in legislation → L1<br>38. Automotive market: strong dependence on very few market gatekeepers (e.g., automakers, train manufacturers) → L1 | ***T2: Path-initiation learning***<br>n/a<br><br>***T3: Cross-path learning***<br>39. A good method is to adopt a “wait-and-see” approach in promising markets with high uncertainty about future development → L5, L6 |
| Detailed learnings 40–43from P4 (WHR) | n/a | n/a | n/a | ***T1: On-path learning***<br>40. Learn about WHR technology → L1<br>41. Heat recovery is still a niche market with many different customer applications → L1<br>42. High search costs for other/new customers in markets with very diverse customer applications → L1<br><br>– case by case approach (no standard solutions) |

(Continues)

**TABLE A1** (Continued)

| Impact on Path 1—FCs | Impact on Path 2—SWTs | Impact on Path 3—FS | Impact on Path 4—WHR |
| --- | --- | --- | --- |
| | | | – high-speed solutions only needed in some applications<br>– need to demonstrate advantage of high-speed solutions to customers<br>43. WHR market highly dependent on government regulations → L1 |

Note: FC: fuel cell; FS: flywheel storage; R&D: research and development; SWT: small wind turbine; WHR: waste heat recovery. The detailed Learnings 1–43 are listed and explained in relationship between the Paths P1–P4 they originated on and the Paths P1–P4 they had an impact on. Some detailed learnings have an impact on more than one path. Each detailed learning is related with an "→" to one or more of the six learning outcomes (L1–L6). Some detailed learnings related with two (or more) different learning outcomes. In that case, the table only features their number when they appear the second time (e.g., 2 → L2). Single-loop learning outcomes that were directly useful for the same path (on-path) are described under T1. Single and double-loop learning outcomes useful to initiate new paths (path-initiation learning) are described under T2, and double-loop learning outcomes that allowed an improvement of exploration (across path) under T3.

Coding scheme: first order concepts: detailed learnings (1–43); second order themes: learning outcomes (L1–L6); aggregated dimensions learning types (T1–T3).

## Paper 5

Ambidexterity management for diversification through green innovation: lessons learned from unsuccessful separation in SMEs

# Ambidexterity management for diversification through green innovation: lessons learned from unsuccessful separation in SMEs


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**Abstract:** The ambidexterity literature suggests radical innovation is driven by preventing the undesirable spillover of routines and cognitive representations from the exploitative core business to the exploratory innovation space. This paper presents a longitudinal process study uncovering the anatomy of an unsuccessful exploration of green energy technologies by a medium-sized entrepreneurial technology firm. We investigated their innovation processes to understand how the managers configured and reconfigured the exploration-exploitation interface over time by using various modes of balance. The paper contributes to the ambidexterity theory by identifying three separation pitfalls. First, a 'separation drift' from a textbook-like to a looser form of organizational separation allows for the undesirable spillover of routines which cannibalize the new business over time. Second, a mismatch can occur between the intended product-market strategy and the actual product-market exploration. A third pitfall strongly increases management complexity due to the simultaneous use of several modes of balance originally perceived as a more resource-efficient alternative to a clear-cut organizational separation.

## 1. Introduction

In uncertain, volatile and rapidly evolving industries, the simultaneous orchestration of exploration and exploitation is a precondition for long-term survival (O'Reilly and Tushman, 2008; Cesaroni et al., 2005). Firms with this capability are called ambidextrous organizations. A central issue in managing the balance between exploration and exploitation is the separation and integration of the two distinct innovation spaces in order to prevent the undesirable spillover of harmful routines and cognitive representations from the core business to the explorative innovation space. For instance, 'contamination' or 'leaks' can strongly compromise the emergence of path-breaking product or market innovations (Tripsas and Gavetti, 2000). To avoid spillovers, the literature discusses various generic modes of balance between old and new businesses including organizational separation, temporal separation, contextual ambidexterity, and domain separation (Lavie et al., (2010). While the ambidexterity literature has burgeoned, literature explicitly focusing on how the exploration-exploitation interface can be adequately managed is still rare (Jelinek and Schoonhoven, 1993; Gassmann et al., 2012; O'Reilly and Tushman, 2013).

A new context which is becoming more and more relevant for research in ambidexterity is sustainable development which can be considered as a fundamental driver to changing societies and markets (Seebode et al., 2012). Although to varying degrees in different sectors, sustainability issues lead to changing regulatory frameworks, business environments, market conditions, and customer preferences. This creates both pressures on existing technology regimes and opportunities for entirely new technological spaces together providing the opportunity for green or sustainability innovation (e.g. Schiederig *et al.,* 2012). Companies thus face the challenge to balance the exploration of new green products with their exploitation of the existing business (Noci and Verganti, 1999). Furthermore, the SME context has so far received comparatively little attention in the ambidexterity literature, even though they are just as threatened in the face of volatile markets as large firms (Welsh and White, 1981; Lubatkin, 2006; Voss and Voss, 2013).

Motivated by the call for research by Lavie et al. (2010), Gassmann et al. (2012) and O'Reilly and Tushman (2013), this paper analyzes the management of the exploration-exploitation interface. Specifically, we examine an ultimately unsuccessful exploration, which started with a planned and initially introduced separation followed by an erosion of the separation resulting from cumulative effects of top management decisions, middle management behaviours, and market circumstances. To learn from this unsuccessful innovation process, we examine how managers of an SME dynamically (re)configured the interface between old and new businesses while exploring green innovations. The research strategy of this paper is to analyze exploratory innovation processes in a longitudinal process study (Huber and Van de Ven, 1995) in line with other ambidexterity scholars who have adopted this approach (Walrave et al., 2011; Tripsas, 2009; Khanagha et al., 2014). Particularly, we look at how exploration was managed across value chain functions (i.e. research and development vs. sales and marketing), across various organizational levels (i.e. top management, departments, individuals), and across organizational boundaries (i.e. internal and external through alliances).

The organization examined is a typical hidden champion – an owner-managed entrepreneurial SME in Germany operating as an international technology leader in a business-to-business niche market. When the top management realized that its main market was threatened, and because the founders are attracted to the vision of sustainable development, the company investigated how to use its core technological competencies in the area of renewable energies. In the context of this diversification, it initiated an explorative learning process that has, until now, not led to a successful outcome.

This paper makes a contribution to theory development by the identification and conceptualization of three major pitfalls which can occur in the management of the exploration-exploitation interface. First, a drift from a “textbook-like” organizational separation to a looser form over time allowing a gradual or sudden spillover of undesirable routines and cognitive representations can contaminate the exploratory innovation space and jeopardize innovation outcome. Second, a misfit between intended product-market strategy and the operationalization of the product-market exploration process (Voss and Voss, 2013) can represent a major cause for exploration failure. Third, the paper reveals how several modes of separation can simultaneously coexist and coevolve within the firm. Consequently, the exploration-exploitation interface can be relatively fluid, thus requiring important attention from boundary-spanning mid-level managers (Tushman, 1977; Cohen and Levinthal, 1990; Gassmann et al., 2012). We hypothesize that the advantage of managing ambidexterity with alternatives to organizational separation – even though it appears resource efficient at first sight (Lavie et al., 2010), is off-set by the increase in managerial effort. Our study's practical implication lies in identifying challenges of managing the exploration-exploitation interface over time – particularly in an SME context – and providing guidelines for overcoming these difficulties.

The remainder of this paper is structured as follows: the next section reviews the literature on exploration and exploitation. Section three introduces the methodology. The results are described in section four and analyzed in section 5. The last section discusses the findings and concludes the paper.

## 2. Literature review

Duncan (1976) set the stage for the ambidexterity discussion in his seminal work on dual structures for innovation. He posited that the ability to pursue innovation to secure both immediate and long-term competitive advantage is a fundamental challenge for long-term survival of organizations. This challenge of ambidexterity has become a key issue for firms aiming at diversification through green innovations (Seebode et al., 2012).

### *2.1 Green innovation and the need for ambidexterity management*

In many industries, seeking legitimacy in the face of changing political and regulatory environments, increasing stakeholder pressure, or new managerial mindsets, have raised concerns about how to incorporate the natural environment and other sustainability-related factors into innovation processes. This has led to an increasing interest of innovation management scholars and practitioners in concepts referred to as green, corporate social responsibility, sustainability, or stakeholder-oriented innovation (Hall and Martin, 2005; Hansen et al., 2009; Holmes and Smart, 2009; Schiederig et al., 2012; Seebode et al., 2012) – not only in the context of large firms but also SMEs (e.g. Noci and Verganti, 1999; Dangelico and Pujari, 2010). In addition to a commercial goal, such innovations (in the following simply referred to as 'green innovation') aim at commercial success while reducing negative impacts or increasing positive ones on the natural environment and promoting sustainable development (Schiederig et al., 2012). Green innovations include new processes, products, services, or business models and can be both technological or non-technological (Seebode et al., 2012).

While *incremental* attempts to promote green innovation have been widely adopted in businesses (e.g. energy-efficient production processes as exploitative innovations), there are often calls for more *radical* innovation – and thus exploration – for solutions with more significant contributions to sustainable development. Such radical innovations involve not only making process improvements but also providing innovative products and services (Noci and Verganti, 1999). While some streams of literature deal exclusively with entrepreneurial new ventures being "green" as part of their mission (e.g. Hockerts and Wüstenhagen, 2010; Kuckertz and Wagner, 2010; Schaltegger and Wagner, 2011), here we are more interested in green innovation as a diversification strategy of existing firms. Existing companies need to deal with both maintaining the old conventional business and developing the new "green" business – which sometimes contradict or cannibalize each other. They face challenges typically known in the ambidexterity literature as the exploitation-exploration paradox (Raisch et al., 2009). Take the example of car sharing: the automobile company Daimler AG, renowned for its premium cars, which had hitherto focused on car sales, created the independent organization Car2Go for introducing an innovative and environmentally-friendly free-floating car sharing service (Firnkorn and Müller, 2011). The separate organizations are important for the successful striving of two paradoxical logics in the same company – car *sales* and car *sharing*. Against this background, and in line with the observations of Seebode et al. (2012), the interface of literature on green innovation and ambidexterity can serve as a fruitful background for new research, but has so far been largely neglected.

### *2.2 Balancing exploration and exploitation through ambidexterity*

Ambidexterity involves the joint pursuit of two different forms of innovation: exploration and exploitation. In his seminal work, March (1991) defined *exploration* as learning and knowledge creation that involves search, variation, risk taking, experimentation, play, flexibility, discovery, and innovation. From a technological perspective, exploration involves a shift to a different technological trajectory (Benner and Tushman, 2002). *Exploitation* on the other hand, relates to refinement, production, efficiency, selection, implementation, and execution (March, 1991, p. 71). It involves improvement in the existing components and, most importantly, builds on existing technological trajectories (Benner and Tushman, 2002, p. 697). Exploitative innovation is therefore aimed at improving the existing product-market domain (He and Wong, 2004, p. 483).

Extant literature deals with the organizational antecedents, performance outcomes, environmental factors, and other moderators of ambidexterity, as well as modes of balance (Raisch and Birkinshaw, 2008) which can be used to reduce the inherent tension that emerges when the two opposing modes of innovation co-exist. Modes of balance can be understood as approaches to create an infrastructure for the harmonious coexistence of conflicting organizational architectures. While balancing includes integration, a fundamental prerequisite of ambidexterity is separation. Separation protects the exploratory innovation space from managerial myopia and inertia (Levinthal and March, 1993) and shields it from harmful routines and cognitive representations (Tripsas and Gavetti, 2000) that can prevent the healthy development of new innovation trajectories (Tripsas, 2013). While other related typologies exist (Gupta et al., 2006; Simsek et al., 2009; Raisch et al., 2009), those modes of separation are maybe best captured in Lavie et al. (2010) who distinguishes organizational, temporal, contextual, and domain separation (Table 1).

**Table 1** Types and mechanisms of separation

| *Type of separation* | *Level of analysis* | *Mechanism of separation* |
|---|---|---|
| Organizational | Organizational level | Activities occur simultaneously but are situated within distinct organizational units. |
| Temporal | Organizational level | Exploration and exploitation coexist in the same organization but at different points in time; organizations switch between exploration and exploitation. |
| Contextual | Individual and team level | Exploration and exploitation occur simultaneously in a given organizational unit |
| Domain | Organizational level | Exploration and exploitation occur in particular domains while balancing these activities across domains. |

Source: based on Lavie *et al.* (2010)

While *temporal* separation of exploitation-exploration is important when looking at longer time intervals, we are more focused on how ambidexterity is managed within dedicated episodes of exploration through organizational, contextual, or domain separation. *Organizational* separation is about maintaining structurally independent units reintegrated only by the next hierarchical level (usually top management). Much to the contrary, *contextual* ambidexterity shifts the burden of balancing exploitation-exploration to the individual. This requires creating a task environment that is conducive to both exploration-exploitation (Adler *et al.*, 1999).

A further and less discussed mode of separation is *domain* separation. Lavie et al. (2010) distinguish three domains: value chain function (upstream vs. downstream), network structure (existing vs. new partners), and partner attributes (similar vs. dissimilar to prior partners) and analyze combinations of these domains for characterizing the balancing of exploration-exploitation. Concerning these domains, the value chain function domain – covering both R&D and production/marketing – is most vital in characterizing the nature of innovation activities both in inter-organizational partnerships and within organizations (Lavie and Rosenkopf, 2006). But while they posit that R&D-related activities are *per se* more exploratory and marketing more exploitative, Li et al. (2008) develop this distinction further by considering both exploitative and exploratory approaches not only *within* any of the individual value chain functions (within-functional), but also *across* functions (cross-functional).

A similar view is taken by Voss and Voss' (2013), who, based on Ansoff's (1957) matrix of product-market strategies, present a typology with a continuum from less to more complex forms of exploration: a) product exploration and market exploitation (product ambidexterity), b) product exploitation and market exploration (market ambidexterity), and c) product and market exploration (pure exploration).

