Barriers to, drivers for and non-energy benefits for industrial energy efficiency improvement measures in compressed air systems

Ricardo Parra
Consultora Crowsnest Chile
ricardoph@gmail.com

Therese Nehler
Department of Management and Engineering (IEI),
Division of Energy Systems
Linköping University
SE-581 83 Linköping
Sweden
therese.nehler@liu.se

Patrik Thollander
Department of Management and Engineering (IEI),
Division of Energy Systems
Linköping University
SE-581 83 Linköping
Sweden
patrik.thollander@liu.se

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Abstract

Increased global competition and scarcity of resources drives industrial companies to cut costs where energy can be a significant part, not the least for energy-intensive companies. Improved energy efficiency in industry is complex as is regards numerous various energy using processes which are heavily intertwined. One such energy using process is compressed air systems (CAS) which is used in most industrial companies worldwide. With a few exceptions, previous research on barriers to and drivers for energy efficiency has treated energy efficiency improvement measures as one entity. However, since the characteristics of energy efficiency improvement measures differs, technology-specific measures will face different barriers to and drivers for energy efficiency which will affect the investment decision accordingly. The same applies for the non-energy benefits (NEBs) related to energy efficiency improvement measures. The aim of this paper is to study barriers to, drivers for and NEBs for energy efficiency improvement measures in CASs. Carried out as an interview study combined with a questionnaire, the paper results show that the major barriers are related to the investment, e.g. other priorities for capital investments and access to capital. Major drivers are related to in-house energy management practices, and major benefits include productivity gains and avoidance of capital expenditure. Further research is emphasized in the CAS field.

Introduction

Industrial energy efficiency is viewed as a vast resource in the ambitions for sustainability due to the growing concern about the environment and scarcity of resources (IPCC, 2014). Increased global competition also drives industrial companies to strive for efficiency and since most of the processes in an industrial company, more or less are related to energy, continuous energy efficiency improvements will thus contribute to the overall efficiency in a company (Johansson et al., 2011). However, the link between energy and the processes in a company and the fact that these processes are intertwined also brings complexity into a company's energy efficiency efforts. One such complex energy using process is a compressed air system (CAS) which is used for various applications in most of the industrial companies worldwide. A CAS is supporting the various types of production processes (e.g. assembling, clamping, cushioning, processing, cleaning and drying) in a company (e.g. Björk et al., 2003). Hence, most CASs are designed to fit the individual company and their related production, which brings not only complexity into the system but also uniqueness. However, energy efficiency improvement measures in CASs applies to most systems and companies.

In their review on compressed air energy use, Saidur et al. (2010) conclude that there is a considerable potential for existing energy efficiency improvement measures in CASs and the largest potential relates to sealing of leakages within the CAS. Despite an existing energy efficiency potential (EC, 2011), energy efficiency improvement measures are not always implemented, even if cost-effective, which is explained by the existence of certain barriers (e.g. Sorrell et al. 2004; Schleich and Gruber (2008); Trianni et al., 2012). Hence, there seems to exist a gap between an optimal level of energy efficiency and what actually is realised. Studies of barriers to energy efficiency have shown differences in type of barriers between regions and sectors (e.g. Sorrell et al., 2004; Schleich and Gruber, 2008; Trianni et al., 2012; Rohdin and Thollander, 2006; Rohdin et al., 2007; Thollander and Ottosson, 2008), however, with a few exceptions, previous research on barriers to and drivers for energy efficiency has treated energy efficiency improvement measures as one entity studied at company level. Scientific studies on barriers for specific or technology-specific energy efficiency improvement measures and in particular barriers to energy efficiency improvement measures in CASs are thus scarce. Cagno and Trianni (2014) represents one of few studies that have investigating barriers to specific industrial energy efficiency measures and the authors conclude that there are large differences in barriers between different types of energy efficiency measures. Hence, this stresses the importance to further study barriers to specific energy efficiency measures, which for instance might contribute in decisions regarding energy efficiency investments as well as in the design of energy efficiency policies.

In relation to barriers for energy efficiency, studies on driving forces for energy efficiency are of interest since these might be a means to overcome barriers. Empirical studies on drivers for energy efficiency show that important drivers are; people with real ambition, long-term energy strategy and threat of rising energy prices (e.g. Apeaning and Thollander, 2013; Hasanbeigi et al., 2010; Cagno and Trianni, 2013; Thollander and Ottosson, 2008; Rohdin et al., 2007) but studies on drivers for specific energy efficiency measures are to the authors knowledge scarce. Thus, to investigate the main drivers for specific energy efficiency improvement measures, and in particular for CASs, would be of great importance.

