The characteristics of energy-efficiency measures – a neglected dimension

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Abstract

The diffusion of cost-effective energy-efficiency measures (EEMs) in firms is often surprisingly slow. This phenomenon is usually attributed to a variety of barriers which have been the focus of numerous studies over the last two decades. However, many studies treat EEMs homogenously and assume they have few inherent differences apart from their profitability.

We argue that complementing such analyses by considering the characteristics of EEMs in a structured manner can enhance the understanding of EEM adoption. For this purpose, we suggest a classification scheme for EEMs in industry which aims to provide a better understanding of their adoption by industrial firms and to assist in selecting and designing energy-efficiency policies.

The suggested classification scheme is derived from the literature on the adoption of EEMs and the related fields including the diffusion of innovations, eco-innovations and advanced manufacturing technology. Our proposed scheme includes 12 characteristics based on the relative advantage, the technical and the information context of the EEM. Applying this classification scheme to six example EEMs demonstrates that it can help to systematically explain why certain EEMs diffuse faster than others. Furthermore, it provides a basis for identifying policies able to increase the rate of adoption.

Keywords

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1   Introduction

Improving end-use energy efficiency is seen as one of the most relevant measures to reduce the energy-related emissions of CO_2 (IEA 2011) and as a fast and cost-effective way to improve security of energy supply (European Commission 2011). Considerable cost-effective saving potentials in the industrial sector have been repeatedly identified in the literature (Eichhammer et al. 2009; Worrell et al. 2009), but the adoption of energy-efficiency measures (EEMs) is often slow despite their cost-effectiveness. The literature discusses this phenomenon under the heading of barriers to energy efficiency and provides manifold reasons for the non-adoption (or delayed adoption) of EEMs (DeCanio, Watkins 1998; Jaffe, Stavins 1994; Sorrell et al. 2004). Despite the explanations provided, little effort has been made to explain the adoption of EEM using their characteristics. Instead, EEMs are usually treated as a homogenous aggregate.

In this paper we argue that the characteristics of EEMs play a crucial role in the adoption process. A structured discussion of the characteristics of EEMs would considerably improve the value and quality of energy-efficiency analyses and the resulting policy recommendations. This is particularly the case for EEMs in the industrial sector where the heterogeneity of technologies is the greatest and where technologies are often deeply embedded into broader often individually designed production systems.

In this sense, our argumentation runs parallel to what has been discussed for the diffusion of innovations over the past decades: the enormous variety of innovation types, innovator types and other factors affecting diffusion make the comparison of study results difficult - or even impossible if these factors are not explicitly considered (Damanpour 1988; Dewar, Dutton 1986; Downs, Mohr 1976). Consequently,

generalizations across studies are only rarely valid despite the huge number of analyses which stress the need to take multiple factors into account. Factors affecting the diffusion of innovations (which comprise EEMs) can be sorted into various groups. Wejnert (2002) for example distinguished three main groups: the characteristics of innovations (in our case EEMs), the characteristics of innovators (in our case firms) and the environmental context.

In this paper, we focus exclusively on the characteristics of EEMs. We propose a classification scheme for EEMs to consider their various characteristics in a structured manner. The classification scheme helps to better understand the adoption of EEMs by industrial firms and serves as a basis for the selection and design of energy-efficiency policies.

The explicit consideration of the characteristics of EEM when discussing the adoption behavior of firms has received only little attention in the past. One report comparing emerging energy-efficient technologies applied a classification scheme and showed how it might help to compare different EEMs (Martin et al. 2000). It focuses on emerging technologies, and policy conclusions are mainly restricted to the market introduction of EEMs. De Beer (1998) also researched the likelihood of market entry of EEMs' using a classification of EEMs related to the technical change and the stage of development. Cooremans (2012) analyses behavior of firms with regard to energy efficiency investments and particularly focuses on how the investment characteristics affect the strategic value of an EEM. These approaches all deal with the characteristics of EEMs from particular perspectives. To our best knowledge, no study exists that takes a comprehensive view of the entire set of characteristics with the intention of classifying EEMs.

Our analysis is based on a broad and widely applied definition of energy efficiency as an increase in the ratio of the useful output of a process compared to its energy input (Patterson 1996). This definition implies that any action inducing an improvement of this input-output relation is an EEM. Consequently, we include measures in the classification scheme that do not necessarily save energy. Whether the EEM is adopted with the main intention of improving energy efficiency, or for other purposes, is not relevant for the definition as long as it improves energy efficiency. Similar approaches are being taken in the discussion of eco-innovations, whose introduction is not necessarily dependent on a reduction in environmental harm. The mere fact that a technology is less environmentally harmful than its conventional alternative is sufficient for it to be defined as an eco-innovation (Andersen 2008; Kemp, Foxon 2007). Furthermore, EEMs are always defined in comparison to a baseline or conventional technology. A fluorescent lamp, for example, is only an EEM when compared to an incandescent light bulb, but not when compared to an LED lamp. This example also indicates that the definition of EEMs may change over time as more efficient technologies emerge.

As we intend to develop a broadly applicable classification scheme, we first point out the criteria used for the selection of characteristics for the classification scheme and we then discuss four different fields of literature providing insights into characteristics affecting the adoption of EEM and other innovations (section 2). We then propose and discuss EEM characteristics for the classification scheme (section 3). To illustrate and validate the classification scheme, we use it to characterize and compare a set of different EEMs (section 4). We finally discuss the advantages and drawbacks of our approach and its application (section 5) and make suggestions for further research (section 6).

2   A review of EEM characteristics

2.1   Selection criteria

The initial objective of the classification scheme is to help to better understand the adoption of EEMs by industrial firms and serve as a basis for the selection and design of energy-efficiency policies. Using this as a basis, we choose the following five criteria to select useful characteristics from the broad number of EEM and innovation characteristics proposed in the literature:

- Relevance: The chosen characteristics should affect the adoption of EEMs.
- Applicability: The characteristics should be sufficiently general to allow the characterization of very different EEMs.
- Specificity: The characteristics should remain specific enough to be evaluated as concrete and objectively as possible.
- Independence: The characteristics should not depend on the adopting firm or other contextual factors to increase the comparability among EEMs.
- Distinctness: The characteristics should not overlap and be distinct from each other.

Although it is often not possible to completely fulfill these requirements, we have used them to select and define characteristics. On this basis, we review the literature on EEM characteristics and related fields and discuss their selection with regard to the above criteria. The characteristics chosen for the scheme are then further refined and discussed in section 3.

2.2   The adoption of energy-efficiency measures

The adoption of EEMs has been intensively researched in the last two decades. Research generally focuses on the observation that even cost-effective EEMs diffuse surprisingly slowly through the capital stock. Diverse explanations have been put forward for this observation which are summarized under the label *barriers to energy efficiency*, including imperfect information, split incentives or risk and uncertainty (Sorrell et al. 2004). Discovery of the so called *energy-efficiency gap* (Jaffe, Stavins 1994) prepared the ground for developing energy-efficiency policies (Brown 2001). In the following, we briefly summarize the main findings in the literature, focusing on how the intensity of the barriers varies depending on the characteristics of EEMs.