### 2.3 *Managing ambidexterity*

While the literature on ambidexterity is burgeoning, literature on ambidexterity *management* is still scarce (O'Reilly and Tushman, 2008; O'Reilly and Tushman, 2013). Literature dealing with the management of ambidexterity largely adopts the perspective of top management orchestrating the two different innovation spaces (Tushman et al., 1997). It must be able to manage the co-existence of organizational architectures of conflicting sub-units (Andriopoulos and Lewis, 2010). To succeed, leadership teams are recommended to develop a compelling vision and strategic intent providing direction for the exploration and integration of the new with the old business (Smith and Tushman, 2005).

However, there is even less literature dealing with the exact way how the exploration-exploitation interface can be managed. Jelinek and Schoonhoven (1993) emphasize the need to go "inside" the firms. Heller (1999) studied this interface from the loosely coupled systems perspective and drew attention to the phenomenon that a multitude of daily decisions create more or less strongly coupled exploration and exploitation spaces within the firm. Contextual ambidexterity scholars (Adler et al., 1999; Gibson and Birkinshaw, 2004) see job enrichment, role switching, task partitioning, and meta-routines as exploration-exploitation management approaches. Gibson and Birkinshaw (2004) even argue that those approaches can be used to integrate innovation spaces that were organizationally separated.

While separation provides the exploratory innovation space with independence and autonomy, the interface must also allow for sufficient proximity between the old and new. This has spurred interest in integration and related transition modes (Gassmann et al., 2012; Chen and Kannan-Narasimhan, 2015). Separation and integration are in fact two sides of the same coin. While organizational separation may be the strictest form of shielding the exploratory innovation space from its exploitative counterpart, this is likely to increase at the same time the future difficulty to integrate the new innovation into the existing business (Heller, 1999; Campbell et al., 2003; Gassmann et al., 2012). On the other hand, as we will show in greater depth throughout this study, if separation is not maintained properly, integration attempts may occur too early and put the innovative outcomes of exploration at risk. Hence, while generic modes of separation and integration are already known, the actual management practices at this interface are so far poorly understood.

### 2.4 *SME characteristics and ambidexterity*

Extant literature features a rich discussion on the differences between small and large firms (Welsh and White, 1981; Hockerts and Wüstenhagen, 2010). In many ways small business have their own special features and are not just 'little big businesses', particularly when it comes to green innovation (Noci and Verganti, 1999; Dangelico and Pujari, 2010). While typically facing resource constraints, limited professionalization and management capacity, compared to their larger counterparts, SMEs have the advantage of greater flexibility and can therefore react much faster to changing technological, market, and regulatory environments (Welsh and White, 1981).

Ambidexterity research indicates that resource availability (Sidhu et al., 2004; Cao et al., 2009) and firm size (Prajogo et al., 2013) positively influence the performance of ambidextrous firms. These findings indicate that small firms are disadvantaged compared to larger ones. However, in a survey of 139 SMEs (Lubatkin, 2006) ambidexterity is also found to be positively related to the performance of SMEs. In a recent study, Voss and Voss (2013) analyzed the impact of product and market exploration strategies on revenues, confirming that ambidexterity is positively related to SME performance, with *product* exploration and *market* exploration more strongly benefiting larger and smaller SMEs, respectively. SMEs can thus possibly also pursue successful ambidexterity strategies.

The resource-intensiveness of specific separation (and integration) modes is particularly important for SMEs. While it is often assumed that strict structural (i.e. organizational) separation requires the most resources, other forms of separation may cause less costs. For example, Lavie et al. (2010) argue that domain separation demands less proactive management attention and that coordination efforts are reduced.

Overall the literature review highlights the challenge of businesses in ever more industries to engage in the exploration of green innovations while exploiting their existing business. Balancing this interface requires both modes of separation and integration. The management challenges for top and middle management are great and differ to some extent between SMEs and their larger counterparts. This paper aims to make a theoretical contribution at the interface of green innovation and ambidexterity in the SME context by learning from an unsuccessful innovation project which, despite a well-orchestrated separation at the beginning, faced the erosion of separation over time, with the result that the full potential of exploration could not be realized because integration was apparently too *rushed*.

## 3. Research method

### *3.1 Research design*

To address this research question, we undertook a longitudinal process study in a medium-sized entrepreneurial technology firm (in the remainder of the paper we will refer to it as "TechLtd"). Such process studies of individual organizations are important to unravel the underlying dynamics of a phenomenon (Siggelkow, 2007). We specifically looked at the unfolding innovation processes at TechLtd and the dynamics involved in managing ambidexterity at the interface between old (conventional) and new (green) businesses. We followed other ambidexterity scholars, including Walrave *et al.* (2014), Tripsas (2013) and Khanagha *et al.* (2014), who recently used this method for detailed field studies, but in contrast to them, we focus on an unsuccessful case. To investigate the innovation process, we adopted a qualitative approach suitable for process studies (Huber and Van de Ven, 1995) that enables a better understanding of the dynamics at multiple levels of analysis:

across value chain functions (research and development, production, and sales and marketing), organizational levels (top management, departments, individuals), and organizational boundaries (intraorganizational, interorganizational through alliances). As will be covered in more detail throughout the method section, we assured 'trustworthiness' (Shenton, 2004) by addressing the criteria of credibility (internal validity), transferability (external validity), dependability (reliability), and confirmability (objectivity) with various research strategies such as triangulation of data types and informants, multiple investigators, transparency of the methodological approach, rich description of the phenomena and context as well as consideration of alternative explanations.

### *3.2 Case selection*

#### *3.2.1 Overview*

We followed theoretical sampling (Eisenhardt, 1989) with the aim of extending ambidexterity theory, particularly in the SME context. The case chosen is *critical* for extending well-established theory (Yin, 2014, p. 41) for the following reasons: (i) While most innovation and diffusion studies are subject to a pro-innovation bias in which mostly successful innovations are studied using ex-post analysis, our case presents an example of failed ambidexterity management and therefore unsuccessful innovation which was studied at several points of time (Rogers, 2003, p. 112). (ii) The case rules out two of the often conjured reasons of innovation failures (i.e. lacking top-management commitment and financial resources; Tushman *et al.*, 1997), and thus allows us to concentrate on the role of ambidexterity in general and modes of separation in particular for explaining failure. (iii) In relation to the increasing interest in green innovation – particularly in this journal (Noci and Verganti, 1999; Fichter, 2009; Schiederig *et al.*, 2012) – our study is a first attempt to integrate ambidexterity theory with green (technology) innovation, by analyzing how established firms (in contrast to new ventures) engage in 'green exploration' for new products in new markets (i.e. pure exploration; Voss and Voss, 2013) while continuing to exploit their previously existing product range.

The case is also *revelatory* (Yin, 2014) as it is relatively difficult to get (longitudinal) access to the unfolding innovation process, particularly in the case of unsuccessful innovation, which potentially weakens an organization's (or individual manager's) reputation as 'successful innovator'. In fact, this was only possible through an engaged scholarship approach involving the development of close ties with the organization's top management prior to the research project (Van de Ven, 2007).

#### *3.2.2 Introducing TechLtd*

The study examines TechLtd, an entrepreneurial technology SME employing approximately 220 employees in Germany. The family business, founded in 1962, is owner-managed in the second generation. Despite global market leadership in selected niches, the company operates largely ‘below the radar’ in the regional and national contexts, therefore representing typical characteristics of a ‘hidden champion’ (Simon, 2009) and the German ‘Mittelstand’. The company, driven by a strong engineering culture, develops and produces electronic components (computerized numerical control system, high-speed motor and generator control devices) which they sell to customers (i.e. system integrators) in business-to-business niche markets. Its primary market is machine tools with a focus on the niche market of circuit-board drilling. TechLtd has become a global leader in electronic control systems for high-speed engines. Its products are highly customized to the specific needs of its customers. Product development takes several months and is characterized by intensive R&D collaboration with customers and trust-based, long-term relationships. Production is characterized by small batches and is, contrary to industry trends, located in Germany. Sales offices exist in Europe, the USA, and Asia.

TechLtd decided to develop an entirely new range of green products for a new market in the domain of renewable energy technologies (RET). This represents an ambitious diversification strategy (Ansoff, 1957). TechLtd engaged in a strategic alliance with a new venture already operating in the RET market to develop and commercialize an electricity inverter necessary to connect small wind turbines to the electricity grid. The market for small wind turbines is at a very early development stage compared to more established large-wind turbines (e.g. Gsänger, 2013), not only lacking a dominant design but also without policy support (e.g. feed-in tariffs), thus facing large uncertainties. Nevertheless, the innovation received full top-management commitment and significant resources (about 3 million euros) but eventually had to be terminated because sales figures did not develop as expected. Contrary to the pro-innovation bias in most studies, this study therefore investigates a case of unsuccessful innovation.

### *3.2.3 Organizational structure representing exploitation and exploration*

TechLtd has a rather flat hierarchical organization. Top management, represented by the owner-manager (i.e. CEO) and the chief technology officer (CTO), is responsible for balancing exploitation and exploration across all organizational units. The company is organized along value chain functions – research & development (R&D), production, and sales & marketing (S&M) – and business lines – CNC systems, drive electronics, and feed-in technology. Due to the flat organization, no formal departments (e.g. R&D) or business units (e.g. CNC) exist, but the individual units report directly to the top management; an exception is the production department which serves all three business lines (Figure 1).

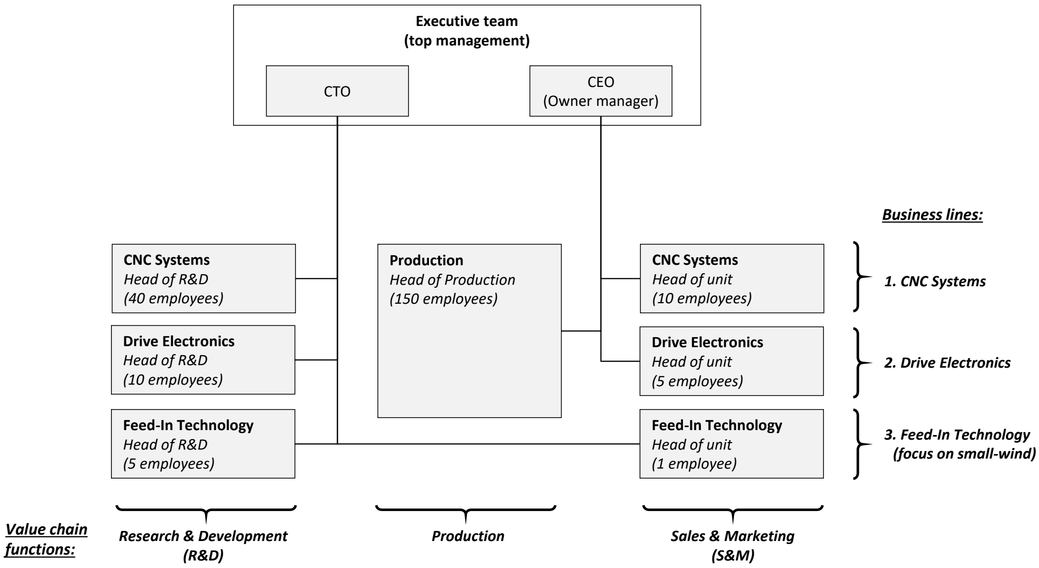


**Figure 1** Organizational chart of TechLtd showing value chain functions in columns and business lines and the associated product flows in rows.

The first business line deals with computerized numerical control (CNC) systems, which represents the core of the company with regard to its historical roots, size and sales. The second business line, drive electronics, was created thirty years ago as a spin-off and contributes about 20 percent of total sales. Instead of control systems for engines, this unit commercializes systems for high-speed generators and is responsible for one of the core competencies of the firm, i.e. the analysis and control of high-speed rotation. These two business lines are characterized by an exploitation rationale focusing on continuously producing incremental innovations to create temporary productivity gains for their customers. The focus of this paper is the third business line, feed-in technology, which was characterized by the exploitation rationale and was formally created in 2003 (12 years ago) to explore how the company could use its engineering competencies for developing new applications for the market of renewable energy technologies (particularly small wind turbines).

### *3.3 Data collection*

We utilized a combination of retrospective and real-time data collection approaches (Pettigrew, 1990) covering a period of 12 years (2002-2014). We were able to observe the last three years of the on-going innovation process (including its phase out) which allowed us to collect first hand insights on the process. Given that we focus on an unsuccessful innovation and that the termination of such innovation projects can take considerable time, longitudinal process studies are best suited for analysis (van Oorschot *et al.*, 2013).

To assure construct validity, we triangulated various data sources (Babbie, 2013) including semi-structured interviews, participatory observation, focus groups, and desk research (Table 2). Moreover, a broad selection of internal and external informants accounted for the consideration of diverse and partly contradicting perspectives (Shanton, 2004). On the company level, informants were members of top and middle management involved in the exploration, including current employees of the company and former (R&D) managers. Semi-structured interviews served to retrace events characterizing the innovation process. Focus group sessions were used in particular to understand the motivation of ongoing strategic and operational choices as well as to develop a deep understanding of the top management's cognitive representations as they evolved over time. Internal documents such as market research reports, technical design descriptions and customer lists were used to obtain facts about the market, product development, and commercialization. Business partners, value chain-related actors (including former customers and competitors) and further representatives of the small wind industry were interviewed to gain an in-depth understanding of the industry dynamics. Furthermore, considerable research effort was made to understand the small wind industry, to clearly identify the role of external factors in the unsuccessful innovation process, and to isolate them from internal factors.

The interview material was fully transcribed and data from site visits and participant-observation was protocolled (Babbie, 2013). This diverse and rich data was then analyzed and coded using software for qualitative data analysis (MAXQDA).

