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Analysis

Adoption of Energy Efficiency Measures for Non-residential Buildings: Technological and Organizational Heterogeneity in the Trade, Commerce and Services Sector

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ABSTRACT

Drawing on agency theory and absorptive capacity literature, this paper empirically analyzes factors of adoption and barriers to adoption of four crosscutting, ancillary energy efficiency measures (EEMs) for non-residential buildings (efficient lighting, building insulation, heating system replacement, and optimization of heating system operations). The empirical analysis employs a large representative sample of organizations in the German trade, commerce and services sector. Results from econometric analyses provide evidence for a negative effect of principal–agent relationships (landlord-tenant; owner-user of energy supply equipment; parent-subsidiary) and for a positive effect of organizational attributes that contribute to absorptive capacity (energy manager in place; energy audit conducted; experience with decentralized low carbon energy). However, the significance of these effects varies by measure. For non-adopters, heterogeneity of crosscutting ancillary EEMs has little impact on the ranking of barriers to adoption. The most relevant barriers for all EEMs are rented spaces, high investment costs, and other priorities; least relevant are technical risk to production and risk to product quality. Finally, we find little evidence for differences in the factors of adoption and barriers to adoption between manufacturing and non-manufacturing organizations. These findings are robust to alternative model specifications.

1. Introduction

For nearly four decades, scholars have shown an interest in understanding the energy efficiency paradox (Blumstein et al., 1980; DeCanio, 1998), the phenomenon whereby the adoption of profitable energy efficiency potential, which almost all carbon abatement strategies rely on, is only partial (e.g. IEA, 2012). The paradox concerns both households and organizations and has received renewed interest in recent years (Gillingham and Palmer, 2014; Gerarden et al., 2015). This paper is concerned with efficient exploitation of organizational energy efficiency potential. A key challenge involves learning where generic energy efficiency policies are cost-efficient and where to adapt to specificities of users and measures. Determining how to balance these options requires a thorough understanding of the relevant dimensions of heterogeneity of both adopter organizations and energy efficiency measures (EEMs). However, assessments of the extent of the paradox tend to neglect relevant differences between organizations. Organizational heterogeneity causes a measurement or modeling flaw (Gerarden et al., 2015) and a systematic positive bias in assessments of efficiency potential, which is why user heterogeneity is a commonly acknowledged explanation of the observed, slower-than-expected rate of adoption of EEMs (Jaffe and Stavins, 1994a; Sorrell et al., 2004; DeCanio and Watkins, 1998; Cohen and Levinthal, 1990). Few studies, however, have investigated how organizational differences affect barriers to adoption.

The heterogeneity of EEMs has long been ignored in empirical studies that are aimed at explaining adoption and barriers to adoption (Fleiter et al., 2012a), thus corroborating the argued need for a better theoretical and empirical understanding of heterogeneity's role in the efficiency paradox.

This paper aims to make a contribution by decomposing the heterogeneity of organizations and measures and empirically investigating factors of adoption and barriers to adoption of crosscutting ancillary

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EEMs in non-residential buildings. The paper mainly draws on literature on agency theory and absorptive capacity for explaining the role of organizational heterogeneity, and looks at the theory of diffusion of innovations to explore the heterogeneity of measures.

An original, large-sample dataset that is representative of organizations in the German trade, commerce and services sector is used for our empirical analysis.[1] This dataset enables the comparative analysis of adoption and barriers to adoption in relation to organizational characteristics for four different measures. Moreover, it mitigates hypothetical bias in its assessment of barriers by soliciting barriers to adoption from rejection cases only. The paper also explores potential differences in the factors of adoption between manufacturing and non-manufacturing organizations in the trade, commerce and services sector. Finally, it integrates more theoretical concepts of agency theory and absorptive capacity with the more applied literature on energy efficiency adoption.

The remainder of the paper starts, in Section 2, with a brief literature review related to the heterogeneity of organizations and measures in energy efficiency studies. Section 3 discusses the conceptual framework and develops the study's hypotheses. Section 4 explains the data and method. Section 5 presents the results of descriptive and econometric analyses, which are then discussed in Section 6. Section 7 concludes by summarizing our findings and discussing policy implications.

2. Literature on Adoption of Energy Efficiency: Heterogeneity of Organizations and Measures

In this section, we briefly review the literature on organizational adoption of EEMs for how it has considered and addressed heterogeneity of users and measures. We focus the review on empirical studies of adoption and barriers to adoption of EEMs in non-residential settings.

2.1. Organizational Heterogeneity in the Context of EEM Adoption

Literature on adoption of EEMs has addressed heterogeneity of organizations in a practical way: it tends to distinguish organizations by sector and/or size.[2] Studies focus on the industrial sector (e.g. Velthuijsen, 1995; de Groot et al., 2001; Sorrell et al., 2004; Sardianou, 2008) or the trade, commerce and services sector (Schleich, 2004; Schleich and Gruber, 2008; Schleich, 2009). Within the industrial sector, the literature distinguishes between the energy-intensive (Cooremans, 2012) and non-energy-intensive industry (Rohdin and Thollander, 2006; Thollander et al., 2007). Energy-intensive firms typically allocate a higher priority to energy-efficiency than less energy-intensive firms. Another focus of the literature is on small to medium-size enterprises (SMEs) (e.g. Gruber and Brand, 1991; Kostka et al., 2011; Cagno and Trianni, 2014) and within SMEs on manufacturing SMEs (Anderson and Newell, 2004; Muthulingam et al., 2011; Trianni and Cagno, 2012; Trianni et al., 2013, 2016). In their review of the empirical literature on barriers to energy efficiency in SMEs, which also form a large part of this study, Fleiter et al. (2012b) conclude that the most relevant barriers for SMEs are lack of capital, and for less energy-intensive SMEs, in particular, lack of information and lack of staff time. Most specific are studies that focus on one particular sector only, such as horticulture (Diederen et al., 2003; Aramyan et al., 2007), foundry or primary metal (Rohdin et al., 2007; Trianni et al., 2013; Cagno et al., 2015), pulp and paper (Thollander and Ottosson, 2008), or breweries (Sorrell, 2004). Such differentiation by sector and size implicitly acknowledges organizational heterogeneity and addresses it by an easily observable, practical dimension. Several of these studies that look at sectoral differences call for a more theoretical look at sources of behavioral differences in firm-specific factors (Fleiter et al., 2012b; Trianni and Cagno, 2012; de Groot et al., 2001; Sardianou, 2008). Trianni et al. (2013) make a contribution in that regard, investigating how perception of barriers to energy efficiency depends on such firm-specific factors as energy expenditures and complexity of the production, and on sector-specific factors such as variability of demand and strength of the competition. Nonetheless, empirical work on organizational antecedents of adoption of EEMs is lacking. Likewise, since empirical studies often rely on convenience sampling, the findings may not be characteristic for the population of the organizations studied. This calls for more analyses employing representative data, as is the case in this study.

2.2. Heterogeneity of EEMs

Fleiter et al. (2012a) observe that the characteristics of EEMs are a "neglected dimension" in the literature on their adoption. For example, while accounting for sectoral differences, Schleich and Gruber (2008) and Schleich (2009) rely on an aggregate indicator of measures to explore factors (including barriers) related to adoption of EEMs. In these and other studies, barrier analyses rely on subjective assessments by respondents, but it is typically not clear, whether organizations had considered adoption of a particular technology prior to rejection. Thus, responses may suffer from hypothetical bias.

The empirical analyses have only rarely distinguished between process-specific and crosscutting measures. A few case studies have looked at adoption of individual technologies or technology groups, whether crosscutting or process-specific (de Almeida, 1998; Ostertag, 2003). More recently, scholars have begun exploring the heterogeneity of measures more seriously in relation to both adoption (Fleiter et al., 2012a; Trianni et al., 2014) and barriers to adoption (Cagno and Trianni, 2014). However, representative large sample surveys substantiating the case study findings are rare (Fleiter et al., 2012b). The scant empirical literature on factors driving adoption also tends to focus on measures related to the core processes of firms, such as product and process innovations (Gruber and Brand, 1991; Sorrell, 2004; Anderson and Newell, 2004; Thollander and Ottosson, 2008; Cagno et al., 2015), but much potential is thought to reside in ancillary processes and crosscutting measures (e.g. lighting, HVAC[3]). Trianni et al. (2014) break ground as they identify no less than 192 crosscutting EEMs applicable to industrial contexts and propose a framework of 17 attributes to explain adoption rates. They group the measures in four functional categories: motors, cooling, lighting, and HVAC. Our paper addresses two of those measures: lighting and HVAC. According to Trianni et al. (2014), HVAC measures tend to have characteristics that are less favorable to adoption than lighting; they tend to have higher investment costs and higher degrees of complexity and customization, which are associated with increased hidden costs and thus possibly greater than estimated payback times. Fleiter et al. (2012a) and Trianni et al. (2014) bring lessons from the innovation diffusion literature on how innovation characteristics influence adoption (e.g., Tornatzky and Klein, 1982; Rogers, 2003; Gatignon et al., 2015) to the context of adoption of EEMs. To gain a better understanding of how the heterogeneity of EEMs affects organizational adoption, empirical studies are needed that draw on this literature and that enable insights that are representative for the organizations studied.

3. Hypotheses

We derive our hypotheses from two streams of literature to improve understanding of decision-making regarding the adoption of EEMs in organizational contexts. First, agency theory emphasizes incentive structures created by contractual arrangements and sheds light on agents' goals that guide their decisions. Second, the literature on absorptive capacity helps explain decisions regarding available alternative

[1] The scope of the sector will be described in detail in the data collection section (Section 4.1).

[2] Fleiter et al. (2012b), Cagno et al. (2013), Gerarden et al. (2015), and Gillingham and Palmer (2014) offer recent reviews of the literature on barriers to adoption of EEMs.

