Doctoral Thesis

Diffusion and Adoption of Technological Innovation in the Energy Sector - the Role of Individuals and Firms

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Diffusion and Adoption of Technological Innovation in the Energy Sector—the Role of Individuals and Firms

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“If you always do what you always did, you will always get what you always got.”

Albert Einstein
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Abstract

Most people now accept that we must reduce carbon emissions if we are to avoid serious, presumably irreversible harm to the biosphere in which we live. Technologies concerned with the conversion, transportation, storage, and use of energy are a critical part of the problem, and also of the solution. We have seen the development and commercialization of numerous novel technologies aimed at reducing carbon emissions, resulting in the emergence of new industries (e.g. photovoltaic, smart home, and electric vehicles, to name just three). Nonetheless, while many ambitious “clean technologies” were widely seen as technically and even economically attractive at the outset, they ultimately failed to reach the expected levels of diffusion. The technical and economic performance of a technology has been identified as a key determinant of its adoption, but neither individuals nor firms decide to adopt technology based on this criterion alone. This thesis explores in more detail how firms and individuals decide to adopt novel, technological innovation.

I examine selected drivers that influence individual and firm technology adoption, and thus moderate the link between technology performance and diffusion. In doing so, I combine and build upon insights from different theories across disciplines, including innovation diffusion theory, technology adoption theory, and organizational learning theory. The thesis comprises four individual papers, each addressing a specific gap in the extant literature. Paper I conducts a technical, quantitative assessment of the performance of a novel, consumer energy technology undergoing commercialization (intelligent, automated heating control). Paper II compares and evaluates two fundamentally different approaches (utility-based versus belief-based) to investigating the adoption determinants of technologies. Paper III extends existing adoption theory to experiential technologies, an increasingly prevalent technology category, and conceptualizes key determinants of individual adoption. Finally, Paper IV scrutinizes adoption-related decision-making mechanisms within firms, with a particular focus on the role of the board of directors.

All four papers are situated within the broader frame of the energy sector. Automated heating control, assessed in Paper I, is a technology directly relevant for, and the individuals and firms assessed in Papers II–IV represent key actors of the sector. However, whereas Paper I is purely technology-focused, Papers II and III both focus on potential adopters of novel smart home technologies to advance our understanding of individual behavior. Paper IV takes a different perspective and focuses on firm behavior by investigating a sample of Switzerland’s largest utility firms. The mounting pressure on Swiss utility incumbents to shift their strategic orientation from exploiting existing technologies to exploring new ones makes this sector an ideal case to study firm adoption behavior.
This thesis applies a mix of quantitative and qualitative methods, reflecting the diverse phenomena investigated. Methods range from quantitative, simulation-supported thermal modeling to quantitative, statistical assessment of survey data with structural equation modeling, as well as qualitative, inductive case-study research.

This thesis makes four major contributions. First, I present empirical evidence that shows that novel intelligent heating control in residential buildings can significantly reduce energy consumption without compromising comfort. This underlines the importance of technology innovation as an enabler of low-carbon energy systems, and points directly to related building-efficiency potential. Second, by testing and comparing utility-based versus belief-based individual adoption models using the same empirical data, I show that belief-based models are far better suited for investigating technology adoption determinants—perception is more important than objective performance. This explains controversial findings in the extant literature, and provides guidance for the avoidance of omitted-variable bias in future studies. Third, I illustrate the importance of “everyday practices” for individual experiential technology adoption. This contributes to extant adoption theory by highlighting a previously unheeded construct that is more influential for early-stage adoption than commonly accepted beliefs such as usefulness or price value. Fourth, I conceptualize in detail the role of the board of directors in organizational exploration, a widely investigated concept that encompasses firms’ technology-adoption behavior and is well suited for studying it. This adds to the literature on organizational learning by highlighting the importance of a set of board-internal learning capabilities for strategic reorientation, and by showing how boards can come to cause organizational inertia.

These insights allow me to derive several recommendations for policymakers, managers, and shareholders. Policymakers should consider novel, experiential technologies more directly when drafting directives for building emission reduction. Moreover, when designing policy measures intended to spur technology diffusion, they should recognize compatibility with everyday practices and hedonic motivation as key drivers of early-stage adoption. According to our results, measures that focus on price value (e.g. subsidies) or address environmental norms (e.g. information campaigns) might suffer from low influence. Additionally, managers, and particularly shareholders, are well advised to facilitate and institutionalize continuous board-internal learning to prevent strategic inertia, notably when firms need to shift toward more exploration. This is particularly relevant in times of increased environmental dynamism, such as liberalization, regulatory changes, or increased competition. Lastly, managers who are concerned with the commercialization of technologies should pay attention to key adoption determinants and understand that they can be more influential than technical performance. Compatibility with everyday practices, for example, is more important for early adopters than
usefulness or price value, and should ideally be considered and integrated as early as possible during product development.
Zusammenfassung


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1. Introduction

1.1. The Increasing Importance of Sustainable Energy Technologies

Climate change is now recognized as a serious threat to global sustainable development (IPCC, 2014a). Without determined intervention, we face a number of detrimental, presumably irreversible transformations of the natural world and human society as we know it (Choat et al., 2012; Easterling & Apps, 2005; Hellmann, Byers, Bierwagen, & Dukes, 2008; Lewis, 2014; Thuiller et al., 2011; Walther et al., 2002). The predicted adverse effects of an increase in global temperatures, ranging from the displacement and impoverishment of entire populations to the fatal disruption of food production, are well documented (IPCC, 2014b; Nicholls et al., 2011).

Energy technologies are central to both the problem and the solution. Both energy-supply and energy end-use (i.e. demand-side) technologies have not only been recognized as key drivers of greenhouse gas emissions (IPCC, 2014c), they also represent our best chance of reducing them in the future¹ (Acemoglu, Aghion, Bursztyn, & Hemous, 2012; Gillingham, Newell, & Pizer, 2008; IPCC, 2007). According to the Intergovernmental Panel on Climate Change (IPCC), energy-supply activities (including electricity and heat) were the single largest contributor to direct CO₂ emissions in 2010, accounting for 25% of the total. These direct carbon emissions are driven by demand from end-use applications, particularly buildings (12%) and industry (11%) (IPCC, 2014c). If we are to become a low-carbon society, we must unlock the technological efficiency potential and lower emissions of both energy-supply and end-use applications (Acemoglu et al., 2012; Gillingham et al., 2008; IPCC, 2007).

Spurred by these insights and (not least) economic motives, various novel "sustainable energy technologies"—which claim to have a smaller carbon footprint than current technologies—have appeared, attracting considerable attention from researchers, businesses, and the general public. Over the last decade, investment in such innovations has rocketed, driving substantial growth in the number of products and users. Total new investments in clean energy-generation technology (photovoltaic, wind, biofuel) have been estimated at USD 310 billion in 2014, a more than fivefold increase compared to the estimated USD 60 billion in 2004 (Mills, 2015). Technologies aiming to reduce energy consumption have also been identified as—often even more cost-effective—measures to spur the transition toward a sustainable energy system.

¹ While energy-supply technologies include renewables such as wind, solar, and biofuels, energy end-use technologies comprise products that convert energy into a useful final service like heating, communication, or mobility (Wilson et al., 2012).
(EEFIG, 2015) and have attracted substantial attention (Bornstein, 2015). In 2013 (and 2012),
the energy-efficiency sector received more venture capital (a share of 20%, according to
Cleantech Group’s i3 database) than any other sustainable technology sector globally (Howell,
2015). Nonetheless, the impact of end-use energy technologies remains underestimated, and
research has shown that chances to achieve additional, large-scale efficiencies are still going
to waste (Wilson, Grubler, Gallagher, & Nemet, 2012).

1.2. Advancing the Understanding of (Failed) Diffusion

Irrespective of the resources invested into their development, many novel technologies
eventually lag behind their “desired” or “expected” market penetration (Chiesa & Frattini, 2011;
Gourville, 2006; Schilling, 2002; Wuestenhagen, Wolsink, & Buerer, 2007).

Although “desirable” from an environmental perspective, some technologies fail to gain
acceptance in the mass market for obvious technical and/or economic reasons. Residential
photovoltaic systems, for example, were initially uncompetitive in terms of both performance
and overall cost2 compared to conventional electricity generation (Peters, Schmidt,
Wiederkehr, & Schneider, 2011) and duly matured only over time (Lang, Gloerfeld, & Girod,
2015). Moreover, the diffusion of solar-power systems in many large markets such as Germany
was, and still is, primarily driven by policy instruments (Hoppmann, Huenteler, & Girod, 2014).

However, the reasons why other technologies do not diffuse as “expected” are far less obvious.
In the building and transportation sector, for example, several technologies are not only
considered technically feasible, but also cost-effective. Theoretically, they allow carbon-
emission reductions at negative abatement costs—i.e., they provide economic benefits to end-
users (see, for example, McKinsey & Company, 2010). Nonetheless, LED3 lighting, more
efficient HVAC4 systems, smart home energy management, and hybrid electric vehicles, to
name just a few, all failed to reach projected market acceptance levels (Balta-Ozkan,
Davidson, Bicket, & Whitmarsh, 2013; Banfi, Farsi, Filippini, & Jakob, 2008; IEA, 2013; Jaffe
& Stavins, 1994; Nair, Gustavsson, & Mahapatra, 2010; Wu, Inderbitzin, & Bening, 2015). In
other words, they failed to complete the process of technological change, or did so later than
anticipated. This process encompasses a) developing new technical capabilities, b) translation
into improved products, and ultimately c) diffusion into the market (Jaffe, Newell, & Stavins,
2002; Schumpeter, 1942). What is perhaps most intriguing about the above-mentioned
technologies is that they have all reached a state of technological maturity that was considered
suitable for widespread commercialization by numerous investors, firms, and policymakers.

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2 Typically measured in, and compared based on, levelized cost of electricity (LCOE).
3 Light-emitting diode.
4 Heating, ventilation, and cooling.
Consequently, advancing our current understanding of technology diffusion is crucial. On the one hand, a more comprehensive and differentiated understanding of diffusion drivers and inhibitors enables the targeted and effective policy measures that are needed to accelerate the transition to a low-carbon energy system (IEA, 2014; IPCC, 2014c). All widely accepted scenarios for a sustainable future, including the de facto international climate target of 2°C (Rogelj et al., 2009), rely upon the large-scale diffusion of sustainable energy technologies (e.g. IEA, 2014). Given that sustainable technological innovation is taking place, and technically viable products are being developed, each one that goes unadopted represents a missed opportunity.

On the other hand, understanding why sustainable energy technologies “do not obtain a worthwhile market share and/or make a profit, even if they 'work' in the technical sense” (Braun, 1992: 214) is particularly relevant for individuals and firms involved in technology development and commercialization. Technology firms only enjoy long-term success when the products they launch end up being adopted. Insights into the mechanisms of diffusion allow companies to address potential diffusion barriers, from stages as early as product conceptualization right up to post-launch of the final product and beyond. Moreover, although most individual firms may be driven by financial performance, the successful large-scale commercialization of sustainability innovations ultimately brings positive side effects such as employment and societal welfare.

Summarizing, a more nuanced understanding of diffusion mechanisms is of great interest for actors who promote technological change, are interested in policy effectiveness, or are concerned with the process of innovation commercialization—all of which are key enablers of a low-carbon society (Jaffe et al., 2002).

1.3. Diffusion Research and the Role of Firms and Individuals

Innovation-diffusion research can trace back its ancestry for over a century (Wejnert, 2002). However, its most widespread and comprehensive theoretical conceptualization was set out by Rogers (1962) in the first edition of his seminal work on the “Diffusion of Innovations.” He describes innovation diffusion as “the process by which an innovation is communicated through certain channels over time among the members of a social system” (Rogers, 2003: 5). While originally focused on “communication,” diffusion theory has quickly expanded to include the actual adoption and even use of technology—although use neither equates with, nor even necessarily follows, adoption or diffusion (Lanzolla & Suarez, 2012). Today, the term “diffusion” most commonly denotes the spread of a technology within a specific market or community (Lanzolla & Suarez, 2012; Loch & Huberman, 1999).
Furthermore, diffusion is conceptualized on multiple levels of analysis (Brancheau & Wetherbe, 1990). Arguably, there are umpteen factors that help or hinder the diffusion of novel technologies. In fact, the main difference between the two often synonymously used words diffusion and adoption is a representation of these different levels and units of analysis; diffusion usually refers to the aggregate level (e.g. organization, national, global), whereas adoption is concerned with the individual level (e.g. individuals, firms). In this respect, the diffusion process embraces adoption, but not vice versa.

Much of the traditional diffusion literature focuses on understanding diffusion at the aggregate level (Hauser, Tellis, & Griffin, 2006). One example is the Bass model of new-product diffusion, originally developed in the 1960s and subsequently refined, which uses a differential equation model to describe how new products are adopted within a population over time (e.g. Bass, 1969; Mahajan, Muller, & Bass, 1990).

More recent studies, however, are often concerned with much more disaggregated diffusion phenomena and make much more granular, localized contributions—an approach that appears more promising for uncovering factors that are less obvious but nonetheless influential. Decades of research have confirmed that the individual behavior of a) consumers and b) firms (e.g. incumbents, technology providers, start-ups) is of particular importance for the overall rate and magnitude of technology diffusion (Labay & Kinnear, 1981; Lanzolla & Suarez, 2012; Rogers, 2003; Venkatesh, Thong, & Xu, 2012).

Evidently, an innovation that improves the status quo of an individual is a necessary but not sufficient condition for economic success or diffusion (Braun, 1992; Chiesa & Frattini, 2011; Hill & Rothaermel, 2003; Malerba, 2002; Schilling, 2002). Every day, countless individuals freely decide to adopt (i.e. purchase) novel technologies based on their subjective preferences (Venkatesh et al., 2012). But it is only when a product offering appeals to the subjective preferences of (first) a group of innovators and early adopters and (later) mainstream customers that mass-market diffusion takes place (Chiesa & Frattini, 2011; Manning, Bearden, & Madden, 1995; Moore, 2002). Existing research has shown that, despite intense entrepreneurial and corporate activity, only a small proportion of new products introduced eventually diffuse successfully (Crawford, 1977; Goldenberg, Lehmann, & Mazursky, 2001; Ogawa & Piller, 2006).5

Moreover, looking at individual adoption is not enough for a comprehensive understanding of diffusion mechanisms. Firms, defined as “stable systems of individuals who work together to

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5 Exact failure rates vary greatly between industries investigated and research methodologies deployed, and are controversially discussed. Although new product failure rates in the range of 37–80% were found in previous research, it was claimed that rates in the 30–40% range are more reasonable (Karakaya & Kobu, 1994).
achieve common goals through a hierarchy of ranks and a division of labor” (Rogers, 2003: 404), merit attention too. Depending on the type (e.g. B2B versus B2C) and development status of a technology, firms either adopt it to advance their own business activities and use it internally, or adopt it to commercialize and sell it to external consumers. Both activities are crucial to technical change, and thus organizations have been recognized as “the ground on which innovations are scattered” (Rogers, 2003: 402). However, these activities require a number of actors within an organization to engage in learning and decision-making. These actors must ascertain whether a (from their subjective perspective) viable, novel technology innovation fits with the firm’s desired strategy (Schilling, 2002) and, thereafter, collectively commit to exploring the novel technological innovation—processes that are arguably not fully understood.

Overall, we are far from comprehensively understanding the catalysts, barriers, and interdependencies of novel technology diffusion—particularly at the micro level of individuals and firms. This not only conflicts with the objective of influencing technology diffusion on a societal level to curtail carbon emissions; it also hampers firms’ aspirations to plan innovation commercialization effectively.

1.4. Research Framework

Amid intensive efforts to spur technical change, this thesis sheds light on some key factors that promote and inhibit technology diffusion. Recognizing that technology diffusion is a process that takes place within a social system (Rogers, 2003), I examine three factors in more detail: technology performance, individual technology adoption, and firm technology adoption behavior (see Figure 1).

Existing research has largely confirmed that technology performance is a key driver and a prerequisite for diffusion (Benbasat & Barki, 2007; Venkatesh, Morris, Davis, & Davis, 2003). In a classical market scenario, however, two protagonists that exert potentially even stronger influence on a novel technology’s fate are consumers and firms—but the individual adoption behavior of neither has been fully understood. Thus, the overarching research question of this thesis is:

*How do individuals and firms decide to adopt novel, technological innovation?*

As illustrated in Figure 1, Paper I investigates the technical performance of an energy-efficiency technology that has attracted substantial attention in recent years: intelligent thermostats. This is relevant for the papers thereafter. Paper II scrutinizes the importance of

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*Business-to-business (B2B); business-to-consumer (B2C).*
technical performance (i.e. utility) versus the importance of subjective perception (i.e. beliefs) for individual adoption. Paper III assesses the importance of previously unheeded beliefs for novel technology adoption. Finally, Paper IV is concerned with the behavior of firms, and the role of boards of directors in particular, for novel technology adoption.

Figure 1: Research framework and paper projects I–IV

In many ways, my research was phenomenologically driven. In order to achieve the level of granularity required for meaningful empirical work, though, the individual papers of this thesis draw from, and contribute to, more specific theoretical realms. I elaborate on this and point to extant gaps in the literature in more detail when introducing the research questions of the individual papers (Chapter 2).

The remainder of this dissertation is structured as follows: Chapter 2 details the research objectives of the four distinct projects that together form the core of my dissertation. Chapter 3 introduces the respective methodologies deployed. Chapter 4 provides a summary of the results of the four papers. Chapter 5 discusses the contributions of the work presented for the extant literature, as well as implications for practitioners, and points to avenues for future research. Finally, an overview and the full versions of all papers are provided in Chapter 6 and the Annex.
2. Theoretical Background and Research Questions of the Individual Papers


In the context of this dissertation, Paper I serves as the baseline for the subsequent investigations on firm and consumer adoption. Although it is a technical review rather than a theoretically oriented contribution, it was meant to test the argument that novel consumer technologies that reduce carbon emissions and significantly outperform existing solutions do exist. Identifying such technologies not only highlights significant potential for technical CO₂ mitigation, but also underlines the relevance of the technology diffusion efforts required to unlock them.

It is generally accepted that energy efficiency in buildings is an area with large, untapped carbon-mitigation potential (IEA, International Energy Agency, & IEA, 2011). Emissions from the building sector reportedly accounted for 19% of global greenhouse gas emissions in 2010 (IPCC, 2014c). Countries such as Germany and Switzerland consume close to two-thirds of their total final energy used in buildings purely for heating, with shares of 74% and 72% respectively in 2010 (Arbeitsgemeinschaft Energiebilanzen e.V., 2011; BFE, Prognos, Infras, & TEP, 2011).

Unsurprisingly, a number of innovation efforts have pursued the goal of more efficient energy use in buildings, driven by developments in information, communication, and automation technology. “Smart home,” a fuzzy term used to describe residential building automation technology, has become a popular notion. Although the market is still in its infancy (Deloitte, 2013), incumbent utility companies and start-ups in Europe (and other industrialized parts of the globe) have begun to develop and market smart-home products (e.g. RWE Smart Home, Nest, tado°, Quivicon).

Particularly prominent in this respect are intelligent thermostats. They aim to automatically reduce energy consumption at night or when people are out, based on individual household behavior. Technological advancements such as mobile internet and GPS-based geolocation services enable such new ways of smart control. However, we know little about the actual performance of these devices—which is striking, given the immense efficiency potential of residential heating-control solutions (IPCC, 2007; Oldewurtel et al., 2012) and the attention that related business activities have attracted. In January 2014, Google Inc. acquired Nest Labs Inc., a relatively unknown intelligent-thermostat manufacturer, for USD 3.2 billion (Winkler & Wakabayashi, 2014).
Some engineering-driven research efforts have targeted a specific heating-control technology, or explored questions of technical implementation (Gupta, Intille, & Larson, 2009; Lu et al., 2010; Scott, Krumm, Meyers, Brush, & Kapoor, 2010). However, a comprehensive comparison that permits meaningful conclusions about the performance of different demand-side heating-control approaches is missing. Hence, it is still difficult to judge whether such technologies are indeed viable—i.e. if they provide benefits to individuals and contribute to carbon-emission reduction, making their diffusion socially desirable.

To address this research gap, Paper I investigates the following research question:

*What is the performance of different heating-control approaches available as of today with respect to a) heat energy required and b) thermal comfort for occupants?*

2.2. **Paper II: A Pre-Study Comparing Two Competing Consumer Technology Adoption Models**

Paper II is the first of two essays concerned with individual adoption behavior as a moderator of the link between technology characteristics and diffusion. In the overall context of this dissertation, Paper II compares the explanatory power of two frequently deployed models, enabling the in-depth investigation of the more purposeful adoption theory presented in Paper III.

Individual technology adoption has received substantial dedicated theoretical attention (Rogers, 2003; Venkatesh, Davis, & Morris, 2007). It is a common theme across disciplines (Venkatesh et al., 2007)—driven not least by the direct potential benefits for practitioners. Effective policy design demands a thorough understanding of the drivers of sustainable technology adoption; technology firms and entrepreneurs are interested in the adoption behavior of their future customers so they can avoid go-to-market failure and debilitating rework or even redevelopment efforts.

Despite existing adoption theories, previous research on the key determinants of consumer technology adoption has generated equivocal results. Even the degree of influence of sustainability-related constructs such as the environmental norms of an individual are matters of controversy (compare e.g. Jansson, Marell, & Nordlund, 2011; Poortinga, Steg, Vlek, & Wiersma, 2003).

The problems largely stem from the parallel use and arbitrary combination of two fundamentally different types of adoption models. On the one hand, objective, utility-based models are frequently applied in the fields of energy or environmental economics. Typically, studies building on this approach analyze technology-centered, objective performance measures and
household characteristics to ultimately derive a (quantitative) proxy for the intention to adopt (e.g. willingness to pay) (see, for example, Achtnicht, 2011; Banfi et al., 2008; Kaenzig, Heinzle, & Wüstenhagen, 2013; Kwak, Yoo, & Kwak, 2010; Scarpa & Willis, 2010).

On the other hand, a number of studies in the management and information systems (IS) literature emphasize the importance of perceptions rather than objective utility, and theorize the influence of technology- and personality-specific “beliefs” on the intention to adopt (and use) (Benbasat & Barki, 2007; Venkatesh et al., 2007, 2012). One can find multiple examples of well-received, theoretically and empirically grounded IS adoption models, such as the Technology Acceptance Model (TAM) from Davis, Bagozzi, & Warshaw (1992) or the Unified Theory of Acceptance and Use of Technology (UTAUT) from Venkatesh, Morris, Davis, & Davis (2003).7 Most of these theories are rooted in prior work on individual behavior in general in the psychology and/or sociology literature (e.g. the Theory of Reasoned Action or the Theory of Planned Behavior (Ajzen, 1991)).

This coexistence of partially conflicting theoretical approaches has contributed little to a coherent understanding of how consumers adopt novel sustainable technologies (or how they are diffused). While both theories have been used to study the same phenomenon and similar technologies, a fundamental comparison of the two approaches is missing. Paper II addresses this discrepancy and investigates the following research question:

*How does the explanatory power of technology-centered utility models compare to the explanatory power of belief-centered behavior models?*

### 2.3. Paper III: Investigating Determinants of Novel Experiential Consumer Technology Adoption

Paper III is the second of two essays concerned with individual adoption behavior as a moderator of the link between technology characteristics and diffusion. It builds on the results from Paper II and aims to shed light on the most important adoption drivers of an increasingly common and energy efficiency-relevant consumer technology category: experiential technologies.

The digitalization of everyday processes is a common objective of novel technologies (Bødker, Gimpel, & Hedman, 2014; Rauhofer, 2008). Grocery shopping with a smartphone, ordering a taxi with an app, and watering plants or turning on the heating over the internet are just a few of the plentiful examples.

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7 For an overview, the interested reader may refer to Venkatesh et al. (2003).
More importantly, the rapid increase in digitalization opens up many new opportunities to improve energy efficiency, and consequently reduce carbon emissions. It holds out the promise of circumventing the challenges of human behavior change (Baca-Motes, Brown, Gneezy, Keenan, & Nelson, 2013; Gifford, Kormos, & McIntyre, 2011). In the case of smart home devices, for example (e.g. intelligent thermostats, see Paper I), the technologies are intentionally designed to blend in with the user’s everyday practices, ideally remaining unnoticed.

Yoo (2010) was among the first to recognize the idiosyncrasies of such embedded technologies and flag up their implications. In his call for research on computing in everyday life, he proselytized the apposite notion of “experiential computing,” explaining that experiential (consumer) technologies enable “experiences in everyday activities through everyday artifacts with embedded computing” (Yoo, 2010: 213)—a notion that fits the context of this research well. From a phenomenological perspective, intelligent thermostats fall into the same category. They can be connected to the existing heating system relatively easily. Devices have very little value in themselves, but once connected, they automatically control in-room temperature with the intent to optimize energy efficiency and comfort.

Such unprecedented embeddedness makes the context of use much more significant—so much so, in fact, that it affects the determinants of technology adoption. In contrast to conventional computational devices such as PCs or laptops, experiential technologies are not used for task-specific work or information purposes. For example, once installed, smart home devices digitalize and control everyday activities inconspicuously, making the use of such devices not so much a dedicated activity as a subtle aspect of everyday practices.

These salient peculiarities of novel, experiential technologies have yet to be addressed in adoption research. This manuscript represents a first humble attempt to specify the notion of compatibility with everyday practices as a construct, develop a suitable measurement scale, and subsequently test the construct’s influence. In addition, technical compatibility and risk are both notions that appear particularly relevant in the context of experiential technology, and also merit attention. While both have been discussed in the extant literature, they have not been specified as individual constructs or tested as direct determinants of adoption in the context of experiential technologies. Consequently, Paper III tests the following three hypotheses:

- H1: Perceived compatibility with everyday practices positively influences the intention to adopt experiential consumer technologies
- H2: Perceived technical compatibility positively influences the intention to adopt experiential consumer technologies
• H3: Perceived risk negatively influences the intention to adopt experiential consumer technologies

In summary, Paper III aims to augment the extant technology-adoption literature by scrutinizing the influence of novel and established belief-based constructs in a theoretically grounded manner within a new technology context. In line with the above hypotheses, it investigates the following overarching research question:

What drives adoption of novel experiential consumer information technologies?

2.4. Paper IV: The Influence of the Board of Directors on a Firm’s Strategic Decision to Explore Novel Technology

Acknowledging the emergence of technically viable and economically attractive sustainable technologies, Paper IV focuses on firm governance as a moderator between technology characteristics and firm adoption. It scrutinizes intra-organizational mechanisms that are often overlooked, yet are instrumental to organizations’ decisions to adopt or reject novel technologies, with particular emphasis on the role of the board of directors.

Because technology adoption\(^8\) at the firm level is a function of collective knowledge about a) the focal technology and b) the consequences of adoption, the subject is well situated within the context of “organizational learning” (see, for example, Attewell, 1992; Burgelman, 2002; Fichman & Kemerer, 1997; Pisano, Bohmer, & Edmondson, 2001). Firm technology adoption requires a number of actors to collectively opt for, and engage in, organizational learning. This is an iterative and often intense process, particularly in view of the sharp contrast between adoption and rejection from a strategic perspective.

The adoption and rejection of novel technologies correspond with the broader concepts of exploration and exploitation, two fundamental gestalts of organizational learning that are described and extensively discussed in the extant literature. While the commitment to adopt a novel technology requires “search, variation, risk taking, experimentation, play, flexibility, discovery, innovation” (i.e. exploration), rejecting it and exploiting an existing technology instead signifies “choice, production, efficiency, selection, implementation, execution” (i.e. exploitation) (March, 1991: 71). Consequently, firm technology adoption is a theme frequently discussed in the organizational learning and exploitation-exploration literature (see, for example, Gilbert, 2005; Lavie, Stettner, & Tushman, 2010; March, 1991).

\(^8\) This applies irrespective of the underlying activity the term adoption is used for, i.e. internal use versus developing, commercializing and selling—see also Section 1.3.
March (1991) was among the first to draw the distinction between exploitation and exploration. While early work posited that an equal balance between the two would produce the best outcome, later studies showed that the optimal balance between exploitation and exploration depends on a variety of factors and can change over time. It was found that exploration plays a particularly important role in dynamic environments, constituting a well of knowledge and capabilities for future firm competitiveness (Jansen, den Bosch, & Volberda, 2006; Jansen, Vera, & Crossan, 2009; Uotila, Maula, Keil, & Zahra, 2009). This implies that during times of heightened dynamism induced by, for instance, regulatory or technological discontinuities, firms need to shift from exploitation to exploration (Gupta, Smith, & Shalley, 2006; Jansen et al., 2009). Exactly how organizations approach these challenges, however, is not fully explored, and merits further attention (e.g. Levinthal & March, 1993).

There is a strong consensus in the literature that executives play a key role when it comes to adopting new technologies (Lavie et al., 2010). It is up to the managers to develop initiatives that shift a firm’s strategic orientation whenever required, i.e. to act in the best interest of the firm and its owners (Boatright, 1994). This is not limited to a temporal separation between exploitation and exploration; it is also possible to strike a balance between the two within (and across) organizations simultaneously—a phenomenon termed “organizational ambidexterity.” Ambidexterity research identifies a number of pathways to integrate both exploration and exploitation into firm strategy (Andriopoulos & Lewis, 2009; Gupta et al., 2006; Lavie et al., 2010; Sirmon, Hitt, Ireland, & Gilbert, 2011; Stettner & Lavie, 2014). Researchers have found that managers can use different “modes,” such as internal R&D, alliances, and mergers and acquisitions, to cope with the challenges of firm-internal ambidexterity (Lavie et al., 2010; Stettner & Lavie, 2014). Empirical research has investigated the effect of such efforts on the financial performance of firms: it was found that adequately balancing exploitation and exploration has a positive effect on firm financial performance and is particularly relevant in industries with high technological dynamism (e.g. Uotila et al., 2009).

Notwithstanding this extensive work on operationalizing the exploitation-exploration balance, the literature has so far neglected the role of non-executive directors. This may be because boards have traditionally been portrayed as entities that merely monitor and control a firm (Walsh & Seward, 1990). Given the prevalence of this reactive role (Mizruchi, 1983), boards’ influence on organizational learning is strongest during times of managerial (and organizational) failure (Tainio, Lilja, & Santalainen, 2001). When performance dips, boards use their legal authority to hire and fire management personnel. Such an intervention paves the way for new competencies, skills, and ideas (Castrogiovanni, Baliga, & Kidwell, 1992), making it one way of inducing organizational learning. More recently, however, an alternative view has emerged, of boards being much more directly involved in organizational learning. Zahra &
Pearce (1989), for example, discuss a) the service role, where boards contribute by fostering (knowledge) exchange with the firm’s external environment, or by giving direct counsel and advice to management, and b) the strategy role, where boards contribute by “initiating their own analysis, or by suggesting alternatives” (Zahra & Pearce II, 1989: 298). Consequently, through initiatives such as developing strategic proposals and making decisions on firm investments, non-executive directors directly influence both the timing and speed of technological exploration.

Whereas existing studies support the notion that exploring (i.e. adopting) novel technologies is important, many studies take an outsider’s perspective, neglecting to provide insights into the detailed mechanisms within the firm. Consequently, boards of directors have received little attention in the exploitation-exploration literature. Paper IV aims to redress this imbalance by addressing the following research question:

*How does a firm’s board of directors influence the degree of firm exploration?*

### 2.5. Summary of Paper Objectives

The preceding sections have outlined four areas of research related to the diffusion of novel sustainable technologies that have yet to receive dedicated attention in the literature. Table 1 summarizes these areas by providing an overview of the four individual papers and their respective research questions.

<table>
<thead>
<tr>
<th>Paper</th>
<th>Title</th>
<th>Research Question</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Turning up the Heat on Obsolete Thermostats: a Review of the Performance of Intelligent Control Approaches for Residential Heating Systems</td>
<td>What is the performance of different heating-control approaches available as of today with respect to a) energy required and b) thermal comfort for occupants?</td>
</tr>
<tr>
<td>II</td>
<td>Utility-Versus Belief-Based Models: Shedding Light on the Adoption of Novel Green Technologies</td>
<td>How does the explanatory power of technology-centered utility models compare to the explanatory power of belief-centered behavior models?</td>
</tr>
<tr>
<td>III</td>
<td>Subtle Servants: The Importance of Everyday Practices for Experiential Consumer Technology Adoption</td>
<td>What drives adoption of novel experiential consumer information technologies?</td>
</tr>
<tr>
<td>IV</td>
<td>Learning to Learn—How Boards of Directors Affect Organizational Exploration</td>
<td>How does a firm’s board of directors influence the degree of firm exploration?</td>
</tr>
</tbody>
</table>

Collectively, the four papers do not just fill gaps in the literature, but also address practical questions that arise during the commercialization of novel sustainable technologies. In this
respect, the overall objective of this thesis is twofold. On the one hand, it offers independent contributions to the literatures on building technology, technology acceptance and adoption, and organizational learning. On the other hand, it proposes practical recommendations for stakeholders interested in the diffusion of novel technologies.
3. Methods and Data

This dissertation deploys multiple research methods, as summarized in Table 2. The core of Paper I is a quantitative thermal simulation, calibrated with data from field observations. Papers II and III build on survey data that was analyzed using structural equation modeling. In Paper IV, interview data is collected and analyzed in an inductive, qualitative case study approach. These methods are discussed in more detail below.

### Table 2: Methods and data sources used in papers

<table>
<thead>
<tr>
<th>Paper</th>
<th>Title</th>
<th>Method</th>
<th>Main data source</th>
</tr>
</thead>
</table>
| I     | Turning up the Heat on Obsolete Thermostats: a Review of the Performance of Intelligent Control Approaches for Residential Heating Systems | Quantitative: empirical observation of households and thermal modeling | • Data from a 14-month observation of 30 households in southern Germany  
• Ten most complete datasets used in the final analysis |
| II    | Utility- Versus Belief-Based Models: Shedding Light on the Adoption of Novel Green Technologies | Quantitative: survey and structural equation modeling | Survey data (N=1,101) from potential intelligent thermostat adopters (Germany) |
| III   | Subtle Servants: The Importance of Everyday Practices for Experiential Consumer Technology Adoption | Quantitative: survey and structural equation modeling | Survey data (N=976, N=971) from potential intelligent thermostat adopters (Germany, Switzerland) |
| IV    | Learning to Learn—How Boards of Directors Affect Organizational Exploration | Qualitative: inductive, comparative case study | • Primary data from annual reports and other firm documents  
• Thirty-three in-person interviews with board members and top-level executives |

3.1. Quantitative, Simulation-Aided Technology Performance Evaluation (Paper I)

Paper I presents a technical evaluation of residential heating-control approaches. It builds on multiple data sources. First, we conducted a technical literature review of existing work related to residential heating-control systems. We discussed the findings with experts, and ultimately derived a taxonomy of the most prominent heating-control approaches selected for further investigation.

Given the timeframe of the project, an integrated simulation approach was used. This allowed us to combine actual field data with the flexible evaluation capacity of a simulation environment. Moreover, it enabled comparison of all the identified approaches in the same building environment over at least one (simulated) year (i.e. a full heating period). For the field data collection, 30 test households were randomly selected from a pool of over 100 qualifying applicants. All were equipped with equipment for real-time data collection and transmission by...
a research partner, an intelligent thermostat manufacturer. Moreover, before real-time data logging began, all participating households completed a survey requesting basic data about their building, its heating system, and the occupants. Thereafter, all households were linked to an online database over a 14-month period. The data ultimately collected over this period included information on the behavior of heating systems and building envelopes such as in-room temperature, occupancy status, user-defined setback temperature, and burner activity. Once the real-time collection phase was complete, all data series were reviewed and the 10 most comprehensive (i.e. error-free) selected for further investigation.9

Because none of the building-simulation tools we reviewed allowed us to simulate different heating-control approaches within the same building envelope (as we desired), we decided to develop a proprietary building model.10 Using MATLAB, we implemented a lumped-parameter, resistance-capacitance simulation environment in parallel with the field-data collection effort. The model was calibrated based on the test household data—i.e. the input parameters (e.g. wind, solar irradiation, thermal properties of the building) were adjusted so that the in-room temperature gradient could be replicated over a period of 12 months. This was possible across all households with surprisingly low discrepancy. Thus, the model proved sufficiently accurate to be used for the following evaluation of heating-control approaches.

Integrating empirically obtained data on occupancy behavior and historical third-party information on local weather conditions, we assessed all eight heating-control approaches in each household. The two prime performance evaluation metrics we selected were net energy required for space heating and total time with unacceptable thermal conditions (see, for example, Meier, Aragon, Peffer, Perry, & Pritoni, 2011; Peffer, Pritoni, Meier, Aragon, & Perry, 2011; Sachs et al., 2012). To compute energy-savings potentials, simple on/off control was used as the reference. In addition to individually assessing energy consumption and thermal comfort, we used an integrated analysis along both dimensions to illustrate the tradeoffs between different heating-control approaches.

3.2. Quantitative Statistical Analysis Based on Survey Data (Paper II, Paper III)

While Paper II tests the explanatory power of two different adoption models, Paper III aims to identify the key drivers of experiential technology adoption based on the most purposeful adoption theory (belief-based). To address the respective research questions, we used

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9 Some of the households were more prone to technical failure of the data logging devices than others. In some instances, this resulted in a lack of data covering a period of several days—a reason for us to exclude the data from the final sample.

10 Crawley et al. (2005), for example, provide an overview and discuss the features of 20 such tools.
quantitative statistical analysis to evaluate theoretical models with empirical data from online surveys.

In both Papers II and III, an extensive literature and theory review formed the foundation for the conceptual models (MacKenzie, Podsakoff, & Podsakoff, 2011). Subsequently, the same technology case (i.e. intelligent thermostats) was used to empirically test the interdependencies between specified latent variable constructs and the intention to adopt. The intelligent thermostat is a novel sustainable-energy technology that has only recently been commercialized. In addition, not only is it attractive for end-users from an energy-efficiency and thermal-comfort perspective (see Paper I), it also exhibits all the relevant characteristics of experiential technologies (digitalized everyday artifact, embeddedness in everyday life, automation of a vital everyday practice) as required for the research described in Paper III.

To collect data for empirical testing, we developed and extensively pre-tested and iteratively refined an online survey. The final survey was sent to several thousand participants in Germany and Switzerland respectively. To ensure only potential thermostat adopters were targeted, responses were only accepted from participants who indicated that they owned both a smartphone and their own heating system. We ultimately received 1,220 survey responses in Germany and 1,185 in Switzerland. Incomplete and disingenuous responses were eliminated, which led to final samples of N=1,101 (Germany only) in Paper II, and N=976 (Germany) plus N=971 (Switzerland) in Paper III.11

All specified models were analyzed and tested with structural equation modeling (SEM) conducted with the WarpPLS software (Version 4.0) from ScriptWarp Systems. SEM offers several advantages with respect to data requirements, is well-suited for theory building (Agarwal & Karahanna, 2000; Boudreau, Gefen, & Straub, 2001; Gefen, Straub, & Boudreau, 2000; Karahanna, Agarwal, & Angst, 2006; Limayem, Hirt, & Cheung, 2007) and has become a quasi-standard in marketing and management research (Hair, Ringle, & Sarstedt, 2011). It is particularly prominent in IS adoption and acceptance research, and has been used in similar, existing studies (see, for example, Venkatesh et al., 2003, 2012).

In the following, I will elaborate on the main methodological differences between Paper II and Paper III. Thereafter, I discuss the procedures for measurement and structural model evaluation as applied in both manuscripts in greater depth.

As discussed in Section 2.2, Paper II is essentially a pre-study to Paper III. While the methodology behind the analysis of the belief-based model is almost identical to the methodology used in Paper III, there are several key differences. First, in Paper II, only data

11 Paper II and Paper III apply slightly different methodologies to identify fraudulent responses.
from the German survey was used, and not the Swiss one—primarily because this data was available earlier and well suited for the comparison of objective, utility-based and subjective, belief-based models. Moreover, while the contribution of Paper III is situated in belief-based theory only, the empirical comparison between belief-based and utility-based theory (Paper II) required additional data. Consequently, objective household- and technology-related variables\textsuperscript{12} were included in the survey and collected.

Aside from these differences, the methodologies used in Paper II and Paper III to test the structural, belief-based models are the same. For the measurement of the latent variable constructs, we used existing and validated measurement items where possible. In the case of new measurement scales, we followed a multi-step approach as recommended by previous research (e.g. Bagozzi, Yi, & Phillips, 1991; Boudreau et al., 2001; Spector, 1992). This included pre-testing and iteratively refining and validating new measurement scales. In total we conducted four pre-tests with different respondents and collected several hundred responses before the final survey was launched. The final survey was administered by a market research firm who provided access to their online panels in Germany and Switzerland respectively. To make the sample more representative, we invited additional survey respondents as long as certain age and gender brackets were underrepresented in each of the two countries respectively. Subsequently, we screened the survey data for incomplete and disingenuous responses based on missing fields, unrealistic survey lead times, and lack of variance.\textsuperscript{13} In both papers, the final dataset was compared to national statistics to evaluate the representativeness of the sample.

