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THE ADOPTION OF ENERGY-EFFICIENT TECHNOLOGIES BY FIRMS

FRAUNHOFER VERLAG

Fraunhofer Institute for
Systems and Innovation Research ISI

Tobias Fleiter

The adoption of energy-efficient technologies by firms

An integrated analysis of the technology, behavior and policy dimensions

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THE ADOPTION OF ENERGY-EFFICIENT TECHNOLOGIES BY FIRMS

An integrated analysis of the technology, behavior and policy dimensions

DE ADOPTIE VAN ENERGIE-EFFICIËNTE TECHNOLOGIE DOOR BEDRIJVEN

Een geïntegreerde Analyse van de Technologie, Gedrag en Beleidsdimensies

(met een samenvatting in het Nederlands)

DIE ADOPTION VON ENERGIEEFFIZIENTEN TECHNOLOGIEN DURCH UNTERNEHMEN

Eine integrierte Betrachtung der Aspekte Technologie, Investitionsverhalten und Politikmaßnahmen

(mit einer Zusammenfassung in deutscher Sprache)

Proefschrift

ter verkrijging van de graad van doctor aan de Universiteit Utrecht op gezag van de rector magnificus, prof.dr. G.J. van der Zwaan, ingevolge het besluit van het college voor promoties in het openbaar te verdedigen op woensdag 26 september 2012 des middags te 12.45 uur

door

Tobias Fleiter

geboren op 12 juli 1981 te Gütersloh, Duitsland

Promotor: Prof. dr. E. Worrell

Co-promotor: Dr. W. Eichhammer

Contents

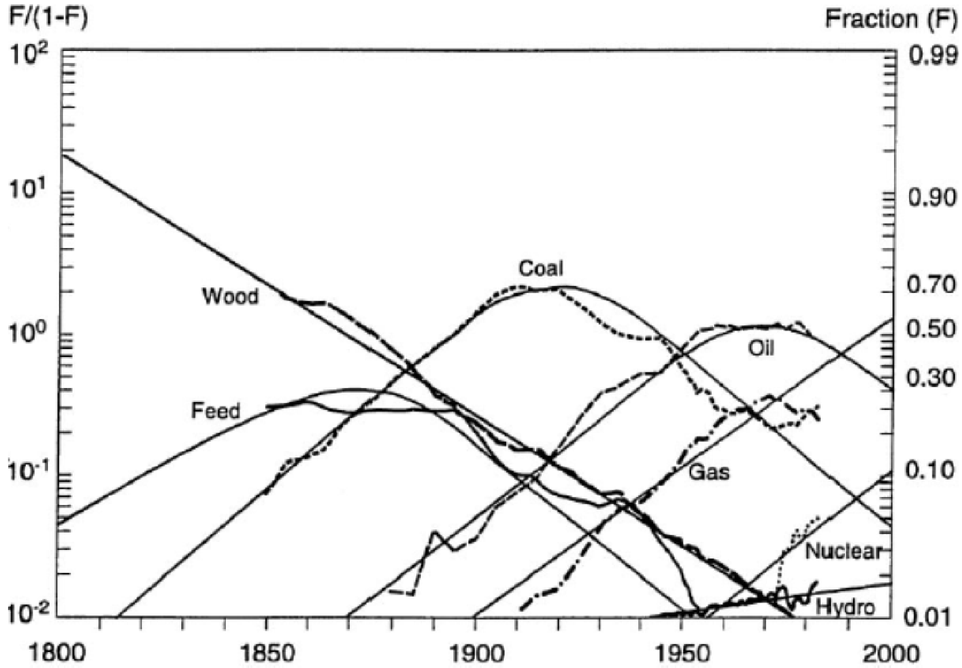
1 Introduction

1.1 Energy demand, energy efficiency and the environment

1.1.1 The dynamics and the consequences of energy demand

Energy use is closely related to the activity of a society and plays a central role in its economic development. Increasing economic output typically results in increasing energy demand, although not necessarily with the same growth rate. The technologies used for generating economic output determine not only the level of that output, but also the energy demand. A main driver of energy demand has been the emergence and diffusion of energy-driven technologies like steam engines, internal combustion engines, steelworks, electric lighting etc. Global energy demand has grown rapidly particularly since the industrial revolution when energy conversion technologies entered into a dynamic co-evolutionary process with other technologies that still continues (Grübler 1998). The resulting technological change and new forms of energy conversion generated substantial increases in productivity, which in turn resulted in a growing total economic output (Grübler 1998). Thus, while the availability of cheap energy has certainly driven economic growth in the past, economic growth has also resulted in a drastically increasing energy demand, particularly in the industrialized countries during the past two centuries (Stern 2011).

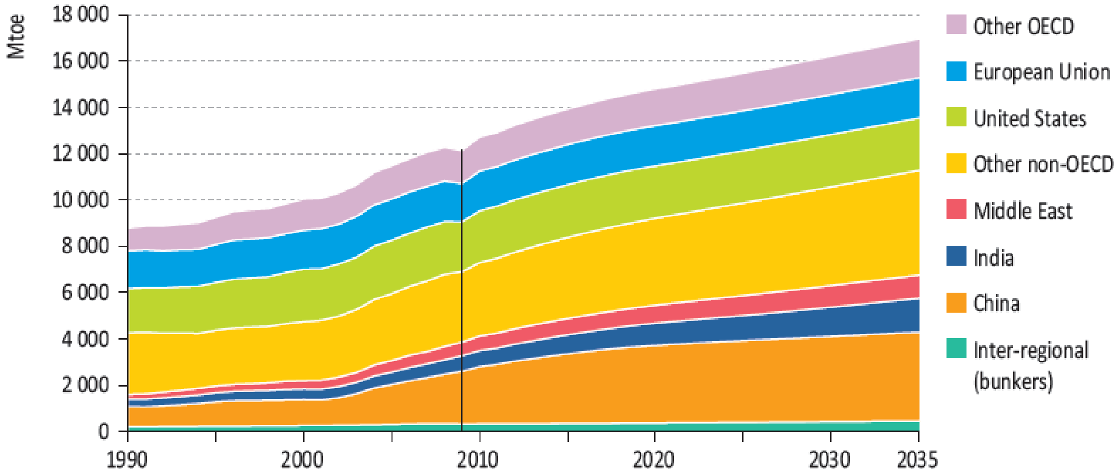
As a result of technological change, global energy use has also changed with regard to the energy sources used (Grübler et al. 1999). Figure 1 illustrates this development for the USA. While renewable energy sources like hydro, wind, solar energy or biomass were mostly used in pre-industrialized times, this changed with the rise of the steam engine that allowed the conversion of coal into mechanical energy resulting in continuously increasing coal use throughout the 19^{th} century. In the beginning of the 20^{th} century oil demand gained dynamics driven by the diffusion of the internal combustion engine and the substitution of coal. A few decades later the use of natural gas expanded rapidly, mainly for electricity and heat generation. With some exceptions, industrialized economies as well as developing and emerging countries are extensively dependent on fossil fuels at the beginning 21^{st} century.



Source: (Grübler et al. 1999)

Figure 1: Historical perspective on US energy demand by type of energy carrier as share of total primary energy demand

During these dynamic developments, technological change induced substantial energy-efficiency improvements. For example energy demand of the OECD-11 countries would have been 58% higher in 2005 if the improvements in energy efficiency since 1973 had not taken place (IEA 2008b). Despite these improvements, total energy demand has grown continuously over this period and energy efficiency improvements have not been able to compensate for the increase in energy use due to economic growth (see Figure 2). Global industrial energy demand has experienced a dynamic development in the past decades and grew by 71 % between 1971 and 2004 (IEA 2007b). While demand in industrialized countries has remained constant or risen slowly, the fast growing developing countries – most of all China - have shown enormous growth rates and have driven the global energy demand. This trend is expected to continue in the coming decades as shown by a recent projection of the International Energy Agency (IEA) in Figure 2 (IEA 2011). 90% of the growth in energy demand is expected to take place in non-OECD countries such as China, India and Brazil. The same scenario indicates that the greatest share of global energy demand will be based on fossil fuels also in 2035.



Source: (IEA 2011)

Figure 2: Global primary energy demand from 1990 to 2035 by world region in the New Policies Scenario [1]

Extensive extraction and combustion of fossil fuels however, does not abide by with the requirements of sustainability.[2] On the one hand, the exploitation rate of fossil fuels is far higher than their regeneration rate, sooner or later resulting in depletion. On the other hand, such exploitation has severe consequences for the global ecosystem such as acid rain, local air and water pollution, radioactive waste and global climatic change. In its fourth assessment report, the IPCC underlines the direct link between human activity and global climatic change: "It is very likely that anthropogenic greenhouse gas increases caused most of the observed increase in global average temperatures since the mid-20th century" (IPCC 2007b). IPCC projections of the likely effect of greenhouse gas (GHG) emissions on the global temperature range from 1.1 to 6.4°C[3] by the end of the 21st century (IPCC 2007b). The temperature increase is expected to be accompanied by numerous global threats that will probably have severe consequences for mankind. Examples are an increasing number of extreme weather events, sea level rise, changes in regional ecosystems and a faster extinction of species. To limit the anthropogenic increase in the global average temperature to about 2°C, cutting global GHG emissions by 50% by 2050 compared to the level of 1990 is required (Rogelj et al. 2011). In 2004 fossil fuel consumption was responsible for 56% of global anthropogenic GHG emissions (IPCC 2007a). Industry currently

1 The New Policies Scenario assumes currently implemented policies plus "[..] policy commitments and cautious implementation of published targets." (IEA 2011).

2 The most cited definition of sustainable development is proposed by the "Brundtland Commission": "Sustainable development is a development that meets the needs of the present without compromising the ability of the future generations to meet their own needs"(UN WCED 1987).

3 The range is given for includes the outcome of various scenario calculations and is given for the period 2090-2099 relative to the period 1980-1999. It includes a probability of 66%.

accounts for about 40% of global CO_2 emissions, which are expected to grow further as production output in most sectors is expected to double or triple by 2050 driven by the large emerging economies such as China and India (IEA 2009). Thus, the transformation to a global low-carbon industrial production system is a precondition to mitigating the worst impacts of climate change. Accelerating energy-efficiency improvement can significantly contribute to this transition, as outlined in the following section.

1.1.2 The rationale and the potentials for industrial energy efficiency

Traditionally, an increasing demand for primary energy was seen as a driver of economic growth and policies aimed towards reducing energy demand regarded as dangerous for economic development as they could hamper economic growth. Since the oil crises have exposed the vulnerability of our energy system, and awareness of the global environmental impact of fossil energy demand has risen, the need for new solutions have also increased. It has increasingly been argued that energy demand and supply are closely related and problems arising on the supply side can be addressed by adequate measures on the demand side. In this line of thinking, studies have emerged that compare the investment in new power plants to investments in energy-efficient technology, challenging the traditional view in which a growing primary energy demand is a prerequisite of economic growth (von Weizsäcker et al. 1997). This argument builds on the distinction between primary energy and useful energy (e.g. light, mechanical work, compressed air). For instance Ayres and van den Bergh (2005) argue that it is useful energy that drives economic activity and not primary energy. This distinction has an important implication: in the current energy system only a fraction of the primary energy input is converted to useful energy leaving a huge potential for energy-efficient improvements hidden in a long sequence of conversion processes. In other words, improved energy efficiency increases the useful energy output while reducing the primary energy input (or one of both).

Furthermore, numerous studies underline that energy savings are often less costly than supply side options (Gillingham et al. 2006) and huge potentials lie in the further diffusion of cost-effective technologies currently available. Studies even show that several energy-efficiency measures[4] (EEMs) are not only less costly than supply side options, but even available at net negative cost (Lovins, Lovins 1991; McKane, Hasanbeigi 2011; Meier et al. 1982; Worrell et al. 2000).[5]

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4 Throughout this thesis, we will focus on energy efficiency measures (EEMs), including both energy-efficient technologies but also organizational measures.

5 This definition of net negative costs already considers energy prices. It certainly depends on the perspective taken. Taking a society perspective by internalizing external costs into costs of energy supply would further increase the number of cost-effective EEMs.

These arguments have also reached the institutional level and a number of broad assessments of energy efficiency potentials and their costs are available for most sectors and regions (Eichhammer et al. 2009; IEA 2007b; IPCC 2007a). For instance, the IEA (2011) estimates that, in order to reach a 2°C climate stabilization path, the annual energy related CO_2 emissions are required to be reduced to 22 Gt by 2035, whereas with current policies, emissions would reach 44 Gt in 2035. This implies a reduction of 50% compared to a business as usual path. It is further assumed that around 50% of this abatement potential will need to be realized through improved energy efficiency, being the main abatement option, and being particularly cost-effective in the short term. The industrial sector was responsible for about one third of global energy use and 40% of global GHG emissions in 2006 (IEA 2009). In the industry sector, the expected contribution of energy efficiency to the total abatement potential is even higher, being close to 60%. To achieve this would necessitate a drastic acceleration of the energy efficiency progress experienced in the past. The IEA estimates that energy efficiency[6] improvements through applying current best available technology (BAT) in the industrial sector could reduce global CO_2 emissions by 1.9 to 3.2 Gt per year, which equals about 7 to 12% of the total energy and process related CO_2 emissions in 2004 (or 19 to 32% of industry's annual CO_2 emissions) (IEA 2007b).

A substantial share of these potentials is located in the iron and steel, chemical and cement industries. Besides improvements in these energy-intensive process related technologies, the less energy-intensive industries also have huge saving potentials often analyzed on the level of cross-cutting technologies. Global energy and CO_2 savings through the diffusion of energy-efficient electric motor systems in all industrial sectors (most of all systems optimization, but also high-efficiency components) are in the same order of magnitude as the potentials in the iron and steel or cement industry (IEA 2007b). Similar analyses are available for single sectors, technologies or regions, but all underline the availability of considerable remaining potentials that could be exploited by improved policies (e.g. Kramer et al. 2010; McKane, Hasanbeigi 2011; Saygin et al. 2011; Worrell et al. 2000; Worrell et al. 2001). Beyond application of BAT a huge number of emerging energy-efficient technologies is being developed and introduced into the market, which might increase the potentials significantly if they diffuse widely through the capital stock (de Beer 1998; Martin et al. 2000b).

Many of the above analyses, however, do not consider a potential rebound effect, which reduces the calculated energy savings. While a huge number of different types of rebound effects are identified in the literature, they all describe an increase in energy demand subsequent to an improvement in energy efficiency (Greening et al. 2000; Sorrell 2009; van den Bergh 2011). Analyzing the last 200 years of lighting, Fouquet (2006 p.139) concludes: "by the year 2000 [..]

[6] Strictly speaking the application of BAT in the IEA calculations also refers to non-energy related process emissions (like reduction of process emissions in clinker production). However, the major share is due to energy efficiency improvements.

lighting services cost less than one three thousandth of their 1800 value, per capita use was 6,500 times greater and total lighting consumption was 25,000 times higher than in 1800". While this example certainly is an extreme choice, it shows the potential dynamics of energy services and energy-efficiency improvements. In their review study, Madlener and Alcott (Madlener, Alcott 2011) find a rebound effect ranging between 30% and more than 100%, while they also argue that the uncertainty in the empirical studies is still very high and the ranges identified are often even larger. More research on the rebound effect is certainly required; it is, however, not subject of this thesis.

Assessments of costs related to the energy-efficiency potentials are often restricted by low data availability and huge heterogeneity among firms. However, in narrower regional or sectoral assessments, cost estimates are given that indicate the high cost-effectiveness of many options available in the industrial sector.

Hence, by widely adopting BAT vast improvements in aggregated industrial energy efficiency would be achievable (IEA 2009). If set in relation to Schumpeter's (1934) division of the technological lifecycle into invention, innovation and diffusion, it becomes obvious that the third phase, the diffusion of (already available) technologies, provides a substantial energy efficiency potential. The high importance of the diffusion phase is also underlined by Grübler (1998):

"Only through diffusion do technologies exert any noticeable impact on output and productivity growth, on economic and social transformations, and on the environment. Without diffusion, a new technology may be a triumph of human ingenuity, but it will not be an agent of global change." (Grübler 1998 p. 5)

In other words, no effect materializes even with break-through technologies with large savings potentials without diffusion through the capital stock. Moreover the potential embodied in the diffusion of BAT can be tapped into in a relatively short time frame, which might reduce stress on the energy system and allow time for the transition to low-carbon technologies. The wide diffusion of emerging technologies however, is a very uncertain process and most technologies do not experience a successful diffusion cycle. Instead they are hampered by diverse barriers.

Given the importance of the diffusion of EEMs and their potential contribution to reduce harm on the global environmental system, this thesis focuses on the diffusion of EEMs; or more precise: on the adoption decision within the diffusion process.

1.2 The adoption and diffusion of energy-efficiency measures

1.2.1 The diffusion of innovations

The theory of diffusion of innovations provides the basis to study the diffusion of energy-efficiency measures (EEMs). Rogers (2003) defines an innovation as “an idea, practice or object that is perceived as new by an individual or other unit of adoption”. He continues by emphasizing that the “newness” of an innovation only depends on the perception of the potential adopter. Innovations can be differentiated into product and process innovations. While the former describe a new product or a new aspect of a product, the latter describe innovations in the production process. Firms can be both adopter of a process innovation and adopter of product innovations. This differentiation of course simplifies aspects such as the interrelatedness of both types of innovations. In reality, process and product innovations often follow co-evolutionary dynamics and mutually affect each other. Nevertheless, in this thesis a demand perspective is taken, as implied in the definition of process-innovations, because many EEMs are available that are not adopted by firms although they would be cost effective. Thus, in the short-term the adoption process is more crucial to the diffusion of energy efficiency measures rather than product innovations in terms of improvements in quality of energy-efficient technologies.[7] This, however, becomes more obvious when exploring the question why cost-effective EEMs often are not adopted by firms in Section 1.2.2.

The research on the diffusion of innovations started with a number of studies analyzing the diffusion of hybrid corn across US farms. Among those was Griliches (1957) who observed that the development of the cumulated number of farms using hybrid corn followed an s-shaped curve over time in each state. A similar observation was made by Mansfield (1961) based on an analysis of 12 innovations from various sectors. The s-shaped diffusion curve implies that during the early stage of an innovation, the number of users is only a relatively small proportion of all potential adopters. The adoption rate, measured as the share of new users in a given time interval compared to all potential adopters, increases continuously until it reaches a maximum at the point of inflexion (of the cumulative number of adopters). Beyond this point it continuously decreases and the diffusion curve slowly saturates towards an asymptote, given by the total number of potential adopters. Although varying mathematical descriptions have been proposed to describe this pattern, including symmetrical and asymmetrical diffusion curves, empirical evidence for the s-shaped development has accumulated over the last decades and has now become widely accepted (Stoneman 2002).

[7] In the long term, product innovations will probably become more relevant, as the efficiency potentials available through the application of BAT will become increasingly scarce.

There are numerous explanations for the s-shaped curve. A prominent one builds on information flows among potential adopters which result in innovations spreading like an epidemic (Griliches 1957; Mansfield 1961). In the early stage of the diffusion process only a few users can spread information about the superiority of the new technology, but this increases until after the point of inflexion when it becomes increasingly unlikely that users get in contact with remaining potential adopters, as their number decreases, and the diffusion process decelerates (Geroski 2000). Mansfield underlines that it is not only the spread of information, but rather the perceived risk of adopting the innovation that reduces as more firms adopt. Potential adopters are very skeptical of the innovation, particularly in the early diffusion stage, and its potential effects and diffusion only continues slowly. Related models assume that the adoption rate of an innovation in year t depends on the level of adoption in year t-1 (Bass 1969; Mansfield 1968). While this explanation allows the construction of the empirically observed s-shaped curve, it excludes further factors that certainly also affect the diffusion curve. Consequently, further explanations have been put forward. A very common one assumes heterogeneity among potential adopters. If, for example, the cost structure of firms follows a distribution function, an innovation might be profitable in a few firms that experience a cost structure in favor of the innovation, whereas it is far from profitable in other firms. Assuming that profitable innovations are adopted, they spread through the capital stock depending on the changes in technology costs. This explanation is referred to as the probit model (Geroski 2000). It also accommodates increasing returns for adoption, for example in the form of learning effects or economies of scale. These reduce specific costs of the innovation making it profitable in further firms, which again reduces costs allowing the diffusion to gain momentum. Consequently, such an approach also allows modeling lock-in effects and path dependency (Arthur 1989).

Empirical studies have been conducted for a huge range of innovations, adopters, regions and by different disciplines. They mostly show that technology diffusion varies widely, but is typically slow (Mansfield 1961) and a full diffusion cycle often takes decades, particularly for long-living industrial process technologies. Ray (1988) analyses six industrial post World War II technologies and concludes that all have taken longer than 30 years from market entry to final saturation. However, diffusion speed varies widely depending on a huge number of factors, which are divided into three classes by Wejnert (2002): the characteristics of the innovation, the characteristics of the innovators (in our case firms) and the environmental context. Certainly, information channels can be added to this classification (Rogers 2003).

Profitability is probably the most researched innovation characteristic which is widely accepted as increasing the diffusion speed (Mansfield 1961; Ray 1988; Stoneman 2002). However, other characteristics also have a significant impact. It has, for example, been shown that the complexity of the innovation is negatively correlated to the rate of adoption (Kemp, Volpi 2008; Tornatzky, Klein 1982). Moreover, innovations can be distinguished according to their link to the existing capital stock. New technologies might extend the current production system or replace it (entirely or partially). In the latter case, the diffusion of new technologies is bound to the replacement of the current capital stock, where a premature replacement is excluded (Worrell, Biermans 2005). Rosegger (1979) for example has shown that continuous casting technology diffused only slowly through the capital stock of the steel industry, because it required replacement of existing casting lines, which would generate high switching costs if not fully depreciated.

Regarding the impact of the characteristics of the adopting firm on the diffusion, size is the widest researched parameter and generally expected to have a positive impact on the adoption rate. This implies that larger firms have a higher likelihood of adoption (Davies 1979), particularly for less costly innovations (Freeman, Soete 1997).[8] Contextual factors can also significantly shape the diffusion curve. For example the competitiveness in the market might accelerate the diffusion of innovations, which could also be a result of prices being closer to the marginal costs (Stoneman 2002). A particular aspect is the regulatory framework, which can stimulate or slow down the diffusion by, for example, providing information or financial support to potential adopters.

Thus, the diffusion of innovations is a complex process and depends on a variety of different factors making generalized conclusions difficult. This observation feeds the view that an entire innovation system needs to be considered for analyzing the diffusion speed of innovations (Freeman, Soete 1997; Hekkert et al. 2007). Such systems have a broad scope and take aspects such as several forms of R&D activities and networks among firms and research institutions, into account.

1.2.2 The diffusion of energy efficiency measures

As mentioned above, EEMs designed for firms can be regarded as a particular type of process innovation. They improve the production process by reducing its specific energy consumption. Even if the main purpose of the adoption is not energy efficiency improvement, they are regarded as EEMs – as long as they improve the ratio between energy input and useful output of a process (Patterson 1996). In this thesis, an even narrower definition is applied, which understands the useful output as the delivery of an energy service. In this sense, energy efficiency is also distinguished from energy saving. While the former describes a ratio of inputs and outputs, the latter is related to a total level of energy use. Consequently, as a result of rebound effects, energy efficiency improvements can result in higher total energy demand, which is less likely for energy savings (van den Bergh 2011). Thus, in this thesis, the term energy efficiency is used,

[8] However, if diffusion is measures as a share of aggregated industrial output produced with a particular production technology, it is not certain whether larger firms really accelerate diffusion. This is because it is not only the initial adoption by a firm that counts, but also the intra-firm diffusion, which might take longer in larger firms.

because it excludes assumptions about behavioral changes resulting from technology adoption.

EEMs describe a broad set of technologies and behavioral changes. EEMs comprise measures as different as fluorescent lamps, building insulation, energy-efficient electric motors, new production plants for steel or aluminum and the recovery of waste heat from various sources or the lowering of room air temperature. EEMs differ in one major aspect from general process innovations: they are (mostly) not related to the core business of the firm and only slightly affect its competitiveness.[9] In firms where resources are constrained, these are first allocated to strategically important investment projects (Cooremans 2011). Thus, the priority of firms to invest in EEMs is generally low (exceptions are firms with high energy cost shares), and often the firms do not even actively search for new possible EEMs.

Due to the above and other reasons, the diffusion of EEMs is often surprisingly slow and many firms refrain from adoption, even if EEMs are cost-effective. Reasons for the non-adoption of cost-effective EEMs are manifold and have been researched for more than three decades. For example Sorrell et al. (2004) review the broad literature on barriers to energy efficiency and derive a taxonomy of barriers combining findings from orthodox economics, transaction costs economics and behavioral economics. They distinguish six classes of barriers: risk, imperfect information, hidden costs, access to capital, split incentives and bounded rationality.

A number of empirical assessments of barriers are available in the literature. Some of these use multivariate regression methods based on large data sets to analyze particular sectors. One of the earliest analyses (Velthuijsen 1995) focuses on the Dutch, Slovak and Czech manufacturing sectors and identifies *lacking financial resources* as a major barrier and *favorable market conditions (such as competition), a short payback time* and *low risk* as central incentives for the adoption of EEMs. A study for the German service sector (Schleich 2009) observes the presence of *split incentives*, the positive impact of *firm size* and *energy intensity* on the adoption rate as well as a negative impact of a lack of time to analyze energy efficiency potentials. Another (Aramyan et al. 2007) analyses about 400 Dutch horticulture firms and finds a significant positive impact on the adoption of EEM from the following items: *farm and family size*, *solvency*, *modernity of machinery* and whether the farm owner has a *successor*. However, they did not include the *profitability* or the *payback time* in their model. An analysis of a sample of 26,000 EEM in the frame of the US energy audit program concluded that a longer *payback period*, as well as higher *initial cost of the suggested EEM* reduce the adoption rate (Anderson, Newell 2004). A number of case studies explore various aspects of barriers. Two analyses of the French and German markets for electric motors, for example, find significant split incentives embodied in the market structure as motors are bought by original equipment manufacturers (OEM) and mostly not directly by the end-consumers who pay the electricity bill (de Almeida 1998; Oster-

9 This is particularly true if the energy cost accounts for a low share of the firm's total costs.

tag 2003). The OEMs have no incentive to buy an efficient motor, while the end-consumers lack information on motors' efficiency as they are integrated into other electric consumer products. Case studies among UK breweries (Sorrell 2004) and the Irish mechanical engineering industry (O'Malley, Scott 2004) identify access to capital as the main barrier. In the Irish study it is further found that firms generally had good access to external funding, but the priority of EEM was low compared to other investment projects.

Jaffe and Stavins (1994b) underline that the existence of barriers is less surprising when considering the fact that all (economically superior) innovations diffuse only gradually through the capital stock. In this broader sense, barriers to energy efficiency are simply factors influencing the diffusion speed of EEMs. A major reason for the slow diffusion beyond the classical discussion of barriers is also the existing capital stock, as discussed in the previous chapter.

Throughout this work, barriers are defined according to Sorrell et al. as "a mechanism that inhibits a decision or behavior that appears to be both energy efficient and economically efficient." (Sorrell et al. 2004). In other words, barriers are obstacles to the adoption of cost-effective energy efficiency measures (Blumstein et al. 1980). Cost-effectiveness is assessed on the level of the adopting organization. Applying a cost-effectiveness definition based on societal costs would widen the system boundary and include aspects such as artificially low energy prices (distorted prices), external costs of energy consumption, or institutional factors. Schleich (2011) explicitly distinguishes barriers on the micro-level from those on the macro-level. Schleich locates firms' access to external capital in the group of macro-level barriers and argues that, particularly for small and medium-sized firms, it is sometimes difficult to raise external money at reasonable interest rates. However, access to capital is also associated with the adoption decision of firms as their internal budgeting rules might also generate a lack of capital for investment in EEMs. This thesis focuses on the micro level, with one exception: access to capital As access to both external and internal capital is recognized as a major barrier to energy efficiency in the empirical literature (Sorrell 2004; Thollander et al. 2007) both aspects are explored here. The choice of the micro perspective also focuses on the individual adoption decision instead of the dynamic diffusion perspective.

However, it is not just barriers that are relevant for the diffusion pattern of EEMs: it is also drivers. A survey addressing self-reported drivers for the adoption of EEMs in the Swedish pulp and paper industry reveals the importance of the motivation of staff towards energy efficiency as well as the firm's long-term strategy (Thollander, Ottosson 2008). Only energy cost savings were found to be more important by the firms. Various other policies were also frequently mentioned as drivers by the interviewees. Although, drivers are less frequently researched than barriers, one certain type of driver has received some attention in the past: the so called co-benefits of EEMs. Illustrative examples are improved in-door air quality after insulation of a building or reduced noise emissions through installation of triple glazing windows (Jakob 2006). While these comfort-related co-benefits are still difficult to quantify, energy efficiency in industrial processes often leads to considerable financial co-benefits. A study analyzing 47 EEMs in the US iron and steel industry estimates co-benefits for 14 of them and finds that the cost-effective saving potential is doubled when the co-benefits are included in the cost assessment (Worrell et al. 2003). Many of the co-benefits are related to reduced material losses (for coke or the electrodes), increased productivity, and lower need for maintenance. A case study for the paper industry concludes that the adoption of shoe presses is only partly due to energy-efficiency improvements, whereas the main motivation comes from productivity gains in the form of faster paper machine speed (Luiten, Blok 2003). Examples of co-benefits can be found for many more technologies and sectors. For some technologies, co-benefits can even exceed the cost savings of improved energy efficiency (Pye, McKane 2000).

To conclude, the diffusion of EEMs across firms is a complex process and depends on various factors that vary by EEM, by firm and also depend on the regulatory framework. A number of barriers are identified that prevent or slow down the diffusion of cost-effective EEMs (from a firm perspective). As these barriers are mainly related to individual adoption decisions by firms, this thesis focuses on the adoption decision rather than the long-term diffusion dynamics.

1.2.3 Policies accelerating the diffusion of energy efficiency measures

Policies have been developed and implemented in many countries that particularly address the above mentioned barriers to energy efficiency and aim to accelerate the diffusion of EEMs. It is argued that the adoption of cost-effective EEMs is a *no-regret option* that facilitates improving energy efficiency and reducing greenhouse gas emissions at net negative costs to the society, not accounting for the reduced external costs of climate change (Ostertag 2003)[10]. Obviously, when being compared to more expensive supply side mitigation options, many energy efficiency policies have a broad acceptance among various stakeholders and are often termed a win-win policy to underline the double dividend of reduced emissions and increased economic efficiency.

Although, it is widely accepted that barriers are the rationale for public policy to improve energy efficiency, various views exist on which barriers should be targeted by policy intervention. While the first empirical studies on barriers lacked theoretical foundation and consistency of definition of barriers (Sorrell et al. 2004), the discussion soon intensified in the 1990s and developed a more or less clear analytical frame. Advocates of energy efficiency have underlined

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[10] The expression no-regret potential was introduced by the second IPCC assessment report (IPCC 1996) to describe greenhouse gas abatement options that are available at negative (net) costs without counting the external costs of greenhouse gas emissions. This argument implies that even if one is skeptical about the effects of climate change and reluctant to invest in expensive abatement options, the no-regret potential is economically attractive and also simultaneously reduces emissions.

the huge economically viable energy saving potentials, often referred to as the energy-efficiency gap, observed in all sectors of the economy, together with the need to overcome barriers (Koomey, Sanstad 1994; Levine et al. 1995; Sanstad, Howarth 1994). Critics argued however, that the energy-saving potential is only profitable on a superficial level[11] and that many barriers can be traced back to rational economic behavior (Sutherland 1991; Sutherland 1996). According to Sutherland only a few barriers qualify as justification for energy efficiency policies. Asymmetric information that is corrected by labeling programs is a policy justifiable on these grounds, however minimum energy performance standards (MEPS) would not be justified as they restrict the consumer's choice and might distort an efficient allocation of resources. Jaffe and Stavins (1994b) further elaborate on these arguments and distinguish between barriers that imply a market failure and those that do not. For example, risk related to future energy prices is not a market failure, because it is rational for the firm to add a risk-premium to the expected payback of an investment. In this case, markets still assure an efficient allocation of resources and there is no rationale for policy intervention. Jaffe and Stavins (1994b) argue that only barriers related to market failures justify the intervention of public policy in order to reduce the barrier and improve economic efficiency. Barriers defined as non-market failures do not justify policy intervention, as although they might improve energy efficiency, they may also reduce overall economic efficiency. Sorrell et al. (2004) criticize this view, because it implies that the reasons for the non-market failure, in the form of hidden costs, are fixed and cannot be influenced by policies. Instead they draw on transaction costs economics and argue that public policies can lower transaction costs resulting in a net social benefit. In this way, public policy intervention is also justified for non-market failure barriers. Or more generally, a policy is justified when the benefits exceed the (societal) costs (Levine et al. 1995).

The resulting framework for the relationship between adoption, barriers and policies as used throughout the thesis is summarized in Figure 3. The figure is intended to give a broad overview, not to cover all details relevant for the adoption of EEMs.

[11] For instance, energy experts assessing the potential EEM only account for the obvious investment costs of the new equipment, neglecting search and implementation costs or the general overhead costs of an energy management group. The argument goes that if these hidden costs are accounted for, the profitable energy-saving potential would shrink significantly leaving less room for policy intervention.

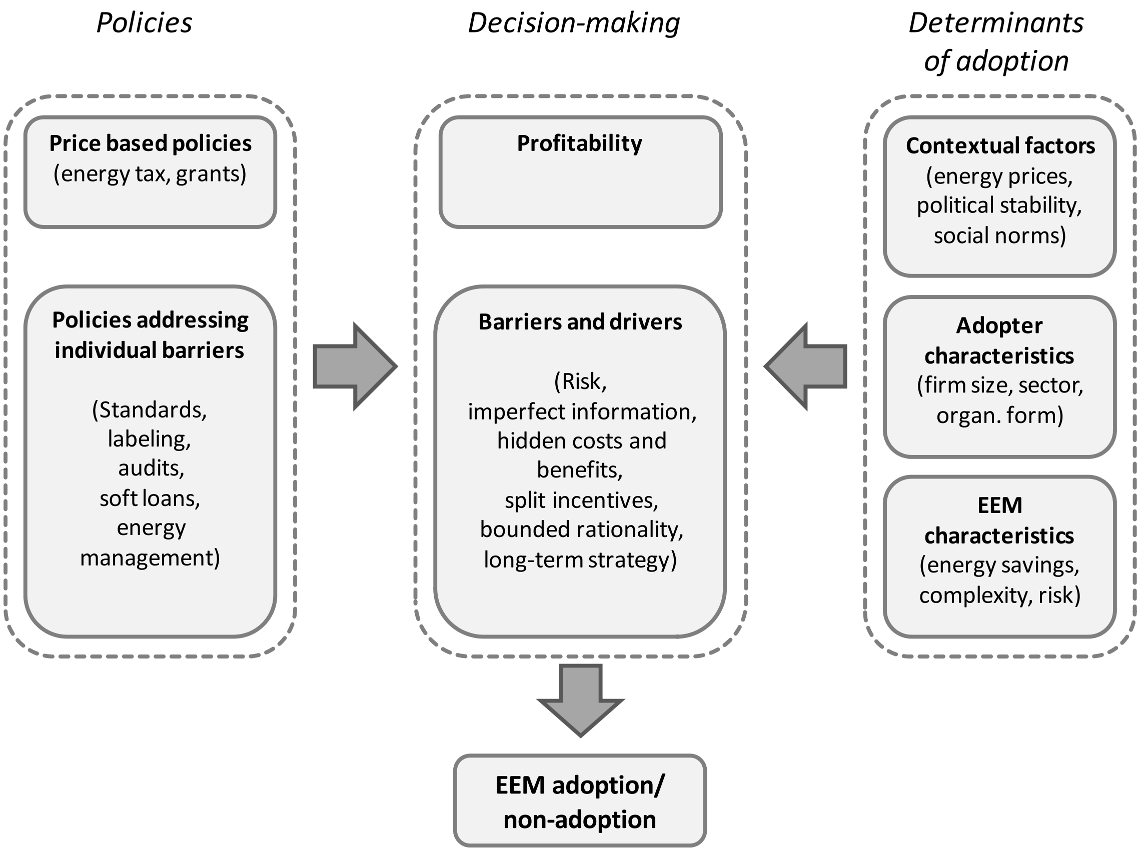

Figure 3: Framework for the determinants of EEM adoption by firms

The spectrum of energy efficiency policies established to overcome barriers is wide and expands continuously (Geller et al. 2006). Some examples, including voluntary agreements, energy audits, energy labels and standards are discussed in the following.

Voluntary agreements where firms or sectors commit to energy saving or greenhouse gas reduction targets have gained popularity since the 1990s and are now implemented around the world (Price 2005). They aim to increase commitment and motivation of firms and industries to improve energy efficiency.

A policy that aims to overcome information related barriers is the support of energy audits. While one of the first energy audit programs for firms was established in the US in 1976 (Anderson, Newell 2004) they are currently installed in most countries around the world (Price, Lu 2011). Energy audit programs often address small- and medium sized enterprises (SMEs) and are based on the observation that such firms do not generally have an energy manager and lack both resources and know-how to properly analyze the options for energy efficiency improvement. Although programs are also designed as stand-alone audits, they are often integrated with broader programs such as voluntary agreements (Price, Lu 2011). For example the Swedish voluntary agreement program for energy-intensive firms (PFE) requires firms to conduct mandatory energy audits in exchange for an electricity tax exemption (Stenqvist, Nilsson 2012). A voluntary program that started in Switzerland and is currently spreading in Germany, is the so called learning energy efficiency networks, and combines (mandatory) energy audits with energy efficiency targets for small groups of firms that meet several times a year. They learn from each other and mutually motivate each other to improve energy efficiency (Jochem, Gruber 2007). The program mainly aims at non-energy intensive medium sized firms and first evaluations show that the participating firms were able to double their annual energy efficiency improvement (Jochem, Gruber 2007). Due to the increasing use of energy audit programs and their clear objective to overcome barriers to energy efficiency, they also receive particular attention in this thesis.

Further successful approaches implemented around the world are the introduction of energy efficiency labels and minimum energy performance standards (MEPS) (Nadel 2002). For example, within the electric motor market it was observed that a lack of information on the efficiency of motors, in combination with split incentives and bounded rationality[12], prevented the diffusion of energy-efficient electric motors. As a reaction, first labeling schemes were implemented in the USA and other countries and continuously extended by increasingly ambitious MEPS.

How such policies affect barriers and the diffusion pattern of EEMs is only rarely analyzed. Where evaluations have been conducted, they mostly counted energy savings and various forms of costs and benefits. The increased spreading of such policies underlines the need for a broad knowledge base that supports the design of effective and efficient policies. This includes techno-economic studies of energy efficiency potentials, studies of barriers, and adoption behavior of firms as well as policy evaluations that take these aspects into account. Policy impact assessments comprise both *ex-post* as well as *ex-ante* assessments. The current state of models frequently used for *ex-ante* impact assessment is summarized in the following section.

1.3 Bottom-up models for techno-economic assessment

Energy demand models are applied to explore the dynamics of future energy demand, its determinants and possible paths, together with the consequences of particular technology choices in the form of policies. The models allow an estimation of the energy saving potential of EEMs and are increasingly used to develop scenarios representing the *ex-ante* effect of energy efficiency policies on energy demand (Capros et al. 2010; Gielen, Taylor 2007; Worrell, Price

[12] De Almeida (1998) shows for the electric motor market in France how the fact that most motors are bought by original equipment manufacturers (OEM) who then sell the motor incorporated into industrial machines or consumer goods further to the end-consumer, results in significant split incentives. The OEM has no incentive to buy efficient motors and primarily demands low prices while the final consumer, who pays for the electricity consumed by the motor, lacks information on the efficiency of the motor which is incorporated into other products.

2001). Most were developed for *ex-ante* simulation of price-based policies or regulations, but in recent years new policy types have emerged that address particular barriers such as a lack of information, high transaction costs or bounded rationality. As the policies work on a completely different mechanism, a generation of *ex-ante* models seem ill suited for simulations of such policies (Worrell et al. 2004).

Energy demand models are typically classified into two broader groups: top-down and bottom-up models. While the former stem from the field of economics, the latter mostly represent an engineering view. The various types of top-down models (e.g. econometric, input-output, general equilibrium models) typically focus on interactions between the energy sector and the other sectors of the economy. Their representation of technologies, however, is very aggregated, for example in the form of production functions. Energy efficiency improvement is often included via an exogenous energy efficiency improvement index. Bottom-up models on the other hand focus on the technology representation and the effects and dynamics of new technologies on the energy system. Their scope if is often restricted to the energy system. Consequently, an increasing number of models couple the two approaches resulting in so called hybrid models.

The most widespread class of bottom-up models, uses optimization algorithms to calculate the least cost paths for the energy system over the entire modeling time horizon considering constraints on, for example, total emissions (Mundaca et al. 2010).[13] Such approaches traditionally assume perfect foresight and perfectly rational adoption decisions, although some variations were developed in the past. A more heterogeneous group of bottom-up models can be summarized under the term simulation models.[14] Although, these do not use intertemporal optimization algorithms, many also use profitability to the firm as an adoption criterion. However, this class is much more heterogeneous with regard to technology adoption. Different adoption rules are applied, though these are mostly linked to classical investment decision rules. Although inclusion of barriers into these models is required for *ex-ante* modeling of policy effects, most models use very simplistic approaches (Mundaca et al. 2010).

Thus, the current generation of bottom-up models (simulation as well as optimization) are not well prepared to model the effect that barriers have on technology diffusion or to simulate policies addressing such barriers (Worrell et al. 2004). However, as bottom-up models have the advantage of a high level of technology detail, they are applied in this thesis for a techno-economic assessment of EEMs.

13 Well established models in this class are MARKAL (Loulou et al. 2004) or AIM/end-use (NIES 2006).

14 Examples for simulation models are CIMS (Jaccard 2005) or Save production (Worrell, Price 2001).

1.4 Objective of the thesis

Understanding of the energy efficiency potentials of EEMs as well as their costs and the underlying pattern of barriers, form the basis for designing effective policies to overcome these barriers. While these aspects have been researched in the past, little attention has been put so far on the interactions between the two dimensions of technology and adoption behavior and how they affect the policy impact.

This knowledge gap is the starting point for this thesis which aims to extend the basis for designing policies to accelerate the diffusion of EEMs in industry. It takes a comprehensive view by exploring the EEM potentials and costs as well as the adoption behavior of firms. A particular focus lies in the interaction between these two fields, as the pattern and intensity of barriers directly depend on the EEMs. Thus, the main research question can be stated as follows.

How are EEMs and the adoption behavior of firms interrelated and what does this imply for the design and impacts of policies in this field?

As such, the research question has a wide scope drawing on the dimensions technology, firm behavior and policy. The chapters of the thesis are structured according to Figure 4. The first part focuses on the dimensions technology and firm behavior and their interrelation. First, the techno-economic characteristics of EEMs in the form of energy saving potentials and costs are analyzed (Chapter 2), before the adoption behavior of firms is assessed (Chapter 3). The following chapter explores the linkages of both fields (Chapter 4). The second part of the thesis then shifts the focus towards the policy dimension. This includes an *ex-post* policy impact evaluation (Chapter 5) and a review of models for *ex-ante* assessment of policy impact on industrial energy demand (Chapter 6). The policy-related analyses particularly focus on the role of barriers and EEMs.

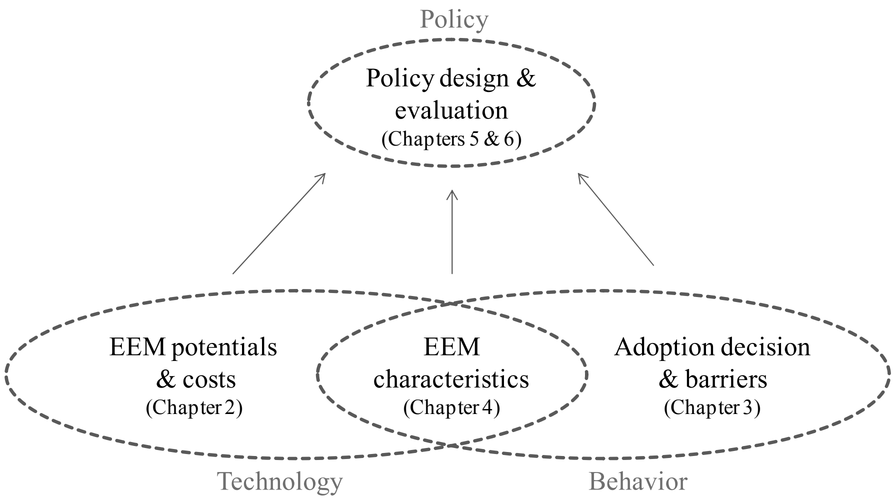

Figure 4: Conceptual framework of the thesis

Accordingly, the thesis is divided into five analytical chapters, of which each follows a concrete research question that contributes to the above objective.

1. What are the energy saving potentials and costs of EEMs and what is their potential contribution to energy efficiency improvement in industry? (Chapter 2)
2. What are the determinants to the adoption of EEMs by firms and what is the particular role of barriers? (Chapter 3)
3. Which EEM characteristics affect the adoption decision by firms and how can the characteristics be used for a classification of EEMs? (Chapter 4)
4. What is the impact of policies in increasing the adoption rate of EEMs by SMEs, which EEMs are addressed and which barriers are overcome? (Chapter 5)
5. How are barriers, EEM diffusion and policies considered in models for *ex-ante* assessment of policy impacts? (Chapter 6)

Each chapter will deal with these questions in a concrete research frame described in more detail in the following section, including the main methodology used for each part of the analysis. This section also provides the detailed outline of the chapters to follow.

1.5 Outline of the thesis

Chapter 2 explores the techno-economic characteristics of EEMs by conducting a case study for the German pulp and paper industry[15]. The analysis follows the traditional approach of a bottom-up assessment of EEMs and their energy saving potentials and cost-effectiveness in the long term. Cost-effectiveness is assessed using so called conservation supply curves that regard EEMs in parallel to energy supply options. We focus on 17 process technologies and explicitly exclude cross-cutting technologies from the analysis, as these have been analyzed in more detail in the past. Scenario construction is used for the calculation of saving potentials and follows explicit assumptions about the adoption (and diffusion) of EEMs by firms.

In **Chapter 3** the focus shifts towards the adoption behavior and the determinants of EEM adoption by firms are explored, particularly focusing on the role of barriers. The chapter focuses on small and medium sized enterprises (SMEs), because many barriers are more intensive in SMEs (Gruber, Brand 1991; Trianni, Cagno 2012) and several policy instruments particularly address SMEs. A regression analysis is applied based on cross-sectional data using self-reported barriers, objective barrier variables and control variables including firm characteristics as indepen-

[15] Paper production is an energy-intensive process and accounted for about 9% of industrial energy demand in Germany in 2008. There have only been slow improvements in energy efficiency in the paper industry over the past twenty years. If policies aim to accelerate the progress made, knowledge about the remaining efficiency potentials and their costs is a prerequisite for their success.

dent variables. The effects of these factors on the adoption rate of firms are explored. The application of factor analysis helps to group individual barrier questions from the survey to broader barrier categories. This allows the number of explanatory variables (and increases the degrees of freedom) to be reduced and at the same time derives more abstract classes of barriers that improve comparability to theory based research in this field. The chapter draws on data from a survey conducted in 2010 among firms that participated in the German energy audit program for SMEs. Thus, the chapter also allows conclusions to be drawn on the contribution of the audit program to overcome barriers in SMEs.

Chapter 4 aims to integrate the two dimensions of technology and adoption behavior, as analyzed in the previous chapters. By assessing the effect of EEM characteristics on the adoption behavior and the intensity of barriers, it establishes a link between both dimensions. The chapter begins with a review of the broad literature on technology diffusion with a particular focus on the impact of technology characteristics on the adoption decision. The review further discusses EEM characteristics typically considered in literature. Based on the review, a classification scheme for EEMs is derived that allows a better understanding of the adoption of EEMs, particularly in comparison to other EEMs. It further provides a useful basis for a more generic classification of EEMs. The scope of the characteristics analyzed goes far beyond what is assessed in classical techno-economic assessments of energy saving potentials (such as in Chapter 2) and also includes more tacit characteristics. As the classification scheme is derived from the literature, an application to six example EEMs is conducted for validation.

Thus, the first three chapters address the technology and the adoption behavior dimensions as well as their interrelation. While such analyses provide the knowledge basis for policy design, in the remaining two chapters, the focus shifts to the policy dimension. Particular note is taken of how the impact of policies is affected by barriers, EEM characteristics and their interaction and in how far this is included in *ex-ante* assessment models.

Chapter 5 evaluates the impact of a policy program on the adoption of EEMs by SMEs, barriers and the role of EEM characteristics. It shows how the integrated analysis of EEM types and adoption behavior allows additional conclusions to be drawn on the policy impact. For this purpose, a case study of the German energy audit program for SMEs is conducted using the same underlying data set as Chapter 3. The audit program targets SMEs, because some barriers such as lack of information and constraints on staff as well as financial resources are more pronounced in SMEs (Gruber, Brand 1991; Trianni, Cagno 2012). The program provides both grants for the conducting the audit and soft loans for implemented the EEMs recommended. In the first part, we calculate the net effect of the program by considering free riders (firms that would have conducted the audit without the grant), additionality (EEMs that were already planned before the audit) and EEMs planned for implementation, but not implemented at the time of the survey. In the second part, the evaluation assesses the types of EEMs recommended and implemented and continues to explore the barriers overcome and not overcome by the program. Finally, key indicators of the program are compared to similar programs in Sweden, USA and Australia. Finally, recommendations for program improvement are derived and discussed.

Effective policy design to overcome barriers requires knowledge about EEMs and adoption behavior on the one hand, but improved tools for *ex-ante* estimations and modeling of potential policy impacts on the other. Bottom-up models are frequently used for this purpose, because they allow a technology-specific analysis.