[3] HVAC = heating, ventilation, and air conditioning

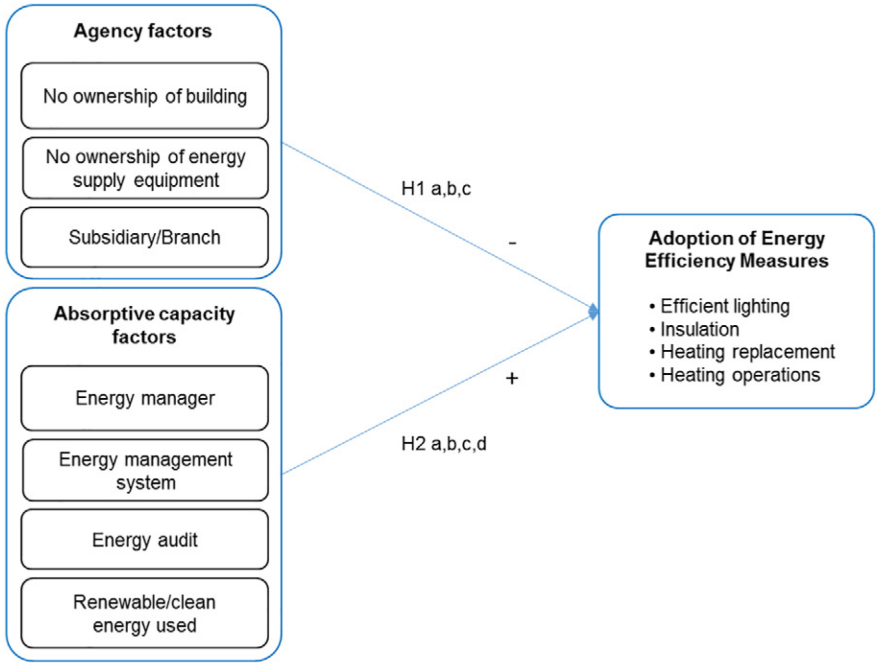

Fig. 1. Research model and hypotheses.

measures that are all consistent with an agent's goals. Fig. 1 gives a schematic overview of the research model and hypotheses.

3.1. Agency Factors

Agency theory is concerned with relationships between principals and agents who act on the principal's behalf. It posits that such relationships are characterized by information asymmetry, conflicting goals, and differences in risk preferences, which can explain the type of contract to which a principal and an agent agree (Eisenhardt, 1989). Information asymmetry exists because a principal cannot perfectly observe an agent's behavior (after entering into a contract) (Holmstrom, 1979), leading to moral hazard, or because the principal cannot observe the quality of the product (before entering into a contract), leading to adverse selection (Akerlof, 1970). Goal conflicts are sustained if contracts do not address the information asymmetry in particular. Transaction costs (e.g. monitoring costs) may discourage principals and agents from entering into such contracts. Therefore, incentives that are split between principal and agent are sustained. We expect that organizations that are engaged in principal-agent relationships are less likely to adopt EEMs.

Split incentives have often been identified as a prominent barrier to organizational investment in energy efficiency upgrades (Sorrell et al., 2004). We observe a classic situation of split incentives in the landlord-tenant relationship. A landlord lacks the incentive to invest in improving the energy efficiency of a property unless it can charge premium rents to recover the investment costs. Charging premium rents is not possible when it is costly to resolve the information asymmetry regarding a building's energy performance, or a landlord lacks the credibility to provide that information, or regulation prevents the extra costs from being passed on to the tenant. On the other hand, the tenant's incentive to invest is compromised by the uncertainty regarding the longevity of his tenancy in relation to the payback time involved in the investment. More generally, the landlord-tenant dilemma concerns situations in which the user of a capital good is not its owner. The scant empirical literature exploring agency in the context of EEM adoption finds that adoption of demand-side EEMs is lower when buildings are rented (Schleich, 2009). We therefore hypothesize the following:

H1a. Organizations that rent or lease their work spaces are less likely to adopt energy efficiency measures (EEMs).

However, independent of tenancy, energy supply equipment varies in the degree to which users have ownership over them. For example, even if an organization owns its (part of the) building, it may depend on a heating system that is shared with other occupants of the same building or with an entire district (in the case of district heating), which raises barriers to replacement. Shared or outsourced ownership of energy supply technologies could increase in the future as new business models (e.g., servitization) emerge as part of the energy transition (e.g., Polzin et al., 2015). To our knowledge no study has yet tested whether ownership of energy supply equipment (such as heating systems) affects EEM adoption (optimization or replacement). We test the following hypothesis:

H1b. An organization in which energy supply equipment belongs to an external actor (e.g. a real estate proprietor) is less likely to adopt EEMs.

Moral hazard was originally studied to determine its role in stockholder-CEO relationships, where a CEO is an agent acting on behalf of a firm's owners, who may not have full insight into the agent's behavior (Holmstrom, 1979). Within organizations, such principal-agent relationships may also arise between a holding firm and its subsidiary, or between headquarters and branches. The distribution of responsibilities between parent and subsidiary or branch companies may increase the likelihood that principal-agent issues occur. For example, depending on the budgeting arrangements, a parent company would pay for the investment but the subsidiary would benefit from lower energy expenditures, thus leading to an owner-user dilemma. Alternatively, incentives to save energy costs at the subsidiary level are low if a parent company appropriates the benefits. Similarly, to mitigate moral hazard on the side of a subsidiary, a parent company may require short payback times for subsidiary investments, thus discouraging adoption of EEMs (DeCanio, 1994). This leads us to formulate the following hypothesis:

H1c. Organizations that are subsidiaries or branches are less likely to adopt EEMs.

3.2. Energy-specific Absorptive Capacity

Absorptive capacity is defined as “the ability of a firm to recognize the value of new, external information, assimilate it, and apply it to commercial ends” (Cohen and Levinthal, 1990:128) (ibid). Absorptive capacity depends on prior knowledge and a firm's external and internal communication structures (Cohen and Levinthal, 1990; Lenox and King, 2004; Pinkse et al., 2010), which function as an organization's ‘senses and synapses’ to expand and valorize the knowledge base. Absorptive capacity was originally proposed as a cornerstone of organizational learning and innovative capability. More recently, scholars have begun investigating the value of absorptive capacity in explaining the successful adoption of environmental strategies (Pinkse et al., 2010; Delmas et al., 2011), recognizing that this more specific form of innovation also requires the acquisition, assimilation, transformation, and exploitation of external knowledge. Delmas et al. (2011) present empirical evidence that a firm's absorptive capacity predicts its proactive environmental strategy. Following this line of reasoning, we argue that absorptive capacity facilitates the adoption of economic EEMs. For the adoption of EEMs the absorption and exploitation of external knowledge is also often required. Such external knowledge may include hitherto unknown information about the energy consumption and performance of an organization's own systems as well as awareness of energy efficient alternatives and their techno-economic performance. We therefore expect that Delmas et al.'s (2011) thesis applies to EEMs as well.

Here, we examine four antecedents of absorptive capacity that are specific to energy information because adoption of EEMs may often be less complex and less crosscutting with respect to functional and disciplinary boundaries (Kemp, 1997) than adoption of innovations in general or proactive environmental strategies more specifically (as in Delmas et al., 2011).

A proactive environmental strategy can manifest in the expansion of environmental competencies, which facilitates adoption of resource-efficiency innovations (Delmas and Pekovic, 2015). We argue that, similarly, adoption of economic EEMs is facilitated by complementary capabilities in energy management. The development of such capabilities is both an outcome of and an antecedent to a firm's absorptive capacity (Delmas et al., 2011). Within the context of energy management, an energy management system (EMS) can be a manifestation of a proactive *energy* management practice. Environmental management systems and EMSs, such as those promoted by ISO 14001 and 15001, are voluntary instruments, intended to establish systems and processes for continual improvement of energy performance, with better energy efficiency as a result. EMS functions include policymaking, planning, implementation, measuring, and evaluation. Environmental management systems tend to be adopted for symbolic reasons, such as to improve image and fend off stakeholder pressure (Frondel et al., 2008; Darnall et al., 2008), and their certification is undertaken primarily to enhance credibility (King et al., 2005). Nevertheless, these systems have been shown to promote adoption of environmental innovations (King et al., 2005; Wagner, 2008). Through its measuring and evaluation functions, an EMS promotes the acquisition of information regarding the energy use and performance of an organization's own operations (Rohdin and Thollander, 2006), expanding its knowledge base. Such a system promotes internal communication through its policymaking, planning, and implementation functions, contributing to an organization's capacity to assimilate, transform, and exploit energy information. Indeed, these informational and procedural functions can assist in the reception and survival of proposals for EEMs within an organization (Ross, 1974). We therefore hypothesize the following:

H2a. Organizations with energy management systems (EMSs) in place are more likely to adopt EEMs.

Several studies emphasize the difference managers can make to an organization's absorptive capacity, acting as drivers of internal communications and catalyzing the flows and transformations of potentially valuable information (Cohen and Levinthal, 1990; Damanpour, 1991; Lenox and King, 2004). An *energy* manager can help develop an organization's absorptive capacity by expanding its knowledge base through investment in internal research and development (e.g. via an EMS) (Lenox and King, 2004). As a professional, an energy manager may increase boundary-spanning activities (Pierce and Delbecq, 1977) and enhance external communications between external knowledge sources and an organization's internal operations (Tushman, 1977). Moreover, an organization's technical knowledge base, professionalism, and external communication practices have been stable predictors of organizational innovation in general (Damanpour, 1991). An energy manager scans the environment and takes part in extra-organizational professional activities and translates technical information into a form that is understandable to internal stakeholders (Cohen and Levinthal, 1990; Damanpour, 1991). For energy efficiency innovations, a gatekeeper function (Tushman, 1977) may be especially useful in sectors where energy is not considered strategic and energy information is distant from the core knowledge base (as is the case in this paper). Indeed, research suggests that organizations with dedicated energy managers are more likely to adopt both EEMs and EMSs (Frondel et al., 2008; Martin et al., 2012).