To test the measurement model, we reviewed internal consistency, convergent validity, and discriminant validity. To check internal consistency reliability, we evaluated both composite reliability and Cronbach’s Alpha (Hess, McNab, & Basoglu, 2014; Raykov, 1997). We assessed convergent validity by means of item loadings and cross-loadings, and average variance extracted (Chin, 1998). To assess discriminant validity, we compared the square root of the average variance extracted to the inter-construct correlation (Fornell & Larcker, 1981). To check for common method bias, we followed the approach of Liang (2007) and compared the loadings of a (unmeasured) common method factor to the loadings of the original constructs and reviewed full collinearity variance inflation factors (Kock & Lynn, 2012). To test the structural model, we computed and compared standardized coefficients and $R^2$ values. In addition, we inspected correlation values for signs of multicollinearity and variance inflation.

\textsuperscript{12} Including: age, education, gender, income, number of people in the household, occupancy times, apartment size, building type, building age, time of latest renovation, estimated building efficiency class, heating cost.

\textsuperscript{13} In Paper III, only incomplete responses were eliminated.
factors. Lastly, we conducted effect-size tests according to the partial least square compatible procedure as outlined by Kock (2014) (Paper III only).

3.3. Qualitative, Inductive Case Study (Paper IV)

To shed light on the firm-internal decision-making dynamics affecting firm technology adoption, Paper IV employs an iterative, qualitative case study methodology. Qualitative case studies are particularly well suited to generating a rich description of organizational mechanisms (Eisenhardt & Graebner, 2007; Eisenhardt, 1989; Siggelkow, 2007). As is recommended for case-study approaches, we used strict theoretical sampling (Eisenhardt & Graebner, 2007). Seeking a set of firms in need of (more) exploration and governed by a board of directors, we ultimately investigated board activities at nine incumbent utility companies in Switzerland. The Swiss energy sector was particularly well suited for our analysis because it was undergoing substantial change at the time of writing. Traditionally, the sector had offered steady revenue streams guaranteed by regulation. Then, disruptive regulatory changes in combination with a dramatically harshening business environment put strong pressure on firms to explore. The prospect of a fully liberalized market obliged firms to differentiate for open competition. In addition, the phase-out of nuclear power and financial incentives for renewable electricity generation required firms to look for alternatives to conventional electricity generation, experiment with a broader set of new technologies and select some for adoption. As confirmed in our interview series, all firms in our final sample have indeed been shifting their focus from exploitation to exploration.

In total, we interviewed 33 directors and top-level executives across nine of Switzerland’s largest utility companies. Each in-person interview lasted between 65 and 130 minutes. This resulted in semi-structured interview data from two to four non-executive directors per firm and eight out of nine CEOs for the empirical analysis in Paper IV. To enhance reliability, all interviews were audio-recorded, transcribed, and stored in a central database (Gibbert et al., 2008; Yin, 2009). Furthermore, all interviews were analyzed and coded independently by three researchers. Construct validity was ensured by using triangulation based on multiple company-external and -internal data sources. Before conducting the interviews, we reviewed annual reports and other firm-related secondary data sources and extracted relevant information. We used the results of this company and board member document analysis to further specify the structured interview guides (Gibbert, Ruigrok, & Wicki, 2008). For each company in our sample, we also developed a timeline with key events related to exploratory activities and management and board personnel turnover. This served as additional guidance for the interviews and research-group internal discussion.
We ensured internal validity by reviewing, discussing, and analyzing rival explanations throughout the research process. Strict analytical generalization via abstraction from empirical observations contributed to external validity (Gibbert et al., 2008). We continued with our interviews until our conceptualization of firms’ exploration mechanisms reached theoretical saturation, i.e. additional interviews led to only marginal improvements of the theorized concepts (Eisenhardt, 1989).
4. Summary of Results

This chapter presents the main findings of this thesis’ papers. For the sake of clarity, only the most important results for each paper will be discussed. For a more detailed, empirically grounded description of the findings, the interested reader is referred to the original papers in Annex I. Implications of the results for the literature as well as for practitioners will be discussed separately in Chapter 5.

4.1. Paper I: Turning up the Heat on Obsolete Thermostats: A Review of Intelligent Control Approaches for Residential Heating Systems

The results of Paper I underline that the use of novel consumer technologies can significantly reduce energy consumption in buildings. Intelligent thermostats with automated setpoint variation have the potential not only to unlock existing efficiency potentials, but also to allow for adequate or even enhanced comfort. This confirms the technical viability of such technologies, and renders them a theoretically desirable consumer technology from a performance perspective.

Overall, Paper I identifies eight archetypical approaches to heating control. These include two standard controllers (i.e. on/off control; standalone PID\textsuperscript{14} control), two commonly used manual temperature setpoint variation approaches (i.e. nighttime temperature setback; programmable thermostats with multiple setback periods), and automated setpoint variation approaches currently undergoing commercialization (i.e. occupancy-state detection; occupancy-state prediction; occupancy-state detection with weather prediction; and occupancy-state prediction with weather prediction).

We found that intelligent heating-control approaches with automated setback functionality required less energy to heat the investigated test households than conventional approaches\textsuperscript{15}. Figure 2 summarizes the results among the 10 test households included in our sample. Although there is a spread between the individual test households (as expected), a clear tendency is observable. While PID controllers reduce temperature overshoot and are primarily a means of more effective temperature control, approaches with manually programmed setback periods (nighttime alone, or daytime and nighttime) enable energy savings of up to approximately 20%. More intelligent control approaches, which automatically adjust setback times based on occupant behavior, however, enable savings in the 25% range, with peak savings of over 30%. Occupancy-state detection enables higher energy savings compared to

\textsuperscript{14} Proportional, integral, derivative.

\textsuperscript{15} On/off controller, standalone PID, nighttime temperature setback, programmable thermostats.
occupancy-state prediction, because homes are not preheated prior to arrival. In addition, weather prediction enables additional energy savings by exploiting opportunities to reduce heater output when periods of high solar irradiation are expected.

![Figure 2: Energy savings of control approaches when compared to on/off control (reduction in percent)]

Nonetheless, the performance of heating-control approaches is not just a function of energy savings. From an adopter perspective, thermal comfort is equally important, if not more so (Meier et al., 2011; Peffer et al., 2011; Sachs et al., 2012).

The results of Paper I reveal that intelligent, automated setpoint variation control approaches outperform traditional, manual setpoint variation approaches in terms of comfort. Figure 3 illustrates the number of hours of below-acceptable thermal conditions for occupants (i.e. discomfort) over a period of one year. Unsurprisingly, control approaches without setback functionality have high comfort levels as, by definition, they aim to maintain a constant temperature level (unless the setpoint temperature is manually adjusted).

With manual setpoint variation, comfort levels depend largely on users’ ability to predict their actual behavior accurately. In line with previous studies (Peffer et al., 2011; Sachs et al., 2012), most people do not program their thermostat setback times particularly well, which explains the high median discomfort times of almost 200 hours p.a. with programmable thermostats. Automated setback approaches perform significantly better, although occupancy detection suffers from thermal lag in the heating system—a shortcoming addressed by occupancy prediction, which allows the system to begin preheating the home before occupants arrive.
Because weather prediction always results in a reduction of heater output, potentially higher energy savings come at the cost of reduced comfort in this case.

4.2. Paper II: Utility- Versus Belief-Based Models: Shedding Light on the Adoption of Novel Green Technologies

Paper II looks at the drivers of individual technology adoption in order to better understand the influence of individual behavior on diffusion. It compares two fundamentally different theoretical approaches to identify the key determinants of adoption as used in previous studies.

The results of Paper II show that the explanatory power of the belief-based models (M2.1, M2.2) is clearly superior to that of utility-based models (M1.1, M1.2). Table 3 summarizes our findings and depicts overall explanatory power (R²), standardized coefficients per determinants, and significance levels for two model variants per theoretical approaches respectively (M1.1, M1.2; M2.1, M2.2).

A total of four model variants were specified, because our literature review revealed that a) previous studies had selectively integrated constructs from the belief-based approach in their utility-based assessments and b) evidence for the importance of environmental norms was contradictory. The variants designated (with references to Table 3) were:

- M1.2. Utility-based approach, including objective measures only
• M1.2 Utility-based approach, including selected belief-based constructs (price value and environmental norms)
• M2.1 Belief-based approach, including beliefs about technology characteristics only
• M2.2 Belief-based approach, including beliefs about technology characteristics and personal characteristics

Table 3: Determinants of the intention to adopt intelligent heating-control devices

<table>
<thead>
<tr>
<th>DV: Behavioral intention to adopt</th>
<th>M1.1</th>
<th>M1.2</th>
<th>M2.1</th>
<th>M2.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>R²</td>
<td>0.060</td>
<td>0.333</td>
<td>0.656</td>
<td>0.675</td>
</tr>
<tr>
<td>Adjusted R²</td>
<td>0.056</td>
<td>0.337</td>
<td>0.654</td>
<td>0.672</td>
</tr>
<tr>
<td>N</td>
<td>1,101</td>
<td>1,101</td>
<td>1,101</td>
<td>1,101</td>
</tr>
</tbody>
</table>

Coefficient (β)

Objective household and technology measures

- Income (INC) 0.106*** 0.078*
- Age -0.110*** -0.075*
- Gender 0.071* 0.106***
- Education (EDU) 0.074* 0.040
- Technical saving potential (TS) 0.138*** 0.111***

Beliefs about technology characteristics

- Price value (PV) 0.403*** 0.007 -0.008
- Usefulness (US) 0.206*** 0.196***
- Hedonic motivation (HM) 0.320*** 0.300***
- Social influence (SI) 0.094*** 0.073*
- Facilitating conditions (FC) 0.175*** 0.154***
- Habit (HA) 0.194*** 0.174***
- Ease of use (EU) 0.024 0.007

Beliefs about personal characteristics

- Environmental norms (EN) 0.234*** 0.061*
- Innovativeness (IN) 0.117***

***p<0.001; **p<0.01; *p<0.05

Both utility-based models (M1.1, M1.2) convey significant influence of the theorized adoption determinants. Whereas in the case of M1.1, technical saving potential, age, and income appear to drive technology adoption, price value and environmental norms seem to have the highest influence on technology adoption when these selected beliefs are considered too (M1.2). Moreover, according to the results of our study, selectively including belief-based determinants enhances the variance explained by the model (adjusted R² of .33 versus .06).

However, when we test a comprehensive set of relevant beliefs as theorized in previous IS consumer adoption research (see, for example, Venkatesh et al., 2012) in M2.1, the
explanatory power of the model improves drastically ($R^2 .65$). In addition, some of the influencing factors that are significant and relevant when included in isolation turn insignificant. While in M2.1 hedonic motivation and usefulness (i.e. expected technology performance) appear to have the strongest influence on technology adoption, price value shows no influence. Similarly, when environmental norms are included in a more comprehensive belief-based adoption model, their influence also appears to be negligible. This exemplifies the effects and danger of omitted-variable bias, and illustrates how it can result in a misleading focus on adoption determinants that are ultimately of only minor importance.

According to the results of measurement and the structural model, and the comparison with the utility-based model variants, a comprehensively specified consumer adoption model situated within existing theory (e.g. M2.2) is best suited to identify key drivers of technology adoption. Perceived fun (i.e. hedonic motivation) as well as perceived usefulness (i.e. technology performance) are the two most influential determinants in both belief-based model variants (M2.1, M2.2). In contrast, both price value and environmental norms are of little or no importance.

### 4.3. Paper III: Subtle Servants: The Importance of Everyday Practices for Experiential Consumer Technology Adoption

The goal of Paper III was to shed light on the determinants of individual technology adoption. In particular, we aimed to extend existing, belief-based adoption theory by focusing on the peculiarities of experiential consumer technologies.

The results of Paper III, as depicted in Table 4, show that compatibility with everyday practices is the most influential driver of experiential technology adoption. According to traditional consumer adoption theory, habit, utilitarian aspects (usefulness), as well as hedonic motivation explain most variance in the intention to adopt (Venkatesh et al., 2012). In our study, however, the adoption of experiential consumer technologies is strongly affected by how seamlessly they can be integrated into adopters’ lives. Concerns such as the fit with the user’s current situation, daily routines, everyday practices, and lifestyle have become much more important for early adopters than mere utilitarian motives.

Overall, our entire, newly theorized adoption model is largely supported. The variance explained by the model is remarkably high in both studies (Study 1: .72, Study 2: .63).\textsuperscript{16} Moreover, with the exception of price value and risk, all latent variable constructs are significant. In combination with the robust statistics from the measurement model evaluation,

\textsuperscript{16} Study 1: survey data collected in Germany; Study 2: survey data collected in Switzerland; see also Section 3.2.
this indicates that the theorized and specified links between the latent variable constructs and intention to adopt novel experiential technologies are indeed influential.

Table 4: Determinants of the intention to adopt experiential technologies

<table>
<thead>
<tr>
<th>DV: Behavioral intention to adopt</th>
<th>Study 1</th>
<th>Study 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>R²</td>
<td>0.721</td>
<td>0.632</td>
</tr>
<tr>
<td>Adjusted R²</td>
<td>0.719</td>
<td>0.629</td>
</tr>
<tr>
<td>N</td>
<td>976</td>
<td>971</td>
</tr>
<tr>
<td>Compatibility with everyday practices (CO)</td>
<td>0.291***</td>
<td>0.330***</td>
</tr>
<tr>
<td>Technical compatibility (TC)</td>
<td>0.130***</td>
<td>0.102***</td>
</tr>
<tr>
<td>Risk (RI)</td>
<td>-0.058*</td>
<td>-0.033</td>
</tr>
<tr>
<td>Usefulness (US)</td>
<td>0.105***</td>
<td>0.162***</td>
</tr>
<tr>
<td>Ease of use (EU)</td>
<td>0.059*</td>
<td>0.026</td>
</tr>
<tr>
<td>Price value (PV)</td>
<td>0.043</td>
<td>0.064*</td>
</tr>
<tr>
<td>Hedonic motivation (HM)</td>
<td>0.281***</td>
<td>0.218***</td>
</tr>
<tr>
<td>Innovativeness (INV)</td>
<td>0.177***</td>
<td>0.152***</td>
</tr>
</tbody>
</table>

Notes: ***p < 0.001; **p < 0.01; *p < 0.05

The direct link between two of the constructs theorized to be characteristic for experiential technologies (compatibility with everyday practices, technical compatibility) shows particularly strong influence. Only risk, the third experiential-specific latent variable construct, shows low influence and significance. In this respect, two out of three hypotheses derived in the theoretical discourse of Paper III can be confirmed (see also Section 2.3):

- H1: Perceived compatibility with everyday practices positively influences the intention to adopt experiential consumer technologies (confirmed)
- H2: Perceived technical compatibility positively influences the intention to adopt experiential consumer technologies (confirmed)
- H3: Perceived risk negatively influences the intention to adopt experiential consumer technologies (not confirmed)

Finally, testing for innovativeness as an important personal belief, the results of Paper III endorse its relevance in the process of early-stage, sustainable consumer technology adoption. This confirms the findings from Paper II, and is in line with previous research (Agarwal & Prasad, 1998; Limayem, Khalifa, & Frini, 2000).
4.4. **Paper IV: Learning to Learn—How Boards of Directors Affect Organizational Exploration**

The objective of Paper IV was to shed light on firm technology adoption mechanisms. Situated in this context, the manuscript illustrates how a firm’s board of directors influences the decision to explore (i.e. adopt) novel sustainable energy technologies. Showing that the commitment to explore novel technologies depends not least on board-internal learning capabilities, Paper IV also highlights that non-executive directors (i.e. board members) can either spur on novel technology adoption or generate inertia. They are one of the numerous yet easily neglected factors moderating the link between technology characteristics and diffusion.

Figure 4 shows the theoretical framework developed in this project. It illustrates as-yet undertheorized interrelations between board influencing mechanisms, management activities, and organizational exploration, and constitutes the core contribution of Paper IV.

First, we found that the shift toward organizational exploration (i.e. adoption) can originate from either management or the board (or both) (1). Moreover, the board engages in fundamentally different activities depending on which body is driving exploration (2). Whenever the board itself initiates the organization’s exploration shift, we find that it primarily relies on instruments
such as service and coaching, giving direct orders to management, or eventually hiring and firing management personnel. Since these board activities aim to increase the number and breadth of management motions, we categorized them as *variety creation* (2a). Whenever management pushes for more exploration, however, the board primarily engages in controlling (i.e. monitoring) and challenging management motions. Since these board activities are aimed at limiting the breadth and scope of management exploration, we subsumed them under *selection* (2b).

Irrespective of which mode a board operates in, we noticed that its capability to judge strategic issues is a fundamental prerequisite for the effective deployment of any of its instruments (3). Only if the board has the capability to make an informed decision (e.g. independently evaluate a strategic topic based on available expertise and thereafter convey a conclusion) can it gauge the degree of management exploration effectively (4). Therefore, board capabilities are key to the organization striking a balance between exploitation and exploration.

Nonetheless, we also find that a shift in this balance affects board capabilities in turn. Whenever a board effectively induces more organizational exploration, this affects the degree of management exploration, as executives are the agents of choice ultimately responsible for execution. As a result, executives who internalize their board’s desire for more exploration and consequently take the lead in exploratory search may then confront the board with new proposals beyond its comfort zone. This adverse interrelation is reinforced by the immanent time and information asymmetry between board and management. A full-time dedicated management team is usually more exposed to, and in possession of, more relevant information than mostly part-time board members. Or, as one chairman put it: the executives are the full-time experts who can’t decide, while the (non-executive) directors are the part-time amateurs who must—ergo, they are doomed to collaborate.

The way to resolve the issue of an increasingly exploratory management generating proposals beyond the board’s comfort zone—without holding back the impetus to explore—is to enhance the board’s capabilities to judge strategic issues. Thus, in times of exploration, boards need to continuously adjust their capabilities by engaging in board learning. This is particularly relevant insofar as there is no organized, hierarchically superior governance body that could stimulate or supervise boards’ learning. In principle, owners (i.e. shareholders) should have ultimate control over their firm; in reality, however, this is difficult to implement. Our interviews confirmed that due to distributed ownership structures and a lack of institutionalized means through which owners could influence firm strategies, owners seldom contribute to organizational learning in a systematic way. Thus, whether board learning takes place is strongly dependent on the presence of a set of higher-order board learning capabilities (5).
We identify and specify four such higher-order learning capabilities: self-evaluation, adaption of board composition, education of board members, and adjustment of decision-making. Self-evaluation refers to the capability to continuously self-assess the strengths and weaknesses of the board as a committee and to take action accordingly (e.g. systematic collection of feedback). Adaption of composition refers to the capability to recognize the need to continuously reconfigure the board’s personnel, and take action (e.g. recruit additional experts to the board). Education of board members refers to the capability to continuously address board knowledge gaps as they manifest over time (e.g. institutionalize debates with external experts). Adjustment of decision-making refers to the capability to continuously adapt board processes enabling effective decision-making as required by the environment (e.g. implement a process for selecting priority topics for the board).

Interestingly, while all interviewees generally agreed that these higher-order board learning capabilities are crucial, the degree to which they were present within a particular firm varied widely. In some cases, we could even observe resistance against measures intended to develop them. Therefore, our research illustrates not only that boards have a major influence on organizational learning, but also that boards differ in the extent to which they themselves are able to learn as part of this process. While identifying the antecedents of this is beyond the scope of this thesis, we point to an important issue in the context of technology adoption: boards as a potential source of exploration inertia.
5. Conclusions

The objective of this thesis is to investigate factors influencing the adoption and diffusion of novel sustainable-energy technology. In this, it focuses on a) technology performance, b) individual technology adoption, and c) firm technology adoption. This chapter synthesizes the most important contributions this work makes to the literature. Based on this, implications for practitioners are discussed, and the thesis concludes by pointing to promising avenues for future research.

5.1. Contributions to the Literature

In view of the heterogeneity of theories that this thesis draws from and contributes to, this chapter is structured along the main literature streams of the individual papers I–IV.

5.1.1. Contribution to the Literature on Building and Environmental Technologies

First, the results from our sample of 10 test households in Germany reveal energy-saving potentials in the median range of 25% when compared to simple on/off heating control. To the best of our knowledge, Paper I is the first of its kind to actually quantify the savings potential of different heating-control approaches. Consequently, our results support the as-yet empirically unauthenticated assumption that demand-side heating control in residential buildings can help to unlock significant energy-efficiency potentials.

Second, the results of Paper I show that programmable thermostats, a widely diffused technology, suffer from users’ inaccurate estimates of their own behavior. This is in line with previous research on the use of setback thermostats; however, their performance has not been compared and quantified against several other heating-control approaches. Fortunately, the digitalization and automation of everyday heating-control processes allows us to circumvent the difficulties associated with individual behavior and behavioral change (e.g. manual programming of thermostats), as shown by this research.

Lastly, we illustrate that savings potential is particularly high in old buildings. This provides guidance for further home-automation engineering efforts, and points to the attractiveness of automated heating as a way to mitigate carbon emissions in existing building stock. In Germany, for example, 69% of existing building stock was constructed before 1977 (Statistisches Bundesamt, 2010). At the same time, the country’s residential sector is responsible for 28% of the nation’s final energy consumption (Arbeitsgemeinschaft Energiebilanzen e.V., 2011).
5.1.2. Contributions to the Literature on (Sustainable) Technology Adoption

First, this thesis contributes to the extant literature on sustainable technology adoption by showing that belief-based approaches are better suited to identifying and explaining relevant adoption determinants. Based on our results, subjective belief-based models have significantly higher explanatory power compared to those based on utility that have so far been deployed.

Second, we point to the risk of omitted-variable bias, in particular when belief-based constructs are selectively included in utility-based assessments. Although such practice is common in existing studies, it can result in a misleading focus on determinants that have only small, potentially insignificant influence.

Third, by taking steps to combat omitted-variable bias, we were able to show that in early-stage diffusion of novel energy technologies, personal innovativeness is far more important than environmental norms. Environmental norms showed significant influence in previous studies when integrated in isolation. However, they show no significant effect on the behavioral intention to adopt novel consumer technologies in a comprehensive model consisting of constructs deemed relevant in previous belief-based theory. With this finding, we hope to ease some of the controversy about the relevance of environmental norms for individual consumer technology adoption.

Fourth, we show that a new set of experiential-specific latent constructs is crucial to the behavioral intention to adopt experiential consumer technologies. In particular, compatibility with everyday practices, a construct capturing the peculiar notion of the embeddedness of technology in everyday life (Yoo, 2010), has become the most influential single adoption determinant, even though it was largely neglected in previous adoption theory. On the one hand, this represents a valuable contribution for future adoption research in itself. On the other hand, it shows that that as technology progresses, the relevance of adoption determinants—despite being considered a rather mature field of research—changes too. The subject of technology adoption is perennially in flux.

Fifth, recognizing the above, we propose a decomposition of the previously theorized latent variable construct facilitating conditions. Based on the results of our study, technical compatibility is an important determinant of adoption in itself, and should not be subsumed in a multi-dimensional latent variable construct with rather heterogeneous measurement items.

Lastly, we can confirm the importance of latent variable constructs previously deemed relevant in the context of early-stage consumer technology adoption. In particular, we reconfirm the increased relevance of hedonic motivation compared to perceived usefulness. However,
based on our empirical assessment, the explanatory power of *usefulness*, *ease of use*, and *price value* has receded, at least in the case of experiential technologies.

### 5.1.3. Contributions to the Organizational Learning and Corporate Governance Literature

First, we contribute to the organizational learning literature by detailing the activities of an important, yet often overlooked organizational layer: the board of directors. In doing so, we show that a lack of learning capabilities at board level can lead to organizational inertia. Firms’ failure to explore novel technology is a frequently discussed subject in management research. However, we conceptualize in detail how boards influence firm exploration strategy, rather than taking the detached perspective of an outsider, in Paper IV.

Second, we point to the importance of the origin of the impulse for firm exploration. Whenever management initiates firm exploration, the mechanisms that subsequently unfold differ substantially from the dynamics triggered by board-driven exploration. In the former case, the board engages in *selection*, i.e. focusing on challenging and controlling management motions. In the latter, the board engages in *variety creation*, i.e. in service and coaching to provide management with information and stimulate management initiatives.

Third, we link previously identified board roles and activities to firm-internal organizational learning processes, and ultimately to firm exploration. The monitoring and control role, for example, which has dominated board research for decades, is important for reducing the degree of management exploration. The service and strategy role, as discussed by Zahra & Pearce (1989), is important for raising the degree of management exploration. In addition, we identified and specified a set of archetypical board activities that operate on a firm’s exploration-exploration balance: challenging and controlling, service and coaching, commanding, and hiring and firing. While these relate well to the board roles discussed before, their conceptualization substantiates our understanding and provides a frame for the further evaluation of board behavior.

Fourth, we show the importance of the board’s higher-order learning capabilities for a firm’s exploitation-exploration orientation. Our findings indicate that when managers are more strongly oriented towards exploration relative to the board, the board is confronted with proposals outside its comfort zone. In such cases, the interplay between board (decision-making) and management (execution) can be disrupted, and consequently organizational exploration is inhibited. Building on our results, these higher-order capabilities might be important for explaining why companies fail to react adequately to environmental discontinuities that go hand in hand with the pressing need for organizational exploration. While
previous research has found that it is primarily external change that destroys competences, our findings offer an example of internal change with competence-destroying consequences.

Lastly, we identify and specify the above-described higher-order learning capabilities. Based on the behavior of the firms in our sample, the capacity for self-evaluation, adaption of composition, board-member learning, and adjustment of decision-making are prerequisites for novel technology exploration from a corporate governance perspective. Conceptualizing the key capabilities that enable boards to support strategic shifts from exploitation to exploration, instead of blocking them, provides future research with testable constructs that were not previously available.

5.2. Implications for Practitioners

Starting with managerial implications, I will first outline selected implications for organizations facing novel technology adoption for firm-internal use. This includes, for example, incumbent utility firms that are required to switch from conventional, carbon-intense electricity generation to renewables. Thereafter, I will address implications for organizations that want to develop or commercialize novel technologies. Then, focusing on implications for policymakers, I will first discuss our findings from a pure technology-performance perspective, before elaborating on policy implications related to individual and, finally, firm technology adoption.

5.2.1. Managerial Implications

Firms facing novel technology adoption

The results of this thesis highlight the peculiarities of traditional governance mechanisms, and some major shortcomings too. As outlined in Paper IV, in a board-governed firm, management will only be able to shift a firm’s strategic orientation from exploitation to exploration if they can overcome any resistance from the board. Such resistance is likely, even when the exploration was recommended by the board itself. These insights help shareholders and managers to better understand the drivers of and how to react to such resistance. Learning at the board level has to accompany reorientation, and is an important prerequisite for effectively redefining and subsequently implementing exploration strategies.

Firms developing or commercializing novel technology

Our findings point to the importance of understanding potential adopter behavior for early-stage diffusion. The importance of compatibility with everyday practices, as discussed in Paper III, implies that firms need to truly understand the everyday practices of potential future (and existing) customers. This is not just relevant for marketing of the final product; it should be considered even at the early stages of technology conceptualization and design.
In addition, we find that price value is less important for novel experiential technology adoption than compatibility with everyday practices or hedonic motivation. Consequently, skimming (i.e. charging a higher price point and focusing on other important beliefs) when introducing novel experiential technology (with inelastic demand) is advisable—as opposed to focusing on the marketing of attractive price value. In particular, when firms can obtain information about their existing and future customer base (“big data”), they may find it worthwhile to invest in dedicated identification of relevant beliefs, then tailor their marketing accordingly.

5.2.2. Implications for Policymakers

Technology performance
This thesis provides policymakers with empirical results on the performance of intelligent heating-control approaches. This adds to the debate about effective technological pathways to reduce the energy consumption of residential buildings. We show that, theoretically, intelligent heating-control technologies do bear potentials for carbon-emission reduction, although these have not been directly considered in national or regional efficiency directives to date (to the best of our knowledge).

Individual technology adoption
The results of this thesis suggest, amongst other things, that it would be worthwhile critically reviewing traditional policy instruments that aim at improving and/or promoting price value (e.g. subsidies) and utility-focused technology characteristics (e.g. information campaigns). Instead of relying on these traditional measures, policy design should acknowledge the beliefs important in early-stage consumer technology diffusion: compatibility with everyday practices, hedonic motivation, usefulness, and technical compatibility. In contrast, price value, ease of use, and environmental norms are of little importance. In this respect, it is advisable to support activities that ensure that novel energy technologies suit the everyday practices of potential adopters, and that adopters recognize this during the adoption decision-making process. It might be more effective to support firms that have the intrinsic motivation to offer future customers a product that serves their needs and is “fun” to use (and also have the knowledge and capacity to do so), rather than providing financial support directly to end-customers to improve their perception of price value. However, we must also bear in mind that as diffusion unfolds beyond innovators and early adopters, the relative importance of adoption determinants might also change.

Firm adoption
Our results highlight that incentivizing firms to adopt and use novel technologies should not overlook the complex interplay of firm-internal decision-making. Addressing firms’ managers in isolation might not be sufficient. We raise the discussion point that it might be viable to
develop policy instruments that encourage boards of directors to spur technology diffusion, alongside direct technology policies such as feed-in tariffs. In any case, guidelines that inhibit board learning—such as the restrictions on board composition that are often present in publicly owned firms, and which are difficult to abrogate—need to be recognized as potential barriers to firm exploration.

5.3. Future Research

Taking a similar line to the previous section, I will point to promising areas for further research along the three core themes of this thesis: technology performance, individual technology adoption, and firm adoption.

Technology performance
Testing the performance of intelligent thermostats and other energy-relevant smart-home technologies with a larger sample certainly constitutes a valuable extension of our simulation-supported quantification approach. In addition, testing the performance of intelligent thermostats in different geographical regions with different weather situations is required to draw meaningful conclusions on large-scale efficiency potential in other industrialized nations. Both avenues would eventually enhance the generalizability of our findings.

Moreover, a detailed economic assessment of smart home technologies across a range of different use cases and households would prove beneficial for targeted marketing as well as effective policymaking. Similarly, computing nationwide potentials and assessment of overall impact on CO₂ emissions would help to put economic considerations into an overall carbon-abatement cost perspective.

Individual technology adoption
In the conceptualization of the adoption model for experiential technology adoption described in Paper III, we intentionally refrained from integrating moderating variables. Some of the literature has described moderators as an essential element of adoption theory, but most studies lack theoretically motivated development and subsequent rigorous testing of moderators. Furthermore, integrating moderators at an early stage of theory development has been described as “unwieldy and conceptually impoverished” (Bagozzi, 2007: 244). Numerous existing studies selectively focus on the most obvious and easy-to-measure factors, such as age, gender, or income. Notwithstanding these challenges, the proper, theoretically grounded integration of moderators into the conceptual model would certainly be a valuable step now that direct effects have been understood more thoroughly.

Additionally, our findings could be strengthened by measuring the intention to adopt and independent latent variable constructs with two different methods and/or at two different points
in time, instead of relying on post-data collection common method bias assessment. Although the techniques we deployed are widely accepted, excluding common method bias by separately collecting data on independent and dependent variables respectively is the least controversial approach.

Moreover, we do not specifically address the fact that the relevance of belief-based adoption determinants can change over time as potential adopters approach the actual point of purchase (i.e. bounded rationality). Consequently, an intriguing area for further inquiry would be to consider adoption as a multi-step process, and explore how the explanatory power of the key determinants of adoption changes over time.

Finally, the investigation of experiential technologies with a different price point and a different risk potential (than intelligent thermostats) also merits further attention. This could be beneficial to better understand how relevant technology context is. Given the rather low influence of risk on adoption in our study, decomposing risk into its key facets, as conducted in previous literature, could be fruitful.

**Firm exploration**

To confirm and extend our findings on board influencing mechanisms, the influence of non-executive directors should be investigated in other industries and countries. The competencies and assumed responsibilities of boards differ subtly between nations, and this could well affect the roles, activities, and interaction mechanisms we observed.

In addition, investigating the antecedents of management- and board-driven exploration respectively would complement our investigation of subsequent dynamics. So far, the drivers of board- versus management-driven exploration remain unknown. Similarly, the influence of potentially relevant factors such as ownership structure and company history on a firm’s desire for exploitation/exploration might contribute to further advancement of organizational learning.

Lastly, the empirical testing of our theoretical findings is a logical next step. One could, for example, empirically test whether board-driven exploration leads to variety creation and, as a result, to higher turnover in management personnel. Alternatively, the presence of second-order capabilities across firms and their influence on performance could be tested. With our conceptual framework, we provide a rich assemblage of (quantitatively) testable constructs.
6. Overview of the Papers

The four papers included in Annex I are shown in Table 5, which lists the target journal and the current status in the review process. The submission status of the papers is as of April 7th, 2014.

Table 5: Overview of the papers included in this dissertation

<table>
<thead>
<tr>
<th>Paper</th>
<th>Title</th>
<th>Authors</th>
<th>Journal</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>II</td>
<td>Utility- Versus Belief-Based Models: Shedding Light on the Adoption of Novel Green Technologies</td>
<td>Girod, B. Mayer, S. Naegele, F.</td>
<td>Ecological Economics</td>
<td>Submitted</td>
</tr>
<tr>
<td>IV</td>
<td>Learning to Learn—How Boards of Directors Affect Organizational Exploration</td>
<td>Naegele, F. Hoppmann, J. Girod, B.</td>
<td>Organization Science</td>
<td>Working paper</td>
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</tbody>
</table>
7. References


## Annex I: Papers

<table>
<thead>
<tr>
<th>Paper</th>
<th>Title</th>
<th>Authors</th>
<th>Target journal</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>Turning up the Heat on Obsolete Thermostats: a Review of the Performance of Intelligent Control Approaches for Residential Heating Systems</td>
<td>Naegele, F.&lt;br&gt;Kasper, T.&lt;br&gt;Girod, B.</td>
<td>Renewable and Sustainable Energy Reviews</td>
</tr>
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</table>
Turning up the Heat on Obsolete Thermostats: a Review of Intelligent Control Approaches for Residential Heating Systems

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Abstract

This article provides an overview and quantitative evaluation of the performance of heating-control approaches for residential buildings. First, heating-control technologies discussed in the extant literature are reviewed and conceptualized in a taxonomy of eight archetypal control approaches. Subsequently, the performance of each heating-control approach is evaluated in terms of energy consumption and comfort for occupants. For this evaluation, data on in-room temperature, heating behavior and occupancy patterns of households in Southern Germany was collected over a 14-month period. Integrating this data into a building simulation, the performance of each control approach was evaluated on a per household basis. Based on this evaluation, we find that automated setpoint variation (i.e. intelligent) control approaches outperform manual setpoint variation control approaches such as programmable thermostats. Compared to simple on-off control without temperature setpoint variation, we find median energy savings potentials in the range of 21% to 26% and observe higher thermal comfort compared to programmable thermostats. Our findings show the theoretical efficiency improvement potential of intelligent heating control, in particular for old buildings and households with high vacancy times. Because of the comparatively low initial investment and high energy savings potential, the results suggest that policy should extend its focus from retrofitting heating systems and building insulation toward more efficient energy use enabled by intelligent control.

Keywords

Residential buildings; heating control; energy efficiency; thermostat; HVAC; control; thermal comfort
1. Introduction

Countries exposed to temperate climate conditions such as Germany and Switzerland use close to 75% of total final energy consumption in buildings for space heating alone [1,2]. On a transnational level, the IEA estimates that, on average, 53% of household final energy consumption can be attributed to space heating [3,4].1 Based on such figures, there is growing consensus that a significant amount of CO₂ emissions can be avoided by introducing more efficient ways of providing and maintaining thermal comfort [5,6]. As a result, coordinated CO₂ emissions reduction efforts have asked for, and started to specifically address, measures to increase space heating efficiency in residential buildings [7–10].

Yet, climate mitigation targets cannot be met with new building designs, improved insulation or advanced heating system technologies alone [7,11]. Such changes to building stock are subject to long renovation cycles [12]. Space heating systems, for example, with refurbishment rates below 3.5% p.a. for Germany [13], are known to be installed and remain largely untouched for decades. Because of this inertia, intelligent heating-control approaches are of particular importance. Compared to the entire heating system installation, electronic heating-control devices are relatively inexpensive and can be installed and replaced more easily. Hence, technologies that accurately reduce heater output during times with lower thermal demand (i.e. times of absence or at night) bear the potential to retrospectively upgrade existing homes (i.e. heating systems) and might serve as an economic complement or alternative to traditional retrofitting.

It must not be forgotten, however, that end-user comfort is also crucial for acceptance and use of heating-control technologies or features [14,15]. Existing technologies frequently struggle to reduce energy consumption and provide acceptable thermal comfort at the same time [16–18]. This trade-off is more or less effectively addressed by various heating-control approaches and has frequently been discussed [16,18–26]. Recently, technological advancements in pervasive computing and real-time information integration have facilitated the development of alternative means of heating control (e.g. automatic prediction of times during which buildings are occupied or empty) [15,24,27,28]. Understanding the improvement of these advanced control approaches requires a comparison with previous approaches that are still widely used. Despite its relevance for climate mitigation, a systematic review and comprehensive comparison of heating-control approaches for residential buildings is missing.

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1 Estimate is based on data from 19 IEA member countries, not including Belgium, Greece and Portugal—for a detailed description of the IEA19 countries, please refer to Annex A in [3].
In this paper, we provide an overview of existing and, subsequently, evaluate the respective performance of (intelligent) heating-control approaches for residential buildings. For the latter, we calculate net energy required for in-door heating, as well as hours with unacceptable thermal conditions for occupants (i.e. thermal comfort). This quantitative performance comparison builds on extensive longitudinal empirical data on the thermal performance and behavior of ten households. Sensors were placed inside buildings over a period of 14 months, allowing us to log data on actual in-room temperatures and the status of the heating system, as well as occupant’s behavior.

The remainder of this paper is structured as follows. In Section 2, we review the technological evolution of residential heating control discussed in the literature and introduce a taxonomy of archetypical control approaches. Building on this conceptualization, we conduct an empirically anchored, simulation-based performance comparison whose corresponding method is described in Section 3. In Section 4, we present the results of the quantitative performance analysis and illustrate the trade-off between energy efficiency and comfort. We discuss the results of our investigation in Section 5 before summarizing our main conclusions in Section 6.

2. Review of heating-control approaches described in the extant literature

This review is structured according to three core functionalities of residential heating control that have evolved over time: reaching and maintaining a pre-defined temperature setpoint (Section 2.1), shifting setpoints during times when lower temperature levels are reasonable (Section 2.2) and incorporating control-loop external influences (Section 2.3). Reaching and maintaining a pre-defined temperature setpoint has been an immanent objective of heating control and can be deployed as a standalone function. The other two functionalities are features built on top of a setpoint controller. In the following, we focus on advantages and disadvantages of the technologies and conclude with a conceptualization of archetypical control approaches (Section 2.4).

2.1. Standalone temperature setpoint controller

A very basic form of heating control is often realized with a two-position or on/off controller (i.e. bang-bang [29] or hysteresis control [30,31]). These devices are able to provide binary output signals only—the burner or valve of a heating system is either switched off or set to maximum output. As a disadvantage, the system typically overshoots and undershoots a fixed target temperature setpoint within a “dead band” [32,33]. Although not suited to attain truly constant temperature, these controller types have been used extensively over the past decades [22].
Their simple design and favorable cost characteristics have led to adoption in residential applications (e.g. simple wall thermostats, thermostatic radiator valves) and industrial applications [34]. Due to their long history and the simple design, on/off technologies are widely accepted as mature technologies and novel research specifically targeting on/off controllers in space heating, ventilation and cooling applications (HVAC) is sparse [32].

A more advanced method of standalone heating control incorporates the technological evolution from discontinuous (on/off) to continuous, or modulating, control using so-called proportional-integral-derivative controllers (PID-controller). This controller type includes an advanced control-loop feedback mechanism intending to minimize temperature undershoot, overshoot, rise time, settling time and steady-state error [35,36]. However, effective design and tuning of PID controllers is not always trivial and can be a laborious and expensive task. Inadequate selection of the parameters in the PID controller can result in system instability [37]. Nonetheless, PID algorithms are widely used for residential temperature control [38] today and are considered “simple yet sufficient for most HVAC applications” [39].

On the one hand, not engaging in any kind of setpoint variation, i.e. using standalone on/off and PID controllers, provides (relatively) constant temperature levels without interruption. Unexpected drops in temperature, caused by improper controller-induced temperature setpoint variation, are not a concern in this case. On the other hand, most users do not demand the same comfort temperature at all times; for example, when absent or at night. Hence, standalone setpoint control disregards the potential of intermittent heating control and, consequently, energy consumption is potentially higher than necessary.

2.2. Temperature setpoint variation features

As a response to inefficient constant temperature levels, slightly more advanced heating-control approaches make use of manually defined temperature schedules (i.e. manual setpoint variation) on top of mere standalone setpoint control. Assuming effective, time-invariant setpoint temperature control (i.e. a robust controller), setpoint variation is the key measure to realize higher levels of energy efficiency [23]. Clock-based nighttime temperature setback was a first step in the evolution toward intermittent heating control. Technological developments, increasing commodity prices and policy further motivated research on temperature setpoint variation and clock-based setback thermostats became commercially available [14,19]. Although not fully realizing the potential of intermittent heating, nighttime setback functionality can be found even in today’s building environment as a common basic feature in heating-control devices [see for example 14,19,40].