Analyses of EEMs and barriers to energy efficiency often classify technologies by their energy end-use. Typical end-use classes include lighting, air-conditioning, space heating, refrigeration, etc. (Harris et al. 2000), or, on a more aggregated level, classes like building-related technologies, motor systems, thermal systems, etc. (Anderson, Newell 2004). The conclusions about the adoption behavior of firms that can be drawn from these classes are limited and, thus, their relevance low, as the end-uses do not describe the EEMs themselves, but only where they are applied. Related to a distinction of end-uses, Martin et al. (2000) distinguish cross-cutting technologies from process-related technologies, which allows more generic conclusions on the adoption rate, as cross-cutting technologies typically face a larger market.

De Beer (1998) classifies EEMs using two dimensions: the degree of technical change the EEMs involve ranging from evolutionary change to radical change, and their stage of development ranging from applied research to demonstration plants. Although De

Beer aims to explain the likelihood of EEM market entry, the dimension technical change also relates to the adoption of EEMs by firms.

Other often considered characteristics are the *payback period* or the level of initial *capital expenditure.* Anderson and Newell (2004) found that the payback period correlates negatively with the adoption rate of EEMs as does the initial expenditure. Thus, both characteristics are relevant for the adoption and also specific enough to be objectively measurable.

Most empirical analyses of barriers do not explicitly distinguish characteristics of EEMs. Nevertheless, some conclusions can be drawn from the importance of different types of barriers. For instance, the *perceived risk of production interruption* was found to be among the most important technology-specific barriers in the paper and the iron foundry industries in Sweden (Rohdin et al. 2007; Thollander, Ottosson 2008). In contrast, *risk of problems with product/equipment* was listed among the least important reasons for not adopting EEMs in an analysis of the US energy audit program (Anderson, Newell 2004). A possible reason for this difference in risk perception might be the fact that, in the US audit program, mainly EEMs were recommended that are not critical to the core production processes, like energy-efficient lighting or compressed air system optimization. In the paper industry, however, EEMs are more likely to be related to the production of paper and survey respondents might therefore perceive a higher risk related to their adoption. Thus, risk is an important factor for the adoption of EEMs (Rohdin et al. 2007; Thollander, Ottosson 2008), but it is not a characteristic of the EEMs themselves. Instead it is embedded in characteristics such as the *distance to the core production process.* Also Dieperink et al. (2003) show that EEMs that require integration into the core production process diffuse slower.

The importance of *access to capital* as a barrier, which has also been underlined by a number of studies (de Groot et al. 2001; Rohdin et al. 2007; Thollander et al. 2007), indicates that the initial expenditure required for an EEM is a relevant determinant of the adoption rate. Nagesha et al. (2006) found that *financial and economic barriers* were ranked as most important in the two analyzed industry clusters in India. Furthermore, seven case studies of the Irish mechanical engineering industry found that access to capital is the most important barrier to energy efficiency, although the firms generally had no difficulty in accessing external capital (O'Malley, Scott 2004). In this case, the *low priority of energy-efficiency investments compared to other investments* seems to be at the root of the problem. In a similar survey among 54 UK breweries, *access to capital* was ranked among the most important barriers (Sorrell 2004). This has also been confirmed for the Italian manufacturing sector (Trianni, Cagno 2012). While access to capital directly depends on the adopting firm, the related size of the *initial expenditure* for an EEM is independent from the context and suitable for the classification scheme. The relevance of the initial expenditure for the adoption decision has also been empirically shown by Anderson and Newell (2004).

Lack of time/staff has been included in a number of surveys and is often ranked among the most important barriers (Anderson, Newell 2004; Schleich 2009; Thollander et al. 2007; Thollander, Ottosson 2008). Lack of staff is a function of both the availability of staff in the firm, which is strongly context dependent, and the transaction costs for the implementation of EEMs.

Related to the above mentioned barriers is the frequently observed *low priority of energy efficiency* when EEMs compete with investments in the core business of a firm (Gruber, Brand 1991; Hasanbeigi et al. 2010; Thollander et al. 2007). Low priority is even more a barrier the smaller the firm's investment budget is. The reasons for the

low priority of EEM investment are related to the EEMs' benefits (also beyond energy efficiency) and the EEMs' value to the strategy or the core business of the firm. Cooremans (2011) underlines the importance of the *strategic character* of investments for the adoption decision and sees an investment as strategic if it "contributes to create, maintain or develop a sustainable competitive advantage". The strategic character of an EEM increases its priority and often weighs more heavily than the pure financial profitability of an investment when investment alternatives are being compared. However, whether an EEM is perceived as strategic not only depends on the EEM's characteristics but to an even greater extent on the culture and priorities of the firm, as also stated by Cooremans (2011 p.486): "[..] sources of competitive advantage are varied and depend on the structure of the industry, as well as on firms' individual activities and resources". Thus, whether an EEM has a strategic value to a firm depends on the EEM's benefits (not only energy-related) as well as on the objectives of the firm. While the second factor is certainly firm dependent, the former is not and thus might be more appropriate for the classification scheme. Such benefits certainly comprise energy savings, but also non-energy benefits, which describe the benefits of EEMs beyond energy savings, such as productivity increases or the reduction of local emissions (Boyd, Pang 2000; Pye, McKane 2000; Worrell et al. 2003). Often, such non-energy benefits are the main argument for adopting an EEM, particularly if they generate significant productivity gains. Non-energy benefits can be, but not necessarily, strategic to the firm. As they certainly affect the adoption of EEM, non-energy benefits are included in the classification scheme. They represent however, a broad group of characteristics.

These findings illustrate that the literature on barriers to energy efficiency already covers a number of relevant characteristics such as the *distance to the core production*

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process (which affects the risk related to EEM investment), *the payback period, the initial expenditure, non-energy benefits or the transaction costs related to the implementation.* We discuss each selected characteristic in more detail in section 3.

2.3 Adoption of technologies in related fields

Next to literature on EEMs, analyses on adoption behavior of technology can also be found in other fields of literature. In the following, we discuss three related fields of literature including the diffusion of (process) innovations, eco-innovations and advanced manufacturing technology (AMT).

Although EEMs can be regarded as a particular type of innovation, the literature on the **diffusion of innovations** has rarely been used to explain diffusion patterns of EEMs. Here, we briefly review the literature that focuses on the characteristics of innovations and how they help to explain the adoption rate. The transferability to EEMs is assessed as part of the review.