Chapter 6 reviews how bottom-up models consider barriers and technology diffusion. We further assess how the models are able to simulate various types of policies and particularly those addressing barriers. Three types of models are considered: optimization, simulation and accounting models, which are all used for energy demand forecasts as well as *ex-ante* simulation of energy efficiency policies.

Chapter 7 closes by summarizing the main findings of the thesis and draws the main conclusions. Also further research directions are derived and discussed.

2 Energy efficiency in the German pulp and paper industry – A model-based assessment of saving potentials [16]

Abstract

Paper production is an energy-intensive process and accounted for about 9% of industrial energy demand in Germany in 2008. There have only been slow improvements in energy efficiency in the paper industry over the past twenty years. Policies can accelerate the progress made, but knowledge about the remaining efficiency potentials and their costs is a prerequisite for their success.

We assess 17 process technologies to improve energy efficiency in the German pulp and paper industry up to 2035 using a techno-economic approach. These result in a saving potential of 34 PJ/a for fuels and 12 PJ/a for electricity, which equal 21 % and 16 % of fuel and electricity demand, respectively. The energy savings can be translated into mitigated CO_2 emissions of 3 Mt/a. The larger part of this potential is found to be cost-effective from a firm's perspective. The most influential technologies are heat recovery in paper mills and the use of innovative paper drying technologies. In conclusion, significant saving potentials are still available, but are limited if we assume that current paper production processes will not change radically. Further savings would be available if the system boundaries of this study were extended to e.g. include cross-cutting technologies.

[16] The chapter has been published as *Fleiter, T.; Fehrenbach, D.; Worrell, E.; Eichhammer, W. (2012): Energy efficiency in the German pulp and paper industry - A model-based assessment of saving potentials. Energy, 40 (1), pp. 84-99.*

2.1 Introduction

Energy efficiency[17] is considered a key element in sustainable development. It particularly contributes to reducing energy resource depletion rates and mitigating greenhouse gas emissions. It is a central greenhouse gas abatement option at low specific costs (IEA 2008a), while it also improves firms' competitiveness.

Paper production accounts for about 9% of industrial energy demand and around 2.5% of all energy-related greenhouse gas emissions in Germany. It recorded high growth rates in the past 20 years resulting in an increase of paper production by 75% from 1991 to 2008. The paper industry is considered an energy-intensive industry with energy costs at around 13% of total production costs (VDP 2010). It experienced rapid – cost-driven – improvements in energy efficiency (EEI) in the second half of the 20th century. However, these came to a halt in recent years. Between 1991 and 2008, the specific energy consumption per ton of paper decreased by only 5.7 % (ODYSSEE Database 2011). Implementing suitable policies might accelerate energy efficiency progress in the future. However, knowledge about available EEI potentials and their costs is a prerequisite to designing effective and efficient policies.

This paper analyzes available energy-saving potentials in the German paper industry. We conduct a scenario analysis using a technology-specific, bottom-up modeling approach and combine it with a thorough review of the literature on energy-efficiency measures (EEM).

While several studies on the paper industry have been conducted in recent years, they differ in focus, scope and applied methodology. Davidsdottir and Ruth (2004) analyze the impact of capital turnover and the vintage structure on energy demand in an econometric model for the US pulp and paper industry. They focus on policy impacts and consider technologies only in a stylized way. A group of studies (Giraldo, Hyman 1995; Giraldo, Hyman 1996; Ozalp, Hyman 2006) established an end-use energy demand model based on energy flows for the US paper industry. Although the model is technology-specific, they do not use the model to calculate saving potentials through technology improvement, instead they focus on allocating energy consumption to the distinct end-uses. Szabó et al. (2009) studied the impact of carbon prices on greenhouse gas emissions of the global paper industry. Although their model also contains technical information, like specific energy consumption (SEC), they focus on the market dynamics and paper demand.

Studies of the German paper industry focused on a review of technology improvement options. IUTA et al. (2008) review a large number of technologies and provide guidelines for energy managers, but they do not calculate aggregated saving potentials. Similar studies are available

[17] We define energy efficiency as improvements in the specific energy consumption of particular energy services (e.g. production of paper).

for Austria (Brand et al. 2005), the US (Kramer et al. 2010) or the European Union (European IPPC Bureau 2010). Other engineering studies concentrate on single aspects of the paper production chain (e.g. Bakhtiari et al. 2010; IUTA et al. 2008; Laurijssen et al. 2010; Martin 2004b).

A broad engineering review of the US paper industry (Martin et al. 2000a) is more comparable to our approach. It considers technology costs and calculates saving potentials for the entire paper industry. A similar study was conducted by Möllersten et al. (2003c) for the Swedish paper industry. They assessed CO_2 mitigation potentials of a set of new technologies. However, they do not explicitly consider the development over time and consequently draw no conclusions on the timeframe the potentials would need to unfold. Also Farahani et al. (2004) analyze the impact of new technologies on CO_2 emissions in the paper industry by comparing Sweden to the US, focusing on the more efficient use of black liquor.

In this paper, we assess if there are technologies available to further improve energy efficiency in the German paper industry in the long term (i.e. 2035), and estimate the economic and technical potentials for EEI.

We first review the literature on available energy-efficient technologies. For triangulation of technology characteristics we also conducted interviews among paper mills and technology suppliers. Next, the technology-specific information is integrated in a bottom-up model, allowing aggregated EEI potentials and their cost-effectiveness to be calculated.

We explicitly consider the diffusion of technologies over time, which allows transparency about the degree of maturity of the technologies and yields more detailed policy recommendations. This is particularly important, given the long capital lifetime in the paper industry and has direct implications on the economics.

The analysis is limited to so-called *process-specific technologies*. While their counterparts, cross-cutting technologies (e.g. motors, pumps, lighting, boilers, ventilation), are applied across industrial sectors, process-specific technologies are particular to a chosen industrial sector or process. They are typically deeply rooted in the production process and an in-depth analysis of the process is required in order to assess EEI potentials.

2.2 Modeling approach

2.2.1 Introduction

The approach is based on technology-specific modeling of energy demand. Such models are typically referred to as bottom-up models and have been applied in energy system analysis since the early 1980s (Chateau, Lapillonne 1978; Lapillonne, Chateau 1981; Worrell, Price 2001). Bottom-up models derive final energy demand from changes in the technological structure over time. Exogenous activity parameters like industrial production are translated via technical parameters into energy consumption. The level of detail of technology representation varies among models. While some models only consider aggregated energy intensity, others consider the useful energy demand (e.g. mechanical energy) and estimate the final energy demand as a function of the efficiency of the technical system.

Most recent bottom-up models explicitly consider technologies and their diffusion, and some also stock turnover (Daniels, Van Dril 2007; Fleiter et al. 2011; Murphy et al. 2007). New technologies change the technical system over time, resulting in changing energy demand. The advantage of bottom-up models is the transparency of the underlying technology development, which ensures a "realistic" development path. In most models, diffusion mainly depends on the cost-effectiveness of the technologies. If other determinants like barriers to energy efficiency are considered, they are most often integrated using an ad-hoc approach like an increased discount rate (Fleiter et al. 2011).

On the other side, technology diffusion over time is only rarely considered in technology-specific analyses of saving potentials for particular industries (Hasanbeigi et al. 2010b; e.g. see Möllersten et al. 2003b). Most studies estimate the potential energy savings of new technologies, but do not consider the time required for diffusion. However, particularly in the industrial sector, with often long technology lifetimes, diffusion is an important aspect of saving potentials (Worrell, Biermans 2005) and including it in the model may result in better policy recommendations.

In this paper, we explicitly consider technology diffusion for the model-based assessment of EEI potentials to compare the impact of different diffusion scenarios on energy demand. The diffusion paths are considered as fixed exogenous variables based on expert interviews and the literature. Endogenous modeling of technology diffusion would include a huge degree of uncertainty as many factors beyond the financial cost-effectiveness influence the speed of diffusion (see below) and take the focus of our study away from the analysis of EEI potentials.

2.2.2 Model description

The model applied in this study, ISIndustry, follows the philosophy of technology-specific bottom-up modeling. It explicitly defines technologies and considers investment costs. The model is used as an accounting model and technology diffusion is an exogenous model parameter. Accounting models do not allow forecasting, but are used for scenario analysis to compare alternative futures and draw conclusions on the drivers of energy demand.

The scenarios in our study differ in the assumed diffusion rate of energy-efficiency measures (EEM). The resulting differences in energy demand between the scenarios are the saving potentials achievable by accelerated technology diffusion.

With regard to technology structure, ISIndustry distinguishes processes and EEM. The former are characterized by their specific energy consumption (SEC) and a production output. EEM are defined as technologies or behavioral changes that reduce the SEC of a particular process. Thus, each EEM addresses a specific process.

The annual energy savings (ES) of an EEM in year t for one scenario (Sc) are calculated based on the specific saving potential (sp), the diffusion (Diff) of the saving option in year t and the industrial production (IP) of the related process (p).

$$ES_{t,p,EEM,Sc} = sp_{EEM}(Diff_{t,EEM,Sc} - Diff_{t=2007,EEM})IP_{t,p} \qquad (1)$$

Diffusion is an exogenous assumption and derived from past development and expectations, including assumptions about technology turnover and lifetime, as well as barriers and costs.

The resulting energy demand (ED) of a scenario is then calculated as the reference SEC corrected for the sum of energy savings over the different processes for this scenario for year t and the level of production.

$$ED_{t,Sc} = \sum_{p=1}^{n}(IP_{t,p}SEC_{t=2007,p} - \sum_{EEM=1}^{n} ES_{t,p,EEM,Sc}) \qquad (2)$$

Further, cost-effectiveness of the EEM is calculated and used to construct a scenario. Cost-effectiveness for a given year is determined on the basis of all cash flows in that year. The criterion for cost-effectiveness is the specific cost of EEI (c) in a given year. It is calculated as the total (or net) costs (C) in year t divided by the induced annual energy savings in year t (ES). The specific costs for EEI (c) are similar to the cost of conserved energy usually calculated in such an analysis of EEI potentials. These are typically presented as conservation supply curves (see

Section 2.6.3).[18] The only difference is that the energy cost savings are already considered in the specific costs as we calculate them. This is necessary, because we consider a number of different energy carriers with different prices and are not able to disaggregate them at a later stage.

$$c_{t,EEM} = \frac{C_{t,EEM}}{ES_{t,EEM}} \quad (3)$$

The total annual costs for EEI (C) in year t comprise the investment costs (C^I), the running costs (C^R), the saved energy costs (C^E), as well as the saved costs for emission certificates (C^C). The investment costs are annualized. The interest rate r is often used in energy demand models to consider barriers to the implementation of cost-effective EEM (Fleiter et al. 2011; Worrell et al. 2004). In this case, a discount rate higher than the firms' profit expectations is assumed.

$$C_{t,EEM} = C^I_{t,EEM} \frac{(1+r)^{Lt_{EEM}} r}{(1+r)^{Lt_{EEM}} - 1} + C^R_{t,EEM} - C^E_{t,EEM} - C^C_{t,EEM} \quad (4)$$

The investment costs (C^I) consider both new plants as a result of capacity expansion as well as replacement of retired plants. The assumed specific investment costs (c^I) decline over time according to an exogenous annual cost reduction coefficient, representing technical learning (see Table 5). The calculation of investment costs based on the specific costs of year t (c^I) and the total saving potential in year t (ES) as in formula (5) is clearly a simplification, as the savings in year t also result from investments in earlier periods, when the specific investment costs might have been higher. This simplification was necessary, as we are not using a stock model and thus do not know the characteristics of single vintages. However, in order to derive robust interpretations of the cost-effectiveness, we are calculating a sensitivity analysis of the specific costs, varying the time horizon as well as the discount rate (see Chapter 2.6.3). The simplification still allows for a transparent and realistic depiction of the cost-effectiveness.

$$C^I_{t,EEM} = c^I_{t,EEM} ES_{t,EEM} \quad (5)$$

The modeling approach also poses restrictions on the system boundaries of the analysis. Source: adapted from Möllersten (2003a)

Figure 5 presents different variables that affect energy demand. Of these, we exclusively analyze the specific energy consumption (SEC). Changes in the other variables, like changing paper production, changing product mix towards recycled fibers, or reduced fiber material consumption are unchanged among all scenarios.

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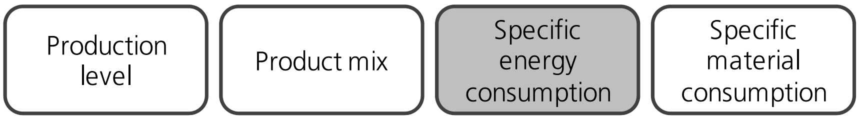
[18] The calculation of the specific cost of conserved energy dates back to Meier (Meier 1982). A recent application similar to our approach has been conducted for the Thai cement industry (Hasanbeigi et al. 2010b).

We further narrow the system boundaries to process-specific technologies, excluding cross-cutting technologies (e.g. motor systems, lighting or space heating). These are not particular to the paper industry and have been studied widely. Thus, in reality the EEI potential will be higher than included in the model in this paper.[19]



Source: adapted from Möllersten (2003a)

Figure 5: Factors determining energy demand in an industry

2.3 The German pulp and paper industry

2.3.1 Overview

With a production of 21 million tons in 2009, Germany is by far the single largest producer of paper in the European Union (VDP 2010). Worldwide, only the United States, China and Japan produce more paper. The major share of paper production was in the form of graphical paper (9.2 million tons) and paper and paperboard for packaging (9.1 million tons). The share of both technical paper and tissue paper is relatively low, at 1.5 and 1.4 million tons, respectively.

The paper industry is heterogeneous in company size, ranging from small and medium-sized enterprises (SME) to large companies. Out of the 104 firms, 57% have an annual production output of less than 50,000 tons, while 12 firms produced more than 500,000 tons of paper in 2009. Production quantity is concentrated in these 12 firms which are responsible for 65% of the total output in 2009.

The German paper industry is highly integrated in the European market. Although domestic paper production exceeded consumption by 13%, significant trade flows exist. The total export accounted for 12.4 million tons of which 79% were exported to other EU member states. Similarly, 83% of imports originated from other EU countries amounting to a total of 10 million tons in 2009 (VDP 2010).

The German paper industry experienced a substantial production growth of 79% from 1991 to 2008. Industry representatives do not expect these growth rates to continue. Driven by the rising output, energy demand increased simultaneously over the same period: by 75% from 1991 to 2008. Consequently, the SEC remained more or less constant (-5.7% between 1991 and 2008).

[19] The processes in the paper industry particularly use mechanical energy for rolling the paper web and pumping pulp and water. Thus, options like replacing inefficient electric motors or pumps have a high EEI potential in the paper industry.

However, CO_2 emissions decreased significantly, mainly due to fuel switch to less carbon-intensive energy carriers (renewable energy and natural gas replaced hard coal and crude oil).

2.3.2 Technology adoption in the paper industry

Empirical evidence exists that firms often do not adopt energy-efficient technologies despite their cost-effectiveness (DeCanio 1998). This gap between the available potential and the real implementation in firms is also referred to as the energy-efficiency gap or the no-regret potential (Jaffe, Stavins 1994b). From a policy point of view, the no-regret potential is very attractive, due to the net benefit it implies for the technology adopter (Ostertag 2003). Several studies have analyzed the structure of the factors or barriers hampering technology adoption. Schleich (2009) analyzed barriers in the German service sector and found lack of staff time, investment priority-setting, information deficits and split incentives to be major barriers. The latter two were also found by de Almeida (1998) for the electric motor market. Further important barriers are competition with alternative investment opportunities and uncertainty with regard to future technology and price development (de Groot et al. 2001).

Although the pulp and paper industry is grouped among the energy-intensive industries with energy costs accounting for more than 10% of the production cost, here too non-economic barriers hamper the adoption of cost-effective, energy-efficient technologies (Thollander, Ottosson 2008).

The structure of barriers varies greatly, depending on technology and firm characteristics. If technologies are integrated into complex production processes, the intensity of barriers is different compared to technologies that are applied somewhat detached from the production process, like space heating or lighting. Thollander and Ottosson (Thollander, Ottosson 2008) confirm this view and find technical risk (of production disruptions) as the main barrier in the Swedish pulp and paper industry. This is followed by hidden costs through production losses and other inconveniences. Further important barriers are lack of time or other priorities and lack of access to capital.

Del Río González (2005) analyzed the adoption of clean technologies[20] using a survey among 46 paper producers in Spain. The three major barriers for technology adoption were all related to high costs (long payback time, high initial investment, not cost-effective). This is further supported by the interviews with German paper industry representatives, indicating that two years is the maximum payback time acceptable for energy-efficiency investments.

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[20] Although energy-efficient technologies are a sub-group of clean technologies, they are somehow idiosyncratic, due to the different motivation for adoption. While clean technologies are mostly adopted to comply with environmental regulation, energy-efficient technologies always affect energy and cost savings, and are less driven by regulation.

2.4 Paper production

2.4.1 Overview

Paper is produced based on wood and recovered paper. The most energy-intensive process steps are the production of pulp and the further processing of this semi-finished product to the paper web. Chemical or mechanical pulp is produced from wood, while RCF (recovered fibers) pulp is produced from recovered paper. The pulp is processed in the paper mill to produce the paper web. Additional non-fiber resources like fillers or additives are used in lower quantities and their production is not included in this study. The three pulp production lines distinguished differ in terms of energy intensity and product characteristics. Also, the core paper production process differs depending on the paper grade and between integrated and non-integrated mills, but the differences are minor when compared to the differences in pulp production lines.

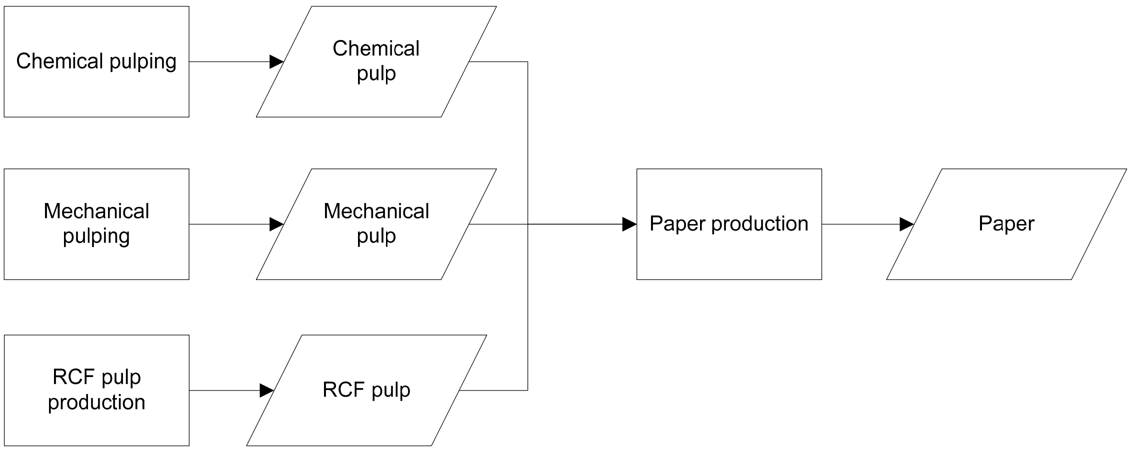

Figure 6: Material flow and process chain for the paper production as modeled

The assumed reference energy consumption per process is given in Table 1. While the production of mechanical as well as chemical pulp shows the highest SEC, the paper production process has the highest total consumption, accounting for 76% of final energy demand of the paper industry in Germany in 2007. Virgin pulp is mainly imported from Scandinavian countries, while the domestic production focuses on RCF pulp.

The definition of energy consumption used in this study is based on German energy balances (AGEB), and assumes final energy demand. Thus, primary energy used for on-site electricity generation is not considered, instead the total net consumed electricity is included (including self-generated and purchased electricity).

Table 1: Assumed specific fuels and electricity consumption (SEC) and resulting total energy consumption and CO_2 emissions in 2007 [c]

Process	Energy use						CO_2 emissions		
	SEC Electricity [kWh/t]	SEC Fuels [GJ/t]	Total Electricity [PJ]	Total Fuels [PJ]	Total [PJ]	Share [%]	Indirect [Mt CO_2]	Direct [Mt CO_2]	Total [Mt CO_2]
Chem. pulp	639	12.6	3.5	19.5	23.1	10%	0.6	1.0	1.6
Mech. pulp	2,200	-2.0[a]	11.5	-2.9	8.6	4%	2.1	-0.2	1.9
RCF pulp	260	0.5	14.7	8.5	23.2	10%	2.6	0.4	3.1
Paper	530	5.5	44.5	128.2	172.7	76%	8.0	6.6	14.6
Sum			74.3	153.4	227.7	100%	13.3	7.9	21.2

[a] The negative fuel consumption represents heat recovery that is used in integrated paper mills for drying paper

[b] CO_2 emissions are calculated using the emission factors given in Table 13. Indirect CO_2 emissions comprise those resulting from electricity generation (onsite and offsite) and direct CO_2 emissions comprise all fuel combustion processes in the paper mills (excluding electricity generation).

[c] The German energy balances do not provide energy demand by process, but only for the pulp and paper industry as a whole, which is used to cross-check if the assumptions on the process-level are realistic. These assumptions are further broken down in the following tables.

Source: own calculations based on (Blum et al. 2007; European IPPC Bureau 2010; VDP 2009; Worrell et al. 2007)

2.4.2 Pulp production

Chemical pulp. The wood chips are cooked together with chemicals and water in a digester at around 130-150°C. Lignin is separated from the fibers (defibration), while the structure of the fibers remains intact. Chemical pulp production is further distinguished into sulphite and sulphate (kraft) pulp. In Germany, four integrated paper mills use the sulphite pulp process, while two kraft pulp plants were built in 1999 and 2004. The latter have a combined capacity of 975 kt of pulp per year. The sulphite production capacity is around 600 kt.

Mechanical pulp. The mechanical breakdown of wood into fibers by grinding or refining yields pulp with different characteristics compared to chemical pulping. As the lignin remains in the pulp, yield is higher and paper strength is lower. Mechanical pulp production is typically integrated into the paper mill.

In Germany, mainly two alternative processes are used for mechanical pulp: ground wood pulp (GWP) and thermo-mechanical pulp (TMP). The ground wood pulp process (GWP) consumes 4 to 7.9 GJ of electricity per ton of pulp (European IPPC Bureau 2010). Thermo-mechanical pulping relies on refining at elevated temperatures, resulting in higher pulp quality, at an SEC of 6.5 to 13 GJ electricity/t of pulp (European IPPC Bureau 2010). In 2008, 1.45 million tons of mechanical pulp were produced in Germany, of which 30% TMP and 70% GWP (VDP 2009).

The typical process steps for GWP and their assumed SEC are given in Table 2. The most energy-intensive step is grinding (for TMP it is refining). Both GWP and TMP processes mostly consume electricity. During mechanical processing, large amounts of waste heat are released, which are typically used in the drying section of the paper mill.

Table 2: Assumed specific electricity and fuel consumption (SEC) per process step for mechanical pulp (GWP)

Process step	**SEC Electricity**		**SEC Fuels/heat**	
	[kWh/t]	[GJ/t]	[kWh/t]	[GJ/t]
Wood handling	50	0.18	42	0.15
Grinding	1,800	6.48	-	-
Washing	50	0.18	-	-
Bleaching	100	0.36	-	-
Heat recovery	-	-	-375	-1.35
Total	2,000	7.20	-333	-1.2

Source: own assumptions based on (European IPPC Bureau 2010)

Recycled fibers (RCF) pulp. In Germany, the largest share of pulp production is based on recovered paper. In 2008 a total of 16 million tons of recycled fiber pulp (RCF) was produced (VDP 2009). The process steps and their SEC depend on the pulp quality. The values assumed for our analysis are shown in Table 3.

Table 3: Assumed specific electricity and fuel consumption (SEC) per process step for the production of RCF pulp

Process step	**SEC Electricity**		**SEC Fuels**	
	[kWh/t]	[GJ/t]	[kWh/t]	[GJ/t]
Pulping	40	0.14	-	-
Screening	50	0.18	-	-
De-inking (Flotation)	80	0.29	-	-
Concentration and dispersion	40	0.14	150	0.54
Bleaching	30	0.11	-	-
Others	20	0.07	-	-
Total	260	0.94	150	0.54

Source: own assumptions based on (European IPPC Bureau 2010)

2.4.3 Papermaking

In papermaking, pulp and other raw materials are processed to a paper web. Two main production steps can be distinguished: the stock preparation and the paper machine (see Table 4). In non-integrated paper mills, stock preparation begins with the pulping of the delivered (dry) fibers to produce a fibrous slurry. Depending on the required paper grade, the fibers are again refined to e.g. increase paper strength. Before screening, the slurry enters the first part of the paper machine, the wet end, where the fibers are filtered and the paper web is formed. It has a solid content of 16 to 25% at this stage. In the dry end, the paper web enters the pressing section where the solids content is further increased to about 50 to 55%. The remaining water cannot be removed by mechanical means, but is evaporated in the dryer section, through conventional drying cylinders. The thermal drying is by far the most energy-intensive process step. The finished paper web has a solids content of more than 90%.

Table 4: Assumed specific electricity and fuel consumption (SEC) per process step for paper production

Process step	Sub-step	SEC Electricity		SEC Fuels	
		[kWh/t]	[GJ/t]	[kWh/t]	[GJ/t]
Stock preparation	Pulper	10	0.04	-	-
	Refiner	130	0.47	-	-
	Screening	30	0.11	-	-
Wet end	Head box	40	0.14	153	0.55
	Forming section	30	0.11	-	-
Dry end	Press section	100	0.36	-	-
	Dryer section	90	0.32	1,069	3.85
	Coating and finishing	40	0.14	153	0.55
Others	Other processes (effluents, compressed air)	60	0.22	153	0.55
Total		530	1.91	1,528	5.50

Source: own assumptions based on (Blum et al. 2007; Brand et al. 2005; European IPPC Bureau 2010; IUTA et al. 2008)

Note that the average values used for the modeling may differ significantly from the situation in individual paper mills, because:

- The SEC may differ significantly, depending on the paper grade produced (see for example IUTA et al. 2008).
- Certain process steps such as pulp drying or pulping are not required in integrated paper mills. Also waste heat from refining and grinding may be used in the papermaking process in integrated mills.
- The number of finishing steps differs (e.g. calendaring, coating).

- The structure and quality of the fibers.
- The past implementation of EEM.

However, the publicly available data does not allow us to further differentiate paper grades or integrated from non-integrated mills. Indeed, the assumed average values reflect a realistic situation in an "average" German paper mill taking the shares of the different paper grades in Germany into consideration.

2.5 Review of energy-efficient technologies

2.5.1 Chemical pulp

Black liquor gasification (1). Chemical pulp plants are favorable for the production of a variety of "green" chemicals as well as bio-fuels. This extension of a pulp plant into a bio-refinery would allow improved use of wood residues. Bio-refining is intensively discussed in the literature, especially in connection with black liquor gasification (Joelsson, Gustavsson 2008).

In a conventional chemical pulp plant, the black liquor, a mixture of lignin and chemicals, is concentrated and then burned in a recovery boiler. These boilers have strict thermodynamic limitations resulting in a low electrical efficiency of about 10 to 15% (European IPPC Bureau 2010). Alternative processes like a gasification of black liquor allows a combined cycle to be used, resulting in higher efficiencies for electricity generation (Naqvi et al. 2010). It is assumed that this could even double electricity generation, while heat production remains constant (IEA 2008a). Although demonstration plants are in operation, it is still a challenge to integrate the technology into the production process of a chemical pulp plant.

2.5.2 Mechanical pulp

Energy demand for the production of mechanical pulp is characterized by a high consumption of electricity for the wood grinding or refining, and releasing considerable amounts of waste heat, as 95% of the mechanical energy used is transformed into heat. Consequently, energy efficiency improvements concentrate on efficient grinding and refining as well as waste heat use.

Heat recovery (TMP, GW) (2). In integrated plants, the waste heat can be used in the paper machine. Depending on the process design and grinding intensity, about 20 to 40% of the electricity consumed can be recovered in the form of steam, and a further 20 to 30% in the form of hot water (European IPPC Bureau 2010). This concept, however, is standard in new plants and thus the remaining diffusion potential is limited.

Effluent water from the bleaching process is a potential heat source at a lower temperature level which was not as extensively used in the past. However, for integrated paper mills with a high demand for process heat, it might be cost-effective. Also, certain heat sinks are not fully exploited, like the preheating of bark or sludge that is burned in the bark boiler (Ruohonen et al. 2010).

High-efficiency grinding (GW) (3). Different concepts aim at EEI of wood grinding design. One of these is to use fully metallic grinders with optimized grinding surface patterns instead of stone or ceramics. First results from pilot plants at the Finnish research institute KLC attained electricity savings of around 50%, while pulp characteristics were unchanged and production capacity doubled (Leinonen 2006).

Enzymatic pre-treatment (TMP) (4). Pre-treating woodchips using enzymes reduces the mechanical energy needed for wood processing. A variety of processes and enzymes have been discussed since the 1980s, but no single dominant process design has evolved so far (Viforr 2008). New approaches combine the use of enzymes with low-intensity refining to improve the penetration of the enzymes into the wood. Electricity savings are expected of 10 to 40 %, depending on the type of enzymes and the process design (Viforr 2008).

High-efficiency refiner, pre-compression and use of wood shavings (TMP) (5). Many technologies aim to improve refining efficiency. In the past 20 years, research activity was aimed at refining and several innovations entered the market. One example is the high-efficiency refiner RTS from Andritz, which is claimed to save up to 10-15% of energy compared to conventional disc refiners (Sabourin 2006). Gorski et al. (2010) found that compression prior to refining could reduce specific electricity demand by up to 20%, and the first applications are commercially available. Another option is the use of wood shavings instead of wood chips, which could reduce electricity consumption by around 25% (Viforr, Salmén 2005).

2.5.3 Pulp from recovered fibers (RCF pulp)

High consistency pulping (6). In pulping, most of the energy is used to circulate and move the slurry. Consequently, by increasing the consistency of the slurry, the electricity demand of the pulper could be decreased, due to reduced mass flow. Electricity savings of 2 to 10 kWh per ton of de-inked pulp are expected if the solids content is increased from a typical 5-7%[21] to 20% (Blum et al. 2007). High-consistency pulping is already used in a number of plants in Germany. Further savings in pulping are possible if the spiral coil is hydro-dynamically optimized and driven at lower speed. Depending on the explicit process design, these optimizations could result in an EEI of up to 20% (Brettschneider 2007).

[21] The different levels of solid content (see number 7 and 9) refer to different process steps.

Efficient screening (7). Improvements were made in the field of screening and filtering. Increasing the slurry consistency from 1.5 to 2.5% results in considerable EEI (Blum et al. 2007). Further optimization of the screening process showed energy savings of 5 to 30 %, depending on the plant characteristics (Brettschneider 2007).

Waste heat recovery from bleaching (8). Bleaching waste water has an increased temperature. This heat can be recovered to preheat fresh water. Steam savings of around 30 MJ/t of pulp are reported (Blum et al. 2007). According to Blum et al. (2007), several plants in Germany already apply this technology.

De-inking flotation optimization (9). The most important process step in the de-inking process is flotation. While the solids content is very low, at around 1%, chemicals are added and air separates the ink particles from the fibers. Energy demand during flotation is mainly a result of pumping slurry. Better demand-related control of pumps as well as a reduced flow speed enable significant energy savings.

Efficient dispersers (10). Dispersion is a post-treatment of fiber suspension to improve the strength and to separate remaining particles from the fibers. Energy-efficient dispersers are being increasingly used and show savings of around 20% when compared to conventional dispersers (Brettschneider 2007).

2.5.4 Paper

Efficient refiners and optimization of refining to reduce idle time (11+12). According to Blum et al. (2007), the reduction of idle running comprises a large saving potential. They expect that new refining concepts will allow reduction of the idle-running losses by up to 40%. An example of such a refining concept is the Papillon refiner (Gabl 2004). It uses a cylindrical form that separates the refining process from the fiber transportation process, resulting in a better control of the refining process. Compression refining that changes the fiber structure by compression forces could improve refining efficiency even further. Dekker (2008) expects electricity savings of up to 30% compared to conventional single disk refiners - based on results from a pilot plant. Currently, a demonstration plant has been set up and market introduction is planned (Dekker 2008).

Chemical modification of fibers (13). Chemical modification of fibers is based on a new understanding of the adhesive forces between fibers. Following conventional theory, the adhesive forces are based on hydrogen bonds, which depend on the size of the fiber surface. This in turn is increased by energy-intensive fiber refining. The alternative idea of modifying the fibers chemically instead aims to influence other binding effects besides hydrogen bonds to improve paper strength. Current research is experimenting with alternative fiber-binding processes (Erhard et al. 2010c).

The (partial) substitution of refining may result in electricity savings of about 100 kWh/t of pulp, depending on the paper grade. Further, given a similar paper strength, the water retention value is lower than for refining, which results in lower energy demand for dewatering and drying (Erhard et al. 2010b; Stumm 2007). Furthermore, the density of the paper web could be reduced, which resulted in fiber savings of 5 to 15 % (Erhard et al. 2010a). These considerations do not include the energy needed to produce the chemicals. The technology could have considerable co-benefits, like reduced pulp costs and increased productivity. The technical feasibility in a large-scale plant and the market entry is expected for the coming years. It is assumed that it will be possible to upgrade a paper machine already in use.

Steam box (14). The steam box preheats water to reduce its viscosity, improving dewatering efficiency and allowing higher dry contents to be attained in the press section. As a result, less water needs to be evaporated in the dryer section. (Blum et al. 2007; Bos, Staberock 2006). It is assumed that a temperature increase of 10 K results in increased of dry contents of about 1 % (IUTA et al. 2008). Voith mentions steam savings of up to 4 % (Voith 2006). Steam boxes are common in modern paper mills.

Shoe press (15). The shoe press is integrated into the paper machine's press section, improving dewatering of the paper web by an increased pressing surface between the two rollers. This reduces the demand for thermal drying, while the electricity demand increases slightly. As rule of thumb, it is assumed that a 1 % increase in the paper web's dry content results in 5 % steam savings in the drying section (Bos, Staberock 2006). Apart from energy savings, shoe presses have other benefits, such as increased production capacity, improved product quality and space savings due to shorter thermal drying sections. These are the main drivers for technology adoption (Luiten, Blok 2003). Although, shoe presses are widely diffused, further potentials for application remain.

New drying techniques (16). As drying the paper web is the major energy-consuming process in a paper mill, the R&D efforts for EEI are concentrated on the drying section. The literature discusses various new drying concepts that might result in EEI. However, contradictory opinions about the possible energy savings are observed, as well as uncertainty about market entry. Examples are steam/air impingement drying, condensing belt drying and impulse drying.

Impulse drying combines the effects of pressing and contact drying by running the wet paper web through a heated pressing nip (150-500 °C, 100 ms, 0.3-7 MPa), resulting in a steam explosion at ambient conditions behind the pressing nip. Although very effective, this drying method is offset by low achievable paper quality. Expected EEI range from 20 % (Martin 2004a) to 0 % (European IPPC Bureau 2010). Again, productivity increases are the primary motivation for research. Despite 25 years of research activities, including several pilot plants, the technical barriers[22] have not yet been overcome (Luiten, Blok 2004).

Another technology is steam and air impingement drying, where superheated steam or hot air (~300 °C) is blown at high speed against the paper web. Laurijssen et al. (2010) do not expect significant energy savings compared to conventional drying cylinders. The evaporated water would be available as steam that could be used for heat recovery. Despite long research activity in this field, market entry is still uncertain (De Beer et al. 1998; Laurijssen et al. 2010).

For condensing belt drying, steam savings of around 10-20% are expected and two commercial plants have been running in Finland (since 1996) and South Korea (since 1999) (Martin et al. 2000a). However, in the past years no further plants were equipped with condensing belt drying (Laurijssen et al. 2010).

Even if one of the discussed drying technologies would be commercially viable, the diffusion through the paper machine stock would take a long time, as the dryer section of a paper machine typically has a lifetime of 20 to 40 years (Laurijssen et al. 2010).

Heat recovery and integration (17). Heat recovery and the use of waste heat are widespread in the paper industry. Large potentials are found in the use of waste heat from refiners and grinders, but also from the dryer section in the paper machine and the effluent water. In particular, the use of low temperature heat still shows further potential, but also the steam system is often not adequately optimized.

The LfU and PTS (2002) conducted an energy audit in an integrated German paper mill focusing on the use of low temperature waste heat. Using pinch-analysis, they found several opportunities for waste heat use that would amount to steam savings of up to 25 %. These included the external use of heat for district heating. All measures had a payback time of less than four years, while many were even shorter than one year. Further studies confirmed these saving potentials. Another study found a cost-effective saving potential of 7 to 13 % by optimizing and replacing heat exchangers in three paper machines (Sivill et al. 2005a; Sivill, Ahtila 2009a). A recent thermodynamic optimization of Dutch paper mills reported potentials to reduce the steam demand for paper drying by 32 % (Laurijssen et al. 2010). An optimization of heat flows in five

[22] Blistering on the paper surface as well as delamination.

paper mills in Germany resulted in average steam savings of 9.3 % (IUTA et al. 2008). Bujak (Bujak 2008b) empirically finds fuel savings of 8 % due to modernizing the steam system in a corrugated board mill in Poland. The investment of around 100,000 euros showed a payback time of one year and had as a co-benefit a lower consumption of water and chemical agents.

A survey among 46 paper mills in Germany (IUTA et al. 2008) found that around 70% of firms use waste heat from the paper machine to heat the supply air. The use of waste heat to preheat clear water and white water is implemented by 30 and 40% of the firms, respectively. Waste heat from the coater is less used. 20 % of the firms use it to preheat the supply air and only 5 % to preheat the hot water.

2.6 Scenario analysis and results

2.6.1 Scenario definition

For the scenario analysis, alternative “futures” are constructed, based on differing assumptions of scenario parameters. Comparing the scenarios enables to learn about the potential impact of various assumptions and developments.

The study assesses EEI potentials through the diffusion of energy-efficient technologies. We are defining scenarios by changing the speed of technology diffusion, which is used as an exogenous parameter. The differences between the resulting energy demand in the scenarios equal the EEI potentials. An overview of the scenarios and the related saving potentials is given in Figure 7. Four scenarios are considered and described in the following.

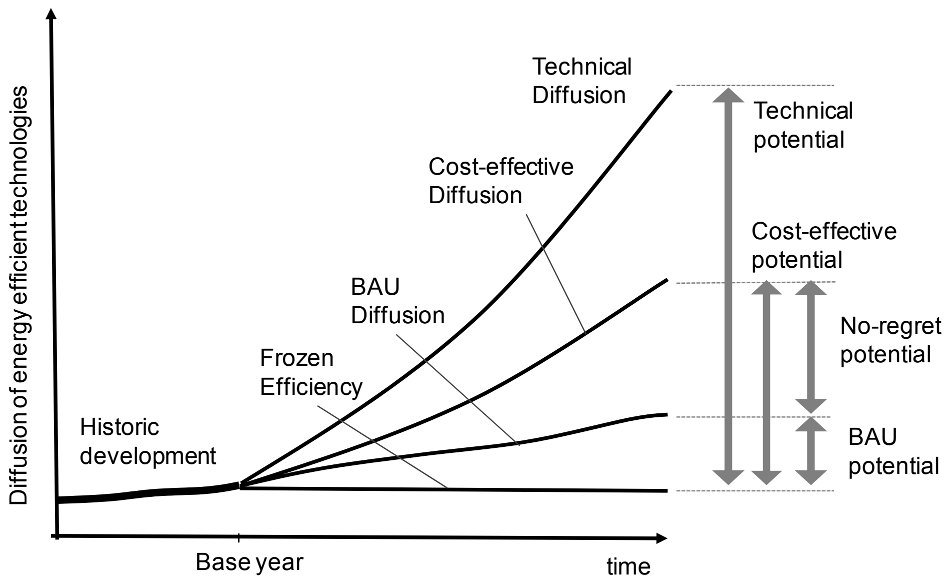

Figure 7: Definition of diffusion paths and saving potentials

Frozen efficiency scenario. For the *frozen efficiency scenario,* energy intensity remains at the 2007 level, see Table 6. It is the baseline to estimate the EEI potentials. Energy demand in this scenario is only impacted by changes in the production output.

Business-as-usual (BAU) diffusion scenario. The *BAU* scenario assumes that barriers to technology diffusion remain high in the future and represents an extrapolation of past trends. The exogenous technology diffusion rates are based on the past development as well as on discussions with paper industry representatives. These diffusion rates are typically lower than they would be in case firms decided purely on the basis of cost-effectiveness (see Chapter 2.3.2).

Cost-effective diffusion scenario. The *cost-effective diffusion* scenario assumes *homo economicus* behavior and the implementation of all cost-effective technologies. Cost-effectiveness is assessed on the basis of the investments annuity, using a discount rate of 15%. It implies the removal of all non-financial barriers. If the technology is calculated to be cost-effective, the exogenous diffusion path from the *technical scenario* is considered. In case it is not cost-effective, the diffusion path from the *BAU scenario* is assumed. This approach ensures that, even if the technology is not cost-effective for all mills, it is applied in a certain number of firms, mainly because it might be cost-effective in a niche of technology adopters, as a result of heterogeneity.

The intensity of barriers in this scenario depends on the level of the discount rate. For example, a discount rate of around 15% implies the above mentioned *homo economicus* investment behavior. However, a higher discount rate of 30 or even 50 % would represent higher barriers. This approach of adjusting the discount rate is indeed widely used in bottom-up models to account for barriers (Worrell et al. 2004). In order to show the impact of the discount rate, we calculate conservation supply curves (CSC) for varying discount rates.

The definition of costs has important implications on the cost-effectiveness. Instead of using the full investment costs of new technologies, we used differential costs. These are calculated as the difference between the costs of conventional technology and energy-efficient technology delivering the same energy service. Consequently, the investment in new technologies is only allowed in case the existing technology has to be replaced. In other words, there is no premature technology replacement and the stock-turnover rate is not adjusted. Furthermore, we exclude co-benefits, such as quality or capacity improvements. Considering co-benefits could further improve the cost-effectiveness of many technologies (for a discussion of co-benefits, see Worrell et al. 2003).

Technical diffusion scenario. The fourth scenario is named *technical diffusion*. It does not include cost considerations for the diffusion of technologies. No premature stock replacement is allowed and thus the diffusion can still be considered “realistic”, although ambitious. Given the long lifetime of certain processes, it can take a long time for the full saving potential to be realized, even in the technical scenario. The scenario may therefore be termed a "realistic" technical diffusion scenario as it does not include completely unrealistic technology options and diffusion paths.

2.6.2 Scenario input parameters

Table 5 and Table 6 give an overview of the resulting assumptions on the modeling input data per EEM. The EEM are sorted according to process and process step they are allocated to.

The relative saving potential is given as the share of energy demand of the corresponding process step. The absolute specific saving potentials are defined per production output of the corresponding process. All costs are defined as differential costs, i.e. the difference between the costs of conventional technology and the energy-efficient option. As cost data is rarely found in the literature, we mainly relied on estimates by representatives from paper mills and technology providers. The specific costs are input to the model, while the payback times help to more easily judge the cost effectiveness of the EEM. As specific investment costs typically fall when technologies diffuse and become more mature, we have included a cost reduction factor, which varies according to the maturity of the EEM.[23] The economic lifetime is used for the investment calculations and is not to be confused with the real technology lifetime, as given in Table 6.

The exogenous assumptions on technology diffusion are given in Table 6. The future diffusion is derived from literature sources (as described in Chapter 2.5) and discussions with experts from paper producing firms, technical research institutes and technology suppliers. Issues like the technology lifetime and the replacement cycle are taken into account. These assumptions may include uncertainties, but a scenario is not a forecast, but rather a method to assess the impacts of different assumptions on future developments. For some technologies, even in the technical scenario, the diffusion remains low. This is mainly due to technical process restrictions and heterogeneity in the process. Enzymatic pre-treatment, for example, is applied in the TMP process, which only accounts for 30 % of all mechanical pulp production plants.

Further model input is the SEC per process in the base year 2007 as discussed and presented in Chapter 2.4.

[23] Ideally this should not be a simple factor but rather follow the "experience curve" methodology as outlined for example by Weiss et al. (Weiss et al. 2010) . However, as virtually no such empirical analyses exist for the considered technologies (Jardot et al. 2010), learning rates would have to be assumed and the more sophisticated approach would probably not result in more robust results.

Table 5: Summary of technology assumptions: specific saving potentials and costs per energy-efficiency measure

Process	Process step	Energy-efficiency measure (EEM)	Specific saving potential [b]				Differential costs [c]				
			Electricity		Fuels		Initial costs (2007)	Cost reduction	Running costs	Payback period [d] (2007)	Economic lifetime
			[%][e]	[MJ/t]	[%][e]	[MJ/t]	[€/t]	[%/a]	[€/ta]	[a]	[a]
Chemical pulp	Chemical pulp	1 Black liquor gasification	16	2,000	-	-	440.0	1.6	4.7	15.0	10
Mechanical pulp	TMP refiner and GW	2 Heat recovery (TMP, GW)	-	-	38	3,475	35.9	0.0	-	1.2	10
	Grinding (GW)	3 High efficiency grinding (GW)	40	2,592	-	-	352.5	1.6	-	8.0	5
	TMP refiner	4 Enzymatic pre-treatment	30	1,862	-	-	433.7	1.6	2.8	15.0	10
	TMP refiner	5 Efficient refiner and pre-treatment	20	1,552	-	-	105.5	1.0	-	4.0	10
Recovered fibers	Pulping	6 High consistency pulping	14	20	-	-	2.4	0.4	-	7.0	10
	Screening	7 Efficient screening	36	65	-	-	5.5	0.4	-	5.0	10
	Bleaching	8 Heat recovery from bleaching	-	-	6	30	1.3	0.4	-	5.0	10
	De-inking	9 De-inking flotation optimization	17	50	-	-	0.9	1.0	-	1.0	10
	Concentration	10 Efficient dispersers	15	22	-	-	1.1	0.4	-	3.0	10
Paper	Refiner	11 Efficient refiners	30	118	-	-	15.2	1.4	-	7.6	10
	Refiner	12 Optimization of refining	16	75	-	-	0.6	0.0	-	0.5	10
	Refiner, press, drying	13 Chemical modification of fibers	15/40[a]	164	5	185	4.1	1.0	3.0	3.0	10
	Drying section	14 Steam box	-	-	5	180	4.0	0.4	-	2.6	10
	Drying section	15 Shoe press	-	-	12	480	28.9	1.0	-	7.0	10
	Drying section	16 New drying techniques	-	-	20	667	86.0	1.6	-	15.0	10
	Paper	17 Heat recovery and integration	-	-	20	1,071	13.8	0.0	-	1.5	10

[a] 15 % is for the press section and 40 % for the refiner

[b] Main sources for specific saving potential: 1: double electricity generation (IEA 2008a); 2: 20 to 40% of electricity consumed (European IPPC Bureau 2010); 3: around 50% electricity savings (Leinonen 2006); 4: 10-40% electricity savings expected (Viforr 2008); 5: 10-15% (Sabourin 2006), up to 20% (2010), around 25% (Viforr, Salmén 2005); 6: 2-10 kWh/t deinked pulp (Blum et al. 2007), up to 20% (Brettschneider 2007); 7: 5-30% (Brettschneider 2007); 8: Steam savings of around 30 MJ/t pulp (Blum et al. 2007); 9: assumption based on product description; 10: 20% (Brettschneider 2007); 11: reduction of idle-running losses by up to 40% . (2007); 12: 30% expected savings (2008); 13: savings estimated from expert interview; 14: steam savings of up to 4 % (Voith 2006); 15: 14% steam savings found in case study (IUTA et al. 2008); 16: Wide range of technologies, e.g. for impulse drying the expected savings range from 20 % (Martin 2004c) to 0 % (European IPPC Bureau 2010); 17: 7 to 13% (Sivill et al. 2005b; Sivill, Ahtila 2009b), steam savings of up to 25% (2002), 32% (Laurijssen et al. 2010), 9.3% (IUTA et al. 2008) and 8% (Bujak 2008a). For a more detailed description of sources please see section 2.5.These sources provided the basis for the assumed values and were verified in expert interviews resulting in deviating assumptions for some EEM in the table.

[c] Only very limited empirical data is available for costs. The costs were mainly estimated based on typical payback periods mentioned in interviews with plant managers and technology experts. Assuming typical energy prices, the specific costs can be calculated from the payback period. The annual cost reduction was assumed to be higher for less mature technologies.

[d] Main sources: 10: about 1 year from case study (IUTA et al. 2008); 15: 9 years from refurbishment case study (IUTA et al. 2008); 17: many <1 year and max 4 years (LfU, PTS 2002) 1 year (Bujak 2008c)

[e] The relative saving potential is related to the fuel/electricity demand of the corresponding process step.