**Table 2** Data collection methods

| *Data types* | *Sources* | | |
|---|---|---|---|
| | *Internal: Top and middle management[1]* | *External: Business partners and value chain actors* | *Total* |
| Semi-structured interviews | 8 interviews | 9 interviews | 17 |
| Participant observation | 11 meetings | 2 industry events | 13 |
| Focus group sessions | 5 sessions | n/a | 5 |
| Document analysis | 25 internal documents (e.g. market studies, sales statistics, customer lists) | 70 publicly available documents (e.g. industry reports, market analysis, newspaper and magazine articles and websites of industry actors) | 95 |

*[1] Includes interviews with former managers not employed in the company anymore*

### *3.4 Data analysis*

To create credibility and objectivity, *multiple investigators* – including two senior researchers – were involved in the analysis, each taking specific roles (Shenton, 2004). The first researcher was strongly immersed in the empirical field by conducting most of the formal interviews, spending considerable time in the organization, and preparing field notes of individual interactions and observations. This researcher also prepared the descriptive case report which is the starting point for any theory-building case analysis (Eisenhardt, 1989). The second researcher, with considerable case research experience, was only partly engaged in data collection and rather took the role of an informed, but still independent observer focusing on the iterative process of data analysis and theory-building. He only took part in major interactions with the organization, particularly in the focus groups, studied, and critically commented on the field notes of the first researcher, suggesting alternative theoretical lenses instrumental for making sense of the events. At major milestones, in-depth discussions between the first two researchers continued until consent over the interpretations was achieved. The third researcher, the most senior in the team, served as a 'critical friend'. Being involved only in selected milestones of the case research (major meetings with top management) and being presented only with preliminary case analyses (rather than raw data), he was able to point to theoretical inconsistencies or weaknesses, draw comparisons to other research studies, and provide fresh perspectives. Such *peer scrutiny* was additionally provided by various reviewers and discussants at major research conferences. *Member checks* were also conducted, both by involving lower management in checking partial analyses, as well as in dedicated meetings with the top management where an in-depth discussion of the overall analysis was conducted.

In line with the recommendations for longitudinal case studies (Van de Ven and Poole, 1990; Huber and Van de Ven, 1995; Yin, 2014), we started the analysis by reconstructing the timeline (which is partly reproduced in Table 3 and Figure 2) of the innovation process. We referred to the fireworks innovation process model (Van de Ven *et al.*, 2000/1989) because it allows rich analysis of the complex, non-linear processes on the micro-level. The fireworks model depicts the innovation process as intertwined and interdependent innovation paths that, taken together, form a complex trajectory. The model focuses on ideas, people, transactions, context and outcomes along the trajectory to explain events such as setbacks, changes in the search direction, the fluid participation of personnel, involvement of top management, evolution in success metrics, cognitive representations and routines (Van de Ven and Poole, 1990). Though we did not apply their categories in a mechanistic exercise, the framework was important for us in analyzing the dynamics of complex non-linear innovation processes and allowed us to obtain a rich understanding of how they were managed over time.

## 4. Descriptive results: phases of the innovation process

The innovation process at TechLtd focused on in this study ranged from 2003 to its termination in 2013 and can be divided into four major phases: 1) technological exploration, 2) product development, 3) market introduction and continuous product improvement, and 4) phase out (Figure 2 and Table 3 provide an overview).

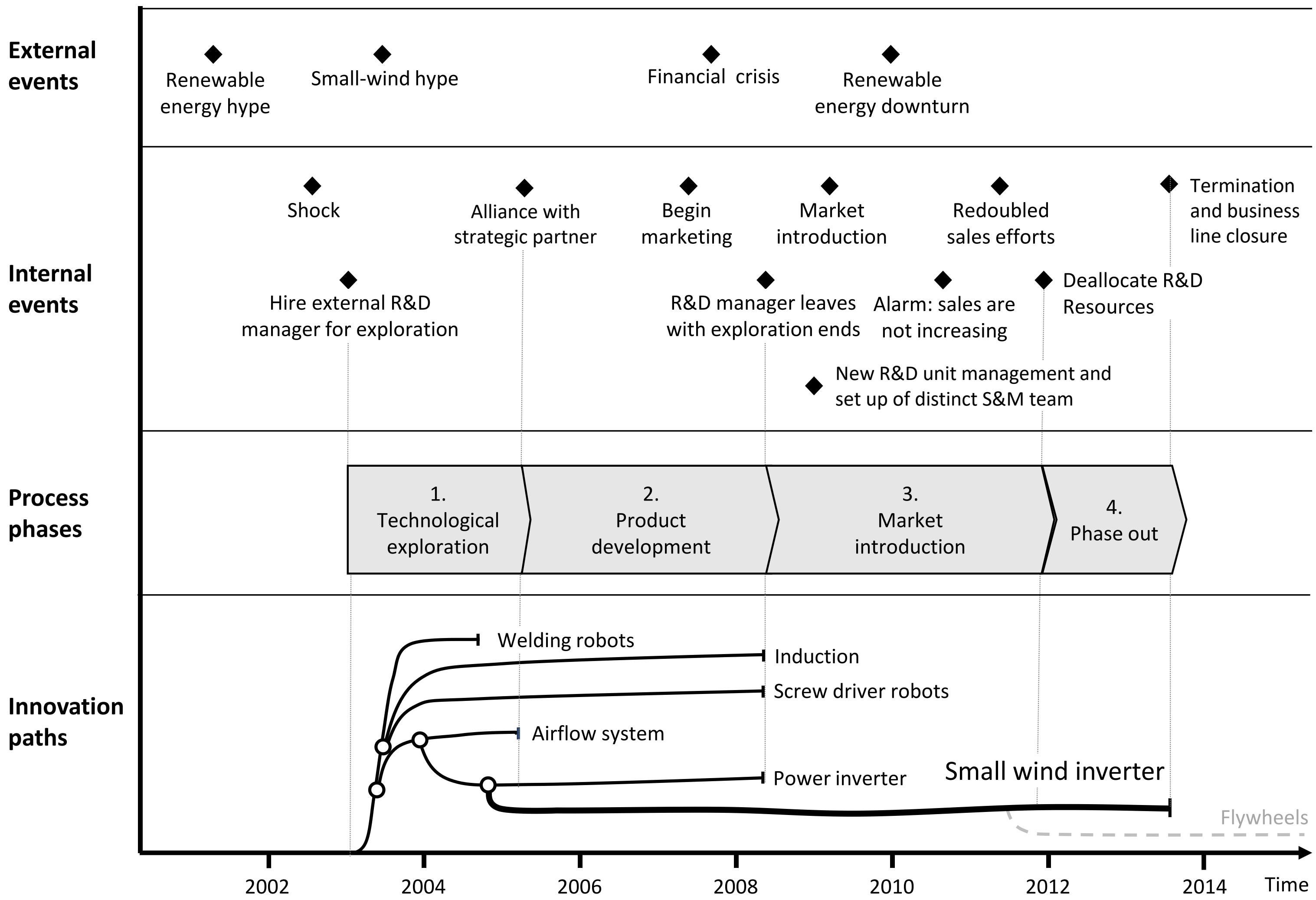


**Figure 2** Visualization of the innovation process over time based on innovation phases, innovation paths, internal and external events.

**Table 3** Activities, events, knowledge developed along the innovation process

| *Activities per level/unit:* | *Phase 1: Technological exploration* (2003-2005) | *Phase 2: Product development* (2006-2008) | *Phase 3: Market introduction* (2009-2012) | *Phase 4: Phase out* (2013) |
|---|---|---|---|---|
| Top management | •Strategic planning<br>•Hires new R&D head and engineers for broad R&D exploration<br>•Approves small wind project as part of exploration | •Supports small wind project<br>•End of broader R&D exploration: refocuses the unit's activity on small wind project | •Sounds alarm<br>•Orders new market research and increases resources for S&M | •Reallocates R&D resources<br>•Starts final marketing attempt<br>•Maintains S&M resources because main competitor left market<br>•Terminates project |
| Research & development (R&D) | •R&D networking, new projects with university and industry partners (e.g. air flow system, fuel cell inverter, induction system, feed-in technology<br>•Decision to develop small wind inverter product<br>•New partnership with university spin-off WindUp (partner for product development)<br>•Preliminary product design | •Product development/design:<br>- Intense collaboration with WindUp<br>- Builds prototypes<br>- Tests product<br>- Improves product with three pilot customers | •Transfers blueprints to production department<br>•Product improvement:<br>- Develops version 2 and updates<br>- Cooperates with lead users<br>- Cooperates with producers to trouble-shoot poor quality turbines | – |
| Sales & marketing (S&M) | – | •WindUp: market analysis for product design<br>•Client acquisition results in many purchasing intentions<br>•Sales strategy: high-quality, customized inverter to maximize performance of wind turbine | •Increases own sales efforts<br>•International market research (e.g. Spain)<br>•With WindUp: client acquisition in Europe and USA | •Last intensive sales efforts targeted at clients in Germany |

### *4.1 Phase 1: Technological exploration*

In 2003, top management hired an external engineer as head of R&D of the then newly created feed-in technology business line. His task was to lead the exploration of potential new RET applications with overlaps with the company's core technologies. Given the company's core competencies in controlling high speed rotational devices, this led to the focus on 'rotation-based' RET (basically turbines for harvesting energy from wind or water) and, later, also other rotation-based green energy storage technologies (e.g. flywheel storage). Under his lead, several options were explored relating to the feed-in of green electricity into the power grid. Among these, a collaboration with a technical university allowed TechLtd to develop a new central technological component of the new business line: the electricity inverter. In this context, TechLtd came to work with a university spin-off, a young, dynamic, engineering-minded start-up. Besides some knowledge in solar photovoltaic-related markets, the young firm had particularly mastered technologies related to small wind power and had access to the global small wind market, but lacked production and commercial capabilities (in the following we will refer to this start-up as 'WindUp'). Given their complementary expertise and assets, TechLtd saw an opportunity for collaboration and began to explore several ways to leverage it. The start-up was indecisive between the development of several RET products. As TechLtd hoped to develop a product close to its own core competencies, it eventually persuaded the spin-off to jointly develop a small wind control system which seemed to be technically overlapping with the control of high-speed motors dealt with in the second business line of TechLtd.

When the company started exploring the technology, not much different than today, small wind was a global niche market at an early stage of development with globally around 300 manufacturers (BWE, 2011; Gsänger, 2013). In Germany, approximately thirty firms manufactured small wind turbines in 2003, with a typical size below 100 kilowatt output power (BWE, 2010). At this time, the total installed capacity was less than 100 megawatt in Germany (Brück, 2013). This is much different to large wind energy technology, characterized by approximately 1-6 megawatts per turbine and about 10,000 megawatt installed capacity in 2002 (Böhme, 2012). However, even though market development had been slow, industry associations predicted encouraging double-digit growth figures and forecasted installed capacity of over one gigawatt by 2020 (Gsänger, 2013). Many experts foresaw the same growth patterns as in the 'large wind' and solar industries (Luethi, 2010). This assessment is not surprising given the overall positive outlook for renewable energies at that time and a peaking of policy support in Germany during 2004 and 2008, making Germany one of the world's most important renewable energy markets (particularly due to the EEG electricity feed-in tariff regulation; see e.g. Luethi, 2010).

Motivated by the success of other companies in this emerging market – manufacturers and various service providers – and because the small market fitted its niche market strategy, TechLtd entered a collaboration with WindUp and began to develop an electricity inverter specifically conceived for small wind turbines. WindUp carried out preliminary market research which confirmed the absence of a satisfactory inverter: the ones used at that time in combination with small turbines were originally developed for photovoltaic applications and their inappropriate design reduced turbine performance. The absence of an adequate solution for electricity conversion for small wind turbines represented a major technological bottleneck inhibiting industry development. The analysis of TechLtd and WindUp further showed positive market signals and a favorable competitive situation. Therefore, a small wind turbine inverter seemed to have commercial potential and, in addition, promised to bring the small wind industry forward, which appealed to the sustainability-minded top management. Based on this positive outlook, the two firms began product development. The R&D tasks and costs were shared between the two firms. To leverage each other's assets, it was decided that TechLtd would be responsible for manufacturing and WindUp for bringing the product on the market.

### *4.2 Phase 2: Product development*

While other exploration activities were maintained at TechLtd, most R&D efforts went into an intensive R&D collaboration with WindUp. Product development reached full speed when seven engineers worked on the project. The new product was customized to the needs of three German pilot customers. These pilot customers, which appeared to be typical for the industry, were all small entrepreneurial firms focusing on turbine development and manufacturing. TechLtd used the collaboration with pilot customers to understand the needs for turbine management and controlling (e.g. emergency stop systems), partially following the product development rational of the core business which is characterized by customizing a product to the needs of their customers. In parallel to these collaborations, TechLtd mandated WindUp to carry out an international market study focusing on regulations and electricity feed-in tariffs in various countries (e.g. Spain, Portugal, and Scotland). This analysis together with collaboration with pilot customers was used to determine the final product design. In the subsequent years, TechLtd and WindUp R&D teams worked on developing the first inverter prototypes until a mature product was obtained for production in small series.

This phase ends in 2008 with the top-management decision to end all but one exploratory project in the feed-in-technology business line and to focus efforts on the small wind project with emphasis on accelerated product design. The head of R&D for the business line "feed-in technology" (see left lower box in R&D in Figure 1) was replaced. First, the position was temporarily filled with an engineer from a marketing unit in one of the core business lines until he also left for a sabbatical several months later. The position was therefore re-staffed again with an internal engineer, who had extensive product development experience in the two core business lines, with the goal to focus strictly on product development and design. The other engineer, who had previously only temporarily taken over the function as head of R&D, returned after his sabbatical and went back into the domain of marketing, then with responsibility for the S&M of the new feed-in-technology business line. Hence, from this point of time on, the small wind project was formally structured into

R&D and S&M units, matching the organization of the core business lines. The two engineers leading these units brought over ten years of core business experience into the exploratory unit.

After the creation of the new S&M unit, the sales strategy was eventually also defined. Even though WindUp later made large sales and marketing efforts with 60% of the 100 contacted manufacturers, TechLtd mainly defined the sales strategy by applying the sales approaches it had been using so far for its other business lines. The strategy can be described as follows: the largest clients were contacted in each international market with the objective of developing long-standing supplier relationships. Client acquisition was mostly done through direct contact and at trade fairs. The main sales arguments were the inverter's customization to the small wind turbine technology (improving efficiency) and, more generally, engineering excellence. Customization and technological excellence would increases the overall turbine efficiency and provide strong sales arguments to the turbine manufacturer in charge of selling the system (turbine plus inverter; sometimes with additional services such as wind measurements) to end-users.