Several authors have emphasized the role of a change agent (Rogers, 2003) or a ‘champion’ for energy efficiency improvements within an organization (Rohdin and Thollander, 2006; Galvin and Terry, 2016), a role that an energy manager can play.

We therefore hypothesize:

H2b. Organizations with energy managers are more likely to adopt EEMs.

External energy audits can be a specific manifestation of proactive energy management (Sharma and Vredenburg, 1998) and a mechanism for expanding an organization's energy-specific knowledge base. As such, energy audits act as both antecedents to and consequences of energy-specific absorptive capacity. Subsidized energy audits are a common policy instrument that organizations use to overcome market failure caused by imperfect information in energy technology and capital markets, a frequently cited barrier to EEM adoption (e.g., Schleich, 2004; Anderson and Newell, 2004; Thollander and Palm, 2013; Palmer et al., 2013). Although the quality of audits can be lacking (Fleiter et al., 2012b) and effectiveness is partial (Anderson and Newell, 2004; Thollander and Palm, 2013), they can be effective in reducing the information gap (Schleich, 2004). Audits enhance an organization's capacity to assess the “objective feasibility” (Wejnert, 2002) of an EEM and mitigate perceived technological uncertainty (Milliken, 1987), thereby increasing the probability that privately economic efficiency potential is exploited. We therefore derive the following hypothesis:

H2c. Organizations that have conducted energy audits in the past are more likely to adopt EEMs.

Knowledge in one field can add to the ‘prior knowledge’ that promotes the absorption of new knowledge in a related field (Cohen and Levinthal, 1990; Delmas et al., 2011). Prior experience with other clean energy technologies can help organizations learn how to acquire and exploit new knowledge that is specific to energy efficiency innovations. That an organization has already implemented one or more clean energy technologies may testify to the existence of complementary capabilities in terms of the presence of a relevant knowledge base and the communication structures needed to exploit new energy-specific knowledge (Darnall and Edwards, 2006). It may also signal a proactive stance on energy (Sharma and Vredenburg, 1998) and a positive managerial attitude toward energy innovation (Damanpour, 1991).

We therefore hypothesize the following:

H2d. Organizations that use renewable/clean energy technology are more likely to adopt EEMs.

3.3. Heterogeneity of EEMs

Until recently in the literature on the adoption of EEMs, the characteristics of EEMs had long been a "neglected dimension" (Fleiter et al., 2012a; Trianni et al., 2014), whereas the literature on innovation diffusion has identified certain attributes of innovations as predictors of adoption (Gatignon et al., 2015). The perceived relative advantage, compatibility, and complexity of innovations were shown to be stable predictors of adoption (Tornatzky and Klein, 1982).

Relative advantage is "the degree to which an innovation is perceived as being better than the idea it supersedes" (Tornatzky and Klein, 1982, citing Rogers and Shoemaker, 1971). "Better" is an ambiguous criterion. Fleiter et al. (2012a) equate relative advantage to economic profitability of EEMs, based on four profitability parameters: investment costs, payback time, internal rate of return, and non-energy benefits. *Compatibility* is "the degree to which an innovation is perceived as being consistent with the existing values, past experiences, and needs of the receivers" (Tornatzky and Klein, 1982, citing Rogers and Shoemaker, 1971). *Complexity* is "the degree to which an innovation is perceived as relatively difficult to understand and use" (Tornatzky and Klein, 1982, citing Rogers and Shoemaker, 1971).

The theoretical and empirical underpinnings of these antecedents are based on product and process innovations related to often-idiosyncratic core competencies. This study focuses on crosscutting EEMs related to organizations' ancillary functions, which interfere little with the core process once implemented. For these measures, compatibility acts as a determinant of complexity. Complexity affects the cost associated with adoption and implementation and the probability of successful implementation, i.e. of achieving the expected benefits. Hence, compatibility and complexity negatively relate to the relative advantage of an ancillary crosscutting EEM with respect to which, like Fleiter et al. (2012a), we equate relative advantage to economic profitability. Nonetheless, reducing relative advantage to economic profitability conceals its complexity and composite nature. Characterizing an EEM by its relative advantage is problematic as it may depend more on the case-specific context than the measure itself. As a consequence, while previous literature suggests that heterogeneity of EEMs will affect adoption, it is not clear how this will occur. We therefore refrain from developing explicit hypotheses regarding EEM heterogeneity in relation to adoption but explore these relationships empirically.

4. Method and Data

In this section we first present how data were collected. Then, we discuss the operationalization of the variables used in our analyses and present their descriptive statistics. Finally, we discuss the econometric models employed to test the hypotheses.

4.1. Data Collection

This paper uses an original, large-sample data set on adoption of four different crosscutting types of EEMs related to ancillary energy functions in organizations. We first explain the sectoral scope and sampling method, followed by an introduction to the four EEMs.

4.1.1. A Representative Survey of the Trade, Commerce and Services Sector

We collect our data from a survey of a representative selection of organizations in the trade, commerce and services sector in Germany. For studying EEM adoption econometrically, a large sample is required. Germany offers the advantages of being the largest economy in the EU and its trade, commerce and services sector counts relatively many organizations, not least because of Germany's large share of SMEs. This enables the collection of a large sample and generalization of the results in a statistical sense. Moreover, an assessment of the economic energy efficiency potential in the German trade, commerce and services sector concluded that under current policies 141 PJ in savings from attractive EEMs would go unused by 2030 (IFEU et al., 2011, p.52), which is 10% of the sector's energy consumption in 2013 (AGEB, 2016). The vast majority of that efficiency potential would be in insulation, heating system replacement, and efficient lighting (IFEU et al., 2011). This situation extends beyond Germany. In the U.S. for example, the profitable energy savings potential in existing commercial buildings was estimated to range between 10 and 20% of current energy use, as per the criterion that the ratio of net present savings to net present costs is greater than one (PNNL, 2009).

Quota sampling was used to ensure the selection of a representative sample (cf. Schlomann et al., 2015:10–11). The true sectoral scope of our sample is specific to Germany. The term 'trade, commerce and services sector' is an approximation of the German *Gewerbe, Handel und Dienstleistungen*, which includes small manufacturing firms, trade, commerce, and services (see Appendix, Table B.1). It is a statistical group defined for the purpose of keeping German energy balance statistics.[4] The sector contains mostly but not only SMEs. It is very similar to the tertiary sector but includes non-industrial manufacturing as well. In 2014, this sector consumed about 15% of total final energy use in Germany (AGEB, 2016). Investment in measures designed to improve the energy efficiency of buildings in this sector is suboptimal. The survey was carried out by a market research institute (GfK). Trained interviewers conducted structured on-site interviews from February through July 2014 and collected 2440 responses.

4.1.2. Four EEMs

Operationalizing relative advantage of EEMs, the survey distinguished four categories of crosscutting ancillary EEMs related to the energy use of buildings in the trade, commerce and services sector: installation of efficient lighting, insulation of building envelopes, heating system replacement, and optimization of heating system operations. These four EEM categories are defined narrowly enough to exclude incommensurable technologies yet widely enough to obtain sufficient observations and get a valid picture of organizational adoption behavior (Damanpour, 1991). These four categories are typically identified as cost-effective in energy audits and among each other represent an ordinal scale of relative advantage, increasing from insulation via heating system replacement and operational optimization to lighting. The measures are not part of the core production process and are not specific to individual companies. This prevents differences between managerial attentions given to *core* vs. *off-core* processes from dominating the effect of relative advantage.

Installation of efficient lighting involves the replacement of lighting with more efficient alternatives such as T5 lamps, LED bulbs, or more efficient technologies. We subsequently refer to these measures as "lighting" or "efficient lighting". Lighting is the measure with lowest investment cost, as per the median of the cost reported by adopters of lighting (€ 500, $N = 234$) and the shortest payback time (4 years, $N = 35$).[5] This is consistent with the assessment by Trianni et al. (2014), who concluded that replacement of inefficient lighting tends to have low implementation costs and short payback times relative to other crosscutting ancillary measures in industry, such as replacement of HVAC equipment. Furthermore, lighting is a low-complexity and superficial technology: it has a low degree of integration with the building structure (Trianni et al., 2014). Therefore, the installation of efficient lighting is associated with limited additional, indirect costs. *Insulation of the building envelope* ("insulation") involves applying insulating materials to the outer faces of a building, such as the roof and the outer walls, and installing better-insulating windows. Its relative advantage

[4] In the German energy balances, final energy consumption is partitioned into four end-use sectors: industry, private households, transportation, and the combined sector 'trade, commerce, services and other consumers'; this sector also includes small manufacturing companies with <20 employees.

[5] The number of observations *N* from which median investment cost and payback time in this section are determined varies because many respondents failed to report these quantities. Responses may thus not be representative.

may be comparatively low: insulation is the EEM with the highest investment cost (€ 12,000, $N = 57$) and the longest payback time (9.5 years, $N = 12$), according to the surveyed adopters. Furthermore, insulation is highly integrated with the building structure. Its installation can be a relatively lengthy process with considerable impact on the working environment, which adds to the costs of installation and further compromises relative advantage. *Replacement of the heating system* ("heating replacement") involves substituting a more efficient heating system for the current one, such as a new condensing boiler to replace an older, less efficient system. This is a technology replacement or substitution measure. *Optimization of heating system operations* ("operations" or "heating (system) operations") involves energetic optimization of the heating system such as through hydraulic adjustments, nighttime turndown, dynamic control, or thermostat lowering. This is a somewhat hybrid measure that is largely operational but may involve added-on digital technology. The measure captures some of the significant efficiency improvement potential of energy management practices. Operational measures have been estimated to contribute 25%–50% of the full energy efficiency potential, depending on the sector (Paramonova et al., 2015). The observed median investment cost for heating system replacement is relatively high (€ 9000, $N = 56$) and higher than the median cost of optimization measures (€ 5000, $N = 57$). Despite being largely operational, the latter may involve significant costs associated with procuring expert knowledge or accumulating low-cost operational adaptations (Trianni et al., 2014). The observed median payback time is 5 years for both heating system measures ($N = 16$ and $N = 24$, resp.). Moreover, heating systems tend to be (at least partially) customized, which involves additional costs associated with the acquisition and transformation of information (Trianni et al., 2014), compromising relative advantage. Heating systems are more fully integrated with the building structure than lighting, but less than insulation. The implementation of such a measure is, therefore, expected to be less lengthy and disruptive. Based on these direct and indirect observations, optimization of heating system operations is expected to offer a slightly superior relative advantage to that of heating replacement. The relative advantage of both should fall between that of lighting and insulation.