We start with the five widely used characteristics defined by Rogers (2003). He distinguishes the *relative advantage*, *complexity*, *compatibility* (to the existing system), *trialability* and *observability* of an innovation as perceived by the potential adopters[1]. Tornatzky and Klein (1982) added *cost*, *communicability*, *profitability, social approval*

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[1] Rogers (2003) proposes the following definitions for the categories: "*Relative advantage* is the degree to which an innovation is perceived as being better than the idea it supersedes" (p. 213), "*Complexity* is the degree to which an innovation is perceived as relatively difficult to understand and use"(p.230), "*Compatibility* is the degree to which an innovation is perceived as consistent with the existing values, past experiences, and needs of potential adopters." (p.223), "*Trialability* is the degree to which an innovation may be experimented with on a limited basis." (p.231, "*Observability* is the degree to which the results of an innovation are visible to others." (p.232)

and *divisibility* and conducted a meta-analysis of 75 studies addressing innovation characteristics. They found *compatibility* and *relative advantage* to be positively and *complexity* to be negatively related to adoption. The other characteristics were not statistically significant. However, according to Tornatzky and Klein (1982), these characteristics are still too unspecific. Particularly *relative advantage* and *complexity* are often not clearly defined and can embody different effects depending on the interpretation. Similarly, we see the need to specify the characteristics of EEMs in more detail for a structured analysis. In addition, the characteristics defined by Rogers are generally applicable to all types of innovations and potential adopters, while in the following, we concentrate on innovations adopted by firms. Wherever possible we will focus on process innovations (improvements in the production processes of firms) and not on product innovations (improvements in the products manufactured by the firm).

Despite the variety of proposed characteristics, diffusion literature tends to focus on one of them, the *relative advantage* or even more narrowly on the *expected profit* of an innovation (Mansfield 1961; Ray 1988; Stoneman 2002). The relative advantage comprises both the benefits as well as the costs of adoption. Oster (1982), for example, found that *profitability* had a significant impact on the adoption rate of blast furnaces in the iron and steel industry. Profitability, thus, is clearly relevant for the adoption decision and is proposed to be included in the scheme.

However, even when the *expected profits* are obvious, other factors might still prevent adoption as, for example, Rosegger (1979) showed for the case of continuous casting. In this particular case, the costs of switching to a new technology were high, because firms could only adopt the new technology if the old production plant were replaced. The existing production facilities, however, generally entail high sunk costs. Consequently, in this case of *replacement innovations*, the age distribution of the

capital stock and the lifetime of the technologies determine the rate of adoption. Replacement of premature capital stock is possible, but implies higher *costs* (i.e. the sunk costs of the capital stock in place). This is also discussed by Gold et al. (1970), who distinguished investments in new technology as a result of capacity expansion or replacing closed plants on the one hand and investments in replacing non-depreciated production facilities on the other hand. Also, for the case of US electric arc furnaces, Worrell and Biermans (2005) showed that the *rate of stock turnover* significantly affects the energy-efficiency improvement and, thus, the diffusion of EEMs. For the case of "replacement technologies", the rate of stock turnover depends on the *lifetime* of the technologies, which is specific, easily measurable and independent from the adopter.Another widely considered and analyzed determinant is the *complexity* of the innovation, which is typically negatively correlated to the rate of adoption (Kemp, Volpi 2008; Tornatzky, Klein 1982). Complex technologies require more know-how and skills to be implemented and might be associated with higher risks. Also, information gathering and process testing are more time intensive. For the classification, complexity does not comply with the criteria defined, as it can only be objectively measured with difficulties.

Related to complexity is the *radicalness* of the innovation. The distinction between radical and incremental innovations is often used in the literature (Dahlin, Behrens 2005; Damanpour 1988; Dewar, Dutton 1986; Ettlie et al. 1984), although this concept lacks specification and most technologies are located along the continuum between these two poles. Depending on the perspective, it is included in studies as the *degree of knowledge* embodied in the technology (Dewar, Dutton 1986), the *degree of change* imposed on the adopting organization (Damanpour 1988), or the *degree of newness* of the innovation (to the firm) (Bergfors, Lager 2011; Reichstein, Salter 2006). All these

definitions have in common that they are rather subjective and difficult to measure and thus are not useful for the classification scheme. Dahlin and Behrens (2005) also underline the lack of a clear definition of *radicalness* in the literature.

Similarly, *compatibility* as proposed by Rogers (2003) and Tornatzky and Klein (1982) is a rather broad and subjective characteristic that is heavily dependent on the potential adopter and their characteristics and, consequently, not useful for the classification scheme.

A factor used in some diffusion modeling studies is the *expected future improvement* of an innovation (Geroski 2000; van Soest, Bulte 2001). Firms expecting the price of an innovation to fall or its performance to improve in the near future might delay their decision to adopt, particularly if the investment is irreversible and future developments are uncertain (Pindyck 1991; van Soest 2005). However, del Río González (2005) did not find any empirical evidence for this in a survey of Spanish paper mills. In his study, the *expected technology improvement* was rated among the least important reasons for non adoption and, thus, the effect on the adoption of EEM is uncertain.

The supply-side market was also found to have an impact on the adoption rate. According to Stoneman (2002), innovations diffuse faster under conditions of *high competition* than under an oligopoly or a monopoly. This is mainly a result of lower prices which are closer to the marginal costs. Thus, this item overlaps with the initial expenditure and the profitability.

Furthermore, the literature on **eco-innovations** (or environmental innovations) provides various classifications that might also be useful for EEMs.[2] Carrillo-Hermosilla (2010) defines three groups of eco-innovations. These range from *component* change through *sub-system* change to *system change*. Kemp et al. (2007) propose four classes of eco-innovations: *environmental technologies*, *organizational innovation, product and service innovation with environmental benefits,* and *green systems changes*. The classification proposed by Andersen (2008) is similar in certain respects, but adds the distinction between add-on and *integrated eco-innovations* as well as *general purpose eco-innovations*. Rennings (2000) argues that "the nature of an eco-innovation can be *technological*, *organizational, social* or *institutional*". Faucheux and Nicola (2011) combine several approaches and distinguish five characteristics of eco-innovations: the *scope* of the innovation (from integrated to end-of-pipe), the *intensity* of the innovation (from incremental to radical), the *support* for the innovation (by firms, politics), the *application field* (from classical technological/organizational to more service economy) and *user acceptance*. Among others, Hellström (2007) distinguishes between incremental and radical as well as architectural (or system-related) and component related eco-innovations.

For eco-innovations, a differentiation is typically made between *clean technologies* and *end-of-pipe technologies*. The latter can be added to the existing production system whereas clean technologies as defined by del Río González (2005) or Demirel and

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2   EEMs can be regarded as being part of the broader group of eco-innovations, although, in contrast to many other eco-innovations, EEMs do not require a regulative framework to be cost-effective for the firm. They can be profitable simply due to the avoided energy consumption.

Kesidou (2011) impose changes on the production system. Clean technologies may for instance increase resource efficiency by reducing the amount of input needed for a given production output. This differentiation seems to be transferable to EEMs as it suggests distinguishing EEMs that require (risky and more complex) integration into existing technologies from those that are simply *add-on measures*. The adoption of the latter is certainly also less strictly bound to the turnover of the capital stock. Another useful aspect for the classification of EEMs is the separation into *technical and organizational/administrative innovations*, which is also frequently used beyond eco-innovations (Daft 1978; Gopalakrishnan, Damanpour 1997) and is specific enough at it is relatively objectively measurable. Damanpour argues that this distinction is essential because the two types of innovations "imply potentially different decision-making processes" (Damanpour 1988).