The concept of non-energy benefits (NEBs) and their magnitude is argued to be one of the characteristics that affect the adoption rate of energy efficiency measures positively (Fleiter et al., 2012). NEBs refer to the side-effects of energy efficiency improvement measures that goes beyond the actual energy savings related to the measure. Studies have shown that there are benefits of investing in energy efficiency and that the magnitude of them is vast, in particular if the NEBs are quantified and monetized (e.g. Worrell et al., 2003; Pye and McKane, 2000). In addition to that, NEBs might be a means to overcome barriers to energy efficiency or be viewed as drivers to energy efficiency and thereby decreasing or closing the energy efficiency gap. Hence, this calls for a need to also investigate the NEBs for specific energy efficiency improvement measures, and in particular, NEBs for energy efficiency improvement measures for CASs.

As previous research on barriers and drivers has treated energy efficiency measures as one entity with a few exceptions, we believe that it is indeed important to study technology-specific barriers and drivers as well as NEBs for specific energy efficiency improvement measures. Previous research on the characteristics of energy efficiency measures strongly underline this need as well (Fleiter et al., 2012, Trianni et al., 2014). Since the characteristics of energy efficiency improvement measures differs, technology-specific measures will face different barriers to and drivers for energy efficiency which will affect the investment decision accordingly. The same applies for the non-energy benefits (NEBs) related to energy efficiency improvement measures. Thus, to focus on one specific energy efficiency improvement measure is indeed important also from a theoretical perspective because the theoretical implications for this are to deepen knowledge of which theoretical barriers and which other factors (drivers and NEBs) that explain the non-adoption or the adoption of specific energy efficiency improvement measures including CAS measures. Studying barriers, drivers and NEBs in relation to energy efficiency improvement measures for specific industrial processes like CASs should thus be of interest for academia as well as for practitioners and policy makers.

The aim of this paper is to study barriers to, drivers for and NEBs in CAS energy efficiency improvement measures which is addressed in three research questions:

- What are the main barriers to improved energy efficiency in CAS?
- What are the main drivers for improved energy efficiency in CAS?
- What are the major NEBs for energy efficiency improvements measures in CAS?

This paper starts with an overview of industrial CAS and continues with a brief presentation of the barriers to and drivers for energy efficiency followed by the role of non-energy benefits as linked to energy efficiency, barriers and drivers. Next, the applied method of this paper is described, followed by the presentation and discussion of the findings. In the last section concluding remarks is given.

Compressed air systems – a brief overview

Compressed air is a widely used application that supports many industrial processes depending on the specific needs within an individual company and type of production. The compressed air equipment is viewed as practical as well as simple to use and further, the equipment is often not very costly for industrial companies to invest in. However, the efficiency of a CAS is often very low due to for instance heat losses during the compression stage and due to leakages in the system. Björk et al. (2003) states that the efficiency of compressed air is often lower than 10 %. This was acknowledged by Saidur et al. (2010). Findings from their literature review showed that only 10–20 % of the energy utilised is actually related to useful work within a CAS. Yet, a CAS is often a complex system heavily intertwined with other industrial processes in the company, which challenges energy efficiency opportunities in various ways. Compressed air applications often involve different kinds of movements, linear movement, transport and positioning as well as assembling, cushioning, processing, cleaning, drying, dosage and in operation of valves (Björk et al., 2003).

The process in a CAS starts with the generation of compressed air (supply) which thereafter is transported (transmission) to the end use location (demand). CASs consist of various sub-systems and related components and the system can be divided into the supply-side and the demand-side (CEATI, 2007). The supply-side is further divided into air inlet, motor, compressor, after cooler, treatment, controls and storage (primary), while the demand-side includes distribution, storage (secondary) and end use equipment (CEATI, 2007). Sometimes