4.2. Data

This section explains the operationalization of the variables used in our econometric modeling to test the hypotheses. We first explain the dependent variables (adoption and barriers to adoption) followed by the independent variables (one per hypothesis). Finally, a set of control variables is introduced to account for four known and potential confounding factors: sector (manufacturing vs. non-manufacturing), electricity intensity, organization size, and price of energy. Descriptive statistics are presented in Table 1.

Table 1
Descriptive statistics. The observations included are restricted to the organizations included in the main analyses. The first four rows show the data distribution for adoption of each of the four EEMs.

Variable	Obs.	Mean	Std. Dev.	Min.	Max.
Adoption since 2008 (1 = adopted, 0 = not adopted)					
Lighting	1083	0.28	0.45	0	1
Insulation	1073	0.07	0.25	0	1
Heating replacement	948	0.09	0.28	0	1
Heating operations	988	0.10	0.31	0	1
EEM dummies (1 = yes, 0 = no) (stacked data)					
Lighting	4092	0.26	0.44	0	1
Insulation	4092	0.26	0.44	0	1
Heating replacement	4092	0.23	0.42	0	1
Heating operations	4092	0.24	0.43	0	1
Company attributes (1 = yes, 0 = no)					
Tenant	2060	0.54	0.50	0	1
Heating system external	2060	0.44	0.50	0	1
Subsidiary	2060	0.15	0.35	0	1
Energy management system	2060	0.10	0.30	0	1
Energy manager	2060	0.11	0.31	0	1
Audit	2060	0.14	0.34	0	1
Decentralized, clean energy used	2060	0.07	0.26	0	1
Control variables					
Manufacturing (1 = yes)	2060	0.27	0.44	0	1
Electricity cost per employee (k€/a)	2060	0.84	1.05	0.004	14.639
Ln(Employees)	2060	1.83	1.24	0	7.244
Electricity rate (€/kWh)	2060	0.24	0.06	0.059	0.533
Barriers (stacked data; for all barriers: 1 = relevant, 0 = not relevant)					
Already efficient	457	0.19	0.40	0	1
Investment costs	485	0.42	0.49	0	1
Uneconomical	456	0.25	0.43	0	1
Time consumption	483	0.24	0.43	0	1
Lack of know-how	470	0.14	0.35	0	1
Techn. risk to production	473	0.05	0.23	0	1
Risk to product quality	465	0.06	0.23	0	1
Investment priorities	489	0.40	0.49	0	1
Technology and energy price uncertainty	477	0.21	0.41	0	1
Ongoing reorganization	483	0.19	0.39	0	1
Internal disagreement	479	0.15	0.36	0	1
Lack of capital	484	0.33	0.47	0	1
Spaces are rented	486	0.56	0.50	0	1

4.2.1. Dependent Variables

Adoption. Adoption is represented by a dummy variable taking the value of 1 if an organization had adopted EEM *j* in the six years between 2008 and 2014, where *j* indicates one of the four EEMs. To limit the burden on respondents, each was asked about two randomly chosen EEMs only.

Barriers to adoption. The survey presented non-adopters with a list of thirteen barriers to adoption and asked them to select the ones that led them to reject an EEM, generating one dummy variable per barrier that takes the value of 1 if the barrier was considered relevant. These barrier variables provide descriptive evidence of the relative relevance of a diverse set of barriers and are used to explore whether organizational factors found to be associated with adoption are mirrored in the barriers.

Asking only those organizations that had considered adoption mitigates hypothetical bias, a common problem in barrier studies. The list of barriers was derived from several taxonomies proposed in the literature, which tend to distinguish between market failures, non-market-failure economic barriers (or modeling and measurement flaws), and behavioral and organizational barriers (Jaffe and Stavins, 1994b; Sorrell et al., 2004; Gillingham and Palmer, 2014; Gerarden et al., 2015).

4.2.2. Explanatory Variables

To test the hypotheses developed in Section 3, we distinguish variables that are related to agency factors from variables related to absorptive capacity. In addition, in models aggregating the four EEMs, we use dummy variables for each EEM to capture technology-specific effects.

Proxies for Agency

Tenant. To test hypothesis H1a, we use a dummy variable that takes the value of 1 if an organization rents or leases and does not own the spaces it occupies.

Ownership of the heating system. To test hypothesis H1b, we operationalize 'energy supply equipment' by the less generic 'heating system.' We include a dummy variable taking the value of 1 if a heating system is external to an organization and owned by or shared with others and 0 if it is owned.

Subsidiary. To test hypothesis H1c, we use a dummy variable that takes the value of 1 if an organization is a subsidiary or branch of a parent organization.

Measures of Absorptive Capacity

Energy management system. To test hypothesis H2a, we use a dummy variable that takes the value of 1 if an organization has an EMS in place.

Energy manager. A dummy variable taking the value of 1 if an organization has an energy manager is included to test hypothesis H2b.

Energy audit. A dummy variable taking the value of 1 if an organization reported that it had had an energy audit and zero otherwise tests hypothesis H2c.

Decentralized, low-carbon energy use. The use of decentralized, low-carbon energy generators (such as photovoltaic systems, heat pumps, and combined heat and power (CHP) systems) is included as an observed measure of prior knowledge to test hypothesis H2d. For this purpose we introduce a dummy variable that takes the value of 1 if such technology is used and 0 if it is not used.

4.2.3. Control Variables

The following are variables to control for possibly relevant confounding factors.

Manufacturing. Barriers and adoption rates may vary across subsectors of the trade, commerce and services sector (Schleich and Gruber, 2008; Schleich, 2009). For crosscutting ancillary measures, sectoral differences may be less salient. Therefore, we make a higher-level sectoral distinction. The literature tends to make a de facto conceptual distinction between SMEs and large firms (e.g. Anderson and Newell, 2004; Thollander et al., 2007; Fleiter et al., 2012b; Trianni and Cagno, 2012) and/or between manufacturing and non-manufacturing organizations (e.g. Velthuijsen, 1995; Anderson and Newell, 2004; Thollander et al., 2007; Trianni and Cagno, 2012). To control for the latter distinction, we include a dummy variable, “manufacturing”, which takes the value of 1 if an organization is in a manufacturing subsector.[6]

Size of an organization. We do not have data on revenue to accurately identify the true SMEs in the sample. Moreover, the firms with 250 employees or less constitute 98% of the sample. We therefore control for organization size by way of a continuous measure. The thrust of the empirical studies in the literature suggests that organizational size increases the likelihood of adoption of EEMs (de Groot et al., 2001; Kounetas and Tsekouras, 2008; Schleich, 2009; Trianni et al., 2013). Size can bring economies of scale, which can reduce investment and transaction costs per unit (DeCanio and Watkins, 1998), and larger organizations tend to have wider knowledge bases and more financial resources (Damanpour and Schneider, 2006), improving absorptive capacity (Cohen and Levinthal, 1990). We control for organization size by including the number of employees, taking its natural logarithm to mitigate the skewness of its distribution.

Energy Intensity. Extant empirical work further finds a positive correlation between energy intensity and adoption of EEMs (de Groot et al., 2001; Schleich and Gruber, 2008; Schleich, 2009). Higher energy intensity is typically associated with placing higher strategic importance on energy (Cooremans, 2011; Martin et al., 2012) and with higher financial incentives to save energy expenditures. Similarly, larger and more energy-intensive organizations typically face fewer or lower barriers to energy efficiency, in particular lack of capital (e.g. Schleich, 2004; Trianni and Cagno, 2012). We measure energy intensity as electricity cost per employee, similar to Schleich and Gruber (2008) or Schleich (2009).[7]

Energy price. Finally, energy prices should directly affect the economic incentives to adopt EEMs since they represent the revenue per unit of energy saved. Prices directly affect widely used strategic evaluation methods associated with investment projects such as the payback period (Cooremans, 2011), which has been shown to negatively correlate with EEM adoption (DeCanio, 1994; Anderson and Newell, 2004). We use the price of electricity as a proxy for the price of energy. The electricity price is an incomplete measure of financial incentives for adoption, since EEMs relate differentially to distinct energy sources. However, sufficient comparable price data were available only for electricity, not for other energy carriers.

4.3. Econometric Analyses

4.3.1. Econometric Analysis of Adoption

To test the study's hypotheses, we estimate a random-effects probit model, which accounts for unobserved heterogeneity over the various EEMs under study. The dependent variables y_{ij} are dummies which indicate whether an organization $i = 1, \dots, n$ adopted an EEM $j = 1, \dots, 4$ in the past six years (since 2008). The data are stacked over all EEMs j. We define y_{ij} as a dichotomous variable that takes the value 1 if $y_{ij}^* > 0$ and zero if $y_{ij}^* \leq 0$, where the unobservable latent variable y_{ij}^* is defined as:

$$y_{ij}^* = \boldsymbol{\beta}_j{}' \boldsymbol{x}_{ij} + \varepsilon_{ij} \qquad (1)$$

For each organization i and for each measure j, the vector $\boldsymbol{x}_{ij}$ consists of a set of explanatory variables, with $\boldsymbol{\beta}_j$ the unknown parameter vector. It follows that $P(y_{ij}^* > 0) = P(y_{ij} = 1)$, which denotes the probability that organization i adopted EEM j. We employ probit models, assuming that the error terms ε_{ij} are normally distributed.