EEMs show conceptual similarities to **advanced manufacturing technology (AMT)**[3]. Still, hardly any spillovers to energy efficiency studies can be observed. The literature on AMT reveals the high importance of (intangible or non-financial) benefits beyond pure financial profitability (Godwin, Ike 1996). A study on the adoption of AMT in Canada (Baldwin, Rafiquzzaman 1998) found that benefits like *increased productivity, product quality improvement, reduced setup time, greater product flexibility, improved working conditions, and lower inventory* were often mentioned by plant managers and

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[3] The term "Advanced Manufacturing Technology" (AMT) designates a large variety of modern computer-based systems used to improve the efficiency and effectiveness of manufacturing operations and thus increase a firm's competitiveness (Small, Yasin 1997). You could argue that AMT and EEM usually overlap as the adoption of AMT aims to increase productivity and probably affects energy consumption at the same time. Furthermore, AMT like EEM is usually perceived as requiring higher investments than conventional technology and the implementation of AMT is, like EEM, subject to various barriers (Chan et al. 2001; Saberi et al. 2010).

showed a significant impact on the adoption rate. The study also found a broad range of costs like *technology acquisition costs, software development costs, education and training costs, and increased maintenance expenses* affect the rate of adoption of AMT. Since then, an entire body of literature has been developed on justifying the adoption of AMT, which discusses the relevance of additional benefits for AMT adoption (Baldwin, Lin 2002; Raafat 2002; Son 1992). Investment justification approaches can be classified into three broad categories (Chan et al. 2001; Small 2006): economic approaches relying on classical financial methods (e.g. net present values, payback periods, internal rate of return, return on investment); strategic approaches considering aspects such as the compliance with business objectives or the competitive advantage; and analytic approaches including value analysis, portfolio analysis and risk analysis. Using economic approaches to justify AMT investments is deemed unsuitable (Small 2006). Kreng et al. (2011) observe a shift from cost/finance to strategic considerations that are able to consider tangible and intangible benefits and a preference for hybrid approaches over conventional financial approaches. This underlines the importance of intangible benefits in the AMT literature. While the consideration of *intangible benefits* is an important issue in the AMT literature, only a few studies in the EEM literature explicitly discuss such *non-energy benefits* (Boyd, Pang 2000; Cooremans 2011; Pye, McKane 2000; Worrell et al. 2003).

To conclude, the literature provides relevant conclusions for EEMs and a useful starting point for our classification scheme. It is highly likely that characteristics such as *profitability, other intangible benefits or the prevailing technology stock* are relevant for EEMs as well. This is also true for the distinctions made between *integrated and add-on* as well as *organizational* and *technical* innovations. However, some characteristics used in diffusion research seem less promising for EEMs as they are not specific

enough and not independent from the adopter – even though they might arguably be relevant for the adoption. Among these are *complexity* and *radicalness*. In their place, we consider more specific characteristics like *type of modification*, *knowledge requirements* and the *scope of the impact* (see section 3). Although, *compatibility* was found to be relevant for the adoption, we do not explicitly consider it, as it is strongly dependent on the adopter's characteristics. To a certain degree it is covered by the three aforementioned characteristics. In addition, the *concentration on the supply market* is beyond the scope of EEM characteristics as analyzed in this paper.

3 Development of a classification scheme

3.1 General structure

In this section we suggest a classification scheme for EEMs based on the above literature review. Using a morphological box (Zwicky 1967) for the classification scheme seems an effective way to structure and illustrate the characteristics of EEMs. The total number of twelve characteristics can be grouped into three areas: relative advantage, technical context and the information context of EEMs (see Figure 1). The order of the characteristics does not represent a weighting. For each characteristic we define a set of attributes and arrange them according to their likely effect on the adoption rate such that the expected adoption rate of the EEM is higher the further to the right an attribute is located.

Figure 1: Classification scheme for EEMs

Characteristics		Attributes			
Relative advantage	Internal rate of return	Low (< 10%)	Medium (10 - 30%)	High (> 30%)	
	Payback period	Very long (>8 years)	Long (5-8 years)	Medium (2-4 years)	Short (<2 years)
	Initial expenditure	High (> 10% of invest. budget)	Medium (0.5-10% of invest. budget)	Low (<0.5% of invest. budget)	
	Non-energy benefits	Negative	None	Small	Large
Technical context	Distance to core process	Close (Core process)		Distant (Ancilliary process)	
	Type of modification	Technology substitution	Technology replacement	Technology add-on	Organizational measure
	Scope of impact	System (system-wide effects)		Component (local effects)	
	Lifetime	Long (>20 years)	Medium (5-20 years)	Short (<5 years)	Not relevant
Information context	Transaction costs	High (> 50% of in. expenditure)	Medium (10–50% of in. expenditure)	Low (< 10% of in. expenditure)	
	Knowledge for planning and implementation	Technology expert	Engineering personnel	Maintenance personnel	
	Diffusion progress	Incubation (0%)	Take-off (<15%)	Saturation (>85%)	Linear (15-85%)
	Sectoral applicability	Process related		Cross-cutting	

Lower adoption rate — Higher adoption rate

3.2 Relative advantage

Profitability is often found among the most important characteristics for technology adoption (Kemp, Volpi 2008; Oster 1982; Rogers 2003; Stoneman 2002). To compare EEMs' profitability, we suggest using the **internal rate of return (IRR)**. Alternatives like the net present value have the disadvantage that they represent absolute monetary values which make it more difficult to compare different EEMs. The IRR covers various aspects such as the additional expenditure compared to the standard technology, changes in running costs and the expected energy (cost) savings. Thus it is not

necessary to explicitly consider energy savings in the classification scheme. A higher IRR implies higher profitability and typically results in higher adoption rates.

Companies often use the **payback period** as a simple investment decision rule for EEMs (Cooremans 2011). However, the payback period is actually a poor indicator for profitability, because it does not take the EEM's lifetime into account. It is only an indicator of the risk of an investment. The accepted payback period requirements vary among firms, sectors and EEMs, but are usually shorter than suggested by profitability considerations alone. A payback period threshold of below three years (Cooremans 2011) is often required by firms, while a US study found a mean payback period of 1.4 years for investments in EEMs (Anderson, Newell 2004). A shorter payback period typically results in higher adoption rates (Anderson, Newell 2004).

Another important factor influencing the adoption of an EEM is the required **initial expenditure** of an investment (del Río González 2005; Harris et al. 2000; Kemp, Volpi 2008). High initial expenditures are frequently mentioned as a barrier to the adoption of EEMs (Anderson, Newell 2004) because of restricted access to internal and external capital. Note that we do not consider the total expenditure of an EEM here, but rather the marginal expenditure expressed as the difference between the expenditure needed for an energy-efficient technology and that required for the conventional technology. This is important as many EEMs do replace equipment and if this would have been replaced anyway, only the marginal costs are relevant. We suggest expressing the marginal initial expenditure of an EEM as the share of a firms' investment budget to correct for different sizes of firms with varying budgets. The initial expenditure is closely related to the IRR and payback time but adds the additional insight concerning access to capital as a barrier to the adoption and is typically negatively correlated with the adoption rate (Muthulingam et al. 2011).