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2 The interested reader may refer to [98] for an historical overview of the development of PID controllers.
Advancement of electrical components, and in particular the development of memory and microprocessors, then led to commercialization of *programmable thermostats* (PT), which allow more than one setback temperature and a variety of sophisticated means of programming personal schedules. A combination of government intervention [19] and end-users’ desire to increase comfort as well as reduce energy consumption and operating cost [20,25] led to their adoption. However, only approximately 30% of U.S. households have PT actually installed [19] and several studies question the actual effectiveness of PT [25,26]. According to Meier et al. [17], over 30% of the households equipped with programmable thermostats are not setting up any programs. In addition, over 89% never used a weekday or weekend program. Inability to set up programs properly [41], inaccurate, and rather comfort oriented, scheduling habits and disabling of program features or manual override [14,17,19] are among the challenges associated with today’s PT. Empirical studies indicate little or no energy savings in households equipped with PT when compared to households without PT [19]. Uncertainty regarding the savings potential actually realized remains high, which led the US Environmental Protection Agency to eventually discontinue the EnergyStar programmable thermostat program effective December 2009 [19,26]. Recent research confirms that even high usability PTs fail to facilitate the use of energy saving features due to occupants primarily striving for optimal thermal conditions [14]. Apparently, static, self-defined schedules do not sufficiently address the real-life needs of end-users.

To overcome the inefficiencies of manual, deterministic setpoint variation, and with the advancement of sensors and later wireless communication technologies, more focus has been put on usability and comfort. The idea of automated setpoint variation, e.g. via *occupancy-state detection*, arose. Integrating occupancy information has been identified as an important aspect of building climate control [28]. The search for an optimal technical solution for occupancy-state detection includes review of door sensors [42] or key card access control, infrared sensors [43], motion-sensors [24,28], a combination of motion and door sensors [23], cameras [27,44–46], radio frequency identification (RFID) [47,48], and wireless sensor networks [49]. All of the above listed solutions have one primary objective in common: to increase energy savings, comfort, or both, when manual setback approaches (i.e. nighttime setback, PT) fail to effectively reflect real-life events.

However, an aspect that is poorly accounted for in occupancy-state-based setpoint variation is the fact that most residential heating systems are inert [6,50,51]. Real-time information alone does not allow for preheating of homes, which might force residents into cold rooms at the immediate time of arrival. This has led to *occupancy-state prediction* based setpoint variation. Ideas discussed in this context include Global Positioning System (GPS) based tracking of vehicles, location-based services [50,52], or algorithm aided arrival-time prediction based on
occupancy information [28]; all of which are intended to better predict estimated times of arrival and/or departure, thereby increasing the chance of better aligning actual thermal demand with heating system operation. Research has demonstrated that it is possible to obtain occupancy prediction information for heating control with high levels of accuracy [for example 15,24]. This can further increase the comfort experienced by users of intermittent heating control. Nonetheless, developing mature commercial technologies for the prediction of occupancy states (arrival, departure, sleeping times, etc.), as well as heat-up times, remains challenging [47–49].

### 2.3. Disturbance prediction features

Control-loop external heat sources and sinks that cannot be controlled—only predicted at best—impose additional challenges. The effects of weather, i.e. ambient air temperature, solar irradiation and wind, can be both a blessing and a burden for the use of building thermal capacity. A frequent subject of academic inquiry [see e.g. 53], integration of weather forecasts (weather prediction) into building climate control remains a demanding undertaking due to inert and heterogeneous thermal behavior of buildings, as well as the stochastic nature of atmospheric processes.\(^3\) Nonetheless, several commercially active residential heating-control solution providers advertise the capacity of their products to consider and adapt to changing weather conditions [see for example 54,55].

Approaches that control for more than one parameter (i.e. a temperature setpoint), and which include various forms of disturbances, are being developed and deployed; model predictive control (MPC), neural networks or genetic algorithms are, for example, frequently discussed [6,20,22,24,28,37,56–64]. Yet, we did not find these approaches commissioned in marketable applications for residential end-users. They are typically developed for more comprehensive, commercial HVAC arrangements, which many times require building specific modeling of thermal behavior [37]. For residential households and temperature control only, such requirements impede upscaling and widespread diffusion. Hence, we excluded additional closed-loop control approaches from the scope of this review.

### 2.4. Overview of archetypical control approaches

Overall, the existing literature suggests that thermostat users themselves cannot be expected to contribute much to energy efficiency [14]. Currently deployed thermostats are, in many cases, not an effective device for optimization of energy efficiency and comfort [17,19,25,65]. In contrast, comfort has been recognized as a key driver affecting the actual use of efficiency-increasing control features [14], which has stimulated recent development of new ways of

\(^3\) A comprehensive literature list on this topic can be found on the website of the OptiControl project [see 53].
heating control. As a result, the portfolio of commercially available heating-control technologies is growing.

The differences in performance between these technologies can still be attributed to few underlying control approach principles, even though these are, in practice, operationalized differently. Since technical implementation can only increase the extent to which a theoretical performance maximum is realized—it cannot by itself stretch the boundaries of maximum potential—we focus on exactly these underlying control principles. Consequently, we categorized archetypical approaches in a taxonomy (see Table 1). This taxonomy illustrates key characteristics, irrespective of technology-specific issues (e.g. how to best measure arrival of occupants). Table 1 distinguishes between these control approaches along three main dimensions and summarizes advantages and disadvantages respectively.\(^4\)

In this taxonomy, the first distinction is made between today’s simplest (on/off) and most common (PID) controller types for residential application (standalone controllers). For all systems that include features beyond standalone controllers, a state-of-the-art PID controller is assumed as the backbone upon which advanced features are added. Building on this, setpoint variation ranges from “none” to “automated and predictive”. If setpoint variation is implemented, matching the heating needs of tenants with real-time behavior can either be done manually, e.g. via programmed schedules, or automated, e.g. with sensors detecting activity inside a building. Thereby collected information is used to adjust the temperature setpoint in accordance with periods of varying comfort requirements, such as sleep, home, or away. Accurate interpretation of such information requires system intelligence beyond regular target temperature control. Hence, in the remainder of this paper, we use the term “intelligent” to refer to control approaches that incorporate automated setpoint variation. Furthermore, to increase comfort by more accurately matching thermal demand and setback periods, preheating (i.e. predictive setpoint variation) is implemented.

The third dimension, disturbance prediction, uses information describing external heat sources and sinks that will affect the heating-control system state in the future. The predominantly discussed external influences within temperate climate conditions are the impact of outside temperature and solar irradiation. This information can be used to, for example, lower the heater output before times of high solar irradiation, which will supply thermal energy to a building. However, this requires at least basic information on building characteristics (windows size, solar transmission rates), as well as accurate, real-time weather forecasts.

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\(^4\) This categorization applies to feedback (closed-loop) control systems, in which the controller reacts to measured room temperatures.
Table 1: Taxonomy of heating-control approaches for residential buildings

<table>
<thead>
<tr>
<th>Control approach</th>
<th>Control approach features</th>
<th>Advantages and disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) On-off controller</td>
<td>On-off</td>
<td>+ Constant temperature (i.e. thermal comfort)</td>
</tr>
<tr>
<td>(standalone)</td>
<td></td>
<td>- Temperature over-/undershoot</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Inefficient energy use</td>
</tr>
<tr>
<td>2) PID controller</td>
<td>PID</td>
<td>+ Constant temperature (i.e. thermal comfort)</td>
</tr>
<tr>
<td>(standalone)</td>
<td></td>
<td>- Inefficient energy use</td>
</tr>
<tr>
<td>3) Nighttime temperature setback</td>
<td>PID Manual</td>
<td>+ Increased efficiency (two setpoints)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Reduced comfort (manual scheduling deficiencies)</td>
</tr>
<tr>
<td>4) Programmable thermostat</td>
<td>PID Manual</td>
<td>+ Increased efficiency (multiple setpoints)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Reduced comfort (manual scheduling deficiencies along multiple setpoint periods)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Low usability and acceptance</td>
</tr>
<tr>
<td>5) Occupancy-state detection</td>
<td>PID Automated</td>
<td>+ Increased efficiency (multiple setpoints)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>+ Real-time setpoint adjustment (occupancy information)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Reduced comfort (no preheating possible)</td>
</tr>
<tr>
<td>6) Occupancy-state prediction</td>
<td>PID Automated and predictive</td>
<td>+ Increased efficiency (multiple setpoints)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>+ Real-time setpoint adjustment (occupancy information)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>+ Increased comfort (preheating possible)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Development of advanced intelligence for prediction required</td>
</tr>
<tr>
<td>7) Occupancy-state detection with weather prediction</td>
<td>PID Automated Weather influence</td>
<td>+ Increased efficiency (multiple setpoints)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>+ Real-time setpoint adjustment (occupancy information)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>+ Integration of control-loop external heat sources</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Reduced comfort (no preheating possible)</td>
</tr>
<tr>
<td>8) Occupancy-state prediction with weather prediction</td>
<td>PID Automated and predictive Weather influence</td>
<td>+ Increased efficiency (multiple setpoints)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>+ Real-time setpoint adjustment (occupancy information)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>+ Integration of control-loop external heat sources</td>
</tr>
<tr>
<td></td>
<td></td>
<td>+ Increased comfort (preheating possible)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Development of advanced intelligence for prediction required</td>
</tr>
</tbody>
</table>

3. Methodology and data

To compare the performance of archetypical heating-control approaches, we combined empirical observations with a simulation-based analysis according to the taxonomy introduced above. Figure 1 illustrates the main methodological elements further detailed in this section: collection of empirical data on household heating behavior and development of a building-simulation environment, as well as the actual performance comparison metrics.
3.1. Empirical household data

Having only a priori knowledge about the exact influence of buildings structures, heating system specifications, occupancy patterns, local weather, etc. on the performance of heating-control approaches, we aspired to include data that resembles realistic household setups. Having an assortment of potentially relevant parameters at hand, household-specific conditions can be reproduced on a per case basis rather than relying on top-down estimates and potentially misleading averages. However, we could not find existing data that was compatible and granular enough to allow for robust assessment. Consequently, we decided to closely monitor 30 households located in the south of Germany over a period of 14 months.\(^5\)

Building on this extensive data collection effort, we ultimately evaluated the ten most comprehensive (i.e. error free) data series as further detailed below. Table 2 provides an overview of the main data categories collected per household.

All households participating in the study were asked to complete a one-time survey requesting basic data on occupants, as well as building characteristics, before real-time data collection began. In the case of incomplete or ambiguous responses, additional telephone or in-person interviews were conducted. To log longitudinal household heating data on indoor room temperature (on a per minute basis), temperature setpoints as defined by end-users (on a per

\(^5\) Participation in the field study was advertised via mail, email and personal communication to a broad audience. Several hundred interested households replied and we ultimately received 119 full applications. All applications were screened for technically compatibility (i.e. internet access and the use of at least one smartphone), which was necessary to enable data collection. Subsequently, to match the scope and resources of this study, 30 households were selected randomly to ultimately participate in our data collection effort.
minute basis) and controller output (on a ten-second basis), temperature sensors and a heating system tracking device were installed in all households. Detecting the occupancy state (home, sleep, away; on a per minute basis) was operationalized through installation of a geo-location software application on mobile phones of all occupants. The geo-location application was provided by an industry partner and underwent extensive testing before the beginning of this study. Furthermore, to reduce distortion of results, we ultimately included the ten most comprehensive and accurate datasets into the quantitative review of this study. As a result, average data quality is very high across all households included in this review, with over 99.5% of the acquired data being free of errors such as temperature sensor outages or data connection failure.

Table 2: Overview of empirical data collected and integrated into the performance evaluation

<table>
<thead>
<tr>
<th>Household survey (ex-ante)</th>
<th>Household heating data (real-time)</th>
<th>External disturbances (ex-post)</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Building unit</td>
<td>• Temperature</td>
<td>• Local weather data</td>
</tr>
<tr>
<td>— Location</td>
<td>— Indoor temperature [°C; on a per minute basis]</td>
<td>— Outside air temperature in [°C]</td>
</tr>
<tr>
<td>— Year of construction</td>
<td>— Occupancy status</td>
<td>— Wind speed [m/s]</td>
</tr>
<tr>
<td>— Insulation standard [building code; renovations]</td>
<td>— Occupancy status along three distinct states: home, sleep, away [on a per minute basis]</td>
<td>— Solar irradiation [W/m²]</td>
</tr>
<tr>
<td>— Dimensions [shape, length, width, height]</td>
<td>• User preferences</td>
<td>— Ground temperature [°C; one meter below the surface]</td>
</tr>
<tr>
<td>— Adjacent structures [floor level, adjacent buildings, shadow]</td>
<td>— User-defined setback schedule times [°C for home, sleep, away; discrete information]</td>
<td></td>
</tr>
<tr>
<td>• Heating</td>
<td>— User-defined setback schedule temperatures [°C for home, sleep, away; discrete information]</td>
<td></td>
</tr>
<tr>
<td>— Heating system specifications</td>
<td>— Heating system controller signal [in percent of maximum heater output; on a 15 second basis]</td>
<td></td>
</tr>
<tr>
<td>— Heat exchanger, boiler, piping</td>
<td></td>
<td></td>
</tr>
<tr>
<td>— Annual heating expenses and final energy consumption for heating [EUR, kWh]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Occupants</td>
<td>• Heating system status</td>
<td></td>
</tr>
<tr>
<td>— Number of occupants</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

3.2. Control approach building simulation environment (CABSE)

3.2.1. CABSE development

Several well-established building energy simulation programs are in use globally. Crawley et al. [66] provide an overview and discuss the features of a selection of twenty building energy simulation programs with diverse capabilities and features. Two predominant simulation tools which have been considered extensively in related research are EnergyPlus [67,68] and

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6 In the case of system failure, a fallback schedule was automatically activated. Hence, mandatory user interaction throughout the observation period was reduced to a minimum.
However, none of the reviewed tools fully satisfied the needs of this study. Shortcomings of existing programs were in particular related to dynamic implementation of several advanced control approaches, integration of empirical occupancy data, occupancy comfort measurement, thermodynamic accuracy and the inability to allow for small simulation time-steps (minutes) required for effective controller comparison and parameterization. This led to the development of a customized Control Approach and Building Simulation Environment (CABSE) using MATLAB code.

CABSE is a lumped-parameter, resistance-capacitance (RC) simulation environment [see also 56,70–72]. To derive the respective resistance-capacitance elements, buildings units were simplified to a room and adjacent building structures, i.e. foundation, floor, windows, ceiling, roof, exterior walls and related surface layers. Every simulated building is represented by a network of first-order equations (see Figure A1 in the appendix). Heat sources, e.g. the heating system, appliances or human body heat are added on nodes as direct heat fluxes. Occupants’ behavior that causes a variation of heat fluxes (occasional window openings, sleep times) is employed on a per-minute basis. The system is solved using a sampling time of one minute. Changes in controller output and external disturbances are accounted for at every time-step. The impact of external disturbances is derived based on outside air temperature, wind speed and solar irradiation data and integrated using variable heat transfer coefficients. Parameterization of the simulation model allows for accurate description of a wide range of building setups (including all test households) and was conducted numerically within four main categories: building, environment, occupancy and PID parameters. Further details on the implementation of archetypical heating-control approaches in CABSE can be found in the appendix (Section 8.2).

### 3.2.2. CABSE validation

After manually specifying each test household building unit based on the collected empirical data, we calibrated the model across remaining variables that were difficult to observe or measure directly, i.e. thermal inertia, weather impact, and actual heating system performance.

The objective of the calibration process was to minimize the coefficient of variation of the root mean squared deviations (CV\(_{\text{RMSD}}\)) between simulated and observed in-room temperature [see also 73]. Figure 2 illustrates the calibration results from the test household with the lowest

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7 Computer aided modeling tools are commonly used to investigate HVAC control system related issues [see e.g. 24,28,37,41,42,56,99–101].

8 Uncertain about the impact of this simplification, we tested the simulation model by comparing its results to empirical temperature time series (see Figure 2). The results indicated more than sufficient representation of reality (see also Figure 2).
(TH5) and the highest (TH1) deviation (CV(RMSD) value) over a randomly selected 200-hour period. Note that once calibrated, the household-defining variables maintain the same value over the entire simulation assessment. Hence, the representation of measured data over time as illustrated in Figure 2 shows the ability of the model to capture the temporal dynamics in indoor temperature. Furthermore, when comparing the obtained deviation values (CV(RMSD) ranging from 3.30 to 1.08 with an average of 2.38 across all test households—with similar work, it appeared to be well suited to our investigation [73].

![Figure 2: CABSE calibration results—comparison of actual in-room temperature and solar irradiation with simulated in-room temperature](image)

### 3.3. Performance evaluation metrics

A review of the extant literature on heating-control approaches confirmed that both energy consumption and thermal comfort are relevant performance dimensions. Ultimately, end-users opt for means of heating control which ensure that their homes are well-tempered [see for example 14,19,25]. Hence, net energy required for space heating and the total time with unacceptable thermal conditions, respectively, were assessed to address both dimensions.

Net energy required for space heating—measured in kilowatt hours per square meter per anno (kWh/m² p.a.)—is calculated as the Riemann sum of heat energy delivered to the inside of a building unit. This is the net of all external heat sources, such as solar irradiation, but does not account for heat losses in the burner, boiler or the piping between boiler and radiator (focusing on useful energy). This allows a review of control performance irrespective of heating system technology related peculiarities. Moreover, we discuss net energy required in relation to a reference control approach rather than absolute values. A standalone on-off controller was
used as the reference control approach in order to compute relative energy savings ($\Delta e$) for a comparison across technologies (Table 3).

Although $\Delta e$ is a suitable measure for performance comparisons within one building unit, it falls short when comparing heating control approaches across different households. A large living unit with average insulation will naturally show higher $\Delta e$ values than a household with a significantly smaller living area and proper insulation. Consequently, we also compare normalized relative energy savings ($\Delta e_n$). This measure corrects for the household-specific, building related reduction potential by defining a 100% energy savings benchmark per household. This benchmark is set by the control approach with the lowest energy consumption value – which turns out to be occupancy-state detection with weather prediction for all households evaluated in this study.

The second dimension, total time with unacceptable thermal conditions ($t_{tc}$, in hours p.a.) is equal to the sum of all times during which a household is occupied and the temperature conditions can be considered unacceptable [74,75]. Unacceptable thermal conditions were translated into a maximum temperature error. Hence, as long as in-room temperature minus the user-desired setpoint stays within a temperature error margin, we assumed acceptable thermal conditions. This temperature error margin was calculated in accordance with ISO International Standard 7730. By that definition, an acceptable thermal environment requires a predicted percentage of dissatisfied (PPD) occupants below 10% [see 74]. By means of the computation method in ISO 7730, the temperature error margin for an acceptable thermal environment is approximately 2 °C [see 75]. To better illustrate control approach performance (Figure 3), we translated $t_{tc}$ into the share of times with or above acceptable thermal conditions ($t_{tsac}$).

4. Results

4.1. Energy savings potential

Standalone on-off control results in the highest energy consumption across all test households and therefore serves as the baseline for relative energy savings ($\Delta e$) calculations across the ten test households (TH1-TH10) as presented in Table 3. Using standalone PID control instead of on-off leads to moderate energy savings, with $\Delta e$ ranging from 1.2% to 6.4%. This is a consequence of the PID algorithm that prevents oscillation around the setpoint by lowering heater output before the setpoint is reached. For nighttime setback control, $\Delta e$ vary significantly from -0.8% to 23.1%. This wide spread is driven mainly by diverse day and nighttime temperature setpoint preferences between users. In the case of TH4, one can observe that unusual scheduling behavior can even increase energy consumption. This household’s
negative $\Delta e$ is driven by a nighttime setback temperature that was occasionally set above the daytime temperature setpoint.\(^9\) Programmable thermostats, with the possibility of defining two setback temperatures (for sleep times and vacancy times), provide higher $\Delta e$ between 9.1% and 36.6%, with a median of 19.2%. Hence, implementing a second setback temperature for vacancy times increases $\Delta e$ by approximately 7 percentage points (comparison of median values).

Automated setpoint variation control approaches, with medians between 20.6% and 26.2%, allow for further reduction of energy consumption. Occupancy-state detection, for instance, enables $\Delta e$ between 12.3% and 42.2%. Based on a comparison of median values, $\Delta e$ of occupancy-state detection approaches are approximately 5 percentage points greater than the $\Delta e$ of programmable thermostats. Here, actual occupancy behavior drives energy savings rather than user-defined heating schedules.

**Table 3: Relative energy savings ($\Delta e$) across test households**

<table>
<thead>
<tr>
<th>Test household</th>
<th>On-off controller (stand-alone)</th>
<th>PID controller (stand-alone)</th>
<th>Nighttime temperature setback</th>
<th>Programmable thermostat</th>
<th>Occupancy-state detection</th>
<th>Occupancy-state prediction</th>
<th>Occupancy-state detection with weather prediction</th>
<th>Occupancy-state prediction with weather prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>TH1</td>
<td>2.6%</td>
<td>14.2%</td>
<td>21.7%</td>
<td>25.1%</td>
<td>20.5%</td>
<td>25.2%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TH2</td>
<td>3.0%</td>
<td>15.3%</td>
<td>23.2%</td>
<td>27.3%</td>
<td>23.9%</td>
<td>31.4%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TH3</td>
<td>5.6%</td>
<td>9.8%</td>
<td>9.8%</td>
<td>12.3%</td>
<td>11.1%</td>
<td>13.7%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TH4</td>
<td>4.4%</td>
<td>-0.8%</td>
<td>9.1%</td>
<td>19.2%</td>
<td>18.4%</td>
<td>19.7%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TH5</td>
<td>2.2%</td>
<td>8.9%</td>
<td>14.6%</td>
<td>15.8%</td>
<td>13.2%</td>
<td>16.8%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TH6</td>
<td>5.0%</td>
<td>16.0%</td>
<td>20.0%</td>
<td>29.2%</td>
<td>25.4%</td>
<td>33.2%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TH7</td>
<td>1.2%</td>
<td>10.6%</td>
<td>18.4%</td>
<td>22.8%</td>
<td>20.7%</td>
<td>24.7%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TH8</td>
<td>6.4%</td>
<td>23.1%</td>
<td>36.6%</td>
<td>42.2%</td>
<td>38.8%</td>
<td>47.0%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TH9</td>
<td>1.0%</td>
<td>5.5%</td>
<td>13.6%</td>
<td>18.2%</td>
<td>16.8%</td>
<td>19.8%</td>
<td></td>
<td></td>
</tr>
<tr>
<td>TH10</td>
<td>6.1%</td>
<td>14.5%</td>
<td>22.1%</td>
<td>25.3%</td>
<td>22.7%</td>
<td>27.8%</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Median</strong></td>
<td><strong>3.7%</strong></td>
<td><strong>12.4%</strong></td>
<td><strong>19.2%</strong></td>
<td><strong>24.0%</strong></td>
<td><strong>20.6%</strong></td>
<td><strong>26.2%</strong></td>
<td><strong>23.7%</strong></td>
<td><strong>23.7%</strong></td>
</tr>
</tbody>
</table>

Furthermore, comparing occupancy-state prediction to occupancy-state detection shows the effect of preheating periods ultimately leading to lower relative savings. $\Delta e$ for occupancy-state prediction are slightly below the $\Delta e$ of occupancy-state detection with a range from 11.1% to

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\(^9\) The same household also configured its programmable thermostat schedule unrealistically, which resulted in low comfort levels due to tenants arriving while the controller was in setback mode. Such behavior contradicts the intended use of the nighttime temperature setback feature (i.e. to lower temperatures during nighttime) and has been discussed as a disadvantage of manual scheduling in previous research (see Section 2.2).
38.8% and a median of 20.6%. Comparing occupancy-state prediction to programmable thermostats, however, reveals ambiguous differences in energy savings at first glance. While occupancy-state prediction increases \( \Delta e \) slightly in eight of the ten households, it causes a minor decrease of \( \Delta e \) in two households (TH1, TH5). This is an empirical example where programmable thermostats allow lower energy consumption than control approaches with automated setpoint variation. However, although such conservative programming of actual attendance times does understandably allow occupants to reduce energy consumption, it comes at the cost of reduced comfort as subsequently illustrated in Table 4.

Adding a weather prediction feature on top of automated setpoint-variation approaches leads to the highest \( \Delta e \) of 13.7% to 47.0% in the case of occupancy-state detection with weather prediction and to \( \Delta e \) of 12.3% to 43.9% in the case of occupancy-state prediction with weather prediction. Overall, this feature further increases \( \Delta e \) by approximately 2 to 3 percentage points compared to corresponding control approaches without weather integration. Remarkably, in five of the ten households the maximum \( \Delta e \) potential exceeds 25%, exceeding 30% in three of the ten households, when employing occupancy-state detection with weather forecasting instead of a standalone on-off control.

4.2. Thermal comfort

The calculation results for total time with unacceptable thermal conditions per control approach and year (\( t_{ic} \)) across all test households are summarized in Table 4. Control approaches without setpoint variation, i.e. standalone on-off and PID controller, show unsurprisingly high levels of thermal comfort with \( t_{ic} \) of less than one day (between 0.0 and 18.2 hours). Under static conditions, i.e. when setpoints are kept constant, these controllers do not fall short on delivering acceptable thermal conditions. Occupants do over time occasionally reset the home temperature setpoint though to account for individually varying comfort requirements. This induces an “artificial” control variation to which the system can only respond slowly due to thermal lag. As a result, occupants can be exposed to some discomfort (i.e. non-desired temperature) until the new setpoint is reached, resulting in slightly increased \( t_{ic} \) values between 0.5 and 18.0 hours for TH1-TH2 and TH4-TH9.

Comparing on-off control with PID control shows only marginal differences in comfort. \( t_{ic} \) differences remain below 1 hour, with the exception of TH8 where PID control resulted in lower comfort with a \( t_{ic} \) increase of 3.7 hours. When further investigating this result, we found that TH8 has a boiler with comparatively low heat output. It is reasonable to assume that the PID algorithm parameterization was not able to fully compensate for the heater’s limited responsiveness.
Overall, both manual setpoint variation control approaches achieved significantly lower comfort levels, with a median $t_{ic}$ of 46.3 and 195.5 hours respectively, compared to standalone controllers, with medians of $t_{ic}$ of 2.9 and 2.6 hours. Exceptions include, again, TH4, which shows higher comfort, i.e. lower $t_{ic}$ values, for the nighttime temperature setback approach when compared to PID. As described before, the occupants of TH4 occasionally set the temperature for sleep time above the home temperature for daytime thermal control.

The median $t_{ic}$ of 195.5 hours for programmable thermostats is the highest across all control approaches. $t_{ic}$ values for manual setpoint variation approaches varied significantly, ranging from 0.0 to 682.9 hours for nighttime setback and from 7.2 to 877.5 hours for programmable thermostat. The wide range is explained by household-specific settings and building system peculiarities. Heat-up times for example vary based on heating system setup and heat losses affected by properties of the building envelope.

Generally, heating-control approaches with automated setpoint variation enable superior thermal comfort (maximum median $t_{ic}$ of 172.4 hours) compared to programmable thermostats (median $t_{ic}$ of 195.5 hours). According to the median of a household-per-household comparison, occupancy-state detection can reduce $t_{ic}$ by approximately 25% and occupancy-
state prediction can reduce $t_c$ by approximately 81%.\textsuperscript{10} The high overall comfort levels in the case of occupancy-state prediction are a result of preheating enabled by arrival prediction.

Adding weather prediction to occupancy-detection and -prediction approaches leaves occupants with lower levels of comfort due to reduced heater output during times of expected solar irradiation. A direct comparison between programmable thermostats and occupancy-detection with weather prediction per household reveals that $t_c$ of the latter approach is higher for five out of ten households. In the case of occupancy-state prediction with weather prediction, only TH3 and TH10 show a slightly higher $t_c$ when compared to programmable thermostats. However, absolute $t_c$ for these households are comparatively low for both control approaches. This indicates that occupants of both households enjoy comparatively high comfort for either control approach.

4.3. Trade-off between energy and comfort

Combining our results for relative energy savings potential and hours below acceptable thermal conditions illustrates the trade-off between energy savings and comfort. Figure 3 depicts normalized relative energy savings ($\Delta e_n$) on the horizontal axis and the share of occupancy times at or above acceptable thermal conditions ($t_{saC}$) on the vertical axis for all control approaches and households. Energy savings increase from left to right and thermal comfort increases from bottom to top.

Automated setpoint variation control approaches appear in the upper right corner (dark grey shading). This indicates relatively high energy savings and high levels of comfort at the same time. In general, standalone on-off and PID controller are in the upper left corner (small light grey shading) and show the highest of all comfort levels, but also require a high amount of energy to maintain desired temperatures. Here the lack of setpoint variation eliminates chances for missed temperatures. Hence, the reduction of comfort imposed by these control approaches is marginal. Noticeably high $\Delta e_n$ values for TH10 in the case of PID control (41%) are affected by the low overall savings potential, since the most energy efficient control approach was used as a baseline for normalization.

Manual setpoint variation approaches significantly increase energy savings compared to standalone controllers, but also cause lower levels of comfort and show the largest spread of $\Delta e_n$ and $t_{saC}$ values (large medium grey shading). Here, performance cannot be generalized and depends heavily on end-user preferences and scheduling capabilities. Nighttime setback for example results in $\Delta e_n$ ranging from -4% to 52%. This is lower than the energy savings that

\textsuperscript{10} Comparing the median of the entire sample, including TH3, TH6, TH10, which show higher comfort for the programmable thermostat approach when compared to occupancy-state detection.
are possible with programmable thermostats or automated setpoint variation approaches. Yet, nighttime setback shows higher comfort levels than programmable thermostats, with $t_{\text{sa}}$ values ranging from 100% to 86%. Programmable thermostats show higher $\Delta e_n$, but also a wider range of comfort levels. Overall, manual setpoint variation approaches cause both the lowest $\Delta e_n$ as well as the lowest $t_{\text{sa}}$ across our sample. This confirms the discrepancy between actual daily routines and manually defined schedules and illustrates the effects of irrational scheduling (see also Section 2.2). For eight out of the ten households, an automated setpoint variation approach is available that provides both higher comfort levels as well as higher energy savings compared to programmable thermostats. In the case of TH8, all control approaches with setpoint variation resulted in rather low comfort levels.

![Figure 3: Trade-off between comfort and relative energy savings (all test households depicted)](image)

Compared to manual setpoint variation approaches, automated setpoint variation approaches can further increase energy efficiency and comfort levels are higher. All households achieved generally acceptable thermal conditions during at least 89% (with weather prediction feature) and 95% (without weather prediction feature) of total occupancy time. The results are generally more consistent across households, too. Variations of $\Delta e_n$ and $t_{\text{sa}}$ are significantly lower compared to manual setpoint variation approaches, with a $\Delta e_n$ variation (31 percentage points) even below the $\Delta e_n$ variation of standalone controllers (41 percentage points). Compared to programmable thermostats, occupancy-detection (without weather prediction) shows higher
\( \Delta e_n \) due to the lack of preheating periods, but also shows lower comfort levels. Adding weather prediction to both occupancy-detection and occupancy-prediction approaches further increases \( \Delta e_n \) per household. However, times below acceptable thermal conditions also increase because of reduced heating system output during times of expected high solar irradiation.\(^{11}\)

Summarizing, the performance of automated setpoint variation approaches shows much lower variance when compared to control approaches with manually adjusted setpoints. Furthermore, on a per-household-basis, all intelligent heating-control approaches using automated setpoint variation or setpoint variation and weather prediction features achieved superior results compared to programmable thermostats. Occupancy-state detection and weather prediction control approaches resulted in the highest energy savings across all households.

Finally, we also conducted a separate sensitivity analysis across the technical parameters to better understand the drivers of the results described above. This revealed that insulation standards have a significant impact on absolute energy savings potential, whereas occupancy times have the greatest influence on relative energy savings potential when deploying intelligent heating control (i.e. automated setpoint variation). For the sake of brevity, the interested reader may find additional information on our sensitivity results in the appendix (Section 8.3).

## 5. Discussion

In this section, we first discuss the theoretical mitigation potential of intelligent heating-control approaches based on the results of our quantitative performance evaluation. Thereafter, we reflect on the technology development trajectory, putting into perspective the findings of our qualitative review presented in the beginning of this paper (Section 2). Subsequently, we briefly touch upon possible adoption barriers and policy implications. We conclude the discussion section with a paragraph on the limitations of our approach and possible follow-up research.

\(^{11}\) Reducing heater output during times of expected solar irradiation does negatively affect heat-up times—regardless of the control algorithm. The time until a setpoint is reached is always a function of the total available energy during heat-up (heater plus solar irradiation). Aside from the case of a more complex HVAC control setup with active cooling, an early reduction of heater output is the only method to help reduce temperature overshoot during subsequent times of extensive solar irradiation. Nonetheless, in such cases the benefits of reducing temperature overshoot would still have to outweigh the disadvantages of lower comfort during prolonged heat-up times.
5.1. Theoretical mitigation potential of intelligent heating control

Our findings show that intelligent—i.e. automated setpoint variation—heating-control approaches bear the potential to significantly increase energy efficiency in the residential sector. We find high median relative energy savings potentials of more than 26% across all test households, with a maximum savings potential of 47%. This is in line with previous work on individual heating-control technologies, where average energy savings of 28% [23] and up to 34% [28] were reported.

Moreover, intelligent heating-control approaches are particularly suited to address the thermal efficiency challenges associated with old building structures. In our sensitivity assessment, we find absolute energy savings for buildings with insulation standards prior to 1978 to be 80% higher when compared to newer buildings types with insulation according to the building code of 2001 (see Section 8.3). This highlights potentially attractive climate mitigation opportunities. In Germany for example, 69% of existing building stock consists of buildings constructed in or prior to 1977 [76]. At the same time, Germany’s residential sector contributes to 28% of the nation’s total final energy consumption [1].

When investigating intelligent (i.e. automated setpoint variation) control approaches and comparing their performance to manual setpoint variation control approaches, the former can unlock the highest efficiency potential when deployed in high vacancy households. Vacancy time and patterns have been identified as the most important driver for energy savings potential of intelligent heating-control approaches. In our sample, differences in occupancy patterns contributed as much as 29 percentage points to the respective relative energy savings potential. The test household with the lowest energy savings potential (TH3) also exhibits the lowest observed total vacancy time (approximately 67 days or 18% of total time). In contrast, the highest energy savings (TH8) coincide with the highest observed total vacancy time (approximately 166 days or 46% of total time). With greater vacancy times, intermittent heating can be applied more often [28], whereas programmable thermostats in such cases often face the challenge of conservative programming and do not fully exploit existing efficiency potentials. These insights may become even more relevant in the light of the increasing share of single-person households [77] or for households in which all occupants are employed full-time.

Lastly, intelligent heating-control approaches allow for more consistent performance. Their use results in higher median relative energy savings and comfort levels across a diverse group of

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12 However, in cases where total vacancy time is high, accurate prediction and effective system calibration (i.e. fast response) is particularly important for households with many short vacancy periods and frequent setpoint variations.
buildings, heating preferences and occupancy patterns when compared to programmable thermostats. A result that is of particular relevance for the retrofitting of heterogeneous building stock. In the EU, for example, building age, type, renovation rates and energy performance differ significantly between member states [78].

5.2. The evolution of heating-control technologies

When putting the historical evolution of residential heating-control technologies described in the beginning of this paper into perspective, one can draw an interesting technology development trajectory (see Figure 4). This trajectory starts with high comfort, energy intensive approaches (standalone on/off and PID control), before shifting toward increasingly energy-savings oriented approaches (nighttime setback and programmable thermostats). Over the last decade, the trajectory has shifted again. Control technologies that further increase energy efficiency as well as comfort needs (occupancy-state detection and occupancy-state prediction approaches) have emerged. We see two influencing factors that have shaped this technology trajectory: first, a shift in the energy environment and related user objectives and, second, the advancement and cost reduction of peripheral technology such as semiconductors and ubiquitous computing.

In the early stages, residential heating control was primarily deployed to realize high levels of comfort by closely aligning the heating system output with a target temperature. Over time events such as the oil crises in 1973 and subsequent policy reactions (e.g. building efficiency standards) demanded more efficient methods of heating control and the idea of intermittent heating, i.e. setpoint variation, became more widely adopted [19,79]. However, today’s widely diffused manual setpoint variation control technologies (e.g. programmable thermostats) have come under criticism. Insufficient usability and comfort have led to failed acceptance of efficiency-enhancing features [14,17,19,25,26] and make it difficult to actually realize energy savings.

Our quantitative performance comparison of different heating-control approaches (Section 4) validates the theory that programmable thermostats yield either low comfort levels (users arrive in cold homes) or little—and sometimes even negative—energy savings (users program their thermostat conservatively). This fact explains the shift toward control approaches that integrate the idea of automated temperature setpoint variation, instead of manual user input, to lower heater output during times of reduced thermal demand. Our research also confirms that these

13 Unfortunately, to the best of our knowledge, no data on actual market share of different heating-control technologies was available at the time of this study. According to the existing literature, however, manual setpoint control is frequently discussed and appears to be most common in the US and in Europe [see for example 14,17–19,25,41,50].
automated setpoint variation control approaches can successfully reduce the trade-off between energy efficiency and thermal comfort—a trade-off particularly noticeable when deploying standalone controllers or manual setpoint variation (i.e. common nighttime temperature setback and programmable thermostats). In the sample investigated, intelligent heating-control approaches are more capable of accurately aligning different temperature setpoint periods with user requirements than manual approaches. On average, programmable thermostats impose significantly higher discomfort on occupants compared to automated setpoint variation such as occupancy-state prediction control (see Table 4).

While semiconductors and microprocessors enabled the earlier evolution from mechanical setback to programmable thermostats, it is now the widespread and low cost availability of smartphones, geo-location technology, advanced algorithms and cloud-based computing resources that determine the boundaries of advanced residential heating-control approaches. In this respect, heating control is an illustrative case. Its evolution shows that emerging “smart” technologies and the digitalization of everyday processes can in fact unlock new ways to increase energy efficiency. Currently, a growing number of “smart home” solutions and intelligent thermostats—which operationalize different control approaches—are being developed or are already commercially available [see e.g. 54,55,80,81].

5.3. A perspective on technology diffusion

Although we deliberately excluded costs from the scope of this technical review, one can easily find commercial heating-control products and comparable smart home solutions offered for below EUR 300 today [see fo example 54,55,80,81]. Considering the fact that German households paid EUR 11.79 per m² for heat in 2012 [82] and that the country’s average
apartment size is 118.6 m² [76], efficiency increases in the 20% range would already theoretically yield attractive payback times. Hence, successful diffusion of intelligent heating-control approaches may allow for monetary household savings as well as a reduction in energy consumption.

Theoretically appealing economics alone might not be enough, however, to enable technology diffusion [83]. Technologies enabling for example occupancy-state prediction such as GPS-tracking need to be accepted by the individual users. The occupancy-state prediction approach decreased the number of hours of unacceptable thermal conditions by over two-thirds on average compared to occupancy-state detection (see Table 4).14 However, it remains to be seen whether measures necessary to achieve these improvements—such as increased automation via GPS-tracking, or comprehensive data collection in general—will be accepted by the mass market. When Google Inc. acquired Nest Labs Inc., the manufacturer of an intelligent residential thermostat, in January 2014 for USD 3.2 billion, data confidentiality was a frequently appearing topic in discussions and the media [84,85].

At this point, it is difficult to predict the net impact of these technical nuances on total energy consumption reduction. It remains unclear whether comfort enhancing features such as preheating via arrival prediction primarily increase satisfaction of existing adopters, or if they might become a significant motivation for additional groups to adopt and deploy efficient heating control (and thus to save energy). Hence, such techno-sociological interdependencies are to be better understood before judging whether occupancy-state prediction allows for higher comfort alone or for additional total energy savings (due to accelerated diffusion) as well.

5.4. A perspective on policy

Building energy efficiency has been a persistent focus of German policy-makers and has resulted in the regulated market environment currently in place. In the case of Germany, the energy savings ordinance (EnEV) sets requirements for the minimum energy performance of buildings and building components [86]. Energy efficient construction and refurbishments are subsidized and supported by Germany’s government-owned development bank (KfW) to further increase efficiency. The renewable energies heat act (EEWärmeG) compels new building owners to use an increasing share of renewable energies for heat generation. All of these regulations are intended to contribute to the achievement of targets that are based on the government’s energy concept (Energiekonzept) [87] and the energy package (Energiepaket) adopted in 2011 [87,88].

14 At the same time, occupancy-state prediction leads to a slight increase in energy consumption (compared to occupancy-state detection) due to preheating of an apartment until the actual arrival of occupants.
In the energy concept decided in 2010, the German government set a target to reduce building heat energy demand by 20% by 2020. These targets are considered very ambitious and only realizable with an intensified political framework [88]. However, even with traditionally low building refurbishment rates [12,13], intelligent heating-control technologies have not been considered in political instruments thus far as an alternative or complementary means. Today’s policy focus is on structural improvements of the building envelope, improvements of installations, or the deployment of renewable energy technology [87]. Based on the findings of this paper, developments in the field of intelligent heating control are an area worth addressing in future policy discussions. Policy support, which is today predominantly “hardware” and construction oriented [87,88], should also include operation optimization and advanced heating system “control” [89].

Our study also points toward peculiarities that become directly relevant for effective deployment of intelligent residential heating-control solutions. The high abatement potential in old buildings with predominantly higher heating costs, high savings potential for high vacancy households and potentially attractive payback periods suggest addressing non-cost diffusion barriers for selected building and household types rather than providing general subsidies.

Possible non-cost diffusion barriers are frequently discussed [96–98] and include information about the product, access to the product or technical compatibility. Hence, policies providing targeted information could contribute to the deployment of intelligent heating control deployment in old buildings and high abatement potential household categories. This would complement capital intensive and structural complex building retrofit with the option to improve energy efficiency at immediate implementation with comparatively low capital investment.