In the aggregate random-effects probit model, unobserved heterogeneity is assumed to be uncorrelated with $x_{ij,}$ and is captured by the error terms ε_{ij}. Stacking the data across EEMs allows us to capture differences in their conditional means. In all cases, the dummy variable *heating system operations* is omitted to prevent singularity of the regressor matrix.

Our second econometric approach involves the estimation of univariate probit models without random effects to explore the moderation effect of the relative advantage of EEMs by proxy of EEM type. Thus, unlike the aggregate model, this single-measures model does not assume that the parameter estimates are identical across the four EEMs. This enables us to compare the effects of agency and absorptive capacity proxies on adoption for the four EEMs and to show whether relevant differences are lost if the four technologies are aggregated (as in the random-effects model) and thus that moderation may be occurring.

Since the adoption of EEM measures may be correlated, univariate binary probit models may lead to biased and inconsistent parameter estimates (e.g., Greene, 2012). With our third econometric approach, we therefore employ a multivariate probit model, wherein the error terms capture and reveal possible correlations between the dependent variables.[8] We can do this only for pairs of EEMs, since adoption data are available for two (randomly picked) EEMs per respondent.

We also test for the sensitivity of the results to the sectoral scope by estimating the random-effects model with sub-samples that include either only non-manufacturing organizations or only manufacturing firms.

4.3.2. Econometric Analysis of Barriers

In the second set of econometric analyses, the dependent variables y_{ij} are dummies that indicate whether an organization $i = 1, \dots, n$ reported a barrier $j = 1, \dots, 13$ to be a relevant reason for the organization's not having adopted an EEM in the past six years (since 2008). In this case, $P(y_{ij} = 1)$ denotes the probability that organization i cited barrier j as relevant. We employ separate probit models for each barrier j. This approach lets parameter estimates vary across the

[6] See Appendix, Table B.1 for the decomposition of the sectors.

[7] The self-reported energy cost share as a percentage of total expenditures is available, but this is unreliable and has many missing observations ($N = 1397$ out of 2440). Total revenue data are not available and total energy costs can be calculated only by adding up amounts expended on all sources, but we cannot be sure that organizations reported all of the energy sources they use.

[8] The simulated maximum likelihood estimations relied on robust estimations of the standard deviation of the parameter estimates.

barriers but not across the four EEMs, which are included in $\boldsymbol{x}_i$ as dummy variables. Our sample size precludes technology-specific barrier analysis. Since barriers may be correlated, we employ a seemingly unrelated regression (SUR) analysis of all barrier models simultaneously. A full multivariate probit model would be preferred but is not feasible due to lack of convergence.

5. Results

We first present the random-effects and univariate probit estimations for the adoption models, followed by the results of the barrier analyses.

5.1. Adoption

Table 2 presents the results of the random-effects and univariate probit regressions of recent adoption on organizational characteristics and, in the case of the random-effects model, on EEMs.[9] Both the coefficients and the marginal effects are reported.

5.1.1. Organizational Heterogeneity

The results obtained with the random-effects model provide the evidence for hypotheses H1a through H2d. As expected, the agency variables show an inverse relation with adoption that is statistically significant at the 5% level. The individual coefficients for *tenant*, *heating system external*, and *subsidiary* provide support for hypotheses H1a, H1b, and H1c. The marginal effects suggest that, on average, a tenant is 2.6 percentage points less likely to have adopted an EEM. Having a heating system that is external to an organization decreases the likelihood of adoption by 4.9 percentage points (although the effect varies by EEM). It must be noted that tenancy and a heating system's being external to an organization often coincide ($r = 0.54$, $p = 0.000$). A subsidiary or branch is 3.3 percentage points less likely to adopt an EEM.

The four proxies for absorptive capacity show the expected positive association with adoption. Hypotheses H2b, H2c, and H2d are supported by the statistical significance of the coefficients for *energy manager*, *audit*, and *current use of clean energy technology*. The marginal effects of these three dummy variables are 4.0, 9.0, and 5.4 percentage points, respectively. The coefficient for *energy management system* is statistically significant at the 20% level, providing only weak evidence in support of hypothesis H2a. A fairly strong correlation between *energy management system* and energy manager ($r = 0.58$, $p = 0.000$) may play a role here.

Of the four EEMs, adoption of lighting is 13.1 percentage points more likely than adoption of heating system operations while adoption of insulation is 3.9 percentage points less likely. There is no statistically significant difference between the two heating system measures. These results reflect the presupposed order of relative advantage.

The results of the analysis of sensitivity to the in- or exclusion of manufacturing firms in the sample are shown in Table A.6.[10] Descriptive statistics for both models are reported side by side in Table A.5. Adoption rates of the four EEMs have the same order and, with the exception of lighting, very similar sizes. The signs of the coefficients of the model estimates with the non-manufacturing and manufacturing-only subsamples are consistent. Looking at p-values, the largest differences are for *tenant* and the energy management variables. The coefficient of *tenant* is further away from significance for the manufacturing-only sample than for the non-manufacturing sample, while we observe a lower tenancy rate among manufacturing firms (35% are tenants, compared to 60% of non-manufacturing firms). The coefficient for *energy management system* is closer to statistical significance while the coefficient for *energy manager* is further away from significance for the manufacturing sample. For the manufacturing-only sample, energy management has diffused a bit more widely and correlation between *energy management system* and *energy manger* is slightly weaker ($r = 0.51$ compared to $r = 0.59$, $p = 0.0000$ for both).

5.1.2. Heterogeneity of Measures

Turning to the univariate probit models, a more heterogeneous picture of the relationships emerges. Signs are consistent with the aggregate random-effects model, but significance varies by measure. Tenancy and a heating system's being external affect heating system measures statistically more significantly than adoption of insulation and, especially, lighting. For *heating system external*, the effect sizes (marginal effects and marginal effect relative to mean adoption rate) show a clear distinction between heating system measures and lighting and insulation. Heating replacement is sensitive to an organization's having an external heating system as opposed to controlling its own system, while heating operations are still affected by tenancy if we control for having control over the heating system. This may be because heating operations require intervention in parts of the system that are tied more closely to the real estate (such as tubes and radiators) than the single piece of equipment that is the heart of a heating system (such as a boiler). For *tenant*, the effect on heating replacement and insulation is quite similar in terms of both significance and effect size. Tenancy does not affect adoption of lighting.

For *subsidiary* it is the inverse. We find low p-values and effect sizes for the heating system measures and small, comparable p-values ($p < 0.1$) for lighting and insulation. For insulation, the marginal effect relative to the mean adoption rate is −86% compared with −24% for lighting. *Subsidiary* affects the adoption of lighting and insulation more significantly than the adoption of heating system measures but the effect of *subsidiary* on adoption of lighting and insulation is only marginally significant.

Overall, the effects of agency proxies show a dependency on measures but the moderation pattern seems complex.

Among the absorptive capacity proxies, having either an EMS or an energy manager does not have a significant effect on adoption of any of the EEMs except for a marginally significant association between *energy manager* and adoption of heating operations (with a marginal effect of 5.6 percentage points). Collinearity with *energy management system* ($0.52 < r < 0.65$) and reduced power compared with the random-effects model may explain the lack of significance in the univariate probit models. Individually, *energy management system* and *energy manager* both come out as significantly and positively related to the adoption of efficient lighting ($p < 0.01$) and insulation ($p < 0.1$), with comparable marginal effects (13.2 and 9.9 percentage points for lighting, respectively, and 4.6 percentage points for both for insulation).

Audit is significantly and positively related to adoption of all EEMs, but the association is strongest for lighting and heating system operations (the marginal effects are 17.0 and 10.0 percentage points, respectively). Existing use of renewable or clean energy technology is most significantly related to heating replacement (with a marginal effect of 7.3 percentage points) but has a stronger marginal effect on the adoption of lighting (8.8 percentage points).

As for the agency proxies, the effects of absorptive capacity variables show a dependency on measures but the pattern is complex.

Regarding the controls, manufacturing seems to be inversely related to adoption, but the effect is marginally significant and is due to a relatively strong and negative effect on lighting only (which is apparent in Table A.6 as well).[11] As expected, organizations that are more electricity intensive are more likely to have adopted, but only marginally and only for lighting (the only entirely electricity-related measure). For heating

[9] All models are significant. Individual variance inflation factors vary between 1.05 and 1.96. Thus, the variables do not appear to be highly inter-correlated.

[10] Individual variance inflation factors do not exceed 1.73.

[11] Results appear robust irrespective of how we break out sectors. We also ran the models with individual sector dummies. Sector coefficients were insignificant except for the association of hospitality and lighting (positive). The significance of other variables was not affected by alternative ways of including sectors. All findings that are not shown in this paper to save space are available upon request.

Table 2
Results of random-effects and univariate probit regressions of EEM adoption: coefficients and average marginal effects.