Non-energy benefits describe the benefits of EEMs beyond energy savings. They are commonly not captured in the economics of EEMs, although they might have considerable influence and in certain cases even be the real reason for adopting an EEM (Pye, McKane 2000; Rosegger 1979; Worrell et al. 2003). Non-energy benefits often improve productivity but can also be much broader. Examples are waste reduction, lower emissions, decreased maintenance and operating costs, increased production and product quality and an improved working environment (Worrell et al. 2003). Martin et al. (2000) further distinguish non-energy benefits into environmental and other benefits. Depending on the type of EEM, monetary non-energy benefits might have a stronger impact on technology adoption, yet non-monetary non-energy benefits also have to be accounted for, especially if they are related to the strategy of a company (Cooremans 2011; Small 2006).Note that EEMs can also yield "negative" non-energy benefits (e.g. the early fluorescent lamps with a lower light quality compared to incandescent light bulbs). Typically, higher non-energy benefits are expected to increase the adoption rate.

3.3   Technical context

A major factor influencing the adoption of an EEM from a technical perspective is its **distance to the core process**. We distinguish EEMs closely integrated into the core production process of a firm (e.g. heat treatment in metal works) from those applied to ancillary processes (e.g. factory lighting or water pumps). Core processes are closely related to the firm's competitiveness and core competences. Their proper operation and process know-how are critical assets for the company and any intervention here often implies a cessation of continuously running processes (Thollander, Ottosson 2008). Dieperink et al. (2003) find that firms often were reluctant to integrate heat

pumps into the production process, whereas they often installed combined heat and power plants, because they have no effect on the core production process. Thus, firms are more reluctant to allow external experts access to the production process and may perceive a higher risk associated with possible changes. Consequently, EEMs that affect the core process are usually considered more critical and are less likely to be adopted than those applied to ancillary processes.

Regarding the **type of modification**, we first distinguish technical EEMs from organizational measures (Rennings 2000). Organizational measures describe changes to firms' routines like new responsibilities, e.g. dedicating personnel to energy, or instructions to switch-off equipment not being used. We further distinguish between add-on measures and replacement/substitution of entire processes/components (Andersen 2008; Demirel, Kesidou 2011). We consider "technological add-on EEM" as not having any functional impact on the processes involved (e.g. insulating steam pipes). We further distinguish simple technology replacement from broader technology substitution. Technology replacement covers the replacement of one production technology with a similar, but more energy-efficient alternative (the replacement of an old throttle-controlled hydraulic press with an improved hydraulic press using a variable speed pump). Technology substitution comprises the adoption of different processes/components (e.g. replacement of a hydraulic drive with an electric motor). It implies a more disruptive change for the company and requires new know-how and routines to be established, i.e. a higher degree of change and complexity. A higher degree of change typically necessitates changes in the structure, roles, power and status of employees and is more difficult to implement (Damanpour 1988) which consequently results in a lower adoption rate. The replacement or substitution of existing technologies either entails high opportunity costs (in the form of the sunk costs

of the existing equipment) or is bound to the replacement rate of the old capital stock (Gold et al. 1970; Rosegger 1979). In the latter case, adoption rates are typically lower, particularly given the long lifetimes of industrial equipment and plants. In contrast, the adoption of add-on technologies does not depend on replacement considerations and adoption rates are not restricted by the existing capital stock.

Depending on the type of modification, there are two reasons why the **lifetime** of the EEM can significantly impact the adoption rate. First, if the EEM is classified as a replacement or substitution EEM, which implies that it mainly enters the capital stock by replacing decommissioned equipment, EEM adoption is constrained by the turnover of the prevailing capital stock. The rate of stock turnover depends on many factors including the lifetime of the EEM or its base technology (Worrell, Biermans 2005). Second, firms might be more reluctant to invest in EEMs with long lifetimes since this is an irreversible decision which binds their capital. If the technology is likely to improve rapidly, they have an additional incentive to delay investment and wait for the superior technology (Geroski 2000).

A characteristic directly affecting the adoption process is the **scope of the impact** of the EEM. We distinguish EEMs with a local impact on the component level from those that affect the wider surrounding system. A similar distinction is proposed in the literature distinguishing architectural from component innovation (Hellström 2007). The broader the impact of an EEM, the more complex and risky its implementation becomes as more parts of the firm/plant are affected and staff members with different responsibilities have to agree to make the relevant decisions. Consequently, adoption rates are expected to be lower for EEMs with system-wide effects beyond the component level, i.e. that are more complex (Tornatzky, Klein 1982).

3.4   Information context

The adoption of EEMs is not only influenced by costs that can be easily quantified like the initial expenditure, but also by more intangible factors like the **transaction costs** for procurement and implementation. These are often difficult to quantify, but if they are perceived as high, firms are more reluctant to invest. Transaction costs are typically high when new internal routines need to be established and know-how accumulated. Although we propose to measure transaction costs as a share of the initial expenditure, we are aware that they do not increase proportionately to it, because many tasks are independent of the size of the investment, as for example shown by Ostertag (2003) for the case of electric motors. As transaction costs are difficult to measure, they are seldom accounted for in surveys among firms. However, *lack of time/staff* is a barrier related to transaction costs that is included in many surveys and generally shows high levels of importance (Anderson, Newell 2004; Thollander et al. 2007; Thollander, Ottosson 2008).

With regard to the **knowledge required for planning and implementation,** we distinguish EEMs for which implementation requires maintenance personnel, engineering personnel and experts. The stricter the knowledge requirements, the harder and more costly it is to get the staff needed for implementation and the less likely it is that the company possesses the relevant knowledge. Knowledge requirement is also related to broader characteristics like complexity and compatibility (Tornatzky, Klein 1982). For complex EEMs, firms might have to rely on external experts, e.g. from technology providers, which implies strong dependence and additional transaction costs. Further, a higher level of knowledge is also expected to be required for the implementation of more radical innovations (Dewar, Dutton 1986). Empirical studies show that the lack of qualified employees might also prove a significant barrier to the

adoption of EEMs (Sardianou 2008). Thus, the adoption of an EEM is more likely if less knowledge is required for its implementation.

The **diffusion progress** of an EEM gives information about the extent to which it is already established on the market and also reflects its technological maturity. EEMs just entering the market are expected to have more (perceived) risks than mature technologies. We focus on the market diffusion phase covering EEMs which are close to market entry (incubation phase). Furthermore, new technologies on the market might still show considerable technological learning potential (both in terms of technological quality and technology costs). The expected imminent improvements of a technology can delay adoption decisions as firms prefer to wait for superior versions of the technology (Geroski 2000). In the typical model assuming an s-shaped diffusion curve, the diffusion rate is highest in the linear phase once half the potential adopters have adopted the innovation.

The **sectoral applicability** of EEMs is often considered in the energy-efficiency literature (Martin et al. 2000). Two types of EEMs are distinguished: cross-cutting and process-specific EEMs. The former are applied industry-wide, while the latter are only applied in certain branches or processes. The distinction between cross-cutting and process-specific EEMs is not always unambiguous and these should be seen as two poles on a continuous scale. The distinction is still useful, as it helps to better understand the market since a wider potential deployment of EEMs has implications for the adoption decision: More information is available about the EEM and its adoption, energy experts are more informed about it and its visibility is higher. These factors contribute to the adoption of cross-cutting measures. In this context, it should also be noted that the spread of information is probably faster within sectors and networks and slower across their borders.