5.3 Limitations and further research

Like any simulation-based assessment, our approach is based on assumptions and abstractions that need further exploration. For example, although we were able to include a vast amount of field data into our simulation-based assessment, the size of our empirical sample with ten test households is not large enough for a representative estimate of e.g. the nationwide energy savings potential. However, when comparing our sample characteristics to statistics, we find building units that are typical for German building stock. In our sample, eight out of ten households are built prior to 1986. Similarly, in Germany approximately 84% of all building units are built prior to 1986 [76]. The two remaining households are built in the 1990s and after 2000 respectively. The apartment size of our sample ranges from 45m² to 150m² with an average of 83 m², compared to the nation’s average apartment size of approximately 90 m² [76]. Nonetheless, both energy savings and comfort are household specific variables and can vary significantly. In addition, occupancy patterns may not be representative. In
addition, we have made assumptions necessary for the implementation of archetypical control approaches along our taxonomy. The exact design of a control approach may deviate from our assumptions and, hence, validity of our results for specific technologies may be limited. Moreover, we included only one weather region into our assessment, because all test households are located in the south of Germany. Although we conducted a sensitivity analysis regarding weather related parameters (i.e. solar irradiation and wind), it would be interesting to compare our findings to an analysis of buildings in other climate regions, potentially including heating and cooling.

Further research avenues could also include the assessment of the nationwide potential of intelligent heating as a retrofit option to improve energy-efficiency of existing buildings stock, potentially using simplified but more representative assumptions about occupant behavior and building characteristics. Since building refurbishment rates in Europe are low [93,94], it would be interesting to quantify the effect on final energy consumption and aggregated national CO₂ reduction potentials. We also deliberately excluded any detailed economic assessment of the control approaches, dedicating all our efforts to the assessment of technical potential. Cost and monetary savings are said to play a significant role in the diffusion of green technologies and it would be interesting to link existing building stock, energy savings and cost in an integrated evaluation. Understanding the diffusion process is an interesting topic by itself and it would be worthwhile to investigate the determinants of end-user adoption, and especially the behavior of early-adopters. This could inform researchers, developers and policy makers on how to effectively address the needs of homeowners and tenants, thereby expediting the reduction of final energy consumption.

6. Conclusions

Objective of this work is to provide an overview of existing archetypical control approaches for residential buildings and to subsequently identify and quantify related energy efficiency potentials. Moreover, we contrast the identified efficiency potentials with the comfort levels that can be realized per identified control approach respectively.

We find that most recently commercialized, automated temperature setback variation (i.e. intelligent) control approaches significantly outperform other, more established control approaches. Our results show for example that simple heating control with on/off or PID controllers is well-suited to realize high levels of thermal comfort, but does not address energy efficiency. Moreover, while programmable thermostats operationalize the idea of temperature setpoint variation (e.g. at night and throughout vacancy times) to reduce energy consumption, these manual scheduling approaches do not live up to their potential. On the one hand,
conservative programming to increase the chance of having a warm home upon arrival results in little energy savings. On the other hand, inaccurate estimation of sleep and away times leads to reduced comfort (i.e. unheated homes upon arrival). Automated temperature setback variation approaches, however, allow addressing both energy efficiency and thermal comfort, according to our results.

Based on these findings, future policy activities should take into account novel intelligent heating-control approaches to tap so far unexploited efficiency potentials. Mass diffusion of computation and communication capacity and high smartphone penetration rates have extended the portfolio of means to effectively increase energy efficiency in the residential sector. Interestingly, since the required initial investments for the individual appear to be comparatively low, economic hurdles might not represent the most challenging diffusion barriers. Lack of information, technical compatibility issues, standards and product access are potentially more important factors. In addition, our empirical analysis of the households shows that intelligent heating-control approaches reduce energy consumption most effectively in old buildings and households with a high share of vacancy time. Both characteristics are well reflected in the current building stock and household situation of many European (and other industrialized) nations.

Lastly, the quantitative results of our research as well as the potential implications for environmental policy as summarized above point to intriguing avenues for further research. First, the median mitigation potentials in the range of 21% to 26% observed for the evaluated household sample motivates the evaluation of overall (e.g. national) efficiency potentials. Second, a detailed economic assessment of intelligent heating-control solutions would complement our mere technical perspective. Both of these efforts would eventually contribute to a more comprehensive understanding of aggregated CO₂ abatement potentials. Third, while this study evaluated the performance of heating-control approaches, other factors influencing its diffusion require further research. In particular, understanding the perception of potential adopters related to the usability of intelligent heating control, the enjoyment of using such a technology or the technical compatibility with existing heating systems would aid to recognize diffusion catalysts as well as barriers.
7. References


8. Appendix

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8.1. CABSE thermal resistance-capacitance network graph

Figure A1: Basic illustration of the thermal resistance-capacitance network of the simulation environment (CABSE)—red circles represent building elements that are assigned a corresponding temperature throughout a simulation run.
8.2. Implementation of archetypical heating-control approaches in CABSE

In accordance with controllers in practice, our standalone on-off controller implemented in CABSE adjusts heater output\(^{15}\) based on a temperature error variable. To prevent short cycling due to fast-frequent setting changes, the error differential implemented is set to 0.5°C with a reaction time of 1 minute. For the standalone PID controller, we implemented the standard algorithm that minimizes the temperature error \((e)\) between setpoint and measured temperature with the aid of a proportional \((K_p)\), integral \((K_i)\) and derivative \((K_d)\) tuning parameter as depicted in Eq. (A1). In addition, we added basic anti-windup capabilities commonly found in practice where the integral part \((K_i)\) is limited in its value (conditional integration) and also reset to zero when setpoint changes affect the system [see for example 32,95].

\[
PID \text{ controller output (error)} = K_p e + K_i \int e \, dt + K_d \frac{de}{dt} \tag{A1}
\]

Temperature setpoints for the desired indoor temperatures are either kept constant throughout a simulation period, manually adjusted by a weekly, predefined heating schedule, or automatically varied based on occupancy states (home, away, sleep). Predefined, weekly heating schedules were adopted from actual schedules of test households’ residents. To implement preheating in occupancy-prediction control, we assumed accurate prediction of arrival times throughout a one-hour look-ahead period. This one hour look-ahead period is a literature-based assumption that has been realized with accuracies above 90% [15,24]. In previous research, arrival prediction accuracy between 30 and 90 minute look-ahead varied only slightly [see e.g. 24]. During this period, the setpoint is automatically adjusted to the desired temperature upon arrival (i.e. home setpoint).

The basic disturbance prediction feature uses a three-hour forecast of local solar irradiation. It is assumed that the weather forecast for this period is accurate and that the forecast information is always available. Based on predefined parameters, i.e. window size and average share of radiated window area to total window area, the simulation environment calculates the average expected heat impact for the following hours. The forecasted heat impact is fed forward to the control system and subtracted from the output of the space heater.

\(^{15}\) Space heater status is limited to binary operation: on (maximum output) and off (no output).
### Table A1: Overview of model specification of control approaches

<table>
<thead>
<tr>
<th>Control approach</th>
<th>Model specification for quantitative control approach comparison</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) On-off controller (standalone)</td>
<td>Standalone on-off (bang-bang) controller with a threshold value of 0.5°C, constant temperature over simulation period</td>
</tr>
<tr>
<td>2) PID controller (standalone)</td>
<td>PID controller with $K_p$, $K_i$, $K_d$ terms and anti-windup algorithm (integral limitation at 40% of positive controller boundary, integral reset at set point variation)</td>
</tr>
<tr>
<td>3) Nighttime temperature setback</td>
<td>PID controller as above; set point variation along two temperature set point positions for occupant states ‘HOME’ and ‘SLEEP’ on a week-long schedule with 30-minute resolution</td>
</tr>
<tr>
<td>4) Programmable thermostat</td>
<td>PID controller as above; set point variation along three temperature set point positions for occupant states ‘HOME’, ‘SLEEP’ and ‘AWAY’ on a week-long schedule with 30-minute resolution</td>
</tr>
<tr>
<td>5) Occupancy-state detection</td>
<td>PID controller as above; detection of occupant states home, sleep and away on a one-minute resolution (e.g. motion sensors)</td>
</tr>
<tr>
<td>6) Occupancy-state prediction</td>
<td>PID controller combined with occupancy detection as above with additional one-hour occupancy-state prediction for preheating (e.g. GPS tracking)</td>
</tr>
<tr>
<td>7) Occupancy-state detection with weather prediction</td>
<td>PID controller combined with occupancy detection; weather conditions prediction: three-hour prediction of solar irradiation influence on heat balance through window transmission. Inclusion of predicted heat on control system and heat load reduction to 50% for times of solar irradiation</td>
</tr>
<tr>
<td>8) Occupancy-state prediction with weather prediction</td>
<td>PID controller combined with occupancy detection and weather conditions predictions (see above)</td>
</tr>
</tbody>
</table>

### 8.3. Sensitivities

To shed light on the drivers for energy efficiency, we conducted a sensitivity analysis. To isolate the effect of individual parameters best, we tested sensitivities in an average household setup. For this, we used parameters from literature as well as empirical data when no literature-based information was available (e.g. granular occupancy behavior data). Hence, the following results are derived from the simulation of an intermediate level apartment with insulation standards from the 1970s assuming usual occupancy behavior. Intermediate floor apartments built prior to 1978 are the most common building unit type in Germany [76] and also occurred most frequently in our test household sample. Occupancy behavior with a total share of away times of 34% relates well to daily routines of the German working population [compare to e.g. 96].

By simulating occupancy-state prediction with weather prediction control we were able to analyze the impact of occupants’ behavior (i.e. vacancy time, air exchange rate), heating system dimensioning (i.e. maximum heater output), building peculiarities (i.e. adjacent structures, insulation standards) and solar irradiation, respectively.

When deploying automated setpoint control approaches, occupancy times have the greatest impact on relative energy savings. Using the occupancy time extrema from the test household...
sample, relative energy savings are considerably higher (29 percentage points) in the case of 46% vacancy time when compared to 18% vacancy time. In contrast, for heating approaches without setpoint variation (e.g. PID controller), vacancy times have no effect on relative energy savings. We also varied air exchange rates between 0.1/h to 0.5/h, the latter being the exchange rate specified and recommended [97]. For an air change rate of 0.5/h, relative energy savings were a moderate 2 percentage points greater than for an air exchange rate of 0.1/h.

Due to the more frequent cool-down and heat-up periods when deploying setpoint variation control, we tested for the impact of maximum heater output, i.e. peak performance of the heating system. Comparing results for a slightly under-dimensional boiler, with only 70% of the optimal peak performance (ceteris paribus), to one with 200% peak performance, relative energy savings were 7 percentage points lower for the case of below-optimal maximum heater output. However, this also caused a significant decrease in comfort illustrated by a \( t_c \) change from 32 to 296 hours.

Furthermore, sensitivities related to the building were tested. In the case of heated adjacent structures (i.e. other apartments), relative energy savings are 4 percentage points higher for a linked, compared to a detached, home. Variation of the insulation standard on the other hand reveals only small differences in relative energy savings (approximately 2 percentage points). Nonetheless, insulation standards still have a significant impact on absolute energy savings with differences of more than 80% when comparing, for example, a detached house built in 1980 with a building from the year 2010.

When varying the solar irradiation incident on a building envelope, relative energy savings change only moderately. Using solar radiation exposure extrema from the test household sample, relative energy savings are approximately 2 percentage points lower in the case of low solar irradiation (shadowed ground-floor apartment) when compared to high solar irradiation (non-shadowed penthouse).
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Utility- versus Belief-Based Models: Shedding Light on the Adoption of Novel Green Technologies

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Abstract

Understanding the determinants for the adoption of novel green consumer technologies is important for mitigating environmental problems. While the environmental science literature typically takes an approach based on objective household utility theory, subjective personal belief-based theories from lateral academic fields are increasingly being considered. We compare these adoption model types based on a single set of empirical data. For this we conduct a survey on the adoption of an exemplary novel green consumer technology (intelligent thermostats). Our evaluation shows that the belief-based model explains above 65%, while the utility-based model explains only 5 to 35% of the variance in the intention to adopt. Individual perception of the technology, such as the perceived pleasure and ability to adopt, are more important than objective technology performance or price-value. However, the two latter variables do show relevant and significant influence when tested in a model that ignores other belief-based determinants. Similarly, environmental norms show low importance when more influential determinants such as personal innovativeness are considered. Thus, our results point to the risk of omitted-variable bias if only a few, selected beliefs are considered. The results in addition allow to indicate how the effectiveness of environmental policy can be improved.

Keywords

Adoption; consumer decision; innovation diffusion; eco-innovation; intelligent thermostat
1. Introduction

Novel green consumer technologies comprise emerging technologies that have a significantly lower environmental footprint than current technologies or that help to lower the footprint of current consumption. Prominent examples of such technologies include energy-saving smart home appliances or electric vehicles. Accelerated development and adoption of such technologies is an essential part of transitioning to a low-carbon society, raising the importance of thorough understanding why these technologies are being adopted (or rejected).

In existing research within the environmental community, the majority of green consumer technology adoption studies are based on objective household utility theory. These studies typically evaluate the influence of objective technology performance measures and household characteristics on the willingness to pay (Achtnicht, 2011; Banfi, Farsi, Filippini, & Jakob, 2006; Kwak, Yoo, & Kwak, 2010). In the last years, an increasing number of studies, however, consider adoption determinants from subjective personal belief-based theory. For instance, Claudy et al. (2011) include the influence of subjective perceptions about renewable micro-generations in addition to objective household characteristics in their evaluation of willingness-to-pay. Gerpott and Paukert (2013) include technology perception and environmental awareness in a similar study on smart meters. Jansson et al. (2011) evaluate the influence of objective household characteristics and subjective environmental norms on the adoption of alternative fuel vehicles. These studies usually find that the included determinants from belief-based theory are relevant. Nevertheless, the selective consideration of belief-based adoption determinants in such studies is in contrast to the more comprehensive application of belief-based adoption theory in information system research (e.g. Venkatesh, Thong, & Xu, 2012).

Two important research gaps become apparent: First, while environmental scholars tend to pick constructs from belief-based theory, a fundamental comparison of the utility-based and belief-based approach is missing. Second, in sustainability and policy research the frequently addressed influence of environmental norms is often included in isolation. Alternative, potentially more influential personality beliefs as well as indirect influence via other beliefs is beyond the scope of most environmental studies.

This article aims to contribute a more robust understanding of green technology adoption by comparing the explanatory power of objective household utility-based adoption models to subjective personal belief-based adoption models. Subsequently, the influence of environmental norms on technology perception is investigated. To address these questions, a survey on a novel green consumer technology, namely intelligent, energy-saving thermostats, is used (N=1,101). For the model comparison, the essence of the two theoretical approaches is first distilled and translated into testable model variants. The two model types are then compared using the same dataset. Moreover, the influence of environmental norms on
technology adoption is compared to the influence of personal innovativeness, which is suggested by the literature as the most important alternative personal characteristic (Agarwal & Prasad, 1998; Limayem, Khalifa, & Frini, 2000). Finally, in addition to the direct influence of these two personality beliefs on intention to adopt, the indirect influence via beliefs about technology characteristics is also evaluated.

The results reveal that models based on subjective personal belief theory explain adoption considerably better than the model based on objective household utility theory. Hence, to support adoption of novel green technologies, a focus on objective characteristics such as promoting technology performance and lowering costs is potentially less effective or even misleading. Instead, during the early stages of a technology’s diffusion, important beliefs are those involving the fun or pleasure related to adoption (and use) as well as the concerns regarding technological and social compatibility of the technology. Our results also suggest that approaching people with high environmental norms is potentially less effective than targeting those with high technological innovativeness. This is explained by the higher familiarity with novel technologies (and their adoption) by such individuals. Overall, isolated consideration of adoption determinants from belief-based theory might lead to omitted-variable bias, making a more systematic approach advisable. In addition, our results challenge the effectiveness of conventional policy instruments. Spurring market adoption of truly novel green consumer technologies by means of, for example, supporting firms inherently motivated to sell such products is potentially more promising than taxation or conventional information campaigns.

The remainder of the article is structured as follows: Section 2 describes objective household utility-based theory as well as subjective personal belief-based theory and their application in the context of green technology evaluation. Next, variable measurement and the survey methodology are described (Section 3). Section 4 (results) compares the explanatory power of the models investigated and the influence of personal beliefs (innovativeness and personal norms) on perceived technology characteristics. Finally, we discuss our contributions to the literature on green technology adoption and derive implications for environmental policy and green business (Section 5). The last section concludes (Section 6).

2. Theories of the adoption of novel green consumer technologies

We reviewed adoption studies, which investigated technologies such as smart meters, renewable micro-generation and hybrid or alternative fuel vehicles. From these, we identified two fundamental approaches to theorizing green consumer technology adoption. First,
approaches based on objective household utility, which are the most widely applied in the environmental literature. Such models use predominantly technology characteristics in combination with household characteristics that can be observed and measured (Figure 1). Second, subjective personal belief-based approaches, which have been applied in the context of environmental studies more recently. These models try to measure an individual’s perception of technology-related and personality-related factors (Figure 1). The following subsections further detail the development and current status of the two approaches. Subsequently, the two approaches are compared and testable model variants are derived.

![Figure 1: Two model types used for the explanation of the adoption of novel green consumer technologies. This study will a) compare the explanatory power of utility and belief-based models and b) investigate the influence of beliefs about personal characteristics on beliefs about the technology to be adopted (dashed line).](image)

### 2.1. Objective household utility-based adoption models

Traditional utility theory can be traced back to Adam Smith (1776). It describes human decisions in general as rational and narrowly self-interested, aiming at optimizing personal utility. The theory was advanced to describe household consumption as a function of available household income and time as well as the utility and costs of available consumption options (Becker, 1978). Studies applying utility theory in the context of green technologies (e.g., Achtnicht, 2011; Banfi et al., 2006; Kaenzig et al., 2013; Kwak et al., 2010; Scarpa and Willis, 2010) build on Becker’s description and in principle apply the following utility function \( U \) for an individual or a household \( i \) and the technology attributes \( j \):

\[
U_{ij} = V(X_{ij}, z_i) + e_{ij}
\]

Eq. 1
where $V$ is a (deterministic) vector of technology performance ($X_{ij}$) for and individual characteristics ($Z_j$) of a potential adopter. $e_{ij}$ is the stochastic element. Because utility cannot be measured directly, willingness-to-pay (WTP) is used as a proxy.

To measure WTP as the dependent variable, various approaches are applied in existing environmental studies. For example, revealed preferences, combined with technology costs, can be used to approximate WTP. Most utility-based studies aim to use such objective variable measurement. This, however, is only possible if the technology is already diffused to a certain extent (Jansson et al., 2011; Michelsen & Madlener, 2012). Actual adoption cases are needed to be able to observe revealed preferences. Consequently, for sparsely diffused green consumer technologies, the dependent variable is often assessed ex-ante based on stated preference (i.e. intention to adopt). Ex-ante methods include choice experiments. These derive WTP based on the price sensitivity of respondents when confronted with different product options/bundles (Banfi et al., 2006; Hoyos, 2010; Kwak et al., 2010) or by contingent valuation, which directly asks respondents to state a price threshold (Claudy et al., 2011).

For the independent variables, technology characteristics and household characteristics are taken into account. Technology characteristics are most often described with technology-specific design attributes or performance indicators. These typically embody environmental impact and/or economic performance. Examples for such design attributes, which are directly linked to the technology’s energy savings potential are: ventilation with and without heat exchangers, thickness of window glazing, and facade insulation in the case of building efficiency technologies (Banfi et al., 2006; Kwak et al., 2010). For fuel switch technologies (e.g. alternative heating or micro-generation systems), the energy carrier type (solar, wood, wind) was used as the relevant characteristic (Michelsen & Madlener, 2012; Scarpa & Willis, 2010). More general environmental and economic performance indicators being used include energy savings, carbon emissions, payback time and acquisition cost Achtenicht (2011). Objective household characteristics included in utility-based models are typically demographic factors such as income or education (Michelsen & Madlener, 2012). However, even studies following the objective criteria-focused approach are of the opinion that subjective environmental consciousness of potential adopters should be considered too (Banfi et al., 2006). Arguably, many individuals adhere to personal environmental norms, which might also influence their technology adoption behavior.

### 2.2. Subjective personal belief-based adoption theory

Psychology and sociology emphasize the influence of human beliefs. This has resulted in consideration of beliefs about what one should do and beliefs about consequences of an action rather than mere objective factors to explain human behavior—an ontology that eventually
found its way into adoption models. Among the most prominent are the theory of reasoned action (Fishbein & Ajzen, 1975) and the theory of planned behavior (Ajzen, 1991). While both of these theories originally aimed at explaining behavior in general, they were subsequently applied and further specified to explain technology acceptance, in particular in the information systems domain. Prominent advancements in this respect include the technology acceptance model (Davis, 1985) and the unified theory on acceptance and use of technology (Venkatesh, Morris, Davis, & Davis, 2003; Venkatesh et al., 2012).

These adoption models are relevant for and applicable to the context of novel green consumer technologies for at least two reasons. First, the adoption decision process is similar for both new information as well as novel green consumer technologies. In both cases, consumers usually weigh the advantages and disadvantages of adopting a particular technology and subsequently decide upon adoption or rejection. Second, many green technologies are actually built around emerging information technologies (e.g. smart meters, intelligent heating). In line with this reasoning, the reviewed studies on green technologies refer to and include constructs from models developed in information systems research (e.g. Gerpott and Paukert, 2013; Michelsen and Madlener, 2013; Ozaki, 2011). However, studies in the environmental literature tend to selectively pick constructs from belief-based theory without careful consideration of their origin and the relevance of other constructs. To improve on this, we take a step back and describe belief-based theory in accordance with its original definition and specifications as discussed in the information system literature in the following.

As the dependent variable, belief-based models use intention to adopt, which is the most proximal influence on behavior and mediates the effect of other determinants on individual behavior (Venkatesh & Brown, 2001). Similarly to most constructs used in belief-based adoption models, intention to adopt has typically been operationalized as a reflective construct, using multiple survey items (see Section 3.2).

Furthermore, the independent variables can be categorized in technology-specific and personality-specific beliefs. Technology-specific beliefs are not necessarily linked to one particular technology only; they can convey a more general notion. Building on the theory of planned behavior (Ajzen, 1991), the technology acceptancy model by Davis (1989) for example specified two major technology beliefs: perceived usefulness and perceived ease of use. Perceived usefulness is defined as “the degree to which a person believes that using a particular system would enhance his or her job performance”. Perceived ease of use is defined as “the degree to which a person believes that using a particular system would be free of effort” (see e.g. Davis, 1989: 985). Venkatesh et al. (2003) later extended the technology adoption model by adding facilitating conditions and social influence. Facilitating conditions refers to the adopter’s “perceptions of the resources and support available to perform a behavior” (see e.g.
Venkatesh et al., 2012: 159). Social influence is defined as the extent to which adopters “perceive that important others believe they should use a particular technology” (see e.g. Venkatesh et al., 2003: 451). In the consumer context, three additional determinants of adoption—hedonic motivation, habit and price value—were identified (Venkatesh et al., 2012). Hedonic motivation is defined as “the fun or pleasure derived from using a technology” (Venkatesh et al., 2012: 161). Habit is defined as “prior behavior” and, in addition, the belief of the individual that “the behavior is automatic” (Venkatesh et al., 2012: 161). Price value is defined as “consumers’ cognitive trade-off between the perceived benefit of the application and monetary cost for using them” (Venkatesh et al., 2012: 161). Usefulness (i.e. performance expectancy) has been adapted to the consumer context and is defined as “the degree to which using a technology will provide benefits to consumers in performing certain activities” (Venkatesh et al., 2012: 159).

**Personality-specific** beliefs on the other hand describe how people perceive themselves, complementing an otherwise mere technology-focused perspective. In the realm of novel green consumer technologies, two personality-focused beliefs are of particular importance: environmental norms and personal innovativeness. The influence of environmental awareness was for example evaluated and theorized by Stern (2000). His value-belief-norm theory proposes that rather than environmental values (altruistic values) or environmental beliefs (e.g. human action affects the biosphere), *environmental norms* (i.e. the moral obligation to act) are what influence pro-environmental behavior. Environmental norms can, however, also be described as beliefs, i.e. the belief that one should act in keeping with the environment. The positive influence of environmental norms on green consumer technology adoption has for example been shown in the context of alternative-fuel vehicles (Jansson et al., 2011). However, other studies find the contrary for the more value oriented *environmental awareness* construct. They show for example that people with high environmental awareness tend to invest significantly less in energy efficiency measures—a conflicting observation that is difficult to explain (Poortinga, Steg, Vlek, & Wiersma, 2003).

A potentially relevant factor for demystifying these controversial findings could be the omission of other relevant variables. In fact, we observe that in environmental science, environmental-related beliefs are often considered in isolation from other beliefs (e.g. Jansson et al., 2011; Michelsen & Madlener, 2013; Poortinga et al., 2003). At the same time, it has been found that “individuals with higher personal innovativeness are expected to develop more positive beliefs about the target technology” (Lewis, Agarwal, & Sambamurthy, 2003). Consequently, to test for relevant alternative personality traits potentially affecting green consumer technology adoption, personal innovativeness should be considered too. Among the many studies
investigating the relevance of (personal) innovativeness, Agarwal & Prasad (1998) define personal innovativeness as "the willingness of an individual to try out any new technologies."

2.3. Overview of the model differences

The main differences between the two model types are summarized in Table 1. A general methodological difference is that belief-based models use subjective measures and reflective constructs instead of objective data. In other words, beliefs are defined as variables which are subsequently measured by several survey items. Such constructs can thus more easily be applied and compared across technologies. As a result, we find efforts to unify various existing models to propose a general set of significant determinants for adoption (e.g. Venkatesh et al., 2012). In contrast, utility-based models use, socio-demographic household characteristics or technology specifications. These variables are not easily condensed to more general constructs and can therefore not always be compared across studies.

<table>
<thead>
<tr>
<th>Criteria</th>
<th>Utility-based models (as used in environmental literature)</th>
<th>Belief-based models (as used in information system literature)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dependent variable</td>
<td>Willingness-to-pay (WTP) based on stated/revealed (subjective) preferences</td>
<td>Behavioral intention (reflective construct)</td>
</tr>
<tr>
<td>Independent variables</td>
<td>Technology-related measures; focus on monetary benefit (some include environmental benefit)</td>
<td>Subjective measure; reflective constructs; focus on technology performance, hedonic motivation, social influence, and ease of use</td>
</tr>
<tr>
<td></td>
<td>Focus on objective household criteria (e.g. sociodemographics) - except for environmental awareness or norms</td>
<td>Subjective measures; reflective constructs; focus on personal innovativeness</td>
</tr>
</tbody>
</table>

Nonetheless, utility-based models often also integrate subjective data selectively. This occurs for example when no adoption data is available and revealed preferences need to be considered instead of stated preferences. In this case, behavioral intention is revealed either by a choice experiment and/or an estimate about the individuals’ WTP. It also occurs whenever environmental norms or beliefs about the environment are considered, as these are a form of subjective influence. For most technologies, environmental performance can actually be measured with objective variables (e.g. carbon footprint). However, environmental awareness of adopters requires subjective inquiry. This might explain why environmental researchers have added variables from subjective belief-based models without comprehensively comparing the two approaches first.
In both approaches, the dependent variable is similar. The main difference is that utility-based models either transform the revealed or stated adoption decision together with the price of the technology into WTP, or directly ask for it. In contrast, belief-based models present the technology (including a price tag) and then inquire the individual’s intention to adopt. In such a case, price value is then considered as an independent variable only. Concerning the set of independent variables, utility-based models, on the one hand, focus on the economic and environmental benefits. Belief-based models, on the other hand, take into account beliefs about the pleasure related to using a technology, ease of use as well as social influence. Moreover, in the green technology context, utility-based adoption models focus on measuring objective household characteristics and include, in some instances, environmental awareness as the only belief. This is in contrast to belief-based models, which find personal innovativeness to be the most important personal belief.

2.4. Model comparison and evaluation

To adequately compare the two adoption approaches, a common dependent variable is essential. Ideally, actual adoption would be observed and considered. However, this is typically impossible for technologies on the verge of diffusion. In addition, questioning actual adopters might introduce a recall bias with respect to beliefs about the technology in focus (Nisbett & Decamp, 1977). The most proximal influence to behavior is the intention to adopt (Venkatesh & Brown, 2001). Moreover, a methodological advantage of measuring the intention to adopt in comparison to choice experiments is that more technology characteristics can be considered. Only a limited number of product variations can be presented to a respondent throughout choice experiments such as conjoint analysis, because of the number and duration of iterations required for meaningful results. Furthermore, compared to contingent valuation, the advantage of using intention to adopt is that (individual) price value can be retrieved and evaluated as an independent variable instead of being merged with the dependent variable. This is in line with Dodds et al. (1991), who conceptualized price as a determinant for willingness-to-buy.

For the independent variables, we specify two variants for each of the compared model types (Figure 2). For the utility-based model, the first variant includes objective measures only (M1.1). Savings potential is considered as the major technology characteristic. It captures both monetary as well as environmental benefits as both are a direct result of a reduction in energy consumptions. For household characteristics, the socio-demographic variables typically used in utility-based models are considered (age, gender, education, income). In our second variant of the utility-based model (M1.2), we take into account the influence of price value, which is normally included in the dependent variable (see Section 2.1). In addition, we include environmental norms to embrace the environmental valuation of green technologies by potential adopters, a practice commonly observed in environmental research.
The first variant of the belief-based model (M2.1) corresponds to a unified model suggested for consumer technologies by Venkatesh et al. (2012). This model focuses on technology perception only; general personality beliefs are not included. Therefore, in addition, we test a variant where personality beliefs are also reflected (M2.2). Again, we thereby consider a personality belief typically used in the environmental literature: environmental norms. In addition, we add personal innovativeness as an alternative explanatory personality belief as suggested by belief-based adoption research. Following our basic model comparison, the belief-based model is further investigated by evaluating the impact of the personality beliefs on the technology perception (dashed arrow in Figure 2). Since the objective technology characteristics are independent of the household characteristics, such an interdependency
evaluation is only meaningful for belief-based models. In the case of belief-based models it does, however, contribute to the understanding of the role of environmental norms, which is of particular interest in the context of green consumer technology adoption.

3. Method

In this section, we first explain the rationale behind our selection of intelligent thermostats as the green consumer technology of choice for this research (3.1). Subsequently, the model measurements are described in more detail (3.2). Lastly, the applied survey method and data collection (3.3) as well as the model statistics are shown (3.4).

3.1. Case selection: Intelligent thermostats

Intelligent thermostat are a typical, representative novel green consumer technology for three reasons: First, this technology allows carbon emissions caused by residential heating to be reduced by approximately 25% (Kasper, 2013). Second, intelligent thermostats rely on information technology to reduce environmental impact—a characteristic typical of many emerging, novel green consumer technologies.1 Furthermore, intelligent thermostats are a technology that has been commercialized only recently (Winkler & Wakabayashi, 2014).

The devices are usually sold directly to end-users and are designed such that self-installation is possible, even for users with average dexterity. Most products consist of a retrofit controller that is to be wired to the installed heating system’s main control unit. Devices are of little standalone value, but once connected, they can automatically control in-room temperature. This allows for a reduction in energy use while maintaining (or even increasing) the comfort level by switching off the heating system when no one is at home and/or lowering the temperature when inhabitants are asleep. The location of household inhabitants is measured by sensors or by tracking the geo-location status of inhabitants with a smartphone application. For a more detailed description of intelligent heating thermostats, see for example Kasper (2013).

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1 In private homes, for example, emerging smart home devices such as energy storage and demand response control technologies pave the way for the integration and self-use of intermittent solar electricity. As a result, sustainable energy generation can substitute for electricity from fossil power plants. Other examples include car sharing—often possible only due to information technology-related applications—or the majority of smartphone apps aiming at reducing a user’s individual environmental footprint.
3.2. Variable measurement

All belief-based determinants are operationalized as reflective, latent variable constructs (see Table 2). This includes all variables of the belief-based model variants, price value, and environmental norms when added to the utility-based model (Figure 2: 2.1, 2.2).

We use three survey items to measure each construct (see Table 2). For intention to adopt, items are adapted from Davis’ (1989) seminal work on the technology acceptancy model. To capture the subjective perception of price value, all survey respondents were told that the price of an intelligent thermostat offering is 300 Euro and were later asked to indicate whether they believe this is a reasonable price tag. Survey items for price value and the remaining technology beliefs were adopted from Venkatesh et al.’s (2012) comprehensive review to maintain validity and comparability of constructs with existing work. Survey items for environmental norms were adopted from Sütterlin (2012), Steg et al. (2005), and Jansson et al. (2011). The measurement scale for innovativeness is adapted from Agarwal & Prasad (1998); it has also been used in more recent research on adoption (e.g. Lu, Yao, & Yu, 2005; Yi, Jackson, Park, & Probst, 2006).

Objective variables used in utility-based model variants (age, income, education, gender) are measured using interval, ordinal and nominal variables. Technical savings potential was measured by means of energy use and occupancy time data of a household (Kasper, 2013). Households tend to have high energy savings potential as soon as they have poor insulation and are frequently unoccupied. The technical savings potential figures are thus computed using surveyed occupancy (for weekdays and weekends) and total energy cost information. To capture this information in case respondents do not know their heating cost, questions about general building characteristics with high influence on energy end-use (e.g. apartment size, building type, building age and estimated building efficiency) were also included in our survey and subsequently used to approximate heating cost.
<table>
<thead>
<tr>
<th>Construct</th>
<th>Items</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>Behavioral intention</td>
<td>BI1 I can imagine using intelligent thermostats regularly in my household.</td>
<td>Davis et al., 1989; Venkatesh et al., 2012, 2003</td>
</tr>
<tr>
<td></td>
<td>BI2 I plan to use intelligent thermostats in the future.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>BI3 I intend to use intelligent thermostats in everyday life.</td>
<td></td>
</tr>
<tr>
<td>Environmental norms</td>
<td>EN1 I have a bad conscience when energy is wasted in the household.</td>
<td>Jansson et al., 2011; Sütterlin, 2012</td>
</tr>
<tr>
<td></td>
<td>EN2 I feel personally obliged to avoid unnecessary energy consumption wherever possible.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>EN3 I personally feel that it is important to think about the environment in my everyday behavior.</td>
<td></td>
</tr>
<tr>
<td>Price value</td>
<td>PV1 Intelligent thermostats are reasonably priced.</td>
<td>Dodds et al., 1991; Venkatesh et al., 2012</td>
</tr>
<tr>
<td></td>
<td>PV2 Intelligent thermostats are a good value for the money.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>PV3 At the current price, intelligent thermostats provide a good value.</td>
<td></td>
</tr>
<tr>
<td>Usefulness</td>
<td>US1 Using intelligent thermostats increases my energy efficiency at home.</td>
<td>Venkatesh et al., 2012</td>
</tr>
<tr>
<td></td>
<td>US2 Using intelligent thermostats helps me to lower my heating cost.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>US3 Using intelligent thermostats helps me to reduce my energy consumption at home.</td>
<td></td>
</tr>
<tr>
<td>Hedonic motivation</td>
<td>HM1 Installing smart home products, such as intelligent thermostats, at home is fun.</td>
<td>Agarwal and Karahanna, 2000; Kim et al., 2007; Venkatesh et al., 2012</td>
</tr>
<tr>
<td></td>
<td>HM2 Using intelligent thermostats is enjoyable.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>HM3 Using intelligent thermostats is very entertaining.</td>
<td></td>
</tr>
<tr>
<td>Ease of use</td>
<td>EU1 Learning how to use intelligent thermostats is easy for me.</td>
<td>Davis et al., 1989; Moore and Benbasat, 1991; Venkatesh et al., 2012, 2003</td>
</tr>
<tr>
<td></td>
<td>EU2 Using intelligent thermostats is clear and understandable.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>EU3 I find intelligent thermostats easy to use.</td>
<td></td>
</tr>
<tr>
<td>Facilitating conditions</td>
<td>FC1 I have the resources necessary to use intelligent thermostats.</td>
<td>Ajzen, 1991; Venkatesh et al., 2012, 2003</td>
</tr>
<tr>
<td></td>
<td>FC2 I can get help from others when I have difficulties using intelligent thermostats.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>FC3 Intelligent thermostats are compatible with other appliances and technologies I use.</td>
<td></td>
</tr>
<tr>
<td>Habit</td>
<td>HA1 The use of smart home products (such as intelligent thermostats) has become a habit for me.</td>
<td>Venkatesh et al., 2012</td>
</tr>
<tr>
<td></td>
<td>HA2 I am addicted to using smart home products (such as intelligent thermostats).</td>
<td></td>
</tr>
<tr>
<td></td>
<td>HA3 I must use smart home products (such as intelligent thermostats).</td>
<td></td>
</tr>
<tr>
<td>Social influence</td>
<td>SI1 People who are important to me think that I should use intelligent thermostats.</td>
<td>Venkatesh et al., 2012</td>
</tr>
<tr>
<td></td>
<td>SI2 People who influence my behavior think that I should use intelligent thermostats.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>SI3 People whose opinions that I value prefer that I use intelligent thermostats.</td>
<td></td>
</tr>
<tr>
<td>Innovativeness</td>
<td>IN1 I like to purchase new, innovative products.</td>
<td>Agarwal and Prasad, 1998; Lu et al., 2005; Yi et al., 2006</td>
</tr>
<tr>
<td></td>
<td>IN2 Among my peers, I am usually the first to explore new information technologies.</td>
<td></td>
</tr>
<tr>
<td></td>
<td>IN3 If I heard about a new information technology, I would look for ways to experiment with it.</td>
<td></td>
</tr>
</tbody>
</table>
3.3. Survey development and data collection

Survey development, evaluation and refinement were conducted in a two-step process along four pre-tests. First, the green technology-specific survey items were iteratively discussed with an expert panel, as recommended by Boudreau et al. (2001), consisting of CEO, CTO and CMO of technology and utility firms active in the field of intelligent thermostat commercialization. In addition, we presented the final set of constructs and survey items to a group of academics and experts in the field of marketing and consumer behavior.

Following item refinement, in the next step a first measurement model was specified. We conducted four pre-tests, during which we sent survey iterations to over 1,000, and eventually analyzed the (valid) responses of over 400 participants. Prior to each pre-test, we asked at least three persons to complete our entire questionnaire. Thereby, at least one researcher observed the response process and, after completion, individual feedback on the response-process was collected. Besides the objective household variables (income, age, education) and technical savings potential, all items were measured using a seven-point Likert scale ranging from “strongly disagree” to “strongly agree.” Since our final survey as well as all pre-tests were conducted in German, while existing scales are reported in English, we used translation and back-translation procedures. Furthermore, several native speakers supported the entire survey development process to ensure that loss of information due to translation is not an issue. An overview of the final items is depicted in Table 2.

To collect the final data, we conducted an online survey. Respondents were filtered according to two criteria: having their own heating system and possession of a smartphone. Both are prerequisites for intelligent thermostat adoption. A market research firm provided us with respondents from their online panel, allowing for a sample representative of the German population based on age and gender. Access to the online survey was sent to a total of 1,975 potential respondents. Out of this, 874 were filtered or disqualified based on the representativeness criteria for age and gender. A comparison of the final sample (N=1,101) with statistics for the German population—including not only the filter criteria for age and gender, but also for education and income—can be found in the Annex (Table A1).

3.4. Measurement and model statistics

To test the performance of the two theoretical approaches and their respective model variants, we deployed “second generation statistical techniques” (Boudreau et al., 2001), i.e. structural equation modeling (SEM). SEM offers several advantages (Venkatesh et al., 2012) and has become a quasi-standard in marketing and management research (Hair, Ringle, & Sarstedt, 2011). More specifically, we applied partial least squares (PLS) analysis, using the software WarpPLS to perform computations (Kock, 2013).
Results of the measurement model are outlined in Table 3 and Table 4 (relevant for reflective variables only). To assess internal consistency and reliability, we computed both composite reliabilities (CR), as well as Cronbach’s alphas (α) (Hess, McNab, & Basoglu, 2014; Raykov, 1997). Only the facilitating conditions construct is at the lower range of the loading needed to enable robust results (Chin, Marcolin, & Newsted, 2003; Hess et al., 2014). For all other multi-item constructs, CR and α values greater than .85 suggest high reliability.