Table 6: Summary of technology assumptions: Technology diffusion scenarios per energy efficiency measure

Process	Process step		Energy efficiency measure (EEM)	Technology life cycle	Technical lifetime [b] [a]	Diffusion 2007 [a, b] [%]	Diffusion BAU scenario [b]		Diffusion technical scenario [b]	
							2020	2035	2020	2035
Chemical pulp	Chemical pulp	1	Black liquor gasification	R&D	20	0	0	16	5	45
Mechanical pulp	TMP refiner and GW	2	Heat recovery (TMP, GW)	Standard	20	92	95	98	100	100
	Grinding (GW)	3	High efficiency GW	Demonstration	5	0	4	10	25	67
	TMP refiner	4	Enzymatic pre-treatment	R&D	15	0	0	5	10	17
	TMP refiner	5	Efficient refiner and pre-treatment	Commercial	20	7	12	18	22	33
Recovered fibers	Pulping	6	High consistency pulping	Commercial	20	30	43	58	70	100
	Screening	7	Efficient screening	Commercial	20	20	30	42	55	100
	Bleaching	8	Heat recovery from bleaching	Commercial	20	20	30	42	55	100
	De-inking	9	De-inking flotation optimization	Demonstration	15	0	13	25	40	100
	Concentration	10	Efficient dispersers	Commercial	15	30	43	60	83	100
Paper	Refiner	11	Efficient refiners	Commercial	20	5	13	22	30	80
	Refiner	12	Optimization of refining	commercial	20	30	45	60	85	100
	Refiner, press, drying	13	Chemical modification of fibers	R&D	20	0	3	13	10	70
	Drying section	14	Steam box	Standard	15	64	67	70	80	80
	Drying section	15	Shoe press	Standard	20	57	63	69	70	81
	Drying section	16	New drying techniques	R&D	20	0	5	16	15	75
	Paper	17	Heat recovery	Standard	20	50	65	80	100	100

[a] Diffusion is defined as the share of technology stock that is equipped with the related energy efficiency measure

[b] There are only very few empirical sources for the technical lifetime and diffusion (2007 as well as scenarios). They result from discussions with experts from paper producing firms, technology providers and research institutes and clearly involve a substantial degree of uncertainty. Often only qualitative information was available. In this case we discussed it in Section 2.5. The scenarios business-as-usual (BAU) and technical diffusion are presented in Section 2.6.1.

In order to calculate the total EEI potentials for the entire paper industry, we take interactions among technologies into account. These might occur in two ways. First, technologies are alternatives (which mutually exclude each other) and second, two technologies address the same energy flow. Alternative technologies are accounted for by restricting the maximum diffusion of the technologies. In the second case, the technology implemented first reduces the energy flow and, simultaneously, the remaining saving potentials of the technologies implemented afterwards. To account for this effect, we calculated the technology saving potentials step-by-step, accounting for changes in the addressed energy flow. Table 7 shows the saving options concerned by interactions and the implementation order assumed. While this approach is clearly a simplification of the real circumstances in paper producing firms, it does capture the main effects of technology interaction, which is sufficient for our interpretation of the scenario results at national level.

Table 7: Assumed implementation order of energy-efficiency measures (EEM) addressing the same energy flow

Process	**Process step**	**Order of EEMs**
Paper	Refiner	12, 11, 13
Paper	Drying section	15, 14, 13, 16, 17
Mechanical pulp	Refining and grinding	5, 4, 3, 2

Other input parameters like the production output, the energy and emission certificate prices and the CO_2-intensity of energy carriers are shown in the appendix and are derived from a recent energy scenario study prepared for the German government (Prognos et al. 2010). We use the average CO_2-intensity of German electricity generation to calculate CO_2 emissions based on energy demand. It changes over time, due to fuel switch and efficiency improvement in the electricity generation sector.

The total level of energy demand is influenced by production output per process. The future paper production was estimated together with experts from the paper industry at the level of paper grades.[24] The assumed development of the different pulp products was derived from the paper production taking paper recycling and the use of fillers into account.[25] Import and export shares are assumed to remain constant. The resulting production per process is given in Table 8. The shift to recovered fibers and the increased use of fillers reduces the demand for virgin pulp

[24] The assumed average annual growth rates are: graphical paper 0.3%, packaging paper 0.9%, tissue paper: 0.9%, technical paper: 1.2%.

[25] The share of "fillers" increases from 17 to 19% and the share of recycled paper from 69 to 71% between 2009 and 2035.

over time and, according to our assumptions, also the production in Germany.

Table 8: Production output as assumed for all scenarios by process [kt]

Process	2007	2010	2015	2020	2025	2030	2035
Chemical pulp	1,545	1,520	1,520	1,490	1,346	1,217	1,100
Mechanical pulp	1,456	1,383	1,383	1,355	1,225	1,107	1,001
RCF pulp	15,737	15,378	16,476	17,242	17,785	17,929	17,799
Paper	23,319	22,509	24,008	25,040	25,536	25,567	25,280

Source for 2007 values: (VDP 2010)

2.6.3 Scenario results

The resulting energy savings across all four processes are given in Figure 8. Excluding economic considerations, the EEI potential is estimated at 21 % for fuels and 16 % for electricity when comparing the *technical diffusion scenario* to the *frozen-efficiency scenario* until 2035. The cost-effective EEI potential amounts to 15 % for fuels and 13 % for electricity, when compared to the *frozen-efficiency scenario*.

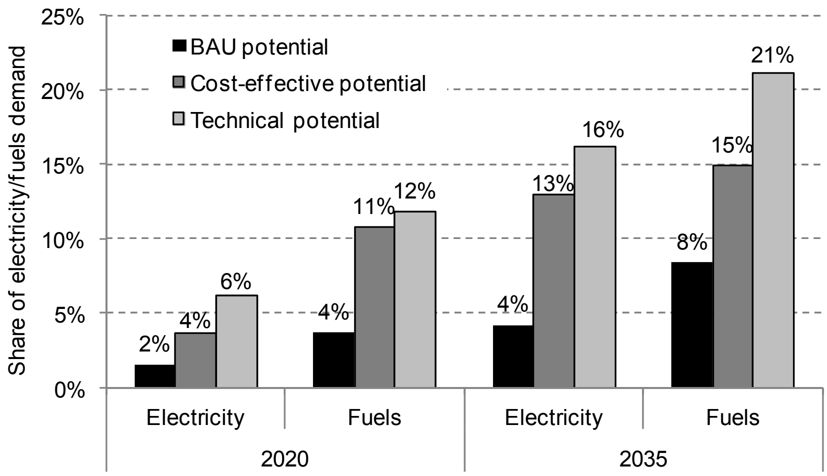

Figure 8: Resulting saving potential across all processes by scenario as share of the electricity /fuel demand in the frozen-efficiency scenario

Figure 9 depicts the EEI potentials in relation to the total electricity and fuel demand. While the *frozen-efficiency* energy demand increases slightly until it peaks around 2025, the total energy demand falls continuously when the cost-effective or technical potentials are exploited. For fuel savings, the cost-effective scenario is closer to the technical scenario in most years than is the case for electricity savings. There are two main explanations. First, the higher increase in fuel prices compared to electricity prices (see Table 11) and, second, fuel savings imply a reduction of direct CO_2 emissions for which the producer is required to deliver emission certificates.[26]

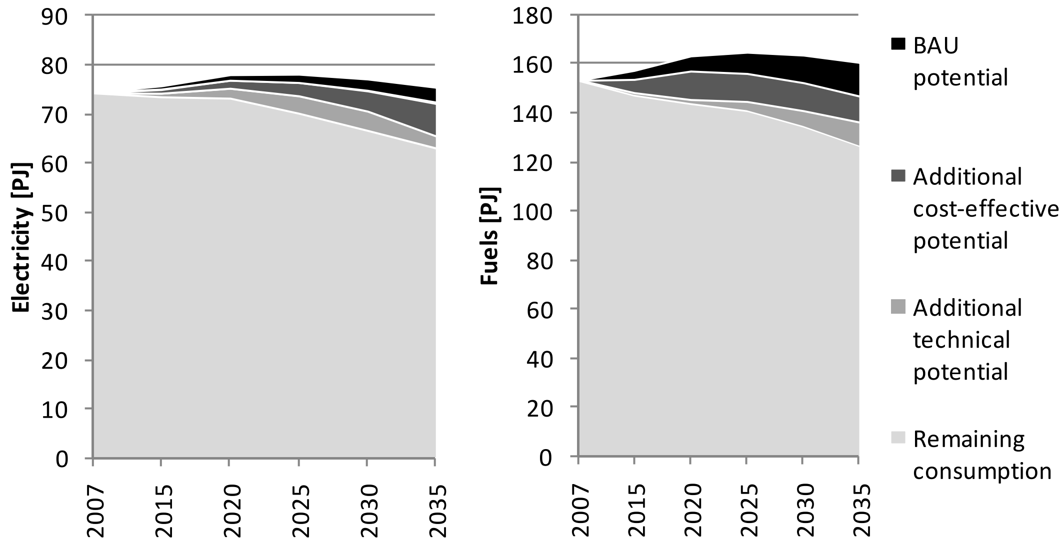

Figure 9: Energy demand of all processes in the *frozen-efficiency* scenario and resulting saving potentials by scenario

The contribution of single technologies to the aggregated EEI potentials is given in Table 9. High impact options are heat recovery and integration, new drying techniques and the chemical modification of fibers.

[26] Note that the CO_2 emission certificate price, which is already integrated in the assumed electricity prices, will also affect electricity prices.

Table 9: Technical EEI and CO_2 mitigation potentials by process and EEM in relation to the frozen-efficiency electricity/fuel/heat demand

	Energy-savings [a]						CO_2 mitigation [a]		
	Electricity [PJ]		Fuels [PJ]		Electricity [%]	Fuels [%]	[kt CO]		[%]
	2020	2035	2020	2035	2035	2035	2020	2035	2035
Pulp and paper industry	4.85	12.25	19.25	33.84	16%	21%	1,803	2,985	19%
Chemical pulp	0.15	0.99	-	-	39%	0%	25	108	11%
Black liquor gasification	0.15	0.99	-	-			25	108	
Mechanical pulp	1.45	2.47	0.38	0.28	31%	14%[b]	264	282	37%
Heat recovery (TMP, GW)	-	-	0.38	0.28			19	14	
High efficiency grinding (GW)	0.88	1.74	-	-			148	189	
Enzymatic pre-treatment	0.25	0.32	-	-			42	35	
Efficient refiner and pre-treatment	0.32	0.41	-	-			54	45	
RCF pulp	1.07	2.33	0.18	0.43	14%	4%	189	275	12%
High consistency pulping	0.14	0.25	-	-			23	27	
Efficient screening	0.39	0.92	-	-			66	101	
Heat recovery	-	-	0.18	0.43			9	21	
De-inking flotation optimization	0.34	0.89	-	-			58	97	
Efficient disperser	0.20	0.27	-	-			33	29	
Paper	2.18	6.46	18.70	33.13	13%	24%	1,325	2,320	19%
Efficient refiners	0.74	2.24	-	-			124	244	
Optimization of refining	1.03	1.33	-	-			173	144	
Chemical modification of fibers	0.41	2.90	0.46	3.28			93	476	
Steam box	-	-	0.72	0.73			37	35	
Shoe press	-	-	1.60	2.95			82	144	
New drying techniques	-	-	2.50	12.64			128	616	
Heat recovery and integration	-	-	13.41	13.54			688	660	

[a] The relative potentials are related to the electricity/fuel demand or CO_2 emissions of the process in the frozen-efficiency scenario. The CO_2 emissions comprise direct emissions from fuels combustion and indirect emissions from electricity generation

[b] The 14% fuel savings for mechanical pulp represent the increase in the excess-heat already recovered in this process.

The resulting specific fuel and electricity demand in the four scenarios is shown in Table 10. The SEC for RCF pulp changes slowly, which is the result of the fact that EEI potentials are distributed among a large number of smaller options. These are difficult to account for in our analysis so that besides the five EEM considered further potentials are probably available. Furthermore, RCF process steps also depend on the paper grade. For example, bleaching and de-inking are not applied in the production of packaging paperboard. Thus, the presented average savings will be different for different paper grades.

For chemical pulp, the SEC for fuels remains constant, because we only considered black liquor gasification as EEM, which results in a more efficient on-site electricity production (and does not affect final energy demand). Chemical pulp is mainly produced in two relatively new plants in Germany, which already apply recent technology. Although this does not imply that no EEI potentials are available, they are relatively low compared to the other processes.

Table 10: Resulting specific electricity and fuel consumption (SEC) by scenario and process

	Specific electricity consumption (SEC) [GJ/t]						
	Base year	BAU diffusion		Cost-effective diffusion		Technical diffusion	
Process	**2007**	**2020**	**2035**	**2020**	**2035**	**2020**	**2035**
Chemical pulp	2.3	2.3	2.0	2.3	2.0	2.2	1.4
Mechanical pulp	7.9	7.7	7.4	7.6	7.2	6.8	5.5
RCF pulp	0.9	0.9	0.9	0.9	0.8	0.9	0.8
Paper	1.9	1.9	1.8	1.8	1.7	1.8	1.7

	Specific fuel consumption (SEC) [GJ/t]						
	Base year	BAU diffusion		Cost-effective diffusion		Technical diffusion	
Process	**2007**	**2020**	**2035**	**2020**	**2035**	**2020**	**2035**
Chemical pulp	12.6	12.6	12.6	12.6	12.6	12.6	12.6
Mechanical pulp	-2.0	-2.1	-2.2	-2.3	-2.3	-2.3	-2.3
RCF pulp	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Paper	5.5	5.3	5.0	4.8	4.6	4.8	4.2

Resulting costs for CO_2 emissions abatement

As energy efficiency is regarded as a major greenhouse gas (GHG) abatement option, often available at low cost, we also discuss the resulting abatement costs. The abatement cost curve[27] shows the abatement potential available by 2035 and its related costs for a discount rate of 15 %. The discount rate is used to calculate the annuity of the distinct investments and thus influences the specific costs of CO_2 abatement (see Figure 10*)*. It is not used to discount all financial flows to the base year 2008. The specific costs comprise both avoided energy costs as well as CO_2 emission certificate costs.

Figure 10 shows that most of the EEM are cost-effective for the given assumptions. However, the total cost-effective potential depends largely on key abatement options like “new drying techniques”.

The distinction into three classes of technologies, namely process optimization, best available technology (BAT) and process innovations not only allows conclusions to be drawn on policy recommendations, but also on the reliability of technology data. For process innovations, data mainly originates from experience gained in pilot plants and these were extrapolated to industrial applications, taking the expectations of technology experts into consideration. Process opti-

27 For a critical review of the use of abatement cost curves for policy-making see (Kesicki, Strachan 2011).

mization and BAT assumptions are considerably more reliable as they are often based on results from case studies in paper mills.

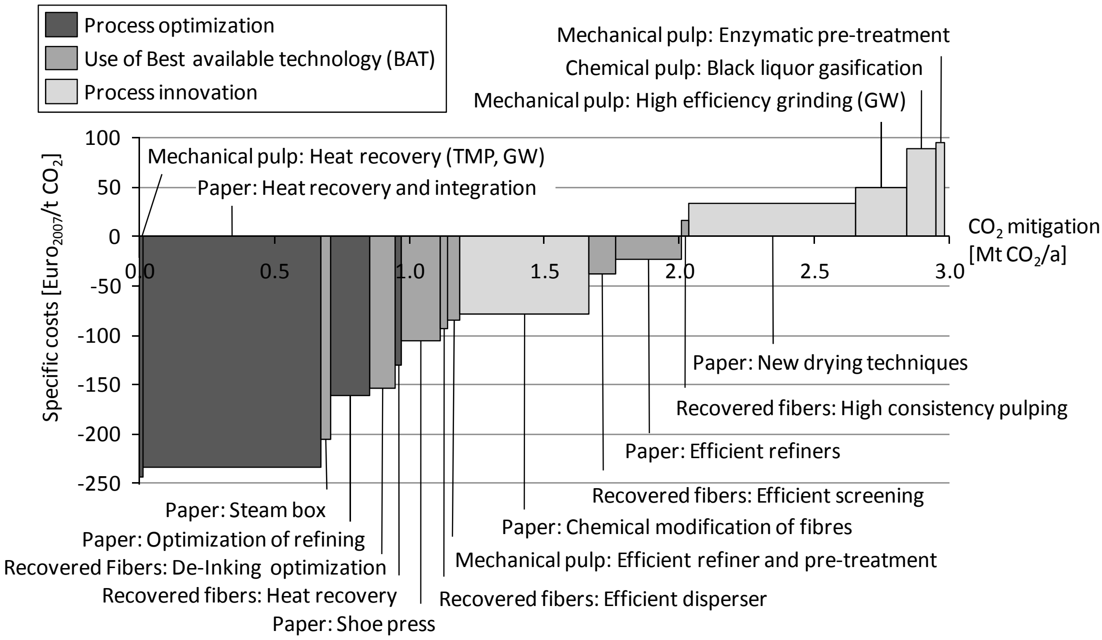

Figure 10: CO_2 abatement cost curve for 2035 (discount rate 15 %)

Sensitivity analysis of cost-effectiveness

For a better understanding of the costs-effectiveness, we calculate conservation supply curves (CSC)[28] for varying discount rates and years. Changes in other factors influencing the specific costs, like energy prices, potentials for EEI, or investment costs result in proportional changes in the specific conservation costs. The curves are similar to Figure 10, except that they are not related to CO_2 emissions but to energy demand.[29]

The discount rate is often used in energy demand models as an ad-hoc way to consider barriers to cost-effective EEM. A higher discount rate represents barriers like information deficits, capital constraints, capacity and knowledge constraints, or more generally bounded rationality. Figure 11 shows how an increasing discount rate increases the slope of the CSC and consequently reduces the number of cost-effective saving options. However, the resulting potential is not fundamentally different when comparing a 15 % with a 50 % discount rate. The main reason is that the EEM with very short payback times remain cost-effective even for high discount rates.

[28] For a broader discussion of CSC, see (Loulou et al. 2004; Stoft 1995).

[29] Using the underlying CO_2 intensity of energy carriers as shown in Table 13 allows converting one curve into the other.

Discussions with paper mill representatives showed that a payback time of 2 years is often used as a threshold for investment decisions, while at the same time, most of the equipment has a technical lifetime of more than 10 years. However, longer payback times are accepted for strategic investments that also improve the production process and go beyond pure energy-efficiency motivated retrofits (see also Cooremans 2011).

Figure 11 also shows the change of the CSC depending on the year. Generally, technologies become more cost-effective as a result of falling investment costs and increasing energy prices. The size of the potentials also increases, due to continuing technology diffusion.

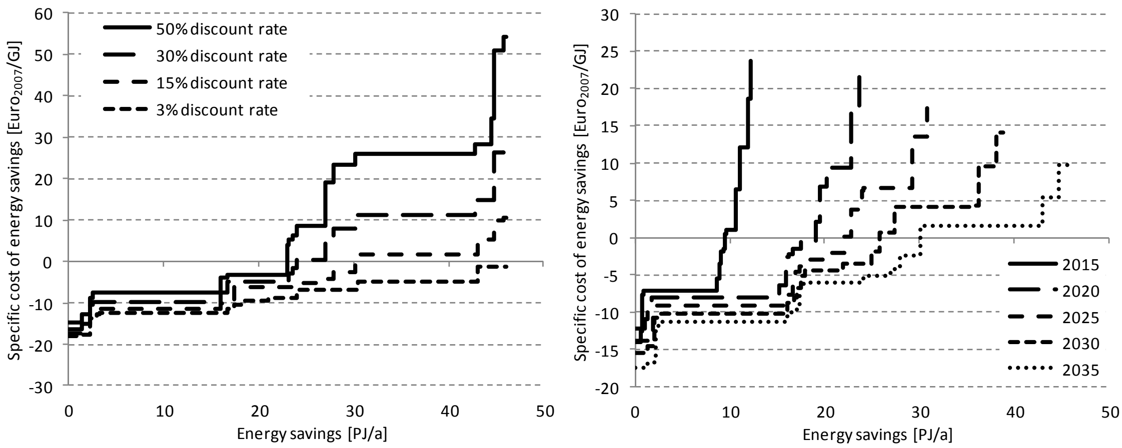

Figure 11: Sensitivity of Conservation supply curves to different discount rates for the year 2035 (left) and to different years with a 15% discount rate (right)

2.7 Discussion and conclusions

2.7.1 Energy-saving potentials

The analysis demonstrates that further EEI potentials exist in the paper industry. Although the SEC of paper production has hardly improved in the past 15 years, new technologies are being developed that could result in considerable EEI. The analyzed 17 technologies would result in an EEI of 21% (34 PJ/a) for fuels and 16 % (12 PJ/a) for electricity until 2035 – as compared to the *frozen-efficiency* development. These EEI would result in CO_2 abatement of about 3 Mt/a, or 19 % of the frozen-efficiency development. In addition, cross-cutting technologies (not considered in this study) may result in further savings.

Technologies with the greatest EEI potentials mainly address the core paper production process. Heat integration promises a fuel-saving potential of 13.5 PJ/a, of which most is realized before 2020. Innovative drying techniques could result in substantial savings of around 13 PJ/a. However, this is a long-term option, which develops its effects only after 2020. Two options, efficient refiners and the chemical modification of fibers, contribute most to the electricity savings, with more than 2 PJ/a each until 2035.

Technology diffusion rates are critical assumptions for the calculated potentials. New technologies only enter the technology stock when old technologies are retired. Consequently, we considered the differential costs between a conventional technology and the energy-efficient technology. This assumption generally results in comparably slow technology diffusion, but low costs.

Most of the assessed technologies were found to be cost-effective, given the assumed development of energy and CO_2 prices. Cost-effectiveness was defined from a firm or decision-maker perspective, assuming a discount rate of 15 %. Given the ambitious expectations of firms on payback time, as well as the non-monetary barriers discussed, it is likely that large parts of these potentials will not be implemented in a BAU scenario.

Rising energy and CO_2 certificate prices would further improve the cost-effectiveness of the technologies considered. However, within the European emissions trading scheme (EU ETS), the paper industry is not obliged to purchase all CO_2 emission certificates, at least up to 2020, in order to maintain a level playing field with international competitors. Instead, paper mills receive a free allocation up to a certain CO_2 benchmark according to their CO_2 efficiency. From an economic theory point of view, the financial incentive to mitigate emissions as induced by the EU ETS is not affected. Firms with emissions above the benchmark are obliged to purchase certificates on the market; firms below the benchmark have the opportunity to sell the remaining certificates. In both cases, an emission certificate has the same value and thus induces the same incentive to mitigate emissions. In practice it might be different. As discussed in Section 2.3.2, the adoption of energy-efficient technologies not only depends on financial profitability, but also on a number of other factors and barriers. In a similar way as for energy prices, the incentives from emission certificate prices are also not likely to take full effect (Schleich et al. 2009). However, so far, only little empirical evidence is available for the impact of the emissions trading scheme on the paper industry. A first analysis of the impact of the EU ETS on the paper industry found that although paper mills clearly take the EU ETS into account in their technology adoption decision, other market factors are more influential (Rogge et al. 2011).

As many of the observed barriers to the adoption of energy-efficient technologies are non-monetary, additional policy instruments could further contribute to exploiting the cost-effective saving potential (no-regret potential). These range from energy management to R&D support. The close collaboration between the paper mill and the technology supplier is essential, particularly for complex process technologies. A significant share of the calculated saving potentials was due to process innovations, which still depend on successful technology development. Thus, technology suppliers represent an important target group for energy efficiency policy in the pulp and paper industry. Furthermore, risk of production interruption is a main barrier in the paper industry (Thollander, Ottosson 2008). Demonstration plants could contribute by demonstrating the reliability of energy efficiency innovations and support their market entry. Significant potentials are available also in the short term through optimization of production plants in place. The main option is a better integration of heat sources and sinks. Energy management and intensive energy audits as well as improved process control systems help exploiting these short-term potentials.

Technology-specific assessments of EEI potentials are typically unable to cover all potential possibilities for EEI. All options beyond the chosen system boundaries are excluded from the analysis (see Figure 5). Among them are fuel-switch, increased use of recycled fibers (see Nathani 2002), radical process innovations like dry-sheet forming, reduction of paper consumption[30], EEI in cross-cutting technologies and end-of-pipe solutions, like carbon capture and storage. Further, it is very likely that new innovations that were unknown at the time of this study will emerge in the future.

2.7.2 Modeling methodology

The methodology used allows a transparent comparison of the impact of different energy-efficient technologies and aggregation of EEI potentials for the entire paper industry. Explicitly considering SEC of processes and process steps improved the accuracy of the assumptions. The focus on technology diffusion over time added an important dimension to the analysis of EEI potentials, which is frequently ignored. It allowed us to distinguish between the degree of maturity of the technologies in the assumptions as well as in the results.

However, the paper industry shows a great degree of heterogeneity at the plant level with regard to specific energy demand, but also firm size and technology structure. Consequently, certain technologies are cost-effective in single paper mills, while they are still too expensive in others. This effect is not considered with the chosen approach based on average values. This becomes more important, if technology costs were considered as an endogenous variable, which they are not in our current model. In this case, further technology diffusion would result in falling costs, which again accelerates diffusion.

A further critical input is the breakdown of the average energy demand to the level of processes and process steps in Section 2.4, because the saving potential is given as a share of the energy demand in a process step. Again here, the lack of data and the heterogeneity of paper processes (e.g. among paper grades) increases the uncertainty of the results. Distinguishing paper grades in such an analysis would help to reduce the level of uncertainty, but would most likely not affect our general conclusions.

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30 For example through e-book readers, printing on demand or even in-office paper recycling (Counsell, Allwood 2006; Hekkert et al. 2002; Moberg et al. 2010)

The approach of using an adjusted discount rate to simulate barriers to energy efficiency showed certain disadvantages. Among them is the fact that a higher discount rate only increases the slope of the CSC, and the low-cost options remain cost-effective even for very high discount rates. In reality, however, even these options are not implemented in all cases, due to the existence of a variety of barriers. We assumed an exogenous diffusion rate for the BAU scenario. While this approach allowed us to extrapolate past diffusion rates on a technology level, it certainly has its inconveniences as well, among which is the non-elasticity of energy demand and technology diffusion for changes in energy prices.

Furthermore, the technology stock is not explicitly modeled by representing different vintages. Technology stock turnover is only implicitly assumed in the exogenous assumptions on technology diffusion. Explicitly considering the technology stock would improve both the transparency and the dynamics of the modeling approach. It would further allow differentiating more explicitly between technologies that enter the market via modernization and those technologies that are bound to the plant turnover. The latter would experience a slower diffusion.

2.7.3 Conclusions

In this paper we assessed options to improve energy efficiency in the German pulp and paper industry up to the year 2035. This paper combines engineering studies of energy-efficient technologies with bottom-up modeling of energy demand and saving potentials. 17 process technologies are assessed, resulting in a technical saving potential of 34 PJ/a for fuels and 12 PJ/a for electricity by 2035. These represent 21 % of the fuel demand and 16 % of the electricity demand of the pulp and paper industry. The larger part of this potential was found to be cost-effective from a firm perspective. In terms of CO_2 mitigation, these energy savings translate to 3 Mt CO_2 in 2035. The most influential technologies were heat recovery in the paper mill and the use of innovative, highly efficient paper drying technologies. In conclusion, significant saving potentials are still available in the German pulp and paper industry. However, the potentials are limited if we assume that current paper production processes would not undergo radical changes. Further savings would be possible if the system boundaries of this study were extended to include cross-cutting technologies, paper recycling or the increased replacement of fibers by less energy-intensive additives.

The modeling methodology proves useful for the analysis; however, certain potentials for improvement remain. Further insights could be gained, by explicitly considering the technology stock and the age distribution of technologies for the modeling of the technology diffusion path. Furthermore, relying on average values does not adequately represent the huge heterogeneity in the paper industry. If energy consumption data were available, differentiating among paper grades would enable more explicit consideration of the structure and niches in the paper industry. We have shown that the assessment of cost-effectiveness greatly depends on the discount rate assumed, as well as the shape of the cost curve. As long as the cost curve consists of average values of single EEM, adapting the discount rate to simulate barriers to energy efficiency is only a very rough estimation that does not adequately reflect reality. This is particularly the case when large EEM instantly become cost-effective with only little price or discount rate changes (penny-switching effect).

Appendix

Table 11: Energy carrier prices as assumed for all scenarios [€/GJ]

Energy carrier	2007	2015	2020	2025	2030	2035
Electricity	19.72	15.71	13.89	15.56	17.22	19.17
Light fuel oil	16.33	17.75	18.39	20.16	21.94	23.22
Hard coal	4.03	4.71	5.02	5.6	6.18	6.8
Lignite	4.03	4.71	5.02	5.6	6.18	6.8
Natural gas	7.69	9.47	10.28	10.97	11.67	12.36
Heavy fuel oil	7.16	11.87	14.01	15.9	17.8	18.84
Liquefied petroleum gas, refinery gas	7.69	9.47	10.28	10.97	11.67	12.36
Waste	2.01	2.35	2.51	2.8	3.09	3.4
Biomass	4.83	5.65	6.02	6.72	7.41	8.16
District heat	13.15	15.28	16.29	18.17	20.06	22.08

Source: own calculations based on reference scenario from (Prognos et al. 2010)

Table 12: Assumed development of CO_2 emission certificates for all scenarios

	2007	2015	2020	2025	2030	2035
Price EUAs [€/tCO_2]	1 *	15	20	25	30	35

* Certificate prices fell dramatically at the end of the first trading period in 2007

Source: own calculations based on reference scenario from (Prognos et al. 2010)

Table 13: CO_2-intensity per energy carrier [t CO_2 /GJ]

Energy carrier	2007	2015	2020	2025	2030	2035
Electricity *	0.179	0.172	0.168	0.151	0.133	0.109
Light fuel oil	0.074	0.074	0.074	0.074	0.074	0.074
Hard coal	0.094	0.094	0.094	0.094	0.094	0.094
Lignite	0.112	0.112	0.112	0.112	0.112	0.112
Natural gas	0.056	0.056	0.056	0.056	0.056	0.056
Heavy fuel oil	0.078	0.078	0.078	0.078	0.078	0.078
Liquefied petroleum gas, refinery gas	0.060	0.060	0.060	0.060	0.060	0.060
Waste	0.046	0.046	0.046	0.046	0.046	0.046
Biomass	0	0	0	0	0	0
District heat	0.082	0.08	0.078	0.07	0.062	0.051

Source: own calculations based on reference scenario from (Prognos et al. 2010) for electricity

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3 Adoption of energy-efficiency measures in SMEs – An empirical analysis based on energy audit data from Germany [31]

Abstract

This paper empirically investigates the factors driving the adoption of energy-efficiency measures by small and medium-sized enterprises (SMEs). Our analyses are based on cross-sectional data from SMEs which participated in a German energy audit program between 2008 and 2010. In general, our findings appear robust to alternative model specifications and are consistent with the theoretical and still scarce empirical literature on barriers to energy efficiency in SMEs. More specifically, high investment costs, which are captured by subjective and objective proxies, appear to impede the adoption of energy-efficiency measures, even if these measures are deemed profitable. Similarly, we find that lack of capital slows the adoption of energy- efficiency measures, primarily for larger investments. Hence, investment subsidies or soft loans (for larger investments) may help accelerating the diffusion of energy-efficiency measures in SMEs. Other barriers were not found to be statistically significant. Finally, our findings provide evidence that the quality of energy audits affects the adoption of energy-efficiency measures. Hence, effective regulation should involve quality standards for energy audits, templates for audit reports or mandatory monitoring of energy audits.

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3.1 Introduction

Improving energy efficiency is typically seen as a key strategy to reduce greenhouse gas emissions, especially in the short and medium term. For example the results of modeling simulations by the IEA (2011) for the year 2035, suggest that under cost-minimization about half of the cumulative emission reductions required to meet the 2°C target would have to be achieved through improved energy efficiency. In the industry sector, this share is even higher with about 60% (IEA 2011). Such an objective, however, would imply drastically accelerating progress in energy-efficiency improvements.

While engineering-economic studies (e.g. Granade et al. 2009) typically find substantial cost-saving potentials under current economic conditions for many energy-efficiency measures (EEMs), in reality, various "barriers" prevent households and organizations from realizing this potential (e.g. Worrell et al. 2009). Sorrell et al. (2004) classify these barriers into the following broad categories: *imperfect information, hidden costs, risk, access to capital, split incentives and bounded rationality.* Policies to overcome these barriers which target companies include energy management obligations or soft loan programs (Brown 2001; Jochem, Gruber 1990), subsidies for energy audits (Anderson, Newell 2004; Schleich 2004), best practice programs (Neale, Kamp 2009), energy labeling schemes and minimum standards (Garcia et al. 2007). Recent policíes also include combinations such as linking voluntary targets with energy management requirements or energy audits (Jochem, Gruber 2007; Stenqvist, Nilsson 2012; Thollander, Dotzauer 2010). In any case, effective and welfare-improving policy design requires a thorough understanding of the barriers and the differences across sectors and companies (e.g. Allcott, Greenstone 2012; DeCanio, Watkins 1998; Schleich 2009). For example, energy-intensive firms tend to allocate a higher priority to energy-efficiency projects than less energy-intensive firms and larger firms tend to adopt more EEMs than smaller firms (Schleich 2009). In particular, small- and medium sized enterprises (SMEs) consider investments in energy efficiency low priority projects, devote fewer resources to energy management, and exhibit lower adoption rates for EEMs (e.g. Cagno et al. 2010; Gruber, Brand 1991). Thus, barriers related to information, hidden costs and transaction costs are expected to be more pervasive for SMEs, in particular for those with non-energy intensive production processes.

Empirical analyses of barriers to energy efficiency either rely on case studies, and therefore include only a few observations (e.g. de Almeida 1998; O'Malley, Scott 2004; Rohdin, Thollander 2006), or on surveys involving larger samples. The survey results are often presented as descriptive statistics (e.g. total numbers or shares) of self-assessed barriers (Harris et al. 2000; Thollander, Ottosson 2008). Only some studies apply multivariate methods to analyze the determinants of EEM adoption (e.g. Anderson, Newell 2004; Aramyan et al. 2007; DeCanio, Watkins 1998; Schleich 2009; Schleich, Gruber 2008). However, survey-based analyses typically rely on a rather general description of EEMs and it is often not known whether the EEMs suggested are technically feasible for a particular company. Often, the profitability of the considered EEMs has to be assumed based on data taken from literature rather than empirically assessed at the individual company level.

In this study, we analyze factors influencing the adoption of EEMs by SMEs, focusing on the impact of barriers. Our empirical analysis is based on novel cross-sectional data obtained from a 2010 survey conducted in order to evaluate the German energy audit program for SMEs. Prior to the survey, all participating companies had been subject to (subsidized) in-depth energy audits. Hence, the information on the cost-effectiveness and other characteristics of the EEMs considered in the survey is specific to the individual firm. The survey also includes a set of questions (items) on barriers to the adoption of EEMs and information on general company characteristics. We employ factor analysis to empirically assess which of the barriers identified in the literature describe the same underlying factor. Grouping the items into these broader barrier factors facilitates the interpretation of the results and contributes to theory building as it allows to better relate the empirical findings to the barriers derived from the theoretical concepts. In our multivariate econometric analysis, these broader barrier factors serve as explanatory variables together with proxies for more objective barriers and for firm characteristics.

In Section 3.2 we review previous empirical work on barriers to energy efficiency in industry, with a particular focus on SMEs. In Section 3.3 we describe the underlying data set, the variables and the analytical model used. Section 3.3 also includes the factor analysis of the barrier items of the survey questionnaire. Results of the econometric analyses are presented in Section 3.4. In Section 3.5 we discuss these results and derive policy implications. The final section concludes.

3.2 Literature review

Over the last two decades, a substantial body of literature drawing on a variety of concepts including neoclassical economics, institutional economics, behavioral economics, psychology, sociology, and management theory has analyzed why companies and individuals fail to adopt cost-efficient EEMs. The difference between the cost-efficient energy saving potential and the observed adoption of EEMs has been termed the "energy-efficiency gap" (Jaffe, Stavins 1994b). The energy-efficiency gap is the rationale for policy intervention to correct investment inefficiencies in addition to policy interventions to correct negative environmental externalities associated with energy use (Allcott, Greenstone 2012; Brown 2001).

For detailed discussions of different types of barriers and classifications, we refer to Brown (2001), Jaffe and Stavins (1994b), Sathaye et al. (2001), Sorrell et al. (2004), or Sorrell et al. (2011). We review the empirical work on barriers to energy efficiency in the industry sector, distinguishing between case studies and surveys, and highlighting the studies which involve energy audit programs. A large share of recent empirical studies (Rohdin et al. 2007; Schleich 2009; Schleich, Gruber 2008; Sorrell 2004; Thollander et al. 2007; Thollander, Ottosson 2008; Trianni, Cagno 2012) relies to some extent on the barrier taxonomy developed by Sorrell et al. (2004). Based on concepts taken from neoclassical economics, institutional economics and behavioral economics Sorrell et al. (2004) develop a taxonomy consisting of the following six broad categories of barriers:

- *Imperfect information*, which includes transaction costs (e.g. search costs) for identifying the energy consumption of products and services
- *Hidden costs*, which include the overhead costs for management, the transaction costs associated with gathering, analyzing and applying information, the costs associated with disruptions to production, or with staff replacement and training
- *Risk*, which captures the technical risks of energy-efficient technologies as well as the financial risks associated with irreversible investments and the uncertainty about the returns of EEMs (e.g. because future energy prices are uncertain)
- *Access to capital*, which includes lack of external and internal funds for energy-efficiency investments. In the case of external funds, the costs to assess the risks associated with the investor (e.g. small EEMs) or the technology might be too high. Internal funds may be inhibited by internal capital budgeting procedures, investment appraisal rules, or the short-term incentives of energy management staff
- *Split incentives,* which imply that the investor in EEMs cannot fully appropriate the benefits (e.g. landlord-tenant or user-investor problem)
- *Bounded rationality*, which means that constraints on time, attention, and the ability to process information prevent individuals from making "rational" decisions in complex decision problems. Rather than optimizing, they use heuristics and rules of thumb to decide on investments in EEMs.

Clearly, as pointed out by Sorrell et al. (2004) these barriers may overlap, co-exist and interact, and a phenomenon may fall under more than one barrier category. When interpreting the findings from surveys conducted after an energy audit has been carried out (e.g. Anderson, Newell 2004; Harris et al. 2000; Thollander et al. 2007), it must be taken into account that the audit may have reduced or eliminated some barriers, such as *lack of information* and *lack of staff* (e.g. Schleich 2004).

Case studies

Case studies are typically carried out for a few companies, and provide a better understanding of complex decision-making processes and structures within organizations. Theory-guided or explorative in-depth interviews are carried out, transcribed and analyzed to identify the relevant causal mechanisms (Yin 1994) leading to the observed outcomes. In this sense, the findings of case studies may be generalized in an analytical rather than a statistical sense. In the realm of energy efficiency, the case study of the French electric motor market by de Almeida (1998) finds that *split incentives* (or *investor-user dilemma*) in particular impede the diffusion of high efficiency motors: Most motors are bought by original equipment manufacturers who will not be paying the final electricity bill for their use. In addition, bounded rationality (e.g. Simon 1959; Simon 1979) is often observed in firms' decisions to replace broken motors. They often use routines like simply buying the same type of motor again, without searching for more efficient alternatives. Ostertag (2003) derives a similar finding for the German electric motor market, but also points out the role of *information deficits* and *transaction costs*. In a case study of the Irish mechanical engineering industry, O'Malley and Scott (2004) conclude that *access to capital* is the most pervasive barrier. Although firms generally had good access to external funds, EEMs were given a *lower priority* than other projects. The *low priority* might result from the fact that energy expenditures typically account for only about 1% of the total turnover in the mechanical engineering sector. In contrast, in a case study of Swedish non-energy-intensive manufacturing companies by Rohdin and Thollander (2006), *access to capital* was not found to be a major barrier to energy efficiency. Instead, *cost of production disruption/hassle/inconvenience, lack of time* and *other priorities* are ranked highest. Cooremans (2011; 2012) conducted interviews with managers in electricity-intensive firms in Switzerland and found that financial factors are less important for a firm's adoption decision than strategic factors. Consequently, in order to increase the adoption rates of EEMs, their strategic value would have to be emphasized. Cooremans (2011) also notes that most companies use payback time as an investment decision criterion. However, the payback time may systematically influence investment decisions against adopting EEMs. In particular, EEMs are often characterized by long lifetimes with benefits accruing in the longer term, but the payback time does not account for differences in the time path of costs and benefits across projects and also ignores differences in lifetimes. However, because of bounded rationality, payback time may be applied as a rule of thumb.

Surveys

Studies based on surveys may be distinguished by the type of analysis. Survey results are either presented as descriptive statistics of self-assessed barriers, or are derived from multivariate (or bivariate) econometric analyses.

Barrier variables in surveys are often taken from subjective judgments by the respondents. One disadvantage of using such self-assessments is that interviewees may adjust their responses to justify their own actions with regard to the adoption of EEMs. Further, Gruber and Brand (1991) for example show that small firms tend to underestimate the cost-efficient potential to improve energy efficiency because they misjudge EEMs available to their firms. Barrier variables may also be constructed from objective information such as whether there is submetering of energy consumption, whether buildings are rented, or whether there is an energy management system in place. In a few cases, actual data on profitability or payback time is also available. Descriptive analyses typically report frequencies or shares of particular barriers, or "average" responses based on ordinal assessment such as Likert scales. In econometric analyses, an indicator of observed or reported adoption behavior is regressed on a set of explanatory variables including proxies of barriers as well as other control variables such as organizational size or energy costs. While surveys allow for a generalization of findings in a statistical sense, there are some caveats. For example, results based on descriptive analyses may not hold in a multivariate setting, where correlations across all explanatory variables are taken into account to estimate the impact of a particular variable on the dependent variable. Further, correlations do not imply a causal relationship. And more generally, it is challenging to find adequate proxies for barriers such as bounded rationality.

In a survey among UK breweries by Sorrell (2004), *technology inappropriate at this site* was ranked as the most important barrier, followed by *other priorities for capital investment* and *lack of time/other priorities*. For the Swedish pulp and paper industry (Thollander, Ottosson 2008) and foundry industry (Rohdin et al. 2007) descriptive statistics suggest that *technical risk of production disruption* counts as one of the most important barriers to energy efficiency investments. *Lack of capital* is perceived as more important in the foundry than in the pulp and paper industry. For less energy-intensive SMEs in the Swedish manufacturing sector which participated in an audit program, Thollander et al. (2007) find *lack of time* and *low priority for energy efficiency* to be the main barriers. Internal allocation of capital to EEMs in *competition with other investment projects* and the lack of *access to capital* are ranked second and third. In contrast, based on a survey among Australian firms participating in an audit program, Harris et al. (2000) conclude that *lack of capital* and *lack of time/staff* are among the least important barriers. Instead, *payback time too long* and *rate of return too low* were the two most frequently given reasons for non-adoption of EEMs. To some extent, these differences may be explained by the fact that the firms participating in the Australian program are on average four times larger than those in the Swedish program (measured by the average number of employees) and hence less likely to face barriers like lack of staff or knowledge, for example. A survey among SMEs in the Italian manufacturing sector during an energy audit revealed a *lack of capital* as the single most important barrier as perceived by the respondents (Trianni, Cagno 2012). This barrier is likely to be amplified by the current financial crisis, which also makes it difficult to compare the findings with those from earlier studies difficult. *Lack of information about energy consumption and EEMs* is ranked as the second most relevant barrier. Finally, in an early survey among German SMEs, which also included in-depth telephone interviews, Gruber and Brand (1991) find that information on available EEMs and support programs is positively correlated with company size.

Anderson and Newell (2004) rely on a large panel of around 40,000 EEMs recommended in more than 9,000 manufacturing plants participating in an energy audit program administered by the US Department of Energy's Industrial Assessment Centers (US IAC). Anderson and Newell (2004) present descriptive statistics for self-assessed barriers as well as findings from multivariate regression analyses involving objective barriers. Of the more than 20 possible reasons given for not adopting proposed projects, *initial expenditures are too high* was mentioned the most (7.1%) followed by *lack staff for implementation* (6.8%) and *cash flow prevents implementation* (6.7%).

In their multivariate regression analysis, Anderson and Newell (2004) control for differences across EEMs and find that *payback time*, as well as the *project cost of the suggested EEMs* negatively affect the adoption rate of EEMs. Muthulingam et al. (2011) extend the analysis of Anderson and Newell by including behavioral factors from the domain of bounded rationality into their multivariate regression of the same US data set considering about 89,000 EEMs recommended by the auditors. They find that the order of EEM recommendations in the audit report affects adoption rates, which fall from above 50% for the first recommendations to around 40% for the last ones. Muthulingam et al. (2011) also conclude that the "attractiveness" of the first measure implemented by a firm influences the likelihood to adopt subsequent measures. Further, by classifying of EEMs into two groups - one requiring high managerial attention and one requiring low attention - they observe that the adoption rate is significantly lower for the former group. The impeding effect on the adoption rate lies in the same order of magnitude as an increase of the investment cost from $ 18,000 to $ 353,000.

DeCanio and Watkins (1998) econometrically analyze survey responses of the corporate executives of firms participating in the voluntary US Green Lights program. Accordingly, participation in the program is mainly driven by firm-specific factors reflecting complex corporate decision-making rather than conventional investment criteria. Based on data from Dutch horticultural firms, Aramyan et al. (2007) find that the adoption of EEMs increases with *farm size, family size*, *solvency*, *modernity of machinery and* if the farm owner has a *successor*. Their set of explanatory variables, however, did not include investment criteria. Diederen et al. (2003) also focus on the Dutch horticultural sector and find that uncertainty about future energy prices increases the hurdle rates and lowers the adoption rate. Thus, as implied by real options theory, it may be best to postpone irreversible investments in energy efficiency if future economic conditions are uncertain (Hassett, Metcalf 1993). The bivariate correlation analysis by Trianni and Cagno (2012), which highlights problems affecting SMEs ("operational" barriers), reveals that the barriers *lack of time* and *lack of internal capital* are more pronounced in smaller firms (< 100 employees) than in larger firms (100 to 250 employees). As do Trianni and Cagno (2012), various econometric analyses of barriers (de Groot et al. 2001; Sardianou 2008; Schleich 2009; Velthuijsen 1993) also account for differences across industry sectors and highlight the importance of considering firm-specific factors. De Groot et al. (2001) find that the adoption of EEMs is mainly driven by profitability, and that the most important barriers are o*ther, financially more attractive investment opportunities* as well as *incomplete depreciation of the existing capital stock*. Schleich (2009) Schleich and Gruber (2008) and Schleich (2004) focus on the German services sector and small businesses. Findings by Schleich (2009) imply that *lack of information about energy consumption patterns, lack of information about energy-efficiency measures*, *lack of time to analyze potentials for energy efficiency*, *priority setting within organizations*, and *split-incentives* are all relevant barriers, but barriers vary significantly across sub-sectors. Results from individual regressions for 19 sub-sectors in Schleich and Gruber (2008) suggest that *lack of information about energy consumption patterns* and *split incentives* are the most frequent barriers. According to Schleich (2004) most barriers are more pronounced in less energy-intensive firms as well as in smaller firms. His findings further suggest that energy audits help to reduce most of the barriers, but audits conducted by engineers tend to be more effective than audits conducted by utilities or industry sector organizations. This indicates that the *quality of the audit* also affects barriers and hence the adoption rate of EEMs.

An early econometric assessment of barriers in the Dutch industry by Velthuijsen (1993) indicates that the price elasticity of firms' energy demand might be influenced by firm characteristics and the importance of perceived barriers. These barriers are *limited access to capital, lack of knowledge about EEMs, lack of relevance* (in terms of energy bill), *lack of strategic importance* (i.e. not core business), and *stranded investments* (i.e. capital costs of the technology in place had not yet been recovered). By extending the above analysis to the Dutch, Slovak and Czech manufacturing sectors Velthuijsen (1995) assessed the investment behavior in manufacturing. He identifies *lacking financial resources* as a major barrier and *favorable market conditions (such as competition), a short payback time* and *low risk* as the main incentives for the adoption of EEMs. In her econometric analysis of the Greek industry, Sardianou (2008) points out that the affiliation to economic sector and firm characteristics need to be taken into account for policy design as they affect the intensity of barriers.

Nagesha and Balachandra (2006), employ multi-criteria analysis to prioritize policies to address five broad types of barriers in two Indian energy-intensive small industry clusters, foundries and bricks and tiles. Based on criteria related to the intensity of a barrier and to the costs and benefits of the removal of a barrier they find *financial and economic* and *behavioral and personal* barriers to be the most promising barriers for policy intervention.

To sum up, the findings from case study as well as survey-based analyses imply that the corporate adoption of EEMs depends on a variety of interdependent factors including specific barriers, the characteristics of the firm and the EEM, as well as broader contextual factors like market structure or the accessibility of external capital. Table 14 summarizes the main findings of our literature review.

Comparing findings across studies is problematic since apart from applying different methodologies, the studies differ by country, time, sector, technologies, or barriers considered (types, objective vs. self-assessed). Nevertheless, many of the empirical literature finds that SMEs tend to face more barriers to adopting EEMs than larger companies. The most prevalent barriers for SMEs appear to be lack of capital, and for energy-intensive SMEs, also the technical risk of production interruption. In comparison, adopting EEMs in less energy-intensive SMEs is hampered in particular by lack of information and lack of staff time. These latter barriers could effectively be overcome by energy audits.

Table 14: Overview of empirical studies addressing the role of barriers for adopting EEMs

Study	Region	Sector /market	Sample size (No. firms)	Prior energy audit?	Main barriers and findings
Case studies					
(de Almeida 1998)	France	Electric motor market	n.a.	No	Split incentives resulting from structure of motor market and bounded rationality in motor replacement decisions.
(Ostertag 2003)	Germany	Electric motor market	~10	No	Split incentives resulting from structure of motor market, lack of information and transaction costs.
(O'Malley, Scott 2004)	Ireland	Mechanical engineering industry	7	No	Low priority of EEMs compared to other investment projects.
(Rohdin, Thollander 2006)	Sweden	Non-energy-intensive manufact.	8	Yes	Cost of production disruption / hassle / inconvenience, lack of time and low priority for EEM investment.
(Cooremans 2012)	Switzerland	Electricity-intensive firms	35	No	Lack of strategic dimension; financial factors are less important.
Surveys – descriptive analyses					
(Gruber, Brand 1991)	Germany	SMEs	500	No	Lack of information and low priority for EEM investment. Lack of information is more prevalent in smaller firms.
(Harris et al. 2000)	Australia	All sectors	100	Yes	Required payback time and rate of return.
(Sorrell 2004)	UK	Breweries	53	No	Inappropriate technology, low priority for EEM investment and lack of time.