4 Application of the classification scheme

In this section, we illustrate the proposed classification scheme by applying it to a set of EEMs. We contrast the theoretical conclusions with empirical observations. Finally, we propose policy conclusions. These examples aim to demonstrate the use of the classification scheme, but do not replace in-depth studies to derive policy recommendations for the EEMs considered.

4.1 Description and specification of the EEM

The six example EEMs are chosen to represent a broad variety of different types of EEMs. Three EEMs are from the field of cross-cutting technologies, while the remaining three are process-specific. For each group, we consider one technology already commercially available and one still at an R&D stage as well as an organizational measure.

The large heterogeneity and context-dependency of EEMs only allow valid conclusions if the EEMs are correctly specified. We thus provide a brief background description and specification for each EEM (Table 1).

Table 1: Description and specification of EEM examples

Name	Description	Specification
Energy-efficient electric motor (IE2 motor)	Replacement of an electric motor (IE 1) by a high efficiency motor complying with the international IE2 standard (McKane, Hasanbeigi 2011).	We assume a typical industrial application with a rated power of around 20 kW and 3000 annual running hours. The new motor replaces a broken motor in an auxiliary water pump, which implies that only the marginal costs are relevant.
Shoe press	The shoe press is used in the drying section of the paper machine resulting in improved dewatering (Luiten, Blok 2003).	The shoe press is installed in an existing paper mill undergoing a major retrofit.
Inert anode	Inert anodes are developed for aluminum electrolysis. They replace conventional graphite anodes and last 20 times longer (about 1.5 years) (U.S. Department of Energy 2007). They enable the distance between anode and cathode to be reduced, resulting in lower resistance losses.	We assume that the installation of inert anodes comprises the replacement of existing cells and pot lines. Although retrofitting existing cells is possible, it would result in lower energy efficiency improvement as compared to replacement (Keniry 2001).
Low temperature thermal cooling	Recycling industrial waste heat for cooling is an option to reduce energy consumption in industry. Modern closed absorption and adsorption chillers promise an acceptable performance with driving temperatures below 100°C and thus reduce the electricity demand needed for cooling (Schall, Hirzel 2012).	We assume that a thermal cooling system with a rated cooling power of 40 kW is driven by waste heat at temperature levels of 70-85°C. It is an additional system compared to a compression chiller with a similar cooling capacity.
Closed furnace	Crucible melting furnaces are used in the non-ferrous	We assume that a manually operated furnace lid is

lid	metal industry. Open furnaces lead to considerable energy losses to the environment during operation. Closing the furnace with a lid can substantially reduce energy losses (LfU 2005).	already installed. The EEM aims to raise awareness about losses from the open furnace lid and encourage operators to close it regularly.
Compressed air leakage reduction	Leakages lead to substantial energy losses in compressed air systems (European Commission 2009; Radgen, Blaustein 2001). Regular maintenance checks on the compressed air network help to reduce these losses.	We assume an industrial compressed air network with an installed compressor power of about 200 kW (3500 annual operating hours) in which 20% of the generated compressed air is lost as leakages.

Energy-efficient electric motor (IE2)

Characteristics		Attributes			
Relative advantage	Internal rate of return	Low (< 10%)	Medium (10 - 30%)	High (> 30%)	
	Payback period	Very long (>8 years)	Long (5-8 years)	Medium (2-4 years)	Short (<2 years)
	Initial expenditure	High (> 10% of invest. budget)	Medium (0.5-10% of invest. budget)	Low (<0.5% of invest. budget)	
	Non-energy benefits	Negative	None	Small	Large
Technical context	Distance to core process	Close (Core process)		Distant (Ancilliary process)	
	Type of modification	Technology substitution	Technology replacement	Technology add-on	Organizational measure
	Scope of impact	System (system-wide effects)		Component (local effects)	
	Lifetime	Long (>20 years)	Medium (5-20 years)	Short (<5 years)	Not relevant
Information context	Transaction costs	High (> 50% of in. expenditure)	Medium (10–50% of in. expenditure)	Low (< 10% of in. expenditure)	
	Knowledge for planning and implementation	Technology expert	Engineering personnel	Maintenance personnel	
	Diffusion progress	Incubation (0%)	Take-off (<15%)	Saturation (>85%)	Linear (15-85%)
	Sectoral applicability	Process related		Cross-cutting	

Lower adoption rate — Higher adoption rate

Shoe press

Characteristics		Attributes			
Relative advantage	Internal rate of return	Low (< 10%)	Medium (10 - 30%)	High (> 30%)	
	Payback period	Very long (>8 years)	Long (5-8 years)	Medium (2-4 years)	Short (<2 years)
	Initial expenditure	High (> 10% of invest. budget)	Medium (0.5-10% of invest. budget)	Low (<0.5% of invest. budget)	
	Non-energy benefits	Negative	None	Small	Large
Technical context	Distance to core process	Close (Core process)		Distant (Ancilliary process)	
	Type of modification	Technology substitution	Technology replacement	Technology add-on	Organizational measure
	Scope of impact	System (system-wide effects)		Component (local effects)	
	Lifetime	Long (>20 years)	Medium (5-20 years)	Short (<5 years)	Not relevant
Information context	Transaction costs	High (> 50% of in. expenditure)	Medium (10–50% of in. expenditure)	Low (< 10% of in. expenditure)	
	Knowledge for planning and implementation	Technology expert	Engineering personnel	Maintenance personnel	
	Diffusion progress	Incubation (0%)	Take-off (<15%)	Saturation (>85%)	Linear (15-85%)
	Sectoral applicability	Process related		Cross-cutting	

Lower adoption rate — Higher adoption rate

Inert anode

Characteristics		Attributes			
Relative advantage	Internal rate of return	Low (< 10%)	Medium (10 - 30%)	High (> 30%)	
	Payback period	Very long (>8 years)	Long (5-8 years)	Medium (2-4 years)	Short (<2 years)
	Initial expenditure	High (> 10% of invest. budget)	Medium (0.5-10% of invest. budget)	Low (<0.5% of invest. budget)	
	Non-energy benefits	Negative	None	Small	Large
Technical context	Distance to core process	Close (Core process)		Distant (Ancilliary process)	
	Type of modification	Technology substitution	Technology replacement	Technology add-on	Organizational measure
	Scope of impact	System (system-wide effects)		Component (local effects)	
	Lifetime	Long (>20 years)	Medium (5-20 years)	Short (<5 years)	Not relevant
Information context	Transaction costs	High (> 50% of in. expenditure)	Medium (10–50% of in. expenditure)	Low (< 10% of in. expenditure)	
	Knowledge for planning and implementation	Technology expert	Engineering personnel	Maintenance personnel	
	Diffusion progress	Incubation (0%)	Take-off (<15%)	Saturation (>85%)	Linear (15-85%)
	Sectoral applicability	Process related		Cross-cutting	