Variables	Random-effects model			Lighting			Insulation			Heating replacement			Heating operations		
	Coeff.	*p*-val.	dy/dx	Coeff.	*p*-val.	dy/dx	Coeff.	*p*-val.	dy/dx	Coeff.	*p*-val.	dy/dx	Coeff.	*p*-val.	dy/dx
Lighting	0.952***	0.000	0.131												
Insulation	−0.286***	0.006	−0.039												
Heating replacement	−0.143	0.133	−0.020												
Heating operations (base)															
Tenant	−0.191**	0.026	−0.026	0.006	0.954	0.002	−0.241	0.109	−0.029	−0.222	0.147	−0.031	−0.381***	0.010	−0.056
Heating system external	−0.353***	0.000	−0.049	−0.130	0.222	−0.041	−0.221	0.135	−0.027	−0.764***	0.000	−0.106	−0.517***	0.002	−0.076
Subsidiary	−0.241**	0.030	−0.033	−0.219*	0.066	−0.069	−0.481*	0.051	−0.058	−0.116	0.591	−0.016	−0.052	0.786	−0.008
Energy management system	0.189	0.184	0.026	0.275	0.140	0.086	0.263	0.233	0.032	0.197	0.383	0.027	−0.188	0.450	−0.028
Environmental/energy manager	0.287**	0.047	0.040	0.194	0.267	0.061	0.223	0.326	0.027	0.183	0.407	0.025	0.381*	0.086	0.056
Energy audit	0.653***	0.000	0.090	0.544***	0.000	0.170	0.449**	0.010	0.054	0.351**	0.038	0.049	0.676***	0.000	0.100
Renewable or clean energy used	0.390***	0.004	0.054	0.280*	0.091	0.088	0.081	0.711	0.010	0.527***	0.006	0.073	0.303	0.136	0.045
Manufacturing sectors	−0.149*	0.098	−0.021	−0.283***	0.008	−0.089	0.002	0.990	0.000	−0.094	0.513	−0.013	0.038	0.787	0.006
Elec. cost per employee (*1000 EUR)	0.063*	0.082	0.009	0.090**	0.041	0.028	0.002	0.968	0.000	0.019	0.717	0.003	0.065	0.128	0.010
Ln(Employees)	0.042	0.213	0.006	0.035	0.385	0.011	−0.022	0.684	−0.003	−0.015	0.803	−0.002	0.143**	0.011	0.021
Electricity rate (EUR/kWh)	1.758***	0.003	0.242	1.710**	0.022	0.536	0.676	0.524	0.082	0.771	0.437	0.107	2.400**	0.017	0.353
Constant	−2.105***	0.000		−1.141***	0.000		−1.539***	0.000		−1.382***	0.000		−2.135***	0.000	
lnsig2u	−0.582**	0.017													
Observations	4092			1083			1073			948			988		
Nr. of organizations	2060														
Pseudo R^2				0.068			0.073			0.136			0.181		
Log pseudolikelihood				−600.8			−244.9			−243.2			−270.6		
Chi^2	260.1			79.51			41.16			78.62			133.9		
df	14			11			11			11			11		
Prob > Chi^2	0.000			0.000			0.000			0.000			0.000		
log likelihood	−1368														
log likelihood restricted	−1389														

*** $p < 0.01$.
** $p < 0.05$.
* $p < 0.1$.

system operations the *p*-value is only slightly above 0.1. The effect of the price paid for electricity shows a similar but stronger pattern. A price difference of 1 euro-cent per kWh is associated with a 0.24 percentage point difference in probability of adoption, due largely to significant effects on lighting and heating system operations. Contrary to expectations, firm size is not significantly associated with adoption of any EEM except for heating system operations.

The results of the univariate probit regressions appear robust to inter-equation correlation. The multivariate probit regression (Table A.4) yields coefficients that are equivalent in sign and similar in size and significance despite significantly correlated error terms.

5.2. Barriers

5.2.1. Barriers Distribution

The samples for the barrier questions contain only organizations that actively considered adoption but decided to reject: these are 162, 148, 131, and 113 organizations for lighting, insulation, heating replacement, and heating operations, respectively. The distribution of the prevalence of the barriers for each EEM is shown in Fig. 2. The ranking patterns for each of the four EEMs appear quite similar. The three most prevalent barriers are the same for all four EEMs: *rented spaces, too high investment costs*, and *other investments have priority*. For three of the EEMs, *lack of capital* was rated as the fourth most relevant barrier. The two least prevalent barriers are the same for all four EEMs as well: *technical risk to production* and *risk to product quality*. This is consistent with what Fleiter et al. (2012b) found for German SMEs and may be explained by the EEMs' relating to ancillary processes rather than to core production processes. *Lack of know-how* is not an important barrier, which could hint at the low-complexity character of the measures.

5.2.2. Barriers and Organizational Heterogeneity

Table 3 summarizes the results of the univariate probit regressions using the barriers as dependent variables.[12,13] Four variables are frequently recurring significant predictors: most barriers depend on the technology (i.e., lighting or other), tenancy, whether a heating system is external to an organization, and electricity intensity.

The cited barrier most often, *rented spaces*, is significantly less likely to be perceived as relevant if lighting is involved as compared with heating operations. For most other barriers this technology dependency runs in the opposite direction, being more frequently perceived as relevant if the technology is lighting. The *rented spaces* barrier is most strongly associated with whether an organization is a tenant or not ($r = 0.81$, $p < 0.0001$). Among organizations that are tenants, this was judged a relevant barrier in 86% of the cases. Independent of tenancy, organizations with external heating systems are more likely to cite *rented spaces* as a barrier as well. These two agency variables - *tenant* and *heating system external* – relate negatively to most other barriers. *Rented spaces* appear considerably less often a reason for rejection to organizations that had been subject to energy audits. The control variable *electricity cost per employee* also negatively relates to most other barriers. The dominant pattern is that the sign of a coefficient of *rented spaces* is mirrored in the signs for (most) other barriers. In other words, for variables with a strongly significant (inverse) relationship with the *rented spaces* barrier, other barriers tend to be less (more) relevant.

[12] Individual variance inflation factors vary between 1.11 and 2.07. Thus, the variables do not appear to be highly inter-correlated.

[13] The results of the univariate probit regressions are robust to correlations between their error terms. A multivariate probit model for all thirteen barriers did not converge. However, for the four most relevant barriers as per Fig. 2, the multivariate probit model yielded coefficients that were consistent in sign, size, and significance with the univariate probit estimates (using the same observations). Also the estimated coefficients of a seemingly unrelated regression including all thirteen barriers appeared consistent in sign, size, and significance with the marginal effects of the univariate probit models.

To look behind the dominance of the *rented spaces* barrier, we restrict the sample to non-tenant organizations (see Table A.7 for the results). This yields mostly negative coefficients for the absorptive capacity factors, most strongly so for energy manager. This is consistent with hypothesis H2b, but the support is weak due to lack of power. Interestingly, energy manager is positively related only to the *internal disagreement* barrier, with which *energy management system* has a statistically significant negative association.

Other significant relationships to highlight are the following: a subsidiary is less likely to cite *lack of capital* as a relevant barrier; if an energy manager exists, *internal disagreement* is more likely to be a barrier; organizations that had been subject to energy audits appear more likely to point to *investment priorities* and *investment costs* as relevant barriers; users of renewable or clean energy technology are less likely to be deterred by *technology or energy price uncertainty*; and manufacturing firms are comparatively more concerned with *technical risk to production* and less often by *investment costs* or *lack of capital*.

6. Discussion

6.1. Heterogeneity of Measures

The relative direct effects of the EEM terms on recent adoption are consistent with the expected order of their relative advantage. However, these effects may also reflect the turnover rate (i.e. lifespans) of the specific technology categories (as appropriability is controlled for via the tenant variable). Passive technology such as wall–floor-roof insulation has the longest lifespan (50 to 100+ years, depending on type and the quality of the installation) and lighting the shortest. In addition to lifespan, the "divisibility" or "trialability" (i.e., "the degree to which an innovation can be experimented with on a limited basis" (Tornatzky and Klein, 1982, citing Rogers and Shoemaker, 1971)) of EEMs may have played a role in these effects. It is a hypothesized predictor of adoption taken from the diffusion of innovations literature (Gatignon et al., 2015), for which empirical evidence may be inconclusive (Tornatzky and Klein, 1982) but which may be relevant to crosscutting ancillary EEMs. Most organizations have a multitude of lights and adoption of efficient lighting is divisible in installments and can be tried out first in a small part of an organization prior to an organization-wide rollout. If such a trial does not produce the expected benefits (in energy savings or other attributes), it can be undone or the consequences are minor. In comparison, adoption of building insulation is not divisible for no benefits can be expected if significant heat escapes remain. Insulation is a low-frequency all-at-once operation, which is very impractical and costly to undo. Hence, divisibility may be a significant positive antecedent of adoption of crosscutting EEMs for ancillary systems.

6.2. Agency Factors

In aggregate, we find evidence for the decelerating role of principal-agent relationships in organizational adoption of crosscutting, ancillary EEMs. However, our proxy variables represent specific agency situations, the effects of which depend on the specific measure.

Lighting is least susceptible to agency issues. Reported payback times are shortest for lighting and, unlike the other EEMs, lights can stay with an organization that moves out of its rented accommodation, reducing the financial risk of not being able to recover the investment costs.

The variable *heating system external* is an agency proxy tied to the heating system measures and thus directly acting at the technology level. It shows that the split incentives in the landlord-tenant relationship can be technology specific and the same kind of split incentives may arise in organizations that are not tenants. Measuring owner-user relationships at the technology level helps separate tenancy from control over the technology, for which tenancy is often taken as a valid but imperfect proxy. Arguably, renting, leasing, or shared ownership