Study	Region	Sector /market	Sample size (No. firms)	Prior energy audit?	Main barriers and findings
(Thollander et al. 2007)	Sweden	Non-energy-intensive manufacturing SMEs	47	Yes	Lack of time, low priority of energy, internal allocation of capital and lack of access to external capital.
(Rohdin et al. 2007)	Sweden	Foundry industry	28	No	Lack of access to capital and technical risks.
(Thollander, Ottosson 2008)	Sweden	Pulp and paper firms	40	No	Technical risks and costs from disruption / hassle / inconvenience.
Surveys – econometric analyses					
(Velthuijsen 1993)	Netherlands	Horticulture, various industry and tertiary sectors	70	No	Energy price elasticity interacts with firm characteristics and the intensity of perceived barriers such as limited access to capital or lack of knowledge.
(Velthuijsen 1995)	Netherlands, Slovak Republic, Czech Republic	Various manufacturing sectors	313 (NL), 40 to 55 (SK), ~40 (CZ)	No	Lack of access to capital, high risk, long payback time, unfavorable market conditions.
(DeCanio, Watkins 1998)	USA	All sectors	> 1,000	Yes	Program participation is mainly driven by firm-specific factors rather than conventional investment criteria.
(de Groot et al. 2001)	Netherlands	Nine industry sectors	135	No	Low priority of EEMs compared to other investment projects, stranded investments.
(Diederen et al. 2003)	Netherlands	Horticulture (greenhouses)	603	No	Uncertainty about future energy prices slows down adoption (real option value concept).
(Anderson, Newell 2004)	USA	Manufacturing SMEs	> 9,000	Yes	Required payback period, projected costs / initial expenditures, lack of staff and liquidity constraints.
(Schleich 2004)	Germany	Services and small industry	> 2,000	Yes	Most barriers are more pronounced in less energy-intensive firms as well as in smaller firms. Energy audits help reducing most of the barriers.

Study	Region	Sector /market	Sample size (No. firms)	Prior energy audit?	Main barriers and findings
(Aramyan et al. 2007)	Nether-lands	Horticulture	397	No	Adoption increases with farm size, family size, solvency, modernity of machinery and if the farm owner has a successor.
(Sardianou 2008)	Greece	Industrial sector	50	No	Intensity of barriers interacts with firm characteristics and the affiliation to an industrial sector.
(Schleich, Gruber 2008)	Germany	Services and small industry	57 to 291 per sector	No	Lack of information about energy consumption patterns and split incentives.
(Schleich 2009)	Germany	Services and small industry	> 2,000	No	Lack of information about energy consumption patterns, lack of information about energy efficiency measures, lack of time to analyze potentials, and priority setting.
(Muthu-lingam et al. 2011)	USA	Manufac-turing SMEs	> 9,000	Yes	Confirm findings of Anderson and Newell (2004); adoption affected by the order of recommendation and the managerial attention required for implementation.
(Kostka et al. 2011)	China	SMEs	479	No	Lack of information.
(Trianni, Cagno 2012)	Italy	Manufac-turing SMEs	128	Yes	Lack of access to capital. Lack of time and lack of internal capital are more pronounced in smaller firms.
Multi-criteria analyses					
(Nagesha, Balachan-dra 2006)	India	Small firms from foun-dries and bricks and tiles indus-try clusters	88	No	Effective policies should address financial and economic barriers and behavioral and personal barriers.

3.3 Choice of barriers, data and model used

3.3.1 Empirical representation of barriers used for the model

Our descriptive and econometric analyses, which will be presented in the subsequent sections, capture most of the relevant factors for the adoption of EEMs identified in the literature. A list of factors was derived from previous studies using surveys (Anderson, Newell 2004; Sorrell et al. 2004; Thollander, Ottosson 2008), adapted to the particular situation of SMEs, and extended based on the experiences from past evaluation studies and audit program operators. In total we consider 18 barriers. Our econometric analyses further include control variables reflecting firm size, energy costs, and organizational factors like decision-making criteria and energy management activity, which may also affect the adoption of EEMs. Our econometric analysis distinguishes self-assessed barriers and objective barriers. The former are based on the self-assessment of survey respondents, while the latter represent objectively measurable information.

3.3.2 Description of the data

The German energy audit program titled "Sonderfonds Energieeffiezienz in KMU" was established in 2008 and provides grants for on-site energy audits in SMEs (< 250 employees). Besides Germany, many countries have also established energy audit programs geared towards SMEs, including Australia, Canada, Japan, the US and most European countries (Price, Lu 2011). As the US IAC program (Anderson, Newell 2004) for example, the "Sonderfonds" is also a stand-alone audit program, i.e. it is not integrated into broader energy efficiency programs involving, for example, voluntary agreements or energy management obligations. While the US program, which was established in 1976 and is one of the largest and best documented energy audit programs worldwide, is limited to firms from the manufacturing sector (< 500 employees), the "Sonderfonds" also addresses non-manufacturing sectors such as services. Thus, in the German program a higher share of the recommended EEMs than in the US program is related to buildings rather than to industrial equipment and production processes. Under the "Sonderfonds" the energy audit is carried out by professional engineers and consists of two components. An initial onsite audit provides a rough indication about potential cost-efficient EEMs focusing on measures that are typically available in most firms. In a more detailed analysis, more complex site-specific EEMs are explored. While the audits can be conducted sequentially, firms can also choose to use either the initial or the detailed audit separately. Depending on whether an initial or detailed audit is conducted, the audits take two or more days and result in a list of recommended EEMs deemed to be profitable for the firm based on engineering-economic analyses. Up to 80% of the costs for the audits are paid by the program. The costs for the implementation of the EEMs may be financed by soft loans, which is the second pillar of the "Sonderfonds".

The soft loan program is also available to firms which did not undergo an energy audit. For comparison, the US program includes free of charge energy audits offered by teams of engineering students and faculty, but it does not include a financing mechanism. The energy savings achieved via energy audit per firm are about ten times higher in the US program, while the number of audits conducted per month is lower than in the German program. A more detailed discussion of the German audit program may be found in Fleiter et al. (2012b).

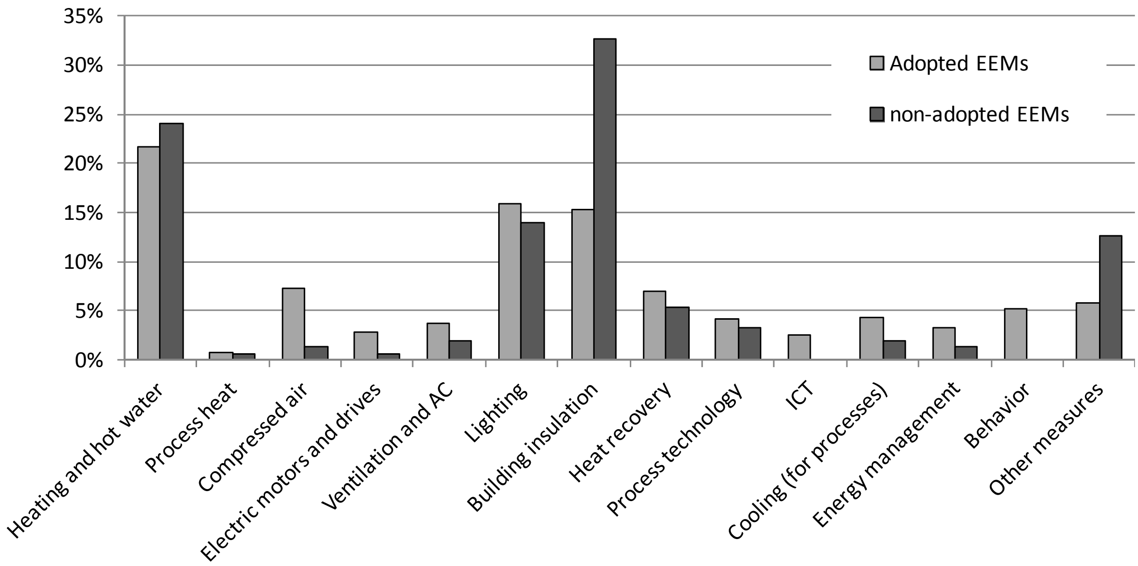

Figure 12: Distribution of adopted and non-adopted EEMs across end-use classes as fractions of the sum of adopted and non-adopted EEMs (n=779)

Our analysis is based on a survey conducted in July 2010 via an online questionnaire sent out to all 4,434 participants in the "Sonderfonds" audit program for which an Email address was available. The main purpose of the survey was to evaluate the impact and the processes of the program.. About 20% logged into the internet portal which hosted the survey and 542 (i.e. 12%) completed the questionnaire but did not necessarily respond to all questions. The length of the survey was a major barrier to completion. Two aspects required a rather long survey. First, the survey was also used for a detailed program evaluation including all its processes. Second, the detailed characteristics of the EEMs recommended by the audit had to be entered for an impact assessment. In total, the survey contained 51 questions on firm characteristics (sector, number of employees, energy consumption, energy cost share, energy management system), on the program application process, on the audit process and quality, on the adoption of EEMs after the audit and on reasons for not adopting recommended EEMs. **Fehler! Verweisquelle konnte nicht gefunden werden.** shows the distribution of adopted and non-adopted EEMs across the categories of end-uses after the audits had been conducted. For example, 32% of the non-adopted measures were in the category building insulation and 24% in the category heating and hot water. Most adopted EEMs address building related end-uses and particularly heating and hot water equipment. Arguably, some of the adopted EEMs may have been implemented even without the audit. In contrast, building insulation is the mode for non-adopted measures. In general, the majority of recommended EEMs address ancillary processes rather than the core-production processes.

For EEMs which were recommended by the audit but not adopted by the company, survey participants were asked to assess the reasons for non-adoption measured on a 4-point Likert scale ranging from "not relevant" to "very important". The list of 15 reasons (items) included in the survey is shown in Figure 13. The length of the survey, however, did not allow EEM-specific answers to be elicited. Instead, the answers relate to all non-adopted EEMs (i.e. similar to Schleich and Gruber (2008) and Schleich (2009)). Likewise, the limited length of the survey did not allow the inclusion of an exhaustive list of all the possible barriers to energy efficiency identified in the literature. For methodological reasons, the survey did not include questions related to *lack of information* about energy efficiency potentials because it targeted specific EEMs identified in the audit. Hence, respondents can be assumed to be well informed about EEMs. Also, barriers like *split incentives embodied in the market structure* (observed in two case studies on electric motors) are difficult to capture in a survey. In general the items in Figure 13 reflect most of the barriers to energy efficiency identified in the literature.

Figure 13 suggests that the three most important self-assessed barriers to the adoption of EEMs in the sample are too high investment costs, low priority of EEMs and lack of profitability. Since most of the recommended EEMs are related to ancillary processes, it is not surprising that barriers related to *technical risks* appear to be unimportant on average.

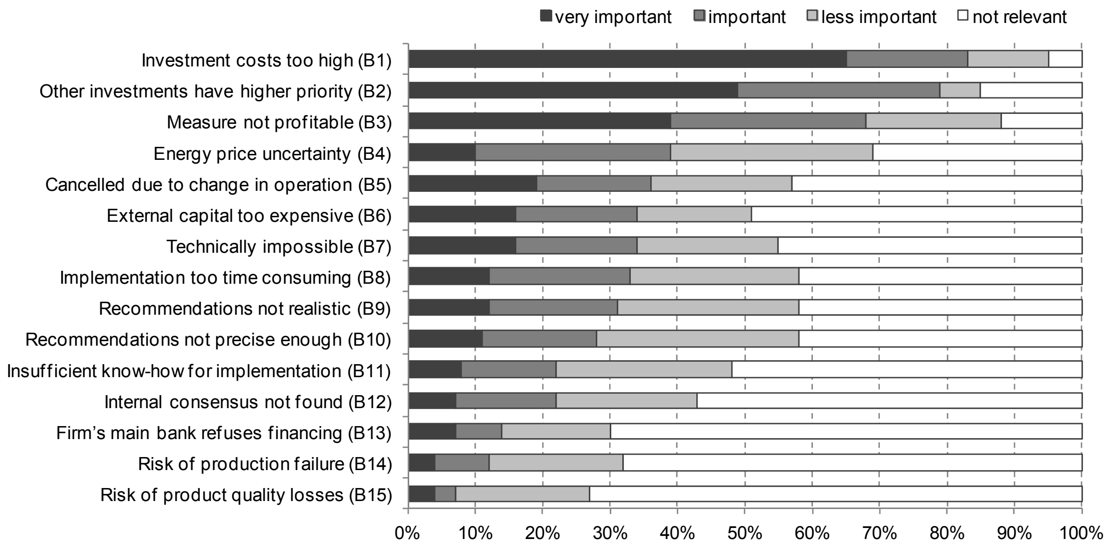

Figure 13: Self-assessed reasons for not adopting recommended EEMs (n=160)

The questionnaire also contains eight questions (items) about the firms' satisfaction with the audit quality, such as the report, the explanations or the auditor's competence. Figure 14 suggests that firms were generally satisfied with the audit quality.

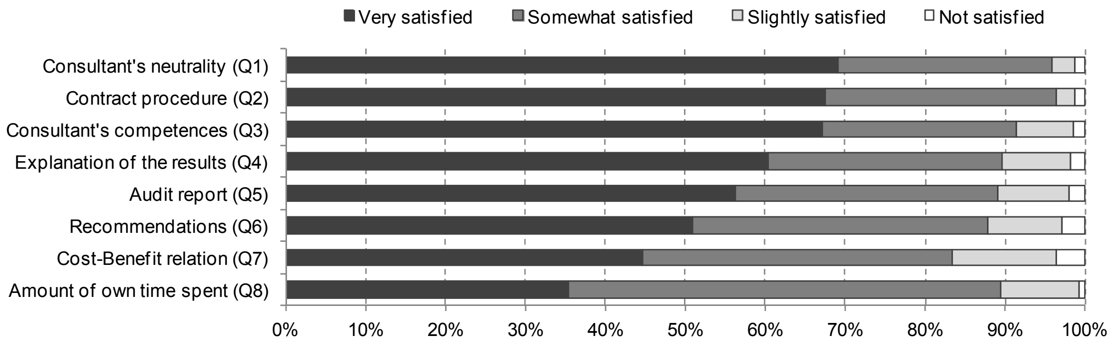

Figure 14: Respondents' satisfaction with different aspects of audit quality (n=456)

3.3.3 Factor analysis

To facilitate the interpretation of the results and to reduce the number of explanatory variables for the subsequent econometric analysis, we apply exploratory factor analysis to group the 15 items of Figure 13 into underlying barrier factors.[32] Similarly, the eight items in Figure 14 are grouped into quality factors. We employ the principal component factor method for factor extraction.[33] Based on the Kaiser criterion and the Scree test (see for example Costello, Osborne 2005; Fabrigar et al. 1999) we retain the same number of factors: five barrier factors and one audit quality factor. Table 18 shows the results of the 15 barrier items based on the 138 observations with a complete set of responses to the items in Figure 13and Figure 14. Accordingly, the five barrier factors account for 64.7% and the audit quality factor accounts for 66.1% of all variances, respectively. Table 15 provides the loadings of rotated factors using the VARIMAX rotation. Most of the factors comprise a relatively homogenous group of observed variables, such as *lack of capital*, *technical risk* and *low profitability*. Only the factors *transaction costs* and *low priority and uncertainty* comprise a wider set of barriers. Higher factor loadings imply a stronger effect of the variable on the underlying factor. The values for Cronbach's α indicate that most factors are reliable. For the factor LOWPROFIT, however, the value of Cronbach's α is well below 0.6, which casts doubts on the internal consistency of the items.

[32] For an overview of factor analyses see Fabrigar et al. (1999).

[33] The Bartlett's test of sphericity $\chi^2(105) = 654$, $p<0.001$ and the Kaiser-Meyer-Olkin measure of 0.71 indicate that the principal component factor method is suitable.

Table 15: Results of factor analysis for variables of self-reported barriers

Factors and items	Factor loading	Cronbach's α
Lack of capital (LACKCAPITALF)		0.69
External capital too expensive (B6)	0.871	
Firm's main bank refuses financing (B13)	0.788	
Low profitability (LOWPROFIT)		0.38
EEM not profitable (*lackprofit*) (B3)	0.815	
Investment costs too high (*highinvest*) (B1)	0.663	
Transaction costs (TRACOSTF)		0.77
Recommendation not realistic (B9)	0.799	
Recommendation not precise enough (B10)	0.747	
Implementation too time-consuming (B8)	0.619	
Insufficient know-how for implementation (B11)	0.632	
Technically infeasible (B7)	0.437	
Technical risk (TECHRISKF)		0.92
Risk of production failure (B14)	0.908	
Risk of product quality losses (B15)	0.899	
Low priority and uncertainty (PRIORITYF)		0.62
Cancelled due to change in operation (B5)	0.795	
Energy price uncertainty (B4)	0.665	
Other investments have higher priority (B2)	0.647	
Internal consensus not found (B12)	0.486	
Audit quality (AUDITQUALF)		0.92
Explanation of the results (Q4)	0.89	
Consultant's competence (Q3)	0.88	
Audit report (Q5)	0.87	
Recommendation (Q6)	0.85	
Consultant's neutrality (Q1)	0.82	
Contract procedure (Q2)	0.80	
Cost/benefit relation (Q7)	0.78	
Amount of own time spent (Q8)	0.54	

We now briefly relate the outcome of the factor analysis to the literature. The barrier factor LACKCAPITALF reflects lack of capital for EEMs, which has been identified as a main barrier in the literature (Anderson, Newell 2004; Rohdin et al. 2007; Sorrell 2004; Sorrell et al. 2011). In the taxonomy of Sorrell et al. (2004) LACKCAPITALF is closely related to lack of access to external capital.

Similarly, LOWPROFITF captures the lack of profitability of EEMs, directly via B3 and indirectly via B1. While lack of profitability may not qualify as a true barrier, i.e. as "a mechanism that inhibits a decision or behavior that appears to be both energy efficient and economically efficient" (Sorrell et al. 2004), it is expected to inhibit the adoption of EEMs for profit-maximizing companies.

TRACOSTF reflects a number of barriers, mostly related to information costs and staff time, which have typically been found in the literature to impede the adoption of EEMs, including Anderson and Newell (2004), Ostertag (2003), Schleich and Gruber (2008), Schleich (2009), Trianni and Cagno (2012). The items B10, B8 and B11 reflect elements of hidden costs as well as imperfect information in the taxonomy of Sorrell et al. (2004). The interpretation of the findings for items B7 and B9 is less clear. On the one hand, they may be a rational explanation for non-adoption of an EEM, and hence not qualify as a true barrier. On the other hand, since the EEMs had been suggested by energy auditors, respondents' perceptions may be wrong and the auditors' recommendation realistic and technically feasible. In this case B7 and B9 would reflect a lack of information or bounded rationality on the side of firms.

TECHRISKF captures the technical risk of implementing EEMs, which may lead to interruptions in production or to lower product quality. Technical risk was found to impede the adoption of EEMs, among others, in Sorrell (2004), Rohdin et al. (2007), and Thollander and Ottosson (2008), in particular if EEMs are related to the core production processes of energy-intensive firms (Anderson, Newell 2004; Dieperink et al. 2003). In the terminology of Sorrell et al. (2004), TECHRISKF falls into the broader barrier categories of risk and hidden costs.

The factor PRIORITYF comprises a broad set of barriers which are mainly related to internal factors internal in firms' decision-making and organizational processes. The importance of these factors for the adoption of EEMs has been highlighted by Cooremans (2011; 2012) and DeCanio and Watkins (1998). In the terminology of Sorrell et al. (2004), the items in PRIORITYF reflect a lack of access to internal capital (B2 and B12) and economic risk (B4).

The factor AUDITQUALF covers eight items that describe the respondents' satisfaction with the audit and the auditor. Audit quality shows a very high Cronbach's α, indicating that the combined items represent a consistent factor. While these items do not directly represent an objective and comprehensive measure of an audit's quality, it seems reasonable to assume that higher quality audits translate into higher satisfaction scores.

In sum, the factors derived from the factor analysis seem consistent with the literature. The results allow the grouping of individual items into broader classes of barriers, which are largely consistent with the classification of barriers used in recent empirical studies. One point of divergence from the taxonomy of Sorrell et al. (2004) relates to the barrier category of risk. Rather than grouping technical and financial risks together in a single risk category as in Sorrell et al. (2004), our findings from the factor analysis suggest that technical and financial risks represent rather distinct barriers to energy efficiency.

Instead of identifying single important items, the factors make the underlying construct visible and allow the identification of broader patterns. Moreover, using the factors derived from the factor analysis as explanatory variables for the adoption of EEMs in the subsequent econometric analysis increases the degrees of freedom and hence lowers the standard errors: Five barrier factors capture the information contained in the 15 barrier items, and one audit quality factor captures the information of eight quality items.

3.3.4 Econometric model

3.3.4.1 Dependent variable

As the dependent variable in the regression model we use the adoption rate per firm, which is calculated as the share of adopted EEMs compared to all EEMs recommended in the energy audit. In essence, our dependent variable is comparable to the dependent variable employed by Schleich and Gruber (2009) or Schleich (2009). However, the EEMs considered in our study have been suggested by energy auditors as being suitable and profitable for the individual company. The adoption rate is neither corrected for EEMs that were already planned before the audit nor does it include EEMs that were planned but not realized at the time the survey was conducted. The mean adoption rate of all EEMs in the sample used for the regression is 40%.[34]

By design, our dependent variable is bound between zero and one. In addition, a large share of companies has either adopted none of the EEMs recommended by the audit (40%), or all of them (27%); with high shares of observations at the boundaries, the effects of the explanatory variables tend to be non-linear and the variance tends to decrease when the mean approaches zero or one. Hence, linear regression analysis is not appropriate. Instead, we apply the fractional logit model (FLM), originally developed by Papke and Woolridge (1996). Using the FLM model means an improvement compared to prior multivariate regression analyses of barriers. For example, Schleich and Gruber (2008) and Schleich (2009) apply logit models after transforming the adoption rate into a dichotomous dependent variable that is set to one if the adoption rate exceeds an arbitrary cut-off point of 50 % and zero otherwise. FLM avoids the loss of information resulting from the transformation of the continuous adoption rate into a dichotomous index.

[34] By comparison, the average adoption rate in Anderson and Newell (2004) is 53 % including planned EEM. Schleich (2009) und Schleich and Gruber (2008) provide figures on the share of organizations which had adopted (or planned to adopt) at least half of the EEMs considered suitable. This share is around 35 % if only adopted EEMs are considered (Schleich 2009), and around 45 % if also planned EEMs are considered. Thollander (2007) reports adoption rates of 22 % and 41 %, respectively. The adoption rate in Harris (2000) is 81 % (not including planned EEM).

3.3.4.2 Explanatory variables

The set of explanatory variables includes self-assessed as well as objective barriers to energy efficiency and as additional control variables also characteristics of the firm, the EEMs and the audit itself.

Self-assessed barriers

To capture the effects of barriers on the adoption of EEMs as perceived by the respondents, we use the barrier factors LACKCAPITALF, LOWPROFITF, TRACOSTF, TECHRISKF, PRIORITYF derived by factor analysis in Section 3.3.3. Since in light of the relatively low value of Cronbach's α, the barrier factor LOWPROFIT may not be reliable, one alternative model specification includes the original items *lackprofit* and *highinvest* in lieu of LOWPROFITF. All barrier factors are expected to have a negative effect on adoption of EEMs. Similarly, AUDITQUALF is included to reflect the impact of the perceived quality of the energy audit on adoption of EEMs. Since the form in which information is provided and the credibility of the source of information are likely to affect adoption (e.g. Sorrell et al. 2004; Stern 1984; Stern 1986) AUDITQUALF also reflects barriers related to information costs and other transaction costs. In any case, the associated parameter should be positive.

Objective barriers

In addition to the subjective factors reflecting the respondents' subjective self-assessment of barriers and audit quality on the adoption of EEMs, we also include a set of more objective factors, reflecting characteristics of the EEMs and of the firms.[35] We consider the initial investment cost of the EEMs, information on whether firms have rented their buildings, and the criterion used by firms to appraise investments in EEMs. These factors have been found in the literature review to also affect the adoption of EEMs.

Since the responses regarding the payback time of EEMs were often incomplete, we only included information on the investment cost in the regression. Information on a firm's investment costs enters the set of explanatory variables as an index. The investment cost index INVEST is calculated by the following three steps. First, since data was usually not available for all the EEMs recommended, we use the average investment costs per category of EEM (see **Fehler! Verweisquelle konnte nicht gefunden werden.**). The average investment costs vary between € 400 for behavioral EEMs and € 28,700 for building insulation. The average investment cost across all the EEMs listed in the sample is € 22,700. Second, we divide the sum of the invest-

[35] The survey asked firms to report information for four of the recommended EEMs they had adopted and four EEMs they had decided not to adopt. This information included annual energy savings, investment costs and the payback time per measure. If firms adopted (or failed to adopt) more than four EEMs, we do not have an account of their characteristics.

ment cost of all the EEMs recommended to a particular firm by the number of EEMs recommended to this firm to calculate the average costs per EEM for each firm. Finally, we divide this value by the average cost of all EEMs in the sample (€ 22,700). Thus, if the resulting index INVEST is below one the package of EEMs recommended to a particular firm is less costly than the average EEM in the entire sample, and vice versa. Higher INVEST is expected to lower the adoption of EEMs, as for example found by Anderson and Newell (Anderson, Newell 2004)

The dummy variable RENTED is set to one if a firm's office/building/production site or parts thereof are rented, partially rented or leased, and set to zero otherwise. Thus RENTED is supposed to capture the split-incentives to invest in EEMs resulting from the landlord/tenant dilemma, and its expected impact on the adoption of EEMs is negative (e.g. IEA 2007a). Among others, Schleich and Gruber (2008), and Schleich (2009) found that organizations renting buildings have a lower adoption rate than those owning the buildings.

PAYBACK takes on the value of one if the firm uses only the payback time to assess investments in EEMs and zero if (also) other financial methods like the internal rate of return are used. Applying payback rates may reflect bounded rationality in energy-efficiency investment decisions (Stern 1984), or (extreme) risk aversion of investors, and is expected to negatively affect the adoption rate.

Although these objective barrier variables are related to broader categories of barriers like the financial capability of the firm, split incentives and bounded rationality, they can only reflect particular dimensions of these barrier categories.

Control variables

Finally following the literature employing multivariate analyses to study the adoption of EEMs, the set of explanatory variables also includes several control variables capture the effect of firm characteristics.

ECOSTSHARE stands for the share of energy costs compared to the total annual costs of the firm. The survey included the following classes for the energy cost share: <1%, 1-2%, 3-5%, 6-10% and >10%.[36] To construct ECOSTSHARE we use the lower bound of the respective classes. A higher energy cost share signals higher cost-saving potentials and hence stronger economic incentives to overcome information-related barriers and adopt EEMs. Thus, we expect a higher ECOSTSHARE to be associated with a higher adoption rate as, for example found in de Groot et al. (2001), Schleich and Gruber (2008), Schleich (2009), Kostka et al. (2011), or Velthuijsen (1995).

[36] The distribution of observations across the classes is as following: <1%: 12%, 1-2%: 23%, 3-5%: 34%, 6-10%: 19%, >10%:12%.

EMANAGE is a dummy variable, which takes the value of one if the firm has an energy management system. EMANAGE is expected to have a positive impact on the adoption of EEMs, since energy management systems should help to overcome barriers related to lack of information and the lack of time for the implementing of EEMs (Horbach 2008; Rennings et al. 2006), and may also be seen as an indicator of a firm's commitment to improve energy efficiency.

The survey also inquired to which extent firms had adopted EEMs in the past. Respondents could answer on a 3–point Likert scale, i.e. "scarcely", "to some extent" and "to a large extent". EHISTORY is set to one if the answer was "to a large extent" and zero otherwise. On the one hand firms that had adopted EEMs prior to the audit are also more likely to adopt recommended EEMs. In this sense, EHISTORY captures the importance of the existence of a long-term strategy for implementing EEMs (e.g. Rohdin et al. 2007; Thollander, Ottosson 2008). On the other hand, for firms which had intensively adopted EEMs prior to the audit, the remaining potential may be small, costly, or both. Hence, the expected impact of EHISTORY is ambiguous.

SIZE is measured using the number of employees per firm. We expect SIZE to have a positive impact on the adoption of EEMs, since, for example, larger firms face lower specific transaction costs per EEM, or are less likely to face constraints related to capital or know-how (e.g. Aramyan et al. 2007; Schleich 2009). Of course, to some extent, these aspects are also captured more directly by the self-assessed barriers.

Table 16 provides an overview of the variables used in the regression analyses. Complete data are available for 100 observations. Among others, it shows that for this sample 26% of the firms have an energy management system installed, 61% use only payback time to assess investments in EEMs and only 6% had implemented EEMs on a large scale prior to the audit.

Table 16: Overview of variables used for the regression analysis (N=100)

Variable	Mean	Min.	Max.	Expected sign	Description
ADOPTRATEF	0.40	0.00	1.00		Adopted EEMs as share of recommended EEMs per firm.
Self-assessed barriers					
LACKCAPITALF	0.00	-1.71	2.56	–	Lack of access to external capital.
LOWPROFITF	0.00	-3.13	1.67	–	Low profitability and high initial investment cost.
TRACOSTF	0.00	-2.01	3.52	–	Transaction costs related to knowledge, time and resource constraints.
TECHRISKF	0.00	-1.54	3.65	–	Technical risk of production interruption and product quality losses.
PRIORITYF	0.00	-2.33	2.20	–	Barriers related to firms' internal process and low priority of EEMs.
AUDITQUALF	0.00	-3.67	0.97	–	Audit quality.
Objective barriers					
INVEST	1.12	0.22	2.50	–	Index of average investment costs of all EEMs recommended to a firm divided by the average investment costs of all EEMs listed in the sample.
RENTED	0.35	0.00	1.00	–	Indicator for rented or leased office/building/production site (or parts thereof).
PAYBACK	0.61	0.00	1.00	–	Indicator if only use payback time as investment criterion.
Control variables					
ECOSTSHARE	3.56	0.75	10.00	+	Firms' annual energy cost as share of total production costs.
EMANAGE	0.26	0.00	1.00	+	Indicator for energy management system in place.
EHISTORY	0.06	0.00	1.00	+/–	Indicator for active adoption of EEMs in the past.
SIZE	53.6	1.00	215	+	Number of employees.

3.4 Results

We use STATA 11 to estimate the fractional logit model, which recognizes that large shares of the values for the dependent variable ADOPTRATE are at the lower and upper boundary, i.e. either zero or one.[37] Table 17 presents the findings of three specifications[38]. Model 1 includes all the barrier factors derived from the factor analysis. Since the barrier factor LOWPROFITF may not be reliable, Model 2 includes the original items *lackprofit* and *highinvest* rather than the factor LOWPROFITF. Since access to capital may be more important for EEMs with higher investment costs, Model 3 employs INTERCAPINVEST[39], an interaction term between LACKCAPITALF and INVEST.

As indicated by the (multiple) Wald statistics reported in Table 17, we may reject the null hypothesis that the models do not contribute to explaining the variance of ADOPTRATE. Based on the Akaike Information Criterion (AIC), which hardly differs across Model 1 to 3, a preferred model cannot be selected[40]. However, parameter estimates and p-values hardly differ across models.[41]

The barrier factor LACKCAPITALF, which reflects the lack of capital, is statistically significant (only) in Model 1 (at $p<0.05$). Combined with the results of Model 3, where the interaction term INTERCAPINVEST is found to be statistically significant (at $p<0.1$), this suggests that lack of capital impedes the adoption of EEMs, but only for larger investments. While the factor LOWPROFITF is not statistically significant in Model 1, including the original items (*highinv-*

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[37] Since the sample available for the econometric analysis differs from the sample used for the factor analysis reported in Table 17 as well as in Table 18 and Table 19 in the Appendix, we recalculated the factors for the somewhat smaller sample employed in the regressions. This factor analysis reveals the same factors as before and the Cronbach's α's are almost identical (i.e. 0.69; 0.40; 0.75; 0.92; 0.61; and 0.91 using the order of factors as in Table 15). All results not shown are available from the authors upon request.

[38] We also ran fractional probit models to test the robustness of findings in Models 1 to 3 with respect to the assumptions about the underlying distribution. Results are virtually identical to the findings presented for the fractional logit specification.

[39] INTERCAPINVEST is calculated as the product of lack of capital and a dummy variable of the investment cost index which is 1 if INVEST is above 1 and 0 otherwise.

[40] The same finding holds using an alternative criterion, the Bayesian Information Criterion (BIC), which is not reported in Table 17 to save space.

[41] To save degrees of freedom in light of the relatively small sample size, we ran additional regressions omitting all explanatory variables, where parameter estimates are far from being statistically significant (implemented as $p>0.5$). Findings for the remaining variables did barely change compared to the results presented in Table 17. Also, we carried out analyses allowing for additional explanatory variables to control for sector belonging (using dummies for services versus industry sectors), time passed between survey and audit, and the level of decision-making competences (using a dummy for branches versus headquarters). None of these variables turned out to be statistically significant or lead to any other meaningful insights.

est and *lackprofit*) in Models 2 and 3 yields more insights. The subjective barrier *highinvest* - but not *lackprofit* - appears to impede the adoption of EEMs.

Notably, no other subjective barrier turns out to be statistically significant (associated p-values tend to be well above 0.3). In comparison, we find some empirical evidence that a higher quality of the energy audit is likely to increase the adoption of EEMs: the factor AUDITQUALF is statistically significant (at $p<0.1$) in Model 3 and almost statistically significant in Model 2 (at $p<0.11$).

The only objective barrier found to be statistically significant is the investment cost index INVEST ($p<0.05$ in all three models). As expected, higher investment costs result in a lower adoption rate, corroborating the finding for the subjective barrier *highinvest*. In all models, RENTED and PAYBACK are far from being statistically significant – the associated p-values exceed 0.85.

The parameter estimate associated with ECOSTSHARE is, as expected, positive, and statistically significant at $p<0.05$ for Model 1 (p-values for Model 2 and 3 are 0.11 and 0.16 respectively). Hence, our findings provide some empirical evidence that more energy-intensive firms assign a higher priority to energy efficiency.

Employing an energy manager tends to increase the adoption of EEMs, but the parameter associated with EMANAGE is not statistically significant (p-values are around 0.2 for Models 2 and 3, and 0.4 for Model 1). Similarly, active adoption of EEMs in the past (EHISTORY) appears to have no effect on the current adoption rates of EEMs (p-values > 0.5 in all models). As discussed earlier, this outcome may be the result of countervailing effects: a higher EHISTORY may reflect a higher propensity to adopt EEMs in general, but may also indicate that there are fewer cost-efficient EEMs left. Finally, the parameter associated with company SIZE is not statistically significant.

Table 17: Results of fractional logit regressions (robust standard errors in parentheses)

Dependent Variable: ADOPTRATE	(1)			(2)			(3)		
LACKCAPITALF	-0.29	*	(0.13)	-0.11		(0.14)	0.40		(0.37)
INTERCAPINVEST							-0.60	*	(0.36)
LOWPROFITF	0.08		(0.14)						
highinvest				-1.03	***	(0.39)	-0.99	**	(0.41)
lackprofit				0.38		(0.31)	0.32		(0.31)
TRACOSTF	0.09		(0.10)	0.08		(0.11)	0.08		(0.10)
TECHRISKF	0.15		(0.10)	0.09		(0.10)	0.07		(0.10)
PRIORITYF	0.07		(0.13)	0.02		(0.14)	0.01		(0.13)
AUDITQALF	0.13		(0.11)	0.17		(0.11)	0.18	*	(0.11)
INVEST	-0.80	*	(0.38)	-0.86	**	(0.39)	-0.89	**	(0.40)
RENTED	0.03		(0.26)	0.01		(0.25)	0.02		(0.24)
PAYBACK	-0.03		(0.28)	0.00		(0.28)	0.05		(0.29)
ECOSTSHARE	0.09	*	(0.04)	0.08		(0.05)	0.07		(0.05)
EMANAGE	0.22		(0.27)	0.34		(0.29)	0.39		(0.29)
EHISTORY	0.25		(0.74)	0.31		(0.65)	0.40		(0.64)
SIZE	-0.10		(0.10)	-0.14		(0.11)	-0.17		(0.11)
Constant	0.42		(0.60)	1.23	**	(0.60)	1.37	**	(0.61)
Sample size	100			100			100		
-log likelihood	-48.9			-47.9			-47.6		
aic	1.259			1.259			1.272		
Wald statistic (p-value)	27.45 (0.011)			32.80 (0.003)			33.80 (0.004)		

*** indicates significance at the p=0.01 level.

** indicates significance at the p=0.05 level and

* indicates significance at the p=0.1 level in a two-tailed t-test

3.5 Discussion

In this section we discuss the findings of our empirical analyses and derive implications for policymaking. We also relate our findings to the literature, in particular to studies which also rely on data from stand-alone energy audit programs.

The first, and arguably clearest, finding of our regression analyses is that high investment costs, which are captured by both subjective and objective variables in our model, appear to impede the adoption of EEMs. Similarly, we find that *lack of capital* slows EEM adoption, primarily for larger investments. When combined, these findings underline the fact that lack of *access to capital* is a crucial barrier in the decision to adopt EEMs, even when they are profitable. Among others, Anderson and Newell (2004) and Thollander et al. (2007) (but not Harris et al. 2000) also conclude that the *initial investment costs* negatively affect the adoption rate. Hence, while this finding per se is not a novel one, our analysis provides a statistically-supported foundation for policy design, at least for the German audit program. Specifically, our findings suggest that investment subsidies or soft loans are effective policy measures to accelerate the diffusion of EEMs in SMEs. The net benefits would be highest if support were limited to larger investments. In addition, promoting energy service contracts via energy services companies (ESCOs) could also be effective in overcoming finance-related barriers (see e.g. Marino et al. 2011; Mills 2003). As most EEMs are cross-cutting (or ancillary) technologies, which are similar across firms, ESCOs could benefit from providing standardized solutions. However, energy services companies may be hesitant to do so, because SMEs bear higher financial risks than larger companies or public organizations, and because the individual projects are relatively small. In addition, energy audits could be linked with energy-efficiency obligations and white certificate schemes, which are already in place in several European countries (e.g. Bertoldi et al. 2010; Sorrell et al. 2009). For example, such a scheme could recognize energy savings identified and certified by an independent auditor. This could contribute to overcoming finance-related barriers, as utilities (or other entities that are subject to the energy-efficiency obligation) would be responsible for financing the measures. Such a link would also make it easier to extend the scope of white certificate schemes from mostly simple standardized measures to more complex measures, and enable larger energy-efficiency gains to be realized by these schemes.

Company size appears to have no effect on the adoption of EEMs. This is somewhat surprising, since most empirical studies (Aramyan et al. 2007; Schleich 2009) – but not all (Anderson, Newell 2004) – find that larger firms are more likely to adopt EEMs. Since our multivariate analysis includes a comparatively broad set of explanatory variables, size effects may also be picked up by some of the other variables. For example, larger firms face lower specific transaction costs per EEM, or are less likely to face constraints related to capital resources or know-how (e.g. de Groot et al. 2001). On the other hand, Velthuijsen (1995) presents some evidence that larger firms with more complex decision-making processes may be even slower in adopting EEMs. An alternative explanation is that our sample of SMEs may not provide sufficient variation in firm size to produce statistically significant effects, because firms with more than 250 employees are not eligible for support under the German energy audit program. In other words, size effects are more likely to be detected in samples which also include larger firms, as was the case in the US IAC program (Anderson, Newell 2004).

In our analyses, technical risks like production interruption or loss of product quality were not found to be statistically significant barriers. This finding may be rationalized by the way the dependent variable is constructed. The adoption rate of EEMs tends to be dominated by those related to ancillary processes rather than to core production processes (see also **Fehler! Verweisquelle konnte nicht gefunden werden.**). Our results provide some evidence, however, that the energy cost share of a firm positively affects the adoption rate, supporting the findings by de

Groot et al. (2001), Schleich and Gruber (2008), Schleich (2009), and Velthuijsen (1995). Higher cost shares indicate higher cost-saving potentials and higher economic returns on companies' efforts to surmount the barriers to energy efficiency. Alternatively, a higher cost share may signal a higher strategic relevance for the company and may thus automatically attract attention from top management (Cooremans 2011). In this case, lack of capital (as a result of internal priority setting) should be less of a barrier.

Besides *lack of capital* and *investment cost* related barriers, no other barrier considered in the econometric analysis was found to be statistically significant in our sample. This finding differs from the majority of the literature on barriers to energy efficiency in SMEs, which suggests that SMEs typically face multiple barriers (Gruber, Brand 1991; Schleich 2009; Schleich, Gruber 2008; Thollander et al. 2007). As the survey in this study was conducted after the energy audits had been carried out, one possible interpretation of our finding is that the audits effectively removed these barriers. Notably, Anderson and Newell (2004), Thollander et al. (2007) and Harris et al. (2000) also find that energy audits contributed to removing barriers related to *information and other transaction costs for gathering knowledge about EEMs*. In light of the relatively small sample size and the absence of a control group, such an interpretation can only be tentatively suggested in our case and further research is required for validation.

It should also be kept in mind that the lack of data did not allow us to explore barriers at the level of individual EEMs. Insights into EEM-specific factors could be gained by following an approach similar to Anderson and Newell (2004), for example.

Our findings also provide evidence that the *quality of the energy audits* (measured by satisfaction with the audits) affects the adoption of EEMs. Although this finding is not very surprising, our study is the first which enables the corresponding policy recommendations to be made based on a statistical analysis. The EU Directive for Energy End-Use Efficiency and Energy Services (European Union 2006) requires EU Member States to ensure that final consumers have access to efficient and high quality energy audits. In addition, the proposal for the EU Energy Efficiency Directive (European Commission 2011) calls on Member States to establish energy audit programs for SMEs. Our results suggest that these regulations as well as energy audit regulations in other regions should include measures addressing the quality of the energy audit. For example, standards for energy audits could be developed, such as the European energy audit standard that is currently under way (DIN prEN 16247-1 2011). For the German audit program, mandatory report templates and quality requirements for auditors (e.g. three years of work experience and an engineering degree or similar) already exist. But similar to most other existing programs (Price, Lu 2011), a specific certificate is not required. Further, software tools and standardized methodologies to support the analytical part of the audit could further improve its quality and ensure that the major potentials for efficiency improvements are addressed (see for example Cagno et al. 2010). Finally, as is already the case for several audit programs, (mandatory) follow-up cooperation between the auditor and the firm could be introduced (Price, Lu 2011). Such follow-up activities could range from simple telephone calls to much closer cooperation to implement more complex EEMs. Also ex-post evaluations could contribute to ensuring audit quality. To save costs, rather than including all the companies participating in an audit, such evaluations could be limited to randomly selected companies.

As a caveat, our findings should be interpreted with caution in view of the relatively small sample size. More observations would lead to lower standard errors, ceteris paribus, and more barriers and control variables might become statistically significant. To save degrees of freedom, we also ran additional regressions omitting all explanatory variables where parameter estimates are far from being statistically significant (implemented as $p>0.5$). The results for the remaining variables barely changed compared to those presented in Table 17.

3.6 Conclusions

We used multivariate regression analysis to investigate the effects of a broad range of factors on the adoption of energy-efficiency measures in German SMEs. Our analyses are based on a unique dataset compiled from a 2010 survey of SMEs which had participated in the German energy audit program. In particular, the EEMs considered in our analyses had been identified as cost-efficient following detailed firm-specific engineering-economic investment appraisals by professional energy experts. Subjective factors are derived via factor analysis from a large set of individual items and include self-assessed barriers to energy efficiency reflecting lack of capital, lack of profitability, transaction costs, technical risks, priority setting/uncertainty and the perceived quality of the audit. The objective factors considered include investment costs, the landlord-tenant dilemma and the use of payback time. In addition, control variables are included in the econometric analysis to account for the effects of firm-specific factors like energy-intensity, energy management, past energy-efficiency activity, and firm size.

Since the range of the dependent variable (adoption rate) is between zero and one, and since a large proportion of observations are at the upper and lower bounds, we employ a fractional logit model. Compared to previous multivariate analyses of barriers to energy efficiency, using the FLM model offers a more efficient use of information. Our findings from the regression analysis are generally robust to alternative model specifications and are consistent with the theoretical and (still rather scarce) empirical literature on barriers to energy efficiency in SMEs. Our results identify high initial investment costs as a main barrier to the adoption of EEMs. Thus, to accelerate the adoption of EEMs via audit programs, these should be accompanied by financing programs. Further, we find evidence that higher satisfaction with the energy audit increases the firms' propensity to implement the suggested EEMs. Assuming that higher satisfaction scores are correlated with higher audit quality, this result rationalizes policy regulation which includes measures to ensure a high quality of the energy audits. Such measures may involve templates for audit reports, certification of auditors, ex-post evaluations, or mandatory monitoring of energy audits.

Our findings for the factor analysis of the subjective barrier items by and large validate the theoretical framework and barrier taxonomy previously used in the literature to conceptualize and empirically analyze barriers to energy efficiency. Hence, results from the factor analysis allow the barriers to energy efficiency to be considered at a more abstract level than individual concrete obstacles. As a point of discrepancy to the broader barrier categories developed by Sorrell et al. (2004), our results suggest that technical and financial risks do not fall into the same broader barrier category, but instead represent distinct barriers to energy efficiency.

Future research could apply a similar factor analysis to other sectors or countries, using additional barrier items or EEM-specific information to validate and refine our approach and further enhance the taxonomy of barriers to energy efficiency for empirical and conceptual analyses.

Appendix

Table 18: Results of the factor analysis using the principal component factor method for self-assessed barrier variables

Factor analysis/correlation		Number of observations	=	138	
Method: principal component factors		Retained factors	=	5	
Rotation: (unrotated)		Number of parameters	=	65	

Factor	**Eigen-value**	**Difference**	**Proportion**	**Cumulative**
Factor 1	3.985	2.130	0.265	0.265
Factor 2	1.854	0.439	0.123	0.389
Factor 3	1.415	0.108	0.094	0.483
Factor 4	1.306	0.154	0.087	0.570
Factor 5	1.151	0.267	0.076	0.647
Factor 6	0.884	0.044	0.059	0.706
Factor 7	0.839	0.119	0.056	0.762
Factor 8	0.720	0.128	0.048	0.810
Factor 9	0.591	0.040	0.039	0.849
Factor 10	0.551	0.057	0.036	0.886
Factor 11	0.493	0.031	0.032	0.919
Factor 12	0.462	0.087	0.030	0.950
Factor 13	0.374	0.124	0.025	0.975
Factor 14	0.249	0.128	0.016	0.991
Factor 15	0.120		0.008	1

Table 19: Results of the factor analysis using the principal component factor method for self-reported audit quality variables

Factor analysis/correlation		Number of observations	= 437	
Method: principal component factors		Retained factors	= 1	
Rotation: (unrotated)		Number of parameters	= 8	
Factor	**Eigen-value**	**Difference**	**Proportion**	**Cumulative**
Factor 1	5.283	4.509	0.661	0.661
Factor 2	0.775	0.206	0.097	0.757
Factor 3	0.569	0.187	0.071	0.829
Factor 4	0.382	0.051	0.048	0.876
Factor 5	0.332	0.029	0.041	0.918
Factor 6	0.303	0.092	0.038	0.955
Factor 7	0.210	0.065	0.027	0.982
Factor 8	0.145	-	0.018	1.000

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4 The characteristics of energy-efficiency measures – a neglected dimension [42]

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.

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4.1 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 1994b; 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. 2000b). 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 4.2). We then propose and discuss EEM characteristics for the classification scheme (Section 4.3). To illustrate and validate the classification scheme, we use it to characterize and compare a set of different EEMs (Section 4.4). We finally discuss the advantages and drawbacks of our approach and its application (Section 4.5) and make suggestions for further research (Section 4.6).

4.2 A review of EEM characteristics

4.2.1 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 determine the selection and definition of 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 4.3.

4.2.2 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 1994b) 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. (2000b) 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 invest-*

ments 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. 2010a; 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 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 4.3.

4.2.3 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[43]. Tornatzky and Klein (1982) added *cost*, *communicability*, *profitability, social approval* 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

[43] 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).

(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.[44] 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 Kesidou (2011) impose

[44] 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.

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)**[45]. 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 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 impor-

45 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).

tance 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 4.3). 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.

4.3 Development of a classification scheme

4.3.1 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 15). 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 15: 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

4.3.2 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. (2000b) 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.

4.3.3 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).

4.3.4 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. 2000b). 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.

4.4 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.