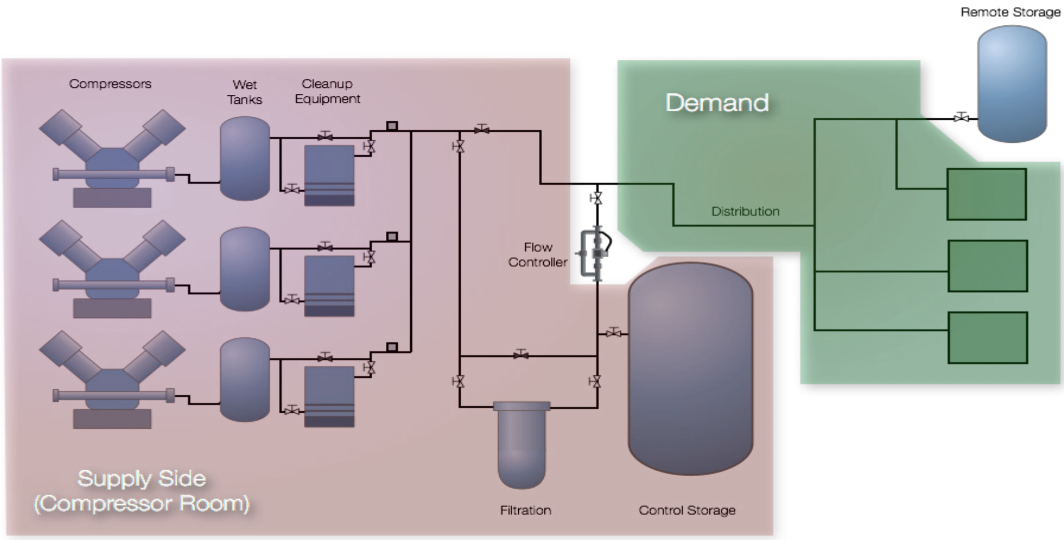

Figure 1. A CAS divided into supply- and demand-side.

the distribution of compressed air is viewed as an own subsystem (e.g. ASME, 2009). In Figure 1 the main features of a CAS is visualised.

The compressor is most often driven by an electric motor which can be integrated into the compressor unit or separately installed to the compressor. Either way, the motor is part of the compressed air system. There are two main principles for compression of air used in compressed air systems: displacement compressors and dynamic compressors. Atmospheric air contains water vapour and as the concentration of water in air increases with higher temperatures and higher pressures, the amount of water vapour is a parameter that must be considered in all CASs because moisture can cause problems in the compressed air equipment, for instance if water precipitates in the piping. Hence, the air has to be dried and that is facilitated by using an after-cooler and drying equipment. The compression of air also generates heat which requires cooling of the air after the compression stage, and often an inter-cooling system can help in the overall efficiency, but this is not always feasible, being a function of the discharge pressure and the technology being used. The compressed air produced should be of the right quality, which is the air quality specified by the application and this in turn depends on which type of role the air has within companies' processes. As described above, the compressed air can contain water (drop or vapour), but also oil (drop or aerosols) and particles (e.g. dust and micro-organisms). As regards the content of oil in the compressed air it depends on the type of compressor; if it is oil-lubricated or not, and the filtration used downstream. For oil-lubricated compressors, the compressed air will contain oil and the quantity depends on the type of compressor, on its design, age and condition. The various types of particles that exist in the air stream of a CAS may differ in size and that will govern which type of filter required to separate particles; this factor also affects the efficiency, redundant filtration results in elevated pressure drops, which in exchange require a higher pressure on the point of production. Further, the cost of compressed air also increases with the quality requirements, therefore understanding actual requirements is also a part of operating an efficient system. To move the produced compressed air to the place for use, a distribution system is required and the design of the distribution system should consider low pressure drops between the compressor and the place for use, minimisation of leakages from the piping and an optimal condensation if an air dryer is lacking, because these factors affect efficiency, reliability and cost of the compressed air system. One or more extra air receivers can be installed in the system as buffers of compressed air (Atlas Copco, 2015).

ENERGY EFFICIENCY IMPROVEMENT MEASURES FOR CASS

Typically, a CAS offers several energy-efficient opportunities. Neale and Kamp (2009) divide energy efficiency improvement measures for CASs into demand-side measures (sealing leaks, decrease artificial demand/inappropriate use, peak demand management, pressure minimisation inefficiencies in distribution) and supply-side measures (compressor operation, environmental control (intake and operational conditions), system ancillary equipment (driers, filters, drains etc.), installation of new equipment). In their study of industrial energy efficiency opportunities for CASs in New Zealand, Neale and Kamp (2009) found that 50–70 % of the CAS energy efficiency potential was related to the demand-side. In addition, the authors found that investment costs and payback periods for the demand-side measures were lower than for the supply-side measures. Typically, estimated payback periods for demand-side efforts were less than 6 months (which is similar to the results of Saidur et al. (2010)) and the typical capital investment cost were often less than $10,000, while the corresponding figures for the supply-side measures were significantly higher; payback periods of 3–5 years and capital investment costs in the range of $50,000–200,000. The authors point out that risk might contribute to the figures regarding the supply-side; in general process and manufacturing industries often install oversized CASs. Neale and Kamp (2009) further stress the importance of independent auditing to be able to identify opportunities on the demand side of a system.