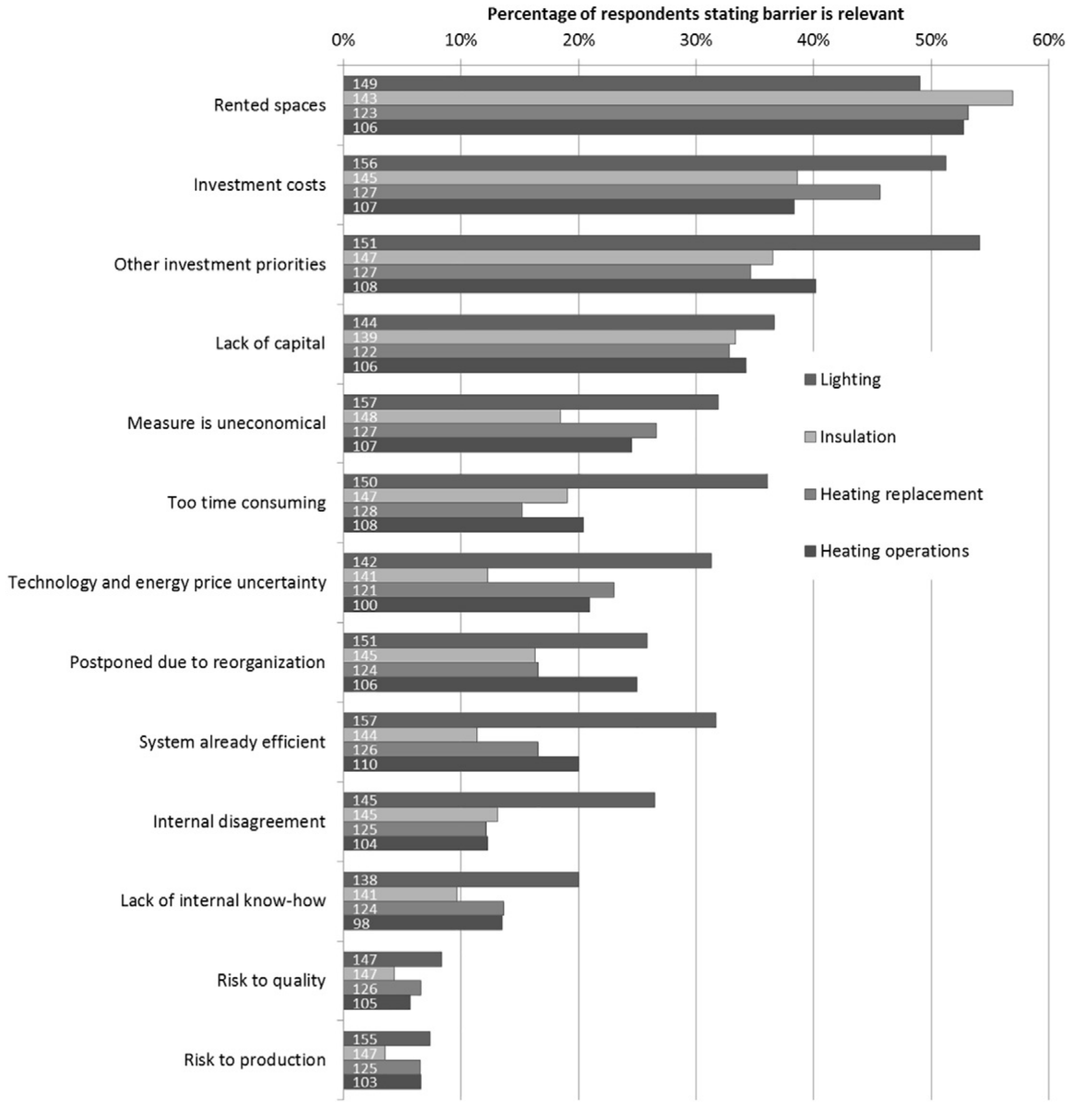

Fig. 2. Share of respondents citing a barrier as relevant reason for their not adopting (Sample size *N* in white).

of energy supply technologies will disseminate in the future as part of the energy transition involving decentralization of energy supply and new business models.

The results for subsidiary are consistent with the idea that an organization embedded in a larger organizational structure (e.g. holding) faces greater principal-agent asymmetries that lead to lower adoption rates. The evidence is supportive only in the case of lighting and insulation. Several explanations for these results are plausible. Management of real estate appearance may be centralized in holding firms, affecting decisions regarding insulation and lighting, whereas heating systems tend to require considerable customization (Trianni et al., 2014) and managing them would be more decentralized to take into account location specific attributes such as the available heat or fuel infrastructure and prices. Insulation is the most capital intensive of the measures, the responsibility for which may lie at a higher level within an organization. Insulation is also the measure with the longest reported payback time. Holding organizations with subsidiaries may be more likely to face accountability toward shareholders and short-term evaluation cycles and short payback criteria.

Previous studies found higher adoption rates of resource- (including energy) efficiency strategies for subsidiaries (Pekovic, 2010; Delmas and Pekovic, 2015). Moreover, it is argued that subsidiaries may benefit from an advantage in access to financial resources (internal or external). A testament to this is our finding that subsidiaries are less likely to perceive lack of capital as a barrier. Other benefits include economies of scale and shared absorptive capacity (Darnall and Edwards, 2006; Pinkse et al., 2010; Delmas and Pekovic, 2015). Practices, including blueprint energy strategies, may diffuse faster though the network ties within a holding organization, and may lower the transaction costs associated with their implementation (Darnall and Edwards, 2006;). However, when it comes to adoption of the low-complexity, crosscutting EEMs on which we focus, such benefits offered by the parent (and/or sister) organization(s) may make little difference.

6.3. Absorptive Capacity

The evidence for the role of absorptive capacity proxies in adoption is internally consistent and supportive of hypotheses H2a to H2d. Absorptive capacity depends on prior knowledge and is thus partly dependent on the innovation to be adopted. Organizational attributes that contribute to absorptive capacity that are relevant to ancillary crosscutting EEMs seem to consistently promote adoption.

We find evidence that, in itself, having an energy manager may promote adoption while having an EMS may not. Having an EMS may be contingent on there being an energy manager. An energy manager would be both an antecedent to and integral to EMS adoption. Conversely, in the barrier models restricted to non-tenant organizations only, we found weak evidence that having an EMS may provide an

Table 3
Results of the univariate probit regressions of barriers: coefficients.

Variables	System already efficient	Investments costs	Uneconomical	Too time-consuming	Lack of know-how	Technical risk for production	Product quality risk	Investment priorities	Technological and energy price uncertainty	Postponed due to reorganizations	Internal disagreement	Lack of capital	Rented/leased space(s)
Lighting	0.541***	0.384**	0.281	0.684***	0.279	0.043	0.215	0.511***	0.499**	0.060	0.593***	0.223	−0.671**
	(0.006)	(0.037)	(0.143)	(0.000)	(0.189)	(0.882)	(0.475)	(0.004)	(0.011)	(0.759)	(0.005)	(0.223)	(0.016)
Insulation	−0.384*	0.071	−0.213	−0.019	−0.261	−0.384	−0.239	−0.105	−0.442**	−0.427**	0.015	0.001	−0.061
	(0.068)	(0.678)	(0.252)	(0.918)	(0.231)	(0.129)	(0.358)	(0.555)	(0.026)	(0.040)	(0.941)	(0.994)	(0.818)
Heating replacement	−0.143	0.155	0.080	−0.173	−0.004	−0.155	0.017	−0.211	0.054	−0.292	−0.069	−0.036	−0.154
	(0.482)	(0.374)	(0.685)	(0.380)	(0.986)	(0.605)	(0.957)	(0.217)	(0.786)	(0.136)	(0.770)	(0.839)	(0.512)
Heating operations (base)													
Tenant	−0.777***	−0.744***	−0.511***	−0.422**	−0.283	−0.349	−0.986***	−0.706***	−0.662***	−0.220	0.014	−0.484***	2.948***
	(0.000)	(0.000)	(0.006)	(0.027)	(0.199)	(0.152)	(0.004)	(0.000)	(0.001)	(0.254)	(0.946)	(0.005)	(0.000)
Heating system external	0.189	−0.748***	−0.414**	−0.621***	−0.392*	−0.393	0.219	−0.637***	−0.444**	−0.812***	−0.490**	−0.620***	0.546***
	(0.314)	(0.000)	(0.024)	(0.001)	(0.064)	(0.150)	(0.512)	(0.000)	(0.024)	(0.000)	(0.018)	(0.000)	(0.009)
Subsidiary	−0.036	−0.183	0.098	−0.210	−0.063	0.207	−0.100	−0.321*	−0.149	0.032	−0.092	−0.417**	−0.009
	(0.861)	(0.307)	(0.606)	(0.297)	(0.763)	(0.456)	(0.704)	(0.072)	(0.474)	(0.875)	(0.671)	(0.028)	(0.967)
Energy management system	0.031	0.006	−0.142	0.212	−0.257			−0.235	0.122	−0.280	−0.470	0.036	−0.181
	(0.925)	(0.987)	(0.686)	(0.554)	(0.504)			(0.508)	(0.740)	(0.418)	(0.185)	(0.914)	(0.729)
Environmental/energy manager	0.470	−0.074	−0.254	−0.459	−0.151	−0.406		−0.067	−0.012	−0.149	0.709**	0.241	0.385
	(0.103)	(0.806)	(0.352)	(0.133)	(0.597)	(0.429)		(0.830)	(0.970)	(0.590)	(0.019)	(0.368)	(0.484)
Energy audit	−0.261	0.457*	0.327	−0.229	−0.239	−0.599	−0.858*	0.454*	−0.258	0.152	−0.329	0.221	−1.177***
	(0.228)	(0.054)	(0.140)	(0.329)	(0.342)	(0.162)	(0.063)	(0.063)	(0.240)	(0.472)	(0.173)	(0.329)	(0.000)
Renewable or clean energy used	0.211	−0.102	0.372	−0.232	−0.164		0.154	−0.324	−1.226**	−0.323	−0.087	−0.394	−0.727
	(0.482)	(0.726)	(0.232)	(0.510)	(0.737)		(0.786)	(0.297)	(0.027)	(0.336)	(0.849)	(0.188)	(0.256)
Manufacturing sectors	0.271	−0.393**	−0.159	−0.057	−0.085	0.559**	−0.066	0.035	−0.160	0.240	−0.002	−0.287*	0.363
	(0.131)	(0.025)	(0.367)	(0.742)	(0.656)	(0.011)	(0.811)	(0.838)	(0.386)	(0.166)	(0.993)	(0.088)	(0.148)
Elec. cost per employee (*1000 EUR)	−0.037	−0.217***	−0.170***	−0.119**	−0.179***	−0.108	−0.076	−0.151**	−0.101	−0.300***	−0.177**	−0.130**	0.128*
	(0.577)	(0.000)	(0.009)	(0.047)	(0.008)	(0.222)	(0.333)	(0.015)	(0.108)	(0.000)	(0.013)	(0.028)	(0.082)
Ln(Employees)	0.122	0.009	0.118	0.041	−0.025	−0.032	−0.100	0.140*	−0.152*	0.042	0.049	0.043	−0.134
	(0.117)	(0.917)	(0.172)	(0.591)	(0.769)	(0.841)	(0.469)	(0.085)	(0.092)	(0.607)	(0.559)	(0.580)	(0.278)
Electricity rate (EUR/kWh)	0.846	1.424	2.423	2.093	−0.489	−1.996	−1.494	−1.252	3.074*	−2.505	−3.594*	1.738	−0.102
	(0.657)	(0.379)	(0.166)	(0.219)	(0.793)	(0.533)	(0.520)	(0.501)	(0.056)	(0.246)	(0.054)	(0.275)	(0.960)
Constant	−1.098*	0.320	−0.923*	−0.704	−0.304	−0.586	−0.399	0.569	−0.554	0.469	−0.082	−0.237	−1.608**
	(0.065)	(0.533)	(0.095)	(0.180)	(0.580)	(0.507)	(0.601)	(0.317)	(0.282)	(0.461)	(0.887)	(0.640)	(0.024)
Observations	457	485	456	483	470	410	391	489	477	483	479	484	486
Pseudo R^2	0.152	0.204	0.121	0.135	0.070	0.126	0.115	0.225	0.162	0.150	0.114	0.146	0.643
Log pseudolikelihood	−191.1	−262.5	−224.4	−231.2	−179.1	−84.63	−84.64	−254.7	−206.4	−199.9	−181.1	−262.3	−119.2
Chi^2	64.49	96.56	52.10	74.71	28.47	36.36	29.17	104.7	72.73	57.11	47.62	76.52	206.7
Prob > Chi^2	0.000	0.000	0.000	0.000	0.012	0.000	0.004	0.000	0.000	0.000	0.000	0.000	0.000
df	14	14	14	14	14	12	12	14	14	14	14	14	14