4.4.1 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 20)

Table 20: 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 lid	Crucible melting furnaces are used in the non-ferrous 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).	We assume that a manually operated furnace lid is 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

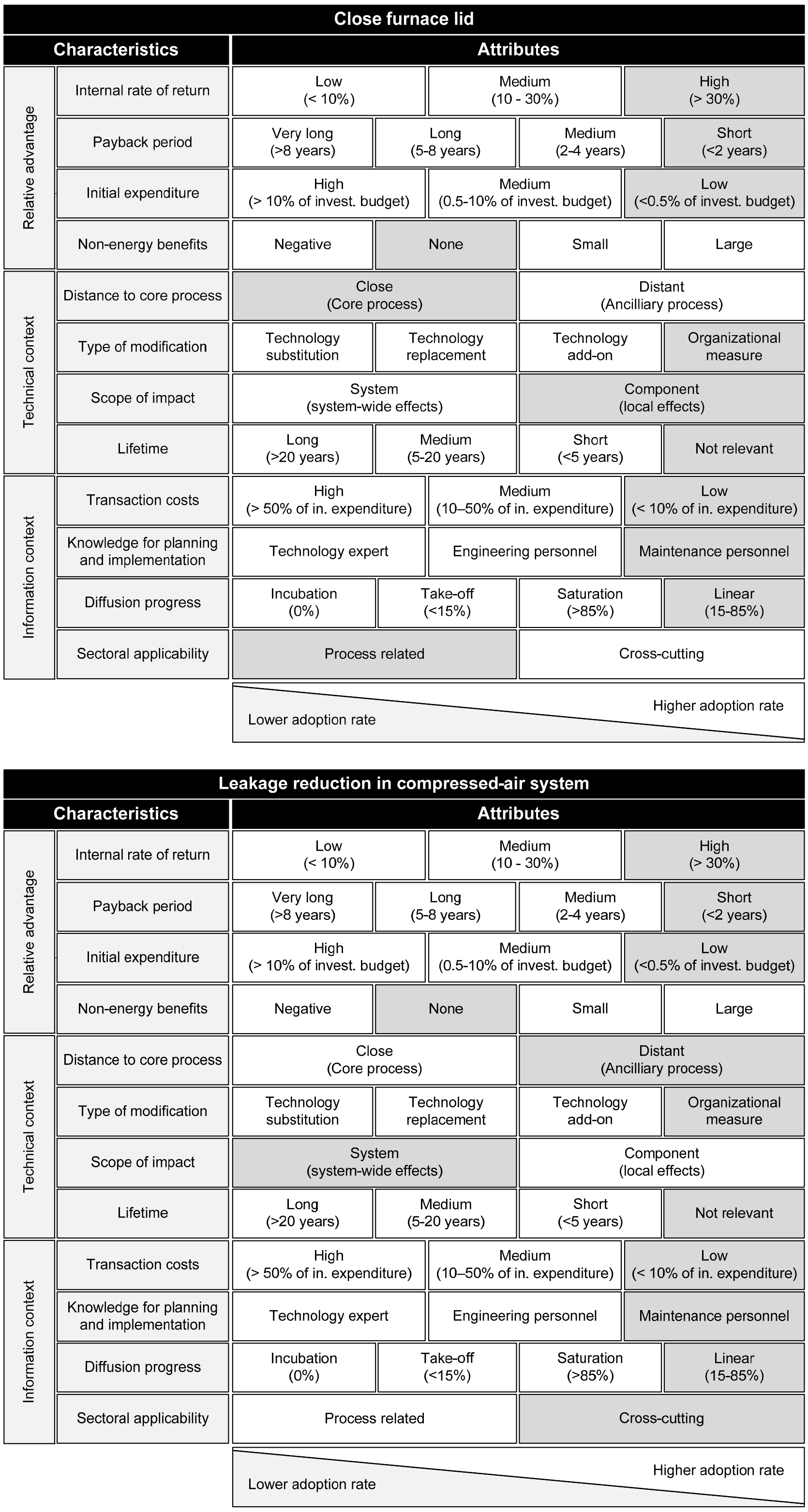

Figure 16: Classification scheme applied to EEM examples

4.4.2 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 16).

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. 2012a).

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.

4.5 Discussion

4.5.1 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 4.4.2. 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.

4.5.2 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 4.4, we infer the strength of each characteristic rather than measuring characteristics as perceived by potential adopters.[46] 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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[46] Inferring the characteristics of innovations is also identified by Tornatzky and Klein (Tornatzky, Klein 1982) as the dominant approach in studies of innovation characteristics.

4.6 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.

Acknowledgements

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5 The German energy audit program for firms – A cost-effective way to improve energy efficiency? [47]

Abstract

In 2008, a program was established in Germany to provide grants for energy audits in small and medium-sized enterprises. It aims to overcome barriers to energy efficiency, like the lack of information or a lack of capacity, and is intended to increase the adoption of energy-efficiency measures. We evaluate the program's impact in terms of energy savings, CO_2 mitigation, and cost-effectiveness. We find that firms adopt 1.7-2.9 energy-efficiency measures, which they would not have adopted without the program. Taking a firm's perspective, the program shows a net present value ranging from € -0.4 to 6 per MWh saved, which very likely implies a net benefit. For the government, each ton of CO_2 mitigated costs between € 1.8 and 4.1. Each euro of public expenditure on audit grants led to € 17-33 of private investment. The cost-effectiveness of the program for firms and the low share of public expenditure underline its value for the German energy efficiency policy mix and suggest that it should be expanded in Germany. Further, the good experiences with the program in Germany should encourage countries which have not yet established an audit program to do so.

[47] The chapter has been published in Energy Efficiency as *Fleiter, T.; Gruber, E.; Eichhammer, W.; Worrell, E. (2012): The German energy audit program for firms - a cost-effective way to improve energy efficiency? Energy Efficiency, http://dx.doi.org/10.1007/s12053-012-9157-7.*

5.1 Introduction

It is widely recognized that firms' investment behavior with regard to energy-efficiency measures (EEMs) does not follow rational cost minimization. Indeed, a number of barriers often prevent investment in cost-effective technologies (de Almeida 1998; DeCanio 1998; Schleich, Gruber 2008; Thollander, Ottosson 2008). The barriers can be classified into imperfect information, hidden costs , risk and uncertainty, access to capital, split incentives and bounded rationality (Sorrell et al. 2004). This observation is often named the "energy-efficiency gap", which implies that energy-efficiency potentials are available that can increase both the overall economic efficiency as well as the energy efficiency of firms (Jaffe, Stavins 1994a; Jaffe, Stavins 1994b). Closing the energy-efficiency gap is a priority for policy-making, because the resulting energy savings and greenhouse gas abatement result in net benefits. In particular, many barriers prevail in small and medium-sized enterprises (SMEs), which tend to consider investments in energy efficiency as low priority projects, do not spend resources devoted specifically to energy management, and experience more intense barriers resulting in lower adoption rates for EEMs (e.g. Gruber, Brand 1991).

One policy (among several) addressing the energy-efficiency gap is the promotion of energy audits in firms (Schleich 2004). By now, energy audits are part of the national policy mix in many countries worldwide and often particularly address SMEs (Price, Lu 2011). Price and Lu (2011) identify 22 audit programs established worldwide, which show a huge degree of variation with regard to program design: while 6 programs are defined as stand-alone energy audit programs, the majority of 16 programs integrate the audits into a broader framework which also comprises elements like voluntary agreements, efficiency targets or energy management systems. The audit programs further differ, among other things, in terms of government support for the audit cost or requirements in terms of monitoring and auditor certification. One of the first programs established is the US IAC program, which has provided energy audits to small and medium-sized enterprises (SMEs) since 1976 (Anderson, Newell 2004; Muthulingam et al. 2011). Also the Swedish "Highland" program addressed SMEs (Thollander et al. 2007), and in Denmark two programs separately addressed small as well as large enterprises (Larsen, Jensen 1999). Another Swedish program, the PFE, combines audits with long-term agreements and is only applicable for energy-intensive industries (Petersson et al. 2011; Stenqvist, Nilsson 2012). Further programs were established in Australia, like the Enterprise Energy Audit Program EEAP (Harris et al. 2000) and the Energy Efficiency Opportunities EEO (Crittenden, Lewis 2011) programs or in China, which particularly addresses motor systems (Williams et al. 2005). Also, the EU Directive for Energy End-Use Efficiency and Energy Services (European Union 2006) requires member states to ensure the availability of efficient and high quality energy audits to all final consumers. Beyond this, the proposal to the Energy-Efficiency Directive (European Commission 2011) explicitly requires member states to establish energy audit programs for SMEs. While currently only a few energy-efficiency policies in Europe have been thoroughly evaluated (Harmelink et al. 2008), both directives increase the need for ex-post evaluations, which are the basis for future program design.

The German energy audit scheme for SMEs[48] was established in 2008 and is still operating. It is a stand-alone audit program offering grants to SMEs to conduct energy audits. Up to now, the program has not been evaluated.

We present an ex post evaluation of the German energy audit program. We assess the impact in terms of energy and CO_2 savings as well as the cost-effectiveness of the program. Further, we provide an overview of the types of energy-efficiency measures (EEMs) conducted and how the program contributes towards overcoming barriers. Our study is the first assessment of the German program and is based on a survey among the participating firms and energy consultants, as well as a sample of audit reports used for cross-checking.

Our paper extends the existing literature, as cost-effectiveness of audit programs for SMEs is only rarely analyzed, mostly due to lack of data and difficulties with heterogeneity among firms. Also, by calculating the net impact corrected for free-riders and other effects, we go beyond standard evaluations of audit programs.

We explicitly focus on the outcomes of the program and its cost-effectiveness and do not conduct a process-related evaluation.[49] Further, our study does not cover the entire program period, but only evaluates the first two years, as the program is still operating.

Thus, our empirical analysis aims to contribute to a more efficient policy design as well as a more realistic ex ante policy assessment. This kind of knowledge is obligatory to translate assumptions about policy design into input parameters for ex ante assessment models (Fleiter et al. 2011; Worrell et al. 2004).

The paper is structured as follows. In Section 5.3, we calculate the program impact in terms of energy savings and costs, using a bottom-up methodology starting with the savings induced by each EEM adopted. These are aggregated and extrapolated to the whole population of participating companies to calculate indicators for impact and cost-effectiveness. The results are compared to evaluations of similar audit programs in the USA, Australia and Sweden. In Section 5.4 we analyze the program impact with regard to EEM (or end-use) types. By grouping the EEMs according to their end-uses, conclusions can be drawn on the scope of the end-uses addressed by the program. Section 5.5 explores the barriers to the adoption of EEM, which the program helps to overcome and those which still persist despite the program.

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48 German title: “Sonderfonds Energieeffizienz in KMU“.

49 For a more process-oriented assessment of the role of the energy auditors and the regional partners, we refer to Gruber et al. (2011).

5.2 Program characteristics

In 2008, the German Ministry of Economic Affairs launched the energy audit program which was designed on the basis of a market study completed in 2006 (Gruber et al. 2006). The target group comprises all SMEs[50] in all sectors. The program includes two kinds of audits, which can be combined or used separately. These are:

- An "initial" or screening audit of one or two days which includes a short check of the energy-using equipment and records the energy demand, existing deficiencies and recommendations for improvement; 80 % of the total costs are granted for this type of audit.
- A "comprehensive" or detailed audit of up to 10 days with a detailed inspection of one or more energy end-uses and suggestions for related EEMs; subsidies cover up to 60 % of the audit cost.

For both types of audits, a standardized template for the audit report is provided that ensures that all important aspects of firms' energy use are analyzed. The program does not provide any standardized assessment tools besides the templates. The (supported) cooperation between the auditor and the firm ends with the delivery of the audit report. Further follow-ups are not foreseen in the program, but they sometimes take place. The auditors themselves do not require a particular certification or assessment to be approved as an auditor in this program. However, a number of basic qualifications such as three years of auditing experience and an university degree in engineering or similar are required to be approved as auditor.

The program is managed by the KfW, the German Promotional Bank owned by the federal republic and the federal states. It is responsible for approving applications and paying out grants. The communication with the companies is delegated to "regional partners", mainly chambers of trade and commerce, but also business development institutions or energy agencies. They check and process the applications to the KfW. A database of qualified and independent consultants is provided by the KfW on the internet, which enables interested companies to find a suitable consultant in their region. The KfW checks consultants' qualifications before listing them in the online database.

The KfW also provides soft loans to implement EEMs. However, the audit is not a precondition of receiving a loan. The program does not contain additional elements like voluntary targets or obligations to implement energy-management schemes.

During the evaluated period from March 2008 to June 2010, a total 10,400 audit grants were approved by the KfW. Of these, 80% were initial audits and 20% comprehensive audits. The

[50] Defined as firms with less than 250 employees.

monthly approvals remained at around 400-500, after an initial increase at the start of the program in 2008.

Firms from all sectors applied for audit grants (Figure 17). However, compared to the number of all firms active in a sector, the food processing sector and food retail trades are highly represented.

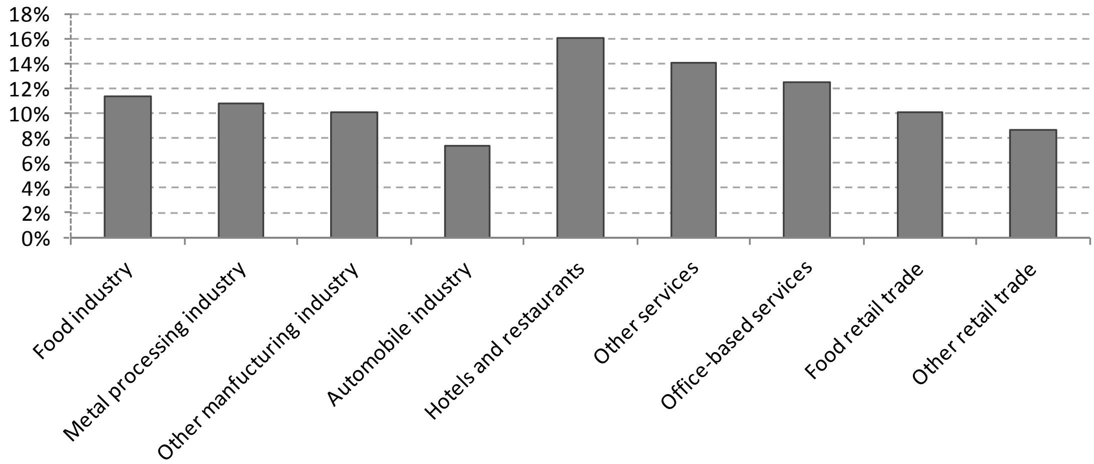

Figure 17: Distribution of participating firms by branch (on the left industry, on the right services) (Based on KfW database)

According to the KfW statistics, the mean participating firm has around 38 employees, while 50 % of the firms have less than 20 employees. The distribution of firms participating in the survey by number of employees is shown in Figure 18. The share of larger firms is particularly low and only 10% of firms have more than 100 employees. On the other hand, the 10% of the largest firms account for more than 30% of energy demand, whereas the firms below 25 employees only account for 20% of energy demand, although they represent about half of the firms in the sample.

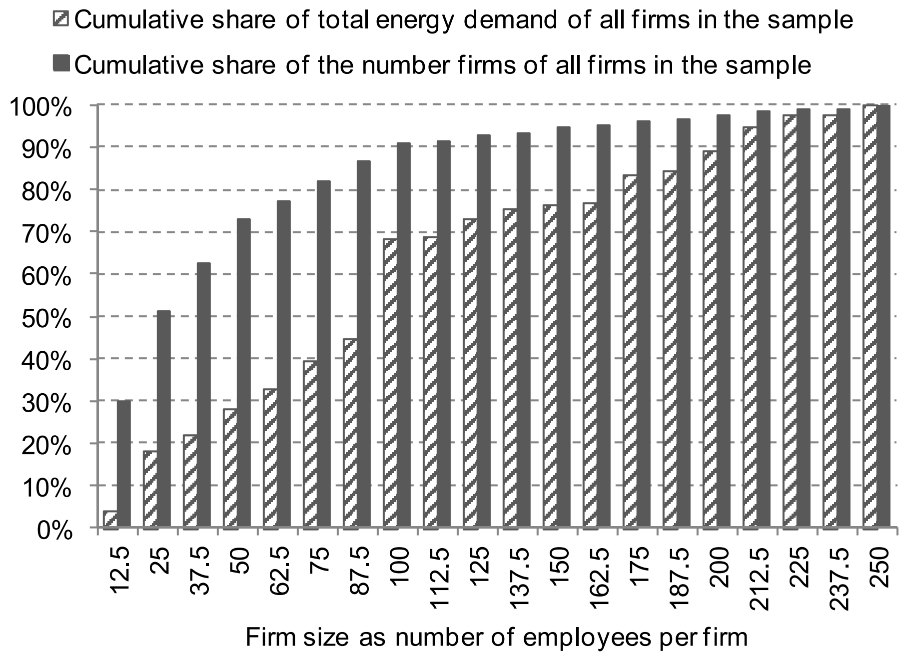

Figure 18: Cumulative distribution of energy demand and number of firms participating in the survey

Within the German policy mix, the energy audit program analyzed in this paper is one of the rare instruments which directly addresses energy efficiency in SMEs. “Learning energy-efficiency networks” is another one addressing medium-sized firms (Jochem, Gruber 2007). Other programs are broader in sectoral scope, but address only a particular type of energy end-use and many stem from EU directives. Examples are a program providing soft loans for energy-efficient retrofitting of buildings or information-based campaigns provided by the German energy agency which address particular end-uses like the use of compressed air or lighting. In its energy concept of 2010, the federal government summarizes central future challenges and strategies. Regarding SMEs, the extension of audit programs is envisaged as well as new rules for exceptions under the energy tax law. These rules may comprise the stricter requirements like implementing energy management schemes for firms to be eligible for tax rebates. However, as only a few policies particularly address energy efficiency in SMEs, the program plays an important role within the German energy efficiency policy mix.

5.3 Impact assessment

5.3.1 Data sources

In order to build on as robust a dataset as possible, we rely on three main data sources: an online survey among the participating firms, a sample of audit reports and further program statistics collected by the KfW.

A main challenge of the impact assessment is the fact that the German program does not require participating firms to report achieved energy savings of adopted EEMs as is mandatory in other programs like the Swedish PFE or the US IAC. Consequently, data to calculate energy savings has to be gathered by a survey. The survey was conducted in summer 2010 among all participating firms which had at least one completed audit. Thus, we approached 4,434 firms out of the initial number of 10,400[51] approved grants. The survey contained detailed questions relating to the adoption and non-adoption of EEMs. Due to the length of the survey and the detailed questions, many respondents only answered parts of the survey. We received 542 usable responses which means a response rate of 12 %. A similar survey among a control group of firms not participating in the program could not be used for this analysis due to a very low response rate. Drawing conclusions from a small sample is particularly challenging for such a heterogeneous group of program users.

Additionally, we analyzed 107 audit reports. Unfortunately, the audit reports do not contain information about whether the recommended measures were adopted by the firms. Despite this limitation, we could still use the reports to cross-check the results of the survey and to estimate characteristics of the EEMs, like energy savings and payback period.

Furthermore, KfW program statistics provide the total number of audits conducted, which is used to extrapolate the results from the company level to the entire program.

The high degree of company heterogeneity in terms of sector or size is a challenge for the analysis. This is amplified as only a limited number of firms responded to the questionnaires. In order to obtain as large a sample size as possible, we use varying samples depending on the data availability, particularly in Section 5.4. We believe the estimated results are robust and that they provide a reliable picture of the program's impact. A comparison of company size and sector shares between survey sample and all companies participating in the audit program shows no particularly strong deviations and we regard the data sample as representative.

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[51] This figure also considers omitted firms that did not provide an e-mail address or that objected to data processing. Further, in the case where a firm conducted both audits, it was only asked about the comprehensive audit.

5.3.2 Methodology

For the quantitative impact assessment, we calculate indicators in terms of energy savings or CO_2 emission mitigation and indicators for the cost-effectiveness, like the discounted NPV per energy saved. We apply a bottom-up approach such as is commonly used to evaluate energy audit programs (e.g. see Harris et al. 2000; Thollander et al. 2007).[52]

The bottom-up calculation is based on the impact of distinct EEMs and the total number of EEMs adopted. The question, whether the EEMs are induced by the audits or whether they would have been adopted even without the audit program, thus, the distinction between net and gross energy savings, needs particular consideration. In contrast to gross savings, net savings are corrected for free-rider effects, spill-over or multiplier effects and double counting of impact from other policies (Thomas et al. 2011). Vine et al. (2012) add market effects to this list and underline that there is no dominant definition of net energy savings; instead, varying definitions are applied by evaluators. We explicitly calculate net savings by correcting for free-rider effects. Data availability, however, did not allow us to consider possible spill-over effects to non-participating firms or indirect market effects as well as rebound effects in this study. Neither were we able to disentangle the induced energy savings from impacts of other parallel policies.

Four steps are distinguished for the impact calculation (see Figure 19). We first assess the impact of distinct EEMs (step I), second the impact on single firms (step II) and third for the entire program, extrapolating from the sample to all participating firms (step III). Finally, we calculate indicators for the cost-effectiveness of the program (step IV). These four steps imply different methodological aspects, which are discussed in the following.

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[52] Another approach would be to calculate energy savings based on a comparison of firms' energy bills before and after the audit. However, due to the relatively low share of energy savings compared to firms' energy demand, and the fluctuating energy demand as a result of production variation, the success of such an approach is very uncertain. A similar approach, that is, comparing energy bills of audited companies against those of a control group, is hardly possible because of the heterogeneity among firms. Furthermore, we had to rely on a survey and energy audit reports as our main data sources, because metering in firms would have been too costly.

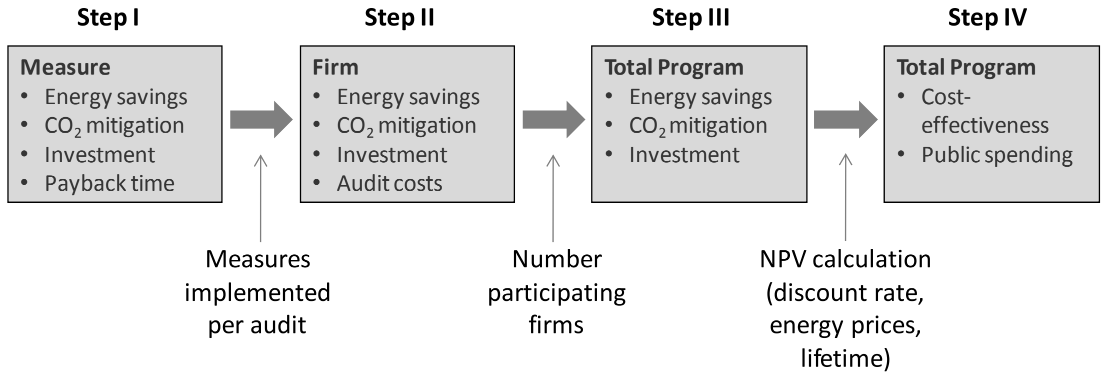

Figure 19: The four-step calculation approach

Step I

In the first step, we calculate average energy and CO_2 savings, investment costs and payback time per EEM. While most of these variables are calculated as a simple mean of the data sample, the calculation of CO_2 savings per measure requires more explanation. In order to estimate the resulting CO_2 savings, we use a CO_2 emission factor which is multiplied with the annual energy savings. Energy savings are differentiated according to three energy carriers: light fuel oil, natural gas and electricity. For light fuel oil and natural gas we assume 74 kg CO_2/GJ and 56 kg CO_2/GJ, respectively. As the exact share of fuel oil and natural gas is unknown, we assume an equal distribution between these two energy carriers. Regarding electricity savings the underlying CO_2 factor represents the mean CO_2 emissions of the German generation mix and falls from an initial 601 tCO_2/GWh in 2008 to 520 tCO_2/GWh in 2029, when the longest living vintage is being decommissioned.[53] The decline represents an increasing share of low-carbon energy sources in the generation mix and is in line with current business as usual scenarios for Germany (Prognos et al. 2010).

Step II

In order to extrapolate the program impact from the level of single EEMs to the firm level, we first calculate the net number of measures adopted per firm. Therefore, we explicitly take the following three effects into account.

[53] In contrast to the CO_2 factor for fuel oil and natural gas, CO_2 emissions of electricity generation vary over time, depending on the dynamics in the generation mix. While we are not able to consider hourly variations, the data allows the consideration of annual variations. See Vine et al. (2012) for a more detailed discussion of this aspect.

- *Additionality of EEMs* (α)*:* about 21% of the EEMs recommended in the audit report and adopted by the company were already planned before the audit.[54] Measures certainly planned before the audit were excluded for the calculation of net savings.
- *Non-energy efficiency measures* (β)*:* around 5% of measures do not directly improve energy efficiency, but imply the use of renewable energies or combined heat and power generation. In terms of CO_2 mitigation, these measures would certainly increase the impact of the program; however, due to the small sample and huge heterogeneity, we were not able to consider them.
- *EEMs to be adopted in the near future* (γ)*:* due to the short period between the audit and the evaluation, many recommended EEMs had not been adopted at the time of the survey; however, companies stated that they planned to implement them in the near future. If firms state that they will possibly implement these EEMs, we assume that 50% of them will actually be adopted.[55] For "certainly planned EEMs" we assume that all will be adopted in the near future. We calculate two sets of results: one including and one excluding planned measures.

The survey asks firms to list the gross number of recommended (N^{rec}) and adopted (N^{ado}) EEMs.[56] The net number of EEMs adopted ($N^{net,expl}$) is calculated, correcting for the share of EEMs that were already planned for adoption before the audit has taken place (α) and the share of EEMs that are not related to energy savings (β).

$$N^{net,expl} = N^{ado}(1-\alpha)(1-\beta) \quad (6)$$

Similarly, the net number of non-adopted EEMs ($N^{net,non\text{-}ado}$) calculates as following.

$$N^{net,non-ado} = (N^{rec} - N^{ado})(1-\alpha)(1-\beta) \quad (7)$$

The net number of EEMs adopted including planned measures ($N^{net,incpl}$) is calculated by correcting for the share of non-adopted measures that is certainly planned for adoption (γ).

$$N^{net,incpl} = N^{net,expl} + \gamma N^{net,non-ado} \quad (8)$$

Finally, the energy and CO_2 savings ($S_t^{j,f}$) as well as the investment costs per firm *f* at time *t* are calculated by multiplying the average impact per EEM ($\overline{S_t}^{EEM}$) with the net number of EEMs adopted ($N^{net,incpl}$).

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[54] Question in survey: "Was the implementation of measures already planned before the audit? – "certainly planned" (20.9%), "considered" (42.3%), "no" (36.8%)

[55] List of four EEMs not adopted followed by the question in survey: „Do you plan to implement these measures in the near future?" – "certainly" (33.5%), "possibly" (35.9%), "rather not" (30.6%)

[56] Question: "How many measures were recommended in total?"
Question: "How many measures did you implement?"

$$S_t^{j,f} = N^{net,incpl} \overline{S}_t^{EEM} \qquad (9)$$

Further, we calculate the adoption rate (δ) as the net number of adopted EEMs divided by the net number of recommended EEMs.

$$\delta^{incpl} = \frac{N^{net,incpl}}{N^{net,incpl} + N^{net,non-ado}} \qquad (10)$$

Step III

The total program impact is calculated by extrapolating the effect on the firm level to the entire number of participating firms, which is derived from official program statistics. The net impact excludes free-rider effects, which describe firms that might have used an energy audit in the theoretical case that the program did not exist.

The survey addressed free-riders by explicitly asking whether the firms would have conducted a similar audit even without the grant.[57] This is true for 9.1% of the firms.[58] The variation by type of audit (initial, detailed or both) is very low, so that we assume 9.1% independent of the audit type. Further, firms that would have used a less comprehensive energy audit without the grant are not counted as free-riders, because the more comprehensive audit probably also induced more energy savings.

Thus, the net annual energy (j=energy) and CO_2 (j=CO_2) savings (S^j) are calculated by multiplication with the number of firms participating in the audit program (F) corrected for the share of free-riders (ε).

$$S_t^j = S_t^{j,f} F(1-\varepsilon) \qquad (11)$$

Step IV

The indicators for cost-effectiveness are based on a classical capital budgeting calculation where all future cash flows are discounted to attain the net present value (NPV). The cash flows considered are the initial investment, the audit costs, the costs of saved energy, and the administrative costs.

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57 Question in survey: "Would you have conducted the audit even without the program?" – "Yes, with the same level of comprehensiveness" (9.1%), "Yes, but less comprehensive" (42.6%), and "No, rather not" (48.3%).

58 As the response rate of the control group was very low, we were not able to cross-check this statement by control group comparison.

Relevant input parameters like the lifetime of the EEMs and the future energy prices are uncertain, which is why we calculate a lowe*r and an upper boundary* for the profitability of the program. We assume a mean lifetime per type of EEM ranging from 3 (information technology) to 30 (building envelope) years (see annex). For the upper boundary the mean lifetime across all EEM types is about 5 years longer than for the lower boundary. We consider energy prices for electricity, light fuel oil, and natural gas. Moderately rising energy prices are assumed in both cases, but these are assumed to be higher for the *upper boundary*, reaching a maximum of 130% in 2030 compared to 2008 (real prices of 2008). The figures are given in the annex.

The cost-effectiveness of the program is then calculated, based on the NPV of all cash flows and the impact in terms of cumulated energy (j=energy) and CO_2 (j=CO_2) savings ($S^{j,cum}$). The latter is calculated as the sum of the annually induced savings over the entire lifetime of all adopted EEMs.

$$S^{j,cum} = \sum_{t=0}^{n} S_t^j \tag{12}$$

The NPV of all cash flows comprises different elements, depending on the perspective (*k*) taken. From a firm perspective (*k*=firm), relevant cash flows are the investment costs (IC), the share of the audit costs carried by the firm (ACF) and the energy cost savings (ECS). All cash-flows besides the ECS only occur from 2008 to 2010 and are set to zero the remaining years.

$$NPV^{firm} = \sum_{t=0}^{n} \frac{ECS_t}{(1+i_{firm})^t} - \sum_{t=0}^{n} \frac{IC_t}{(1+i_{firm})^t} - \sum_{t=0}^{n} \frac{ACF_t}{(1+i_{firm})^t} \tag{13}$$

The total costs from a public perspective take program costs like monitoring and the processing of applications (PC) and the public share of the audit costs (ACP) into account.

$$NPV^{public} = -\sum_{t=0}^{n} \frac{PC_t}{(1+i_{public})^t} - \sum_{t=0}^{n} \frac{ACP_t}{(1+i_{public})^t} \tag{14}$$

Finally, the society perspective considers all cash flows relevant to the program. Non-financial effects e.g. in the form of external costs are not considered.

$$NPV^{society} = \sum_{t=0}^{n} \frac{ECS_t}{(1+i_{society})^t} - \sum_{t=0}^{n} \frac{IC_t}{(1+i_{society})^t} - \sum_{t=0}^{n} \frac{ACF_t}{(1+i_{society})^t} - \sum_{t=0}^{n} \frac{ACP_t}{(1+i_{society})^t} - \sum_{t=0}^{n} \frac{PC_t}{(1+i_{society})^t} \tag{15}$$

The different perspectives do not only imply varying cost elements, but also a varying discount rate (*i*) (Harmelink et al. 2008). We assume 15%, 3% and 3% for the firm, public and society perspective, respectively. Due to the long lifetime of most EEMs, the discount rate has a significant impact on the net benefit of the program.

Finally, the cost-effectiveness is calculated by dividing the NPV of all future cash flows by the cumulated energy or CO_2 savings ($S^{j,cum}$). For both NPV and impacts, all audits conducted during the evaluation period are considered and the entire lifetime of the induced EEMs is taken into account.

$$npv^{k,j} = \frac{NPV^k}{S^{j,cum}} \tag{16}$$

For the public perspective, we additionally provide an indicator representing the share of public investment in relation to the private investment induced (*spi*).

$$spi = \frac{\sum_{t=0}^{n} ACP_t + \sum_{t=0}^{n} PC_t}{\sum_{t=0}^{n} IC_t} \tag{17}$$

5.3.3 Results

5.3.3.1 Step I: Impact per energy-efficiency measures (EEMs)

The adopted EEMs show mean annual final energy savings of about 70 MWh/a or equivalent to 247 GJ/a (see Table 21), of which 75% are fuel savings and 25% electricity savings. The fact that the mean savings are a lot higher than the median savings is resulting from a few EEMs with very high savings and indicates a skew distribution of savings per EEM. The (weighted) mean savings per measure account for 1.7% of the companies' energy demand. Due to the great heterogeneity among companies, this value varies significantly among firms and is considerably higher for smaller firms.[59] The non-weighted mean is 6%, which results from the huge share of smaller companies and the large spread in energy demand (see Figure 18).[60] These energy savings result in 22 tons of CO_2 savings, on average.

[59] This mainly results from the fact that many firms consume energy only for building-related end-uses. In this case, single measures like insulation or replacement of heating systems show high impacts when compared to the firm's total energy consumption.

[60] The weighted mean energy savings are calculated as $MeanSavings^{w} = \frac{\sum_{i=1}^{n} Savings_i}{\sum_{j=1}^{m} EnergyDemand_j}$ while the non-weighted savings are calculated as $MeanSavings^{nw} = \frac{\sum_{i=1}^{n} \frac{Savings_i^j}{EnergyDemand^j}}{n}$, where i = EEM and j = firm

On average, firms invested € 23,000 per adopted EEM. This figure excludes measures that were planned before the audit (non-additional measures). If these were included, the average investment would be € 51,000, which indicates that particularly expensive measures were already planned by firms before the audit has taken place.

Table 21: Average impact per EEM

	Unit	Mean	25%	50%	75%	Sample
Final energy savings [a]	[GJ/a]	247	18	54	193	382
as share of firms' energy demand [c]	[%]	1.70 %				
CO_2 mitigation [a]	[t CO_2/a]	22				
Investment expenditure [b, d]	[€]	23,000	500	3,000	15,000	520
Payback time [b]	[a]	6.1	2	5	8	382

[a] Source: firm survey and audit reports (in order to increase the sample size, we also used measurement descriptions from the audit reports. However, the mean value is similar to the mean of only the firm survey data, so this approach does not significantly bias the results)

[b] Source: firm survey only

[c] Weighted by firm's energy demand (measures in larger firms tend to account for a lower share of energy demand).

[d] Corrected for non-additional measures

The payback period is still the dominant decision criterion for companies when investing in EEMs. The payback period of the adopted measures ranges from 0 to 32 years.[61] The mean payback period is 6.1 years, while 50% of adopted measures are below 5 years (see Figure 20).

Many measures go beyond pure energy-saving investments. Replacing old boilers or other equipment may be necessary, simply because of their age and not due to energy-saving considerations. Particularly building-related investments are often strategic or obligatory, so that the payback period is only a secondary criterion and long payback periods may be accepted by companies.

[61] Very long payback times are mainly observed for measures related to building renovation (see Section 5.4).

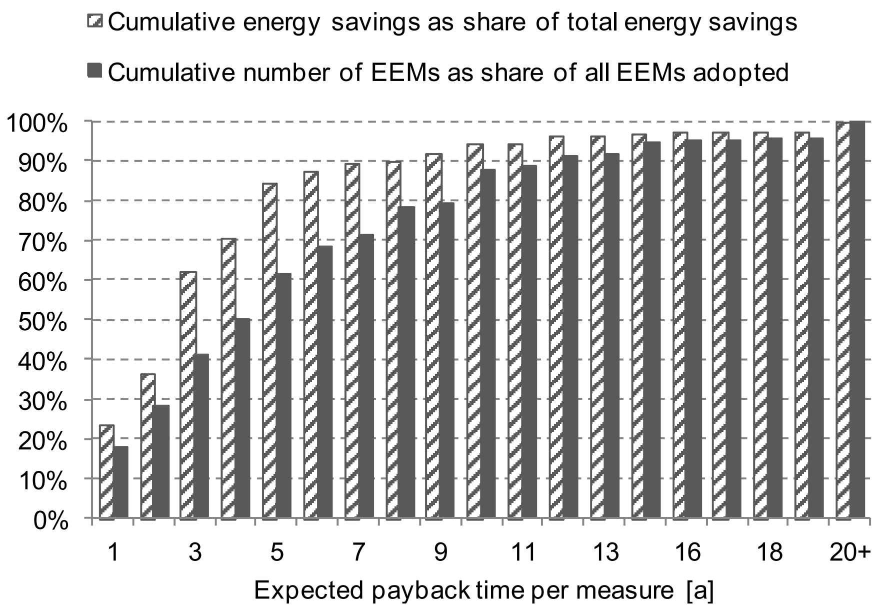

Figure 20: Cumulative share of total energy savings and total number EEMs adopted over payback period (based on firm survey and audit reports)

5.3.3.2 Step II: Impact at the firm level

In order to extrapolate the program impact from the level of single EEMs to the firm level, the number of measures adopted per firm is used, as shown in Table 22. On average, 5.3 measures were recommended per firm, while 2.3 of these measures were adopted at the time of the survey. While this describes the gross impact, the net impact corrects for non-additional measures and non-EEMs and arrives at a net number of 1.7 adopted measures per firm. This figure is slightly higher for detailed audits, while it is lower for initial audits. If counting measures not adopted but certainly planned for future adoption this figure increases to 2.9. The net adoption rates are 43 % and 72 %, respectively.

Table 22: Average number of EEMs recommended and adopted per firm d (n=386)

Gross number EEMs recommended [a]	(N^{rec})	5.3	
Gross number EEMs adopted (at time of survey) [b]	(N^{ado})	2.3	
Share of non-additional measures (planned before the audit)[C]	(α)		21%
Share of non-EEMs (e.g. fuel switch)	(β)		4.9%
Net number EEMs adopted (excluding planned future EEMs)	($N^{net,expl}$)	**1.7**	
Net number of non- adopted EEMs	($N^{net,non\text{-}ado}$)	2.3	
Share of non- adopted EEMs planned for future adoption	(γ)		51%
Net number EEMs adopted (including planned future EEMs)	($N^{net,incpl}$)	**2.9**	
Net adoption rate (excluding planned future EEMs)	(δ^{expl})		43%
Net adoption rate (including planned future EEMs)	(δ^{incpl})		72%

a The 25%, 50% and 75% quantiles are 3, 4 and 7;

b The 25%, 50% and 75% quantiles are 1, 2 and 3;

c Non-additional measures are assumed to be equally distributed over the adopted EEMs and the non-adopted EEMs.

d These figures are average values over all audits in the sample. For the calculations, however, we distinguish between audit types (initial, detail or both), although the differences are small.

The impact at the firm level in terms of energy savings, CO_2 mitigation and investments is given in Table 23 and based on 2.9 and 1.7 measures per firm and the average impact per EEM as shown in Table 21.

Table 23: Average impact per firm

	Unit	Including planned future measures	Excluding planned future measures
Average final energy savings	[GJ/a]	711	423
As share of firms' energy demand [b]	[%]	5	3
Average CO_2 mitigation	[t CO_2/a]	63	37
Average investment expenditure [a]	[€]	66,300	39,400

a Figures corrected for non-additional measures (see methodology).

b Weighted by firm's energy demand (measures in larger firms tend to account for a lower share of energy demand).

Besides the costs for adopting EEMs, firms also face costs for the audit itself. For an initial audit, a company paid € 900 on average from own funds, while it received € 1,200 of public funding. For the detailed audits, the average firm paid € 3,600 and received additional € 4,000 from public funds.[62] A full economic analysis of the program is presented below.

5.3.3.3 Step III: Impact of the total program

Table 24 shows the aggregated results for net energy savings, CO_2 mitigation and costs. Also here we consider two cases, one including and one excluding planned measures. All figures are corrected for free-rider effects, which amount to 9.1% of all audits[63], and non-additional measures as well as non-EEMs.

The audits in the evaluated time period from March 2008 to June 2010 induced annual energy savings of about 0.95 to 1.63 TWh, corresponding to annual CO_2 emission reductions of 310 to 531 kt. The savings induced by the measures in 2009 amount to about 0.04 to 0.07 % of the annual final energy demand of all companies in Germany. The energy demand of the firms audited in 2009 amounts to about 1.5 % of the energy demand of all firms in Germany. The savings may seem low at a first glance. However, if one considers the past energy efficiency progress in the industrial sector, which was around 1.3%[64] per year in Germany (Graichen et al. 2011), the figures are put into perspective. Assuming that the audit program continues at a similar level of activity, this would imply that the past energy efficiency progress is accelerated by about 3.3 to 5.6 %.

Companies paid € 14.7 m for the audits, while € 17.7 m were publicly funded. The administrative costs were comparatively low at € 900,000 for 2008 and 2009 together. The investments induced by the audits amount to € 334 to 562 m and the resulting energy cost savings to € 57 to 98 m per year.

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62 The corresponding shares of audit costs paid by the company are more than 20% (initial audit) and 40% (detailed audit) that were defined as maximum in the program. This is due to the fact that the program provides grants only for 2 days for initial audits and 10 days for detailed audits andseveral audits exceeded these limits.

63 Particularly firms with energy management show a higher share of free-riders (15.4%), whereas this is lower for firms without (7.2%).

64 Measured as energy efficiency progress for industry using the ODEX indicator to correct for structural change.

Table 24: Total program impact resulting from audits between March 2008 and June 2010

	Including planned measures	Excluding planned measures
Final energy savings [GWh/a]		
Electricity	395	230
Fuels	1241	723
Total	1635	953
CO_2 emission reductions [kt CO_2/a]		
Indirect emissions (from electricity savings)	237	138
Direct emissions (from fuel savings)	295	172
Total	531	310
Costs [m€]		
Expenditure of investment	562	334
Annual energy cost savings [m€/a]	98	57
Audit costs (paid by participating firms)	14.7	14.7
Audit costs (public grants)	17.7	17.7
Public administrative costs [a]	1.2	1.2

[a] As no figures were available for 2010, we assumed similar annual costs as in 2009.

5.3.3.4 Step IV: Cost-effectiveness of the program

An overview of the cost-effectiveness of the program is given in Table 25. Assuming that the planned EEMs will be adopted, the audits conducted until mid 2010 induced annual CO_2 emission reductions of about 530 kt, which will accumulate over the lifetime of the measures to 7.7 - 10.2 Mt (for a mean lifetime of 15 or 20 years, respectively). Over the same period, 25 to 33 TWh of energy will be saved.

The results for the indicators of the specific benefit per impact differ, depending on the perspective taken. Taking a firm perspective, the NPV ranges from € -6 to 196 m and thus is very likely to be positive, which implies a net benefit for the participating firms. Or, in other words, the discounted energy cost savings overcompensate the costs for the adoption of EEMs and the audits. From the public perspective, the NPV is at € -18 m, implying net costs, which is certainly not astonishing as the only direct benefit is the saved energy for the firms. Taking a societal perspective, considering all cash flows of the two former perspectives, results in an NPV ranging from € 298 to 1,212 m. The huge difference to the firm perspective is mainly explained through the lower discount rate of 3% instead of 14%. So at the societal level the discounted energy cost savings compensate by far the costs for the adoption of EEM and the audits.

Setting the NPV in relation to the net impact in terms of energy and CO_2 savings reveals that firms profit from a net benefit of € -0.4 to 6.0 per MWh saved (or -0.04 to 0.6 eurocent per kWh saved). The public perspective experiences a negative net benefit ranging from € -1.3 to -0.6 per MWh saved. Thus, for each MWh saved, the public authorities invest about € 1, which is equivalent to 0.1 eurocent per kWh saved.

Furthermore, the public authorities invest € 1.8 to 4.1 per ton of CO_2 mitigated. In contrast, for society as a whole, the CO_2 mitigation is related to a net financial benefit of € 67 to 119 per ton, not including external costs, which would further increase the benefit.

Despite the large range, the analysis shows that the program results in net financial benefits for firms and the whole society (a positive NPV) and even for the public authority costs are low, particularly when being compared to alternative CO_2 abatement options.

Moreover, public expenditures of 3 eurocent induced € 1 of private investments, stimulating the market for energy services and energy-efficient technologies.

Table 25: Indicators for the cost-effectiveness of the program by audits conducted between 2008 and 2010*

	Variable	Unit	Including planned future measures	Excluding planned future measures
Cumulated impact				
Cumulated energy savings	$S^{energy,cum}$	[TWh]	25 to 33	14 to 19
Cumulated CO_2 emission reduction	$S^{CO2,cum}$	[Mt CO_2]	7.7 to 10.2	4.7 to 5.9
Firm perspective (14% discount rate)				
NPV all cash flows	NPV^{firm}	[M€]	8 to 196	-6 to 103
NPV per energy savings	$npv^{energy,firm}$	[€/MWh]	0.3 to 6.0	-0.4 to 5.4
NPV per CO_2 savings	$npv^{CO2,firm}$	[€/tCO_2]	1.0 to 19.2	-1.4 to 17.4
Public perspective (3% discount rate)				
NPV all cash flows	NPV^{public}	[M€]	-18	-18
NPV per energy savings	$npv^{energy,public}$	[€/MWh	-0.6 to -0.7	-1.3 to -1.0
NPV per CO_2 savings	$npv^{CO2,public}$	[€/t CO_2]	-1.8 to -2.4	-3.1 to -4.1
Public expenditure per investment induced	spi	[€/€]	0.03	0.06
Society perspective (3% discount rate)				
NPV all cash flows	$NPV^{society}$	[M€]	545 to 1,212	298 to 686
NPV per energy savings	$npv^{energy,society}$	[€/MWh]	22 to 37	21 to 36
NPV per CO_2 savings	$npv^{CO2,society}$	[€/tCO_2]	71 to 119	67 to 116

Lower boundary: 15 years average lifetime, low energy prices. Upper boundary: 20 years average lifetime, high energy prices. All figures corrected for free-riders and non-additional measures. A positive NPV implies a net benefit and a negative NPV net cost.

5.3.4 Comparison with other programs

We compare the above results with similar programs in other countries. As mentioned in the introduction, a number of audit programs have been established worldwide in the past decades (Price, Lu 2011). However, they differ greatly in terms of program characteristics. Price and Lu (2011) differentiate two types: stand-alone audit programs and integrated programs. The latter often combine setting voluntary saving targets or energy management with energy audits. They often apply to large or at least medium-sized energy-intensive firms. Examples are the Swedish program for energy efficiency in energy-intensive industries (PFE) (Loulou et al. 2004; Petersson et al. 2011; Stenqvist, Nilsson 2012), the Irish Large Industry Energy Network (LIEN) (Cahill, Ó Gallachóir 2011) or the Australian Energy Efficiency Opportunities (EEO) program (Crittenden, Lewis 2011). On the other hand, stand-alone audit programs also address SMEs and particularly smaller firms. The program analyzed in this study is a stand-alone program, therefore we focus on stand-alone programs in the comparison. Three similar programs are considered for this comparison: the US IAC program (Muthulingam et al. 2011), the Australian EEAP program (Harris et al. 2000) and the Swedish “Project Highland” (Thollander et al. 2007). Of these, only the IAC program is still running. “Project Highland” was a regional Swedish program and is the smallest program. Table 26 provides a summary of program characteristics and selected indicators. Although these programs differ in terms of scope (firm size, sectors), auditor obligations, and the maturity and degree of standardization, some of the main indicators are still comparable.

One of the most cited success indicators is the adoption rate. It is defined as the number of adopted EEMs divided by the total number of EEMs recommended per audit. For the German program we found an adoption rate of 43% or of 72% if certainly planned measures are included. The US IAC program shows an adoption rate of 50%, also considering the measures planned for adoption at the time of the survey (Muthulingam et al. 2011). The lowest adoption rate is observed for the Swedish Project Highland program with 40%, even including previously planned measures (Thollander et al. 2007). This might be a result of the relatively high number of 13.7 measures recommended per audit on average. A particularly high adoption rate of 81% is found for the Australian EEAP program (Harris et al. 2000). The average annual energy savings per firm are highest in the Australian program, which is mainly a result of the higher average firm size. Comparing energy savings per employee, the differences are lower, but the Australian program still shows the highest savings, at around 42 GJ per employee. The main reason is the high number of 4.7 adopted measures per firm. Note that only in the German program are energy savings corrected for free-rider effects and non-additional savings, thus reducing the savings by about 9 and 20 %, respectively. Not correcting for these effects would result in 30% higher adoption rates and energy savings.

Noticeable is the comparably high mean payback period of the adopted recommendations for the German program of 6 years as compared to 1.1 years for the US and the Australian programs. For a Danish stand-alone audit program, an average payback period of 3.6 years is reported (Dyhr-Mikkelsen, Bach 2005). We do not have a simple explanation for these differences; however, the types of EEMs adopted certainly play an important role, which is further explored in the following section.

Table 26: Comparison of chosen stand-alone energy audit programs (all figures relate to the given evaluation period)

	KfW fund for SMEs (Germany)	**IAC (USA)**	**EEAP (Australia)**	**Project Highland (Sweden, regions)**
Source	This study	(DOE 2011; Muthulingam et al. 2011) [g]	(Harris et al. 1996; Harris et al. 1998; Harris et al. 2000)	(Thollander et al. 2007)
Scope of the program	SME (<250 employees)	SME (< 500 employees) sales <$100 million/a energy bill < $2 million/a and > $100.000 /a	no entry requirements	SME (< 500 employees)
Still running?	Yes	Yes	No	No
Evaluation period	March 2008-June 2010	1981-2009	1991-1997	2003 to 2008
Number firms (evaluation sample)	9,292 (542)	14,800 (12,249)	~1,200 (100)	139 manufacturing firms (47) [d]
Number of employees per firm (sample)	38 (46)	(164)	297	72
Total number EEMs adopted	14,500 [b f] / 24,400 [a f]	55,500 *	5640 *	142 [b] / 281 [a] (For 47 sample only)
EEMs recommended per firm	5.3	8.4	5.8	13.7
EEMs adopted per firm	2.3 [b] / 3.8 [a] (1.7 [b] / 2.9 [a])[f]	4.2 * [a]	4.7 [b]	3.0 [b] / 6.0 [a]
Adoption rate	43% [b] / 72% [a]	50% [a]	81% [b]	22% [b] / 41% [a]
Energy savings per EEM	247 GJ/a	1090 GJ/a *	2650 GJ/a *	204 GJ/a *
Average savings per firm	423 [b] / 711 [a] GJ/a	4,600 GJ/a *	12,489 GJ/a	1,225 GJ/a *
Average savings per employee	9.2 [b] / 15.5 [a] GJ/a	27.9 GJ/a *	42.1 GJ/a	17.0 GJ/a
Total annual energy savings[c]	3.8 [b] / 6.5 [a] PJ/a	67.8 PJ/a	15 PJ/a *	25 [b] / 58 TJ/a [a]
Free-rider excluded?	yes [f]	Not explicitly excluded	Not explicitly excluded	Not explicitly excluded
Mean simple payback period of adopted EEMs	6.1 years	1.1 years [e]	1.3 *	n.a.

* calculated

a Including measures planned for future implementation

b Not including measures planned for future implementation

c Energy savings are given as cumulated annual savings induced by all adopted EEMs from audits during the evaluation period

d In total 349 firms participated in the program, but only the 139 manufacturing firms were evaluated and of these 47 answered the survey.

e Relates to all recommended measures

f Free-riders and non-additional measures are corrected (measures adopted, but already planned before the audit took place)

g All indicators in this column regarding energy savings are calculated based on DOE (2011) other indicators stem from Muthulingam et al. (2011)

5.4 Technology characteristics

While we based the above impact assessment on average values per EEM, in this section we assess the diversity of EEMs adopted and recommended in the program. A better understanding of the EEMs facilitates more efficient program design as well as more accurate ex-ante assessment of policy impact.