Lower adoption rate — Higher adoption rate

Low temperature thermal cooling

Characteristics		Attributes			
Relative advantage	Internal rate of return	Low (< 10%)	Medium (10 - 30%)	High (> 30%)	
	Payback period	Very long (>8 years)	Long (5-8 years)	Medium (2-4 years)	Short (<2 years)
	Initial expenditure	High (> 10% of invest. budget)	Medium (0.5-10% of invest. budget)	Low (<0.5% of invest. budget)	
	Non-energy benefits	Negative	None	Small	Large
Technical context	Distance to core process	Close (Core process)		Distant (Ancilliary process)	
	Type of modification	Technology substitution	Technology replacement	Technology add-on	Organizational measure
	Scope of impact	System (system-wide effects)		Component (local effects)	
	Lifetime	Long (>20 years)	Medium (5-20 years)	Short (<5 years)	Not relevant
Information context	Transaction costs	High (> 50% of in. expenditure)	Medium (10–50% of in. expenditure)	Low (< 10% of in. expenditure)	
	Knowledge for planning and implementation	Technology expert	Engineering personnel	Maintenance personnel	
	Diffusion progress	Incubation (0%)	Take-off (<15%)	Saturation (>85%)	Linear (15-85%)
	Sectoral applicability	Process related		Cross-cutting	

Lower adoption rate — Higher adoption rate

Close furnace lid

Characteristics		Attributes			
Relative advantage	Internal rate of return	Low (< 10%)	Medium (10 - 30%)	High (> 30%)	
	Payback period	Very long (>8 years)	Long (5-8 years)	Medium (2-4 years)	Short (<2 years)
	Initial expenditure	High (> 10% of invest. budget)	Medium (0.5-10% of invest. budget)	Low (<0.5% of invest. budget)	
	Non-energy benefits	Negative	None	Small	Large
Technical context	Distance to core process	Close (Core process)		Distant (Ancilliary process)	
	Type of modification	Technology substitution	Technology replacement	Technology add-on	Organizational measure
	Scope of impact	System (system-wide effects)		Component (local effects)	
	Lifetime	Long (>20 years)	Medium (5-20 years)	Short (<5 years)	Not relevant
Information context	Transaction costs	High (> 50% of in. expenditure)	Medium (10–50% of in. expenditure)	Low (< 10% of in. expenditure)	
	Knowledge for planning and implementation	Technology expert	Engineering personnel	Maintenance personnel	
	Diffusion progress	Incubation (0%)	Take-off (<15%)	Saturation (>85%)	Linear (15-85%)
	Sectoral applicability	Process related		Cross-cutting	

Lower adoption rate — Higher adoption rate

Leakage reduction in compressed-air system

Characteristics		Attributes			
Relative advantage	Internal rate of return	Low (< 10%)	Medium (10 - 30%)	High (> 30%)	
	Payback period	Very long (>8 years)	Long (5-8 years)	Medium (2-4 years)	Short (<2 years)
	Initial expenditure	High (> 10% of invest. budget)	Medium (0.5-10% of invest. budget)	Low (<0.5% of invest. budget)	
	Non-energy benefits	Negative	None	Small	Large
Technical context	Distance to core process	Close (Core process)		Distant (Ancilliary process)	
	Type of modification	Technology substitution	Technology replacement	Technology add-on	Organizational measure
	Scope of impact	System (system-wide effects)		Component (local effects)	
	Lifetime	Long (>20 years)	Medium (5-20 years)	Short (<5 years)	Not relevant
Information context	Transaction costs	High (> 50% of in. expenditure)	Medium (10–50% of in. expenditure)	Low (< 10% of in. expenditure)	
	Knowledge for planning and implementation	Technology expert	Engineering personnel	Maintenance personnel	
	Diffusion progress	Incubation (0%)	Take-off (<15%)	Saturation (>85%)	Linear (15-85%)
	Sectoral applicability	Process related		Cross-cutting	

Lower adoption rate — Higher adoption rate

Figure 2: Classification scheme applied to EEM examples

4.2 EEM analysis using the classification scheme

Based on the specification provided, the six EEMs are classified using relevant technology studies, literature and the authors' experience (Figure 2).

Prior studies identified the use of **energy-efficient electric motors** (IE2) as being very beneficial compared to standard motors (de Almeida et al. 2008). Internal rates of return are well above 30% and payback periods are short. As an IE2-motor is a standardized mass product, it is a comparatively cheap EEM, requiring only minimal expenditure. We assume that the motor is used in an auxiliary water pump and that the implementation does not affect the core production process. Furthermore, the EEM replaces existing equipment, is well-known to the company and no major impact is expected on the rest of the system. With regard to the information context, electric motors are used in all industrial branches and are available from many manufacturers; the relative transaction costs increase with decreasing installed motor power, but should be moderate overall. It should be noted, however, that IE2-motors are still in the take-off phase in Europe (de Almeida et al. 2008).

The overall configuration indicates that the discussed IE2-motor EEM performs well with few inherent technical risks. Assuming that the specified EEM is representative of its kind, one might expect a high adoption rate of IE2-motors in practice. Yet the dynamics of IE2 motor sales in Europe with a market share of around 15% (CEMEP) suggest that the market for IE2-motors is only evolving slowly. Thus the classification suggests there may be important barriers, which are not related to the EEM's characteristics; and, indeed, it could be shown that lack of information and split incentives are major barriers (de Almeida 1998).

The EEM characteristics suggest that policymakers do not need to offer grants here, as there is already a high profitability. Instead, they should aim to overcome barriers related to market structure or the potential adopters, e.g. by establishing minimum standards or labeling schemes.

The **shoe press** has a longer payback period and a higher initial expenditure. However, it also has very high non-energy benefits in terms of increased production capacity and space savings (Luiten, Blok 2003). The EEM has complex technical characteristics because the whole system is widely affected, the core production process is affected and implementation requires a technology expert. The shoe press is a process-specific EEM and its implementation requires specific specialist knowledge.

These attributes suggest a medium to low adoption rate for the shoe press - if non-energy benefits are not accounted for. The main driver for its adoption seems to be its high non-energy benefits in terms of increased production capacity and space savings but also energy savings (Luiten, Blok 2003). The current diffusion level of shoe presses is somewhere above 50% of the potential adopters in many countries, but has substantial remaining potentials (Fleiter et al. 2012).

Non-energy benefits are driving the diffusion in this case, and it is unclear whether energy-efficiency policies can speed things up. However, one lever could be to improve the cost-effectiveness by offering grants or addressing the high initial expenditure by providing soft loans.

While research on **inert anodes** has been ongoing since the 1970s, the technology has still not entered the market. As the technology is still being developed, no reliable

cost data can be provided. With regard to the other characteristics, the inert anode shows a similar pattern to the shoe press.

As inert anodes are still not commercially available, there is no possibility to contrast the conclusions with empirical data. Yet the classification suggests that, once on the market, adoption rates could be high, driven by the high non-energy benefits (Schwarz 2008).

Based on this pattern, policies should focus on R&D and pilot or demonstration plants to support market introduction.