### *4.3 Phase 3: Market introduction and continuous product improvement*

The beginning of phase 3 is marked by a difficult transition time and the teams had to get used to the new management structure. The R&D team continued to refine and improve the product throughout phase 3 leading to new product versions with additional features (e.g. improved rotor speed control), which subsequently replaced the initial design. The production department received the blueprints of the first product version and began production of the first batch even before formal product launch. During this time, the S&M team worked on the market introduction which official took place in early 2009. Sales took off gently but remained low, at approximately thirty pieces per year.

About one and a half years after market introduction, the first end-users expressed disappointment and complained about the low energy yields of the turbine and blamed both turbine manufacturers and TechLtd. Therefore, TechLtd's engineers analyzed the problem, discovered important weaknesses in the actual turbines (not their inverter) and further intensified collaboration with various small wind turbine manufacturers for trouble-shooting. It turned out that TechLtd was better equipped for trouble-shooting and customizing than the turbine manufacturers themselves. TechLtd had extensive long-term knowledge in electrical engineering and ultimately realized that the pilot customers had developed turbines in a bricolage style far less professionally than expected. To compensate for the poor turbine quality, TechLtd decided to develop extra features (e.g. entire turbine management including run-on and -off), thus shifting more turbine management functions than initially intended to the inverter. This resulted in a much more complex design. By significantly increasing the initial degree of inverter customization, TechLtd saw the opportunity to develop an even better product, improve client relationship, and secure competitive advantage, as it learned from the core business markets.

Notwithstanding this effort, sales figures were not increasing as expected and topped at 150 units in total about three years after market introduction. WindUp, who had the overview of the market, started to realize that the small wind turbine market was more complex than initially estimated (see Table 4). First, given the early and immature stage of the market, it was more fragmented than originally expected: larger professional turbine firms and small bricoleurs coexisted in the market and expressed very different needs. By increasing customer-specific development efforts, TechLtd inadvertently reoriented its product towards the need of the bricoleur segment. Second, the inverter market evolved more rapidly than expected. Competitors improved their design substantially, launched ad-hoc small wind inverters that partially copied TechLtd's design features, and, given their competitors' success and economies of scale in the solar photovoltaic industry, drastically reduced prices. Furthermore, TechLtd began to realize that the product design choices it had made earlier, being largely based on national norms and regulations in force in Germany, did not sufficiently consider international market requirements. And most importantly, with the decision to increase customer-specific development efforts, TechLtd narrowed its focus too early to the specific requirements of one customer segment which turned out to be not representative of the market, thereby drastically reducing the already small market size.

**Table 4** Comparison between old and new markets

| *Market criteria* | *Market of main business line (CNC Systems)* | *Market of new business line (feed-in technology for small wind turbines)* |
|---|---|---|
| Maturity | High | Low |
| Volatility | Low | High |
| Dominant design | Available | Not available |
| Customer-specific development | Important (made-to-order) | Less important |
| Nature of customers | Large companies | Mostly micro companies; few medium/large companies |
| No. of customers | 20-30 international buyers (medium to large international companies) | 300 very diverse international buyers (micro, small and medium-sized companies alike) |
| Regulatory complexity | Low | High (diverse regulatory environments for RE(T) increase complexity) |

Realizing that they had not yet sufficiently explored the small wind market, TechLtd's top management ordered further market research to explore new international markets and strengthened its own sales team to increase client acquisition capacity, taking over some of WindUp's tasks.

### *4.4 Phase 4: Phase out*

The additional sales efforts did not translate into increased sales figures. As a result, top management eventually decided to stop production and reallocate R&D resources to other projects, leaving the most recent product design as a blueprint in the drawer of the head of R&D. As over one hundred inverters were still waiting on the shelves, the salesperson at TechLtd continued his work in the hope to diminish the losses that occurred through this project.

About half a year after production end, the largest competitor abandoned the small wind inverter market, too. TechLtd interpreted this as a positive market signal and decided to give the product a second chance by doubling its sales efforts and testing market reactions. The former customers of the competitor were systematically contacted. The most promising potential customer rejected their offer because TechLtd’s product was similar to one of their competitors but offered fewer functions for double the price. Seeing an important defeat in this negative reaction and considering that the most interesting prospective customer was lost, TechLtd decided to disinvest the project by also reallocating S&M resources to other projects and to formally end the collaboration with WindUp. The small wind innovation journey was terminated in 2013, ten years after its inception.

While this journey came to an end, new small-scale exploratory investigations were initiated by the top management as an attempt to utilize the generic parts of their product design as well as the knowledge gained in energy-related markets. They sought related energy-efficiency markets in need of competencies for controlling high speed rotation, such as fluid flow machines (e.g. used in combined heat and power plants) and flywheel energy storage (kinetic energy storage based on a rotating mass). Though the focal innovation failed, knowledge and competencies gained during the unsuccessful project provided input to subsequent explorations – which are, however, not further considered in this paper.

Based on this overview of the individual phases, the next section analyzes these from the perspective of ambidexterity theory.

## 5. Analysis

Our analysis of the unsuccessful innovation process consists of two parts: first, we analyze how organizational separation metamorphosed through separate business lines. Second, we look at the misfit between product-market strategy and exploration approach.

### *5.1 Separation drift*

The most important finding of our analysis deals with how top and middle management changed the ambidexterity course and related modes of separation, together leading to separation drift. The organizational boundary between old and new businesses became porous and a drift from a textbook-like organizational separation to much looser and partly dysfunctional forms can be observed (Table 5).

This drift is analyzed in more detail in the domains of R&D and S&M in the respective sub-sections.

### *5.1.1 Drift in the R&D function*

At the beginning of technological exploration (phase 1), TechLtd established the new feed-in R&D unit, which in the first phase effectively followed an exploratory pathway with a clear organizational separation. This effective separation and the drift that followed can be observed in the staffing policy, the R&D networking, and new and distinct cognitive representations and routines. First, in terms of *staffing*, an externally hired engineer was appointed head of the exploratory R&D unit and acted as a gatekeeper and bridge between the old and the new business. He brought new knowledge, new open innovation practices, and an integrated approach to project management (his view of product development covered the whole range from idea generation to commercialization, crossing the boundaries between R&D and S&M). Later, with the abrupt change in unit management, the former R&D manager had to leave and the position was re-staffed several times with in-house engineers who had gained their experience in the core business. This sudden and abrupt management change significantly weakened the exploratory orientation and allowed for separation drift.

Second, networking activities burgeoned and several exploratory R&D *alliances* (see also Table 3, previous chapter), were initiated by the new head of R&D leading to the development of new, cognitively distant knowledge. This exploratory networking ended after the first two phases, after which, besides product development with customers (core business routine), no networking activities were observed.

Third, in terms of *cognitive representation*, the way of doing business in the established business was to 'pack' engineering knowledge into a physical product through in-house design and manufacturing to prevent that knowledge from being copied or stolen. The new R&D manager, by contrast, explored new ways of selling knowledge, in particularly through consultancy services (Table 3). This shows that the protection of the innovation space was effective and exploration possible, even extending towards the S&M space. Later the alliance with WindUp was initialized and the development of a product (small wind inverter) was started, while still maintaining exploration of other technological pathways. Then, at the end of phase 2, top management suddenly and radically narrowed down and restructured the organization due to resource constraints ending all but the exploratory small wind projects. This is also a sign that the cognitive representations of the old business migrated into the exploratory space, therefore strongly reducing its exploratory orientation.

Overall, exploration of a new technology could be successfully completed, but due to separation drift, they too quickly narrowed down the technological pathways to a single one and too quickly specified product design for the remaining small wind pathway – which later turned out to fit only selected segments of an overall small market.

**Table 5** Exploration process and separation drift

| | *Phase 1: Technology exploration* | *Phase 2: Product development* | *Phase 3: Market introduction and continuous product improvement* | *Phase 4: Phase out* |
|---|---|---|---|---|
| *Overview* | | | | |
| • Mode of separation pursued | Organizational separation (covering R&D and S&M) | Organization separation (R&D) and contextual separation (S&M) | Organization separation (R&D) and contextual separation (S&M) | Organization separation (R&D) and contextual separation (S&M) |
| • R&D exploratory orientation | Strong | Strong | Low | Low |
| • S&M exploratory orientation | Medium | Medium | Low | Low |
| • Effectiveness of separation | Strong | Medium | Low | Low/None |
| *Internal structure and staff:* | | | | |
| • Staffing in new business line (head of R&D) | Externally hired | Externally hired | Internal | Internal |
| • Management approach | Project based, holistic | Project based, holistic | Line management | Line management |
| • Adoption of old routines | Low | Medium | High | High |
| *Networking and partnering:* | | | | |
| • Exploratory networking | High | Medium | Low | Low |
| • Involvement of strategic alliance partner | n.a. (seeking partners) | High | Medium | Low |
| *Outcomes (knowledge generation):* | | | | |
| • Exploration of new technology pathways (R&D) | Many | Few | None | None |
| • Exploration of new S&M approaches | Few | Few | None | None |

### *5.1.2 Drift in the S&M function*

The drift in the S&M function can also be analyzed for staffing policy, networking, and cognitive routines. First, regarding staffing at TechLtd, initially no formal S&M responsibilities existed for the new exploratory unit as marketing planning was *de facto* covered by the R&D manager, who also interpreted his position to include S&M exploration and marketing planning. Later, a distinct S&M unit was created at TechLtd which was staffed with one salesperson appointed for the collaborative sales approach with the alliance partner. This person still had some sales responsibilities for the old business – representing a form of contextual ambidexterity. Contextual ambidexterity was, however, not effective and exploratory orientation was low. This situation worsened when the exploration oriented R&D manager left, who had to date also provided selected impetuses for S&M exploration.

Second, regarding networking, some ideation activities could be recognized at the beginning when S&M exploration was partially realized through the alliance partner so that (inter)organizational separation existed through the strategic ally. For example, product-related services for the small wind inverter were explored together with the alliance partner WindUp, who was already active in this domain. This was however a rather temporary phenomenon until the S&M team took over responsibility. Then, the exploratory potential of the strategic ally was not leveraged anymore as the S&M strategy was defined by TechLtd based on core business routines with the strategic ally only executing parts. This was astonishing given the better market knowledge of the ally. S&M activities were in fact reduced to finding new customers in the new market. Hence, while TechLtd's organizational chart shows an organizational separation (individual S&M units for each business line), this was not the case in practice and a weakly pursued contextual ambidexterity led to a poorly managed interface between old and new businesses resulting in a low level of S&M exploration.

Third, at least two critical cognitive representations and routines "contaminated" the new S&M unit, which illustrates the unsuccessful separation. The prevailing cognitive frame of TechLtd was linked to their perception of their role in business-to-business markets and related value chain configurations. Their core business is based on long-term, personal, trust-based relationships with system integrators and involved customer-specific product development in rather mature niche markets. The related sales units are structured to serve this market: a handful of senior engineers take care of the sales and maintain trust relationships with customers over the years. Incorrectly assuming that the small wind market would function in a similar way, the same sales approach was replicated, even though the new market – young, volatile, and rapidly evolving – was significantly different from the old (cf. Table 4). To rely on the turbine manufacturers to take over the role of professional "system integrators" combined with the expectation that they would successfully serve and develop the end-user (turbine) market turned out to be ill-conceived. Moreover, TechLtd tried to compensate for the weaknesses of the customers' turbines by intensifying co-development efforts and troubleshooting with pilot customers. This led to more complex designs of their own product, which made it more expensive and less attractive for other customer segments and the already small market segment was further narrowed down. A second pervasive cognitive representation was the belief that engineering knowledge needs to be packed into physical products and sold to customers in order to exploit the existing manufacturing capacity. The team therefore discarded any ideas of business model innovation previously developed (e.g. consultancy services, forward integration etc.).

Overall, S&M was characterized by low and diminishing exploratory orientation, more typical of exploitation patterns. Consequently, a strong exploratory orientation (though also diminishing over time) only existed in the R&D domain. In sum, we conclude that despite the initial ambition for organizational separation covering both R&D and S&M, only a separation within the function domain existed, leaving functions other than R&D with an exploitative orientation. This supports the analysis that an organizational separation drift occurred, preventing the innovation to reach maturity and compromising its commercial success. We speak here of a drift, because the erosion of the organizational boundary happened too early, preventing the exploratory innovation from reaching maturity and leading to a rushed integration into operational business.

### *5.2 Misfit of product-market strategy and form of exploration*

The *new* small wind inverter *product* was to be sold in a *new market*. For the success of this intended product-market strategy, an exploration in both the *product* and the *market* domains – a pure exploration (Voss and Voss, 2013) – would have been necessary, which however did not take place. Therefore, a mismatch between the intended product-market strategy and the actual product-market exploration can be observed. The following two factors indicate a mismatch. First, and most evidently, given that a clear-cut organizational separation was only implemented in the R&D function, the conditions for exploration were created in the R&D function but not in the S&M function. The porous exploration-exploitation boundary of the predominantly contextual separation in the S&M function (next to some attempt at "inter-organizational" separation by involving the alliance partner in S&M, who, however, was not provided with the necessary freedom to develop such exploratory approaches) allowed for the spillover of routines and cognitive frames that resulted in the adoption of the core business sales approach in the new business line. This adoption prevented further market exploration and is consequently the primary candidate for explaining their inability to successfully market the product. As explained in sub-section 5.1, important differences exist between old and new markets and the adopted sales strategy was misaligned with the needs of the new market. Considering the high market volatility, it would have made sense to pursue market sensing and exploration as the first R&D manager had initially practiced and planned to expand.

Second, the staffing policy also illustrates the mismatch between actual and intended strategy. In contrast to the 15 S&M officers serving relatively narrow and focused markets in the main business lines, only one S&M officer had to penetrate a much more fragmented market with ten times more customers in the new business line. This strong underestimation of required S&M efforts indicates that top management had not seen the need for marketing exploration. Unsurprisingly, this meant little new knowledge was developed in this domain. This lack of exploration is also visible in Figure 2: whereas the exploration in the R&D domain translated into the emergence of various new technology innovation trajectories (left side of the figure), no similar emergence could be observed in the sales approaches (right side).