Table 3: Factor-loadings, cross loading, Cronbach’s alphas (α) and composite reliabilities (CR)

<table>
<thead>
<tr>
<th>Construct</th>
<th>Item</th>
<th>BI</th>
<th>EN</th>
<th>PV</th>
<th>US</th>
<th>HM</th>
<th>EU</th>
<th>FC</th>
<th>HA</th>
<th>SI</th>
<th>IN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Behavioral intention</td>
<td>BI1</td>
<td>0.86</td>
<td>0.02</td>
<td>-0.04</td>
<td>0.17</td>
<td>0.11</td>
<td>0.10</td>
<td>-0.07</td>
<td>-0.18</td>
<td>-0.05</td>
<td>-0.01</td>
</tr>
<tr>
<td></td>
<td>BI2</td>
<td>0.95</td>
<td>-0.02</td>
<td>0.02</td>
<td>-0.08</td>
<td>-0.04</td>
<td>-0.06</td>
<td>0.04</td>
<td>0.06</td>
<td>0.03</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>BI3</td>
<td>0.96</td>
<td>0.00</td>
<td>0.01</td>
<td>-0.07</td>
<td>-0.05</td>
<td>-0.02</td>
<td>0.03</td>
<td>0.11</td>
<td>0.02</td>
<td>0.00</td>
</tr>
<tr>
<td>Environmental norms</td>
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<td>-0.02</td>
<td>-0.04</td>
<td>0.04</td>
<td>-0.02</td>
<td>-0.04</td>
<td>0.08</td>
<td>0.06</td>
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<tr>
<td></td>
<td>EN2</td>
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<td>-0.02</td>
<td>-0.01</td>
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<td>0.03</td>
<td>-0.02</td>
<td>0.02</td>
<td>-0.01</td>
</tr>
<tr>
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<td>EN3</td>
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<td>0.89</td>
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<td>-0.03</td>
<td>0.01</td>
<td>0.01</td>
<td>-0.06</td>
<td>-0.07</td>
<td>-0.03</td>
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<tr>
<td>Price value</td>
<td>PV1</td>
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<td>0.00</td>
<td>0.89</td>
<td>-0.03</td>
<td>0.01</td>
<td>0.02</td>
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<td>0.01</td>
<td>-0.03</td>
<td>-0.02</td>
</tr>
<tr>
<td></td>
<td>PV2</td>
<td>-0.02</td>
<td>-0.01</td>
<td>0.90</td>
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<td>-0.03</td>
<td>-0.03</td>
<td>0.02</td>
<td>0.04</td>
<td>0.01</td>
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</tr>
<tr>
<td></td>
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<td>0.02</td>
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<td>-0.02</td>
<td>-0.03</td>
<td>-0.03</td>
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</tr>
<tr>
<td>Usefulness</td>
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<td>0.96</td>
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<td>-0.01</td>
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<td>0.04</td>
<td>-0.05</td>
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<tr>
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<td>-0.03</td>
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<td>0.01</td>
</tr>
<tr>
<td></td>
<td>US3</td>
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<td>0.95</td>
<td>0.02</td>
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<td>0.01</td>
<td>-0.01</td>
<td>0.01</td>
<td>0.02</td>
</tr>
<tr>
<td>Hedonic motivation</td>
<td>HM1</td>
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<td>0.01</td>
<td>-0.04</td>
<td>0.92</td>
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<td>0.02</td>
<td>0.00</td>
<td>0.03</td>
<td>0.07</td>
</tr>
<tr>
<td></td>
<td>HM2</td>
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<td>0.00</td>
<td>0.01</td>
<td>0.01</td>
<td>0.94</td>
<td>0.04</td>
<td>0.04</td>
<td>-0.04</td>
<td>0.02</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>HM3</td>
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<td>0.01</td>
<td>0.02</td>
<td>0.92</td>
<td>0.06</td>
<td>0.03</td>
<td>0.04</td>
<td>-0.05</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>Ease of use</td>
<td>EU1</td>
<td>0.02</td>
<td>-0.03</td>
<td>-0.04</td>
<td>0.00</td>
<td>0.05</td>
<td>0.90</td>
<td>-0.04</td>
<td>-0.06</td>
<td>0.02</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
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<td>0.03</td>
<td>0.02</td>
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<td>-0.09</td>
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<td>0.07</td>
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<tr>
<td></td>
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<td>0.01</td>
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<td>0.04</td>
<td>0.06</td>
<td>0.06</td>
</tr>
<tr>
<td>Facilitating conditions</td>
<td>FC1</td>
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<td>0.01</td>
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<td></td>
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<td>-0.07</td>
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<td>0.80</td>
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<td>-0.23</td>
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<td>Habit</td>
<td>HA1</td>
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<td>0.02</td>
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<td>0.07</td>
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<td></td>
<td>HA2</td>
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<td>0.06</td>
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<td>0.01</td>
<td>0.93</td>
<td>0.04</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>HA3</td>
<td>-0.03</td>
<td>0.01</td>
<td>0.02</td>
<td>-0.01</td>
<td>0.01</td>
<td>-0.03</td>
<td>0.02</td>
<td>0.94</td>
<td>0.04</td>
<td>0.00</td>
</tr>
<tr>
<td>Social influence</td>
<td>SI1</td>
<td>-0.06</td>
<td>0.01</td>
<td>0.00</td>
<td>0.06</td>
<td>0.04</td>
<td>-0.03</td>
<td>0.03</td>
<td>0.04</td>
<td>0.93</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>SI2</td>
<td>0.02</td>
<td>-0.01</td>
<td>-0.01</td>
<td>-0.04</td>
<td>-0.01</td>
<td>0.03</td>
<td>-0.05</td>
<td>-0.01</td>
<td>0.94</td>
<td>0.02</td>
</tr>
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<td>SI3</td>
<td>0.05</td>
<td>0.00</td>
<td>0.05</td>
<td>-0.02</td>
<td>-0.03</td>
<td>-0.01</td>
<td>0.02</td>
<td>0.94</td>
<td>0.04</td>
<td>0.01</td>
</tr>
<tr>
<td>Innovativeness</td>
<td>IN1</td>
<td>0.12</td>
<td>0.03</td>
<td>-0.02</td>
<td>0.03</td>
<td>-0.01</td>
<td>0.05</td>
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<td>-0.12</td>
<td>-0.04</td>
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</tr>
<tr>
<td></td>
<td>IN2</td>
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<td>-0.05</td>
<td>0.02</td>
<td>0.00</td>
<td>0.01</td>
<td>-0.02</td>
<td>0.01</td>
<td>0.05</td>
<td>0.01</td>
<td>0.91</td>
</tr>
<tr>
<td></td>
<td>IN3</td>
<td>-0.03</td>
<td>0.02</td>
<td>0.03</td>
<td>0.03</td>
<td>-0.04</td>
<td>0.02</td>
<td>0.07</td>
<td>0.03</td>
<td>0.92</td>
<td>0.02</td>
</tr>
</tbody>
</table>

Table 4: Variance inflation factors (VIF), correlations, and average variance extracted (AVE)

<table>
<thead>
<tr>
<th>Construct</th>
<th>VIF</th>
<th>BI</th>
<th>EN</th>
<th>PV</th>
<th>US</th>
<th>HM</th>
<th>EU</th>
<th>FC</th>
<th>HA</th>
<th>SI</th>
<th>IN</th>
</tr>
</thead>
<tbody>
<tr>
<td>BI Behavioral intention</td>
<td>3.08</td>
<td>0.93</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EN Environmental motivation</td>
<td>1.38</td>
<td>0.37</td>
<td>0.88</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>PV Price value</td>
<td>1.66</td>
<td>0.49</td>
<td>0.33</td>
<td>0.89</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>US Performance expectancy</td>
<td>2.29</td>
<td>0.63</td>
<td>0.40</td>
<td>0.47</td>
<td>0.96</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HM Hedonic motivation</td>
<td>2.67</td>
<td>0.72</td>
<td>0.28</td>
<td>0.49</td>
<td>0.62</td>
<td>0.92</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EU Effort expectancy</td>
<td>2.04</td>
<td>0.52</td>
<td>0.35</td>
<td>0.44</td>
<td>0.56</td>
<td>0.54</td>
<td>0.91</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>FC Facilitating conditions</td>
<td>2.41</td>
<td>0.63</td>
<td>0.37</td>
<td>0.50</td>
<td>0.56</td>
<td>0.55</td>
<td>0.62</td>
<td>0.79</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>HA Habit</td>
<td>1.88</td>
<td>0.55</td>
<td>0.12</td>
<td>0.43</td>
<td>0.29</td>
<td>0.50</td>
<td>0.29</td>
<td>0.45</td>
<td>0.91</td>
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<td></td>
</tr>
<tr>
<td>SI Social influence</td>
<td>2.31</td>
<td>0.63</td>
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<td>0.51</td>
<td>0.53</td>
<td>0.62</td>
<td>0.39</td>
<td>0.60</td>
<td>0.55</td>
<td>0.94</td>
<td></td>
</tr>
<tr>
<td>IN Innovativeness</td>
<td>1.99</td>
<td>0.60</td>
<td>0.34</td>
<td>0.42</td>
<td>0.42</td>
<td>0.56</td>
<td>0.48</td>
<td>0.53</td>
<td>0.53</td>
<td>0.91</td>
<td></td>
</tr>
</tbody>
</table>

Notes: Diagonal elements are AVE, off-diagonal elements are correlations
The average variance extracted (AVE) as shown in the diagonal of Table 4 is above .77. This indicates that the variance captured relative to measurement error is sufficient to justify using all constructs. High item loadings on the corresponding latent constructs, in combination with low cross-loadings (Table 3) and adequate AVE values (Table 4), exhibit high convergent validity (Gefen, Straub, & Boudreau, 2000).

Furthermore, we inspected correlation values (Table 4) for signs of multicollinearity. With one exception (.72), all correlations are below .70. According to Grewal et al. (2004), correlations from .75 to .95 are considered high and Billings & Wroten (1978) report a threshold of .80. Yet, we followed common practice and also reviewed variance inflation factors (VIF). All VIF are well below 3.5—far below the conservative threshold of 5.0 (Hair et al., 2011; Hair, Sarstedt, Ringle, & Mena, 2012; Venkatesh et al., 2012). In combination with high measurement reliability, large sample size and high explained variance (Hair et al., 2012), these results suggest that multicollinearity is not a concern in our study.

Missing values in our reflective constructs were not an issue since respondents had to answer all questions to be able to complete the survey. For objective variables, however, this was not required. In case of missing objective variables (e.g. age, income), arithmetic mean imputation was applied. A general rule of thumb is that missing values per variable should not be more than 10%; a more relaxed rule sets the threshold to 20% (Hair, Black, Babin, & Anderson, 2009). However, Kock (2014) has recently shown that even 30% missing data will not lead to significant bias from the perspective of theory testing. In our sample, the missing value share is below 2% for gender and education and 13% for income. Constructing the technical savings with the indicated heating costs resulted in 56% missing values, mainly because respondents did not know their actual heating costs. We therefore had to estimate heating costs for approximately half of the sample based on energy efficiency-related building characteristics as outlined in Section 3.2. This allowed us to reduce missing values for the technical savings potential to 15%. The comparison of the technical savings potential based on heating costs indicated by respondents versus heating costs derived from building characteristics shows typical and sufficient correlation levels (.71).

4. Results

In this section, first the basic comparison of the main models variants is presented. Thereafter, the influence of personality-related beliefs on beliefs about technology characteristics is introduced.
4.1. Model comparison

Performance of the different model types is summarized in Table 5. The comparison shows that the explanatory power of the belief-based model is considerably higher (above 65% compared to below 34%). The utility-based model, which uses only objective measures as independent variables (M1.1), can explain only 6% of the variance in intention to adopt. Still, all coefficients are significant in this model and indicate that young men with high income and education as well as high savings potential (low apartment occupancy and high energy use) are most willing to adopt intelligent heating thermostats. Adding the subjective measures often used in utility-based models (price value and environmental norms) leads to a significant improvement of the explanatory power. Moreover, this model indicates that addressing people with high environmental norms and showing that the product has a good price value is even more important.

Table 5: Determinants of the intention to adopt intelligent heating control devices (standardized coefficients)

<table>
<thead>
<tr>
<th>DV: Behavioral intention to adopt</th>
<th>M1.1</th>
<th>M1.2</th>
<th>M2.1</th>
<th>M2.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>R²</td>
<td>0.060</td>
<td>0.333</td>
<td>0.656</td>
<td>0.675</td>
</tr>
<tr>
<td>Adjusted R²</td>
<td>0.056</td>
<td>0.337</td>
<td>0.654</td>
<td>0.672</td>
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<tr>
<td>N</td>
<td>1,101</td>
<td>1,101</td>
<td>1,101</td>
<td>1,101</td>
</tr>
</tbody>
</table>

Coefficient (β)

Objective household and technology measures

<table>
<thead>
<tr>
<th>Income (INC)</th>
<th>0.106***</th>
<th>0.078*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>-0.110***</td>
<td>-0.075*</td>
</tr>
<tr>
<td>Gender</td>
<td>0.071*</td>
<td>0.106***</td>
</tr>
<tr>
<td>Education (EDU)</td>
<td>0.074*</td>
<td>0.040</td>
</tr>
<tr>
<td>Technical saving potential (TS)</td>
<td>0.138***</td>
<td>0.111***</td>
</tr>
</tbody>
</table>

Beliefs about technology characteristics

| Price value (PV) | 0.403*** | 0.007 | -0.008 |
| Usefulness (US)  | 0.206*** | 0.196***|
| Hedonic motivation (HM) | 0.320*** | 0.300***|
| Social influence (SI) | 0.094*** | 0.073* |
| Facilitating conditions (FC) | 0.175*** | 0.154***|
| Habit (HA)        | 0.194*** | 0.174***|
| Ease of use (EU)  | 0.024 | 0.007   |

Beliefs about personal characteristics

| Environmental norms (EN) | 0.234*** | 0.061* |
| Innovativeness (IN)      |          | 0.117***|

***p<0.001; **p<0.01; *p<0.05
However, using the belief-based model and including all theoretically relevant beliefs about technology and personality characteristics results in a very different picture. All other tested beliefs about the technology characteristics are more important than price value, which becomes insignificant in a more theoretically grounded, comprehensive belief-based model. Here, the model suggests that the price is not relevant; rather, what is important is the fun-factor (hedonic motivation), the perceived usefulness of a technology and overcoming compatibility concerns (facilitating conditions and habit). Social pressure to buy such a technology is less important. The influence of environmental norms remains significant, however less important than the above-mentioned technology beliefs. In addition, personal innovativeness is nearly twice as important as environmental norms.

In summary, the model comparison reveals three important results. First, the explanatory power of the belief-based model is clearly superior to the utility-based model. Second, the focus on objective variables and/or the isolated selection of certain variables of the belief-based model can result in omitted-variable bias and a misleading focus on adoption determinants of minor importance. Third, for novel green consumer technologies, the perceived fun (hedonic motivation), usefulness and compatibility (habit, facilitating conditions, social influence) of the technology, and the innovativeness of the adopter is decisive. Price value and environmental norms are of little or no importance.

4.2. Influence of personality traits on technology perception

Beliefs about technology characteristics are, in contrast to objective technology measures, not independent of other beliefs. Instead, beliefs about personal characteristics are theorized to influence beliefs about technology characteristics, and thereby also exert an indirect influence on intention to adopt. Accordingly, we evaluate the influence of personality beliefs on technology beliefs (see Figure 3). This reveals that both personality beliefs tested (environmental norms, personal innovativeness) positively influence intention to adopt via the aforetested technology beliefs. Comparison of the coefficients shows that overall, personal innovativeness has a significantly higher influence on the other direct determinants. However, the difference is rather small for performance expectancy and price value, while it is high for hedonic motivation, facilitating conditions and habits. Interestingly, the latter constructs all relate to the familiarity with the technology and are among the most important determinants of adoption.

These results support the premise of lower influence of environmental norms compared to personal innovativeness as previously found: Compared to people with high innovativeness, environmentally motivated people feel less at ease with the adoption of new consumer technologies, although they believe that these technologies have a high price value and
(environmental) performance. They do not enjoy (hedonic motivation) the technology adoption to the same extent, are less accustomed to using such novel technologies (habit), have fewer facilitating conditions for the adoption, and even experience considerably lower social pressure.

Figure 3: Comparison of the effect of personal innovativeness versus environmental norms on influential, belief-based constructs (indicated values correspond to standardized coefficient; thickness of arrows represents effects size; dashed arrows indicate non-significant effects)

5. Discussion and implications

5.1. Explaining the adoption of green technologies

Our results show that a comprehensive, belief-based model is best suited to explaining intention to adopt novel green technologies. Subjective belief-based variables have a higher explanatory power than objective measures. Nonetheless, one can think of research cases where the use of objective technology and household characteristics might still be preferable: for example when intending to optimize technology performance, features and design. In this case, consideration of objective technology attributes might be advisable. However, a sole focus on price value (or willingness-to-pay) could be misleading. Improvements in the technology design that increase its perceived fun-factor or compatibility are according to our results more important in the early stages of a green technology’s diffusion phase. The second
reason to use objective measures is that such data is often available for a large part of the population without laborious collection of survey data on individual beliefs. Hence, potential adopters could be investigated and identified without having to assess subjective norms and perceptions first.

However, according to our research, the explanatory power of objective variables is low. Moreover, firms interested in commercializing such technologies often already have access to consumer behavior data. Given the low explanatory power of objective constructs, they should make use of this data to extract information related to adoption-relevant beliefs. Besides the low explanatory power, an additional drawback of using objective measures is the risk of omitted-variable bias. In particular when variables from belief-based models are included selectively in utility-based models (i.e. without careful theoretical consideration), results are likely to be distorted. We show this for price value, which is highly significant and relevant when used together with objective variables only (Table 5), but turns insignificant when other important beliefs such as hedonic motivations and habit are considered too.

Our results also contribute to a better understanding of the controversial role of environmental norms in early-stage adoption. The model comparison shows that the familiarity with new technologies in general (personal innovativeness) is significantly more important than a positive attitude toward pro-environmental behavior (Table 5). The evaluation of the effect of these personality beliefs on technology beliefs suggests that such effect will be less pronounced for products where price value and performance expectancy are more important (Figure 3). While environmental norms still positively influence technology perception (and hence adoption), this might not be the case for related, but less action-oriented notions such as environmental awareness or concerns. The latter constructs express post-materialistic worldviews and values, which are linked to specific behavior to lesser extent (Stern, 2000). This could explain the “counterintuitive” finding from Poortinga et al. (2003) that people with above-average environmental concern are relatively less willing to adopt measures enabling higher energy savings and vice versa for people with low environmental concern. Our results indicate that the influence of potential adopters’ familiarity with adopting new technologies is more important than environmental beliefs. This could be one reason why for example Poortinga et al. (2003) find that people with below-average environmental awareness show higher acceptance of technical sustainability measures and lower acceptance of behavioral sustainability measures (although these differences were not significant).

Our study is only a step toward a more in-depth understanding of the adoption of green consumer technologies. Further research should apply belief-based models to technologies which already have a higher market share (i.e. are more diffused) or which are similar to already diffused technologies. In such cases, beliefs related to the compatibility of the
technology might fade and price value might become more important. If this is the case, environmental norms might also become more decisive. Our results suggest that such an increase in the relevance of price value amplifies the indirect influence of environmental norms on intention to adopt accordingly (Figure 3).

In addition, it would be valuable to evaluate the robustness of our findings by comparing them to results from studies across different geographical regions and technologies. However, we do not expect large variations as in particular the belief-based adoption constructs have already been applied across multiple technologies and regions, leading to similar findings (see e.g. Venkatesh et al., 2012).

5.2. Implications for environmental policy and green business

To achieve a timely development and diffusion of green technologies, the right determinants of adoption have to be addressed. Our results suggest that for novel green technologies such as intelligent thermostats, improving price value and environmental performance has little influence on early adoption and diffusion. This challenges the effectiveness of conventional environmental policy instruments: Monetary incentives such as carbon taxes or subsidies aim to affect the price value of technologies. Information campaigns typically raise environmental awareness or inform about technology performance (e.g. savings potential). The main determinants of adoption such as hedonic motivation, habit and facilitating conditions are, however, not addressed. More recent environmental policy approaches such as nudges (Sunstein, 2013; Thaler & Sunstein, 2008), which aim at altering the choice architecture, might prove more promising. These emphasize and address non-rational decision making phenomena such as affect and inertia. Moreover, such policy approaches are justified and supported by results from more belief-oriented behavioral economy research (Kahneman, 2011). However, there is no one size fits all approach. For example, labels often used to nudge consumers may indicate and focus on price value or performance of a technology. Hence, they do not address the most important barriers to adoption (i.e. absence of fun factor or compatibility). In addition, providing novel green consumer technologies per default can be problematic too. Installation and use might be hurdles that many in the mass market cannot overcome without extensive support—all of which is amplified by the tendency for early-stage technologies to be more error-prone.

From our perspective, the most promising policy approach is to promote the early market diffusion of novel green technologies with targeted marketing efforts. Consumer psychology has been considered for decades in sales strategies (Cialdini, 2001). Firms are used to emphasizing emotional beliefs such as the fun-factor, adjusting technologies to match consumer habits and providing facilitating services. Therefore, policies asking or even
incentivizing firms to sell novel green technologies to households are an effective lever to accelerate the adoption of green technologies. The European Union has already followed this train of thought. Emission targets for vehicle fleets for instance incentivize car OEMs to develop and offer low-emission vehicles (European Parliament and the Council of the European Union, 2009). In addition, selling innovative cars is rewarded with extra emission credits. Similarly, promoting voluntary building standards for efficient houses supports the diffusion of novel technologies (Grösser, 2013). Such instruments could be expanded to further environmentally relevant areas. Telecommunication or utility firms could for example be incentivized to support the diffusion of intelligent heating thermostats and similar smart home consumer technologies.

Our results also provide important insights for firms aiming to sell novel green consumer technologies, regardless of whether the motivation stems from above-mentioned policy incentives or firm-intrinsic business objectives. To sell novel green technologies to consumers, a narrow focus on technology cost and performance in the early stages of diffusion should be avoided. Instead, marketing efforts should consider a broader set of attributes decisive for belief-based adoption, such as the fun-factor (hedonic motivation) and especially compatibility with the technical and social environment (facilitating conditions, habit, social influence). Our results indicate that it is better to target people with high personal innovativeness instead of individuals with high environmental norms. As more and more firms collect data about their consumers, they might be able to more precisely identify their potential customers’ personality traits upfront. Data on previous purchases for instance could indicate which type of technology is consistent with consumers’ habits and facilitating conditions. Consumers who are early adopters of smartphones and use applications to optimize daily planning might be more likely to adopt an intelligent heating device.

6. Conclusion

In the environmental science literature, the adoption of novel green consumer technologies is typically evaluated with a model based on objective household utility theory. In this, the focus is on objective household and technology measures. Subjective constructs closely related to the economic or environmental perception of a technology are being included merely selectively. More recently however, green technology adoption studies have started to include determinants from models based on subjective personal belief-based theory. We compare these two approaches, using a survey with 1,101 responses about a typical green consumer technology (i.e. intelligent thermostats). This reveals that the utility-based model, which considers objective household and technology performance characteristics only, suggests that young men with high incomes and education as well as high technological savings potential are most likely to adopt. Nevertheless, the model explains only 6% of the variance of the
intention to adopt. Considering price value and environmental norms as additional determinants increases the explained variance to 35% and indicates that these two beliefs are more important than objective measures.

However, contrasting these findings with the belief-based model, which comprises all technology and personality beliefs deemed relevant by previous belief-based adoption research, explains over 65% of the variance. Interestingly, adding relevant belief-based determinants renders price value insignificant and environmental norms less important than other beliefs. Hedonic motivation, usefulness, habit, facilitating conditions and personal innovativeness have the highest effect on the adoption of intelligent thermostats in this case. This shows that belief-based models have significantly higher explanatory power. In addition, picking variables from the belief-based model in isolation as observed in previous environmental studies is prone to omitted-variable bias.

Furthermore, investigating the influence of personality beliefs on technology beliefs explains why environmental norms show lower influence on intention to adopt than personal innovativeness. While people with high environmental norms have potentially similar beliefs about price value and usefulness, they have a much less positive view of the compatibility of the technology with their technical and social environment. Moreover, they derive less pleasure from adopting these technologies compared to people with high personal innovativeness, according to our results. Consequently, environmental norms might be more important for technologies where price value and usefulness (i.e. performance) are the main barriers to adoption. However, additional research is needed to substantiate the interpretation of our results. Using comprehensive, theoretically grounded belief-based models to assess other technologies and different cultural settings represents a viable options for further research in this respect.

For environmental policy, the results suggest that improving the price value or increasing the environmental awareness contributes comparatively little to early-stage green consumer technology diffusion. This challenges the effectiveness of conventional instruments such as environmental taxes and information campaigns. Instead, our results suggest that incentives for technology providers and retailers are more effective given that firms are potentially more capable of and in a better position to emphasizing diffusion-relevant technology attributes (e.g. pleasure instead of price).
7. References


8. Appendix

Table A1: Comparison of survey sample with country statistics

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<th>Variable</th>
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<td></td>
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<td>16%</td>
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<td>Vocational training</td>
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Subtle Servants: The Importance of Everyday Practices for Experiential Consumer Technology Adoption

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Abstract

Advances in computing technology have spurred the digitalization of the world around us. More and more everyday artifacts with built-in computing capability affect our daily practices and experiences. These experiential consumer technologies are very different from their traditional counterparts. No longer seen as discrete computing devices, they are instead conflated with existing everyday objects and increasingly entangled with our everyday practices. We argue that these distinctive characteristics also affect the relevance of traditional determinants of technology adoption, and aim to extend existing technology- adoption theory to the emerging field of experiential consumer technologies. We systematically theorize the key points of difference between experiential and non-experiential consumer technology adoption, and propose a concept for evaluating the former. We test our theoretical model and show the significance of our theorized constructs and their influence on the behavioral intention to adopt. We find strong empirical support for the effects of the experiential-specific latent constructs. Based on our results, compatibility with everyday practices emerges as the single most influential determinant of the adoption of experiential technologies. Thus, a new set of determinants is required to complement existing constructs such as perceived usefulness and hedonic motivation, which are regarded as central to consumer technology adoption.

Keywords

Technology adoption; technology acceptance; experiential computing; consumer technology; diffusion
1. Introduction

“The advance of technology is based on making it fit in so that you don’t really even notice it, so it’s part of everyday life.” Bill Gates

In a world that relies more and more on technology, the digitalization of everyday processes has become central to our lives (Bødker, Gimpel, & Hedman, 2014; Rauhofer, 2008). We now have many terms intended to describe this incursion of computing into everyday life; they include “the internet of things” (Fleisch, 2010; Jin, Zhuo, Hu, Chen, & Yang, 2013), “pervasive systems” (Adipat, Zhang, & Zhou, 2011), and “ubiquitous computing” (Serrano & Botia, 2013; Tang, You, Tang, & Guo, 2013). A new technological paradigm has emerged, where computing capacity is conflated with everyday artifacts (Yoo, 2010). Google’s 2014 acquisition of Nest Labs Inc., which manufactures an inconspicuous intelligent thermostat for private homes, for USD 3.2 billion, is just one illustration of the relevance these new technologies have already acquired.¹ In his call for research on computing in everyday life, Yoo (2010) proselytized the apposite notion of “experiential computing,” which we have adopted for the purpose of this research. He explains that experiential (consumer) technologies (ECTs) enable “experiences in everyday activities through everyday artifacts with embedded computing” (Yoo, 2010). ECTs define, shape, and intervene in well-established activities that are basic, yet often vital too. Prominent examples include personal activity tracking (with smartphone apps and/or wearable technology such as Fitbit²), blood-glucose meters for iPhones, Google Glass (Google’s wearable computer spectacles), Wi-Fi-enabled plant-watering systems, and the aforementioned intelligent thermostats. Even today, we are already free to adopt ECTs that can help us eat, sleep, interact, manage our households, or heat our homes.

Scholars across several disciplines (Limayem, Hirt, & Cheung, 2007; Nelson, Peterhansl, & Sampat, 2004; Venkatesh, Davis, & Morris, 2007), and in particular the information systems

¹ Typically, intelligent thermostats automatically reduce heater output during times with lower thermal demand (i.e. when occupants are out, or at night). This is enabled e.g. by automated location tracking via a smartphone app, or by sensors and algorithms that automatically adapt to the behavior of household members. Compared to the entire heating system, intelligent thermostats are relatively inexpensive, and can be installed and replaced more easily too. Hence, they hold the potential to retrospectively upgrade existing homes (i.e. heating systems) and might serve as an alternative to traditional retrofitting. Mostly, such devices are connected to the internet, and can be controlled remotely with a smartphone or web browser.

² These activity trackers, developed and marketed by the company of the same name, are wearable devices small in size that measure and wirelessly transfer data such as the number of steps walked, calories burned and sleep quality.
(IS) community (Venkatesh, Thong, & Xu, 2012; Yoo, 2010), have investigated the determinants of individual technology adoption (i.e. acceptance, rejection) for decades (Cenfetelli & Schwarz, 2010). In fact, efforts in this area are so numerous that some scholars have warned against adding any further IS acceptance studies to the pile, since “more of the same” simply leads to “theoretical confusion and chaos” (Bagozzi, 2007; Benbasat & Barki, 2007: 212). However, the dynamic nature of technology innovation constantly challenges and stretches the boundaries of existing theories. “Although traditional general-use computers will never disappear, the rapid advances of technology bring fundamental changes in the ways in which we interact with computers” (Yoo, 2010: 215). This is also true of technology adoption. In contrast with earlier computers, ECTs are not used solely for work or finding information. “Using a computer” is no longer a discrete activity, but is subtly interwoven with everyday practices. Moreover, for many people, technology is so pervasive that their “acceptance” of it is no longer even consciously questioned (Yoo, 2010); a new generation of “digital natives” (Vodanovich, Sundaram, & Myers, 2010) have never known a world where computer technology was not part of their daily lives. With such unprecedented embeddedness of technology into everyday practices, we assume that the context of use is rendered sufficiently significant to affect technology adoption as well. However, in IS acceptance and adoption research, the salient peculiarities of these novel, rapidly proliferating experiential products have yet to be addressed. Therefore, our study asks: What really drives the adoption of novel experiential consumer technologies (ECTs)?

We suggest that existing theory is inadequate for capturing the idiosyncrasies of ECTs, and operationalize our efforts by specifying a construct largely neglected in previous adoption research: compatibility with everyday practices. This is complemented by several prevalent latent variables theorized to be relevant to both traditional information technology and ECTs. Our constructs come together in the systematic development of a theoretical framework for researching the adoption of ECTs. We use structural equation modeling to test our theoretical model. For this, we collected data in two stages by conducting a survey in two different European countries, gathering a total of 976 and 971 valid responses respectively. We find empirical support for our hypothesized constructs, showing that a new set of adoption determinants prevails for ECTs. The theoretical model is capable of explaining a significant amount of variance (adjusted R² of .72 and .63 respectively). Our results suggest that perceived compatibility with everyday practices is the single most influential driver for ECT adoption. Several constructs that were shown to be important in the context of “traditional” consumer-technology adoption, such as hedonic motivation or personal innovativeness, also prove to be significant. However, the relationship between, for example, ease of use and price value appears much less pronounced.
This study makes several important theoretical and managerial contributions. From a theoretical perspective, we add to the understanding of novel consumer technology diffusion. ECTs represent a phenomenon that has been broached in adoption research, but not theorized or systematically embraced. From a managerial perspective, we shed light on the adoption determinants of a rapidly diffusing generation of technology that changes not only human-computer interaction, but also the nature of related product and service innovations (Yoo, Boland, Lyytinen, & Majchrzak, 2012). In summary, we offer scholars and practitioners guidance, in the form of a structural model, for the future assessment of the catalysts and barriers to the adoption of ECTs.

2. Theoretical Framework

In this section, we first briefly discuss adoption determinants that have proved significant in previous research. We then go on to outline differences between ECTs and traditional technologies, based on which we develop our main hypothesis. Integrating all arguments, we conclude the chapter with an integral illustration of our theoretical model (Figure 1).

2.1. Extant Technology Adoption Determinants and Their Origins

Originally, adoption theories in IS research were concerned with the acceptance and use of productivity tools in the workplace (e.g. computer terminals, software applications). As a result, utilitarian beliefs were among the first adoption determinants to be theorized. The technology acceptance model (TAM)—developed by Davis (1985) during his doctoral studies—is one such example (see also Davis, 1989). Despite its specificity, TAM has since been applied to a wide range of technologies and contexts (Benbasat & Barki, 2007; Parry, Kawakami, & Kishiya, 2012; Song, Parry, & Kawakami, 2009). Today, it is considered the most influential and commonly used framework for investigating technology adoption (Gounaris & Koritos, 2012; Lee, Kozar, & Larsen, 2003).

TAM focuses on two main beliefs: perceived usefulness and perceived ease of use. Following decades of study, it has been commonly accepted that perceived usefulness is indeed a very influential belief (Benbasat & Barki, 2007). Even when comparing TAM with other prominent IS adoption models, perceived usefulness remains the single strongest predictor of behavioral

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3 Most prevalent IS theories, and many studies, adhere to the term “acceptance” (e.g. Technology Acceptance Model, Unified Theory of Acceptance and Use of Technology) rather than “adoption”. The latter term implies user agency and active choice rather than external imposition and passive acceptance, making it arguably more applicable to the consumer context.
intention (Venkatesh, Morris, Davis, & Davis, 2003). While perceived usefulness was, in its original context, associated only with job performance, Venkatesh et al. (2012, p. 159) later defined it more broadly as “the degree to which using a technology will provide benefits to consumers in performing certain activities.” This definition is comparable to the “relative advantage” notion from the “diffusion of innovations theory” (Moore & Benbasat, 1991; Rogers, 2003; Song et al., 2009). More importantly, perceived usefulness has lost none of its relevance, and remains a central adoption determinant in the consumer context to this day (see e.g. Gounaris and Koritos 2012; Miltgen et al. 2013; Wunderlich et al. 2013).

TAM’s second seminal construct, perceived ease of use, is commonly defined as “the degree of ease associated with consumers’ use of technology” (Agarwal & Karahanna, 2000; Davis, 1989; Gounaris & Koritos, 2012; Miltgen et al., 2013; Moore & Benbasat, 1991; Venkatesh et al., 2012; Yi, Jackson, Park, & Probst, 2006). Perceived ease of use proved to be an important determinant in itself (Benbasat & Barki, 2007), but its direct influence on behavioral intention to adopt is commonly less pronounced than that of perceived usefulness (see e.g. Agarwal and Karahanna 2000; Venkatesh et al. 2012).

Despite the probable influence of usefulness and ease of use, TAM’s parsimonious emphasis on two beliefs has also attracted criticism (Bagozzi, 2007; Hirschheim, 2007), and empirical work revealed that it sometimes has limited predictive power (Sun & Zhang, 2006; Venkatesh et al., 2007). Consequently, a vast number of studies have attempted either to put forward competing models, or to make (incremental) adaptations (Benbasat & Barki, 2007). In an effort to synthesize the resulting proliferation of theories, Venkatesh et al. (2003) compared eight of the most influential models for technology adoption. Building on this comparison, the authors then formulated the unified theory of acceptance and use of technology (UTAUT) and tested it among employees who were introduced to a new technology at work. In addition to perceived usefulness (i.e. performance expectancy) and ease of use (i.e. effort expectancy), UTAUT describes a third direct relationship between social influence and behavioral intention to adopt. However, social influence proves significant only in the context of mandatory usage, and not when adoption is voluntary (Venkatesh et al., 2003), the latter being an inherent characteristic of consumer adoption.

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4 While the exact wording of PU constructs varies across models (e.g. “perceived usefulness”, “performance expectancy”), they all reflect the same underlying idea.

5 The eight models were the theory of reasoned action, the technology acceptance model, the motivational model, the theory of planned behavior, a model combining the technology acceptance model and the theory of planned behavior, the model of PC utilization, the innovation diffusion theory, and the social cognitive theory (Venkatesh et al., 2003).
Recognizing that technology is adopted differently by consumers than in the workplace, Venkatesh et al. published an extension of UTAUT in 2012, dubbed UTAUT2. “A consumer who typically enjoys more discretion and more alternatives (than in a work-setting) may be guided by a host of salient criteria other than whether the medium is useful and easy to use” (Vijayasarathy, 2004: 748). For example, when people must pay for a product or service and are free to adopt or reject it, costs usually figure in their thinking. However, prior theory assumed that the focal technology was being introduced unilaterally by the employer, making price a negligible factor in individual acceptance. To make UTAUT2 more widely applicable, Venkatesh et al. (2012) integrated price into their model. However, costs are difficult to appraise in absolute terms, particularly when comparing technologies with different features. Therefore, price is often conceptualized in combination with the perceived value of a product or service, as “price value” (Venkatesh et al., 2012; Zeithaml, 1988). Several IS studies on technology acceptance account for this by considering “the cognitive tradeoff between the perceived benefits of the applications and the monetary cost of using them” (Dodds, Monroe, & Grewal, 1991; Venkatesh et al., 2012).

Usefulness, ease of use, and price value accentuate the perceived utilitarian value of a technology (i.e. extrinsic motivations). A more intrinsic form of motivation is the hedonic desire to experience pleasure and satisfaction (Vallerand, 1997; Van der Heijden, 2004). Given the embeddedness of today’s technologies into people’s lives, and their resulting emotional resonance, the hedonic motivation to adopt them has become particularly relevant (see e.g. Agarwal and Karahanna 2000; Venkatesh et al. 2012). Venkatesh et al. (2012), for example, demonstrate empirically that “the fun or pleasure derived from using a technology” (Agarwal & Karahanna, 2000; Kim, Chan, & Gupta, 2007; Venkatesh et al., 2012) is a significant, important predictor of the behavioral intention to adopt mobile internet.

Another non-utilitarian trait covered in prior adoption studies is innovativeness (Midgley & Dowling, 1978; Rosen, 2005). Some previous conceptualizations of innovativeness characterize the point in time at which a person adopts new technology (e.g. early adopters, late majority) rather than measuring innovativeness as a personality trait (Lewis, Agarwal, & Sambamurthy, 2003; Rogers, 2003). Others, such as Agarwal and Prasad (1998), reconceptualize and complement this view by arguing that “individuals with higher personal innovativeness are expected to develop more positive beliefs about the target technology” (Lewis et al., 2003: 663). Studies on technology anxiety follow a similar path; one such is that from Meuter et al. (2005), where the authors show that a negation of innovativeness (i.e. technology anxiety) may lead to the avoidance of technological tools. Overall, it is well documented that personal innovativeness, defined as “the willingness of an individual to try out any new information technology” (Agarwal & Prasad, 1998: 206), can influence technology
adoption. Indeed, a number of studies find a direct relationship between personal innovativeness and behavior (e.g. Eastlick and Lotz 1999; Goldsmith 2002; Limayem et al. 2000).

Summing up, IS adoption research has emancipated itself from the narrowly utilitarian perspective, and numerous studies have given us a better understanding of consumer technology adoption. Usefulness, ease of use, price value, hedonic motivation, and innovativeness are among the most prominent and uncontroversial adoption determinants.

We are well aware of the heated debate about technology adoption being over-researched. Indeed, “technology adoption research seems to see a lot of replication with minor ‘tweaking’” (Venkatesh et al., 2007: 268). However, we must remember that our phenomenon of interest is in flux. Technology continues to advance; in particular, “the pervasive adoptions of and innovations with digital technologies are radically changing the nature of products and services” (Yoo et al., 2012: 1398). Therefore, we would argue that we are at the threshold of a new phase of technology adoption study. Just as we saw a shift from organizational to consumer technologies, the shift from traditional computers to ECTs has fundamentally altered the nature of adoption determinants. To substantiate this further, we now discuss differences between traditional consumer information technologies and ECTs, and introduce our hypotheses.

2.2. ECT Adoption Determinants

2.2.1. Digitalization of Existing Artifacts and Everyday Practices

The term “ECTs” denotes products and services that add new digital capabilities to artifacts that are already central to everyday practices (Yoo, 2010). This includes, for example, a pair of running shoes to which a radio-transmitting microchip for tracking personal performance is added (Yoo et al., 2012), wearable glasses that are augmented by an optical head-mounted display, or a home thermostat that is upgraded to automatically detect the presence of the user. With such embeddedness, technology usage becomes more subliminal, to the extent that users need not deliberately call on the device in order to realize its benefits (Bødker et al., 2014). For example, a sensor-automated home thermostat can adjust the in-room temperature once it detects someone going out. This differs from traditional computer usage patterns, where using a device would be a conscious, bounded, and often exclusive activity.

Whenever a digitalized artifact (ECT) is designed to control, intervene in, or mediate processes related to various everyday practices, these practices in turn shape consumers’ attitude towards adoption. More specifically, everyday practices in themselves become highly relevant for adoption. Note that such practices should not be confused with the notion of habits (or daily
routines) in previous IS research, i.e. behaviors associated with the prior experience or use of a technology. According to this perspective, experience is a necessary (though not sufficient) condition for habits to be formed (Limayem et al., 2007; Venkatesh et al., 2012). With ECTs, however, compatibility with everyday practices does not require prior experience. Rather, it describes the perceived fit between an ECT and an individual’s existing habits and routines in the area relevant to the ECT, and reflects the individual’s willingness to allow the ECT to become a part of their day-to-day life.