Systems to recycle **low temperature waste heat for cooling** are currently expensive compared to conventional systems using compression chillers, especially with low cooling power. This means low internal rates of return and long payback periods. As a typical add-on measure, this EEM only has a low impact on the rest of the production system. While the technical concepts for thermal cooling systems are well-known, the development and deployment of small and medium scale systems are still at an early stage with only a few technology providers. Furthermore, considerable transaction costs are incurred for gathering the relevant information about this young technology.

While the technical characteristics favor adoption, the others indicate a low adoption rate. This is also reflected in the current rate of adoption: A recent survey of the German market (Schall, Hirzel 2012) indicated that there are just over 1000 units of installed closed absorption and adsorption chillers below 100 kW and that their market share is less than 1%.

Consequently, suitable policies could support research efforts to decrease costs or providing grants for first-mover companies.

Reducing leakages in compressed air systems and **closing lids of furnaces** are both organizational measures requiring little or no initial expenditure, and therefore implying high profitability. The classification further suggests that they are not likely to affect the core production process.

Based on these characteristics, one might expect a high adoption of these measures. Yet Radgen (2004) found that, on average, 30% of the input energy in compressed air systems is lost to leakages.

The major reasons for the non-implementation of cost-effective EEMs in compressed air systems are attributed to a lack of cost accounting, lack of awareness and a complex management structure (Radgen 2002), but not to the EEM itself. Abundant information material on leakage reduction are available from various sources (Radgen 2007; U.S.Department of Energy 2003). Suitable policy measures could focus on encouraging the implementation of these measures in companies, e.g. by explicitly requiring regular documentation of corrective actions to reduce losses.

The classification scheme also indicates only a few EEM-specific barriers concerning lid closing in furnaces. A suitable policy approach could aim to first simply raise awareness about this EEM.

To summarize, adoption barriers and policy recommendations differ for different EEMs and many can be derived from the classification scheme. The heterogeneity involved stresses the need to consider the characteristics of EEMs when analyzing barriers and adoption behavior. The application also shows that the classification scheme can serve as a starting point to identify policies accelerating diffusion. However, the latter examples also illustrate that it is necessary to include information about adopters and

contextual factors like the market structure if suitable policy measures are to be developed.

Besides identifying suitable policies, the classification also helps to indicate which combinations of EEMs and policies are probably not effective. If EEMs have large non-energy benefits for the firm, policies may not be necessary as the non-energy benefits are probably a sufficiently important driver (e.g. shoe press or inert anodes). For technologies with a very high internal rate of return, the barriers are probably not related to cost-effectiveness and, in this case, subsidies to further increase cost-effectiveness are probably ineffective (e.g. IE2-motors). If EEMs are directly embedded in the production process, energy audit programs are typically less effective, because external auditors typically focus on ancillary processes. In such cases, energy management systems might achieve better results.

5   Discussion

5.1   Implications for policy design and assessment

The developed classification scheme has several implications for the design and assessment of policies and the analysis of firms' adoption of EEMs.

It helps to better understand the adoption process and contributes to understanding why certain EEMs diffuse faster than others.

The classification used to evaluate EEMs provides support for policy design as demonstrated in section 4.2. Suggestions for policy recommendations could be derived from the classification scheme for three of the six selected EEMs. For the remaining three EEMs, the scheme did not indicate major barriers which are found in other fields instead, i.e. among potential adopters. The screening of EEMs is only the starting point for identifying suitable policies and is in no way intended to replace in-depth analyses. However, on the other side, an in-depth analysis requires the EEM characteristics to be taken into account.

If included in *ex-post* assessments of energy-efficiency policies, the scheme can contribute to explain why the adoption rate of certain types of EEMs is successfully increased, while other EEMs are less affected.

Furthermore, the classification can improve the model-based *ex-ante* assessment of. As such assessments often consider large numbers of different EEMs, a classification of EEMs is required if the adoption decision is to be modeled explicitly. Including more realistic adoption behavior in the models used is expected to significantly improve the value of the modeling results, but requires EEM characteristics to be considered

(Fleiter et al. 2011; Worrell et al. 2004). The classification scheme further helps to estimate the types of EEMs addressed by a chosen policy, which in turn may improve the robustness of *ex-ante* estimates of the energy-saving potential.

5.2   Reflection on the method used

The classification methodology used proved to be applicable and provides a structured way to compare and classify EEMs. However, certain restrictions may still apply.

Heterogeneity is not only observed among EEMs but also for a single EEM (e.g. an energy-efficient electric motor might show a significant range with regard to size, initial expenditure, profitability, etc.). Therefore it was necessary to further specify the EEM with regard to the annual running hours, the application and also whether it represents the premature replacement of equipment. Data availability is low for certain EEM regarding the financial characteristics. The classification of the characteristics is always a trade-off between data availability and accuracy. However, since we propose only a few broad ranges of attributes per characteristic, the classification still seems suitable for most EEMs. To apply the methodology, the scheme could be extended by indicating the reliability of the data. This would improve transparency and allow for more robust conclusions.

We developed the classification scheme based on existing literature. Additional validation could be provided by gathering empirical data from a survey of experts. Further, when applying the scheme to example EEMs in section 4, we infer the strength of each characteristic rather than measuring characteristics as perceived by

potential adopters.[4] Thus, in a second step, measuring characteristics by systematically assessing the perceived characteristics could further improve the accuracy of the classification scheme.

Though we aim to use context-independent characteristics, certain characteristics are still (weakly) linked to firm characteristics, like the *share of expenditure in the investment budget,* or contextual factors such as price-based policies that affect energy prices and thus the profitability of EEMs. This has the effect of slightly weakening the classification, but also shows that EEM characteristics cannot be completely captured in isolation from their context. Our proposal is thus a compromise between characterizing the most relevant characteristics while striving to remain as independent as possible of a specific firm's characteristics.

Although this paper only addresses some of the factors affecting the adoption of EEMs, we think that focusing only on EEM-specific characteristics and excluding effects stemming from the firm and the environmental context is useful as it improves the comparability among EEMs. When designing policies, however, other factors also need to be taken into account. Similar work could be conducted for other issues like the type of firm potentially adopting an EEM. An in-depth analysis of the concepts and analyses developed in the literature on AMT could provide a good starting point for this.

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[4] Inferring the characteristics of innovations is also identified by Tornatzky and Klein (Tornatzky, Klein 1982) as the dominant approach in studies of innovation characteristics.

6   Conclusions

We develop a classification scheme to better understand the adoption of EEMs by industrial firms and to serve as a basis for selecting and designing suitable energy-efficiency policies.

The proposed scheme features twelve different characteristics of EEMs from the fields of relative advantage, technical context and information context. The characteristics and their respective attributes show the large diversity existing among EEMs. This underlines the need to explicitly characterize EEMs when studying barriers to and drivers for their diffusion. This enhances the quality of and comparability among different studies of EEMs.

The six discussed examples demonstrate that the proposed classification scheme can indeed help to gain a better understanding of the adoption process of EEMs. If used to compare EEMs, it helps to systematically explain why certain EEMs diffuse faster than others. It can provide a basis to identify suitable policies to increase their adoption rate. It might also explain why certain EEMs are effectively addressed by a policy, while the same policy fails to address other EEMs. However, it does not replace an in-depth evaluation of policies.

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