## 6. Discussion and conclusion

While the literature on ambidexterity is burgeoning (O'Reilly and Tushman, 2013), our knowledge of the management of the exploration-exploitation interface remains sparse (Gassmann *et al.*, 2012). With this fine-grained process study on a failed innovation project involving an initially carefully planned separation, then separation drift, and ultimately rushed integration, we shed light on three essential management pitfalls which, if not addressed adequately, may constrain the successful pursuit of ambidexterity.

### *6.1 Separation drift*

Separation drift – an analogy to "mission drift" discussed in the literature on social and sustainable entrepreneurship (Hockerts and Wüstenhagen, 2010) – is the unintended erosion of the exploration-exploitation boundary and the rushed and uncoordinated integration of the exploratory innovation outcomes into the core business. While businesses may start exploration in good faith with textbook-like modes of separation and adequate resource allocation for the protected exploration unit, due to staff replacement, resource fading, top management myopia, or unexpected events, they may gradually shift priorities away from exploration readopting more exploitative practices and letting the thinking and practices from established units gradually or suddenly take over even separated units. Though separation drift occurs at the exploitation-exploration interface, it differs from integration (Gassmann *et al.*, 2012) because the drift demonstrates cases where exploration has not gone far enough for outcomes to be ready for transition into operational business – for the same reason the drift also differs from mere temporal separation. In the case of organizational separation, for example, separate organizational structures (e.g. departments) may still exist, but their inner functioning no longer differs and may or may not ultimately lead to the dissolution of formal separation.

This paper hypothesizes that SMEs are prone to stop exploratory processes too early and therefore are often not able to reap the potential benefits from exploratory activities and are left with little more than failed opportunities and sunk costs. Hence, we thus contend with Lavie *et al.* (2010) that exploration and exploitation are associated in time and thus argue that parsimonious resource spending over the project period can increase the odds of success. A too early focus of resources on a single innovation pathway not only compromises its success but also limits options for future exploration.

Beyond further investigating the management of the exploration-exploitation interface, further research is needed to deepen our understanding of how exploration and exploitation are linked in time, in particular to better understand how integration timing influences the success of an exploratory innovation.

### *6.2 Misfit of product-market strategy and form of exploration*

As a result of an iterative process of idea exploration and selection, the SME ultimately focused on a distinctively exploratory innovation project with the aim of developing a new product for a new market. Exploration with regard to both product and market can be classified as pure diversification (Ansoff, 1957). Our analysis reveals that the degree of innovation exploration is related to the success of various types of separation or ambidexterity. For example, exploratory innovations simultaneously focusing on new products in new markets (pure exploration according to Voss and Voss, 2013) cannot adequately be addressed only with exploration in the R&D function. Rather cross-functional exploration in both R&D and marketing is needed: while a new product requires a new R&D approach, new markets may require new marketing approaches. However, *new* products for *existing* markets or *existing* products for *new* markets could very well be addressed by "within-functional exploration" in a selected value chain function only (Li *et al.*, 2008) – which we label 'functional separation'. This bias towards exploratory product development without an accompanying market exploration and related new business models can be a major cause of exploration failure, especially for SMEs.

Particularly the domain of renewable energy and other green technologies are predisposed to the most radical form of innovation, with exploration both in the product and the market domains (pure exploration). The challenge of simultaneous exploration in the product and in the market area makes such a pure diversification difficult to achieve (Bos-Brouwers, 2009). Market exploration in the RET market is subject to increased complexity and uncertainty, as market introduction and diffusion needs to be tailored to the various national political and institutional contexts – which may change frequently (e.g. feed-in-tariffs for renewable energy have changed various times over the last few years). We thus contend with Hill and Rothaermel (2003) and Bessant *et al.* (2014) that exploration in technology fields with strong political and regulatory influence and high market uncertainties can be more challenging than innovation in more conventional areas. Particularly for SMEs, and despite their higher flexibility, resource constraints make it difficult for them to monitor (or even influence) institutional contexts. This, in turn, ultimately results in higher risks of highly diversified exploration endeavors for SMEs.

While our understanding of green entrepreneurial ventures has increased over the last couple of years (e.g. Hockerts and Wüstenhagen, 2010; Kuckertz and Wagner, 2010), green innovation as a diversification strategy for existing firms is still an under-researched area. In particular, how firms can contribute to green innovation (or even sustainable development) with their core competences is poorly understood and offers a new context for innovation management and ambidexterity research.

### *6.3 Combination, interaction, and embeddedness of various modes of separation*

Our analysis revealed that separation did not only change dynamically over time but also a combination of modes of separation coexisted within the firm at various points in time. This confirms the analyses of Raisch (2008), Lavie *et al.* (2010) and O'Reilly and Tushman (2013). Lavie *et al.* (2010) hypothesized that a combination of modes and hence a more flexible, or even decentralized, way of managing the exploration-exploitation interface may reduce costs and management attention. It seems likely for SMEs – who typically struggle with resource scarcity and limited management capacity – to pursue such resource-efficient separation, for example, by limiting exploration to specific time periods (temporal separation) or to selected value chain functions (functional separation). Modes of separation are simultaneously pursued and therefore interact. Their proper combination can enable a more resource-efficient exploration – and is therefore attractive for SMEs – but, at the same time, this increases the complexity, inconsistencies and risk of exploration failure. In turn, such an approach requires stronger top and middle management attention, which is linked to exploration costs. We thus question Lavie *et al.*'s (2010) assumption that alternatives to organizational separation are less resource intensive. In line with Gassmann *et al.* (2012) and Chen and Kannan-Narasimhan (2015), who draw attention to the role of middle-management, we hypothesize that the resource burden is shifted from costs related to set-up and maintenance of structural separation towards human resource management, which in essence consists of briefing and coaching middle managers on the dual (ambidextrous) demands of their management tasks. Therefore, not only does the replacement of organizational separation with more flexible forms of ambidexterity management increase the burden on top management, it also increases the necessary involvement and efforts of middle management. Overall, contingent on the exploration type (pure vs. partial; see Voss and Voss, 2013), it should be carefully weighed whether full organizational separation covering all functions – with enough breadth to maintain this organizational design – or a combination of functional separation with other modes of ambidexterity is most fruitful.

Further research should explore in more depth and breadth the management of the exploration-exploitation interface, in particular the essential but under-researched aspect of how top management decides on a mode of balance and how leadership and management practices influence the middle management's ability to successfully implement separation and manage the exploration-exploitation interface over time.

### *6.4 Limitations*

Our study is limited in three ways. First, while our study presents longitudinal evidence on failed ambidexterity management, we do not know whether this was the only reason for failure. The difficult characteristics of the immature small wind market could have significantly limited innovation success even for a firm with an optimized ambidexterity management. Second, the research design studies a single organization and is therefore not generalizable. Still, the challenges and pitfalls described may be representative for hidden champion-type (Simon, 2009) technology SMEs and, more generally, entrepreneurial SMEs embarking in diversification through green innovations. By providing sufficient contextual information, comparability with other settings and "transferability" is enabled (Shenton, 2004).

A third limitation is that a large part of the innovation process was analyzed using ex-post analysis, which, given a timeframe of over 10 years, is not unusual. Still, this partial ex-post analysis is subject to bias due to the retrospective account by the individuals interviewed. We used triangulation and reflexive interpretation (Alvesson, 2003) to cope with this limitation.

### *6.5 Managerial implications*

Three managerial implications can be drawn from our research. First, an important threat for exploration is that unexpected events or resource fading – and linked to that, changes in management positions – may gradually shift priorities away from exploration and towards readopting more exploitative practices and letting the thinking and practices from established, more exploitative units even take over separated units. This gradual shift may not be well recognized if it occurs slowly over time.

Second, SMEs should carefully determine the nature of the innovation project(s) throughout the process and adapt the scope of exploration – regarding involvement of R&D and S&M – accordingly. In case a new product is intended for an unknown market, top management should provide space for cross-functional exploration in R&D and S&M. This is in fact likely to be of high relevance for firms pursuing diversification with environmental or sustainability-oriented innovation such as renewable energy technologies, as developments in markets and products are both likely to be characterized by fast and large changes.

Third, even though several modes of separation between the old and the new businesses can coexist within the firm, top management should carefully weigh the advantages and disadvantages of the different modes, particularly in SMEs. Drawing on too many modes of separation simultaneously (rather than a clear-cut organizational separation) can lead to an overwhelming complexity which a) might simply compromise the success of the innovation endeavor and b) require a tremendous increase in management efforts.

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## Paper 6

Exploration of Green Technologies in SMEs: The Role of Ambidexterity, Domain Separation and Commercialization

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# Exploration of green technologies in SMEs: the role of ambidexterity, domain separation and commercialization

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**Abstract:** A central issue in innovation management is the undesirable spillover of harmful routines and cognitive representations from core business to the exploratory innovation space, as dealt with in ambidexterity research. This paper examines a conventional manufacturing SME in a business-to-business market that developed renewable energy technologies in the scope of a new business unit, but has ultimately failed in the market. The aim is to examine how the interface between the old and new business was managed over time. Using an in-depth qualitative longitudinal case study, we investigated innovation processes over time and identified three major sources of failure. First, an organizational separation drift from a textbook-like to a looser form of separation allows for undesirable spillover of routines cannibalizing the new business over time. Second, a mismatch exists between the intended product-market strategy and the actual product-market exploration. A third source of failure is the simultaneous coevolution of several modes of separation, which increases management complexity.

**Keywords:** new product development (NPD); product exploration; market exploration; renewable energy; sustainability; small and medium sized enterprise; case study

## 1 Introduction

In uncertain, volatile and rapidly evolving industries threatened by disruptive technology development, the balance between exploration and exploitation for long-term survival is particularly challenging and firms are increasingly required to simultaneously exploit and explore (O'Reilly and Tushman, 2008; Cesaroni *et al.*, 2005). Firms with the capability to effectively balance exploitation and exploration are called ambidextrous organizations. A context which becomes more and more relevant for research in ambidexterity is the increasing recognition of sustainable development as a driver for fundamentally changing societies and markets. Though to varying degrees in various sectors, sustainability issues lead to changing regulatory frameworks, business environments, market conditions and customer preferences, therefore giving reason to both pressures towards existing technology regimes and opportunities for entirely new technological spaces often referred to as green or sustainability-oriented innovations (e.g. Schiederig *et al.*, 2012). Companies thus face the challenge to balance exploration of new sustainable products and services with the exploration of the existing business.

A central issue in managing this balance, discussed under the notion of ambidexterity, is the undesirable spillover of harmful routines and cognitive representations from the core business to the explorative innovation space. For instance, 'contamination' or 'leaks' strongly compromise the emergence of path-breaking product or market innovations from the exploratory innovation space (Tripsas and Gavetti, 2000). The ambidexterity literature about large firms (Gupta *et al.*, 2006; Lavie *et al.*, 2010; O'Reilly and Tushman, 2013) discusses four modes of balance between the old and new business: organizational separation, temporal separation, contextual ambidexterity and domain separation (Lavie *et al.*, (2010).

Whereas the extant literature has focused on large organizations, small and medium-sized enterprises (SME), which are just as threatened in the face of volatile markets as larger firms (Welsh and White, 1981), have so far received comparatively little attention in research. The management of the exploration and exploitation interface is furthermore still poorly understood and more in-depth research is needed (Gupta *et al.*, 2006; Lavie *et al.*, 2010; O'Reilly and Tushman, 2013).

Learning from a case of failed exploration, this paper aims to examine the problems which occurred over time in managing the interface between the exploratory and exploitative business. In line with ambidexterity scholars who used the case study method (Adler *et al.*, 1999; Tripsas and Gavetti, 2000; Walrave *et al.*, 2011), the research strategy of this paper is to examine exploratory innovation processes and obstacles across value chain functions (research & development, production and sales & marketing), across various organizational levels (top-management, departments, individuals) as well as internal and external exploration (through alliances) in an in-depth longitudinal case study (Yin, 2014).

The case examines an owner-managed manufacturing SME of about 200 employees operating as an international technology leader in a business-to-business market. As top-management realized that its main market was threatened and because the founders are convinced about sustainable development, the company searched for new applications for its core technology in the area of renewable energies. It initiated a successful explorative learning process that did, until now, not lead to a successful outcome.

The contributions to theory are threefold. First, the paper demonstrates that several modes of separation can simultaneously coexist and coevolve within the firm. The consequence is that the interface between the old and the new business can be relatively fluid, thus requiring important managerial efforts to separate old and new. Not only must top-management integrate the two with a strong competitive vision (Tushman *et al.*, 1997), it must also select and coach middle-level managers who adopt boundary-spanning roles (Tushman, 1977; Cohen and Levinthal, 1990). Hence, we hypothesize that the advantage of decentralized management of ambidexterity, even though it appears resource efficient at first sight (Lavie *et al.*, 2010), is off-set by the increase in managerial effort. Second, a drift from a "textbook-like" to a looser form of separation is observed over time allowing for gradual or sudden spillover of undesirable routines and cognitive representations to contaminate the exploratory innovation space (Tripsas and Gavetti, 2000). Finally, the paper reveals that the misfit between intended product-market strategy and the actual product-market exploration can be a major cause for failure. Management myopia (Levinthal and March, 1993) might induce that the form of ambidexterity chosen does not fit the intended product-market strategy.

The rest of this paper is structured as follows: first the literature on exploration and exploitation is reviewed (Section 2). Then, the methodology is introduced (Section 3). The results are described in Section 4 and analyzed along three core lines in Section 5. The last section discusses the findings and concludes the paper.

## 2 Literature review

### *2.1 Exploration and exploitation*

March (1991) set the stage for the ambidexterity discussion in his seminal work on exploration and exploitation. He posited that the ability to pursue innovation to secure immediate and long-term competitive advantage is a fundamental challenge for the survival of organizations.