Thus, our proposed notion is closest to the idea of compatibility with “all aspects of my work” or “the way I like to work,” as explicated by Moore and Benbasat (1991), who draw from Rogers’ (2003) extensive work on innovation attributes. While the general idea of “compatibility” as an important determinant of adoption dates back several decades (e.g. Rogers & Shoemaker, 1971), many early versions of this concept were rather broad, and proved difficult to operationalize due to e.g. overlap with other adoption determinants (Moore & Benbasat, 1991). More recently, IS scholars such as Karahanna et al. (2006) have refined the notion. Investigating the acceptance of a customer relationship management (CRM) tool in a bank, the authors focus on workplace-related compatibility dimensions such as compatibility with preferred work style, compatibility with existing work practices, compatibility with prior experience, or compatibility with values. However, there is no counterpart to this model aimed at non-organizational contexts, as far as we know—the aspects we believe are most relevant in an experiential consumer context, i.e. perceived compatibility with everyday practices, have received little attention. Synthesizing these ideas and transposing them into the realm of ECT adoption, we adapt (Tornatzky & Klein, 1982: 33) definition of compatibility, which is “congruence with the existing practices of the adopters,” and hypothesize:

\[ H1: \text{Perceived compatibility with everyday practices positively influences the intention to adopt ECTs.} \]

2.2.2. Interconnectedness with Existing Technology and Technical Compatibility

ECTs function in concurrence with other technologies (Bell & Dourish, 2007), translating activities and complex information into homogeneous data streams that are sharable among devices. As a result, they transcend the “strict boundaries of complex physical products” (Yoo et al., 2012: 1404), form networks with other IT-enabled artifacts, and connect to extant information infrastructure such as the internet (Yoo, 2010). Without such connectivity, their functionality is often impaired. Running shoes equipped with a distance-measurement sensor, for example, might rely on a radio connection to the user’s smartphone to display recorded data. In theory, such connectivity allows an unlimited number of connections between
experiential technologies, enabling myriad new features. In practice, however, technical compatibility is pivotal for actual user connectivity, and is thus decisive for the performance of ECTs.

The idea of compatibility in acceptance and adoption research can be traced as far back as the theory of planned behavior. Perceived behavioral control (Ajzen, 1991) describes the idea that the resources available to a person—including existing technology infrastructure—must affect behavioral intention to some extent (Ajzen, 1991). Venkatesh et al. (2003) have built on this idea and integrated similar notions from Thompson et al.'s (1991) model of PC utilization, as well as the innovation diffusion theory (Moore & Benbasat, 1991), into a single reflective scale termed “facilitating conditions.” This scale includes one item capturing the perception of technical compatibility.\(^6\) The influence of facilitating conditions on behavioral intention, however, tests non-significant in the context of new technology introduced at the workplace. In the consumer context, though, Venkatesh et al. (2012) later showed that facilitating conditions—including the item for technical compatibility—are indeed a significant determinant of behavioral intention to adopt. The measurement scale still subsumed several different dimensions, such as personal resources, knowledge, and assistance during use (Venkatesh et al., 2012). However, we believe that a general “facilitating conditions” construct cannot precisely capture diverse and potentially unrelated factors such as technical compatibility and personal resources,\(^7\) so we put forth a more fine-grained theory. The more embedded a technology is, the more important technical compatibility becomes. Consumers are less likely to adopt if they perceive that compatibility with an existing system will cause them problems. Therefore, we argue that technical compatibility is not only distinct from other factors that have previously been aggregated under “facilitating conditions,” but also a significant determinant of adoption for ECTs in itself. Hence, we hypothesize:

\[H2: \text{Perceived technical compatibility positively influences the intention to adopt ECTs.}\]

2.2.3. Embeddedness in Existing, Vital Activities and Risk

ECTs do much more than just process information. They affect a broad range of everyday activities, some of them vital, and are profoundly “interwoven into the very fabric of our lives” (Vodanovich et al., 2010: 713). In contrast, when traditional home computers first appeared, they were often used for bounded, peripheral tasks such as basic word processing, playing videogames, managing household accounts, or drawing family charts (Haddon, 2011). Even today, there is a marked difference between deliberately sitting down to use a desktop or laptop

\(^6\)“Mobile Internet is compatible with other technologies I use” (Venkatesh et al., 2012).
\(^7\)We also share methodological concerns related to reliability and internal consistencies of the measurements when operationalized as one latent, reflective construct.
computer and the fragmentary, impulsive, and often location-independent manner in which ECTs are typically used (largely enabled by advanced wireless communications and mobile connectivity). ECTs have permeated their users’ lives, achieving an unprecedented level of “closeness” and affecting quality of life much more directly than previous technology generations. Consequently, users delegate much more responsibility to the technology, whether voluntarily or not.

Because of this, ECTs might trigger concerns about potential negative consequences once they are adopted. A technology that becomes so interwoven in everyday practices will probably be approached with caution. Furthermore, the more interconnected an artifact, the more it can affect other devices and systems. Previous research has shown that products which are interconnected, collect, process, and produce information, and which respond to their environment are perceived risky (Rijsdijk & Hultink, 2009). In addition, emerging technologies in particular often have flawed designs that only mature over time (Anderson & Tushman, 1990; Schilling, 2002). Novel technologies are more prone to failure (Foxon et al., 2005) and to interfering with or even damaging existing systems with which they interact. They can pose a heightened risk to privacy (Featherman & Pavlou, 2003; Hess, McNab, & Basoglu, 2014; Luo, Li, Zhang, & Shim, 2010; Pavlou, 2003; Rauhofer, 2008). Finally, they might also be introduced by early-stage companies who lack a proven track record (Cassar, 2004; Lounsbury & Glynn, 2001).

Lancelot Miltgen et al. (2013) show the importance of perceived risk in the context of technologies that affect the privacy of adopters (biometrics) based on TAM, UTAUT, and Rogers’ (2003) diffusion of innovation theory, while Martins et al. (2014) integrate perceived risk into UTAUT to investigate the adoption of online banking. Risk has long been a topic of interest in consumer behavior research (e.g. Bauer, 1960; Martins et al., 2014; Ostlund, 1974); however, it has not been recognized as a generally influential belief for adoption. Our argument is that the importance of risk is magnified by the characteristics of ECTs. The more embedded a technology is in everyday practices, and the more it interconnects with other systems, the more vigilant potential adopters will be. Accordingly, in line with (Featherman & Pavlou, 2003: 1035), we define risk as “uncertainty regarding the possible negative consequences of using a product or service,” and propose the following hypothesis:

\[ H_3: \text{Perceived risk negatively influences the intention to adopt ECTs.} \]

The technology characteristics described above are by no means exhaustive. However, we argue that they do represent the most crucial differentiating factors relevant for a better understanding of ECT adoption in today’s world. Based on this theoretical rationale, our conceptual model to investigate the determinants of ECT adoption is illustrated in Figure 1.
This model allows to test the direct effects of experiential-specific latent variables (compatibility with everyday practices, technical compatibility, risk) on the intention to adopt. Intention is “the most proximal influence on behavior” (Venkatesh & Brown, 2001: 76) and has been successfully used as a substitute measure for adoption in previous research (e.g. Davis, 1989; Venkatesh and Bala, 2008; Viswanath Venkatesh et al., 2003; Venkatesh et al., 2012). Furthermore, we can control for non-experiential specific direct determinants (usefulness, ease of use, price value, hedonic motivation, innovativeness) that have proven relevant for consumer technologies in general. Focusing on the direct effects on behavioral intention allows us to achieve a parsimonious presentation of our ideas at this early stage of ECT adoption research; broadening adoption models without profound theoretical rationale and/or an established empirical fact base can easily do more harm than good (Bagozzi, 2007).

3. Methodology

To test our hypotheses, we chose potential adopters of intelligent thermostats as our target population.8 Intelligent thermostats are a recently commercialized ECT that embody all the

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8 Companies such as Nest Labs Inc. in the US or tado GmbH in Europe are examples of players that were founded with the intent to commercialize intelligent thermostats. In addition, large incumbents such as Honeywell were also
idiosyncrasies of the breed. They add digital features to a previously mostly low-tech, non-networked product. They affect and intervene in basic, everyday activities, aiming to digitalize and automate an everyday practice (i.e. home heating), and to this end they connect to, and are embedded in, existing information technology. Intelligent thermostats are designed as retrofit controllers for existing heating systems, and several commercially available models can be self-installed. Once wired to the heating system, they can be linked to an online server, and the user can then monitor and adjust the heating system with a smartphone app or via a web browser. Furthermore, intelligent thermostats can automatically control in-room temperature to optimize energy efficiency and comfort. They typically feature sensors and algorithms that adapt to the behavior of a household, with some even deploying location-based temperature regulation enabled by data from users’ smartphones (geo-fencing).

3.1. Measurement and Survey Development

To operationalize theorized and defined constructs, we adopt items used in previous work where possible. Measures for behavioral intention to adopt are adapted from Davis et al.’s (1989) seminal work on TAM, which has been used frequently from its publication to the present day (see e.g. Venkatesh et al., 2012). Likewise, scales for usefulness and ease of use are adopted from Davis (1989), while measures for perceived price value and hedonic motivation are adopted from Venkatesh et al.’s (2012) recent work. The measurement scale for innovativeness is adapted from Agarwal and Prasad (1998) (see also Lu, Yao, & Yu, 2005; Yi et al., 2006).

For our focal, experiential-specific constructs (Figure 1), however, we could not draw on existing measurement scales. Consequently, we developed new scales in accordance with our theory, based on an extensive review of existing measures. The measurement scale of compatibility with everyday practices was influenced by work from Gounaris and Koritos (2012), Moore and Benbasat (1991), and Vijayasarathy (2004). A measurement item for technical compatibility was adapted from Venkatesh et al. (2012). We drew on work by Featherman and Pavlou (2003), Pavlou and Gefen (2004), and Bélanger and Carter (2008) to develop an integrated measurement scale for perceived risk.

Subsequently, we tested all our experiential-specific measurement scales according to the procedures for new measurement scale development discussed by Bagozzi, Yi, and Phillips (1991), Boudreau, Gefen, and Straub (2001), Spector (1992), and MacKenzie, Podsakoff, and Podsakoff (2011). More specifically, in addition to theorizing and specifying the nature of the construct and its conceptual theme in unambiguous terms and in a manner that is consistent offering comparable products at the period of this study. The interested reader may refer to any of these firms for further technical information on their ECT offerings.
with prior research” (MacKenzie et al., 2011: 298), we reviewed the content validity of the instruments. For this, constructs and measurement items were iteratively discussed with an expert panel (Boudreau et al., 2001) consisting of the CEO, CTO, and CMO of an intelligent-thermostat manufacturer; product and marketing managers from Germany’s three largest utilities\(^9\) working on intelligent thermostat product offerings; and experts from academia.

Following theoretical and discussion-based scale reduction and item refinement, we specified a first measurement model, and conducted a total of four pre-tests. While the first pre-test was exploratory and distributed to a group of researchers only, the three pre-tests thereafter were full-fledged surveys sent to several hundred participants. After excluding incomplete and invalid responses from these three pre-tests, we conducted an in-depth analysis, including valid responses from 55 to 141 participants. Prior to each pre-test, a group of two or three people was asked to complete the entire questionnaire. A researcher was present to observe the response process, and individual feedback was collected once the surveys were completed. Hence, scale evaluation and refinement was conducted in a two-step process along four pre-tests. Measurement scales validated in previous research were included, and their validity in the new context of experiential technologies was confirmed. After each pre-test—following iterative scale purification—the psychometric properties of the scales were reevaluated (see e.g. Jarvis et al. 2003; MacKenzie et al. 2011). An overview of all constructs, related final measurement items, and sources is included in the appendix (Table A1).

Irrespective of scale origin, reflective indicators are used across all constructs and all items are measured using a seven-point Likert scale, with the anchors being “strongly disagree” and “strongly agree.” Since our final survey as well as all pre-tests were conducted in German, but existing scales are reported in English, rigorous translation procedures were deployed. Two researchers, assisted by native speakers, translated English items into German, and a group of three researchers then reviewed the others’ translation before settling on an agreed wording. Before the final survey was carried out, all items were translated back into English to confirm translation equivalence. Nonetheless, the reliability of the translated scales should not be taken for granted (Brislin, 1986; Geisinger, 1994), and was evaluated throughout pre-testing. Evidence from the pre-tests showed that all final measurement scales are likely to be valid, reliable, and suited for our main research effort.

### 3.2. Samples and Data Collection

To collect our main data, we conducted two online surveys in sequence. The first survey (study 1) was launched in Germany. Two months later, we sent the same questionnaire to Swiss

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\(^9\) Based on 2013 revenues.
residents (study 2) to check if the findings could be replicated in two samples without overlapping respondents. The countries share a common border and have been shown to have similar cultural values and beliefs (Hofstede, 1980; House, Hanges, Javidan, Dorfman, & Gupta, 2004; Ronen & Shenkar, 1985). In each country, a market research firm gave us access to their online panel. To ensure we addressed potential adopters, survey participants were only invited to complete the survey if they indicated possession of a smartphone and their own heating system. To allow for generalizability, representativeness of the samples based on age and gender was addressed by inviting additional respondents as long as certain age and gender brackets were substantially underrepresented (see Table 1) and by directly excluding respondents pertaining to a bracket that had already reached its threshold. Participants were offered a small monetary compensation for their efforts by the market research firm running the online panel. All survey participants were given a brief introduction and illustration of intelligent thermostats at the beginning of the survey in order to avoid random answers based on a lack of conceptual understanding. We also included manipulation checks in the final surveys so we could better identify fraudulent respondents.

Following this approach, we ultimately received 1,220 survey responses in study 1 and 1,185 in study 2. An additional 244 questionnaires from Germany and an additional 214 questionnaires from Switzerland were either incomplete or showed unambiguous signs of disingenuous responses\(^\text{10}\); all were eliminated from the sample. The remaining samples used for our analysis consist of N=976 valid responses for study 1 and N=971 valid responses for study 2. A comparison of the final sample with figures from the national statistical offices can be found in Table 1. It compares not only the filter criteria age and gender, but also education and income, which were evaluated only after the survey was conducted. Given the comparatively low bias across gender, age, education, and income, we have reason to believe that our findings are generalizable, at least to the wider populations of the two countries involved.

\(^{10}\) E.g. zero variance, zero variance per survey page, unrealistic survey lead times.
3.3. Data Analysis

To test the nomological validity of our scales, and also to assess their psychometric properties, we deployed structural equation modeling (SEM), which offers several advantages (Agarwal & Karahanna, 2000; Boudreau et al., 2001; Gefen, Straub, & Boudreau, 2000; Karahanna et al., 2006; Limayem et al., 2007; Venkatesh et al., 2012). SEM has become a quasi-standard in marketing and management (Hair, Ringle, & Sarstedt, 2011) and in particular in IS adoption and acceptance research (Ringle, Sarstedt, & Straub, 2012). The integrated analysis of measurement and structural model allows measurement errors of observed variables to be included in the model, and factor and causal path analysis are combined (Gefen et al., 2000).

Table 1: Comparison of survey samples with country statistics

<table>
<thead>
<tr>
<th>Variable</th>
<th>Characteristic</th>
<th>Study 1 (Germany)</th>
<th>National statistics (Germany)</th>
<th>Study 2 (Switzerland)</th>
<th>National statistics (Switzerland)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gender</td>
<td>Male</td>
<td>52%</td>
<td>49%</td>
<td>45%</td>
<td>50%</td>
</tr>
<tr>
<td></td>
<td>Female</td>
<td>48%</td>
<td>51%</td>
<td>55%</td>
<td>50%</td>
</tr>
<tr>
<td>Age (in years)</td>
<td>18-29</td>
<td>20%</td>
<td>21%</td>
<td>29%</td>
<td>22%</td>
</tr>
<tr>
<td></td>
<td>30-39</td>
<td>17%</td>
<td>18%</td>
<td>24%</td>
<td>20%</td>
</tr>
<tr>
<td></td>
<td>40-49</td>
<td>25%</td>
<td>24%</td>
<td>21%</td>
<td>23%</td>
</tr>
<tr>
<td></td>
<td>50-59</td>
<td>22%</td>
<td>21%</td>
<td>17%</td>
<td>20%</td>
</tr>
<tr>
<td></td>
<td>60-69</td>
<td>17%</td>
<td>16%</td>
<td>9%</td>
<td>15%</td>
</tr>
<tr>
<td>Education</td>
<td>Without degree</td>
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<td>1%</td>
<td>6%</td>
<td>11%</td>
</tr>
<tr>
<td></td>
<td>Lower school degree</td>
<td>9%</td>
<td>7%</td>
<td>46%</td>
<td>41%</td>
</tr>
<tr>
<td></td>
<td>Middle school degree</td>
<td>26%</td>
<td>34%</td>
<td>15%</td>
<td>15%</td>
</tr>
<tr>
<td></td>
<td>Abitur (A levels equ.)</td>
<td>15%</td>
<td>15%</td>
<td>25%</td>
<td>28%</td>
</tr>
<tr>
<td></td>
<td>Vocational education</td>
<td>25%</td>
<td>28%</td>
<td>25%</td>
<td>16%</td>
</tr>
<tr>
<td></td>
<td>University degree / PhD</td>
<td>25%</td>
<td>16%</td>
<td>6%</td>
<td>11%</td>
</tr>
<tr>
<td></td>
<td>Obligatory basic education</td>
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<td>1%</td>
<td>6%</td>
<td>11%</td>
</tr>
<tr>
<td></td>
<td>Vocational education</td>
<td>46%</td>
<td>41%</td>
<td>46%</td>
<td>41%</td>
</tr>
<tr>
<td></td>
<td>Maturität (A levels equ.)</td>
<td>11%</td>
<td>8%</td>
<td>11%</td>
<td>8%</td>
</tr>
<tr>
<td></td>
<td>Higher vocational training</td>
<td>16%</td>
<td>16%</td>
<td>16%</td>
<td>16%</td>
</tr>
<tr>
<td></td>
<td>University degree / PhD</td>
<td>21%</td>
<td>24%</td>
<td>21%</td>
<td>24%</td>
</tr>
<tr>
<td>Income (in EUR/CHF per month)</td>
<td>EUR &lt;1300</td>
<td>6%</td>
<td>19%</td>
<td>6%</td>
<td>19%</td>
</tr>
<tr>
<td></td>
<td>EUR 1300-2600</td>
<td>26%</td>
<td>33%</td>
<td>26%</td>
<td>33%</td>
</tr>
<tr>
<td></td>
<td>EUR 2601-3600</td>
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<td>19%</td>
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<td>19%</td>
</tr>
<tr>
<td></td>
<td>EUR 3601-5000</td>
<td>22%</td>
<td>16%</td>
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</tr>
<tr>
<td></td>
<td>EUR &gt;5000</td>
<td>9%</td>
<td>14%</td>
<td>9%</td>
<td>14%</td>
</tr>
<tr>
<td></td>
<td>No comment</td>
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<td>n/a</td>
<td>13%</td>
<td>n/a</td>
</tr>
<tr>
<td></td>
<td>CHF &lt;2000</td>
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<td>7%</td>
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</tr>
<tr>
<td></td>
<td>CHF 2001-4000</td>
<td>15%</td>
<td>22%</td>
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<td>22%</td>
</tr>
<tr>
<td></td>
<td>CHF 4001-6000</td>
<td>27%</td>
<td>35%</td>
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</tr>
<tr>
<td></td>
<td>CHF 6001-8000</td>
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<td>16%</td>
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<tr>
<td></td>
<td>CHF 8001-10000</td>
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<td>7%</td>
<td>14%</td>
<td>7%</td>
</tr>
<tr>
<td></td>
<td>CHF 10001-12000</td>
<td>7%</td>
<td>3%</td>
<td>7%</td>
<td>3%</td>
</tr>
<tr>
<td></td>
<td>CHF 12001-14000</td>
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<td>2%</td>
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</tr>
<tr>
<td></td>
<td>CHF 14001-16000</td>
<td>3%</td>
<td>1%</td>
<td>3%</td>
<td>1%</td>
</tr>
<tr>
<td></td>
<td>CHF &gt;16000</td>
<td>3%</td>
<td>2%</td>
<td>3%</td>
<td>2%</td>
</tr>
</tbody>
</table>

11National statistics Germany: age, gender (Statistisches Bundesamt, 2012); education (Gesellschaft für integrierte Kommunikationsforschung mbH & Co. KG, 2013); (Statistisches Bundesamt, 2011). National statistics Switzerland: age, gender (Bundesamt für Statistik, 2013a); education (Bundesamt für Statistik, 2013b); income (Bundesamt für Statistik, 2013c).
Building on previous research in this area, we have chosen partial least squares (PLS), using the WarpPLS software (Version 4.0).\(^{12}\) Compared to several covariance-based alternatives, PLS is capable of modeling latent constructs when data is not multivariate normally distributed (Barclay, Higgins, & Thompson, 1995; Chin, 1998), and is well suited for exploratory research and theory building (Gefen et al., 2000; Ringle et al., 2012) due to its high statistical power (Hair et al., 2011).

4. Results

4.1. Measurement Model

The results of the measurement model are outlined in Table 2 and Table 3. To assess internal consistency reliability, we compute both composite reliabilities (CR) as well as Cronbach’s alphas (\(\alpha\))—the latter being considered only the lower bound of internal consistency (Chin, Marcolin, & Newsted, 1996; Hess et al., 2014; Raykov, 1997). CR was greater than .90 for both study 1 and study 2, suggesting reliability across all multi-item scales (Fornell & Larcker, 1981; Hair et al., 2011). Average variance extracted (AVE), as shown in Table 3, is above .75 for both studies, indicating that the variance captured relative to measurement error is sufficient to justify using all constructs (MacKenzie et al., 2011). High item loadings above .87 (study 1) and .85 (study 2) on the corresponding latent constructs in combination with low cross-loadings (Chin, 1998) as well as adequate AVE values exhibit high convergent validity. Discriminant validity for both studies is suggested by the fact that the square root of the AVE per construct is higher than the inter-construct correlation with other latent variables (Fornell & Larcker, 1981).

4.2. Structural Model

To identify the common method bias that is potentially inherent in all self-reported data, we evaluated common method variance following the approach of Liang et al. (2007). Congruent with Podsakoff et al.'s (2003, p. 889) suggestion to add “a measure of the assumed source of the method variance as a covariate in the statistical analysis,” we added a latent common method factor in the structural model (Liang et al., 2007). We then compared the squared values of the method factor loadings to the squared values of original latent variables (i.e. substantive constructs), which indicated that common method bias should not be an issue in

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\(^{12}\) For all our analysis, we used the default setting of the WarpPLS software: “PLS regression” as the outer model analysis algorithm, “Warp3” as the default inner model analysis algorithm, and “Stable” as the resampling method. The interested reader may refer to Kock (2013) for further details.
Table 2: Factor-loadings, cross loading and internal consistency reliability

**Study 1 - Germany**

<table>
<thead>
<tr>
<th>Construct</th>
<th>Item</th>
<th>Factor 1</th>
<th>Factor 2</th>
<th>Factor 3</th>
<th>Factor 4</th>
<th>Factor 5</th>
<th>Factor 6</th>
<th>Factor 7</th>
<th>Factor 8</th>
<th>Factor 9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compatibility with everyday practices</td>
<td>CO1</td>
<td>0.89</td>
<td>-0.03</td>
<td>0.00</td>
<td>0.00</td>
<td>0.03</td>
<td>0.03</td>
<td>-0.03</td>
<td>0.04</td>
<td>-0.07</td>
</tr>
<tr>
<td>α</td>
<td>0.93</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CR</td>
<td>0.96</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Technical compatibility</td>
<td>TC1</td>
<td>-0.07</td>
<td>0.07</td>
<td>-0.05</td>
<td>0.03</td>
<td>-0.03</td>
<td>0.03</td>
<td>-0.03</td>
<td>0.04</td>
<td>-0.07</td>
</tr>
<tr>
<td>α</td>
<td>0.96</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CR</td>
<td>0.96</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Usefulness</td>
<td>US1</td>
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this research effort. The squared values of the method factor loadings, which are interpreted as the percent of indicator variance caused by method, are below .022. Next, we inspected
correlation values (Table 3) for signs of multicollinearity. Except for two correlations in study 1 (.72 and .71) and one correlation in study 2 (.72), all correlations are below .70. Although correlations above .70 or even beyond .80 are not necessarily a cause for concern (Grewal, Cote, & Baumgartner, 2004), we followed common practice and also reviewed (vertical) variance inflation factors (VIF) (Kock & Lynn, 2012). All VIF are under 3.3, well below the already-conservative threshold of 5.0 (see e.g. Hair et al., 2011; Hair, Sarstedt, Ringle, & Mena, 2012; Venkatesh et al., 2012). Furthermore, we conducted full collinearity tests for both surveys, and all full collinearity VIFs were well below 3.3. This confirms the absence of collinearity—and, at the same time, as proposed by Kock and Lynn (2012), provides further evidence that common method bias is unlikely to be an issue.

Table 3: Descriptive statistics, correlations, and AVE

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Study 2 - Switzerland

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Notes: Diagonal elements are AVE, off-diagonal elements are correlations. All correlations are significant with p < 0.001.

We show the results of our structural models for the two surveys in Table 4. Our theorized structural research model is largely supported in both cases. Except for price value (PV study1: p=.069), which is not statistically significant in study 1, and risk (RI study2 p=.128) and ease of use (EU study2 p=.187), which are not statistically significant in study 2, all other direct effects are significant. More specifically, compatibility with everyday practices, technical compatibility,
usefulness, hedonic motivation and innovativeness are consistently significant at the .001 level. Hence, we find evidence for a significant direct effect of our focal constructs perceived compatibility with everyday practice, technical compatibility, and risk (study 1 only). The variance explained of the structural model is remarkably high in both cases, in particular considering that we have not added any additional moderating variables. We find an $R^2$ of .72 for survey 1 and an $R^2$ of .63 for survey 2.

### Table 4: Structural model results

<table>
<thead>
<tr>
<th>DV: Behavioral intention to adopt</th>
<th>Study 1 Effect size</th>
<th>Study 2 Effect size</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compatibility with everyday practices (CO)</td>
<td>0.29*** 0.21†</td>
<td>0.33*** 0.23†</td>
</tr>
<tr>
<td>Technical compatibility (TC)</td>
<td>0.13*** 0.07†</td>
<td>0.10*** 0.04†</td>
</tr>
<tr>
<td>Risk (RI)</td>
<td>-0.06* 0.02†</td>
<td>-0.03 0.01</td>
</tr>
<tr>
<td>Usefulness (US)</td>
<td>0.11*** 0.07†</td>
<td>0.16*** 0.10†</td>
</tr>
<tr>
<td>Ease of use (EU)</td>
<td>0.06* 0.03†</td>
<td>0.03 0.01</td>
</tr>
<tr>
<td>Price value (PV)</td>
<td>0.04 0.02†</td>
<td>0.06* 0.03†</td>
</tr>
<tr>
<td>Hedonic motivation (HM)</td>
<td>0.28*** 0.20†</td>
<td>0.22*** 0.14†</td>
</tr>
<tr>
<td>Innovativeness (INV)</td>
<td>0.18*** 0.10†</td>
<td>0.15*** 0.07†</td>
</tr>
</tbody>
</table>

Notes: ***p < 0.001; **p < 0.01; *p < 0.05  
† above the effect size threshold for practical relevance

Lastly, we also tested for effect size. In PLS algorithms, the common stepwise regression procedure as outlined by Cohen (1988) to compute Cohen’s $f^2$ can cause bias (Kock, 2013). Thus, we report effect sizes calculated according to Kock (2014, p. 2) using “absolute values of the individual contributions of the corresponding predictor latent variables to the R-square coefficients of the criterion latent variable in each latent variable block.” For study 1, all direct effects are above the .02 threshold suggested as a general guidance for practical relevance. For study 2, risk and ease of use fall slightly below the threshold. However, this is in accord with the low beta coefficients of these predictors, which were .03 and .03 respectively.

Not only is the effect of compatibility with everyday practices significant at the .001 level, but its beta coefficient is also consistently the highest among all latent variables. The influence of technical compatibility and risk also tests significant at the .001 and .05 level in study 1. In study 2, however, risk showed no significant influence on intention to adopt, and has a low effect size. Interpreting these results, we find significant support for H1 and H2, and can confirm them. However, we find mixed evidence for H3, which is marginally supported at best and merits further inquiry.
While *usefulness* consistently shows strong influence on intention to adopt and is significant at the .001 level, *ease of use* was only marginally significant in study 1 and not significant at all in study 2, and appears to have only slight influence on the intention to adopt. Similarly, *price value* appears to be neither a constantly significant nor a strong predictor in the context of ECTs. *Hedonic motivation* and *personal innovativeness*, on the other hand, both appear to be strong predictors of the intention to adopt. They test significant at the .001 level in both studies, and have high path coefficients of .28/.22 and .18/.15 respectively. Summarizing the findings from both surveys, we show the results of our structural model in Figure 2.

![Figure 2: Results of structural model for both samples (study 1, study 2)](image)

5. Discussion

5.1. Theoretical Contribution

Our empirical analysis shows that the so-far under-theorized factor *compatibility with everyday practices* has become the strongest predictor of intention to adopt ECTs. Compared to traditional consumer adoption, where utilitarian aspects (usefulness, ease of use) as well as hedonic motivation and price value significantly influence adoption (Venkatesh et al., 2012), the adoption of ECTs is strongly affected by how seamlessly they can be integrated into adopters’ lives. Concerns such as fit with the user’s current situation, daily routines, everyday
practices, and lifestyle have moved center stage (see items in Table A1). This confirms that as technology progresses, technology-specific adoption determinants can change. Previous IS acceptance research focused on habits rather than everyday practices. The notion of habit was primarily associated with prior exposure to, and experience with, a target technology (Venkatesh et al., 2012). In this respect, scholars drew a distinction between habit as an automaticity (Kim & Malhotra, 2005), i.e. behavior instantly activated by a stimulus cue, and habit as an action, preceded by more deliberate cognitive response patterns (Ajzen, 2002). This is important in the context of understanding use behavior, but less so when investigating novel (experiential) technology adoption. Since use experience is a prerequisite for the formation of habit, and adoption is obviously a prerequisite of use, it is unlikely that habit precedes adoption. Potential adopters might not have had a chance to use or even encounter the target technology before taking their adoption decision (e.g. novel, unheard-of product). Everyday practices, however, exist irrespective of the introduction or prior use of novel technologies.

One possible explanation for the significance of everyday practices in the context of ECTs could be that consumers today are generally more familiar with IT, and do not regard it as alien (Vodanovich et al., 2010). For many, IT is now so commonplace that the key question is not confidence in the utility of a technology, but how well it will fit with their day-to-day life. This is not to say that adopters do not scrutinize technology offerings—just that the focus of their attention has shifted.

Data for our second experiential-specific construct suggests that technical compatibility is also a significant determinant of adoption. Despite this, it has received little attention in previous IS acceptance research—potentially because it is less of a concern in the workplace. Employees are less likely to be confronted with incompatible IT, since they will usually have knowledgeable colleagues whose job it is to select and service the firm's information infrastructure. However, in the consumer realm, this responsibility has devolved to consumers themselves. Although tech firms do their best to make their consumer products as compatible as expected (i.e. as advertised), most of us have experienced the opposite at first hand. Examples that may be familiar from everyday life include being unable to connect to a Wi-Fi network or link a mobile device to one’s car via Bluetooth, struggling to configure internet and email access, or using a new or borrowed printer for which the correct driver is not installed. It is plausible that the more interconnected devices become, and the more their performance depends on compatibility, the more sensitive consumers are likely to be to such issues.

In contrast to previous studies where technical compatibility has been subsumed into a broader notion of “facilitating conditions” (section 2.2), our findings reveal that this factor alone can be a significant determinant of adoption. This does not conflict with previous findings from Ajzen
(1991) and Venkatesh et al. (2003, 2012), all of whom acknowledge the relevance of a broader
tonight of facilitating conditions (i.e. behavioral control). Rather, it complements these findings
with a more nuanced perspective, underlining the relevance of the technical compatibility belief
for embedded and interconnected generations of technology. Nonetheless, perceived
*technical compatibility* has less explanatory power in our model than *compatibility with
everyday practices, hedonic motivation, and personal innovativeness*, although it has more
than *price value, ease of use, and risk*. Since adopters potentially perceive more responsibility
when deciding whether to adopt ECTs as opposed to non-embedded products, it would be
interesting to investigate the discrepancy between perceived compatibility and actual
compatibility—a potential avenue for further research.

The relationship between perceived *risk* and intention to adopt shows low explanatory power
in both of our studies, and tests marginally significant only in study 1. Given the mixed
evidence, further refinement of the construct is required. As it stands, the newly composed
scale, which measures a more general notion of risk, exhibits little influence on adoption. This
might also be affected by our choice of focal technology: intelligent thermostats. It seems
plausible that the subjective perception of risk varies depending on the everyday practices in
which the technology is ultimately embedded. Potential adopters might not feel particularly
intimidated by the potential consequences of adopting an intelligent thermostat—compared to
applications in areas such as personal health or finance (Martins et al., 2014). One can still
argue that the sources of risk when adopting novel technology are plentiful, including company,
technology, or privacy risk. Notwithstanding, we refrained from the subtle disaggregation that
is essential to form reflective second-order variables (see Martins et al., 2014), or even a
formative construct, in order to preserve the parsimony of our theory. Hence, further research
is needed to better understand the relevance of different risk dimensions, as well as causal
links to the technology under investigation. Featherman and Pavlou (2003), for example,
elaborate on a total of seven risk facets in the context of internet-delivered e-services adoption.
It remains to be evaluated if all are relevant determinants across ECTs. Future research
following the objective of refining our notion of risk and testing for different sub-facets could
thereby build on the study of Lancelot Miltgen et al. (2013), on acceptance of biometrics, and
on the study of Martins et al. (2014), which draws on Featherman and Pavlou’s (2003) work to
understand the role of risk in online banking.

Among the adoption determinants from previous research for which we control (*usefulness,
ease of use, price value, hedonic motivation, and personal innovativeness*), perceived
*usefulness* exhibits comparatively high explanatory power. However, for ECTs, it is not the
key influential belief, which is in line with previous work on acceptance in the consumer context
(Venkatesh et al., 2012). Compatibility with *everyday practices, hedonic motivation, and*
personal innovativeness all exert a greater influence on behavioral intention. In contrast, ease of use, the second seminal TAM construct, seems to have low explanatory power in the context of ECTs. Although it was said to be almost certain that perceived ease of use “is an important determinant of use in its own right” (Benbasat & Barki, 2007: 212) in the organizational context, our data suggests that ease of use as conventionally measured is not an important determinant of experiential consumer technology adoption.

Price value also shows low predictive power for behavioral intention. While the study from Venkatesh et al. (2012), for example, showed moderate but significant influence in a non-experiential specific context, we find mixed evidence and at best marginally significant, minor influence on adoption. This might appear controversial at first sight, but could be caused by a comparatively low current price point of 200–300 EUR and/or the novelty of intelligent thermostats. All the adopters in our study can be considered early adopters, who are generally less price-sensitive than late adopters (Mohr, Sengupta, & Slater, 2009; Parker, 1992). Consequently, further research studying the importance of price value in the context of more established ECTs with a higher price point is needed. It would certainly be interesting to see if ECTs are in general goods with lower price elasticity compared to conventional consumer technologies, or if the influence of price value is a function of price point and/or technology.

Hedonic motivation strongly influences experiential technology adoption, confirming the results of previous, non-experiential specific research (Dabholkar & Bagozzi, 2002; Holbrook & Hirschman, 1982; Nysveen, Pedersen, & Thorbjørnsen, 2005; Van der Heijden, 2004). Likewise, based on our data, we can confirm the existence of a strong direct relationship between personal innovativeness and behavioral intention to adopt. Compared to hedonic motivation and personal innovativeness, only compatibility with everyday practices explains more variance. As a matter of fact, when we model and test for the explanatory power of only the most significant constructs (i.e. compatibility with everyday practices, technical compatibility, usefulness, hedonic motivation, innovativeness) we still observe a remarkably high R² of .66 (data from study 1) and .61 (data from study 2). Therefore, while the newly derived construct compatibility with everyday practice is the most influential determinant of adoption, a new set of relatively few determinants is sufficient to explain a substantial amount of variance in ECT adoption.

5.2. Managerial Contribution

Beyond the theoretical implications outlined above, our results have important implications for practitioners. If compatibility with everyday practices is crucial, firms commercializing ECTs must thoroughly understand customer lifestyle and behavior. In addition to utilitarian and hedonic aspects, use context should be considered at every stage from design concept to
market rollout. Likewise, processes for the integration of customer context become more important. Our findings emphasize that firms’ early market research efforts must include a sufficiently broad range of everyday practices from the target context of use—a challenging task in times of shortening product lifecycles. Similar ideas have been formalized in, for instance, the human-centered design approach (Maguire, 2001), which indirectly acknowledges the importance of compatibility with everyday practices. A lack of understanding of the context of use may lead to non-rectifiable design errors, or costly post-development rework. Furthermore, the individuality (i.e. variety) of everyday practices must also be addressed. This could imply more differentiated advertising, or even the development of different products aligned with clusters of similar practices. In this respect, firms should also consider whether these practices might change over the diffusion cycle of a product, i.e. if early adopters exhibit different everyday practices compared to late adopters (Moore, 2014).

In addition, technical compatibility should be addressed early on. For highly interconnected devices in particular, a lack of standards in the early stages of a technology can be a considerable hurdle\textsuperscript{14}—a topic widely discussed in the literature (e.g. Anderson and Tushman, 1990). However, companies with competencies across a range of products that can be interconnected by a novel ECT could leverage this to their advantage. For example, an industrial conglomerate active in both the heating-system and consumer-electronics markets might be in a better position to design a compatible data interface for an intelligent thermostat—as well as already having valuable access to owners of potential host systems. Arguably, the provider of the host system is in a better position than new entrants to become the natural owner of a supplementary ECT.

Furthermore, if the importance of price value is less pronounced for certain novel ECTs, firms would be wise to reclaim development expenses based on a revenue-maximizing pricing strategy (i.e. skimming). Moreover, since ECTs are less prone to perceived commoditization, marketing should focus on experiential-specific features (i.e. seamless integration into daily routines) rather than price value. Conversely, following a low-cost strategy for the introduction of a novel ECT is probably the wrong course.

### 5.3. Limitations

First and foremost, we have collected data on the intention to adopt just one ECT. Many other ECTs have begun to spread around the globe (including a multitude of smartphone-based applications). While we have outlined good reasons why intelligent thermostats are a well-suited example that exhibit all the relevant idiosyncrasies of ECTs, further research should

\textsuperscript{14} Every reader that has ever tried to pair a Bluetooth device in the early stages of the radio technology will immediately sympathize with this argument.
build on our work and test our theoretical concept across other ECTs. In this context, the drivers behind perceived compatibility with everyday practices could be evaluated to foster a more comprehensive understanding (see also Benbasat and Barki, 2007). Venkatesh and Bala's (2008) work is one example where similar critique pertaining to TAM was addressed.

Second, we limit our focus to one geographical region (i.e. Central Europe) and have evidence from a one-time survey in two countries only. In comparison to other acceptance studies, which often have to commit to the best data available (e.g. working with university students), we have made an attempt to raise generalizability by careful selection of respondents as outlined in the methodology section. Based on age, gender, education, and income, our final sample is roughly comparable to the German and Swiss population. Combined with a relatively large sample sizes (N=976, N=971), we suppose our results to be fairly generalizable to the two countries’ populations. Nonetheless, given that compatibility with everyday practices is the most important determinant of adoption, it is essential to test the model in different countries and across differing cultures (see also Leidner and Kayworth, 2006; Srite and Karahanna, 2006).

Third, we have operationalized newly developed latent variables reflecting the experiential character of novel technologies with newly developed measurement scales. This is a risky and laborious task, and many researchers shy away from it. On the one hand, reluctance to develop new measurement scales can lead to imprecise adoption of existing scales, potentially reducing validity of results. On the other hand, it also induces additional path dependency due to unavailability of scales for emergent but potentially relevant constructs (such as compatibility with everyday practices). We carefully tested and developed all our new scales as outlined in the methodology section, but we also acknowledge that new scales inevitably take time to mature.

Fourth, since the measured dependent variable of interest is intention to adopt, we limit ourselves to a particular phase of the decision-making process. In reality, adoption is not a single decision that can be measured and explained at any one moment in time. For example, Rogers (2003) describes a five-step process for making innovation decisions. Ideally, additional factors providing a more comprehensive portrait of the entire process need to be determined. A change in the relevance of the factors that explain early versus late adoption over time is not only relevant in the context of firm-level technology adoption (see e.g. Waarts, Everdingen, & Hillegersberg, 2002). Gounaris and Koritos (2012), for example, discuss bounded rationality in the context of individuals meandering through the adoption-decision process. This would certainly be a valid extension to our humble proem.
Fifth, in order to inhibit variable inflation, we do not explicitly theorize moderators. Without further insights into the fundamental mechanisms, broadening of the model at this early point would be both unwieldy and conceptually weak. “The consideration of moderating variables is one way of deepening any model” (Bagozzi, 2007: 244). If conducted with careful theoretical consideration, however, it is a viable pathway for further research.

Lastly, we use intention to adopt as a proxy for actual adoption behavior. Bagozzi (2007) criticizes the assumed linkage between intention to use and actual use in TAM. This is a controversial and multifaceted discussion. Ajzen and Fishbein (1980, p. 41), for example, have previously stated that “intention is the immediate determinant of behavior, and when an appropriate measure of intention is obtained it will provide the most accurate prediction of behavior,” while Ajzen (1991, p. 186) later reassures us that when “behaviors pose no serious problems of control, they can be predicted from intentions with considerable accuracy.” Despite this discussion, it is worth emphasizing that our study aims to explain adoption rather than use. Adoption is closer to intention than a construct for measuring actual use, and we remain confident that we have obtained data reflecting adoption with sufficient accuracy. Furthermore, we deliberately opted not to conduct a mixed-sample study with potential and actual adopters simultaneously, due to potential cognitive bias such as sensemaking and bounded rationality (Gounaris & Koritos, 2012). Nonetheless, further research should investigate actual adoption decisions, and possibly extend the scope of adoption research to actual usage behavior as suggested by Bagozzi (2007).