Figure 21 shows a breakdown of the EEMs adopted and those not adopted by type of technology or end-use (for a definition of the groups used, see annex Table 28). It is evident that building-related measures account for the larger share of around 60% of all measures adopted. These include improvements to the heating system, ventilation and air conditioning, the lighting system and building insulation. The non-adopted measures show a peak in the group of building insulation. Possibly because these measures typically need a relatively high investment, which turned out to be a major reason for non-adoption (see Section 5.5). The number of measures adopted in the field of compressed air and electric motors is astonishingly low, given the great saving potential that are typically found in these systems (Eichhammer et al. 2009). Similarly, low shares of process-related EEMs are found, which included all kinds of improvements to the production processes of the firm (in fact, mostly reducing idling). On the other side, lighting as well as heating systems are prevalent even in small service firms and improvement possibilities are easy to identify. It is possible that also the auditors' qualifications may have influenced the types of measures.

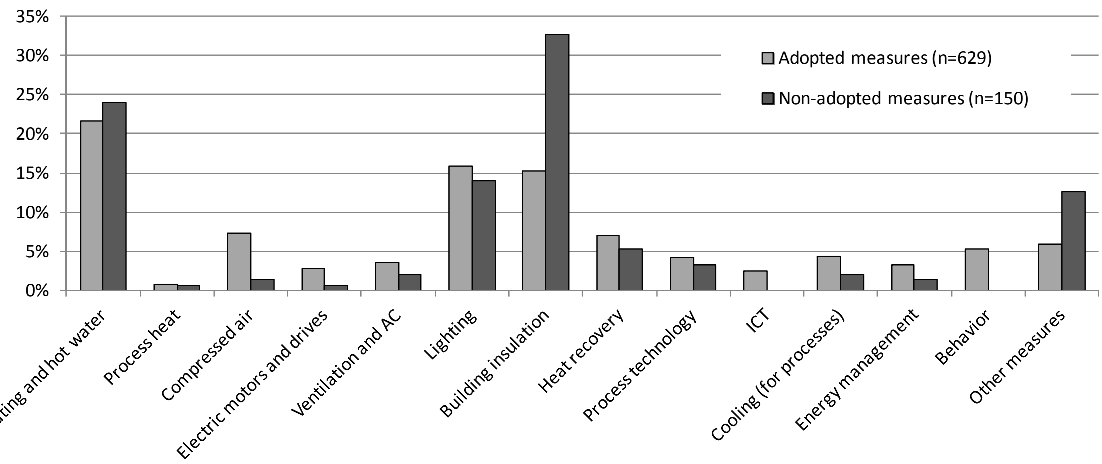
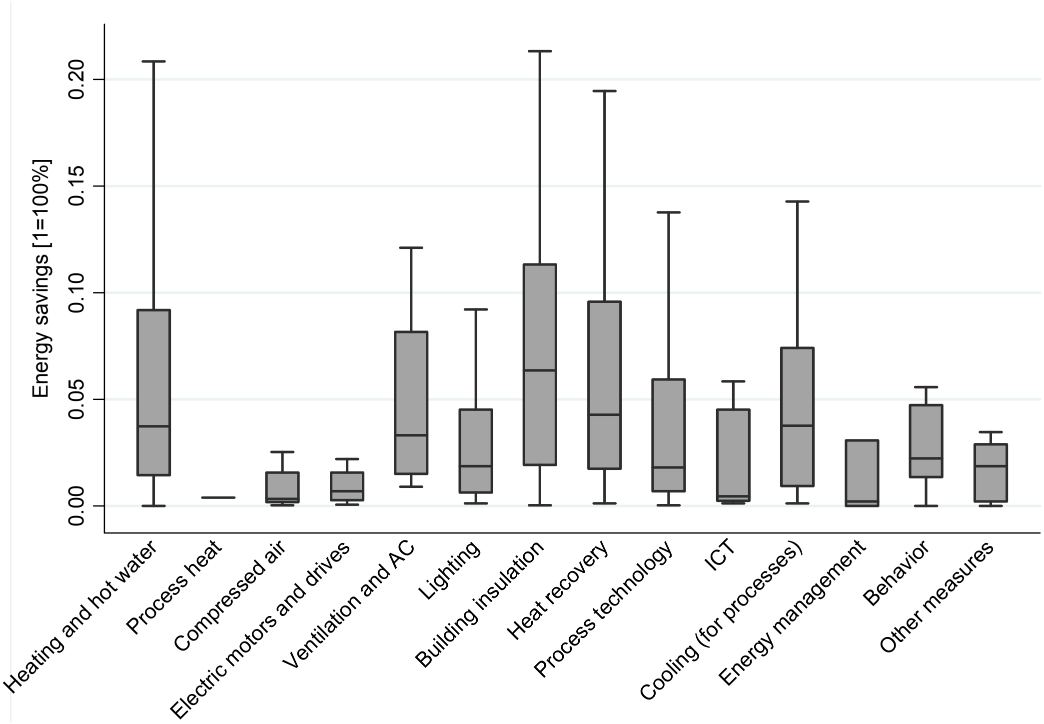


Figure 21: Distribution of adopted and non-adopted EEMs by end-use

The energy savings per type of EEMs reveal great differences. Due to the large spread in energy demand of the participating firms, savings are best analyzed as a share of the firms' total energy demand (see Table 27 and Figure 22). The average relative savings are lowest for compressed-air systems and electric motors, at 0.9 and 1.2%, respectively. Highest savings were observed for building insulation (10%) and heating and hot water (8%). This pattern may also be explained by the fact that, particularly for small firms, space heating accounts for the largest single energy end-use, whereas rather the opposite is true for compressed-air systems.

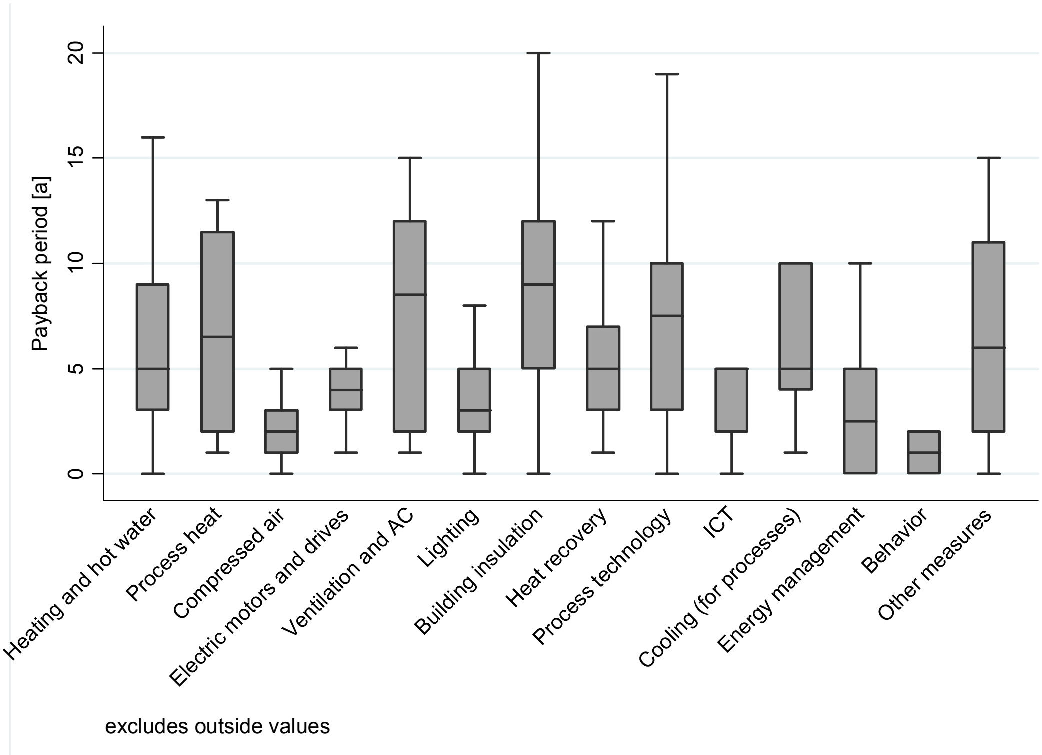


The boxes represent 25% and 75% percentiles and the dividing line the median. The upper and lower adjacent values are given by the whiskers.

Figure 22: Energy savings as share of firms' total energy demand by type of end-use (n= 380)

A factor strongly influencing the adoption of EEMs is the investment cost. As shown in Table 27, the average investment ranges between € 400 and 49,100 per adopted measure. However, this picture again is heavily influenced by the firm size and single very large investments. For most technology groups, the mean values are even higher than the 75%-quartile, indicating a skewed distribution resulting from a few very high investments.

An indicator that is more comparable among firms is the payback period. The values in Table 27 and Figure 23 are based on firms' stated payback period for a total number of 362 EEMs. Lowest mean payback periods are observed for measures in the groups: compressed-air systems (2 years), behavioral measures (2 years), ICT (3 years) and cooling (3 years). The highest payback periods are found for building insulation (11 years), ventilation and air-conditioning (8 years) and process technologies (7 years).



The boxes represent 25% and 75% percentiles and the dividing line the median. The upper and lower adjacent values are given by the whiskers. Outliers are not shown.

Figure 23: Average payback period by type of EEM (n=342)

To conclude, most adopted EEMs can be characterized as cross-cutting technologies (see Table 27). They are relatively easy to identify for the external auditors, because the energy end-uses they address are similar (e.g. space heating, lighting) and the EEMs often show a large degree of standardization. Further, most of the recommended EEMs only display a limited degree of innovation. Moreover, they are mostly applied to ancillary processes and not to the core production process.

Comparing the distribution of adopted EEMs by end-use to the programs in the USA (Anderson, Newell 2004), Sweden (Thollander et al. 2007) and Australia (Harris et al. 2000) reveals that for these programs the focus of the measures was also not on the production process, but on cross-cutting technologies. Some differences are observed. The Australian program, for instance, shows a strong focus on lighting-related measures (21 %), whereas these represented 16 % of the measures in Germany and 14 % in Sweden. On the other side, space heating including building insulation and hot water was far less prominent in Sweden (25 %) and Australia (11 %) than in Germany (36%). Although the evaluation of the US program used more highly aggregated end-use groups, it still reveals that the focus is more on motor systems (35 %) and less on building-related end-uses (37 %) as is the case in the other three programs – particularly in the German program, where motor systems represent only 18 % of the adopted measures.

The differences are explained – among others – through the pattern of the participating firms (rather small firms in the German program), the know-how of the auditors, the climate conditions (focus on space heating or air conditioning, which might explain differences to Australia), the structure of the audit report templates, the total number of EEMs suggested (which for example is twice as high in the Swedish program) and the initial efficiency level.

Table 27: Characteristics of EEMs by type of end-use (source: firm survey and audit reports)

Type of measure	Relative energy savings [a] [%]					Payback period [a]					Initial expenditure [k€]				
	Mean	25%	50%	75%	Sample	**Mean**	25%	50%	75%	Sample	**Mean**	25%	50%	75%	Sample
Heating and hot water	**7.6**	1.5	3.7	9.3	80	**6.3**	3	5	9	79	**27.7**	1.0	3.5	25.0	99
Compressed air	**0.9**	0.2	0.3	1.6	20	**2.4**	1	2	3	25	**7.0**	0.3	2.5	6.0	41
Electric motors and drives	**1.2**	0.3	0.7	1.6	8	**4.4**	3	4	5	11	**33.5**	12	2.5	8.0	17
Ventilation and AC	**4.9**	1.5	3.3	8.2	15	**7.9**	2	9	12	14	**38.2**	0.3	1.2	45.0	21
Lighting	**3.3**	0.6	1.9	4.5	56	**4.2**	2	3	5	53	**5.1**	0.5	2.0	5.0	87
Building insulation	**10.1**	1.9	6.4	11.7	67	**10.6**	5	9	12	55	**28.7**	4.5	10.0	26.8	84
Heat recovery	**7.1**	1.8	4.3	9.6	47	**5.2**	3	5	7	33	**38.6**	5.0	15.0	30.0	31
Process technology	**3.8**	0.7	1.8	5.9	24	**7.2**	3	8	10	16	**49.1**	0.0	15.0	50.0	23
ICT	**3.4**	0.2	0.4	4.5	9	**3.4**	2	5	5	5	**13.5**	0.4	5.0	15.0	13
Cooling (for processes)	**4.9**	0.9	3.8	7.4	29	**6.2**	4	5	10	13	**23.2**	0.3	1.5	20.0	19
Energy management	**1.1**	0.0	0.2	3.1	3	**3.2**	0	3	5	10	**3.5**	0.1	0.6	6.0	14
Behavior	**2.8**	1.3	2.2	4.7	5	**1.7**	0	1	2	7	**0.4**	0.0	0.0	0.5	27
Other measures	**3.3**	0.2	1.9	2.9	18	**6.4**	2	6	11	17	**25.5**	0.0	0.3	3.0	22
Total	**5.9**	1.0	2.6	7.3	382	**6.1**	2.0	5	8	342	**22.7**	0.5	3.0	15.0	502

[a] Energy savings as share of firm's energy demand

5.5 Contribution towards overcoming barriers to energy efficiency

The evaluation in Section 5.3 showed that the program encourages the adoption of EEMs which firms would otherwise not have adopted. In this section, we further highlight firms' adoption decisions and analyze how the program helps to overcome barriers to the adoption of EEMs.

As the definition for barriers we follow Sorrell et al (2004): "Barriers are claimed to prevent investment in cost-effective energy efficient technologies". In our case, cost-effectiveness is assessed by the auditors using classical engineering economic assessment methods. The literature provides various ways for classifying barriers. Papers from the field of economics mostly aim to classify barriers into two groups, of which one group justifies policy intervention and the other does not. For example, Jaffe and Stavins (1994b) differentiate between market failure barriers and non-market failure barriers. While the former justify policy intervention, the latter do not. Non-market failures, for example, comprise uncertainty regarding future energy prices or hidden (and intangible) costs not accounted for in the initial cost assessment. Here, policy intervention would result in a less efficient allocation of resources. Contrasting this view, Sorrell et al. (2004) include reasons such as bounded rationality of decision-makers and argue that a policy should only be justified on the grounds of a cost/benefit analysis. Even policies addressing non-market failure barriers could result in a net benefit, as for example high transaction costs are not fixed, but can be reduced significantly by policy intervention through e.g. minimum standards. For the following analysis, we follow the above definition of barriers proposed by Sorrell et al. (2004) and do not distinguish between non-market failure and market failure barriers.

The intensity of the barriers is determined by both the kind of firm as well as the specific EEM. Smaller firms typically experience different barriers than large firms do (de Groot et al. 2001; DeCanio, Watkins 1998; Gruber, Brand 1991; Schleich 2009). 76% of the firms applying for an audit subsidy have less than 50 employees and the remaining 24% have 51 to 250 employees. The structure of the EEMs addressed was intensively discussed in the previous section.

We address barriers in the survey through two questions. The first focuses on how the program contributes towards overcoming barriers (see Figure 24) and the second is related to the barriers still persisting despite the program (see Figure 25). Both sets of questions were used and tested in earlier evaluations in Germany. The questions regarding barriers were compared to other recent surveys (e.g. Anderson, Newell 2004; Thollander, Ottosson 2008). The questions are:

1. “The energy audit helped...?” – followed by a predefined list of 12 barriers allowing for the answers “yes” or “no”.
2. “Why were these EEMs not implemented?” – Followed by a predefined list of 15 reasons allowing for answers ranging from “important reason” to “not relevant”.

We received 300 usable responses to question one and 160 to question two, which was placed at the end of the survey.

Both questions have to be interpreted in the context of the survey. Question one followed on a detailed description of up to four EEMs the company had adopted. Question two followed on a detailed description of up to four EEMs recommended in the audit, but not adopted by the firm. Thus, the answers pertaining to barriers are closely related to particular EEMs, which is an advantage compared to many other surveys on barriers that are very unspecific about what an EEM is.

From a methodological point of view, it is difficult to address barriers which are related to firm behavior in such a survey, because the respondents answer on the basis of their perception of the barriers (self-assessed barriers). Consequently, the results have to be interpreted cautiously, but, some conclusions can still be drawn.

Question one (Figure 24) shows – as would be expected - that the energy audit helped to overcome information-related barriers through a detailed analysis of energy demand (86%) and potential EEMs (80%). 73% of the respondents stated that the energy audit confirmed their earlier planning and intentions, while 62% said that they were not aware of the measures recommended before the audit.

Obviously, the energy audit did not contribute significantly to overcoming the two barriers related to risk of production disruption and product quality losses. However, this could also result from the types of EEMs recommended. The cross-cutting technologies mainly recommended in the audits (building insulation, heating system, lighting, etc.) mostly do not affect the core production process or product quality. This argumentation is further consolidated by the analysis of question two (Figure 25), where the risk-related types of barriers are not very relevant.

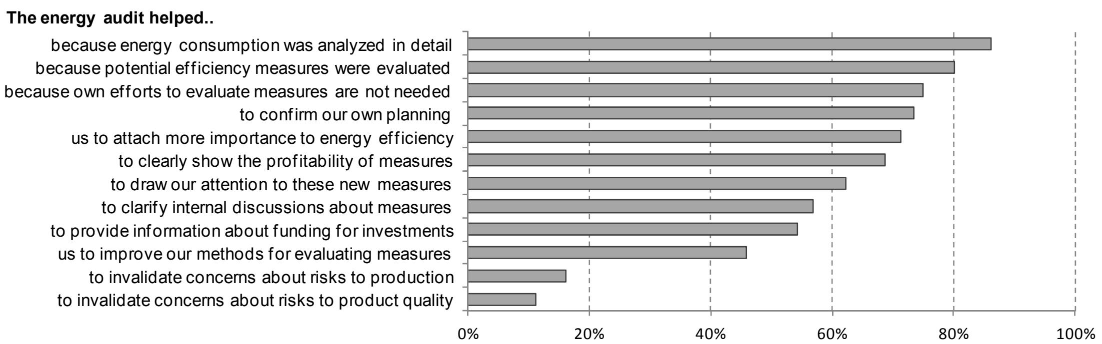


Figure 24: Question 1 - How did the program help to overcome barriers? (n=300)

The responses to the second question are shown in Figure 25. Accordingly, “too high investment cost” is the single most important reason for not adopting the recommended measures (important for more than 80% of respondents). Close to 80 % mentioned “other investments have higher priority” as an important reason. This reason however, overlaps with other barriers like financial or capacity constraints.

Astonishingly, the high share of nearly 70% of respondents stated that the EEMs were not profitable, although the audits should only propose cost-effective measures with acceptable payback period. An explanation could be that firms have stricter expectations of profitability than the energy auditors do. Firms often consider measures with several years payback period as not profitable. If such high payback expectations represent e.g. risk associated with energy price development, the non-adoption can still be justified on grounds of a rational decision, however, if the payback expectations are far more restrictive for EEMs than for other types of investments, they also classify as a barrier. Another explanation may be the existence of hidden costs (for implementation), which the auditors did not consider in their assessment and which make the EEM less attractive to the firm. The reason ”implementation too time consuming” also indicates that for some EEM the implementation implies considerable transaction costs, which are probably not accounted for by the auditor.

Also the answers “recommendation not realistic” and “recommendation technically impossible”, which are ranked important by more than 30% of the respondents, indicate that the auditors and the firms’ assessment of EEMs differ.

The remaining reasons were perceived as less important. Interestingly, energy price uncertainty was mentioned by only 10% as a very important reason, whereas 30% regarded it as important and 30% as less important. This indicates that energy price uncertainty is not a primary reason, although a point of interest for most firms.

Too expensive external capital was mentioned by around 35% as an important factor. This is astonishing, given the fact that the German KfW also provides low-interest loans particularly for implementing EEMs. A reason for this surprising result could be the observation that particularly for smaller credits (below € 20,000), firms state that the administrative effort and time involved prevent them from applying for such a credit. However, there are probably other factors as well.

Reasons such as “measures are not profitable”, “cancelled due to change in operation”, or ”technically impossible”, are typically not classified as barriers. However, the fact that firms perceive measures as technically impossible opens room for discussion, because this may be wrong and could be a result of a lack of know-how or high transaction costs.

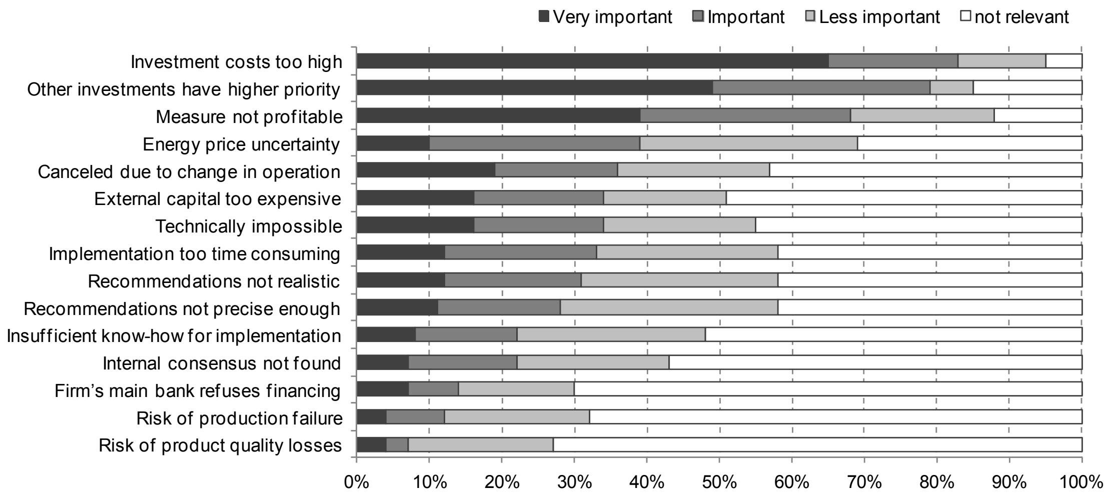


Figure 25: Question 2 - Reasons for not adopting energy-efficiency recommendations (n=160)

To summarize, typical barriers that persist after the audit are mostly related to financing (external capital too expensive, too high investment costs). Other "classical" barriers like "implementation too time consuming" or "insufficient know-how for implementation" only persist in a few cases, which indicate that the program helps to overcome many relevant barriers.

A comparison of the persisting barriers with those in the US audit program (Anderson, Newell 2004) reveals certain similarities. There, high investment costs are also the most important reason not to adopt the recommendations. This reason was followed by "lack of staff for implementation" and "cash flow prevents implementation", two reasons which our analysis also found to persist after the audit.

In the Australian program (Harris et al. 2000), only about 20% of the measures recommended were not adopted by firms. The main reason given for non-adoption was the low profitability of the measures. However, the difficulty of financing was rated as far less important than in the German audit scheme, whereas reasons indicating lack of capability to implement measures or inaccurate description of measures in the audit reports were ranked as more important than in the German program.

In the Swedish program (Thollander et al. 2007) only 40% of the recommendations were adopted. The most often mentioned reason for not adopting is "lack of time or other priorities". Reasons related to financing, like "other investment priorities" and "access to capital" are ranked second.

This comparison, however, has to be interpreted with caution, due to the varying answers predefined in the surveys. For instance, the barrier "too high initial costs" does not appear to be considered in the questionnaire of the Australian and the Swedish program, while it was ranked most important in the German and US program. Furthermore, the profitability of the measure was not taken into consideration in the Swedish survey, but was ranked as very important in the other three countries.

5.6 Discussion

5.6.1 Policy implications

Our evaluation shows that the German energy audit program for SMEs provides a way to improve energy efficiency in firms cost-effectively. From a societal perspective, the program implies a clear net benefit, while also the governmental spending e.g. per ton of CO_2 reduced is rather low, when compared to other programs (see Section 5.3).The energy end-uses addressed are mainly from the field of cross-cutting technologies for ancillary processes, such as building heat demand (see Section 5.4). Furthermore, the program narrows the “energy-efficiency gap” by overcoming barriers e.g. related to information, bounded rationality and transaction costs (see Section 5.5).

Comparing the German audit program to similar programs in the US, Australia and Sweden reveals many similarities, but also some differences. First, with an average payback time of about 6 years in the German program, the profitability requirement used by firms is far less restrictive than e.g. in the US program with 1.1 years or the Australian with 1.3 years. The particular focus on building-related EEMs in Germany, which typically have longer payback periods, certainly explains parts of this pattern. While the adoption rate of EEMs in the German program is within the range of the other programs, the total number of EEMs recommended is lowest. A possible reason could be the fact that the average participating firm also is far smaller in the German program than in the others or the restriction of the audit report template for initial audits that foresees only space for four recommendations.

With regard to barriers overcome by the program (Section 5.5), we find that the audit program contributes towards overcoming information- and capacity-related barriers. Barriers related to risk of production disruption or product quality are not relevant in the audit program. The barriers which still persist after the audit are mostly finance-related. Most dominant and identified by more than 80 % of the respondents as important barriers is the “too high initial investment”. This is closely related to other frequently mentioned barriers like “external capital too expensive” and “priority given to other investments”. Similar barriers related to access to capital were also found important in the US and the Swedish program. Furthermore, close to 70 % mentioned that the EEMs were not cost-effective as an important reason not to adopt them. This indicates that the firms apply a more restrictive investment criterion than the auditors, but also that they are prepared to adopt most EEMs if they are cost-effective. As a general lesson from this, one has to further investigate ways to overcome the financial barriers and how the companies set up their investment criteria and whether this can be changed by suitable information or voluntary schemes. An assessment of the German soft-loan program for SMEs and why it is not more utilized by firms to adopt the recommendations in the audits could provide further insights.[65]

The analysis of end-uses addressed by the program (Section 5.4) reveals a focus on cross-cutting measures and ancillary processes. The reasons are probably that the auditors have more knowledge of cross-cutting measures that are to be found in many firms, but also that the firms are reluctant to allow external persons to analyze the production process in detail. Also, the time constraints of the auditors and the type of participating firms may play a role. As also process technologies typically entail huge saving potentials, this “blind spot” should be addressed by the German policy mix. Therefore, the audit program could support the specialized education of auditors for particular industrial branches.

Assuming that the program continues at the current level, the cumulated annual savings would reach 24 PJ/a in 2016 and contribute to about 3% of the German target under the Second National Energy Efficiency Action Plan (NEEAP) of 748 PJ/a (BMWi 2011). The EU Energy Service Directive (European Union 2006) requires all Member States to submit NEEAPs to report the implemented energy-efficiency policies and their progress towards the 20% energy-efficiency target set at the EU level. Given the cost-effectiveness of the program, doubling or tripling the number of annual audits could significantly contribute to Germany’s energy-efficiency target and improve the cost-effectiveness of the entire policy mix to reach these targets. Gruber et al. (2006) estimate a potential of 28,000 initial audits per year. Compared to these estimates, the number of 3,800 initial audits in 2009 represents 14% of the potential market and still contains potential for growth.

In addition, the proposed EU Directive for Energy Efficiency (European Commission 2011) requires Member States to establish support programs to foster energy audits in SMEs. This is somewhat more ambitious than the EU Directive for Energy End-Use Efficiency and Energy Services (European Union 2006) that “only” requires member states to “ensure the availability of efficient, high-quality energy audit schemes”. Thus, member states, which have not yet established such a scheme, may also have to do so in the coming years.

Finally, ex ante energy demand models are applied to estimate the impact of possible policy designs for energy planning and designing new policies. These models are often technology-specific simulation or optimization models, which simulate policies using ad hoc approaches, like adjusting the discount rate applied for the investment calculations (Fleiter et al. 2011; Worrell et al. 2004). A bottleneck to using a more sophisticated modeling approach is the availability of empirical data. In this sense, our study provides an improved basis for model calibration,

[65] About 42% of firms used KfW soft loans for financing, while 47% used own funds and 11% other types of loans.

program impact modeling and program cost modeling, than for example was used in the ex ante assessment of the German NEEAP (BMWi 2011).

5.6.2 Methodology and data used

Some implications arise from the methodology chosen and the data used. These need to be taken into account for the interpretation of the results, and might also be addressed by future research.

Our approach to calculate the net impact of the program which was to consider effects like free-rider, non-adopted measures and non-additional measures, goes beyond similar assessments of audit programs (Anderson, Newell 2004; Harris et al. 2000; Thollander et al. 2007) and represents an advantage of this evaluation. Still, we were not able to consider all effects discussed in the literature, such as spill-over effects or double counting with other programs. Such spill-over effects may occur from the established online database with the contact details of energy auditors, as well as the increased demand for energy audits in firms, which fosters the energy audit market and increases knowledge build-up in more firms in Germany.

Furthermore, we concentrated in the impact assessment on direct impacts in terms of energy savings. The survey, however, revealed that about 5% of the adopted EEMs comprise fuel switches to natural gas or renewable energies. These are not considered in the quantitative results because the sample was too small and the heterogeneity of the measures high.

The program design and budget did not allow metering of the energy use in firms and it was also not possible to perform follow-up surveys to determine the actual adoption of recommended measures. The survey sent to all participating firms had a low response rate of 12% and many data are missing. Therefore, we included actual audit reports in our analysis and used them to estimate EEM specific variables like energy savings or payback period. Furthermore, we used a varying sample to estimate the variables. This was necessary because only a few firms answered all questions in the survey. Better data sources would have certainly improved the robustness of the results.

Finally, our analysis only allows conclusions on the impact and the cost-effectiveness of the program. We cannot draw conclusions on possible improvements in its internal processes etc.

5.7 Conclusions

Our evaluation shows that the German energy audit program for small and medium-sized companies has been successful in improving the energy efficiency in firms cost-effectively and reducing the initially discussed energy-efficiency gap. However, financial barriers, in particular, are still prevalent despite the program. Ways to overcome such finance-related barriers are soft-loan programs, use of contracting or direct grants for the investment cost. In this particular case, it should be investigated whether the established soft-loan program works effectively.

From a firm perspective (14% discount rate), the program is very likely to be cost-effective with a specific NPV of € -0.4 to 6 per MWh saved. For the government (3% discount rate), each ton of CO_2 mitigated costs € 1.8 to 4.1, which is lower than for many other CO_2 abatement options. From a societal perspective, the program clearly implies a net benefit indicated by the positive NPV ranging from € 21 to 37 per MWh saved.

On average, the firms adopted 1.7 to 2.9 measures, which they would not have adopted without the program, and achieved energy savings of 3 to 5% of their energy demand. The energy-efficiency measures adopted have an average payback period of 6 years. Building-related measures account for the largest share of adopted measures. Building insulation has the highest average payback period of 10.6 years, while the payback period for measures to improve compressed-air systems is only 2.4 years on average.

In total, over the evaluated period from March 2008 to June 2010, the program induced final energy savings between 950 and 1,630 GWh/a (310 to 530 kt CO_2/a). Assuming that the audit program were continued at the present level of activity, it would accelerate the (average long-term) progress made in energy efficiency in industry and the service sector by about 3.3 to 5.6%.

Although this estimation considers free-rider effects, we were not able to consider rebound effects, interaction effects with other policies or possible market effects. Future research might fill this gap. Moreover, our analysis only draws conclusions on the outcome of the program; an in-depth analysis of its internal processes could still reveal further room for improvement.

The cost-effectiveness of the program for firms and the low share of public expenditure underline its value for the German energy-efficiency policy mix and suggest that it should be expanded. Further, the good experiences with the program in Germany should encourage countries which have not yet established such an audit program to do so.

Appendix

Table 28: Definition of EEM types and assumed average lifetime

Type of EEM	**Lifetime [a]**	**Frequently observed examples**
Heating and hot water	20	Combined heat and power, renewable energies (e.g. solar, pellets), Use of condensing boiler, fuel switch from fuel oil to natural gas, demand-related control systems, hydraulic alignment, insulation of pipes, water saving, heat pumps
Process heat	25	Optimized generation of process steam
Compressed air	15	Reduction of leakages, lowering of pressure level and matching to demand, replacement of compressors, system optimization
Motors and drives	15	Efficient (circulation) pumps, variable speed drives, energy-efficient motors
Ventilation and air-conditioning	15	Building ventilation and air-conditioning
Lighting	10	Energy-efficient lamps and electronic ballasts, demand-related control systems (motion sensor, light sensor), use of daylight, system optimization
Building insulation	30	Insulation of outer wall, roof or basement, replacement of windows, insulation of doors, system optimization
Heat recovery	15	Waste heat from compressors (cold as well as compressed air), heat exchangers at ventilation and waste heat of processes
Process technologies	10	Replacement of installations, optimized control and reduction of idle-running time
Information and communication technology (ICT)	3	Efficient servers as well as computers, reduction of stand-by
Cooling	15	Improved insulation, efficient compressors, optimization of existing plants
Energy management and controlling	5	Energy management, use of energy indicators, metering of energy use and power demand
Behavior	3	Staff training; comprises also smaller investments
Other measures	15	Photovoltaic plants, stand-by losses, demand-side management to shift demand peaks, others

Table 29: Energy price development as assumed for the NPV calculation [Euro/MWh]

	2008	2010	2015	2020	2025	2030
Lower boundary						
Electricity	105	112	111	127	129	135
Light fuel oil	40	41	42	45	48	51
Natural gas	50	48	49	52	55	58
Upper boundary						
Electricity	140	140	139	158	162	169
Light fuel oil	64	52	53	57	59	62
Natural gas	54	60	60	62	63	64

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6 Barriers to energy efficiency in industrial bottom-up energy demand models—A review [66]

Abstract

The goal of this paper is to review bottom-up models for industrial energy demand with a particular focus on their capability to model barriers to the adoption of energy-efficient technologies. The integration of barriers into the models is an important prerequisite for a more detailed and realistic modeling of policies for energy efficiency. Particularly with the emergence of more and more varying policy instruments, it also becomes crucial for the models to take account of these policies as well as the barriers they address in a more realistic way.

Our review revealed that, despite the broadly evident existence of market failures and barriers for energy-efficient technologies, they are only partly and in a rather aggregated form considered in today's bottom-up models. The state-of-the-art bottom-up model is based on an explicit representation of the technology stock and considers the costs of energy efficiency options in detail. But with regard to barriers, most models only make use of an aggregated approach, like an adjusted discount rate. While some models do not even consider technology costs and energy prices, but instead use exogenous technology diffusion rates, other more advanced models took first steps towards considering barriers in more detail. The latter allows differentiation between multiple parameters that influence technology adoption. Still, even in the most advanced models, only a few of the observed barriers are explicitly considered.

At the same time, new approaches to considering barriers like uncertainty or the (slow) spread of information are being developed in other disciplines. We conclude the paper by summarizing promising ways to improve representation of barriers in bottom-up models.

[66] The chapter has been published as *Fleiter, T.; Worrell, E.; Eichhammer, W. (2011): Barriers to energy efficiency in industrial bottom-up energy demand models - a review. Renewable and Sustainable Energy Reviews, 15 (6), pp. 3099-3111.*

6.1 Introduction

The importance of improved energy efficiency for climate change mitigation, environmental protection in general, and reduction of fuel import dependency has frequently been shown (IEA 2008a). As industry accounts for 36 % of the global final energy demand, improving industrial energy efficiency should have high priority among policymakers. Furthermore, energy efficiency is also a matter of cost saving and competitiveness at the level of firms (Worrell et al. 2009). Consequently, knowledge about future industrial energy demand and the potential impact of energy efficiency policies is an important basis for policy design and investment decisions.

Energy demand models allow the impact of different technological developments on long-term energy consumption to be estimated. A key determinant of the market diffusion of new energy-efficient technologies is the technology adoption behavior of firms. A large body of literature has shown that investments in energy-efficient technologies are affected by barriers and market failures that often prevent the energy-efficient alternative from being chosen, although this would be cost-effective. Barriers can be very different in nature, varying from the availability of information or capacity within firms, to dealing with risk and how it is perceived, to firm internal processes or the availability of financial resources.

Still, current energy demand models work with fairly simple assumptions on the dynamics of technology diffusion, even if they are the type of bottom-up models[67] that are most often characterized by their detailed technology representation. In typical bottom-up models, technology adoption is considered as a strictly rational decision-making process, assuming perfect knowledge. Some models also consider barriers by assuming higher (implicit) discount rates for energy efficiency investments while others work with simple exogenous assumptions of the energy efficiency improvement (Pizer, Popp 2008). While the first approach considerably overestimates investments in energy efficient technologies, the other approaches, i.e. the implicit discount rate and the exogenous assumptions, also lack a detailed understanding of the relevant barriers and their influence on technology adoption (Worrell et al. 2004). At the same time, a detailed consideration of the technology adoption process is indispensable for modeling energy efficiency policies that aim to overcome the barriers to accelerating technological change towards improved energy efficiency.

Indeed, including barriers and market failures into bottom-up energy demand models is frequently mentioned as an important step towards more "realistic" and reliable models and as a necessary step towards the more explicit modeling of policies (Clarke, Weyant 2002; DeCanio, Laitner 1997; Ostertag 2003; Worrell et al. 2004; Worrell, Price 2001). Some promising first steps were taken towards this direction, and some approaches from other disciplines also exist

[67] Bottom-up models are sometimes also called end-use models or engineering-economic models.

that provide helpful insights into technology diffusion modeling.

Despite the growing attention for bottom-up models for industrial energy demand, there is as yet no overview focusing on the process of technology adoption and how it is considered in the models. Recent publications give an overview of particular issues of industrial energy demand modeling, but none of them focuses on the role of barriers in bottom-up models. Algehed et al. (2009) for example compare modern bottom-up and top-down models, while Greening et al. (2007) give an overview of the very broad range of approaches to model industrial energy demand, far beyond typical bottom-up models. Only Worrell et al. (Worrell et al. 2004) exclusively focus on bottom-up models and their development needs, but they do not focus on technology adoption.

In this study we aim to fill this gap by providing an overview of the current status of bottom-up models for industrial energy demand with a particular focus on how these models consider barriers to the adoption of new technologies.

The paper is structured as follows. In the first part, we give a short overview of the barriers to energy efficiency and how they are related to the adoption of energy-efficient technologies by firms. We discuss both the empirical evidence as well as different ways of interpreting and classifying barriers which then provides the basis for the comparison of models.

In the second part, we review the current bottom-up models that aim at long-term forecasting of industrial energy demand. The focus lies on how they model the adoption of new technologies and the impact of barriers to energy efficiency. To answer this question, we analyze the more general modeling of technologies and technology stock (turnover). We also discuss whether the models have the potential to consider policies for energy efficiency. Modeling policies is the main reason for including more realistic firm behavior and barriers into the models.

6.2 Barriers to the adoption of energy-efficient technologies

Empirical evidence of barriers to the adoption of energy-efficient technologies has been widely reported in the literature. The following short overview of the main empirical findings and the different types of barriers will provide the basis for the analysis of the models in the second part.

The definition of barriers applied in this paper is based on Sorrel et al. (Sorrell et al. 2004): barriers comprise all factors that hamper the adoption of cost-effective energy-efficient technologies or slow down their diffusion. They are regarded in contrast to a simple investment decision framework that only considers financial costs (investment costs and energy savings) and perfectly rational cost-minimizing agents with perfect foresight and perfect knowledge.

6.2.1 Evidence for barriers

Many studies have presented empirical evidence for the existence of barriers to energy efficiency. The studies found that many cost-effective options for energy efficiency improvements are not known to firms, or even if they are known and well defined, they are often not implemented - even when they show very low payback times of about a year. Several studies have concluded that - as financial factors alone cannot explain the non-adoption of energy efficient technologies- there must be “other” factors that determine these investments.

DeCanio (1998) for example analyzed the influence of the financial and organizational characteristics of organizations on the payback time of projects undertaken in the frame of the US Green Light Program. A total of 3,673 energy-efficient lighting projects recorded in the database of the Green Light program were analyzed. The results of the regression analysis show that economic variables alone (like lighting hours, electricity prices, time lag or administrative cost) are not able to explain the experienced differences in payback times between organizations. On the contrary, DeCanio concluded that organizational and institutional factors strongly influence firms' investment decisions and that a large potential for energy-savings is still not realized, due to barriers.

An evaluation of the project database of the US Department of Energy’s Industrial Assessment Center (IAC) program presents further evidence of the impact of barriers on investment decisions (Anderson, Newell 2004). The database provided the results of over 10,000 assessments and over 70,000 single project recommendations. They found an implicit payback time threshold of 1.4 years. The analysis revealed further evidence for the hypothesis that simple investment criteria like payback time, initial implementation cost or annual energy savings do not suffice to explain the differences in investment behavior between plants and thus further decision determinants seem to exist. They also found that even recommended projects with a payback time close to zero were not implemented in 30% of the cases, which also indicates the existence of further investment determinants beyond simple profitability and risk criteria.

Harris (2000) conducted a survey among 100 Australian firms that participated in the Commonwealth government’s Enterprise Energy Audit Program (EEAP). They found that about 80% of the recommended efficiency improvements were implemented by firms. This high rate of implementation indicates that prior barriers existed that prevented the implementation of cost-effective efficiency improvements. The remaining 20% were mostly not realized because the rate of return was too low or the payback time too high.

In a similar way, several more studies give empirical evidence of the existence of market barriers to energy efficiency investment (Rohdin et al. 2007; Velthuijsen 1993). Also the often observed high rate of adoption of projects that were recommended by external energy audits indicates that cost-effective opportunities to improve energy efficiency are available in firms, but were neither analyzed nor implemented before the audits (Harris et al. 2000).

6.2.2 Classifying barriers

As shown in the literature, barriers are very heterogeneous in nature and were observed for all actors in the market. They are experienced differently among technology adopters and vary between technologies. As a consequence, many different ways to interpret and classify barriers emerged.

Many studies simply distinguish two main groups of barriers, namely market-related barriers and behavioral as well as organizational barriers (Sardianou 2008; Thollander, Ottosson 2008). Jaffe and Stavins (Jaffe, Stavins 1994b) underline that many of the observed barriers are not market failures, but could well represent rational behavior at the firm level. Examples are dealing with uncertainty and risk by applying high discount rates. On the other side, examples for market failures are information asymmetries or principal agent dilemmas. The IPCC (IPCC 2001) proposes to distinguish four broad groups of barriers, namely, lack of information, limited availability of capital, lack of skilled personnel and a bundle of other barriers. These broad groups are further differentiated by Sorrell et al. (Sorrell et al. 2004) and Schleich (2009) who classify barriers into six groups. They differentiate imperfect information, hidden costs, risk and uncertainty, split incentives, access to capital and bounded rationality. We apply the same definition for our analysis. Empirical evidence and examples are given below for each of these groups.

The importance of **imperfect information** as a barrier has often been empirically shown. The term comprises the knowledge about the availability of an energy-efficient technique, but also about its characteristics like costs and saving potentials as well as the actual energy consumption of the equipment in place. De Groot et al. (2001) conducted a survey among Dutch firms and found that 30 % of the companies interviewed were not, or only to a minor extent, aware of new existing energy-efficient technologies or practices.

Schleich (2009) also groups the transaction costs for the search and information gathering process under the label of imperfect information. Transaction costs might be regarded as one reason for imperfect information. Hein and Blok (1995) quantified transaction costs for the implementation of energy efficiency improvements in twelve plants in the Netherlands. They found transaction costs on the scale of 3-8 % of the necessary investment. Of these, 2-6 % can be attributed to information gathering costs, 1-2 % to decision-making and less than 1 % to monitoring activities. However, Ostertag (Ostertag 2003) finds in her detailed analysis of transaction costs for energy-efficient electric motors that the transaction costs only marginally depend on the price of the motor and that their share generally decreases with increasing motor size.

Hidden costs prevent firms from undertaking energy efficiency projects although they are generally not quantified by firms. They may, for example, result from a poor quality of energy-efficient equipment or the hiring of staff. Although more a driver than a barrier, co-benefits beyond efficiency improvement are often observed for industrial energy-efficient techniques. They may result from waste reduction, reduced material consumption, lower maintenance needs, lower emissions or improved reliability and better product quality (Lung et al. 2005; Worrell et al. 2003). Often co-benefits are the main motive for the implementation of certain projects and energy efficiency is a side effect.

Access to capital is also frequently cited as an important barrier. It concerns external capital, but also the use of internal capital and the priority-setting among alternative investment projects. The survey by Harris et al. (2000) among Australian firms revealed that 35 % of the non-realized but recommended efficiency projects were not implemented because they were assigned a lower priority than investment projects in the firms' core business. However, the survey also revealed a lower importance for the availability of finance as a barrier. Other studies found – slightly contradictory – a high importance for access to capital as a barrier. Examples are Anderson et al. (2004) who found that the cash flow was mentioned most frequently as a barrier. Accordingly, a survey among 50 Greek industrial firms (Sardianou 2008) found that the barriers which were observed by most of the participating firms were "no access to capital" (76%), "high cost of implementation" (76%) and "low rate of return" (74%). Similar results were found by Rohdin et al. (2007) who identified limited access to capital as the single most important barrier in the Swedish foundry industry.

Barriers related to **risk and uncertainty** cover a wide range from uncertainty about future energy prices or technology development to risk of production interruptions and impacts on product quality. In the Swedish pulp and paper industry, the technical risk of production disruption was identified as the single most important barrier (Thollander, Ottosson 2008). For the Swedish foundry industry it was identified as the second most important barrier (Rohdin et al. 2007). With relation to uncertainty, the irreversibility of investments is often mentioned as a relevant barrier (Harris et al. 2000).

Split incentives can hamper the adoption of energy-efficient technologies at very different phases in the diffusion process and between different market actors. This is illustrated in a case study by de Almeida (1998) about the diffusion of high-efficient electric motors (HEM) in France. He observed split incentives between different market actors, but also between different units within a single firm. He underlines the finding that all market actors (motor manufactures, end-users, original equipment manufactures (OEMs)) are focused on motor price and reliability instead of life-cycle cost.

Particularly the OEMs do not demand energy-efficient motors because they mostly compete on price and reliability when selling pumps, fans, etc. As they do not pay for the motor's electricity bill, they have no interest in integrating HEM into their products. A lack of transparency and information about the actual efficiency of the motors even intensifies this barrier, as it does not allow the end-user to compare the efficiencies of alternative motors. Internal split incentives between different departments can even further worsen this situation.

Schleich and Gruber (2008) analyzed a set of 2,800 interviews with firms from the German service sector and found that the investor/user dilemma showed the highest significance as single barrier.

Bounded rationality is classified as a further barrier. However, it is not specific for energy efficiency. Simon (1979) argues that observed business decision-making conforms better with the assumptions of bounded rationality than with the dominant economic theory of rational choice. Many behavioral theories of the business firm assume a greater degree of “satisficing” instead of “maximizing” behavior.

De Almeida (1998) applied this concept to explain firms’ investment in energy efficient motors. In the case of a broken motor, smaller firms especially do not have the capacity to compare alternative motor types. Their focus is on getting a new motor as quickly as possible, because even short production interruptions cost several times the motor price. As a consequence, they replace the broken motor with a new motor of the same brand and type. But even larger firms, who generally have a stock of replacement motors, mostly decide on the basis of motor prices instead of life cycle costs.

6.3 Modeling industrial energy demand

6.3.1 Typology of energy demand models

Energy models can be classified according to a variety of different characteristics like the modeling goal and scope or the methodological approach (Wei et al. 2006). The following discussion will focus on models for energy demand forecasts and apply a classification based on their methodological concept.

Energy demand models are typically differentiated into two general groups, top-down and bottom-up models - representing the two main modeling philosophies. While the latter are rather built on an engineering philosophy, the former tends to represent the view of economists. The most often mentioned characteristic of bottom-up models is their detailed consideration of technologies, which means they allow modeling the impact of distinct, well defined technologies on the long-term development of energy consumption. With their technology explicitness, bottom-up models have the potential to model the effects of technology-oriented policies[68] (Rivers, Jaccard 2006).

In top-down models like computed general equilibrium (CGE) models, technologies are typically represented within aggregated production functions, which have lost any information on the type and the structure of the technologies they comprise. Technological change is traditionally considered as an autonomous energy efficiency improvement (AEEI) factor in these models. The AEEI represents a price-independent improvement of energy productivity. In recent years, improvements were made to incorporate technological change endogenously into top-down models as a price-induced, R&D-induced or learning-induced development (Gillingham et al. 2008). But even when technical change is endogenous to the model, top-down models are not suited to analyze energy demand and its interaction with the evolution of the technological system. Top-down models have another field of application; they model interactions between the energy system and economic variables like employment or economic growth, whereas bottom-up models are restricted to the narrow system boundaries of the energy system (Allan et al. 2007; Zhang 1998).

However, the borders between top-down models and bottom-up models are not as clear as they may seem. In recent years, more and more modeling studies were conducted that integrated aspects of both approaches resulting in different types of hybrid models. They aim at overcoming weaknesses of a single approach by incorporating elements of the other approaches (Bhattacharyya, Timilsina 2009). Barker et al. (2007), for instance, use bottom-up estimations as exogenous input to a top-down framework to measure the economy-wide effects of climate change agreements in industry. The input parameters estimated by a bottom-up model assure transparent assumptions on the evolution of the technical system. Still, feedbacks from the macroeconomic world to the bottom-up model are not considered (compare (Koopmans, Velde 2001)). Several approaches also exist where certain technologies are translated into constant-elasticity-of-substitution (CES) production functions in CGE models (e.g. (Laitner, Hanson 2006; Lutz et al. 2005; Schumacher, Sands 2007)).

However, the technological detail that is modeled in top-down models is rather restricted. For example, Lutz et al. (2005) distinguish between two alternative processes for steel production and Schumacher and Sands (2007) distinguish 5 different processes. Thus, top-down models are not considered in the following analysis in order to allow for a maximum of comparability. Hybrid models are considered only if they contain a typical bottom-up part.

[68] We refer to technology-oriented policies as all kinds of rather technology specific policies like energy audits, information campaigns, standards and labels or technology subsidies. General energy taxes are not regarded as technology-oriented policy.