Considering the important variety of interpretations, we concur with others (Lavie *et al.*, 2010; O'Reilly and Tushman, 2013) that March's original definition ought to be used. March (1991) defined *exploration* as learning and knowledge creation that involves search, variation, risk taking, experimentation, play, flexibility, discovery and innovation. From a technological perspective, exploration involves a shift to a different technological trajectory (Benner and Tushman, 2002). *Exploitation* on the other hand, relates refinement, production, efficiency, selection, implementation and execution (March, 1991). It involves improvement in the existing components and, most importantly, builds on existing technological trajectories (Benner and Tushman, 2002) and therefore exploitative innovation is aimed at improving the existing product-market domain (He and Wong (2004).

Scholars argued that reducing the inherent tensions that appear within an organization that simultaneously explores and exploits a top-management responsibility (Tushman *et al.*, 1997). The extant literature describes mechanisms to reduce this tension, which are captured in several typologies (Gupta *et al.*, 2006; Simsek *et al.*, 2009; Lavie *et al.*, 2010). We base ourselves on the typology proposed by Lavie *et al.* (2010) that includes organizational, temporal, contextual and domain separation (Table 1), which are approaches to create an infrastructure for the harmonious coexistence of conflicting organizational architectures. They serve as mechanisms to protect the exploratory innovation space from managerial myopia and inertia (Levinthal and March, 1993) and shield it from harmful routines, cognitive representations (Tripsas and Gavetti, 2000) that can prevent the healthy development of the new innovation trajectory (Tripsas, 2013). Being the key mode of separation – and maybe also the least understood – domain separation is introduced in the next section more in depth.

**Table 1** Types and mechanisms of separation

| *Type of separation* | *Level of analysis* | *Mechanism of separation* |
|---|---|---|
| Organizational | Organizational level | Activities occur simultaneously but are situated within distinct organizational units. |
| Temporal | Organizational level | Exploration and exploitation coexist in the same organization units but at different points in time; organizations switch between expiration and exportation. |
| Contextual | Individual and team level | Exploration and exploitation occur simultaneously in a given organizational unit |
| Domain | Organizational level | Exploration and exploitation occur in particular domains, while balancing these activities across domains. |

Source: based on (Lavie *et al.*, 2010)

### *2.2 Domain separation*

Domain separation is a mode of balance in which firms carry out exploration and exploitation in distinct domains. A distinctive feature is that the balance is managed independently at each function but in congruence with the needs of the other functions. Its management, being decentralized, demands less proactive management attention and coordination efforts are reduced (Lavie *et al.*, 2009); (Lavie *et al.*, 2010). Thus domain separation seems quite apt for SMEs, who are typical concerned by resource constraints and limited management capacity.

Several domains are identified in the extent literature. At the intra-organizational level, the *value chain function domain* is discussed (Lavie and Rosenkopf, 2006; Li *et al.*, 2008). In this case, exploration and exploitation is balanced along the value chain. A typology of domain separation representing a continuum from less to more complex exploration was identified (Voss and Voss, 2013): a) product exploration and market exploitation (product ambidexterity), b) product exploitation and market exploration (market ambidexterity), and c) product and market exploration (pure exploration). This typology corresponds to Ansoff's (1957) matrix of product-market strategies based on a) product development, (b) market development, and (c) diversification, the latter being the most challenging.

At the inter-organizational level, a balance can be found in the *network structure* and the *partner attribute domain* (Lavie and Rosenkopf, 2006). This means that alliances can be formed with existing (exploitation) or new partners (exploration). Then, alliances can be formed with partners having different attributes (such as size or industry focus) than previous partners. The formation of alliances can be attributed to each value chain function or across functions. R&D alliances are typically used to reduce technology development costs, sales and marketing alliances to leverage market access, cross-functional alliances for both (Lavie and Rosenkopf, 2006).

### *2.3 Ambidexterity in SMEs*

The literature features a rich discussion on the differences between small and large firms (Welsh and White, 1981). In many ways small business are particular and are not just little big businesses. The most frequently discussed differences include: a) the amount of resources available, b) SMEs, unlike large enterprises, often compete in clusters where competitors are prone to price cutting, c) fewer resources are available to hire manager and qualified personnel, as the owner-manager salary represents a much large fraction of the revenues and d) external forces tend to have a more determining impact on SMEs (Welsh and White, 1981). However, compared to their larger counterparts, SMEs have the advantage of greater flexibility and can therefore react much faster to a changing technological, market and regulatory situation (Welsh and White, 1981).

In the innovation management literature, no innovatory advantage is unequivocally associated with neither large nor small firms (Schumpeter, 1934). In fact, the advantage of SMEs is mainly behavioral and the one of large firms material (Rothwell, 1989; Nooteboom, 1994).

In the ambidexterity literature, recent research indicates that resource availability (Sidhu *et al.*, 2004; Cao *et al.*, 2009) and firm size (Zhiang *et al.*, 2007) positively influence the performance of ambidextrous firms. These findings indicate that SMEs, who typically lack resources, are disadvantaged. However, a survey of 139 SMEs, (Lubatkin, 2006) finds that ambidexterity is also positively related to relative firm performance in the SME context. In a recent study, Voss and Voss (2013) analyzed the impact on revenue of product and market exploration strategies, showing that ambidexterity is positively related to SME performance. Thus, the ambidexterity literature concludes that also SMEs can possibly successfully pursue ambidexterity strategies.

### *2.4 Ambidexterity in the context of green innovations*

Even though the number of management publications on eco or green innovations is strongly increasing (Schiederig *et al.*, 2012), to our knowledge, green innovations have not been discussed in the ambidexterity literature. Green innovations include new products, services or business models and include new technologies, such as renewable energies (NBS, 2012). They share many similarities with conventional technical innovations, but differ in purpose, direction of search and complexity (Noci and Verganti, 1999; Paech, 2007; Bos-Brouwers, 2009). Indeed, on top of commercial success, green innovations embrace the explicit double-aim to improve the firm's sustainability performance and to contribute to solving societal issues (Hansen *et al.*, 2009). To fulfil this purpose, firms need to search in a specific direction to make sure that the innovation outcome will eventually have a positive impact, which increases complexity and decreases the number of options (Fichter *et al.*, 2005).

Notwithstanding the significant managerial complexity, empirical investigation demonstrated that some SMEs are highly committed to the development of green innovations (Noci and Verganti, 1999; Klewitz and Hansen, 2014). Depending how radical the innovation is, it might involve product exploration, market exploration or both. While incremental attempts to green innovation have been widely adopted in businesses (e.g. energy-efficient production processes as exploitative innovations), it is often called for more radical innovation – and thus exploration – for more significant contributions to environmental protection and sustainable development (Noci and Verganti, 1999). Therefore, the case of green innovation provides a rich empirical ground for the ambidexterity literature. Conversely, the ambidexterity literature might also fertilize the literature on green innovations.

### *2.5 Innovation process research*

To examine how the interface between exploration and exploitation was managed, we analyzed the innovation processes over several years. To account for its complexity (Cooper, 1983), we referred to the fireworks innovation process model (Van de Ven and Poole, 1990) that allows us to study why and how innovations did or did not developed over time (Van de Ven and Poole, 1990). More specifically, this model allowed to study setbacks, changes in the direction, fluid participation of personnel, involvement and role of top-management as well as evolution in the cognitive representations and routines over time.

## 3 Research method

### *3.1 Research design*

The aim of the research is to examine how several forms of separation were operationalized and how the interface between exploratory and exploitative activities was managed over time. The paper thus adopts an qualitative and longitudinal case study approach (Siggelkow, 2007) considering a time period of 10 years (2003-2013). According to (Yin, 2014), single case-studies are adopted for research that require an in-depth examination of a contemporary topic. Other authors including Adler *et al.* (1999), (Tripsas and Gavetti, 2000), Walrave *et al.* (2011) used this method to study the management of ambidexterity of time. While the larger part of the time frame of 10 years was subject to ex-post analysis, we were able to observe the last two years of the unfolding innovation process allowing us to collect first hand insights on the process.

### *3.2 Case selection*

As indicated before, the case examines an owner-managed manufacturing SME in its second generation employing approximately 220 employees in Germany. The company is driven by a strong engineering culture, developing and producing technological components (Computerized Numerical Control system, high-speed motor and generator control devices) which they sell to customers (system integrators) in the context of business-to-business markets (in the remainder of the paper we will refer to it as "TechLtd"). Within their narrow niche, TechLtd has pursued global market leadership on while operating largely 'below the radar' in the regional and national contexts, therefore representing typical characteristics of a 'hidden champion' (Simon, 2009). TechLtd used its technological and engineering competencies to develop a component for the renewable energy technology (RET) market: an electricity inverter for small-wind turbines. The innovation received full top-management commitment and significant resources (about 3 million euros) but had eventually to be terminated because sales figures did not develop as expected.

The case study was chosen for being critical, revelatory and representative (Yin 2003, p.41): First, we followed theoretical sampling (Eisenhardt, 1989, p. 537) as the case can be considered *critical* regarding three criteria: (i) While most innovation studies are success stories and are therefore linked to the success bias, our case presents an example of a unsatisfactory and terminated innovation. (ii) As the case rules out two of the often conjured reasons of innovation failures (lacking top-management commitment and financial resources (Welsh and White, 1981) allows us to concentrate on the role of ambidexterity in general and domain separation in particular for explaining failure. (iii)

Contrary to green technology or RET start-ups, the case of conventional firms who endeavor to develop such technologies by balancing exploration and exploitation are rarely discussed in the innovation management literature. Second, the case is also *revelatory* as the company provided the research team full access to the innovation process both ex-post and during its unfolding. Last but not least, the case organization is also *representative* for other hidden champions amongst European SMEs in general and the German 'Mittelstand' in particular.

### *3.3 Data collection and analysis*

The research relies on the triangulation of various qualitative data sources including semi-structured interviews, in-depth qualitative data through participatory observation and desk research (Babbie, 2013). Table 2 provides an overview of the case data. The participant-observation data was protocolled and the interview material fully transcribed according to the methods described in (Babbie, 2013). The data was then coded and analyzed using software for qualitative analysis.

**Table 2** Description of case data

| | *Internal: Top and middle management* | *External: Business partners and value chain actors* | *Total* |
|---|---|---|---|
| Semi-structured interview | 7 interviews | 10 interviews | 17 |
| Participant observation | 11 meetings, 5 workshops | 2 industry conferences | 18 |
| Desk-research | 25 internal documents (e.g. market studies, sales statistics, customer lists) | 70 publicly available documents (e.g. industry reports, market analysis, newspaper and magazine articles and industry actors' website) | 95 |

## 4 Descriptive results: phases of the innovation process

This section first introduces TechLtd and its context before examining the development and phases of the innovation for the last 10 years in more detail (see Table 3).

### *4.1 Case introduction and context*

The manufacturing firm, TechLtd has grown for the past 50 years into a global leader in its niche market of electronic control systems for high-speed engines. Its primary market is machine tools, within which it focuses on the electronic control system for drilling applications, in particular for circuit-boards used in electronic devices. Production is located in Germany with sales offices in the USA, Europe and Asia. Its products are highly customized to the clients' needs. Product customization takes several months and is characterized by intensive collaboration between the internal R&D team and the client. As the clients typically equip an inventory of 100-200 machine-tools at the same time, products are manufactured in small series. Given the product-market situation, the sales strategy is to target international niche players and to develop personal, long-standing relationships. Customization and trust are keys to successful sales, which always happens at a technical level, product developers negotiating with engineers of the client.

TechLtd has adopted a matrix organization (Figure 1) that structures the firm into three functional departments – Research & Development (R&D), Production and Sales & Marketing (S&M) – and three business units. The first business unit, which the company's foundation is actually built on, deals with Computerized Numerical Control (CNC) and has been largest one for the last three decades. The second, Drive Electronics was created 40 years ago as a spin-off of the first one and today represents about 20% of total sales. Instead of engine control systems, it sells control systems for high-speed generators and turbines. A third unit was created fifteen years ago to explore new technological solutions for the RET market. The particularity of the matrix structure is the presence of a single production department that receives orders from all business units.

The longitudinal innovation process from its inception in January 2003 to its termination in September 2013 is presented next by structuring it into four major phases (an overview is given in Table 3).

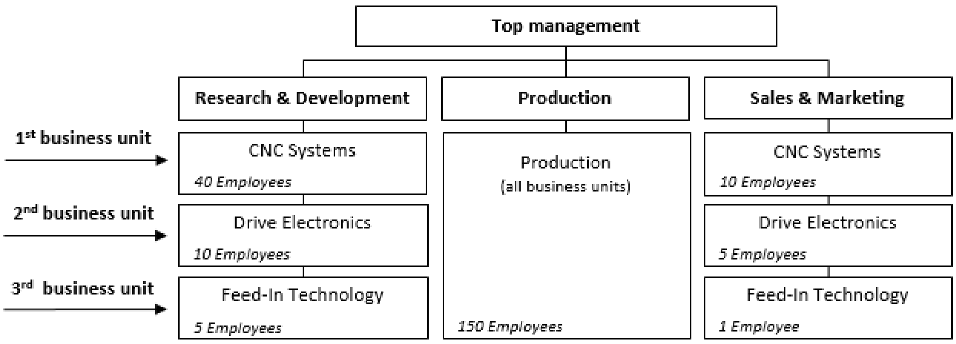


**Figure 1** Organizational chart of TechLtd after market introduction (phase 3, 2009)

### *4.2 Phase 1: Technological exploration*

In 2003, the top-management of TechLtd hired an external engineer as head of R&D of the newly created business unit in order to lead the exploration of new (RET) applications. Under his lead, several options related to the feed-in of green electricity into the grid were explored. Among those projects, a collaboration with a technical university served to develop the technological basis of the new business unit: the electricity inverter. The start-up company 'WindUp' (pseudonym) mastered technologies related to wind power and had access to the small-wind market, but lacked the production and commercial capabilities. Given this complementary expertise, TechLtd saw the opportunity to work with a young, dynamic engineering-minded start-up (WindUp) and began to explore ways to leverage the assets. As the start-up hesitated between the development of a battery and a small-wind turbine control system, TechLtd pushed for the latter as it hoped to develop an application closer to its core competencies of controlling high speed rotation (in this sense, the control of a small wind turbines is similar to that of high-speed generators). The size of the small-wind niche market fitted TechLtd's production facility.