6. Conclusion

This research extends the realm of existing technology adoption theory by advocating a new view on the rapidly emerging field of ECTs. We are aware of the concerns of thoughtful IS scholars that we might be “overwhelmed, confused, and misled by the growing piecemeal evidence behind decision making and action in regard to technology adoption/acceptance/rejection” (Bagozzi, 2007: 245). However, this caution should not be interpreted as a blanket ban on expanding the theoretical space of adoption mechanisms (Bagozzi, 2007; Benbasat & Barki, 2007; Venkatesh et al., 2007). It has been shown, and this study confirms, that ECTs represent a new, truly momentous field of inquiry that is certainly significant enough to change previously theorized relationships (Bødker et al., 2014; Funabashi et al., 2008; Yoo, 2010).

More specifically, in this research effort we have first theorized ECT adoption by proposing a theoretical model based on newly developed constructs. Second, we have tested the model in two separate studies with the same measurement instruments. Thereby, we find ratification for
two out of our three hypotheses. Compatibility with everyday practices and technical compatibility both exhibit significant influence on the behavioral intention to adopt ECTs. Consequently, the newly proposed constructs are necessary to satisfactorily explain technology adoption in an experiential technology context. Furthermore, we have controlled for previously proposed determinants and investigate their influence on ECT adoption. We find that the seminal TAM construct of perceived usefulness (i.e. performance expectancy) remains a strong determinant of adoption. However, compatibility with everyday practices, for example, is even more relevant in the context of ECTs. Moreover, our empirical results confirm significant influence of the two adopter-centric constructs hedonic motivation and innovativeness; in both our studies, hedonic motivation is the second most influential adoption determinant. At the same time, price value does not exhibit great influence. Thus, we conclude that the experiential character of new technology offerings appeals to a different set of salient consumer perceptions that are difficult to fully grasp with prevalent acceptance theories alone. Building on our findings, we hope to have provided a first comprehensive yet parsimonious theoretical frame for further investigation of the adoption of novel ECTs.
7. References


8. Appendix

Table A1: Survey items

<table>
<thead>
<tr>
<th>Construct</th>
<th>Items</th>
<th>Indicator type</th>
<th>Sources</th>
</tr>
</thead>
<tbody>
<tr>
<td>practices</td>
<td>routine.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>EP2 Given my everyday practices, using intelligent thermostats is</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>appropriate.</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>EP3 Using intelligent thermostats is completely compatible with my</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>current situation.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>EP4 Using intelligent thermostats fits with my lifestyle.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Technical compatibility</td>
<td>TC1 There are intelligent thermostats available which are suited to</td>
<td>Reflective</td>
<td>New measurement scale; item TC2 adapted from Venkatesh et al. (2012)</td>
</tr>
<tr>
<td></td>
<td>retrofit my heating system.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>TC2 Currently available intelligent thermostats are compatible with</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>my existing heating system.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>TC3 Currently available intelligent thermostats can be connected to</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>my heating system.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Risk</td>
<td>RI1 The decision to use intelligent thermostats is risky.</td>
<td>Reflective</td>
<td>New measurement scale; item RI1 adapted from Pavlou and Gefen (2004), RI2 adapted from Bélanger and Carter (2008), RI3 adapted from Featherman and Pavlou (2003)</td>
</tr>
<tr>
<td></td>
<td>RI2 In general, I believe using intelligent thermostats is risky</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>RI3 Using intelligent thermostats poses a risk.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Usefulness</td>
<td>US1 Using intelligent thermostats increases my energy efficiency</td>
<td>Reflective</td>
<td>All items of measurement scale adapted from Davis et al. (1989), Venkatesh et al. (2012)</td>
</tr>
<tr>
<td></td>
<td>at home.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>US2 Using intelligent thermostats helps me to lower my heating cost.</td>
<td>Reflective</td>
<td>All items of measurement scale adapted from Davis et al. (1989), Venkatesh et al. (2012)</td>
</tr>
<tr>
<td></td>
<td>US3 Using intelligent thermostats helps me to reduce my energy</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>consumption at home.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ease of use</td>
<td>EU1 Learning how to use intelligent thermostats is easy for me.</td>
<td>Reflective</td>
<td>All items of measurement scale adapted from Davis et al. (1989), Venkatesh et al. (2012)</td>
</tr>
<tr>
<td></td>
<td>EU2 Using intelligent thermostats is clear and understandable.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>EU3 I find intelligent thermostats easy to use.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Price value</td>
<td>PV1 Intelligent thermostats are reasonably priced.</td>
<td>Reflective</td>
<td>All items of measurement scale adapted from Venkatesh et al. (2012)</td>
</tr>
<tr>
<td></td>
<td>PV2 Intelligent thermostats are a good value for the money.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>PV3 At the current price, intelligent thermostats provide a good</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>value.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hedonic motivation</td>
<td>HM1 Using intelligent thermostats is enjoyable.</td>
<td>Reflective</td>
<td>All items of measurement scale adapted from Venkatesh et al. (2012)</td>
</tr>
<tr>
<td></td>
<td>HM2 Controlling my heating system with intelligent thermostats is</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>entertaining.</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>HM3 Controlling appliances (e.g. heating, light) with a smartphone</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>of over the internet is fun.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Innovativeness</td>
<td>INV1 I like to purchase new, innovative products.</td>
<td>Reflective</td>
<td>All items of measurement scale adapted from Agarwal and Prasad (1998), Lu et al. (2005), Yi et al. (2006)</td>
</tr>
<tr>
<td></td>
<td>INV2 Among my peers, I am usually the first to explore new</td>
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<tr>
<td></td>
<td>information technologies.</td>
<td></td>
<td></td>
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<tr>
<td></td>
<td>INV3 If I heard about a new information technology, I would look</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>for ways to experiment with it.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Behavioral intention to adopt</td>
<td>BI1 I can imagine using intelligent thermostats regularly in my</td>
<td>Reflective</td>
<td>All items of measurement scale adapted from Davis et al. (1989), Venkatesh et al. (2012)</td>
</tr>
<tr>
<td></td>
<td>household.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>BI2 I plan to use intelligent thermostats in the future.</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>BI3 I intend to use intelligent thermostats in everyday life</td>
<td></td>
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</tbody>
</table>
Learning to Learn—How Boards of Directors Affect Organizational Exploration

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Abstract
When environments become more turbulent, organizations need to put a stronger focus on exploration compared to exploitation as the dominant mode of organizational learning. In this paper, we use a comparative case study of nine large incumbent companies in the Swiss electricity industry to investigate how the board of directors contributes to such shifts toward organizational exploration. We find that depending on whether an organization’s shift toward exploration is initiated by the management or the board of directors, the board takes on different roles. These roles in return entail the deployment of instruments targeted at either selection or variety creation. Furthermore, we find that as soon as the degree of managerial exploration rises, the board inevitably has to deal with issues that go beyond its extant capabilities. To be able to fulfill its governance duty also in times of exploration, the board therefore needs to engage in a process of continuous learning. From an organization perspective, there is no hierarchically superordinate authority that could trigger or accompany this learning process. Therefore, we find that board learning is strongly dependent on the presence of a set of higher-order learning capabilities within the board itself. We discuss the implications of these findings for the literature on organizational learning and governance. Moreover, we point to a number of practical implications for board governance in times of organizational exploration.

Keywords
Organizational learning; board of directors; exploitation; exploration; ambidexterity; higher-order capabilities; corporate governance
1. Introduction

Organizational learning is critical to firm performance and survival, particularly during times of environmental change (Fiol & Lyles, 1985; March, 1991). March (1991) was among the first to distinguish between two different modes of organizational learning: exploration and exploitation. While exploration is characterized by “terms such as search, variation, risk taking, experimentation, play, flexibility, discovery, innovation”, exploitation refers to “choice, production, efficiency, selection, implementation, execution” (March, 1991: 71). To successfully compete in markets in the longer term, March claimed that organizations need to make use of both exploration and exploitation. Firms preoccupied with exploration alone may suffer the “cost of experimentation without gaining many of its benefits”, whereas firms strongly immersed in exploitation may find themselves “trapped in suboptimal stable equilibria” (March, 1991: 71). Although both exploration and exploitation are necessary, organizations possess limited resources, which leads to a trade-off between the two learning modes at each point in time.

A large stream of research building upon March (1991) has investigated the conditions under which focusing on exploration versus exploitation delivers the largest value to the firm (Lavie, Stettner, & Tushman, 2010; Stettner & Lavie, 2014). In this context, it was found that when facing dynamic environments, firms need to put a stronger emphasis on exploration relative to exploitation (Jansen, den Bosch, & Volberda, 2006; Jansen, Vera, & Crossan, 2009; Uotila, Maula, Keil, & Zahra, 2009). While this implies that firms may need to shift their focus from exploitation toward exploration in times of environmental discontinuities, we currently know relatively little about firm-internal interactions and mechanisms that enable such shifts (Lavie et al., 2010; Tainio, Lilja, & Santalainen, 2001).

The existing literature suggests that the operational responsibility for balancing exploration and exploitation lies with the senior management team (see, for example, Lavie et al., 2010), which holds the fiduciary duty to act in the firm’s and its owner’s best interest. Organizational strategies, however, are seldom the domain of management alone. The fate of many firms is decisively shaped not least by a firm’s board of directors (Johnson, Ellstrand, & Daily, 1996; Judge & Zeithaml, 1992; Lorsch & Young, 1990; McNulty & Pettigrew, 1999; Zahra & Pearce, 1989). For example, corporate boards monitor and control organizational decisions and activities (Walsh & Seward, 1990), provide the management with information from the external environment, hire and fire management personnel (Castrogiovanni, Baliga, & Kidwell, 1992) and are even attributed an active role in devising strategies (Daily, Dalton, & Cannella, 2003; Ravasi & Zattoni, 2006; Ruigrok, Peck, & Keller, 2006; Tuggle, Schnatterly, & Johnson, 2010; Zahra & Pearce, 1989).
In congruence with the above roles, boards can significantly influence organizational learning (Ravasi & Zattoni, 2006; Ruigrok et al., 2006; Tainio et al., 2001; Tuggle et al., 2010). More specifically, they affect the knowledge and/or influence and systematically change the cognition and behavior of firms (Argote & Miron-Spektor, 2011; Argote, 1999). Ruigrok et al. (2006), for instance, find that irrespective of board size and the number of outside directors, boards are largely involved in and important for strategic decision-making. Tuggle et al. (2010) show that boards are vital for the discussion of entrepreneurial issues. Tuschke, Sanders, & Hernandez (2014) discuss how boards influence emerging market entry strategy decisions, to name only a few. Given the superordinate position of the board, it is self-evident and has been confirmed that board conduct affects managerial actions and thus firm behavior.

So far, however, existing research has not specifically addressed the role of boards in the process of rebalancing exploration and exploitation. This might be not least due to the fact that boards remain a subject difficult to study. Access to board members is limited for most scholars and goes hand in hand with the reticence of directors to discuss board internal matters (Daily et al., 2003; Tuggle et al., 2010). Board behavior and the underlying mechanisms are still considered a “black box” by many (Daily et al., 2003; Gabrielsson & Huse, 2004; Hambrick, Werder, & Zajac, 2008; Huse, Hoskisson, Zattoni, & Viganò, 2011; Ruigrok et al., 2006). To demystify board behavior and to better understand the mechanisms that enable or inhibit firms to shift from exploitation to exploration, we address the research question how boards of directors influence a firm’s shift from exploitation to exploration.

To answer our research question, we make use of a qualitative comparative case study approach. The theoretical sample consists of nine of the largest incumbent electric utility companies in Switzerland. Driven by the regulatory changes that aim at simultaneously liberalizing a previously government-regulated market and fostering renewable energy generation, the Swiss energy sector has undergone significant change. Incumbent firms, which previously operated as quasi monopolists1, now face the threat of competition and at the same time need to adapt their technology portfolio. This has induced a shift in learning foci from exploitation toward exploration. The resulting dynamics make the Swiss electricity sector a well-suited environment to study in detail the role that the board of directors plays during a temporal shift from exploitation to exploration.

We find that the role the board of directors plays in organizational shifts from exploitation toward exploration depends on whether the change is initiated by the management or the board itself. If, for example, the management initiates the shift toward exploration, the board

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1 Up until recently, all electricity customers were obliged to procure electricity from the regional electricity supplier of the service area they live or operate in.
engages primarily in selection, i.e. critically accompanying management exploration by focusing on challenging and controlling management activities. If, on the other hand, exploration is initiated by the board, the board focuses on variety creation, i.e. engages in servicing and coaching to provide the management with information and ultimately stimulate exploratory management initiatives. If the management does not respond to such instruments as desired, boards may also directly order (i.e. direct) the implementation of exploratory tasks or ultimately replace members of the executive team to bring in more exploratory characters.

Interestingly, we find that while boards may play an important role in driving organizational exploration by engaging in variety creation, a higher degree of managerial exploration, in turn, has important implications for the board’s ability to exert influence. As soon as the management starts to engage in exploration, the board is increasingly confronted with initiatives and topics that go beyond its present capability to judge strategic issues. The lack of capability to deal with novel issues reduces the board’s ability to engage in variety creation and selection, ultimately affecting its efficacy to govern organizational strategy. Consequently, whenever the organization starts to engage in exploration, the board is required to engage in continuous learning. Since the board of directors is the highest hierarchical layer within an organization, there is no governing body other than the board itself, which could drive and guide board learning. Consequently, to remain effective in times of exploration, boards rely on a set of higher-order capabilities that ensure continuous adaptation of board capabilities (i.e. board learning). In this research, we identified and specified four such major second-order capabilities: self-evaluation, education of board members, adaption of board composition, and adjustment of decision making.

Our study makes several important contributions to the literature concerned with organizational learning and boards of directors. First, we show how boards influence organizational learning by detailing the instruments boards use to induce organizational shifts toward exploration. Second, we point to second-order capabilities at the level of board of directors as an important prerequisite for effectively governing organizations in times of organizational exploration. Without these second-order capabilities, boards are not in a position to deploy instruments required to steer and counterbalance executive strategizing effectively. The four second-order capabilities we identify help directors to systematically reflect on and alter the board’s capability to judge strategic issues in times of environmental change.

The remainder of this paper is organized as follows. We first review in more detail existing work on balancing exploration-exploitation and the role of boards of directors in affecting organizational learning. Next, we outline our qualitative case study approach, including sample selection and characteristics. After presenting our results, we elaborate on our main theoretical
contributions as well as on the limitations of our approach. We conclude with a brief recapitulation and synthesis of our main findings.

2. Theoretical Background

2.1. Balancing Organizational Exploration and Exploitation as a Strategic Challenge

Building upon March’s (1991) seminal work, the distinction between exploration and exploitation as two generic modes of organizational learning has received a large amount of attention in organization theory in recent years. Numerous studies have used and adapted March’s framework to confirm that—while constituting an inherent trade-off—both exploration and exploitation fulfill important functions in organizations, ultimately enabling firm prosperity (Parmigiani & Rivera-Santos, 2011). While initial work posited an equal balance between exploration and exploitation to yield the best outcome, later studies showed that the optimal balance between exploration and exploitation depends on external factors too. It was found that exploration plays a particularly important role in dynamic environments. In times of environmental discontinuities for example, the exploitation of existing knowledge and capabilities becomes insufficient to ensure future organizational performance (Jansen et al., 2006, 2009; Uotila et al., 2009). This implies that during times of increased dynamism, e.g. induced by regulatory or technological discontinuities, firms are well advised to initiate a shift in their balance from exploitation to exploration (Gupta, Smith, & Shalley, 2006; Jansen et al., 2006, 2009).

As described above, shifting from exploitation to exploration (and vice versa) over time is essential for longterm firm prosperity (see e.g. Brown & Eisenhardt, 1997). However, while existing studies support the notion that (re)balancing is important, we currently lack detailed insights into the mechanisms within the firm that enable and induce the actual balance shift in times of need for exploration. Lavie et al. (2010: 143), for example, point out that we require more research “to uncover the underlying processes at different levels of analysis that support the balancing of exploration and exploitation”. Nonetheless, there is strong consensus that, in general, the executive team plays a key role when it comes to balancing exploration and exploitation (Benner & Tushman, 2003; Burgelman, 2002; Gilbert, 2005; Gupta et al., 2006). By developing strategic proposals and by allocating firm resources for example, the executives influence both the timing and speed of exploration relative to exploitation. In this context, recent research points out that managers can balance exploration and exploitation by using a number of different modes such as internal R&D, alliances and mergers and acquisitions (Lavie et al., 2010; Stettner & Lavie, 2014).
2.2. Board of Directors and Strategy

While existing research focuses strongly on the role of senior management in determining an organization’s balance between exploration and exploitation, there is a long line of literature that stresses the potency of boards to devise and affect organizational strategies. In fact, studies have demonstrated a clear link between, for example, the composition and structure of supervisory boards and firm performance (Balsmeier, Buchwald, & Stiebale, 2014; Dalton, Daily, Johnson, & Ellstrand, 1999; Hillman & Dalziel, 2003; Zahra & Pearce, 1989). Given their superordinate hierarchical position relative to the management, few scholars have also started to investigate the board’s influence on organizational learning (Hillman & Dalziel, 2003; Tainio et al., 2001).

Overall, there are two major paths of board inquiries. First, research efforts which aim to better understand board behavior to derive meaningful recommendations for effective corporate governance. Second, the management and strategy literature, which is, so far, largely concerned with comprehending the link between board of directors and firm performance (Huse et al., 2011). Both literature streams rest on two theoretical perspectives, which have dominated research on board of directors for decades: agency theory (Gabrielsson & Huse, 2004) as well as resource dependence theory (Desender, Aguilera, Crespi, & Garcia-Cestona, 2013; Haynes & Hillman, 2010; Hillman & Dalziel, 2003). Agency theory is directly concerned with determining the most efficient contracts governing the relationships between e.g. owners, board members and managers (Eisenhardt, 1989a). Resource dependency theory is the theoretical underpinning of research concerned with “the relationship between the board as a provider of resources (e.g., legitimacy, advice and counsel, links to other organizations, etc.) and firm performance” (Hillman & Dalziel, 2003: 383). Moreover, in particular the role of board capital has become a frequently discussed subject (see e.g. Desender et al., 2013; Haynes & Hillman, 2010; Hillman & Dalziel, 2003; Johnson, Schnatterly, & Hill, 2013).

By scrutinizing issues related to the above outlined topics, scholars have identified and described a number of roles (i.e. functions) and activities of boards, which act on firm strategy. An important role of boards is to monitor and control a firm’s management to safeguard performance and owner interests (Boyd, 1990; Desender et al., 2013; Hillman, Nicholson, & Shropshire, 2008; Johnson et al., 1996; Judge & Zeithaml, 1992; Walsh & Seward, 1990; Zahra & Pearce, 1989). Reviewing the literature on boards, Hillman & Dalziel (2003) identify a number of activities boards use for fulfilling their role of monitoring and controlling. These include “monitoring the CEO (Boyd, 1995; Daily, 1996), monitoring strategy implementation (Rindova, 2003).”

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2 The term refers to both human capital (e.g. experience, expertise, reputation) and relational capital (e.g. network of ties to other firms and external contingencies) (see also Hillman & Dalziel, 2003).
planning CEO succession (Pitcher, Chreim, & Kisfalvi, 2000), and evaluating and rewarding the CEO/top managers of the firm (Conyon & Peck, 1998)" (Hillman & Dalziel, 2003: 385).

While some scholars see (reactive) monitoring and controlling as the main responsibility of the board (Mizruchi, 1983), others have pointed out that boards can take on more proactive roles. Zahra & Pearce (1989), for example, discuss two roles of boards in addition to monitoring: service and strategy. The role of service includes "enhancing company reputation, establishing contacts with the external environment, and giving advice and counsel to executives" (Zahra & Pearce, 1989: 292), whereas the strategy role entails proactive board interference “by initiating their own analysis, or by suggesting alternatives” (Zahra & Pearce, 1989: 298). Hillman & Dalziel (2003) also subsume a number of rather proactive roles under what they ultimately refer to as the resource provision role. This broader notion includes activities such as “providing legitimacy/bolstering the public image of the firm (Selznick, 1949), providing expertise (including the provision of internal firm information by inside directors; Baysinger & Hoskisson, 1990), administering advice and counsel (Lorsch & Maclver, 1989; Mintzberg, 1983), linking the firm to important stakeholders or other important entities (Burt, 1980; Hillman, Keim, & Luce, 2001), facilitating access to resources such as capital (Mizruchi & Stearns, 1988), building external relations, diffusing innovation (Haunschild & Beckman, 1998), and aiding in the formulation of strategy or other important firm decisions (Judge & Zeithaml, 1992; Lorsch & Maclver, 1989)” (Hillman & Dalziel, 2003: 386). Irrespective of the distinction between reactive and proactive role, it is widely accepted that boards are at the apex of firm control and have a set of competencies (and duties) that enable them to exert significant influence. Among the most influential competencies is the legal authority to hire and fire management personnel (Baysinger & Hoskisson, 1990; Conyon & Peck, 1998; Mizruchi, 1983)

2.3. Board of Directors and Organizational Learning

Given the various influences that boards of directors exert on organizational strategies, it is not surprising that boards have also been suggested to play an important role for organizational learning (Tainio et al., 2001). Currently, however, we still lack empirical evidence not only on board behavior in general (Gabrielsson & Huse, 2004; Huse et al., 2011), but in particular on how different board roles (i.e. functions) and activities relate to an organization’s balance between exploration and exploitation as two fundamental gestalts of organizational learning. Many empirical studies shy away from looking inside the board, assuming that the behavior and conduct of the board “can be successfully inferred from the board's demographic characteristics” (Gabrielsson & Huse, 2004: 24). This, arguably, neglects important interactions between a firm’s executive and non-executive leadership. In addition, while the literature has started to shed light on the role of boards in strategic change, there are no
systematic studies that include a clear shift from a focus on organizational exploitation toward exploration. This research therefore aims at uncovering how the board of directors influences an organization’s shift from exploration to exploitation.

3. Methodology

To deepen our understanding of board conduct, we made use of inductive, comparative case study analysis. Qualitative case studies are particularly well suited to provide a rich description of phenomena for which little theory exists (Eisenhardt & Graebner, 2007; Eisenhardt, 1989b; Siggelkow, 2007).

3.1. Research Case

As recommended for case study approaches, we used theoretical rather than statistical sampling (Eisenhardt & Graebner, 2007). Firms needed to fulfill at least four criteria to serve as appropriate empirical cases in accordance with our research objectives. First, they needed to be governed by a board of directors. Second, all firms had to be well-established so that the role perception of both board and management was mature. In new ventures, board and management roles are not always as clearly separated as common in incumbent firms (Fried, Bruton, & Hisrich, 1998). Third, firms needed to be large enough to have sufficient resources for strategic reorientation at their disposal. In case of very small firms, maintaining existing operations might consume all human and financial capital and consequently, exploration capacity is inhibited irrespective of board conduct (Gupta et al., 2006). Fourth, all firms needed to be exposed to a strong need for exploration relative to their previous strategic orientation.

These sampling criteria led us to eventually study board activities at nine large incumbent utility companies in the Swiss energy sector. All firms were governed by a board of directors, with board size varying between five and fifteen active non-executive directors. Moreover, as most firms in the so far highly regulated Swiss electricity sector, all our sample firms looked back on a history of more than a hundred years; enough time to develop mature role perceptions of the firms’ main governing bodies. Focusing on the industry’s largest firms only, we ensured that all firms possessed sufficient resources to be able to engage in exploration. A prestudy of this research, in fact, revealed that small Swiss electricity providers showed indeed little exploratory behavior, because they simply couldn’t afford investments in novel technologies or business models. All firms selected for our sample, on the other hand, had between 150 million and 2,000 million CHF in revenues (2013), which ranks them among the top 25 out of several
hundred electricity companies (ElCom, 2013). Finally, all nine firms have been exposed to a strong need for (more) exploration, as further detailed below.

While the Swiss energy sector has a history of regulated, guaranteed steady revenue streams, since 2004, it has witnessed the introduction of disruptive regulatory changes as well as a dramatically harshening (international) business environment. Until 2004, end-customers were not allowed to freely choose their electricity supplier, leading to regional monopolies which guaranteed stable revenues and predictable profits for utilities. As a result, firms had little to worry about customer churn and both, board of directors and management favored exploitative business practices, i.e. making investments targeted at improving the efficiency and reliability of conventional power plants. The situation changed dramatically with the introduction of a series of regulations, starting in the early 2000s. A public referendum in 2004 and the enactment of the new Electricity Supply Law (StromVG) in 2008 initiated the stepwise liberalization of the Swiss energy sector. This implies that customers are eventually free to select their preferred electricity supplier. Since electricity prices in neighboring countries are often even below the cost of current electricity generation in Switzerland, many firms, all of a sudden, saw the competitiveness of their existing business model eroding. Within the same timeframe, additional legislation providing public subsidies to increase the share of renewable energy in Switzerland and in neighboring countries was introduced. Finally, in 2011, the Fukushima Daiichi nuclear disaster induced the Swiss government to introduce legislation for a phase-out of this technology.

Taken together, these regulatory changes put strong pressure on Swiss electric utilities, to shift their balance from exploitation toward exploration to remain competitive and comply with regulation. The outlook of a fully liberalized market required firms to prepare for open competition by searching for new products and services. In addition, the phase-out of nuclear power and financial incentives for renewable electricity generation required firms to look for alternatives to conventional electricity generation and experiment with a broader set of new technologies. As a result, as one executive noted, “essentially all firms in the industry now behave like pubescent boys—they explore all kinds of things.” Additional evidence for the need for exploration is provided in Table A1 in the appendix.

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3 At the time of this study, the association of Swiss electricity suppliers (VSE) counted over 400 members. The country has an astonishingly high number of local utilities given its population and size. This is less striking when considering that due to the protection of municipal electricity markets even small towns often have their own electricity provider.
3.2. Data and Analysis

To study our research question, we drew on several sources of data. First, to obtain information on the degree of exploration and exploitation over time and potential drivers, we collected a comprehensive set of secondary data. For each of the nine firms, we obtained annual reports, press articles (seven year timeframe), letters to shareholders, company issued brochures, employee presentations, official company releases, earnings call transcripts, general assembly notes and videos (e.g. from CEO or director presentations). We also developed a database containing background information on all board members (e.g. professional background, list of additional board mandates) for our sample companies. Second, we collected primary data in the form of in-person interviews with board members as well as CEOs and top-management personnel. We only approached interview partners that either had long lasting experience in their role at the firm, or for which we had evidence that they played a role in an apparent shift from exploitation to exploration.

In total, we used 33 distinct, semi-structured director and top-level executive interviews for our analysis. Due to board interlocks (i.e. directors with multiple mandates within the sample), we thereby covered 37 different executive and non-executive mandates across nine of Switzerland’s largest utility companies (see Table 1).\(^4\) Each interview lasted between 65 and 130 minutes. Per sample firm, we interviewed between two and four non-executive directors, including the chairman or vice chairman of seven out of nine firms. Moreover, we also discussed the matters with eight out of nine of the CEOs as well as additional top-management personnel. All interviews were recorded, transcribed and stored in a central interview database (Gibbert, Ruigrok, & Wicki, 2008; Yin, 2009). In addition, we conducted several validation interviews with experienced directors, within and outside the Swiss energy sector, and discussed our research results with a panel of industry experts in a series of workshops. Together, these measures ensured a rich data base that allowed triangulation of results (Gibbert et al., 2008).

For analyzing our data, we iterated between empirical data collection and theorizing. Thereby, our analysis followed three main phases. Phase one aimed at forming an understanding of the roles and activities of the boards of directors and the management teams as well as about their exploitation-exploration history. At the beginning of this phase, we synthesized secondary data in an event timeline for each sample firm, depicting both company strategy-related events as

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\(^4\) We refrained from discussing more than two roles within the same interview slot. None of the interview partners selected had more than two interlocking board or executive mandates. To fulfill the confidentiality requirements that were a prerequisite for most of the interviews conducted, we cannot disclose any information that would allow identifying firms or individuals.
well as board and management personnel related events. This allowed us to gain a structured understanding of company histories, the firms’ current situation and changes in their balance between exploration and exploitation. Thereafter, during the first round of interviews, we further detailed our understanding of board of directors and top-management roles and characteristics. We developed an initial coding scheme based on existing theory and complemented and refined the preliminary array of conceptual building blocks based on our first discussions.

Phase two aimed at capturing the activities of and instruments used by the boards to influence the orientation toward exploration. This was done by conducting additional interviews in a second round. For this, we used a newly composed, refined coding scheme focusing on board-management interaction. As part of the interviews, we often discussed certain events in the

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The first category includes e.g. the announcement of investments, strategic initiatives, R&D efforts, pilot projects, divestments, efficiency initiatives, new company visions, product announcements, or reorganizations efforts. The second category includes e.g. the appointment or resignation of board members and top-management staff.
firm’s timeline with the board members and CEOs of the firms to get an idea of the role that the board of directors had played in initiating or accompanying strategic initiatives.

Phase three aimed at further developing and maturing the evolving, preliminary conceptual framework. We synthesized all available interview and archival data and discussed and refined conceptual links on board influencing mechanisms. For this step, we went back and forth between coding and data collection in the form of additional interviews to identify and verify patterns in our data (Eisenhardt, 1989b; Yin, 2009). We conducted interviews until further iterations between theory and data lead to marginal improvements only (Eisenhardt, 1989b). Thereafter, all interviews were coded again based on our final coding scheme and extensively discussed by three independent researchers to avoid potential coding biases (see e.g. Gibbert et al., 2008; Gibbert & Ruigrok, 2010).

We paid careful attention to construct validity, internal validity, external validity, and reliability (Gibbert et al., 2008; Yin, 2009) throughout all phases of our research effort. To ensure construct validity, all structured interview guides and therein occurring constructs were reviewed and refined by all members of the research team prior to interview data collection. Furthermore, we used multiple, company-external and -internal data sources to verify and triangulate the subjective perspectives obtained during our interviews. Constant review and refinement of our coding scheme, in combination with sound coding conducted by three independent researchers as well as the review of specified constructs by key informants during the interviews and in separate workshops complemented our triangulation efforts (Gibbert & Ruigrok, 2010).

Internal validity was addressed by, first, establishing a clear research framework, which was iteratively refined (see Figure 1 in Chapter 4.1). Second, we deployed pattern matching, i.e. compared, for instance, the empirically observed board roles and activities with patterns described in previous research. Finally, we adopted multiple theoretical perspectives (e.g. organizational learning, dynamic capabilities) and reviewed, discussed and analyzed rival explanations throughout the research process.

Building on the strength of qualitative case research, we ensured external validity by conducting analytical generalization based on abstraction from empirical observations (Gibbert et al., 2008). This included strict theoretical sampling, multiple case studies at comparable firms exposed to the same regulatory environment, and cross-case analysis.
Lastly, to enhance the reliability of our study, we made use of transcripts and case study protocols and a comprehensive case study database (Gibbert et al., 2008) in combination with discussions to avoid and eliminate potential contradictions in the data.

4. Results

4.1. Conceptual Framework of Board Influencing Mechanisms

Figure 1 shows the theoretical framework that we developed over the course of this study and which illustrates how the board of directors influences a firm’s shift from exploitation to exploration. We find that the shift toward exploration of a particular firm can originate from two main sources: the management or the board (1). Depending on whether the exploration is primarily driven by the management (1a) or the board (1b), the board engages in different activities affecting the firm’s balance between exploration and exploitation (2). This goes along with the use of different instruments the board eventually deploys. We find that whenever the board itself was the initiator of the organization’s exploration shift, the board primarily relied on instruments such as service and coaching, giving direct orders to the management, or eventually hiring new and firing existing management personnel. Since these board activities aim to increase the number and breadth of management motions, they can broadly be categorized as variety creation (2a). Whenever the management pushed for more exploration, however, we find that the board primarily engaged in controlling (i.e. monitoring) and challenging management motions. Since these board instruments are strongly targeted at limiting the breadth and scope of management exploration, we broadly subsume them under the category of selection (2b). Irrespective of the mode a board operates in, we noticed that the board’s capability to judge strategic issues is a fundamental prerequisite for effective deployment of any of its instruments (3). Only if the board possesses the capability to make an informed decision (e.g. independently evaluate a strategic topic based on available expertise and thereafter form and convey a conclusion), it is able to influence the degree of managerial exploration in an informed manner (4). While, therefore, these board capabilities are important for the board to effectively influence an organization’s balance between exploration and exploitation, we find also that this very balance in turn affects board capabilities. A higher level of managerial exploration can lead to a situation where the board finds itself in a position lacking the capability to judge strategic issues effectively—a status reinforced by the immanent time and information asymmetry between board and management. To handle this adverse state, boards need to continuously adjust their capabilities by engaging

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6 Including interview recordings, transcripts, coding schemes, case study factbooks per firm (press releases, annual reports, letter to shareholders, firm internal data) and interview guides.
in board learning, especially in times of need for more exploration. Interestingly, while learning on the level of top management teams can be stimulated or induced by boards, there is no institutionalized governance body within the organization that could trigger or accompany learning within boards. As a result, we find that whether or not board learning takes place is strongly dependent on the presence of a set of higher-order learning capabilities within the board itself (5). We identify four such higher-order learning capabilities that allow firms to successfully alter their capabilities to judge strategic issues, namely self-evaluation, education of board members, adaption of board composition, and adjustment of decision making. Because we see greatly varying degrees of these higher-order learning capabilities, the degree to which the boards of the organizations in our sample can effectively drive and accompany organizational exploration in times of environmental change strongly differs.

Figure 1: Overview of board influencing mechanisms

In the following, we elaborate in more detail on the framework elements, namely management-vs. board-driven exploration (4.2), related board operating modes and instruments (4.3) as well as the interplay between board capabilities and board activities (4.4). Lastly, we outline our findings related to the need for board learning (4.5) and describe observed higher-order learning mechanisms (4.6).
4.2. Management-driven vs. Board-driven Exploration and Related Board Roles

While the literature currently mainly stresses the role of managers in altering a firm’s balance between exploration and exploitation, we find evidence that a shift toward exploration can be induced by both the management and the board. In the case of Firm A for example, the management early on recognized the need to prepare for the upcoming liberalization and emerging competition. Accordingly, a key executive who later became CEO pushed for reorganization. The board members “on the one hand [they] were skeptical, but on the other hand very pleased to see that we recognize the signs of the time” (IA2). After the designated CEO sensed further need for exploration a few years later, he again sat down with the chairman of the supervisory board “to initiate a much more comprehensive strategy process” (IA2). In the case of Firm G, after retirement of the former CEO, a new executive team engaged in exploration by proposing a number of renewable energy generation projects and new business lines in photovoltaics and heat distribution to the board for review and approval (IG3). Albeit being skeptical at the beginning, the board later approved the proposed initiatives and adjusted its own exploitation-exploration balance accordingly.

Most of our interviewees personally believed that the responsibility for initiating strategic shifts is ideally assumed by the management. Both executive and non-executive (i.e. board) directors reckon that “if it [proposal for exploration] has to come from the board, we might have poor top-management. These guys [management] know what’s happening at the front. […] they have to act, know their business, that’s what I expect from them” (IF2). Nonetheless, in about half of the cases we discussed, the shift towards exploration was not initiated by the executives but by the board of directors. In the case of Firm F for example, the shift was initiated by the board’s ambition for more exploration. It had proactively decided, after regulatory changes were announced, “to establish a separate energy efficiency committee” since such management action was not to be expected (IF1). However, the CEO at that time “did [still] focus very much on basic services and was not willing to move”. As a result, “major course adjustments were initiated by the chairman of the supervisory board” (IF4). In Firm H, we could observe even stronger board interference. Firm H’s board portrayed itself as very proactive, constantly exerting pressure on the management to consider exploratory opportunities. This even lead the CEO to think in-depth how he could effectively channel the discussions between board and management in a way, so that he is not permanently “overcharged by new ideas” (IH3). We provide more evidence for the existence of both, board- and management-driven exploration initiatives in Table A2 in the appendix.

Moreover, we find that depending on the origin of exploration, in turn, the board takes on different roles. When the board’s exploration desire prevails over the management’s at any
given point in time, the board takes on the role of *variety creation*. In such case, it intensifies its demand for exploration such that it engages in “provoking and by pointing out potential external opportunities and new projects” (IE2). In the case of Firm F, for example, the supervisory board forced a conservative CEO after several rounds of arduous discussions to “show if it would make sense to go into contracting—and if not to detail why” (IF4). In fact, it was pointed out that the board deliberately selects, and that the mandate itself provides sufficient leeway for non-executives to engage in creative thinking: “I [as a board member] have a much broader perspective. I am not involved in daily operations, hence can think about topics under the shower in the morning for which the management might not have the time because it is constantly running after its numbers. […] And this then kicks off some momentum” (IC3).

If, on the other hand, the management opts to raise the level of exploration and the board has less exploration appetite, however, the board engages in *selection*. In this case, the board scrutinizes management proposals for exploratory initiatives after they have been brought to its attention. In the case of Firm A, for instance, when the management proposed to invest in additional power generation assets and outlined several opportunities abroad, the board discussed and decided “for God’s sake not to invest in Italy and France” and to rather invest elsewhere. “We are too exposed and already had trouble there in the past, what if suddenly there is again a new tax law, no we don’t do it” (IA1). In general, it was also perceived “much easier [for the board] to receive a set of options to choose from. I would say that, well, this role is actually easier and it is the role that is taken on by the board in our case” (II3). In the case of Firm G however, the board found itself constantly confronted with new, exploratory ideas due to the pioneering nature of its CEO. A member of the board mentioned that most of the time he has to select among the many proposals put forth by the management team. “The board is much more in the position of selecting and has to focus and [we as the board have] to limit ourselves to things that are ultimately feasible” (IG1).

### 4.3. Board Instruments to Influence Organizational Exploration

Synthesizing all interview data, we were able to identify four archetypical board instruments, which boards deploy to fulfill their roles of selection and variety creation: challenge and control, service, direct, and hire and fire. Table 2 lists these, allocates them to their prime board role and provides an excerpt of evidence collected throughout our research effort. In addition to Table 2, we provide an extensive overview of instrument-related interview quotes in Table A3.

In the case of management-driven exploration, the board is confronted with exploratory proposals from the management that are either brought to the board’s attention for constructive discussion and development or because they need formal board approval (Figure 1, (2b)). In
case of such confrontation, we see that boards usually challenge and control the respective requests until the committee agrees on an informed, contented decision. As one director put it: “Today, it is expected that two or three directors are capable of asking: how did you come up with that WACC [weighted average cost of capital]? This NPV [net present value] calculation cannot be correct, because of the WACC actually being in this [and not in that] range” (IC2). Another director told us that he had experienced challenge and control several times not only in the position as a non-executive director of Firm D, but also during his former executive career. He provided one example where he “had initiated projects which were ultimately challenged by the board.” The board approached him with the words: “This is a project that is within our defined strategy, but we have the following concerns. And since it is of such importance for the entire division or the firm, we have to profoundly understand the topic; we cannot simply give our blessing. The key parameters seem to be alright, but there are some open questions” (ID2).

As a result of the challenging and control process, the board can reduce the degree of management exploration. “You can always slow down [the management]. The board has to do this in fact. My board is slowing me down—and rightly so” (E3). This can also occur in the form of declining explorative management requests. “We as the board actually agree that we sometimes have to step on the brakes. And we do this selectively. […] Although this might not always be pleasant, we sometimes intervene, which means we don’t approve certain proposals [from the management]” (IG2).

In contrast to the board role of selection, the role of variety creation is characterized by absence of proactive management exploration activities (Figure 1, (2a)). Hence, all instruments subsumed under this category—service and coaching, direct and hire and fire—aim at stimulating exploration activities. First, with regard to service and coaching, the directors we interviewed pointed out that an important role of boards was to provide resources and information as well as active coaching to the management. One director, for example, pointed out that it can be “an advantage when you have public sector experience. You have a certain focus in which you are naturally the expert” (IC1). Moreover, “if the board realizes that there are no new impulses coming from the management, there are generally ideas from the board at disposal. And these have to be introduced. This can, for example, be done by starting to provoke [the management] or by intensively pointing out opportunities, or ideas or projects” (IE2). In one specific case, a board member had pointed out that “energy efficiency might be a relevant issue for supply security” and that “it should be explored further” (IF1). Consequently, board and management decided to invested resources to explore this, at the time, new topic. In another example, the chairman of the board went to the Silicon Valley with his executives to experience data-based business first hand “and to look at a few start-
ups...and I [chairman] had the feeling that it clicked. [...] I am convinced we will now radically change the business-model understanding of Firm H. It might very well be a five to ten year journey, but I believe this has happened" (IH1).