6.3.2 Review of bottom-up models

Bottom-up models are traditionally based on a detailed representation of energy end-uses like heating, lighting, mechanical energy or process heat (Bhattacharyya, Timilsina 2009). The evolution of the end-uses and of their energy efficiency over time determines the future energy demand. Some bottom-up models explicitly distinguish between final energy and useful energy (Chateau, Lapillonne 1990). The demand for useful energy (e.g. heat, steam, mechanical energy, light) is projected for each end-use based on assumptions of main economic variables like industrial value added or production of energy-intensive products. The resulting amount of final energy is then calculated from the useful energy and the conversion efficiencies of the different technical systems. This distinction allows to separately considering effects resulting from the economic development or changes in industrial structure and effects resulting from the technical structure and energy efficiency. Thus bottom-up models have in common that they link energy demand forecasts to the technological structure of the energy system (Figure 26).

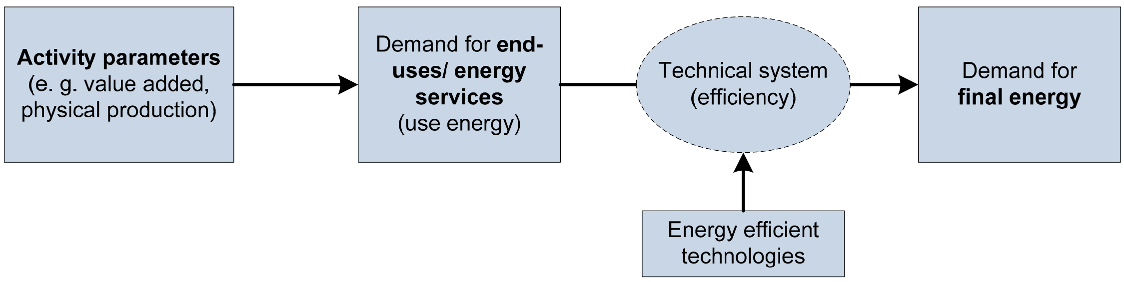

Figure 26: Conceptual overview of typical bottom-up models

With regard to technologies and the adoption and diffusion mechanisms, the models differ significantly. Also the extent to which barriers to energy efficiency are considered varies strongly among the models. Worrell et al. (Worrell et al. 2004) identify three factors that influence technology adoption in most bottom-up models, regardless of how technologies are represented in the model. These are the availability of technologies, the financial costs[69] and operational decision rules.

[69] Fixed and running costs of the investment as well as saved energy costs.

6.3.2.1 Criteria for the comparison of models

The short overview on barriers already revealed a huge variety and showed that they differ between companies and sectors. As most of the discussed models show none or only a very simplified representation of barriers, the analysis of models will not directly build on the classes of barriers, but instead begin a step earlier. Thus, not only the barriers, but also the general capability of the models to take barriers into account is analyzed. The following model characteristics are used as criteria for the discussion below (Worrell et al. 2004).

- Explicit **modeling of the technology stock** is regarded a prerequisite for a more detailed and realistic modeling of technology adoption and its determinants.
- **Financial costs:** Investment costs as well as energy costs are without doubt an important decision parameter for firms and thus their explicit consideration is a prerequisite for a detailed modeling of technology adoption and barriers.
- **Barriers** strongly influence technology adoption by firms. Only their consideration allows a realistic modeling of the technology stock.
- Modeling **policies** is the main goal of considering barriers in the models. The models differentiate in two aspects, the kind of policies they are able to consider and how the policies are linked to the technological structure and technology adoption.

We also consider models with a scope that goes beyond the industrial sector. However, when discussing the model characteristics only the industry part is considered and might differ in its structure, level of detail and assumptions on technical change from e.g. the simulation of the residential energy demand in the same model.

To discuss and compare the bottom-up models, we classify them into three main groups: accounting models, optimization models and simulation models. While optimization models optimize the choice of technology alternatives with regard to the total system costs to find the least-cost path, simulation models lack this system optimization perspective. They are very heterogeneous and some of them optimize from a firm perspective, while others do not optimize and instead consider other non-financial factors for the technology adoption decision. Accounting frameworks are less dynamic and do not consider energy prices, but mainly apply exogenous assumptions on the technical development (Chateau, Lapillonne 1990). Although we group the models into three classes, it should be clear that the borders are not as sharp and that some models show characteristics of more than one group (Table 30).

Table 30: Overview of the models considered

	Reference	Sectors modeled	Methodological approach*
Accounting models			
MURE II	(Faberi et al. 2009; Fraunhofer ISI et al. 2002)	All demand sectors (EU)	Accounting framework
MED-PRO	(Arcadia, Clipper Consult)	All demand sectors	Accounting framework
MAED	(Hainoun et al. 2006)	All demand sectors	Accounting framework
LEAP**	(Heaps 2008; Wang et al. 2007)	Iron and steel	Accounting framework
Optimization models			
DNE21+	(Oda et al. 2007)	Iron and steel + energy supply	Partial-Equilibrium optimization
MARKAL	(Gielen, Taylor 2007)	Industry + energy supply (global)	Partial-Equilibrium optimization
AIM/end-use	(Kainuma 2000; NIES 2006)	Iron and steel (Asia)	Partial-Equilibrium optimization
PRIMES	(Capros, Mantzos 2000; E3MLab 2010)	All demand and supply sectors (EU)	Partial-Equilibrium optimization
Simulation models			
CEF-NEMS	(DOE 2009; Worrell, Price 2001)	All demand and supply sectors (US)	Simulation
ENUSIM	(Fletcher, Marshall 1995)	Industry (UK)	Simulation
SAVE Production	(Daniels, Van Dril 2007)	Industry (NL)	Simulation
POLES	(Criqui 2001; Russ, Criqui 2007)	All demand and supply sectors (Global)	Econometric partial equilibrium
ISIndustry	(Eichhammer et al. 2009)	Industry (EU)	Simulation / accounting
LIEF	(Ross et al. 1993)	Industry	Econometric simulation
CIMS	(Jaccard 2005; Murphy et al. 2007)	All demand and supply sectors (Canada)	Simulation

* This column refers to the industrial sector module only.

** The description only refers to the application of LEAP by Wang et al., while Leap in general offers more functionality that would group it rather as a simulation model.

6.3.2.2 Accounting models

Accounting models represent the first generation of bottom-up models and their first applications date back to the late 1970s (Chateau, Lapillonne 1990). They are generally characterized by exogenous definitions of many variables. They normally do not consider energy prices and thus do not explicitly model firm behavior with regard to the investment decision. The absence of prices as an energy demand determinant and the strong reliance on exogenous assumptions about technological change were recognized as major drawbacks of accounting models. Despite these shortcomings, they were frequently applied and present a powerful tool for the analysis of long-term energy demand, also because their simplicity and transparency is a huge advantage.

The MEDEE[70] model family is based on a long development tradition that started in the late 1970s and aimed to develop a new energy demand forecast tool to overcome the main shortcomings of the predominant econometric models (Chateau, Lapillonne 1978; Lapillonne, Chateau 1981). Many different variants of the MEDEE model were developed, a commercialized and frequently used version of which is the MED-PRO model (Arcadia, Clipper Consult). Energy efficiency improvements are exogenous to the model. For each product or sub-sector, an exogenous energy efficiency improvement rate is applied and determines final energy demand. MED-PRO was frequently used in energy demand forecasting studies, often for France (Enerdata, LEPII 2005). A similar type of bottom-up model is MAED, which is derived from the MEDEE-2 model by simplifying the structure, but also by adding an extra module to calculate hourly electricity demand curves (Hainoun et al. 2006). Technical change in MAED is considered on a highly aggregated level by exogenous changes in energy efficiency over time of an aggregated set of technologies (IAEA 2006). Fuel switch is also exogenously defined.

For both models, MEDEE and MAED, neither a technology stock nor costs are explicitly taken into account. Consequently, barriers as well as the whole technology adoption process are only implicitly considered within the exogenously defined improvement of energy efficiency over time.

A flexible bottom-up modeling environment is the Long-Range Energy Alternative Planning System (LEAP)[71]. In contrast to most of the other models discussed, LEAP is rather a framework that provides the essential tools for energy models, than a clearly defined model itself (Heaps 2008). A typical application of the LEAP environment is presented by Wang et al. (2007), who assessed the technological options and costs for GHG abatement in the Chinese iron and steel industry. Their model contains information on the performance, shares and costs of alternative iron and steel producing technologies. Policies are not explicitly modeled, but

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70 Modèle d’Evaluation de la Demande en Energie.

71 Developed by the Stockholm Environment Institute (SEI).

translated into an exogenous diffusion path of efficient technologies. This means for the investment decision that neither the capital stock nor the costs of the technologies are considered. In contrast to the study by Wang et al., however, LEAP also provides tools for technology stock modeling or cost assessments, resulting in models that would rather be grouped to the simulation models.

6.3.2.3 Optimization models

Optimization models were initially designed to model energy supply, but many of them were gradually extended to certain energy demand sectors or the entire energy demand side. Classical optimization models minimize the total system costs across all time periods and assume equilibrium on energy markets, thus allowing for interactions between demand and supply. Mathematically, they are based on linear programming approaches.

A typical example of bottom-up optimization models is the MARKAL modeling framework, which has been developed by the IEA's Energy Technology System Analysis Programme (ETSAP) during the last 30 years (Loulou et al. 2004). Gielen and Taylor (2007) describe the use of the MARKAL model for the IEA's Energy Technology Perspectives. The model minimizes the costs of the whole energy system for a chosen time period. Energy-saving options on the energy demand side compete with supply side options on the basis of their costs until the least-cost options are finally chosen. The optimization assumes perfect foresight[72] and perfect knowledge, which has two major implications. First, the future characteristics of technologies, energy prices, etc. are known and considered in the investment decision. And second, the minimization of costs over a time period prevents the occurrence of new "lock-ins", at least within the modeling timeframe. This approach is built on a social planner with perfect knowledge and implicitly assumes perfectly rational decision-making as well as perfect markets. The constraints for the technology adoption are the availability of new technology based on stock turnover, a "high" discount rate to account for uncertainty, as well as an exogenous limit for the diffusion speed of new technologies. Besides these three aspects, there are no further factors considered that influence technology adoption. Consequently, the analyses of environmental policies using MARKAL focus on financial policies like a carbon price or a quantitative emissions constraint in an emissions trading scheme. Several studies were conducted for chosen industrial branches like the iron and steel industry (Gielen, Moriguchi 2002a; Gielen, Moriguchi 2002b).

Oda et al. (2007) used the global energy system model DN21+ to evaluate the effect of different greenhouse gas mitigation policies and the contribution from demand side mitigation in the iron and steel sector. They incorporated the global iron and steel sector into an energy system model

[72] SAGE is a version of the MARKAL model that explicitly does not assume perfect foresight (Loulou et al. 2004).

to also capture feedbacks between energy supply and energy demand. The diffusion of new technologies is modeled as in most optimization models, by considering the technologies' capital stock, the lifetime and a discount rate (in this case 5%). The technology adoption then depends on the minimization of cumulative discounted costs of the whole energy system over the modeling period from 2000 to 2030. As in Gielen and Taylor (2007), this approach assumes perfect knowledge and foresight throughout the whole modeling period and does not account for barriers.

An optimization model that was frequently applied in the Asian-Pacific region is the AIM/end-use model. It is part of the broader AIM (Asian Pacific Integrated Model) which aims to analyze climate policies, their costs and possible stabilization paths (Kainuma 2000; Kainuma 2004; Matsuoka et al. 1995). The AIM/end-use model considers technological change by alternative technologies that compete with each other on the basis of payback time or annualized lifecycle costs (Kainuma 2000). The model explicitly considers the technology stock and allows for new technologies to be employed in three cases: first, when old technologies retire or the energy service demand grows, second, by improving existing technologies and third by early replacement of an existing technology. Although the consideration of payback time can be regarded as an element of more realistic investment decision routines, the model is based on a cost-minimization algorithm that does not take barriers and further behavioral aspects into account (NIES 2006).

Also PRIMES which is frequently used to establish long-term energy projections for the European Union (EU) (Capros et al. 2010; Capros, Mantzos 2000), is based on an optimization algorithm that assures market clearing and thus assumes a partial equilibrium in the EU energy markets. However, PRIMES differs from other discussed optimization models in so far as it does not optimize a single economic function, but instead optimizes single sectors (e.g. the steel industry) following the rule of profit-maximization (E3MLab 2010). PRIMES explicitly considers barriers like perceived costs or risk premiums that hamper the diffusion of certain technologies. Risk is translated into a premium on the discount rate and differs between technologies and sectors. Other barriers are considered in a more aggregated way by allowing for alternative technology adoption rules. Technology specific policies can be integrated by lowering the perceived costs of certain technologies.

6.3.2.4 Simulation models

In contrast to optimization models, simulation models show a greater variety of different approaches and modeling philosophies, which makes it difficult to clearly define this type of models. In particular with regard to firms' technology adoption decision, the assumptions and implemented decision rules differ strongly. Many simulation models represent extensions of accounting models with a more detailed modeling of technology stock, technology adoption and firm behavior. We classify all models as simulation models that explicitly consider technologies and their stock and have an explicit technology adoption algorithm - as long as it is not the rule of minimized system costs which the optimization models assume.

A classical representative of simulation models is the NEMS (national energy modeling system) model as used for energy demand projections in the USA (Worrell, Price 2001). The technology adoption rule of NEMS-industry distinguishes two types of technologies, process and cross-cutting technologies (Energy Information Administration 2009).

For process technologies, efficiency improvements take place by either retrofitting the technology stock or by replacing old vintages with new state-of-the-art technologies according to a fixed annual replacement rate. Energy prices influence the annual rate by which the energy efficiency of the technology stock improves due to retrofitting. Thus, only the improvement of the current technology stock depends in part on the energy prices and thus reflects firm behavior that aims to counteract increasing energy prices by introducing energy efficiency measures. For the introduction of new technologies, it is argued that they are not introduced on the basis of energy efficiency considerations, but rather "autonomously", taking other not explicitly defined factors into account.

For cross-cutting technologies, like compressed air or lighting, the stock model is extended by technology costs and the replacement of technology stock depends on a payback time threshold. The dominance of the payback time threshold as an investment criterion has also been empirically observed. However, other barriers are not considered.

ENUSIM is a bottom-up simulation model that exclusively focuses on energy demand in industry in the UK (Fletcher, Marshall 1995; Oxford Economic Group 2006). It applies the typical bottom-up approach and distinguishes between different energy end-uses that are projected based on exogenous assumptions of production output growth. ENUSIM explicitly models the technology stock by considering three different types of technologies, old (outdated) plants (I), present type of plants (II) and future plants (III) with the highest efficiency. Only plants of type III are allowed for capacity expansion. In addition to the plant database, the model also considers technology options that may be implemented to improve the plant efficiency by retrofitting. For the technology adoption rule, investment costs and behavioral factors are stated to be considered and the technology diffusion is based on the S-curve pattern. However, the diffusion curve for cost-effective technologies is exogenous input and thus all assumptions on barriers and investment behavior are only implicitly considered in the curve.

The approach followed by Daniels and Van Dril (2007) for the SAVE Production model considers risk, psychological effects of energy price changes and energy efficiency policies, as well as bounded rationality, besides the cost-effectiveness of the investment as decision factors. The approach is based on a technology stock model where a normal distribution around the average lifetime determines the share of the capacity that is to be replaced. Technologies are distinguished in “base-technologies” and “sub-technologies”. The replacement of sub-technologies depends on their own lifecycle, but also the lifecycle of the relevant base-technology. Risk is considered in the decision algorithm as a parameter that reduces the internal rate of return of the considered technology. Non-financial barriers are considered by limiting the speed of the market diffusion. Also, psychological factors stemming from historical rises in energy prices and the stringency of policies are considered. The influence of the risk parameter and the factors for the psychological effects of policy and energy price changes are – due to data availability - mainly based on expert judgments. Thus the model is among the most advanced to consider barriers, but the empirical foundation of the parameters remains a challenge.

The CIMS (Canadian Integrated Modeling System) model is a further development of the former strictly bottom-up ISTUM model and covers all energy demand sectors as well as energy supply and economic feedbacks (Nyboer 1997). CIMS-industry explicitly models the development of the capital stock and differentiates between stock retirement, retrofit and purchase of new equipment due to production growth (Murphy et al. 2007). The decision-making algorithm is based on the classical algorithm of bottom-up models, but extended by three parameters representing behavioral realism and barriers. These are the heterogeneity of the market, the time preferences of the decision-maker and a factor for all other intangible costs and benefits. Markets with a high degree of heterogeneity observe less dominance of single technologies, even if they are significantly more cost-effective than others. The time preference of the decision-maker can be translated as the applied discount rate. The third parameter covers all remaining intangible costs and benefits that influence the decision-making. This parameter is not empirically derived, but adjusted when calibrating the model to observed market shares. The authors mention the huge amount of behavioral data needed for a technology explicit model and the difficulty of obtaining empirical data on preferences as two major drawbacks of their approach. To address these data needs, the authors combine the modeling work with surveys on consumer and firm preferences (Rivers, Jaccard 2006). However, the CIMS model represents one of the most advanced approaches towards considering barriers and behavioral realism in bottom-up models.

In the following, three models are presented that use econometric estimations in simulation models to better capture firm behavior with respect to technology adoption.

POLES is a simulation model that extends the typical framework of end-use bottom-up models by using econometrically estimated relations to consider fuel elasticity and efficiency improvement on the demand side (Russ, Criqui 2007). The model considers the energy demand and supply side, which are connected by energy markets, allowing for a partial equilibrium. Energy efficiency improvements take place by replacing retired stock with new more efficient plants. The efficiency of new capital stock and the energy carriers used are determined as an econometrically estimated function of short- and long-term price elasticity and an autonomous energy efficiency improvement factor. The considered price elasticities as well as the autonomous non-price related improvement allow for a certain consideration of barriers in technology adoption behavior, but at a rather aggregated level.

Davidsdottir and Ruth (2004) used an econometric model to project energy use in the US pulp and paper industry that incorporates techno-economic data on capital vintages (studies were also conducted for the steel industry and the ethylene production (Ruth 2004)). They explicitly model the capacity expansion and the resulting energy efficiency improvement in new capital vintages. Energy efficiency improvement is considered through both the retirement of less efficient capital and the improvement of capital in place. It incorporates firm behavior by econometrically estimating key variables for the investment, like gross investment as a function of input prices and desired production volumes. However, the model aims to answer the questions, why new investments are made and what the impact of long capital lifetime on technical change is, but does not explicitly model the decision between alternative investments with differing energy efficiency. In other words, it is modeled “when” the investment decision in new capital takes place, but not which type of new capital is chosen.

The model ISIndustry is relatively young, it comprises the industrial sector and was mainly applied to EU countries (Eichhammer et al. 2009). It shows a huge technology detail and explicitly considers technology costs, while – in contrast to many other simulation models – it does not explicitly build a technology stock. The diffusion of energy-saving technologies, which is driving energy efficiency improvements, is to a large extent exogenous to the model. Costs are used to choose between alternative exogenous diffusion paths. Barriers are considered in an aggregated form by a combination of exogenously set diffusion paths and a premium on the discount rate. The model could be grouped as between accounting and simulation models, because on the one hand it shows a huge share of exogenous input parameters, but on the other hand it takes technology costs into account.

The LIEF[73] model made a particular effort to overcome the disadvantages of econometric approaches and traditional bottom-up modeling by combining both model types (Ross et al. 1993). Thus, LIEF is able to determine main variables based on their historical trend and also to ac-

[73] Long-term Industrial Energy Forecasting.

count for the firm behavior, while at the same time explicitly considering the potential of new technologies. Technologies are represented in the model as aggregated conservation supply curves that show the energy-saving potential and the related marginal costs, but that do not allow to identify single technologies. Thus, the technology stock is not explicitly considered. As in the other econometric models, barriers and behavior are implicitly considered in the historic trend, but not explicitly modeled.

6.4 Analysis and discussion

The following summary on the model review starts from the simplest concept and discusses distinct steps towards more complex models to finally arrive at models that would theoretically be able to model different kinds of policies based on a detailed representation of barriers. This discussion also gives an idea about how bottom-up models evolved over the past 30 years.

6.4.1 Technology stock

Although bottom-up models are mostly defined as being technology-explicit, they substantially differentiate in the level of detail and how they consider technologies. Some of the early accounting type models, like MED-PRO or MEAD, consider technologies only as end-uses with a specific useful-energy demand and conversion efficiency. Often an entire production process (e.g. steel production) is reduced to one aggregated end-use. In these cases, the efficiency improves over time due to an exogenously given improvement rate and stock turnover is not explicitly modeled.

However, the technology stock and its turnover rate certainly have a huge impact on technology diffusion. Consequently, many models explicitly consider the technology stock and model energy demand by changes in the technology stock ((2004), (2003), CIMS, MARKAL, DN21+, Save Production, POLES, etc.). The technology stock is at least characterized by technology vintages with differing specific energy consumption assuming that new technologies are more efficient. The decommissioning of old equipment and the introduction of new "state-of-the-art" plants improves energy efficiency in the technology stock. Virtually all models use age as the determining driver for stock turnover, although this may not be fully appropriate, as shown in a case study of the U.S. steel industry (Worrell, Biermans 2005). Some models also consider retrofitting of technologies in use (CIMS, NEMS-industry) or early (premature) replacement (NEMS, AIM/end-use, etc.). The technology stock approach already assures a certain reality with regard to technology diffusion, because the latter is bound to the lifetime of the technologies and their current stock. Thus, new technologies only diffuse when the capacity in the old stock is not sufficient – as a result of demand expansion or technology decommissioning.

Table 31: Overview of the explicit modeling of technology stock by model

	Technology stock not modeled	**Technology stock modeled**	**Technology replacement rules**		
	Technical change mostly exogenous, often as aggregated efficiency improvement	Technology diffusion depends on lifetime and the age of current technologies	Replacement after life-time	Early replacement al-lowed	Retrofitting possible
Accounting models					
Mure II	X				
MED-PRO	X				
MAED	X				
LEAP	X	(X)	(X)	(X)	(X)
Optimization models					
DNE21+		X	X	X	X
MARKAL		X	X		
AIM/end-use		X	X	X	X
PRIMES		X	X	X	X
Simulation models					
CEF-NEMS		X	X	X	X
ENUSIM		X	X		X
SAVE Production		X	X		X
POLES		X	X		
ISIndustry	X				
LIEF	X				
CIMS		X	X		X

6.4.2 Financial costs

All these changes in technology stock imply assumptions of the behavior of firms with regard to technology adoption. A central decision criterion in bottom-up models is the cost-effectiveness of the investment. Thus information about investment costs and saved energy costs are required. They are also a prerequisite to model price policies. Still, not all models consider (financial) costs. Among these are most of the accounting type models (MEDEE, MAED, MURE), but also more sophisticated models like for example the NEMS-industry model. NEMS-industry only explicitly considers costs for cross-cutting technologies, but not for industrial process technologies. Still, the stock turnover rate depends on the energy prices, so that a certain price sensitivity can be observed. Also some of the models working with econometric price elasticities do not explicitly consider investment costs (e.g. POLES, (2004)). The reviewed optimization models all consider technology investment costs.

6.4.3 Barriers

Thus most simulation and optimization models explicitly consider the development of a technology stock and base the technology adoption on the cost-effectiveness of the investment - among other factors. When it comes to the adoption algorithm, i.e. firms' investment behavior and the impact of barriers, the models differ greatly from each other. While most models provide the ad-hoc option to consider high discount rates (to simulate stronger barriers), only individual models consider barriers more explicitly, and only to a certain extent.

In general, the approaches followed by simulation models are much more varied, while the optimization models mainly follow the classical "minimization of total system costs" approach that considers only the financial costs of the investments and neglects e.g. transaction costs and information search costs (AIM/End-Use, DN21+, MARKAL). At best, optimization models represent barriers by higher discount rates (e.g. MARKAL) or by considering short payback periods as investment decision criterion (AIM/end-use). Recent developments aim to consider uncertainty about the development of future model variables like energy prices by introducing myopic agents (MARKAL-SAGE). As a consequence, cost-optimization can then not be conducted over all time periods and it may be possible for the "social planner" to choose a path that is not optimal in the long term, but ends with a lock-in situation.

Some of the simulation models present new approaches to improve the behavioral realism in the technology adoption algorithm (SAVE Production, CIMS). CIMS for example introduces three parameters, the heterogeneity of potential adopters, a discount rate (representing the time preference of the firm) and a factor capturing all other intangible costs and benefits. SAVE Production considers risk (as a discount rate), psychological effects stemming from energy price changes, as well as a policy factor that represents the stringency of policies. Also PRIMES considers a risk premium and perceived costs depending on the type of technology.

Many bottom-up models were extended in recent years to include experience effects, thus falling investment costs with increasing deployment of a technology (e.g. MARKAL, CIMS). However, this effect is mostly considered for emerging energy supply technologies like renewable energies (Berglund, Söderholm 2006). The consideration of experience curves for industrial energy-efficient technologies lags, partly due to rare empirical data and the difficulty of defining system boundaries around very integrated processes (Jardot et al. 2010; Ramírez, Worrell 2006). As long as experience curves are not properly integrated into energy demand models, the costs of reducing energy demand are overestimated and the potential of technological change to improve energy efficiency through the diffusion of new technologies is underestimated, in particular within an approach that considers rational cost optimization behavior. Thus, for an endogenous modeling of technology diffusion, experience curve effects are obligatory.

To conclude, none of the bottom-up models considers barriers in a comprehensive way. Instead, most of them consider barriers in an aggregated way, in the form of higher discount rates. Even the most advanced models in this respect (CIMS, SAVE Production, PRIMES) only consider a very small fraction of the barriers that were identified in the empirical literature Aspects considered in the models were higher discount rates (maybe used as a proxy for risk), payback time threshold as investment criterion, uncertainty about future development, heterogeneity among the adopters, psychological effects as a consequence of energy price increases, or cost reductions due to experience curve effects. Although the list seems long, it should be noted that this list combines all models and no single model considers more than three of these factors. Barriers that were found to be very important in the empirical literature, like no access to capital, lack of information and know-how, bounded rationality or principal agent dilemmas are not explicitly addressed in any of the models.

Also differences in the intensity of these barriers among firms, industrial sectors or technologies are only marginally considered. For example, NEMS-industry applies a higher discount rate to cross-cutting technologies than to process technologies, representing the presence of stronger barriers for cross-cutting technologies. Also CIMS estimates some of the barrier related parameters by technology (Table 32).

Table 32: Overview of the explicit consideration of barriers in bottom-up models

	Not explicitly considered	**Simple aggregated approach**	**Explicitly considered by type of barrier**					
		Price elasticity, discount rate, all approaches that aggregate barriers	Imperfect information	Hidden costs (and benefits)	Access to capital	Risk and uncertainty	Split incentives	Bounded rationality
Accounting models								
Mure II	X							
MED-PRO	X							
MAED	X							
LEAP	X	(X)						
Optimization models								
DNE21+	X							
MARKAL		X						
AIM/end-use		X						
PRIMES		X				X		
Simulation models								
CEF-NEMS		X						
ENUSIM		X						
SAVE Production		X		X		X		
POLES		X						
ISIndustry		X						
LIEF		X						
CIMS		X		X				

6.4.4 Capability to model policies

The way technology adoption and diffusion is modeled and barriers are considered, restricts the types of policies that can be modeled. Two general groups of policies can be distinguished, price and non-price policies. Price policies can be energy or carbon taxes, they can in general be considered in all models that base the technology adoption on a classical investment decision by considering investment costs and saved energy costs (MARKAL, CIMS, DN21+, etc.). In particular, when the model philosophy is total cost minimization without considering barriers or bounded rationality, as in most bottom-up optimization models except PRIMES, simple investment calculation is sufficient to model price policies. However, as for simulation models, a realistic forecast is the goal, they need to consider barriers even to model price policies, otherwise they would end up with a too optimistic diffusion of efficient technologies. Thus, considering barriers is essential in order to arrive at a realistic price elasticity.

The situation is more complex for non-price policies, because these policies are as heterogeneous as the barriers they address. In many bottom-up models of the type of accounting frameworks, policies are typically modeled by exogenously adapting the diffusion rate of energy-efficient technologies or the energy efficiency improvement rates in comparison to a business-as-usual scenario (MED-PRO, MAED). A similar and very common ad-hoc approach to model energy efficiency policies aiming at barriers is the use of scenarios with a lower discount rate (MARKAL, ISIndustry, AIM/end-use). This is possible if barriers were considered in the form of a higher (implicit) discount rate in the baseline scenario. However, all of these ad-hoc approaches consider policies in a very aggregated and stylized way and none really allows representation of the characteristics of distinct policy design and intensity. Furthermore, choosing the "right" discount rate so that it represents a certain policy design and intensity is not practical.

First approaches that go beyond these ad-hoc policy modeling are the CIMS, PRIMES or the SAVE Production models. As these consider barriers in more detail, they should also be able to model policies that address these barriers more realistically. Although the representation of barriers is still rather aggregated, they already experience a strongly increasing demand for empirical data on firm preferences and behavior, which is particularly difficult to collect.

To conclude, most bottom-up models are not capable of explicitly considering distinct non-price policies for energy efficiency, mainly because they do not explicitly consider the barriers and the firm behavior that is addressed by the policies. On the other side, bottom-up models are, due to their technological detail, theoretically very suitable for modeling technology-specific policies, like e.g. energy audits or information programs (Table 33).

Table 33: Overview of the explicit modeling of policies to improve energy efficiency

	Policies as exogenous technology assumption	Price policies	Emission constraints	Technology specific policies		
	Policies exogenously considered in efficiency changes and/or technology diffusion	Taxes on energy or CO_2 emissions	Cap on the total annual emissions combined with trading of emission permits	Minimum standards for technologies	Subsidies and taxes on particular technologies	Policies addressing particular barriers (labeling, energy audits, contracting, low interest loans, etc.)
Accounting models						
Mure II	X			X		
MED-PRO	X			X		
MAED	X					
LEAP	X	(X)		X		
Optimization models						
DNE21+			X			
MARKAL		X	X			
AIM/end-use		X				
PRIMES		X	X	X	X	
Simulation models						
CEF-NEMS	(X)	(X)		X	(X)	
ENUSIM		X	X	X	X	
SAVE Production		X		X	X	(X)
POLES		X	X	n.a.	n.a.	
ISIndustry	X	X		X	X	
LIEF	X	X				
CIMS		X		X	X	

6.5 Conclusions and ways forward

While clear evidence of the existence of barriers has frequently been provided by different empirical studies, only a few bottom-up models consider barriers beyond the simple "discount rate approach". Even these "advanced" models (CIMS, SAVE Production) consider barriers in a rather stylized way, and only partly. They all have problems linking the model assumption to empirically assessed data. Heterogeneity between firms is only rarely considered and then rather stylized (CIMS, SVAE Production). The current state-of-the art bottom-up model explicitly models the technology stock and the costs of new technologies, while it shows only a simple representation of barriers by using an adapted discount rate. Thus, the rather exogenous and stylized consideration of barriers and technology diffusion sets restrictive limits for the modeling of energy efficiency policies.

However, promising approaches exist in the diffusion modeling literature (Geroski 2000) which bottom-up models could learn from (Barreto, Kemp 2008). These models come from disciplines like evolutionary modeling or agent-based modeling.

6.5.1 Uncertainty and spread of information

Various diffusion models present ways to model certain aspects of barriers like uncertainty and the spread of information. Jaffe and Stavins (Jaffe, Stavins 1994a) propose an approach to model the diffusion of energy-efficient technologies while taking into account typical methods for technology diffusion modeling. The model considers both "epidemic" (gradual spread of a technology among adopters) as well as "probit" (heterogeneity among potential adopters) characteristics. Mulder (Mulder P. 2005) builds a diffusion model that is closely related to evolutionary economics and explicitly accounts for learning by using, uncertainty and heterogeneity. Another diffusion model considers irreversible investment and uncertainty about the availability of new (superior) technology (van Soest, Bulte 2001; van Soest 2005). These models show how the potential technology adopter postpones the investment due to a certain option value of waiting, although the investment would have been cost-effective.

A concrete first step towards considering aspects like increasing returns, uncertainty and heterogeneous agents with different attitudes towards risk in bottom-up optimization models has been presented by Ma et al. (2009) by using a rather stylized diffusion model with two agents and three technologies.

6.5.2 Heterogeneity

The consideration of heterogeneity between firms and markets has been discussed as a critical aspect for more realistic bottom-up models. Different methodological approaches to improve the models are found in the literature. In general, probit models seem well suited, they derive the technology diffusion from differing characteristics of potential technology adopters (Jaffe, Stavins 1994a). Blok et al. (Blok et al. 2004), for example, considered heterogeneity in firms by implementing a distribution function of critical discount rates, which are used as an investment decision criterion. Also agent-based modeling may be a way forward to improve technology diffusion in bottom-up models and to explicitly account for heterogeneity between firms, as Schwarz and Ernst (2009) showed for a diffusion model for water-saving technologies. They considered 12,000 potential technology users and classified them in typical consumer types. They linked the modeling work with empirical data from surveys and thus considered a wide set of heterogeneous technology adopters with differing attributes instead of one average adopter only.

6.5.3 Experience curve effects

The faster spread of the use of experience curves to bottom-up demand-side models is basically restricted by the low availability of empirical data on technology-specific learning rates. If this data were available, learning from energy supply-side modeling could help to integrate experience curve effects also in demand-side models (Berglund, Söderholm 2006).

6.5.4 Bottom-up model prototypes with the intention to consider barriers

While the diffusion modeling approaches provide methodologies to improve the modeling of heterogeneity, uncertainty with regard to energy prices or technology development, experience curve effects and spread of information, some important barriers are still not addressed. Among these are technical risk towards production disruptions, access to capital and investment priority-setting, lack of information on energy flow and relevant efficiency options, split incentives and bounded rationality. The following two modeling studies show how also many of these factors could be implemented in the bottom-up models. These models represent promising directions for future research activities.

A very comprehensive approach towards combining the literature on barriers with bottom-up models has been presented by Gillisen et al. (1995). They explicitly model firms' investment decisions by applying a three-phase decision model that breaks down the technology adoption into a knowledge phase, an economic evaluation phase and an implementation phase. All phases are influenced by barriers. Model calibration is done based on a survey among Dutch firms about their characteristics and the impact of barriers. The model considers barriers at a firm level by using barrier-specific variables like the degree of information sources, the importance of the environmental reputation or an uncertainty variable. Particularly the technology adoption module and the link between empirical data and model calibration shall be underlined and would be a good basis for further research.

Blok et al. (2004) also propose a model that directly relates to the barriers discussion. They explicitly include 7 different types of barriers and differentiate between technologies. Examples of these barriers are the complexity of the technology, the financial situation of the industrial sector, threats to operational management by the implementation of a technique or the level of knowledge of the sector. This diffusion model is also linked to the ICARUS database on energy-saving technologies in the Netherlands.[74]

6.5.5 Conclusions

Current bottom-up models mostly represent barriers to the adoption of energy-efficient technologies in a very aggregated and simplified manner. Single models already undertook first steps for improvement, by considering heterogeneous markets, hidden costs or the firms' willingness-to-pay in addition to simple financial cost assessments. Furthermore, methodologies and approaches from other disciplines exist that could be used as a basis for improvement. Many can be found in the whole field of technology diffusion studies.

Still, the enormous technological heterogeneity in the industrial sector already poses challenges to the models (Brown et al. 1998). With a comprehensive incorporation of barriers into the models, model handling and transparency will become even more of a challenge, as the amount of data needed will increase further. Consequently, also transparency with regard to assumptions and model routines will become more important when new and more diversified and complex modeling approaches are used. In general, data on firm behavior might be even more difficult to gather than technology characteristics data. Also here, some models showed first ideas to combine the modeling work with surveys explicitly designed for the model needs.

[74] As the model is described as a research model and not applied to forecast studies, it is not discussed in the model section but rather as a first step to improving the models.

7 Summary and Conclusions

7.1 Introduction

The transformation to a global low-carbon industrial production system is a precondition of mitigating the impacts of climate change. Accelerating energy efficiency improvement can significantly contribute to this transition. The IEA estimates that energy efficiency[75] improvements through applying today's best available technology (BAT) in the industrial sector could reduce total global CO_2 emissions by 1.9 to 3.2 Gt per year, which equals about 7 to 12% of the annual energy and process related CO_2 emissions in 2004 (or 19 to 32 % of industry's annual CO_2 emissions). In other words, the diffusion of already available innovations still embodies a huge potential for energy efficiency improvement and is also the rationale for this thesis.

The diffusion of energy efficiency measures (EEMs), is a complex process and, lying at the intersection between society, economy and technology, it is influenced by a huge variety of factors such as EEM characteristics, adopter characteristics and behavior, the information channels, the regulatory framework and various other contextual aspects (Rogers 2003; Stoneman 2002). Most innovations (including EEMs) typically follow an s-shaped curve when they diffuse among the users (Stoneman 2002). For EEMs, the (surprisingly) slow diffusion of apparently cost-effective measures has attracted much attention from researchers who have put forward numerous explanations for this. These comprise barriers related to risk and uncertainty, hidden costs, transaction costs and imperfect information, bounded rationality, split incentives and access to capital for financing (Sorrell et al. 2004). Empirical evidence for the existence of barriers for firms to adopt EEMs has accumulated (Anderson, Newell 2004; DeCanio 1998; Schleich 2009; Sorrell et al. 2011; Velthuijsen 1995) and increasingly many and various policies have been developed and designed to overcome such barriers (Price 2005; Price, Lu 2011). In a world of constrained resources, it is essential to design effective and efficient policies that reach their objective at the lowest cost. Understanding of the underlying barriers pattern and the energy-saving potentials available, as well as their costs, form the basis for designing effective policies. While these aspects have been researched in the past, little attention has been put so far on the interactions between these dimensions and how they affect the impact of policies.

This knowledge gap is the starting point for this thesis which aims to extend the basis for designing policies to accelerate the diffusion of EEMs in industry. It takes a comprehensive view by exploring the EEM potentials and costs as well as the adoption behavior of firms. A particular focus lies in the interaction between these two research fields, as the pattern and intensity of

[75] Strictly speaking the application of BAT in the IEA calculations also refers to non-energy related process emissions (like reduction of process emissions in clinker production). However, the major share is due to energy efficiency improvements.

barriers directly depend on the EEMs concerned. Thus, the main research question can be stated as follows.

How are EEMs and the adoption behavior of firms interrelated and what does this imply for the design and impacts of policies in this field?

As such, the research question has a wide scope drawing on the dimensions technology, firm behavior and policy. The chapters of the thesis are structured according to Figure 27. The first part focuses on the dimensions technology and firm behavior and their interrelation. First, the techno-economic characteristics of EEMs in the form of energy saving potentials and costs are analyzed (Chapter 2), before the adoption behavior of firms is assessed (Chapter 3). The following chapter explores the linkages of both fields (Chapter 4). The second part of the thesis then shifts the focus towards the policy dimension. This includes an *ex-post* policy impact evaluation (Chapter 5) and a review of models for *ex-ante* assessment of policy impact on industrial energy demand (Chapter 6). The policy-related analyses particularly focus on the role of barriers and EEMs.

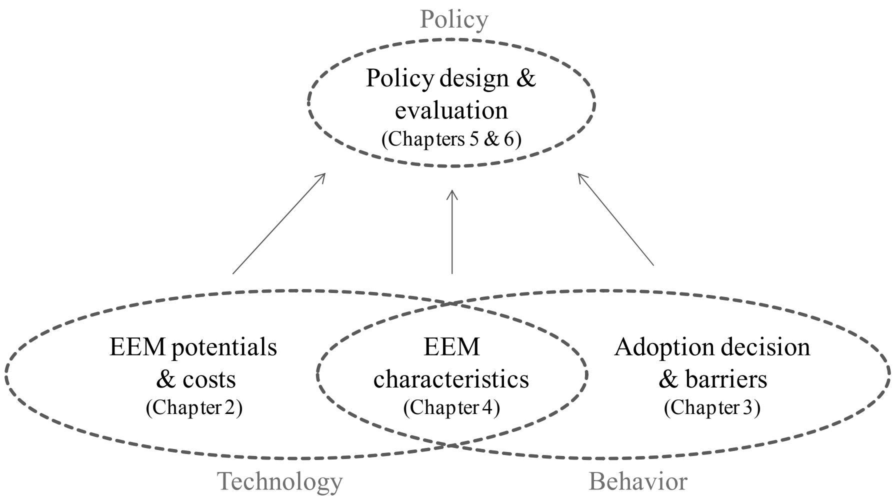


Figure 27: Conceptual framework of the thesis

Accordingly, the thesis is divided into five analytical chapters, each of which follows a concrete research question that contributes to the above research goal.

1. What are the energy saving potentials and costs of EEMs and what is their potential contribution to energy efficiency improvement in industry? (Chapter 2)
2. What are the determinants to the adoption of EEMs by firms and what is the particular role of barriers? (Chapter 3)
3. Which EEM characteristics affect the adoption decision by firms and how can the characteristics be used for a classification of EEMs? (Chapter 4)

4. What is the impact of policies in increasing the adoption rate of EEMs by SMEs, which EEMs are addressed and which barriers are overcome? (Chapter 5)
5. How are barriers, EEM diffusion and policies considered in models for *ex-ante* assessment of policy impacts? (Chapter 6)

7.2 Summary of results

In the following paragraphs, the main conclusions of each chapter are presented and discussed.

Chapter 2 explores the techno-economic characteristics of EEMs using the case of the pulp and paper industry. We use a bottom-up model to assess the long-term energy saving potentials based on the diffusion of 17 process-related EEMs. The EEMs result in a saving potential of 21% (34 PJ/a) for fuels and 16 % (12 PJ/a) for electricity by 2035 – as compared to the *frozen-efficiency* development (without considering rebound effects). These results show that the diffusion of EEMs contains a considerable potential towards a more efficient energy system, even in this energy-intensive industry, which is generally in line with the findings of earlier studies in this field. The large share of these potentials is cost-effective from a firm perspective, depending on the assumptions about energy price development and the interest rate assumed for investment appraisal. Cost-effectiveness is assessed – as typically done in bottom-up models – via the definition of a discount rate that reflects firms' profitability requirements and might also include additional costs stemming, for example, from uncertainty with regard to future energy prices. Thus, it is far from certain if the cost-effective potentials will be exploited by firms. On the contrary, due to the existence of various barriers, one expects – given the absence of strong policies – that large profitable potentials will remain unexploited. To simulate such a case, a sensitivity analysis is conducted by varying the discount rate. While the higher discount rate, for example 50%, lowers the cost-effective potential, it can be doubted whether it realistically reflects the pattern of influence of barriers on the adoption of EEMs. On the contrary, it "only" increases the slope of the cost curve and very profitable measures remain profitable even for high discount rates, indicating that they should be fully adopted. Due to barriers and heterogeneity, however, only a fraction of these profitable EEMs would be adopted in reality. Thus, this classical techno-economic analysis does not allow conclusions on "realistic" adoption behavior and diffusion paths of EEMs.

Two EEMs account for a large share of the total saving potential: heat recovery and the use of new paper drying technologies. While both show a comparable saving potential, they face substantially different costs: the former is available at net negative costs, while the latter is not. However, with regard to the technology characteristics, the analysis stops here. It enables the conclusion that these two EEMS are high-impact options and that heat recovery is even more economically exploitable, which should give it a higher priority for policy-makers.

The chapter further underlines the huge heterogeneity among EEMs. Although the chapter only covers EEMs in the paper production chain and only those that are related to the core production processes (excluding ancillary processes and cross-cutting technologies), the diversity is still large. While some technologies comprise radical changes of the current paper-making process, others represent best available technology. The 17 EEMs comprise very mature as well as recently emerging technologies, some EEMs require comprehensive system optimization and others replacement of well defined components. Judging from this technological diversity, it is likely that the EEMs also comprise varying barriers and have a different effect on adoption behavior. Thus, the classical techno-economic characteristics (costs and saving potentials) are not sufficient to draw conclusions on adoption behavior. Consequently, the diffusion paths calculated for the scenario analysis describe more theoretical developments and do not represent any realistic development.

Thus, the chapter clearly shows that classical techno-economic analysis of energy saving potentials is not a sufficient basis for policy design, although a necessary one. It helps to identify promising EEMs and allows the estimation of aggregated energy-saving potential and related costs. However it does not provide a better understanding of adoption behavior nor give any reasons why the cost-effective potential would not be exploited in reality. Additional analyses of these aspects seem necessary for more comprehensive policy recommendations.

Chapter 3 shifts the focus from the technology dimension to the adoption behavior of firms. The data stems from a survey conducted in 2010 to evaluate the German energy audit program for small and medium sized firms (SMEs). We take barriers based on firms' self-assessment as a starting point and use a multivariate regression to analyze whether such barriers really affected the adoption rate of firms, which is used as the dependent variable. Independent variables are firm characteristics (size, energy management system implemented, energy intensity), objective barriers (indicator for initial investment costs of recommended EEM, and two dummy variables indicating whether the firm uses payback time only for investment appraisal and whether the buildings are rented) and six subjective/self-assessed barriers (lack of capital, low profitability, transaction cost, technical risk, low priority and audit quality). Based on only 100 observations, the regression results robustly indicate that financial factors are the central reason why many recommended EEMs are not adopted. The variable *high investment cost* is statistically significant for both cases: measured as self-assessed variable and measured as objective costs of the recommended EEMs and across all model specifications tested. It suggests that *lack of capital* is a barrier still persisting despite the audit program. Also the *energy cost share of the firm* and the *audit quality* are statistically significant or just below the threshold depending on the model variation used. The fact that barriers such as *lack of capital* persist despite the program suggests that the program should be either adapted or extended towards a broader policy mix. Policies such as soft loan programs, investment subsidies or the support of contracting could help to overcome the investment barrier. The importance of audit quality underlines the need to establish proper quality control mechanisms such as report templates, requirements for auditor qualifications or training opportunities.

With regard to conclusions on EEM-specific barriers the chapter is relatively restricted as a result of the methodology used. Lack of data did not allow us to explore the barriers at the level of individual EEMs. Instead we aggregated a number of EEMs by using the adoption rate per firm as a dependent variable. A similar regression on the level of individual EEMs would allow more insights into EEM-specific factors to be gained.

A further contribution of this chapter is the factor analysis used to group the individual barriers questions from the survey to more abstract categories of barriers, as they are often defined in conceptual studies. While factor analysis has been used in social research for a long time, our study represents the first application of factor analysis to the field of barriers to energy efficiency in firms. More such studies are certainly required and our study has clear room for improvement, but it shows that the use of factor analysis could be a way forward to bridge the large gap between empirical research and theoretical or conceptual research on barriers. For example, regarding the barrier risk, our analysis suggests distinguishing between the technical risk of production failures and the market risk, for example resulting from energy price uncertainties. Thus, both types of risk have different origins and should be distinguished in empirical analyses, whereas a widely used classification of barriers (Sorrell et al. 2004) aggregates both types of risk into one category.

Having analyzed the dimensions of technology and adoption behavior separately in the two previous chapters, **Chapter 4** integrates both dimensions by analyzing which EEM characteristics affect the adoption rate. Based on a literature review, 12 characteristics related to three fields are derived: relative advantage, technical context and information context. The relative advantage is described by profitability in terms of internal rate of return and net present value as well as the investment costs and the co-benefits of the EEM. It is generally assumed that higher profitability, lower investment cost and higher co-benefits increase the adoption rate. The technical context is described by the distance to the core process, the type of modification (add-on technology, replacement or substitution, organizational measure) the scope of the effect (local or system-wide) and the lifetime of the EEM. Finally, the information context includes transaction costs, knowledge required for EEM implementation, the diffusion progress and the sectoral applicability (sector specific or cross-cutting measures). The resulting classification scheme for EEMs extends the list of EEM characteristics typically assessed in techno-economic analyses of energy saving potentials to include a number of more tacit characteristics, many of which cannot be measured quantitatively. This extended list of characteristics allows the adoption behavior of firms to be linked to EEMs and provides a broader basis for policy recommendations. For example the techno-economic analysis in chapter 2 could be extended beyond energy-saving potential and cost-effectiveness by using the derived characteristics. This is illustrated by the above example of heat recovery and new drying technologies. Adding the *diffusion progress* (or the maturity) of the technologies to the analysis would allow additional conclusions to be made. Heat recovery is already widely used and most of the components required are well known. New drying technologies, however, are still in the R&D stage and first pilot plants were only recently established. Thus, the market entry is still uncertain and entails high barriers to adoption for paper mills, such as the technical risk of immature technologies. It also requires a radical change of the current drying techniques, whereas heat recovery can more or less be regarded as an add-on EEM that extends the technical production system in place but hardly alters it. More radical change would typically give rise to higher barriers to adoption.

Although we could not validate this scheme empirically, we have applied it to six example EEMs by inferring the attributes based on expert knowledge and the available literature, in line with the above example for heat recovery and new drying technologies. This application revealed some methodological difficulties, of which many are related to the definition of EEMs. When comparing the implementation of an energy-efficient electric motor with new processes for steel making, the differences between both EEMs might seem clear at first sight. However, the new electric motor requires a number of prior definitions. For example, it is typically very cost-effective to replace a motor by a more efficient one, except for applications with very few annual running hours. Furthermore the replacement is a lot less costly if the new motor is implemented in the regular equipment replacement cycle when the older motor would be replaced anyway. The electric motor can be implemented in ancillary processes, but also at the core-production process. Furthermore, the motor's cost-effectiveness also depends on the electricity tariffs paid by the firm and thus it is not independent of adopter characteristics. For all these aspects, definitions were necessary to derive clear-cut characteristics that are as independent from the potential adopters as possible. Thus, the definition of the EEMs leads to their most likely application. Despite these difficulties, we were able to apply the scheme and derive characteristics for all six EEMs chosen, which shows that the scheme in its current form can be applied. It illustrates that the six example EEMs have systematically different patterns of characteristics resulting in different expectations about barriers. This outcome provides a basis for EEM-specific policy conclusions.