Robust *p*-values in parentheses.
*** $p < 0.01$.
** $p < 0.05$.
* $p < 0.1$.

energy manager with the institutionalization, legitimization, and information needed to make him/her more effective, and through these functions increase an organization's absorptive capacity. These results appear consistent with findings reported in the literature on environmental management systems (King et al., 2005; Darnall et al., 2008; Frondel et al., 2008; Wagner, 2008).

The effects of having an EMS and an energy manager found in our econometric analysis are somewhat plagued by collinearity. Independently, an energy manager can make a difference for the most operational of the measures under study—heating operations—requiring both the most and the most continuous administrative involvement. Not controlling for each other, the absorptive capacity contributed by energy management is not significantly associated with the two heating system measures. A possible explanation is that organizations with energy managers (or EMSs) had already updated and optimized their heating system prior to the focal period (2008–2014). Indeed, pairwise correlation between the presence of an EMS or energy manager and the barrier *already efficient* is much more significant for heating replacement and heating operations than for efficient lighting and insulation (Table A.3). (This does not show in the results of the probit regressions for the barriers (Table 3), because technologies are aggregated.)

The finding that an energy manager appears more prone to experiencing internal disagreement as a barrier could be understood as a function of an energy manager's seeing her/his influence constrained by organizational factors, such as a decision-making hierarchy, conflicting organizational demands, and resource constraints (Goulden and Spence, 2015). One could argue that disagreement requires a proponent in the first place and thus should be regarded as evidence in favor of an energy manager's role as promotor of rational energy use.

Regarding the audit variable, rather than serving as a measure of absorptive capacity it may also represent a demonstration of (partial) absorption. The strongly significant association between audits and adoption adds to the evidence in favor of audit effectiveness but no causality can be inferred. Audits appear to be effective in overcoming agency asymmetry, signaling a possible interaction between agency and absorptive capacity. An energy audit can help mitigate the information asymmetry and transaction costs that are at the root of the landlord-tenant dilemma (Jaffe and Stavins, 1994b) by serving as a communication tool to more credibly transfer information on the benefits of energy efficiency investments from landlord to tenant or vice versa. Hence, it enables contracting to allow the agent to appropriate the benefits of its investment. Positive associations with the *investment costs* and *other priorities* barriers suggest that audits could also yield dissuading economic information leading to rejection, as reported in Frondel and Vance (2013). Based on the combined evidence we are inclined to infer that energy audits are associated with the rationalization of energy use. Prior experience with clean energy technology is significantly related only to adoption of replacement measures. Prior experience may represent an absorptive capacity that is more relevant to measures that are more similar. The finding that prior experience negatively relates to the *technology and energy price uncertainty* barrier corroborates that finding.

In summary, the evidence supports the hypotheses that absorptive capacity factors promote adoption, improving an organization's ability to assess a measure's impact more comprehensively and rationally, thereby reducing perceived inconvenience and effort. At the same time, there can be varying degrees of contingency on this measure.

Finally, our analyses yield few differences in the factors of adoption and barriers to adoption between manufacturing and non-manufacturing organizations. For manufacturing firms tenancy seems less relevant a factor and an energy manager may make less significant a difference. An explanation may be that manufacturing firms dispose of more extensive prior technical knowledge resources and thus relevant absorptive capacity. Overall, the results support our assumption – stated in Section 4.2.3 - that for crosscutting ancillary measures, sectoral differences are less salient than for more specific measures that are closer to the core process.

7. Conclusions

In this paper we explore the relevance of heterogeneity of four crosscutting ancillary EEMs (efficient lighting, building insulation, heating system replacement, and optimization of heating system operations) in relation to organizational antecedents of adoption and barriers to adoption in organizations. Drawing mainly on literature on agency theory and absorptive capacity, we develop a set of hypotheses which we tested employing a large, representative sample of organizations in the German trade, commerce and services sector. For the barriers analysis, only organizations that had actively considered adoption before rejection were included. At the cost of restricting sample size, this mitigated the hypothetical degree of the responses from which most survey-based barrier studies suffer. Based on findings from our microeconometric analyses—which are robust to alternative model specifications—we draw the following conclusions.

We find evidence for a negative effect of principal-agent relationships on adoption of crosscutting ancillary EEMs. The significance of the effect varies by measure. We show that split incentives in the landlord-tenant relationship can be technology-specific. The same kind of split incentives may arise in organizations that are not tenants. Measuring owner-user relationships at the technology level helps separate tenancy from control over the technology.

Organizational attributes that contribute to absorptive capacity that is relevant to ancillary crosscutting EEMs seem to have a positive effect on adoption. An energy manager can be both an antecedent of EMS adoption and an element of an EMS. We found weak evidence that an EMS may provide an energy manager with the institutionalization, legitimization, and information needed to increase an organization's energy-relevant absorptive capacity and promote adoption. Energy audits are associated with significantly higher adoption rates for all measures and appear to be effective in overcoming agency asymmetries in landlord-tenant situations. Evidence from barrier analysis suggests that audits may yield dissuading information as well. Further, our findings provide little support for differences in the factors of adoption and barriers to adoption of crosscutting EEMs between manufacturing firms and non-manufacturing organizations.

Compared with relative advantage, compatibility, or complexity, trialability by way of the divisibility of an energy efficiency measure may be a more significant antecedent of adoption of crosscutting ancillary EEMs. Nevertheless, descriptive analysis of barriers shows that the heterogeneity of crosscutting ancillary EEMs has little impact on the ranking of barriers to adoption. The most relevant barriers for all EEMs are *rented spaces*, *investment costs*, and *investment priorities*, while the least relevant are *technical risk to production* and *risk to product quality*.

7.1. Policy Implications

Capital intensive, long-lifespan space heating measures in particular face an investment barrier and – as an ancillary measure – enjoy little strategic importance. The prime barrier is split incentives in landlord-tenant relationships, which are generally caused by information asymmetry. The undoing of split incentives requires either the transfer of risks and rewards between principal and agent to balance out the uneven distribution or the bundling of risks and rewards in one actor. Energy audits may contribute to the former by lowering perceived financial and technological risks of EEMs. Energy service companies (ESCOs) and energy performance contracting (EPC) are potentially effective instruments for the latter (Nolden et al., 2016). Complementary measures, such as energy or eco-labeling, can help communicate audit results. Indeed, work by Eichholtz et al. (2013) and Fuerst and McAllister (2011) in the U.S. shows that if information asymmetry in superior energy performance is resolved (e.g., via energy labels), organizations are willing to pay higher rent for a more efficient building.

Our findings suggest that the energy efficiency paradox in crosscutting ancillary measures may be addressed by enhancing the ability to acquire, assimilate, and exploit energy-related knowledge. Energy audits and energy management may provide viable levers for policy. Current EU regulation (Energy Efficiency Directive 2012/27) requires audits for large enterprises only and Member States must "encourage SMEs to undergo" them (EU, 2012). Our results suggest that audits may be an effective, direct enhancer of specific absorptive capacity in SMEs as well. Improving energy management through the promotion of energy managers or adoption of EMSs in a sector dominated by SMEs can seem disproportional. Here, ESCOs could aggregate energy management demand and economize solutions.

Moreover, to enable economies of scale in addressing heterogeneity, new homogeneity may be found in expanding the geographic scope of central information repositories so as to include as many similar cases (and their solutions) as possible.

7.2. Limitations, and Future Research Directions

Our study is subject to several limitations. In particular, our cross-sectional data only allow inference on correlation, not causation. In addition, adoption data refer to a fixed, limited historic time frame; they do not take into account initial differences in efficiency levels. Some organizations may have adopted an EEM just before the study's time frame rather than during it, which would be recorded as non-adoption. We found some evidence for this in the correlation between the barrier *already efficient* and the presence of an EMS or energy manager. However, this test is imperfect as those with already efficient systems may not have considered the EEM in the focal period and, hence, may have been excluded from barrier analysis.

Furthermore, we tested only a limited number of organizational characteristics, some of which are quite specific, partial proxies of agency and absorptive capacity. At the same time, some (ownership structure, energy management) call for more detailed exploration.

Finally, the paper suggests that for crosscutting ancillary innovations, the attributes that most significantly determine the rate of adoption may differ from those of the usual core-process innovations (relative advantage, complexity, compatibility (Tornatzky and Klein, 1982; Rogers, 2003)). More research is needed to study the performativity of attributes that is contingent on the type of measures involved.

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Appendix. Supplementary Data

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