Table 2: Board instruments during selection and variety creation

<table>
<thead>
<tr>
<th>Instruments</th>
<th>Exemplary Quotes</th>
</tr>
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</table>
| Selection            | • “Well, by asking questions in the board meetings, questioning in the meetings and by challenging the subject on the basis of the documents provided. That’s pretty much the only way to do it [exert influence].” (IB2)  
• “Then they [the management] have to start selling to get the project approved. Because, we [the board] have to ask as many critical questions as necessary to convince also them to actually say: yes, we are fully behind [the project].” (IB1)  
• “If the CEO, and it happens quite a lot, is challenged by the board and accepts the challenge in a positive way, then this becomes a ritual that I understand and that can happen over and over again.” (ID2) |
| Challenge & control  |                                                                                                                                                  |
| Variety creation     | • “There are directors that have had other experiences [than the CEO], they look at it from a different angle and give their feedback” (IE3)  
• “Stimulating, supporting, coaching—there is a lot it [the board] can do.” (II2)  
• “A board can say: take a look at this sector, or take a look at this company, do you [the management] see this fir? They seem to operate well. This could be complementary to what we are doing.” (IA1) |
| Service & coaching   |                                                                                                                                                  |
| Direct               | • “It is not a request, it is being discussed and then there is a directive [to the management]. For the next meeting, please prepare an overview for it [electric vehicle business] and then we will see how we proceed.” (IH3)  
• “Of course, the board can formulate an order, it indeed can. And commission the order accordingly. And they do that.” (IF2)  
• “It is a question of how to escalate such difference, no? It can certainly be the case that there is an order [from the board] specifying that this is how it is done now.” (II1) |
| Hire & fire          | • “We [the board] actually bet on the CEO. Well, the CEO is either on board or he is dismissed—nothing in between. Either we put all our faith in him and work with him and it needs to work, or if it doesn’t work, then he needs to be replaced.” (IH1)  
• “The biggest lever a board can pull are personnel decisions. Because there is this inherent disconnect between a board’s time and the operational involvement. The selection of persons is probably the biggest value generator.” (IC3)  
• “We [the board] always said: the guy needs to change, in one way or the other. If he does so, ok, but if he doesn’t, we have to say goodbye!” (IA2) |

In addition, if the board does not succeed inducing more exploration via servicing and coaching, we observed that due to their hierarchically superior position, boards may direct the management to act on their behalf, i.e. implement board-desired decisions. For example, in the case of Firm H, the management team was not open to entering into the electric mobility...
business. After several discussion, the board was no longer willing to accept the opposition. It directed the management to “prepare an overview for it [electric vehicle business] and then we will see how we proceed” (IH3). When asked if the board would go as far as forcing the management to execute tasks in case service and challenge fails, several director (ID2, IH2, IA4) gave an immediate and concise answer: “Yes, of course this happens.” Yet, none of our interview partners perceived this as a mid- or long-term solution. If the management is not willing to implement what is considered right by the board, “it depends on the case, but I wouldn’t accept that for very long [and initiate a personnel decision].” (IB2).

In case neither service and coaching, nor direct satisfy the board’s appetite for more exploration, or if the board has second thoughts that the management possesses the skillset to execute rebalancing, the board can make use of its “most influential lever” (IH1), namely to hire and fire management personnel. By law, this “formative instrument is an indefeasible competence and duty that cannot be delegated” (IH1). Throughout our interviews series, several board members confirmed that “if you really want to change something, you have to choose a person when you have the chance, from whom you can expect that he or she implements change” (IA3). It was also confirmed that in case the board really aims for strategic realignment of the firm, changing the CEO “is probably the only option” (IA3). In the case of Firm D, for example, the former CEO was not willing to reckon that environmental change will necessitate a more exploratory strategy. With reference to this case, a board member (IB2) told us: “In such case, you can only change the CEO. If one is not willing to accept the changing circumstances, then he has to go.” In addition, whenever the challenging process between board and management meanders into non-constructive information exchange or if the CEO does not accept the board’s position (anymore), this is considered “a situation which is not permanent. This is unthinkable” (ID2). Yet, several examples discussed during our interviews did not necessarily involve both hiring and firing of an executive. In some instances, a natural change in leadership was perceived as a timely opportunity to strengthen the exploratory capacity of the executive team. In the case of Firms C, F, and G for example, new exploratory-minded CEOs were brought in after retirement of the former chief executives. “As I perceived the board [at the time] and now after my [CEO] recruitment, the board has strongly influenced and played an active role in this personnel decision and in selecting the desired competencies” (IC3). Or as the new CEO of Firm G described: “It was a very deliberate decision [taken by the board] to bring in industry-external people, external people with sales and marketing experience that have a track record outside of the current business” (IG3). In the case of Firm A, the former CEO himself even proposed to step down because he felt that because of a drastic strategic shift, he might no longer be credible. He explained that after he and the board had conjointly drafted the new strategy, “we [he and the board] then said that as a matter of fact for implementation I am not the right guy…not that I couldn’t do it, but it would be worse [if
I would)” (IA2). Subsequent to his withdrawal, he and the board decided together on a strategy-conform successor.

4.4. Board Capabilities and Learning as a Precondition for the Effective Use of Board Instruments

The previous section detailed instruments that the board of directors uses to steer the level of organizational exploration through variety creation and selection. While by using these instruments, the board can potentially exert strong influence on the organization’s balance between exploration and exploitation, we find that the effective use of instruments strongly depends on the capability of the board to judge strategic issues.

Our interview results indicate that without the right expertise at the right time, boards cannot deploy strategy-influencing instruments effectively (Figure 1, (3)). First, a lack of capability to judge strategic issues significantly hurts the ability of boards to fulfill their role of selection in times of managerial exploration. Generally, as one director pointed out, every time a strategic initiative is introduced by the CEO, this usually takes the form of “a massive document, and this huge document is subsequently being discussed. And it is absolutely right that as a board member…all these technical questions…it is really demanding how to deal with this” (IC1). As a result, “a plausibility check [of the proposed initiatives] can be quite difficult due to the information asymmetry” (IE4). If the knowledge gap between the management and the board becomes too large, this may lead to situations where “the strategy is made by the management and that the boards […] just rubber-stamps it” (IH1). The board hence loses its ability to critically judge and select from managerial initiatives, which may lead to a situation where the CEO “dominates the topics and [board] meetings”, i.e. that board influence is inhibited (IG1). Among many of the firms in our sample it therefore appears to be a main principle that in case an issue is not understood to the desired extent by board members and “in case this expertise is not readily available, then you won’t be able to move accordingly” (IE3) and a “project cannot be approved [by the board]” (ID2).

Second, board capabilities to judge strategic issues become even more important when the board takes on the role of variety creation. One director highlighted that the transition from being merely able to control the management to provide active coaching requires substantially more expertise. As one board member pointed out, to be able to give inputs to management “a modern board should be composed accordingly, and be multisided; and then lead the respective [critical] discussions” (IC2). Another director stressed that particularly the instrument of hiring and firing required comprehensive capabilities on the side of the board: “to get a new [CEO] in a difficult environment is challenging; especially to find one that is not off his rocker
[does the right things]...and you only know this after he is on board” (IE3). After bringing the CEO in, the board needs to engage in “support and coaching [which] is intense, but key” (IB2).

Interestingly, we find that while the board’s capability to judge strategic issues is a precondition to initiate or critically accompany organizational exploration, organizational exploration itself can significantly hamper this capability (Figure 1, (3)). Especially when a large number of new (and/or fundamentally different) initiatives is launched, the board often no longer has the required expertise to understand all aspects deeply and, thus, fulfill its critical governance role. One director, for example, expressed that “especially since the phase of liberalization [of the electricity market], complexity has increased dramatically. From my perspective, for the board it is extremely challenging to merely keep up [with this increasing complexity]” (II3). Director IC2 agreed that “especially with respect to new technologies, the know-how of the management team is usually greater. To give you a concrete example: distribution grids. In Firm C, we have fascinating technical and economical interdependencies…but they are highly complex. You have to understand these before you are even in a position to form a decision”.

We provide further evidence for the detrimental effects of managerial exploration on the board's capability to judge strategic issues in Table A5 in the appendix. A director of Firm H summarized the issue with the words: “For a board to be even in the position to take on such visionary [i.e. exploratory] projects and to manage a [strategic] reorientation, you need board members with a lot of expertise. Directors that are [and remain] expertise-wise on par with the executives” (IH1). Overall, hence, boards have to engage in continuous learning to constantly adapt in times of firm-internal as well as -external change.

4.5. Board Higher-Order Learning Capabilities as a Precondition for Board Learning

The previous section showed that to effectively influence organizational learning in times of organizational exploration, boards need to engage in learning to remain capable of critically judging strategic issues. Interestingly, while we find that processes of learning on the level of management can be triggered and accompanied by the board, within the organization there is no hierarchically superior body that could fulfill this function on the level of the board of directors. In general, a board of directors is installed to increase and preserve owner, i.e. shareholder interests. In this respect, governance mechanisms are theoretically designed such that the firm shareholders have ultimate control and the right to appoint (and dismiss) directors who must act on their behalf. Our interviews, however, showed that due to the distributed ownership structure and lack of institutionalized means through which owners could influence firm strategies, owners seldom contribute to organizational learning in a systematic way. One director, for example, pointed out that in his firm an institutionalized process for director appointment exist. Yet, “these [processes] are not competency-based” (IH1). Another director
directly acknowledged that “yes, it is often the case” that there is lack of a concise position from the owners of the firm and that it might take a long time for directors to be replaced (ID1). A director of Firm A even pointed out that in their specific case, the owner influence had even a cumbrous effect on board improvement and exploratory activities. “I believe we have probably progressed slower due to this [owner] constellation. If we had been a committee that was composed much more liberally [independent of political interests], then we would have progressed fast. Yes, I am convinced” (IA3). Even in the case of a setup with an influential 30% majority shareholder, a director of Firm C remained skeptical about his owner’s supervision capacity vis a vis the board. “It [board supervision] doesn’t exist. The general assembly is not able to perform this monitoring and control function…it is a mere formal discharge based on the annual reports” (IC2).

The lack of a body that could monitor the capabilities, provide feedback and systematically influence learning at the level of boards, implies that ultimately board learning is strongly contingent on the presence of higher-order learning capabilities within the board itself (IH2, IA4, ID1). Based on our interviews we were able to identify four main higher-order learning capabilities that affect the boards’ first order capability to judge strategic issues (see also Figure 1, (5)): self-evaluation, adaption of composition, education of board members and adjustment of decision making.

**Self-evaluation** refers to the capability to continuously self-assess the strengths and weaknesses of the board as a committee and to take action accordingly, without or limited supervision of a hierarchical superordinate. One director pointed out that “the only systematic measure I am aware of” to ensure that the individual director lives up to his or her responsibility “is the board of director assessment” (IH1). He added that this can be and in his case is done internally and/or with external support. In Firm A, for example, the new chairman paid particular attention to self-evaluation early on and told his board that he “will talk to his board colleagues about how they work [as a committee]” and subsequently implemented this ritual (IA3). In the case of Firm I, the board had conducted a multi-day offsite event during which it reviewed and adjusted its operational core processes (IA4). In another case, director IE2 illustrated a process where they would use a structured document to anonymously conduct an assessment of both, board and management. The results are subsequently being published and corrections are being initiated accordingly.

**Adaption of composition** refers to the capability to continuously recognize the need for and subsequently implement personnel reconfiguration of the board, without significant exertion of influence of a hierarchical superordinate. One director (IA1), for instance, described that in his firm, the board had decided, amongst other things, to reorganize itself. More specifically, “to bring in new forces that represent the new world, without piling up more knowledge”. In the
case of Firm G, after a more exploratory CEO has been brought in, the board is now not “looking for minions or people of some political color”, they are “looking for folks that are experts and that have the capacity to challenge the management” (IG3). Several board members pointed out that their boards had developed board member competency profiles to address optimal selection of future directors (IA4, IA3, IC2, IG1).

Education of board members refers to the capability to continuously address board knowledge gaps eventually unveiling over time, without guidance from a hierarchical superordinate. According to one chairman, the board of Firm F for example conducted excursions on a regular basis. “On the one hand, these trips are technical so that the non-experts also get a sense… we look at every technology. For example, I wanted [the board] to look at brown coal… to have them see this. One has to see this. It was always discussed in an abstract manner. On the other hand, [we look at] the modern developments, and also always companies that have experience [with a certain technology]” (IF2). In the case of Firm B, the chairman oversees the distribution of supplementary material in addition to the regular board meeting documents prepared by the management. In this respect, education about topics being discussed is not left to director’s own resources (IB2). In the case of Firm I, the board has institutionalized a so called annual “education day” (i.e. workshop) where critical topics are being openly discussed and reviewed in depth at the beginning of the calendar year (IH3). Furthermore, the chairman of this firm revealed to us that he “had just written a training concept for the board itself” (IH1), including a structured agenda for the board to continuously advance firm-specific knowledge (e.g. readings, expert talks, study trips).

Adjustment of decision making refers to the capability to continuously adapt board processes enabling effective decision making as required by the environment, without or with limited support from a hierarchical superordinate. The board of Firm B, for instance, has given itself a clear set of (written) guidelines according to which the management has to prepare future discussion documents for board meetings. This aims at more effective discussion in the case of increasingly complex projects by avoiding “drivel” and focusing on “facts” (IC2). In the case of Firm I, the chairman of the board explained how they had implemented a structured, multi-stage process that forces the board “to take on a certain maximum depth of involvement, so it doesn’t descend into operational topics” (IH1). Every year, the board would select three to five priority topics for them to focus on throughout the year. This ensures that the committee at large can “focus on core issues”, which has also been reported as important by others (IE2). Another director pointed out that the turbulent times may demand different board operations. In today’s times, according to him, “to successfully lead a company, the board has to have board-internal meetings—either aperiodic or topic-specific” (ID2). Table A6 provides an
overview of further evidence related to all of the above described higher-order learning capabilities.

While in the interviews, all interviewees agreed that board higher-order learning capabilities were of large importance in times of organizational exploration, we find that the degree to which such learning capabilities are present strongly differs across firms. While several boards have an elaborate process of self-evaluation, one director recounted that to his surprise, he experiences strong reservation of the board to conduct structured feedback surveys. He as a board member even proposed this but “never [even] got a positive response…it was never incorporated as an idea” (IE2). Others agree that self-evaluation is a wise idea, but that their boards have not incorporated it either (IG2, IF2). The same holds true for board composition, where some interviewees acknowledged that processes for board composition such as development and use of competency profiles for adequate director selection are meaningful but not yet institutionalized (II2, II3). In addition, directors have pointed out that in their experience, replacing directors once they have become part of a board is “extremely rare” (IG2). Similarly, education of board member competencies varies across firms. While for some it is an institutionalized part of their board mandate, others point out that self-development on a committee-wide basis is “not typical” (IA3, IE1). Even with respect to, in most firms, well established routines such as aperiodic meetings of the board without the management, not all firm have developed the capabilities to establish such processes. Director ID2 explains that these meetings are not conducted frequently enough in the case of Firm D and, in Firm G, they do not take place at all (IG1). In sum, while in principle boards can and do play an important role in the process of initiating organizational learning, our research reveals major differences across firms in the extent to which the board itself is able to learn as part of this process.

5. Discussion

5.1. Implications for the Literature

Building on our results, our study makes a number of relevant contributions to the literature. First, we add to organizational learning literature by outlining in detail how boards influence strategic reorientation toward organizational exploration. Previous literature on board of directors has already identified a number of different board roles and functions, such as monitoring, control, service and strategy (Hillman et al., 2008). So, far, however, the literature has provided limited empirical insights into (a) the inner workings of boards and (b) the question how the roles and instruments of boards are linked to organizational learning. We show that depending on the situational peculiarities such as board exploration-level relative to management exploration-level, boards focus on different roles and instruments. The portfolio
of instruments we identify (challenge and control, service and coaching, direct, hire and fire) is much in line with previous literature on board role and functions. Adding to the literature, however, we provide an integrated perspective on under which circumstances and how these board instruments are being deployed. We cluster board instruments according to the two main roles boards play in the process of affecting organizational learning, namely selection and variety creation. Together, these findings also support the literature that takes an evolutionary perspective on strategy, which suggests that the principles of variety creation and selection operate across and within firms to constantly alter the competitive environment (Burgelman, 1991).

Our second theoretical contribution highlights the importance of higher-order learning capabilities of the board for organizational learning. Across instruments, we find that the capability to judge strategic issues is a prerequisite for effective instrument deployment. However, whenever management (i.e. firm) exploration is increased, the capacity of the board relative to its environment is adversely affected. While previous literature has stressed the fact that exogenous change is competence destroying (Henderson & Clark, 1990; Tushman, 1986; Winter, 2003), we posit that internal change in management orientation is hampering the competency of the board in influencing exploitation-exploration. Consequently, board learning is required to ensure that boards remain capable of steering firm strategy. More specifically, in our study we identify and specify four major higher-order learning capabilities that operate on a board’s first-order capability to judge strategic issues: the capability to engage in board- internally provoked self-evaluation, adaption of board composition, education of board members and the adjustment of board decision making. We provide evidence that the lack of these higher-order capabilities might be important for explaining why companies fail to adequately react to environmental discontinuities that go along with a strong need for organizational exploration.

Besides linking the literature on organizational learning and boards, by pointing to the role of higher-order capabilities, our research also contributes to the literature on dynamic capabilities. In the literature, dynamic capabilities have been defined as higher-order capabilities (an assembly of routines) that operate on lower-order capabilities (another set of routines) to alter them (Schilke, 2014; Zollo & Winter, 2002). It has been stressed that dynamic capabilities themselves are subject to change, leading to a theoretically infinite hierarchy of (dynamic) capabilities in which capabilities at a higher order influence the capabilities at the level directly below (Winter, 2003). Our research shows that indeed the conceptual logic of dynamic capabilities operating at different levels can be observed when looking at how learning and changes in capabilities take place within firms. We find that, similar to the conceptual model presented by Winter (2003), governance structures in firms are organized in a way that higher
levels of governance trigger learning at lower levels. For example, we show in detail, how boards can trigger organizational learning by inducing changes at the management level (variety creation).

In addition, we show how organizational learning takes place when no superordinate structure serves as an institutionalized source of higher-order influence. Winter (2003) already raised the question about where the theoretically infinite chain of higher order dynamic capabilities might end and this conceptual question of what triggers learning at the highest level is of direct practical relevance for firms. While boards serve as a source of learning, the board of directors is generally perceived the highest instance of institutionalized firm governance, superseded only by the owner who most often lacks position to actually exert direct influence (in large incumbent companies). Since there is no governing instance higher than the board, we show that learning at the level of boards requires higher-order learning capabilities within the board itself. This implies that boards are a potential source of inertia not only for organizational learning in general, but also specifically for rebalancing exploitation-exploration.

5.2. Limitations

Our study has several limitations that lend themselves as avenues for future research. As with any case study, one may question the degree to which our findings are generalizable to firms in sectors or countries other than the Swiss electricity industry. The electricity sector is highly regulated and with a number of board interlocks across firms. It is likely that industry history influences amount and nature of board dynamics. Our results indicate that many boards have started to change their self-perception, moving away from a reactive to a more proactive role. This implies that in other industries, level of board involvement and instruments deployed differ. Moreover, the competencies and assumed responsibilities of boards of directors differ in nuances from one country to the other (Ruigrok et al., 2006). Future studies should therefore build upon our findings and investigate board mechanisms during rebalancing efforts in other industries and countries.

Second, in our study we provide a detailed account of the dynamics that result from board-versus management-driven exploration. Yet, our study does not uncover the determinants for causing the board or management taking on a more exploratory stance. Preliminary findings from our analysis suggest that this matter is in particular related to the composition of the executive team compared to the board of directors. In line with upper echelon’s theory, hiring industry-outsiders for the executive team or the board seems to induce the respective body to embrace exploration activities more proactively. While these findings provide first hints, we call for further research that investigates the antecedents of board- versus management-driven exploration.
Third, besides board and top-management there is a number of other factors that might shape the exploitation-exploration balance of a firm, such as the firm’s vertical integration or ownership structure. Future research should investigate how these factors may interact with the processes described in this paper to identify potential contingencies and theoretical boundaries of our findings. In this context, it could be interesting to test empirically some of the concepts of this study in larger samples, e.g. that board-driven exploration indeed goes along with a higher likelihood of changes in top-management teams compared to management-driven exploration.

6. Conclusion

Based on the results of an inductive, multi-firm case study in the Swiss energy sector, our work contributes to a better understanding of how boards influence firm strategy and of the role of boards for organizational learning. More specifically, we open the “black box” of board mechanisms and detail the links between board- versus management-induced exploration and different instruments deployed by the board. Whenever management-driven exploration occurs, the board engages in selection. If, however, the board is the driver for more exploration, the board engages in fundamentally different activities targeted at variety creation. This reveals not only that different board activities (i.e. roles, functions) are important for organizational learning, it also uncovers that board influence eventually depends on a set of higher-order learning capabilities at the level of the board. Whenever the impulse for more exploration changes course of the firm, topics brought to the attention of the board change also. A viable option to remain an effective counterpart to the executive team is to engage in continuous learning. We identified a set of higher-order learning capabilities termed self-evaluation, adaption of composition, education of board members and adjustment of decision making that are inevitable for this process. Due to the fact that boards are the highest governing instance within a firm, the impulse for continuous learning has to come from inside this committee. Our results stress the importance for board self-development and open up a new perspective on higher-order learning capabilities. Showing the importance of these higher-order dynamic capabilities and how they relate to exploitation-exploration, we hope to have stimulated the discussion on the link between boards and organizational learning as well as pointed towards related intriguing issues such as the role of boards as a source of inertia.
7. References


Table A1: Exemplary quotes showing need for organizational exploration

<table>
<thead>
<tr>
<th>Firm</th>
<th>Quotation</th>
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<tbody>
<tr>
<td>Firm A</td>
<td>“The biggest changes in the energy sector, or at Firm A in the energy sector, were that all of a sudden the business model was at risk to be completely overthrown. One recognized that there are dark clouds at the horizon. […] It was directly noticeable, one could feel the pressure increasing and that it was time to act, otherwise it might be too late.” (IA1)</td>
</tr>
<tr>
<td>Firm B</td>
<td>“When coming from a monopoly and demanding a change, back then nobody needed such change. It always went well. Until Fukushima, this was the case.” (IB2)</td>
</tr>
<tr>
<td>Firm C</td>
<td>“One has to differentiate between before and after introduction of the new energy strategy. […] Prior, it was good times for energy firms. […] the board was confident that there is only the direction of increasing electricity prices. […] Hydropower was very successful and profits were very good.” (IC1)</td>
</tr>
<tr>
<td>Firm D</td>
<td>“And suddenly change was induced […] margins, cash flow, everything was ok but actually we had realized that the upcoming change will introduce new topics and pose unprecedented challenges for Firm D.” (ID1)</td>
</tr>
<tr>
<td>Firm E</td>
<td>“It might be a bit more difficult because we previously had a cash cow, but we didn’t manage to keep up with the change. And to revert this development [is quite difficult]. […] In the old world, there was only growth. More profit, it was one cash cow. It was a like a bank with an electricity plug.” (IE3)</td>
</tr>
<tr>
<td>Firm F</td>
<td>“It was like that before. Today, [the business] has become much more complicated: grid regulation, regulation and market liberalization in the energy business, all these topics. […] From 2000 to 2008, Firm F made 2-3% of its profits in liberal markets, the rest was monopoly.” (IF4)</td>
</tr>
<tr>
<td>Firm G</td>
<td>“The core electricity business has to be reduced, It can no longer be our cash cow…this part of the business will disappear. That’s why one has started to build businesses such as district heating and cooling.” (IG2)</td>
</tr>
<tr>
<td>Firm H</td>
<td>“The goal is really 100% renewable energy supply of Firm H. We also want to fully convert the heating business. […] Firm H receives about 100 million CHF from the canton to initiate these projects.” (IH4)</td>
</tr>
<tr>
<td>Firm I</td>
<td>“The basis for exploitation disappears or is at least up for discussion […] and that is why there might be no other option than to explore.” (II2)</td>
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### Table A2: Exemplary quotes for board-driven and management-driven exploration

<table>
<thead>
<tr>
<th>Exploration initiated by the management</th>
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<td>• “For our engagement in the new biogas plant. Well, it took two attempts, including a visit at the site until the board was willing to fork over some money. Along the lines of: it will not be successful, you’ll see! But [the CEO] insisted and eventually we spent the money and today the plant works terrific.” (IG3)</td>
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<td>• “The current strategy, the pushing, changing the view are all things that stem 90% from the management. They are at the forefront. They are the ones saying that there is something running faster than expected or something is not moving at all, contrary to the expected.” (IF2)</td>
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<td>• “Since I have been in charge here, only very few impulses came from the board. The impulses were almost every time initiated by the management and have subsequently been reviewed and approved by the board. [...] But the impulses came from the management.” (II3)</td>
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<td>• “The driver for this change is [the CEO]. Which means that a lot is coming from his side.” (IG4)</td>
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<td>• “In many cases, probably in most cases the management will practically pitch the strategy to the board, which will then approve it. This is my utmost believe.” (IG1)</td>
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<td>• “We have a strategy document that is developed and drafted by the management and subsequently discussed and presented [to the board].” (IG3)</td>
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<td>• “The strategy, the basic principles of today’s strategy was written by [the former CEO]. The implementation however…well, it is only reasonable to have this implemented by a new management team as it was agreed upon.” (IA2)</td>
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<tr>
<td>• “The honorable task of the board is to make strategy. However, to be frank, fact is that the board—at least from my perspective [...] I always had the opinion that there need to be options, different alternatives in the strategy discussion so that the board can choose which one to look into.” (IA2)</td>
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<tr>
<td>• “Well, [the CEO] is sometimes even a bit too much of a pioneer for the board.” (IG3)</td>
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<tr>
<td>• “Well, I do think it is the duty of the management to develop strategic options and to give them broad strategic boundaries to operate within.” (IE4)</td>
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Exploration initiated by the board

- “It was decided [by the board] that the management will be replaced, the business segments extended from three to four and that efficiency and renewable energy generation will be increased to the same level as production, trade and the other business segments.” (IA1)
- “There are certainly things that have been introduced by the board. One such thing was the data transmission grid business topic, among other things.” (IG1)
- “How much input is really coming from the board? Well, in our case, there is a lot of input coming [from the board].” (IH3)
- “The major course adjustments are coming from the chairman of the board. […] It was him who said that we need to change the sales approach. […] We need someone that builds up marketing and sales.” (IF4)
- “I find the dialog [between management and board] being […] trust-based and open, including proposals coming from the board, yes.” (ID3)
- “But one had already seen that Firm F has to start taking care of its customers [in anticipation of a liberalized market] and consequently change was induced by the board.” (IF4)
- “This decision to bring in industry-external people, […] this decision was taken very deliberately [by the board].” (IG3)
- “I believe it was [the chairman of the board] that pounded his fist on the table and said we cannot continue like this. We have to prepare for this change. We now have to take this personnel decision and that’s how it was done.” (IF4)
- “Would the management not have addressed the topics that I just mentioned, for sure the board would have been proactive and asked: I have seen firm XYZ invests in photovoltaic in Spain, why are we not doing anything there? Can you please explain this to us?” (IC2)
- “Would that be something for our firm? And I do mention that accordingly. I have read that this is a hot topic, couldn’t we [do this]? Can you [the management] please review this?” (IC1)
- “It is not only reactive, it is also proactive. Look at this topic, take a step back here, develop new fields—very proactive.” (IE3)
- “Usually, there are new ideas coming from the board. […] And it should be possible to introduce them, maybe simply by provoking and by pointing out potential external opportunities and new projects.” (IE2)
### Table A3: Exemplary quotes for board activities and instruments

| Challenge & control | “The decisions that are prepared by the management, they are always decisions to do something rather than to not do something. But the board can say we do not do this. Many times however they express this as we do not do it yet. Or, it needs to be refined before we do it, it is not sufficient, we don’t do it today. […] It is a no, but [with the option to refine and come back]” (IB1) |
| Service & coaching | “If things don’t progress well, or in case progress happens but the return is insufficient, then the board has to intervene and think, request reports. Otherwise, it will not work.” (IA2) |
| | “Every business has to generate at least this and that return. Otherwise you have to report to the board. In case of a business that does not generate a [specified] rate of return, it has to be argued very detailed why we should invest money in it.” (IE1) |
| | “One [board member] has to continuously bring up also the topics that are currently not on the table.” (ID1) |
| | “Such cross-industrial competencies should be acquired. This is important for the challenging process [between board and management].” (ID2) |
| | “Then there is sometimes a bit of corrective action. But, one [the board] has to have faith in the management and in case our proposals hold water and we have ten good answers in response to ten critical questions, then we can go ahead.” (IF4) |
| | “Well, in the case of the chairman it is pretty obvious. He uses his contacts, passes on information and whatever comes to his attention; also with respect to political news. […] The input that I receive and the reactions I observe, well, it is important to pass this on [to the management].” (IA2) |
| | “And it is to be recognized that there is also the role of coaching […]” (II3) |
| | “This is the point of telling them [the management]: Look, we don’t decollate you, in case you take on a business opportunity that eventually turns out not be that fantastic.” (IG2) |
| | “Coaching, of course! I receive intensive coaching from [the chairman]. In this respect, he is my direct superordinate and we have quite a lot of intense sessions together, thereby discussion critical issues. Furthermore, we are constantly in touch using different channels. I receive a lot of coaching, in case I need it.” (IH3) |
| | “Naturally, the chairman of the board plays an important role: he practically coaches the CEO.” (IH4) |
| | “With respect to coaching for example, we discuss the management situation every other month. Well, there I take on his [CEO] perspective and ask him about the situation in the management team; and in case there are open issues, we go into further details.” (IH1) |
| | “I am personally very much in favor of also having board members individually, informally discussing issues they feel competent about with the CEO.” (II2) |
| | “The board is the sparring partner that says: watch out. We have had this and that experience in France, or in Sweden, or wherever. And this sparring function has become much more intensive than before.” (IE3) |
Direct

- "And the task given to the management is then to take the one, two, three open issues, to analyze them systematically and to put them on a risk map." (IA1)
- "Eventually, they say [the board]: nice to see that you are playing around in this area, but take a look at your core business. Your numbers are off and I first want to see that your operations are in order. Mostly, it is direct orders [from the board to the management] that follow." (IC3)
- "It depends on the case, but I wouldn’t accept that for very long and the CEO would be commissioned to change course." (IB2)
- "They [the board] had hired consultants and tried to develop content. […] At the end, there was a presentation for everyone and the board said yes and tasked the management to execute." (IH1)
- "There are decision such as: don’t call for bids here or yes, do call for bids here. Well, there is direct influence being exerted [on the management]." (II3)
- "And at some point, someone from the board says without opposition, or the board as a committee takes the decision that this topic has to be addressed by the management." (II2)
- "I obviously also have the opinion that the board can put topics on the agenda that the firm doesn’t see. For various reasons… and they [the board] can subsequently force them [the management] to consider them as relevant." (IH1)

Hire & fire

- "Well, I would say the most important task of the board is the selection of the management. As one makes his bed, so he must lie." (IE3)
- "The board has adopted a new strategy, which has been publicly announced on [a certain date]. And the top management team has been reconfigured—restaffed and restructured [by the board]." (IA1)
- "Then [the board] started a conventional recruiting process—head hunters and job listings." (IA1)
- "Again, [as the board] it is important to hire the right person. If you really want to change something, you have to choose a person—if you have the chance—from which change can be expected." (IA3)
- "Well, I have a quite simple view on things, including my perspective on the role of the board. For me, one of the most important tasks of the board is the selection of the top management personnel." (IA3)
- "If the board needs to tell the management that we should do wind [power] in Germany, or we should eventually engage in this wind business, we need to become more proactive, we need to be visible there… scorched earth, replacement [of the CEO]!" (IE3)
- "At the end, we reduced them [CEO candidates] to six. These I could personally interview. Then we went down to three. And eventually the board selected the new CEO." (IE1)
- "If the management proves to be resistant, then there is only one way: it is directed that the CEO has to go, initiated by the board and then it works. This was before the collapse; otherwise [the former CEO] would have been in charge much longer." (ID1)
- "Well, the only way I know it in our company is that top management personnel is hired and dismissed only with board approval." (IG1)
Table A4: Importance of board capability to judge strategic issues for the use of board instruments

- “Do we have entrepreneurial board members among us? Do we have a controller? Those [skills] are all important criteria to steer a firm. And if you don’t have these competencies at the table, you won’t be able to move accordingly.” (IE2)
- “Today we [the firm] have many different essential business activities. And you first have to get to know them. Until you know the interdependencies within the firm it takes quite a bit of time, for sure three to four years.” (IE1)
- “Then you take two specialists, who are preparing a topic and who make an independent presentation. They weren’t from the board. They were external and presented it to the entire board. But it was very positive, it enabled them [the board] to think it through and to really look at the different options. This was the basis for the decisions.” (IE4)
- “If you want, one can become really involved, also in topics such as environmental and sustainability issues. And you really have to do that if you are in such as committee, otherwise you don’t know what you are doing.” (ID1)
- “Thanks to the sub-committee I am leading, there is sort of a continuity in the way we work together. I got to know the wording, know when they bring which topic. I had time to understand what does [the CFO] really mean and then you know where you have to challenge them. I can tell you, because they obviously wouldn’t document a lie in a traceable manner. So eventually they formulate it softer. If this happens, then you have to deep-dive and see that you get the facts…this takes time, I must admit this whole [learning] process takes time.” (ID1)
- “The most important thing is that, as discussed in the beginning, in principle to equip the board with different competencies, so that it has the fundamentals to effectively fulfill its role.” (ID2)
- “The board must not be duped by the management due to an information advantage of the executive team.” (ID2)
- “It works in quite compact manner. The management doesn’t have the slightest chance trying to lobby the board members—we would immediately recognize this.” (IH4)
- “The executives are strong experts in the area of operations and it is the responsibility of the board to be able to challenge this expertise…and hence to direct it [the firm] into the right direction, or to not direct it.” (ID2)
"If a CEO wants to build a gas pipeline from Azerbaijan to Italy, it requires from the board to take the time and really look at how is the political situation in these countries, how are we positioned there, how do the contracts look like, do we understand this? I agree with you that the effort increases accordingly." (IC3)

"The board was extremely challenged by [the CEO’s] new projects, by his forward momentum." (IE3)

"The level of expertise in the board…well, not that the old board didn’t have any expertise, but today much more know-how is required." (IE2)

"Well, you install a new CEO and then you know that the new strategy has to be drafted. […] The board is willing to have a one or two day workshop, but not more because they are not used to this […] Once there are concrete proposals for implementation, there is conflict. Do we really have to this, do we really? And suddenly the new strategy is torn apart." (IE3)

"But when you install a new management, a new CEO, only when he starts operating you realize how challenging this [new direction] really is." (IE3)

"Whenever you replace a CEO or someone from the top management team, you do this because you are unsatisfied. You are unsatisfied because he has a weakness somewhere. And the problem is that afterwards you are looking for someone who has a strength in this area instead of the weakness. But to later deal with this strength is also challenging." (IE1)
**Table A6: Board higher-order learning capabilities**

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<th>Self-evaluation</th>
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<td>“In our own firm, we do this deliberately with an internal evaluation. There is a structured document. […] We do it across board and also the management. Every three to four years, we make an anonymous assessment and evaluate the results. These results are subsequently being published and based on this we try to make corrections.” (IE2)</td>
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<td>“It does not matter whether it is a small team that effects performance or the board. Every team has to continuously improve and be proud that it eventually could do the same work more efficient, faster, better.” (IB2)</td>
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<td>“Yes, it [the self-evaluation of the board] is something that happens at the end of the strategy review. That’s where we have our feedback session.” (IF3)</td>
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<td>“Even in the case of well-functioning boards, if there are no changes on the horizon, there should be a self-review every two or three years. Do we have the right board composition? Are we in need for additional competencies?” (IG2)</td>
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<td>“And then there are the self-assessments of the board and such things, which are being conducted. That is an additional side-topic.” (II2)</td>
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<td>But I believe it is always also a chance. The market changes, the requirements [of the business] change, in this sense the whole firm undergoes change. And with this, the committee [board] has to change also.” (IE2)</td>
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<tr>
<td>“He [the new chairman] was early on very keen on discussing the board-internal processes and how we work together and he did so. We had a dedicated event where we spoke about the board-internal processes.” (IA3)</td>
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Composition

- “It is important to have a competence model. For this competence model there are probably three main components: the first component is the general competencies every board members and the committee as a whole should have. O.K.? The second component addresses the current, industry-specific competencies that are required. And the third competence addresses team dynamics-related competencies.” (IH1)
- “Otherwise, the management will understand this [behavior] as harassing cross-fire and will not take it seriously. It needs a certain commitment of the chairman to explore new things and accept critical topics.” (IA3)
- “The board had already given itself guidelines which competencies it generally needs and we searched for someone with this know-how.” (IA2)
- “Every time before a new election, we reflect on the profile required. We have documents that list the profiles we are looking for.” (IA3)
- “I believe there are two, three essential elements [for the board to remain effective]. One thing is to really have a network, to have contact to people that have deep knowledge in this area of expertise, to be able to consult with these people.” (IE2)
- “He actually is not an energy industry expert [the chairman]. And that is not bad at all. He is very open. He listens to the arguments and subsequently finds the solution together with the board. That works well. But he is extremely proficient in process management, strategy, personnel communication, finance, etc.” (IH4)
- “Of course not, this is a loaded questions, obviously everyone is [path-dependent]. Again, it starts with the individual. I cannot speak for others. But I have no [board] mandates really, I have actually projects. This means that there is a pre-defined condition. In this case, I say yes when I am invited to a job because I have realized what I can contribute to the specific topic. But there is also an end to it. For example, when the job is done. In the case of firm H, for example, as soon as the reorganization is done.” (IH1)
- “It was a very deliberate decision to take someone from outside the industry. People that are not from the industry but that have sales and market experience and that have a track record in another industry.” (IG3)
- “At some point, because the energy business was getting so complex, we were debating whether we should reorganize the board. This means, we would imply for example we take the telco business and compose our own board for the telco business.” (II2)
Education of board members

- “What we do is...it is some sort of education, every two, three, four years we go on a trip—a study tour. We have done that. But in a structured, institutionalized manner so that there are institutionalized learning opportunities for board members; no, we don't have that!” (IC1)
- “I find it very important [continuous board member education]. First, I went to a congress. I had asked the CEO which congress they [the executives] would visit and if that would be something I could benefit from. And then I went to that congress, it was in Düsseldorf I believe, an energy congress and it was really interesting.” (IA3)
- “We, well we always had an educational day at the beginning of the year, sometimes on the 24th. In 2014 it was February 11th, but usually it is at the beginning after we have finished the previous year.” (IH3)
- “Competency [knowledge] plays an important role. Definitely, I fully agree. And this requires the permanent effort to keep oneself busy with the topic. Do you that with formal training? Do you do that by consulting your personal network? What do you do to really be up to date, to understand the dynamics of this areas and this industry, no? I do think that with education and training one can cover some issues—and with personal contacts. [...] In today's times, it is extremely important to address certain question very systematically. And maybe this is sometimes a bit missing...” (IE2)
- “We [the board] distribute certain information every board member should study. [...] That is what we expect from every board member. We write it down so that he is in the picture—readings are a part of it. And every, or every second board meeting, we have a general [informative] agenda topic that addresses the market environment.” (IB2)
- “It is not easy for the board members, in particular given the rapid pace at which the world is changing, to assume this responsibility. It takes a lot of time to become acquainted with all the complex issues.” (IF4)
- “The frequency of the board meetings is the same. However, it is a much more extensive agenda. Today, much more topics are being assessed and discussed, in particular those innovative topics.” (IG5)
- “No no, because the board as a committee itself also does something [that exposes them to new ideas]... going to an electricity industry congress in January and so on and so forth...or some are also sitting on other boards and are coming from other committees.” (IF2)
- “How can you ensure that the competencies are being developed further? It is difficult, because time is short. But I think there is enough time and funny enough, I have just written a board member learning concept and have given it to three colleagues for feedback. In essence what I put in writing there is as follows: first, I assume that everyone is responsible for his or her own competencies. One is not being served. Second, I assume that everyone is further developing his or her general board competencies. I don't do anything for this. [...] We even take this a step further. We would be willing to partially finance this. [...] And third, that addresses the firm-specific competencies. [...] There I want to develop an agenda together with the CEO.” (IH1)
Decision making

- “I have the opinion that today, the board does not have to always deal with every topic. [...] There should be board members responsible for specific topics so that the board as a committee can focus on the core topics. And that is something which is not supported everywhere, this believe that not everyone has to deal with every issue.” (IE2)
- “This is important! By no means should the board only have board-internal meetings when issues arise. It should rather be an aperiodic routine. Then they will also be perceived by the CEO as such. If you don’t obey this rule and suddenly things become tricky and the board has board-only meetings…that is not good for the relationship between CEO and board.” (ID2)
- “I have done this on various firms myself. [...] If you want to discuss the organizational design of a firm, you better do so without the management. [...] And these can be traditional workshops, ranging from brainstorming to work cafes or you name it. [...] Usually, it is done with external support, because this is more efficient.” (IA1)
- “What you must never do is: well, we have decided, but we also didn’t know everything, or didn’t care to know everything about the subject. [In this case] you have to take on external consultancy; experts for a specific topic, which can be internal or external.” (IC2)
- “How do you write such a management proposal [to be presented to the board]? First, no spiel but facts. Rational why the board is to be involved; then management summary, one that is reasonable and short and finally, a good motivation and justification. [...] and at the very end there should be a concise request; because of this and that the management makes the following request. Actually, this should be the minimum standard [for the board to be able to make a decision].” (IC2)
- “In a modern board […] they should have the respective discussion and take the time to discuss…and strive for the appropriate discussion culture.” (IC2)
- “Yes, it has to be! When there are requests [from the management], there has to be [constant] tension between the board and management.” (IE3)
- “In good old times, there is not enough challenging going on, no scrutinizing. Again, even though the situation might be o.k. now, there is still room for substantial improvements. These things happen far too seldom in good old times.” (ID2)