**Table 3** Activities, events, knowledge developed and lessons learnt along the innovation process

| *Domain* | *Phase 1: Technological exploration* (2003-2005) | *Phase 2: Product development* (2006-2008) | *Phase 3: Market introduction* (2009-2012) | *Phase 4: Reconsideration and termination* (2013) |
|---|---|---|---|---|
| Top-management | • Strategic planning<br>• Hire new R&D head and engineers for R&D exploration | • Support small-wind project<br>• End of broader R&D exploration: refocus on specific small wind project only | • Pull alarm signal<br>• Order new market research and increase S&M resources | • Reallocate R&D resources<br>• Started final attempt and maintained S&M resources because main competitor stepped out of market,<br>• Project Termination |
| Research & Development (R&D) | • R&D networking, new projects with university and industry partners, e.g.:<br>- Air flow system<br>- Fuel cell inverter<br>- Induction system<br>- Feed-in technology<br>• Decision: develop small wind inverter.<br>• New partnership with start-up WindUp (with whom the product will be developed): including preliminary product design. | • Product development/design:<br>- Intense collaboration with WindUp<br>- Build prototypes<br>- Test product<br>- Improve product with three lead-users | • Product improvement:<br>- New versions and updates,<br>- cooperation with lead users,<br>- Trouble-shooting of poor quality turbines. | – |
| Sales & Marketing (S&M) | – | • WindUp: market analysis for product design.<br>• Cold client acquisition:<br>- Strategy: high-quality, customized inverter to increase turbine efficiency<br>- Outcome: many purchase intentions. | • With WindUp: client acquisition Europe and USA<br>• New market research, focus: Spain, Portugal, Scotland, etc.<br>• Response to bad signal: more internal sales efforts at TechLtd | • Last intensive sales efforts targeting former market leader's clients |

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| *Domain* | *Phase 1:*<br>*Technological exploration*<br><br>(2003-2005) | *Phase 2:*<br>*Product development*<br><br>(2006-2008) | *Phase 3:*<br>*Market introduction*<br><br>(2009-2012) | *Phase 4:*<br>*Reconsideration and termination*<br><br>(2013) |
|---|---|---|---|---|
| Lessons learned and knowledge developed | • R&D networking (to leverage others' assets)<br>• Developed know-how for feed-in (and built and inverter)<br>• Pure engineering consultancy turns production facility into cost center (no option for future)<br>• To avoid idle production facility, need to target niche markets that fits existing organizational structure.<br><br>Consequence: decide on small-wind because:<br>1) leverage WindUp's market access<br>2) project fits S&M organizational structure. | – | • Negative market signals: product did not fitting the market.<br>• Many manufacturers are unprofessional and provided wrong sales figures.<br>• Market is segmented: small and big manufacturers need different inverters.<br>• Inverter market evolved more rapidly than expected: competitors' product improved and prices fall.<br>• Partner WindUp had good market access but little sales experience.<br><br>Consequence: Explored new international markets | |

At that time, the small-wind market was at a very early stage, particularly in Germany. However, even though developments had been slow, industry associations and related actors predicted encouraging double-digit growth figures and many experts foresaw the same growth patterns as in the solar and "big-wind" industry, twenty years ago (Luethi, 2010). This assessment is not surprising given the overall positive outlook for renewable energies with very strong policy support in Germany during 2004 and 2008 making Germany one of the world's most important renewable energy markets (particularly the electricity feed-in tariff regulation "EEG"; see e.g. Luethi, 2010). Small turbines were typically sized between 0.5 and 15 kW output power, which is small compared with the 1-8 MW of big-wind turbines. To WindUp's knowledge, no satisfying inverter existed for small wind turbines at that time. The ones used in the market were originally developed for photovoltaic applications, and therefore undermined wind turbine performance and refrained market development.

Considering the good fit with its production capacity, TechLtd signed a collaboration agreement with WindUp to develop and commercialize an electricity inverter for small-wind turbines. The R&D was to be shared between the two firms, however to leverage each other's assets: TechLtd would produce and WindUp market the product.

### *4.3 Phase 2: Product development*

WindUp first carried out preliminary market research that showed positive market signals and a favorable competitive situation. An intensive R&D collaboration followed between the two firms, product development reached full speed and seven engineers were occupied with this endeavor. Following the principles of the lead-user method, the new product was adjusted to the needs of three turbine manufacturers that appeared to be typical for the industry. Later, TechLtd mandated WindUp to carry out a second market analysis that focused on the different national electricity feed in norms and regulations. This analysis marked an important milestone in product development as it determined the final product design.

By 2008, top-management, motivated by resource parsimony, decided to end all but one exploratory project in the feed-in business unit and focused its efforts on the small-wind project. The business unit's head of R&D left the firm, and top-management subsequently searched for an engineer who would further develop the product development and design. The position was staffed internally. Several months later, a second internal engineer was allocated to the unit and from there on, the management of the exploratory project for small wind turbine inverters was split between the two engineers, one for the R&D, a senior product developer, the other for S&M. From there on it was integrated more explicitly into the matrix organization. Now, unlike before, when one manager was in charge of the entire business unit, two dedicated and independently managed department (R&D and S&M) were created, as shown in Figure 1.

With the creation of the new S&M department, the sales strategy was also defined. Even though WindUp actually did the largest part of the sales (60% of client acquisition), TechLtd dictated the strategy applying its sales approaches which it had been using in the other two (core) business units: the largest clients were contacted in each national market. The acquisitions were mostly done through direct contact and meetings at trade fairs. The main sales argument was high customization and engineering excellence; the excellent inverter which increases the efficiency of the turbine, thus making it more attractive to the final user.

### *4.4 Phase 3: Market introduction*

TechLtd entered pre-production. After market introduction, sales gently took off but remained rather low. Some (wind turbine) end-users were disappointed with the low yields of their installation and incriminated both inverter and turbine manufacturers which their complaints. TechLtd's engineers analyzed the problem, discovered important weaknesses in the turbines and intensified the collaboration with manufacturers (their direct customers) to solve the problems discovered by the end-users. It turned out that they were better equipped to do so than the turbine manufacturers because of their extensive technical knowledge. To compensate for the poor technical quality of some small-wind turbines, extra features were developed, thus shifting parts of turbine management to the inverter. With increasing the efforts to tackle the turbine manufacturer's engineering problems, TechLtd hoped to increase sales figures, improve client relationships and secure competitive advantage.

**Table 4** Comparison old and new markets

| *Market criteria* | *Old market (CNC Systems)* | *New market (Feed-In Technology for small-wind turbines)* |
|---|---|---|
| Maturity | High | Low |
| Volatility | Low | High |
| Customization | High (made-to-order) | Low |
| Size | 20-30 international buyers | 300 very diverse international buyers |
| Customers | Large companies | Mostly micro companies; few large companies |
| State intervention | None | High (multiple regulatory environments increase complexity) |

However, sales figures were not increasing as expected. WindUp, who had the overall overview of the market, was the first to realize that the market was more complex than initially estimated (see Table 4). First, given the early and immature stage of the small-wind turbine market, it was more segmented than originally expected: large professional and bricoleurs (e.g. Garud and Karnøe, 2003) coexisted in the market and expressed very different needs. By increasing customer-specific development efforts, TechLtd inadvertently reoriented its product towards the need of the latter segment. Second, the inverter market evolved more rapidly than expected. The competitors largely improved their design, launched ad-hoc small wind inverters that partially copied TechLtd's design features and, driven by the competitors' success in and economies of scale from the solar branch, drastically reduced prices. The product design choices made earlier, being largely based on national norms and regulations, did not sufficiently consider international market requirements. With the decision to increase customer-specific development efforts, TechLtd narrowed down to early on specific requirements of some customers who were not representative of the market, which halved the already small market segment.

In reaction, top-management ordered further market research to explore new international markets and further strengthened its own sales team to increase client acquisition capacity.

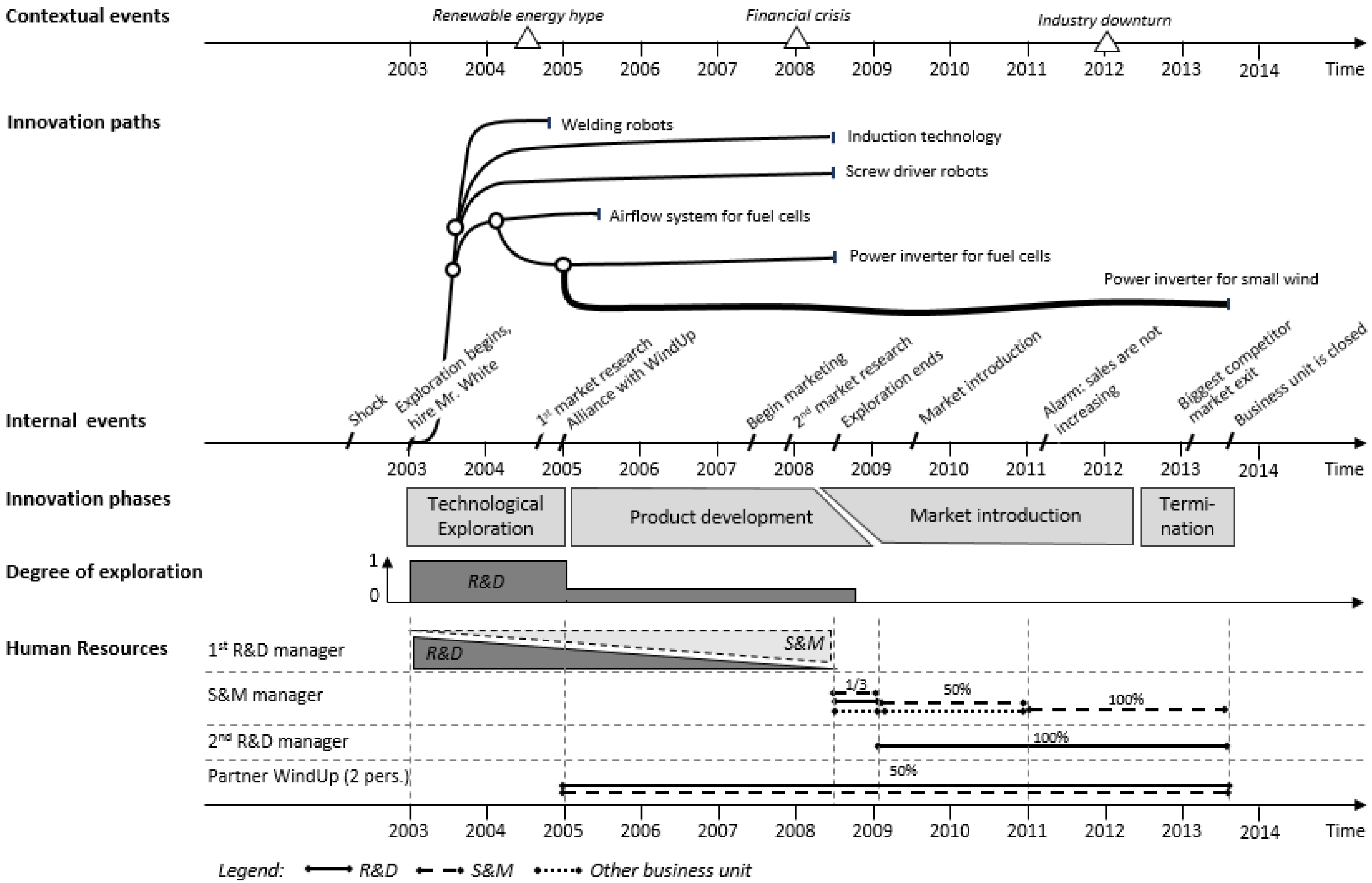


**Figure 2** Visualization of the innovation process over time based on contextual events, innovation paths, internal events, innovation phases, degree of exploration and human resource involvement.

### *4.5 Phase 4: Reconsideration and termination*

The additional sales efforts did not translate into increased sales figures and therefore top-management decided to stop production and reallocate R&D resources to other projects. Several dozen inverters were still waiting on the shelves, only the salesperson has continued his work.

About half a year after the production end, the largest competitor abandoned the small-wind inverter market, too. TechLtd interpreted this as a positive market signal and decided to redouble sales efforts to test market reaction. The customers of the former competitor were systematically contacted. The most promising potential customer rejected their offer because TechLtd's product was similar to one of their competitors but offered less functions for double of the price. Considering that the most interesting prospective customer was lost, TechLtd decided to disinvest the project. The small wind innovation journey was terminated in 2013, ten years after its inception.

While the small wind turbine journey came to an end, new small scale exploratory investigations were initialized by the top-management as an attempt to utilize the generic parts of their product design as well as their gained knowledge in energy-related markets. They sought related energy-efficiency markets in need for competencies of controlling high speed rotation, such as fluid flow machines (e.g. used in combined heat and power plants) and flywheel energy storage (kinetic energy storage based on a rotating mass). Hence, though the focal innovation failed, at the same time, knowledge and competencies gained during the failed project provided input to subsequent explorations – which are, however, not further considered in this paper.

## 5 Analysis

### *5.1 Organizational separation drift*

#### *Organizational separation in the R&D function*

In the phase of technological exploration (phase 1), TechLtd established the new inverter R&D unit which effectively followed an exploratory pathway with a clear organizational boundary towards the more established R&D units, at least in the first phase.

First, in terms of staffing, an externally acquired engineer was appointed head of the exploratory R&D unit who then acted as a gatekeeper and bridge between the old and the new business. He brought knowledge on the renewable energies and related industry contacts into the innovation project. He also adopted a new management style that was based on the integrated profile of product management (for instance, his view of product development covered the whole range from idea generation to commercialization) rather than functional specialization, which represented a new routine in the firm. Further, he strongly relied on open innovation and networking for the R&D exploration: he gathered available competences in-house, initiated knowledge generating and asset leveraging alliances, and coordinated the work of his staff.