Thus, the chapter clearly shows the need to consider EEMs as a heterogeneous group of different measures and technologies with different underlying barrier patterns. This improves both policy design as well as analyses of barriers. This is particularly necessary if studies aim to draw general conclusions about adoption behavior and patterns of barriers. Using a generic, not specifically defined EEM as a reference does not provide a good basis for comparison.

The second part of the thesis adds the policy dimension to the analysis. **Chapter 5** comprises a case study of the German energy audit program for SMEs to evaluate the impact of such a policy on the adoption rate of EEMs and the resulting energy savings and costs. We further analyze the technology dimension, i.e. the types of EEMs assessed, and finally discuss the barriers overcome and those not overcome by the program. The audit program motivates firms to adopt on average 1.7 – 2.9 EEMs that would not have been adopted without the program. As these EEMs were all cost-effective from a firm perspective, an initial conclusion is that the program helped to overcome barriers such as a lack of information and restrictions on staff capacity, and reduced the energy efficiency gap. Total average net energy savings per firm are about 400 to 700 GJ/a and about 400-500 audits were conducted per month. The evaluation reveals that the EEMs recommended (and adopted) in the audits are mainly cross-cutting technologies from ancillary end-uses such as building insulation, heating and lighting; very few EEMs were directed towards process optimization and the core production processes. Thus, although the program is not restricted to a particular kind of EEM, it does address certain EEMs while others are rarely recommended by the auditors. Part of the effect is explained by the fact that around 60% of the firms participating in the audit program come from the Services sector, which typically do not have energy-intensive production processes. Explanations for the remaining 40% can be found in the adoption behavior of firms and how it is affected by the characteristics of EEMs. Firms are expected to be more reluctant to allow external auditors assessing the core-production processes and they attach a high risk to EEMs that might affect product quality or result in production interruptions. For ancillary processes, the perceived risk is far less pronounced. On the other hand, the auditors have only a restricted time to analyze a firm’s energy use, and thus focus on well known cross-cutting technologies and ancillary processes that are to be found in most firms (e.g. lighting, compressed air and space heat for buildings). Consequently, in its current form, the scope of the program is restricted by excluding process-related EEMs, which results in a lower impact in terms of energy savings and thus a less effective program. The case study shows how program design implicitly makes technology choices, resulting from the relationship between EEM characteristics and adoption behavior. Adapting the program to include incentives for auditors to specialize on particular branches or processes could address this issue. Alternatively, the program could be extended by other policies such as energy management obligations. Internal energy managers are expected to experience fewer barriers of addressing the core-production process than those encountered by external auditors.

With regard to the barriers addressed, the program contributed to overcoming barriers related to the identification of EEMs (lack of time/personal/information). Other barriers still persist despite the program, so that on average 28-47% of the recommended EEMs are not adopted by firms. This might be partly explained by a low profitability of the EEMs (from a firm perspective), although, even profitable EEMs are not always adopted. The main reasons for non-adoption stated by the firms are the high investment costs and the low priority of EEMs in comparison to other investments. As discussed above, the barrier of high investment costs can be addressed by suitable financial support programs. The low priority of EEMs relates to the competition of EEM investment with other investment projects. In combination with restricted resources such as financial budget, staff or knowledge, the low priority results in non-adoption of EEMs. A suitable policy to overcome such barriers could be the support of the market for energy service companies (ESCOs).

Design of effective energy efficiency policies is also supported by *ex-ante* assessments of potential policy impacts on energy demand. For this purpose, bottom-up models (such as the model used in Chapter 2) are frequently applied as they show a high degree of technological detail, and thus, should be particularly suitable for modeling effects of technology-specific policies.

Chapter 6 reviews current bottom-up models for industrial energy demand with regard to their technology diffusion algorithms. It assesses how the models represent technologies and how far they are capable of simulating barriers and related policies. The review reveals that technology diffusion is mostly based on simple rules, mainly assuming a rational investment decision. The models mostly consider barriers in an aggregated way by, for example, adjusting the discount rate used for the investment appraisal (as also done in Chapter 2). Thus, most bottom-up models are not only restricted to simulate the effects of barriers, they are further restricted to simulate the effects of policies addressing the barriers. However, best practice models that show first approaches to extend the rational choice adoption framework are identified. These are namely the CIMS and the Save production models. CIMS is a vintage-based simulation model that determines the market share of a technology by its capital costs, running costs, other intangible costs (transaction costs, co-benefits, etc.), a factor for the heterogeneity in the market and the discount rate. Save production also uses the cost-effectiveness of EEMs as the main criterion and adds factors for the perceived risk, psychological effects of energy price changes and the stringency of energy efficiency policies.

However, in contrast to the variety of barriers observed in empirical studies (see also Chapter 3) even the most sophisticated models only consider a fraction of the barriers and they already face difficulties in calibrating the behavioral input parameters due to the lacking empirical data and the complexity of barriers and related policy instruments. Thus, even current best practice bottom-up models show considerable room for improvement with regard to simulating EEM diffusion (and adoption). This has direct implications for the capabilities of the models to simulate policies.

The review further reveals that the state-of-the-art bottom-up model considers price elasticities and thus is able to simulate price policies such as energy taxes. Some also allow the consideration of quantity based policies by for example setting a cap on the total amount of emissions. However, among the more heterogeneous policies addressing barriers, only a few are considered in the models. Minimum standards for example are easily implemented in bottom-up models, by assuming full compliance and setting the market share to 100% starting with the year the standard enters into force. Simulation in bottom-up models, however, is a lot more difficult for policies such as labeling, audit programs or soft loans that imply assumptions on the adoption behavior of firms due to lacking empirical analyses and representative data. This is particularly the case when it deviates from the economic standard model of rational investment decisions. Thus, extending bottom-up models towards more sophisticated diffusion and adoption modeling would also increase their usefulness as a tool to support policy design. Ways forward comprise the consideration of heterogeneity with regard to the potential adopter (firm size, ownership, energy intensity, etc.) and the integration of models from the fields of agent-based modeling and diffusion modeling, which are already able to consider effects such as uncertainty or expectations that deviate from the rational choice assumption.

7.3 Conclusions

The main conclusion of the thesis is that the design of effective policies to overcome barriers and narrow the energy efficiency gap requires consideration of EEM characteristics and adoption behavior of firms, as well as their interrelationship. The following more specific conclusions are derived across the five chapters of the thesis.

The thesis shows that classical techno-economic analyses, as conducted for the case study of the paper industry in Chapter 2, are not a sufficient basis to design policies. While they provide some necessary information by identifying attractive and cost-effective energy-saving potentials, they do not allow conclusions to be made on the difficulty of exploiting the various potentials that result from different EEMs with different barrier patterns. Thus, such analyses should be extended by an analysis of adoption behavior of firms (see Chapter 3) as well as a more barrier related analysis of technologies. In particular, the integration of methods for EEM classification, as used in Chapter 4, could provide a more suitable basis for policy design. More tacit/soft characteristics such as the distinction between component replacement and system optimization or the transaction costs related to an EEM's implementation need to be taken into account, as they critically affect adoption behavior at which policies aim.

This is also underlined by the results of the bottom-up model review in Chapter 6, which shows that current bottom-up models are not capable of capturing barriers and adoption behavior adequately, resulting in restricted possibilities of simulating policy impacts. Extension of such models towards more realistic technology diffusion algorithms seems a necessary step for policy simulation. For this, however, the technological heterogeneity in the industrial sector is a severe challenge. Including a more generic classification of the various EEMs (as proposed in Chapter 4) could provide a useful basis for model improvement. For instance, different adoption rules could be implemented for different types of EEMs.

To comprehensively address barriers, single policies are often not sufficient. The evaluation of the audit program (Chapter 3 and 5) is an illustrative example, because the program helped to overcome information related barriers, but did not reduce the finance related barriers that persisted despite the program. This provides strong support for a policy mix instead of individual programs. The results of Chapter 4 also underline this need as they identify a huge variety of different EEM characteristics and types with various barriers that cannot be addressed by an individual policy.

This argument is further supported by looking at the types of EEMs addressed by particular policy programs. As the case study of the energy audit program (Chapter 5) has shown, even if policies are not explicitly directed towards particular EEMs, they show a clear focus in the types of EEMs addressed. In the audit program EEMs mainly related to cross-cutting technologies and ancillary processes are recommended and adopted, while process-related EEMs are only rarely recommended or adopted. This focus can mostly be explained by the existence of barriers (e.g. limited knowledge of the consultants of production processes, secrecy policies of the companies, or fear that changes in the production processes may reduce the quality of the products) and the adoption behavior of firms and how it varies across EEMs (see Chapter 4)

Thus, it is the EEM-specific implicit pattern of barriers that shapes the policy impact. Consideration of such patterns of barriers can increase the effectiveness of policies by widening their technology scope. The more comprehensively the barriers should be addressed the more necessary is the use of a policy mix.

7.4 Recommendations for future research

In the following paragraphs, some promising directions for future research are proposed, beginning with improvement of techno-economic analyses and then turning to gaps identified in the empirical analyses of adoption behavior. A particular focus lies on the question of how a consideration of the interaction among EEM characteristics and adoption behavior could be used to progress both fields and improve their usefulness for policy design. Studies so far have either concentrated on technology and energy-saving potential assessments or on barriers and firms' adoption behavior analyses. While this thesis contributes to filling this gap, much remains unexplored. In particular, interdisciplinary empirical research that combines the former engineering-based and the economics based approaches, is still rare. The technological classification developed in Chapter 4 could be used as a starting point. It would, however, also require more empirical validation.

With regard to the use of bottom-up models for techno-economic assessments of energy-saving potentials (see Chapter 2), in a next step, additional more tacit/soft technology characteristics could be integrated, as proposed in Chapter 4. This would allow additional and more comprehensive policy recommendations to be developed beyond the simple assessment of size and cost-effectiveness of saving potentials. It would also allow a preliminary assessment of barriers and suggest directions for subsequent barrier analyses.

In the longer term, extending bottom-up models towards a more explicit modeling of barriers could make them even more useful for policy design. This implies extending the technology diffusion algorithm to include barrier-related parameters. A promising approach with this regard seems to be provided by the field of diffusion modeling (Stoneman 2002). Here, a broad variety of approaches has been developed since the early 1950s and provides some useful ideas that could also benefit bottom-up models. Some modelers particularly focused on the diffusion of EEMs using such models (DeCanio, Laitner 1997; Jaffe, Stavins 1994a; Kemp 1997; Mulder P. 2005; van Soest, Bulte 2001; Verhoef 2003). These explore a variety of approaches that would also be useful to improve bottom-up models. Some, for example, explicitly include the effects from uncertainty (Mulder P. 2005; van Soest, Bulte 2001) or co-benefits (Kemp 1997) into the adoption decision. Others combine epidemic and probit approaches to explain the slow diffusion of EEM and integrate the gradual spread of information into a rational choice model (Jaffe, Stavins 1994a). So far, bottom-up modelers only rarely draw on the extensive experiences made in the field of diffusion modeling. Thus, certainly, integrating these two fields of research seems a very fruitful way towards improving bottom-up models (Barreto, Kemp 2008).

With regard to the empirical research on adoption behavior, it is generally observed that empirical studies in the field of adoption of EEMs in firms are relatively scarce, compared to other sectors such as residential buildings, although the energy and CO_2 saving potentials are of a similar order of magnitude. Further, the theoretical/conceptual studies are still two streams of relatively separated literature. For example, classifications of barriers as proposed in conceptual studies are only rarely validated in empirical research. Conversely, empirical research seems very heterogeneous and not directed towards theory building. Using approaches like the factor analysis in Chapter 3 could help to close this gap by bridging between the often very concrete questions in surveys and the more abstract and broader classes of barriers in the theory-focused literature. Another contribution to this gap is the low comparability of barrier studies combined with the huge degree of heterogeneity among firms and a large number of factors affecting the adoption decision and the pattern of barriers. Factors such as the industrial sector and the size of the firm are relatively well documented in barrier studies. However factors related to the type of EEM are often not discussed, implicitly assuming that they have no effect on the adoption behavior or that all EEM form a homogenous group of technologies. If studies were more explicit with regard to the types of EEMs the comparability of empirical work would significantly increase. Thus, more empirical research is not only needed in this field, but it is also required to be as explicit as possible on these assumptions.

Turning to *ex-post* evaluations of policies that aim to overcome barriers, such as the energy audit program in Chapter 5, a substantial gap of empirical analysis is observed. Furthermore, the few studies conducted often focus on calculating the impact in terms of energy savings and costs, while only rarely assessing the implications of the policies on decision-making in firms. In order to identify gaps in a policy mix of a country, evaluations need to take account of the types of EEMs addressed and the related barriers overcome. This way it can be assessed whether all EEMs that generate a significant and cost-effective energy saving potential, but are hampered by barriers, are addressed by policies.

Thus, if future research is to increase its usefulness for policy design in overcoming barriers, it should have a comprehensive approach by integrating the dimensions of EEM characteristics, adoption behavior and policy design. A link between the fields can be established via the explicit consideration of EEM characteristics that inhibit a particular barrier pattern, as shown in this thesis.

Samenvatting en Conclusie

Introductie en doel van het proefschrift

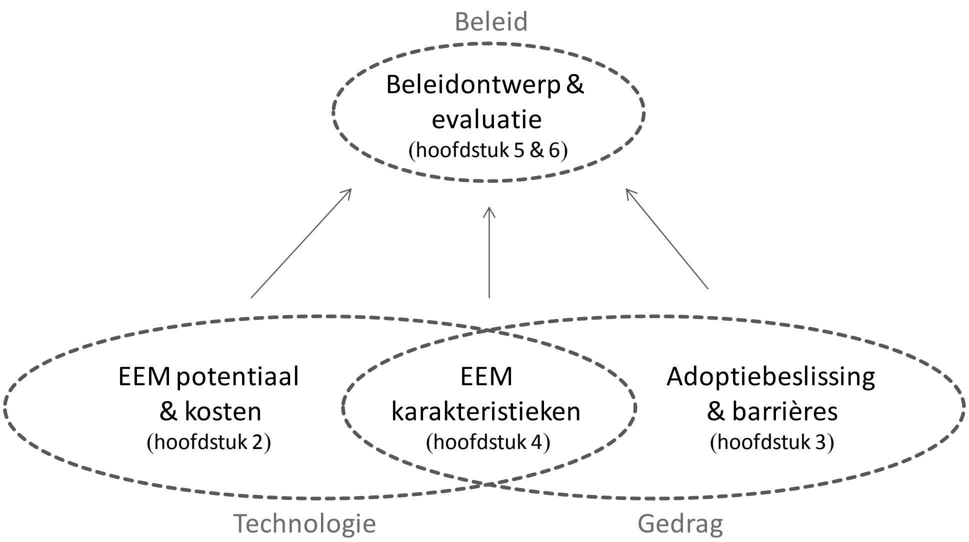
De transformatie naar een "low-carbon" productiesysteem is een voorwaarde om de impact van klimaatverandering te verminderen. Het versnellen van energie-efficiëntie verbetering kan significant bijdragen aan deze transitie. Het Internationaal Energie Agentschap (IEA) schat dat energie-efficiëntie verbetering door de aanwending van hedendaags best beschikbare technologie in de industriële sector, de CO_2 emissies met 1.9 tot 3.2 Gt CO_2 per jaar kan reduceren. Dit is gelijk aan 7 tot 12% van de jaarlijkse energie en proces gerelateerde CO_2 emissies in 2004. Met andere woorden, de diffusie van al beschikbare technologieën omvat nog steeds een groot potentiaal voor energie-efficiëntie verbetering. Dit is de motivatie voor dit proefschrift.

De diffusie van energie-efficiënte maatregelen (EEMs) is een complex proces en wordt beïnvloed door een variëteit van factoren, zoals technologie karakteristieken, karakteristieken van de gebruiker en diens gedrag, informatie verspreiding, regulering en beleid, en verschillende andere contextuele aspecten (Rogers 2003; Stoneman 2002). De meeste innovaties (inclusief EEMs) volgen normaliter een S-curve wanneer deze verspreiden onder gebruikers. Met betrekking tot EEMs, de (verbazingwekkende) langzame diffusie van ogenschijnlijke kosteneffectieve maatregelen heeft de aandacht getrokken van onderzoekers. Verschillende verklaringen zijn voorgesteld omvatten barrières met betrekking tot risico en onzekerheid, verborgen kosten, transactie kosten en imperfecte informatie, gebonden rationaliteit, gespleten motieven en toegang tot kapitaal voor financiering (Sorrell et al. 2004). Empirisch bewijs betreffende het bestaan van barrières voor bedrijven om EEMs toe te passen is toegenomen (Anderson, Newell 2004; DeCanio 1998; Schleich 2009; Sorrell et al. 2011; Velthuijsen 1995) en toenemend meer en verscheidene vormen van beleid zijn gevormd en ontwikkeld om dergelijke barrières te overkomen (Price 2005; Price, Lu 2011). Het begrijpen van het onderliggende patroon van barrières, in combinatie met het beschikbare besparingspotentieel en de kosten, vormen de basis voor het ontwikkelen van effectief en efficiënt beleid. Hoewel deze aspecten al onderzocht zijn in het verleden, is er tot nu toe weinig aandacht besteed aan de interactie van de verschillende dimensies en hoe deze de impact van beleid hebben beïnvloed.

Dit gebrek aan kennis vormt het startpunt van het proefschrift. Het proefschrift tracht de kennis voor de ontwikkeling van beleid voor de versnelling van de diffusie van EEMs in de industrie, uit te breiden. Het proefschrift neemt een geïntegreerde aanpak gericht op zowel het EEM potentiaal, kosten en het adoptiegedrag van bedrijven, met een specifieke focus op de interactie tussen deze velden. De hoofdonderzoeksvraag luidt:

Wat zijn de relaties tussen EEMs en het adoptiegedrag van bedrijven en wat voor betekenis heeft dit voor de ontwikkeling en invloed van beleid in dit veld?

De hoofdstukken van het proefschrift zijn gestructureerd zoals weergegeven in Figuur 1. Het eerste gedeelte richt zich op de dimensies van de technologie, het gedrag van bedrijven en de relatie tussen beiden. Als eerste worden de techno-economische karakteristieken van EEMs in de vorm van energiebesparingpotentiaal en kosten geanalyseerd (hoofdstuk 2), voordat het adoptiegedrag van bedrijven wordt bepaald (hoofdstuk 3). Het daaropvolgende hoofdstuk onderzoekt de verbanden van beiden velden (hoofdstuk 4). Voor het tweede gedeelte van het proefschrift verschuift de aandacht naar de beleidsdimensie. Dit omvat een ex-post evaluatie van beleidinvloed (hoofdstuk 5) en een beoordeling van modellen voor ex-ante beoordeling van beleidsinvloed op de industriële energievraag (hoofdstuk 6). De beleidgerelateerde analyses richten zich voornamelijk op de rol van barrières en EEMs.



Figuur 1: Conceptueel raamwerk van het proefschrift

Het proefschrift is dienovereenkomstig verdeeld in vijf analytische hoofdstukken, waarvan elk een concrete onderzoeksvraag behandeld die weer bijdraagt aan het hierboven genoemde onderzoeksdoel.

1. Wat is het energiebesparing potentiaal en wat zijn de kosten van EEMs, en wat is de potentiële bijdrage aan energie-efficiëntie verbeteringen binnen de industrie? (hoofdstuk 2)
2. Wat zijn de determinanten met betrekking tot de adoptie van EEMs door bedrijven en wat is de specifieke rol van barrières? (hoofdstuk 3)

3. Welke EEM karakteristieken beïnvloeden het adoptiebesluit van bedrijven en hoe kunnen deze karakteristieken gebruikt worden voor een classificatie van EEMs? (hoofdstuk 4)
4. Wat is de invloed van beleid met betrekking to het vergroten van de adoptieratio van EEMs in midden en kleinbedrijf, welke EEMs worden aangewend en welke barrières worden overwonnen? (hoofdstuk 5)
5. Hoe worden barrières, EEM diffusie en beleid overwogen binnen modellen voor ex-ante bepaling van beleidsinvloed? (hoofdstuk 6)

Conclusie

De hoofdconclusie van het proefschrift is dat het ontwerp van effectief beleid, met het oog barrières te slechten en een slag te maken in energie-efficiëntie verbetering, zowel EEM karakteristieken, het adoptiegedrag van bedrijven en de interactie tussen beiden in ogenschouw dient te nemen. Gebaseerd op de verschillende hoofdstukken van het proefschrift zijn de volgende specifieke conclusies getrokken.

Het proefschrift toont aan dat klassieke techno-economische analyses, zoals is uitgevoerd voor de papierindustrie casus in hoofdstuk 2, niet afdoende zijn voor het ontwerpen van beleid. Hoewel deze in staat zijn noodzakelijke informatie te verschaffen door de identificatie van aantrekkelijke and kosteneffectieve energiebesparingmogelijkheden, maken ze het niet mogelijk conclusies te trekken over de moeilijkheid om de verschillende potentiëlen, gerelateerd aan de verschillende EEMs met verschillende diffusiepatronen, te verkennen. Daarom zouden dergelijke analyses moeten worden uitgebreid met zowel de analyse van adoptiegedrag van bedrijven (hoofdstuk 3) als een barrièregerelateerde analyse van technologieën. In het bijzonder zou de integratie van methoden voor EEM classificatie, zoals toegepast in hoofdstuk 4, als een geschiktere basis voor beleidsontwikkeling kunnen dienen. Impliciete en zachtere karakteristieken, zoals het onderscheid tussen componentverwisseling en systeemoptimalisatie of de transactiekosten gerelateerd aan een EEMs implementatie, moeten in ogenschouw worden genomen, omdat deze het adoptiegedrag, waarop beleid zich richt, kunnen beïnvloeden.

Dit wordt ook aangetoond aan de hand van de resultaten van de “bottom-up” model beoordeling in hoofdstuk 6, die aantoont dat huidige “bottom-up” modellen niet in staat zijn de barrières en het adoptiegedrag te modeleren, resulterend in beperkte mogelijkheden om beleidsimpact te simuleren. De uitbreiding van zulke modellen in de richting van meer realistische technologiediffusie algoritmes lijkt een noodzakelijke stap voor beleidsimulatie. Echter, de technologische heterogeniteit binnen de industriële sector is een grote uitdaging. De opname van een meer generieke classificatie van de verschillende EEMs (zoals voorgesteld in hoofdstuk 4) zou een bruikbare basis kunnen vormen voor modeloptimalisatie. Er zouden, bijvoorbeeld, verschillende adoptieregels kunnen worden geïmplementeerd voor de verschillende typen besparingsmaatregelen (EEMs).

Om barrières te kunnen adresseren zijn individuele beleidsmiddelen vaak niet voldoende. De evaluatie van het audit-programma (hoofdstuk 3 en 5) is een illustratief voorbeeld hiervan. Het programma ondersteunde de vermindering van informatiegerelateerde barrières, maar hielp niet financieel-gerelateerde barrières te overbruggen die bleven bestaan. Dit inzicht verschaft een sterke ondersteuning voor een beleidsmix, om tot betere beleidsresultaten te komen. Dit wordt ook onderstreept door de resultaten zoals beschreven in hoofdstuk 4. Hoofdstuk 4 toont dat individuele beleidsvormen niet de grote variëteit van de verschillende EEM karakteristieken en typen kunnen omvatten.

De argumentatie wordt verder ondersteund door te onderzoeken hoe de verschillende EEM typen door beleidprogramma’s worden aangesproken. Zoals de casus met betrekking tot de verschillende audit-programma's al aangaf (hoofdstuk 5) hebben de verschillende beleidsvormen een duidelijke focus op specifieke EEMs, zelfs wanneer het beleid niet direct gericht is op de stimulatie van een EEM in het bijzonder. Deze focus kan voornamelijk worden verklaard door middel van het adoptiegedrag van bedrijven en hoe deze varieert tussen de verschillende EEMs (en daarom een variërende intensiteit van de verschillende barrières). Voornamelijk EEMs die gerelateerd zijn aan “cross-cutting” technologieën en utiliteitsprocessen worden aanbevolen en toegepast. Processpecifieke EEMs worden veel minder geobserveerd. Dit effect kan ten minste voor een deel verklaard worden aan de hand van de karakteristieken van procestechnologie. Zij zijn kritisch voor de productie van een bedrijf en interventies worden door bedrijven waargenomen als operaties met hoge risico’s. Daarom zijn bedrijven terughoudend in te grijpen om energie te besparen. Externe auditeurs kunnen nauwelijks deze barrière overkomen wanneer geen bijzondere drijfveren in het programma worden waargenomen. Aan de ene kant geven bedrijven externe auditeurs geen toegang tot de productielijn, en aan de andere kant kunnen auditeurs alleen die technologieën analyseren waarmee zij bekend zijn, wat vaak de cross-cutting technologieën zijn. Daarom is het een EEM specifiek patroon van barrières die de impact van beleid bepaalt.

Wanneer deze barrières in een omvattende manier overkomen dienen te worden is het gebruik van een beleidsmix noodzakelijk. In het geval van het audit-programma zou dit betekenen dat het toevoegen van een “soft-loan” programma om financiële barrières te slechten de adoptie van investeringintensieve EEMs kan verhogen. Het aanpassen van het programma, door het creëren van drijfveren voor gespecialiseerde auditeurs voor verschillende bedrijfstakken, zou het aantal processpecifieke EEMs vergroten dat door auditeurs wordt aanbevolen. Daarnaast zou de toevoeging van energiemanagementverplichtingen in audit-programma’s – tenminste voor energie-intensieve bedrijven – zowel het aanspreken van processpecifieke technologieën als systeemoptimalisatie kunnen bevorderen.

Vooruitblik

Op basis van het onderzoek kunnen een aantal interessante onderzoeksrichtingen voorgesteld worden, te beginnen met het verbeteren van techno-economische analyses, het vaststellen van de geïdentificeerde tekortkomingen met betrekking tot adoptiegedrag en tot slot met betrekking tot ex-post beleidsevaluatie. Een bijzondere focus ligt op de vraag hoe de interactie tussen EEM karakteristieken en het adoptiegedrag gebruikt kan worden om beide velden verder te ontwikkelen en daarmee het beleidsproces te verbeteren. Tot nu toe hebben studies zich voornamelijk geconcentreerd op technologie- en energiebesparing beoordelingen of op analyses met betrekking tot barrières en adoptiegedrag van bedrijven.

Met betrekking tot het gebruik van “bottom-up” modellen voor techno-economische beoordelingen van het energiebesparingpotentieel (zie hoofdstuk 2), zouden deze in een volgende stap meer impliciete en zachtere technologiekarakteristieken mee kunnen nemen, zoals voorgesteld in hoofdstuk 4. Dit zou het mogelijk maken additionele en meer begrijpelijke beleidaanbevelingen te maken ten opzichte van de simplistische beoordelingen met betrekking tot de grote en kosteneffectiviteit van het energiebesparingpotentieel. Het zou het mogelijk maken een voorlopige beoordeling van barrières te maken en richtingen voor te stellen met betrekking tot additionele analyse.

Op de lange termijn zou het uitbreiden van “bottom-up” modellen, door middel van het expliciet modelleren van barrières, deze bruikbaarder maken voor beleidontwikkeling. Dit betekent het uitbreiden van algoritmes voor technologiediffusie algoritmes door toevoeging van barrièregerelateerde parameters. Een veelbelovende aanpak lijkt het veld van diffusiemodellering te zijn. Sommige modellen richten zich zelf in het bijzonder op de diffusie van EEMs (DeCanio, Laitner 1997; Jaffe, Stavins 1994a; Kemp 1997; Mulder P. 2005; van Soest, Bulte 2001; Verhoef 2003) en nemen bijvoorbeeld expliciet de effecten van onzekerheid (Mulder P. 2005; van Soest, Bulte 2001) of medevoordeel (Kemp 1997) mee in de adoptiebeslissing. Anderen combineren “epidemic” en “probit” benaderingen om de langzame diffusie van EEMs te verklaren en de geleidelijke verspreiding van informatie in een "rational-choice" model te integreren (Jaffe, Stavins 1994a). Tot nu toe maken “bottom-up” modellen weinig gebruik van de uitgebreide ervaringen in het veld van diffusiemodellering.

Gerelateerd aan het empirische onderzoek naar adoptiegedrag is waargenomen dat de theoretische en conceptuele studies aan de ene kant, en de empirische studies aan de andere kant, nog steeds twee gescheiden lijnen van studie zijn. Aan de andere kant lijkt empirisch onderzoek vaak erg heterogeen te zijn en niet georiënteerd op theorievorming. Het toepassen van bepaalde methoden, zoals de factoranalyse in hoofdstuk 3, zou kunnen bijdragen aan dit gebrek door de concrete vragen van veldonderzoek naar barrières in de literatuur te overbruggen. Een andere reden voor dit gebrek is de geringe mogelijkheid om vergelijkingsstudies uit te voeren, vanwege de grote variëteit van bedrijven en grote hoeveelheid van variabelen die adoptiegedrag en barrières kunnen beïnvloeden. Factoren zoals de industriële sector en grootte van het bedrijf zijn redelijk goed gedocumenteerd, terwijl factoren zoals het effect van type EEM op adoptiegedrag niet expliciet wordt meegenomen, impliciet aannemend dat deze een homogeen karakter hebben. Alleen wanneer specifieke barrières expliciet worden geïntegreerd in EEM analyse wordt het mogelijk empirisch vergelijkingstudies uit te voeren.

Kijkend naar de ex-post evaluaties van beleid, zoals het energie audit-programma in hoofdstuk 5, kan een grote lagune in empirische kennis worden vastgesteld. Daarnaast is het beperkte aantal studies dat is uitgevoerd, vaak gericht op het berekenen van de impact met betrekking tot energie- en kostbesparing, en niet of nauwelijks op de implicaties van beleid op het adoptiegedrag van bedrijven. Om deze lagunes met betrekking tot het vormen van een geschikte beleidsmix te kunnen identificeren is het noodzakelijk dat beleidsbeoordelingen het type EEM en de gerelateerde barrières in ogenschouw nemen.

Als toekomstig onderzoek bruikbaarder voor beleidsontwikkeling wil zijn en het slechten van barrières wil vergroten, is het noodzakelijk om alomvattend de verschillende dimensies met betrekking tot EEM karakteristieken, adoptiegedrag en beleidontwikkeling te integreren. Een verbinding tussen deze velden kan worden gevormd door verder te onderzoeken hoe EEM karakteristieken specifieke barrière patronen veroorzaken, zoals beschreven in dit proefschrift.

Zusammenfassung und Schlussfolgerungen

Einleitung und Zielstellung

Um die Wirkungen des anthropogenen Klimawandels zu vermeiden bzw. deutlich abzuschwächen, ist die Transformation des globalen Produktionssystems zu einer CO_2-armen Struktur eine Voraussetzung. Beschleunigter Energieeffizienzfortschritt kann hierzu einen bedeutenden Beitrag leisten. So schätzt zum Beispiel die Internationale Energie Agentur (IEA), dass durch den Einsatz von „bester verfügbarer Technik" (BVT) im Industriesektor die globalen Treibhausgasemissionen um 1,9 bis 3,2 Gt pro Jahr reduziert werden könnten. Dies entspricht ca. 7 bis 12% der energie- und prozessbedingten CO_2 Emissionen im Jahr 2004 bzw. 19 bis 32 % der jährlichen CO_2 Emissionen im Industriesektor. Damit beinhaltet die Diffusion von bereits verfügbaren effizienten Technologien ein großes Einsparpotenzial und stellt das zentrale Thema dieser Arbeit dar.

Die Diffusion von Energieeffizienzmaßnahmen (EEM) ist ein komplexer Prozess, welcher an der Schnittstelle von Gesellschaft, Wirtschaft und Ökonomie liegt. Er ist beeinflusst durch eine große Anzahl von Faktoren, wie die Eigenschaften der EEM, die Eigenschaften der potenziellen Adopter sowie ihr Verhalten, Informationskanäle, der regulatorische Rahmen und weitere kontextuale Aspekte (Rogers 2003; Stoneman 2002). Die meisten Innovationen (inkl. EEM) folgen einem typischen S-förmigen Verlauf, wenn sie unter den potenziellen Nutzern diffundieren (Stoneman 2002). Bezüglich EEM hat die (überraschend) langsame Diffusion von eigentlich wirtschaftlichen Technologien viel Aufmerksamkeit seitens der Forschung erhalten. Für die langsame Diffusion wurden unterschiedliche Erklärungen bzw. Hemmnisse gefunden, wie z.B. Risiko und Unsicherheit, versteckte Kosten, Transaktionskosten, unvollständige Informationen, beschränkte Rationalität, geteilte Anreize („split incentives") oder mangelnder Zugang zu Kapital für die Finanzierung der EEM (Sorrell et al. 2004). Mit einer steigenden Menge an Erkenntnissen über die Wirkung und Struktur dieser Hemmnisse (Anderson, Newell 2004; DeCanio 1998; Schleich 2009; Sorrell et al. 2011; Velthuijsen 1995) stieg auch die Anzahl der politischen Instrumente, welche einzelne oder mehrere Hemmnisse adressieren (Price 2005; Price, Lu 2011). Bei der Ausgestaltung dieser Instrumente steht die Frage nach einer effektiven und effizienten Wirkung im Mittelpunkt. Kenntnisse um die Wirkung und Struktur der Hemmnisse sowie die Kosten und Höhe der vorhandenen Energieeinsparpotenziale stellen somit eine Voraussetzung für die Ausgestaltung von Instrumenten dar. Während diese Aspekte bisher separat relativ intensiv erforscht wurden, so gibt es kaum integrierte Betrachtungen beider Aspekte.

Diese Forschungslücke stellt die Ausgangslage der vorliegenden Arbeit dar. Die Arbeit hat zum Ziel, die Grundlage für die Ausgestaltung von politischen Maßnahmen zur Beschleunigung der Diffusion von Effizienzmaßnahmen zu verbessern. Hierzu wird ein integrierter Ansatz verfolgt, welcher die Einsparpotenziale und Kosten der EEM als auch das Adoptionsverhalten der Unternehmen berücksichtigt. Ein Schwerpunkt dieser Arbeit liegt auf der Interaktion dieser beiden Felder, da die Struktur und die Intensität der Hemmnisse von den betroffenen EEM abhängen. Die zentrale Forschungsfrage dieser Arbeit kann somit wie folgt formuliert werden.

Welchen Einfluss haben EEM-Eigenschaften auf das Adoptionsverhalten von Unternehmen und welche Auswirkungen hat dieser Zusammenhang auf die Wirkung und Ausgestaltung von Politikmaßnahmen?

Die Forschungsfrage enthält somit die Aspekte Technologie, Adoptionsverhalten und Politikmaßnahmen, wie in Abbildung 1 dargestellt. Im ersten Teil der Arbeit liegt der Schwerpunkt auf einer integrierten Betrachtung von EEM-Potenzialen und -Kosten (Kapitel 2) auf der einen sowie der Adoptionsentscheidung und damit verbundenen Hemmnissen (Kapitel 3) auf der anderen Seite. Ein Bindeglied zwischen beiden Bereiche stellen die Eigenschaften der EEM dar, die über Kosten und Potenziale hinaus gehen (Kapitel 4). Im zweiten Teil der Arbeit wird die Verbindung zu den Politikmaßnahmen hergestellt. Hierzu wird zunächst eine ex-post Evaluation, in der besonders auf das Adoptionsverhalten der Unternehmen eingegangen wird (Kapitel 5), und abschließend ein Rückblick von ex-ante Modellen zur Wirkung von Politikmaßnahmen auf den industriellen Energieverbrauch (Kapitel 6), durchgeführt.

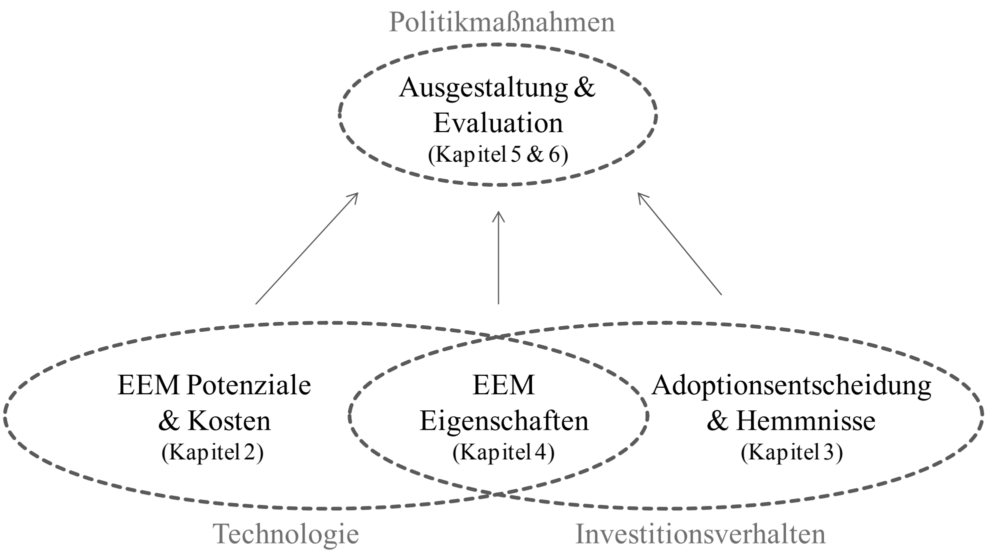


Abbildung 1: Konzeptioneller Rahmen der vorliegenden Arbeit

Entsprechend ist die Arbeit in fünf Hauptkapitel gegliedert, welche den folgenden Forschungsfragen nachgehen.

6. Wie hoch sind die Energieeinsparpotenziale und Kosten von EEM und welchen Beitrag können sie zur Verbesserung der Energieeffizienz und zur Reduktion der THG-Emissionen im Industriesektor leisten? (Kapitel 2)
7. Was sind die Einflussfaktoren der Adoption von EEM durch Unternehmen und welche Rolle spielen Hemmnisse? (Kapitel 3)
8. Welche EEM-Eigenschaften beeinflussen die Adoptionsentscheidung durch Unternehmen und wie können EEM anhand ihrer Eigenschaften klassifiziert werden? (Kapitel 4)
9. Wie ist die Wirkung von Politikmaßnahmen hinsichtlich einer Erhöhung der Adoptionsrate von EEM in kleinen und mittleren Unternehmen (KMU)? Welche EEM werden adressiert und welche Hemmnisse überwunden? (Kapitel 5)
10. Wie werden Hemmnisse, EEM-Diffusion und Politikmaßnahmen in Modellen, die für die ex-ante-Wirkungsschätzung von Politikmaßnahmen eingesetzt werden, berücksichtigt? (Kapitel 6)

Zusammenfassung der Ergebnisse

Als zentrale Schlussfolgerung der Arbeit lässt sich festhalten, dass die Ausgestaltung von Politikmaßnahmen zur effizienten Überwindung von Hemmnissen eine integrierte Betrachtung von EEM-Eigenschaften und Adoptionsverhalten von Unternehmen voraussetzt.

Die Arbeit zeigt, dass die klassischen techno-ökonomischen Analysen von Kosten und Höhe der Energieeinsparpotenziale von EEM, wie in Kapitel 2 durchgeführt, für eine Ausgestaltung von effizienten Politikmaßnahmen nicht genügen. Während diese Analysen wichtige Erkenntnisse für die Identifikation attraktiver Einsparpotenziale liefern, so erlauben sie keine Rückschlüsse über die Schwierigkeiten bei der Ausschöpfung der Potenziale. Folglich sollten entsprechende Analysen um das Adoptionsverhalten von Unternehmen erweitert werden, analog zur Analyse in Kapitel 3. Hier scheinen Ansätze vielversprechend, die EEM anhand ihrer Eigenschaften klassifizieren. Wie in Kapitel 4 gezeigt, können so eher „weiche" EEM-Eigenschaften wie die Unterscheidung in Komponentenwechsel und Systemoptimierung oder Transaktionskosten, die mit der Implementierung von EEM verbunden sind, berücksichtigt werden.

Diese Notwendigkeit wird auch durch die Ergebnisse des Modellvergleichs in Kapitel 6 bestätigt. Die betrachteten ex-ante Modelle sind nicht in der Lage, Adoptionsverhalten und Hemmnisstrukturen realistisch abzubilden und können somit die Wirkung von Politikmaßnahmen nur sehr eingeschränkt simulieren. Auch hier scheint eine Erweiterung der bestehenden Modelle um realitätsnähere Diffusionsalgorithmen ein notwendiger Schritt, wenngleich die technologische Vielfalt im Industriesektor hier eine große Herausforderung darstellt. Eine eher generische Klassifizierung von EEM, wie in Kapitel 4 hergeleitet, könnte dabei eine gute Grundlage sein um die technologische Vielfalt für die Modellierung beherrschbar zu halten. So können z.B. unterschiedliche Adoptionsregeln für unterschiedliche Klassen von EEM definiert werden.

Für eine umfassende Überwindung von Hemmnissen sind einzelne Politikmaßnahmen häufig nicht ausreichend. So zeigt z.B. die Evaluation des deutschen Energieaudit-Programms (Kapitel 3 und 5), dass das Programm dazu beigetragen hat einzelne Hemmnisse zu überwinden (vorwiegend solche, die mit Informationsdefiziten verbunden sind), während andere trotz des Programms weiter bestehen (vorwiegend bezogen auf die Finanzierung und den Zugang zu Kapital). Auch die EEM-Klassifizierung in Kapitel 4 unterstützt diese Schlussfolgerung, indem sie eine große Anzahl unterschiedlicher EEM-Eigenschaften identifiziert, die wiederum unterschiedliche Hemmnis-Strukturen aufweisen. Somit ist nur eine Kombination aus verschiedenen Politikmaßnahmen in der Lage die Hemmnisse umfassend zu adressieren.

Diese Argumentation wird weiter unterstützt, wenn Wirkungen einzelner Politikmaßnahmen in Bezug auf die adressierten EEM betrachtet werden. So hat die Fallstudie des Energieaudit-Programms (Kapitel 5) ebenfalls gezeigt, dass selbst wenn solche Programme keine technologiebezogene Förderung vorsehen, sich doch klare Schwerpunkte bei den adressierten EEM zeigen. Diese Schwerpunkte können über das Adoptionsverhalten der Unternehmen und wie es mit den EEM-Eigenschaften zusammenhängt, erklärt werden. Im Rahmen des Programms wurden viele EEM aus den Bereichen der Querschnittstechnologien und der Hilfsprozesse umgesetzt. EEM, die ein Eingreifen in Produktionsprozesse erfordern wurden kaum umgesetzt. Eine mögliche Erklärung hierfür liegt in den Eigenschaften von so genannten prozessbezogenen EEM: Die adressierten Prozesse sind häufig kritisch für die Produktion und Eingriffe werden von den Unternehmen mit einem hohen Risiko wahrgenommen. Folglich sind Unternehmen eher zurückhaltend hier Änderungen vorzunehmen, „nur" um Energie einzusparen. Auch externe Auditoren können diese Zweifel kaum überwinden, solange keine besonderen Anreize vorgesehen sind. Dies hat vorwiegend zwei Gründe. Zum einen sind Unternehmen eher zurückhaltend, wenn es darum geht, ihren Produktionsprozess von Externen untersuchen zu lassen und zum anderen konzentrieren sich die externen Auditoren auf Bereiche, die sie kennen, wie Querschnittstechnologien. Folglich hat die von den EEM abhängige Hemmnisstruktur großen Einfluss auf die Wirkung von Politikmaßnahmen.

Je umfangreicher solche Hemmnisse adressiert werden sollen, desto notwendiger wird der Einsatz einer Kombination an Politikmaßnahmen. So könnte das Energieaudit-Programm um ein Kreditvergabeprogramm für die Finanzierung von Investitionen in EEM erweitert werden, welches besonders bei EEM mit hohem Investitionsbedarf die Hemmnisse weiter überwinden könnte. Ein anderer Ansatz könnte sein, Auditoren zu fördern, die auf eine ausgewählte Branche spezialisiert sind, um so die Anzahl der prozessbezogenen EEM zu erhöhen. Auch die Verknüpfung des Energieaudit-Programmsmit Verpflichtungen zum Energiemanagement könnte die

Umsetzung von prozessbezogenen EEM und EEM, die auf eine Systemoptimierung abzielen, besser fördern als das separate Beratungsprogramm.

Ausblick

Basierend auf den Erkenntnissen der vorliegenden Arbeit werden im Folgenden einige vielversprechende nächste Schritte und zukünftige Forschungsfragen abgeleitet. Hierzu werden zunächst mögliche Ansätze zur Verbesserung der techno-ökonomische Analyse von EEM diskutiert, bevor auf mögliche Lücken und Verbesserungsmöglichkeiten bei der empirischen Analyse des Adoptionsverhaltens von Unternehmen sowie der Hemmnisse eingegangen wird. Dabei liegt ein besonderer Schwerpunkt auf der Frage, wie eine integrierte Berücksichtigung der beiden Felder Technologieeigenschaften und Adoptionsverhalten von Unternehmen die verwendeten Methoden verbessern kann und deren Nützlichkeit für die Ausgestaltung von Politikmaßnahmen erhöhen kann.

Anwendungen von bottom-up Modellen zur techno-ökonomischen Bewertung von EEM, wie in Kapitel 2 durchgeführt, können in einem nächsten Schritt um eher „weiche" EEM-Eigenschaften erweitert werden, wie z.B. mit der in Kapitel 4 vorgeschlagen Klassifizierung von EEM. Dieser Ansatz würde somit zusätzliche Politikempfehlungen bezüglich der Überwindung von Hemmnissen erlauben, die mit den klassischen, auf Kosten und Höhe der Einsparpotenziale beschränkten, techno-ökonomischen bottom-up Modellen bisher nicht getroffen werden können.

Langfristig könnte die Nützlichkeit solcher bottom-up Modelle weiter erhöht werden, indem sie auch für die Simulation von Hemmnissen erweitert werden. Hierzu müssten die EEM-Diffusionsalgorithmen um hemmnisbezogene Parameter erweitert werden. Das Feld der Diffusionsmodellierung (Stoneman 2002) scheint hierfür bereits eine gute methodische Grundlage zu bieten und hat bereits einige Arbeiten im Bereich der Diffusion von EEM aufzuweisen. So haben einige Autoren explizit die Rolle von Unsicherheit (Mulder P. 2005; van Soest, Bulte 2001) oder „Co-Benefits" (Kemp 1997) berücksichtigt. Andere kombinieren probit und epidemic Elemente um die langsame Diffusion von EEM zu erklären (Jaffe, Stavins 1994a). Vor diesem Hintergrund scheint es erstaunlich, dass bottom-up Modelle bisher so wenig auf diese Arbeiten zurück gegriffen haben.

Bezüglich der empirischen Erforschung des Adoptionsverhaltens von Unternehmen lässt sich zunächst feststellen, dass die empirischen und die konzeptionellen/theoretischen Arbeiten bisher zwei relativ getrennte Literaturstränge darstellen. Empirische Arbeiten scheinen sehr heterogen, schwer vergleichbar und nicht unbedingt hilfreich für das Ableiten von theoretischen Zusammenhängen. Ansätze wie die Faktoranalyse in Kapitel 3 könnten dazu beitragen, diese Lücke zu schließen, indem sie es ermöglichen, die relativ konkreten Fragen aus Umfragen auf die eher abstrakten und breiteren Klassen von Hemmnissen, wie sie in der konzeptionellen Literatur diskutiert werden, zu übertragen. Ein weiterer Aspekt, der zu der oben beschriebenen Lücke beiträgt, ist die relativ schlechte Vergleichbarkeit empirischer Studien, kombiniert mit einer hohen Heterogenität zwischen Unternehmen sowie einer hohen Anzahl an Faktoren, welche die Adoptionsentscheidung sowie die Hemmnisstruktur beeinflussen. Während einzelne Faktoren wie die Unternehmensgröße oder die Zugehörigkeit zu einem Wirtschaftszweig in empirischen Studien relativ gut dokumentiert sind, so werden Faktoren bezüglich der EEM und ihrer Eigenschaften meistens vernachlässigt oder gar nicht berücksichtigt. Eine explizitere Berücksichtigung von EEM-Eigenschaften würde somit die Vergleichbarkeit unter empirischen Arbeiten sowie ihre Nützlichkeit für aufbauende konzeptionelle Arbeiten deutlich erhöhen.

Bezüglich der ex-post Evaluation von Politikmaßnahmen, wie das in Kapitel 5 untersuchte Energieaudit-Programm, kann festgestellt werden, dass sich viele der durchgeführten Studien auf die Maßnahmenwirkung bezüglich Energieeinsparung und Kosten konzentrieren und nur selten auf die Wirkung bezüglich der Adoptionsentscheidung von Unternehmen eingehen. Um Lücken im Politikmix eines Landes zu identifizieren, müssten ex-post Evaluationen auch untersuchen, welche Typen von EEM die einzelnen Politikmaßnahmen adressiert haben und welche Hemmnisse damit überwunden wurden.

Abschließend lässt sich somit sagen, dass zukünftige Forschung die Felder EEM, Adoptionsverhalten von Unternehmen und die Evaluation/Ausgestaltung von Politikmaßnahmen integriert betrachten sollte, um nützlichere Politikempfehlungen abzuleiten. Für eine Verbindung der einzelnen Bereiche ist es notwendig, die EEM-Eigenschaften zu berücksichtigen, wie in der vorliegenden Arbeit gezeigt wurde.

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Curriculum Vitae

Tobias Fleiter studied "Energy and Environmental Management" at the University of Flensburg which included study semesters abroad in Umeå and Halmstad (Sweden), as well as a six month internship at the regional utility MVV Energie AG in Mannheim. His diploma thesis was completed at the Fraunhofer Institute for Systems and Innovation Research (Fraunhofer ISI) on the topic of "Electricity saving potentials in industry". He successfully obtained his university degree in March 2007 with the title "Dipl.-Wirt.-Ing. Energy and Environmental Management".

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The deployment of energy-efficient technologies is a key strategy to reduce greenhouse gas emissions. This thesis analyzes the adoption and diffusion of energy-efficient technologies by firms and derives recommendations for policy makers. It provides new insights by taking a broad perspective that considers technologies and their characteristics as well as firm behavior in an integrated approach.

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