Second, this staffing policy also led to several exploratory R&D alliances (also see Table 3 in the previous chapter) that were new to the firm. In the alliance with WindUp, the firm developed for the first time an entire product in a strategic alliance; earlier collaborations were intended to customize existing products to customer needs. However, this high degree of exploration in the inter-organizational domain dropped after top-management intervention and the R&D manager had left.

Third, in terms of cognitive representation, the way of doing business in the established business was to ‘pack’ engineering knowledge into a product through design and manufacture it in-house to avoid that knowledge could be copied or stolen. As a difference, the new R&D manager explored new ways of selling knowledge, in particularly through consultancy services (Table 3). This shows that the protection of the innovation space was effective and exploration possible. The team later returned to the old way of selling knowledge, but only because they realized that consultancy services did not match the existing business model. Just selling consultancy services would leave the production facility idle and turn it into a cost center.

Overtime, throughout the phases 2 to 4, the organizational boundary between old and new business became porous and a drift from a textbook-like organizational separation to a looser form can be observed. Indeed, the SME’s R&D exploration process was polarized: after a time period of openness and relatively large resource spending for exploring new technological and market opportunities in a separate organizational unit with new (external) managers and R&D partners, top-management suddenly and radically narrowed down and restructured the organization due to resource constraints to become much more exploitation focused. In other words, after a phase of exploring various quite different technological opportunities, they (too) quickly narrowed down the technological pathways to a single one and (too) quickly specified product design – which later turned out to fit only to selected segments of an overall small market. Several factors support this drift.

The quality of the organizational boundary eroded when the R&D unit manager was replaced several times by internal managers, who managed the unit like the established core business of TechLtd. Indeed, the former R&D manager had adopted a holistic project management approach and, even though he was formally only in charge of product development, also worked for S&M (Figure 2). This drift is also captured in the organizational structure. When the S&M unit management was split into two functions (one for product design and the other for S&M), the exploratory business unit became better integrated into the established matrix organization. The new managers also had long-standing core business experiences and shared responsibilities between the old and new businesses. The fact that they were not briefed on the dual (ambidexterity) demands of his new job further contributed to weaken the boundary.

This drift is also observed in the evolution of knowledge development over time (Table 3). In the first phase, new R&D knowledge (such as how to make an inverter) and S&M knowledge (for instance, design a good revenue model) was developed. Latter phases did not show any significant R&D knowledge development. Finally, the drift is also visible in the R&D networking activities (Table 3). While the initial phase was characterized by intensive networking, besides product development with customers, no new alliances were established in the later phases.

These factors support the analysis that an organizational separation drift occurred preventing the innovation to reach maturity and compromising its commercial success. This is different from temporal separation as the integration of the new innovation in the existing business happened too early and in an unplanned manner.

### *Inter-organizational separation and contextual ambidexterity in the S&M functions*

With regard to the *S&M* department, the case is more complex. While the organizational chart of TechLtd pretends some form of organizational separation (individual S&M units for old and new business units), this was not the case in practice. To some extent, an inter-organizational separation existed during technology exploration in phase 1. In TechLtd's S&M department, initially no formal responsibilities existed for the new exploratory unit and marketing planning was *de facto* under the responsibility of the R&D manager who also interpreted his position as including S&M exploration and marketing planning. Important parts of the sales responsibilities – particularly customer acquisition – were taken over by the alliance partner WindUp. However, though the alliance partner suggested an individual S&M approach diverting from existing experiences of TechLtd, the sales strategy was ultimately specified by TechLtd using their experiences from established business units – therefore, seriously limiting the potentials of (inter-)organizational separation, and ultimately exploration. At the end of phase 1, one sales person at TechLtd was appointed part-time for the collaborative sales approach with the alliance partner, though while maintaining sales responsibilities for the old business – representing a form of contextual ambidexterity.

Overall, the interface between old and new was not managed effectively in this function domain, which translates into a low level of (S&M) exploration. Following phase 1, when the R&D manager left, the position was re-staffed several times with in-house engineers who gained their experience in the core business (during more than 10 years) and worked only part-time in the new business unit (as illustrated in Figure 2). This structural situation allowed for the spillover of at least two cognitive representations and routines, which illustrate the unsuccessful separation.

The first cognitive frame that permeated is the understanding of how business-to-business markets function. The old and new markets were significantly different (Table 4) and the old strategy – based on long-term, personal, trustful relationships – matched the need of the mature core business market. Thus the old sales department was structured accordingly: a handful of senior engineers took care of the sales and maintained trust with clients. Assuming that the small-wind market would function in a similar way, the same sales approach was replicated, even though the new market – young, volatile and rapidly evolving – was significantly different from the old.

The second cognitive representation that permeated is the belief that business-to-business is synonym with made-to-order and high customer-specific development and design. When the first end-users complained about the low yields of the wind turbines and TechLtd realized that the turbine manufacturers lacked technical know-how, the R&D team began to improving the inverter with additional functions to compensate for the poor turbine quality, thus increasing product design specificity. By doing so, the product became less attractive to other customer segments, which were not interested in the additional functions. Because customer-specific development was seen as central for success, the routine of developing solutions for customer specific problems was also applied to the new business, even though this eventually drastically narrowed down the already small market segment.

These spillovers are even more problematic, as the market was virtually unknown to TechLtd, that the partner WindUp had access to and knowledge about the market, and that the joint-venture agreement said that WindUp would be responsible for sales. Nevertheless, in this function, the management of the exploration and exploitation interface did not protect the new unit from the old cognitive representations and routines, thus preventing market exploration to unfold. Knowledge about the market was developed, but only towards the end of phase 3 (market introduction), too late to adjust the sales strategy.

### *5.2 Misfit of product-market strategy and domain separation*

The new small-wind inverter *product* was to be sold in a new *market*. For the success of this intended product-market strategy, an exploration in both the *product* and the *market* domain would have been necessary – which, however, did not take place. Therefore, a mismatch between the intended product-market strategy and the actual product-market exploration can be observed.

First and most evidently, given that functional domain separation and organizational separation was only for the R&D function, the conditions for exploration were created in the product domain but not in the S&M domain. The rather porous boundary of the predominantly contextual separation in the S&M domain allowed for the spillover of routines and cognitive frames that resulted in the adoption of the core business sales approach for the new business area. This adoption prevented further market exploration and is consequently largely responsible for the inability to successfully market the product. As shown in Table 4, important differences exist between the old and new markets. The old sales strategy was well adapted to the core business market. Assuming that the small-wind market would function in a similar way, the sales strategy was replicated for the new unit. However, the strategy was misaligned with the needs of the new market. Further, considering the structure of the new market, the department was drastically understaffed. Indeed, with less than half of the personal of the old S&M department, the new department had to penetrate a ten times bigger market. Therefore, the adoption of the old sales strategy also lead to an underestimation of the required S&M efforts for successful commercialization.

The lack of knowledge development in the S&M domain is another signal for the absence of market exploration. Even though knowledge on the market was developed (Table 3), it was gained too late in the product development process and was not translated into a new sales approach. The close cognitive proximity to the old business simply did not allow for sufficient experimentation. This lack is also visible in Figure 2: the exploration in the R&D domain translated into the emergence of various new product innovation trajectories (left side of the fireworks graph). However, in phase 3, no similar emergence in the sales approaches could be observed (right side).

### *5.3 Combination of modes of separation*

Although the formal organization of TechLtd. (Figure 1) may seem like a clear-cut organizational separation between the old and new business, the analysis revealed that a combination of modes of separation coexisted within the firm. The dominant mode of separation at TechLtd was *function domain* separation with exploration being strongly focused on the R&D domain, while the S&M (as well as production) domain ultimately remained as usual. Within the individual functions, TechLtd. tried different forms of managing ambidexterity: in the R&D domain, they used *organizational* separation; in the production domain *contextual* ambidexterity; and in the S&M domain a mixture with *inter-organizational separation* with a strategic start-up partner in the early phases and mainly (unsuccessful) *contextual* ambidexterity in the later phases. Separation, both in the R&D and S&M domains, eroded over time leading to separation drift (section 5.1). At the end, the R&D exploration was to some extent successful (small series production), but the S&M approach turned out to be mostly exploitative, leading to a misfit between the pure (product and market) exploration the firm embarked on and the actual marketing activities (section 5.2).

Our conclusion from this picture is that, while domain separation and contextual ambidexterity may theoretically be a more resource-efficient means for managing ambidexterity than full organizational separation, they also lead to more complex coordination requirements between the different ambidexterity modes and therefore increasing top-management challenges. They also lead to higher risks that the exploration could ultimately fail. Overall, contingent on the exploration type (pure vs. partial; see Voss and Voss, 2013), it should be carefully weighed whether full organizational separation covering all functions or a combination of domain separation with other modes of ambidexterity can be pursued.

## 6 Discussion and conclusion

While academic work relating ambidexterity with firm performance is numerous (O'Reilly and Tushman, 2013), our knowledge on the management of the exploration and exploitation interface remained sparse. With this fine-grained case of a manufacturing SME, we shed light on three essential management challenges, which may constrain the successful pursuit of ambidexterity, if not addressed adequately.

### *6.1 Organizational separation drift*

While businesses may start with good faith, their exploration with textbook-like modes of separation (e.g. organizational separation) and adequate resource allocation for the protected exploration unit, due to unexpected events or simply due to resource fading they may gradually shift priorities away from exploration readopting more exploitative practices and letting the thinking and practices from established units gradually or suddenly take over even of separated units. In the case of organizational separation, for example, separate organizational structures (e.g. departments) may still exist, but their inner functioning no longer differs and may or may not ultimately lead to the dissolution of formal separation – which we then label ‘organizational separation drift’ or ‘exploration drift’.

The paper hypothesizes that SMEs are prone to stop exploratory processes too early and therefore are often not able to reap the potential benefits from exploratory activities leaving not much more than failed opportunities and sunk costs. Hence, we thus content with Lavie *et al.* (2010) that exploration and exploitation are associated in time and thus argue that parsimonious resource spending over the project period can increase the odds of success. Too early resource commitment not only compromises success but also limits the options for future exploration.

### *6.2 Misfit of product-market strategy and domain separation*

As a result of an iterative procedure of idea exploration and selection, the SME ultimately focused on a very exploratory innovation project with the aim of developing a new product for a new market (Ansoff, 1957; Voss and Voss, 2013). This paper finds that the degree of exploration of an innovation task is related to the success of various types of separation or ambidexterity. For example, exploratory innovations simultaneously focusing on new products in new markets (pure exploration according to Voss and Voss, 2013) cannot adequately be addressed with only R&D exploration, which in the case of TechLtd resulted from a function domain separation. Rather it needs cross-functional exploration in both R&D and marketing (i.e. new product requires new R&D and new markets may require new marketing approaches simultaneously). On the contrary, *new* products for *existing* markets or *existing* products for *new* markets could very well be addressed with function domain separation and exploration limited to one function. This bias towards exploratory product development without market exploration can be a cause of exploration failure in manufacturing SME.

The development of environmental and energy technology often involves the most radical form of innovation, which implies exploration both in the product and the market domains (pure exploration) and is known to be difficult to achieve (Bos-Brouwers, 2009). In addition, these innovations are strongly dependent on the political and institutional context, which has the potential both to increase complexity and uncertainty. This shows that exploration in technology fields with strong political influence and high uncertainty can be more challenging than innovation in more conventional areas. Particularly SMEs are usually not capable of monitoring (or even influencing) institutional contexts leading to higher risks in their exploration endeavors.

### *6.3 Combination, (temporal) interaction and embeddedness of various modes of separation*

It seems to be likely for SMEs that, in order to reduce costs and the need for management attention, that different modes of separation and ambidexterity are combined (here temporal separation, function domain separation, organizational separation, and contextual ambidexterity). For example, limiting exploration both to specific time periods (temporal separation) and to selected value chains functions (domain separation) could reduce costs, at least theoretically. Being simultaneously pursued, they of course interact or are even embedded (e.g. organizational separation for selected function domains; contextual ambidexterity for remaining function domains). Their proper combination can enable resource-efficient exploration – and are therefore likely for SMEs – but, at the same time, increases complexity, inconsistencies and risk of exploration failure. In turn, this demands stronger management attention, which is linked to explorations costs. We thus question Lavie *et al.*'s (2010) assumption that domain separation is less resource intensive. We hypothesize that the resource burden is shifted from costs related to set up and maintenance of structure separation towards human resource management and costs of top-management attention.

### *6.4 Further research and limitations*

Further research should explore those three challenges in more depth and breadth and focus on the role of top-management teams, management practices and leadership styles in managing the exploration and exploitation interface. At present, the literature features only isolated strides in this direction (Lubatkin, 2006; Burton *et al.*, 2012), which represents a promising area for future research.

Our study is limited at least in two ways: first, the research design following a single-case study, which limits the generalization of the results. Still, we think that the challenges and pitfalls described are quite representative for the group of hidden champion-type engineering SMEs and, more generally, entrepreneurial SMEs embarking towards green innovations. A second limitation is that the major part of the innovation process was only analyzed using ex-post analysis which is subject to bias due to the retrospective account by the individuals interviewed. We used triangulation and reflexive interpretation (Alvesson, 2003) to cope with this limitation.

### *6.5 Managerial implications*

Three managerial implications can be drawn from our research. First, even though several modes of separation between the old and the new business can coexist within the firm, top-management should carefully consider how it separates old and new. Drawing on too many modes of separation simultaneously (rather than a clear-cut organizational separation) can lead to exploding complexity, which a) might simply compromise the success of the innovation endeavor and b) a tremendous increase in management effort later.

Second, an important threat for the exploration is that unexpected events or resource fading may gradually shift priorities away from exploration, readopting more exploitative practices and letting the thinking and practices from established units take over even of separated units. This gradual shift may not be recognized well if it occurs slowly over time.

Third, is a new product intended for an unknown market, top-management should provide space for exploration both in the R&D as well and S&M domains. This is in fact likely to of high relevance for environmental or sustainability-oriented innovations such as renewable energy.

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