As regards the order in which energy efficiency measures should be considered, Björk et al. (2003) argues that the first step to improve energy efficiency for a CAS in industrial companies should involve a change from compressed air driven equipment to electric driven equipment. The authors also stress that a change to electric-driven equipment should involve both technical and economic assessments, both on short-term and long-term since all compressed air equipment cannot be changed immediately due to technical or economic issues. Next step for improved energy efficiency in CASs involves seeking and sealing leakages of compressed air. Information about the work load of the compressors can contribute with valuable knowledge on the levels of leakages within the system. This should also be complemented with walk-throughs within the facilities, listening for leakages, and this is best done in the nights or in the weekends during non-production hours (Björk et al., 2003). After that equipment possible to convert, has been changed to electric-driven tools and leakages have been sealed, the remaining improvement need for CAS should be analysed and hence, compressors and sub-systems should be adjusted to that new need. For instance, the remaining need might be met by smaller compressors or some sections of the system could be turned off during specific production hours. A step further would be to continuously optimise the work load on the compressors according to the actual compressed air demand. This is facilitated by using the right combination of compressors as well as minimising unload hours. The last measure to consider according to Björk et al. (2003), when all other measures have been addressed, is opportunities for energy recovery, i.e. heat recovery. However, the authors state that this would be a quite expensive "boiler", if operation, maintenance and investment costs are accounted for. Moreover, this also assumes that there is a need for the recovered heat.

Barriers to and drivers for industrial energy efficiency

Energy efficiency can be defined as using less energy for the same level of services, or to use the same amount of energy for a higher level of services (IEA, 2012). An important part of an industrial company's initial energy efficiency work is to conduct an energy audit which starts with an analysis of the energy use within the company (Rosenqvist et al, 2012). The energy use is then allocated into smaller parts and these parts are referred to as unit processes and could either belong to processes in the production or to processes that support the production, e.g. lighting, compressed air and ventilation (Söderström, 1996). The major outcome of an energy audit consists of proposed energy efficiency improvement measures and the allocation of energy use into unit processes enables the description of in which process (production process or support process) energy efficiency improvement measures, i.e. specific energy efficiency improvement measures could be undertaken (Rosenqvist et al, 2012).

Despite the existence of cost-effective industrial energy efficiency improvement measures, far from all are implemented. The question concerning why measures fail to be implemented stresses the importance of studying barriers and drivers to industrial energy efficiency. In this section some previous studies on barriers and drivers are presented together with existing research on barriers to and drivers for specific energy efficient improvement measures, which is the main concern in this study.

BARRIERS

Barrier theory is commonly applied to explain the gap between an optimum level of energy efficiency and the realised level. Barrier theory applies a comprehensive perspective in explaining the gap by combining economic, behavioural and organisational parameters (Sorrell et al., 2004) and the barriers can be categorised accordingly (SPRU (2000)). The categorisation of barriers is presented in Table 1.

Empirical studies of barriers to industrial energy efficiency has been extensively conducted in various contexts and from different perspectives, which have shown that barriers vary between different region and sectors (e.g. De Groot (2001), Sorrell et al. (2004), Schleich and Gruber (2008), Trianni and Cagno (2012), Rohdin and Thollander (2006), Rohdin et al., (2007), Sardianou (2008), and Thollander and Ottosson (2008)).

In a study based on manufacturing SMEs in Italy, Cagno and Trianni (2014) investigated barriers to specific energy efficiency improvement measures for lighting, compressed air, motors and HVAC, and concluded that different barriers were perceived for specific energy efficiency measures and that these barriers also varied depending on the characteristics of the measures. As regards energy efficiency improvement measures

Table 1. Classification of barriers to energy efficiency (based on SPRU (2000)).

Theoretical perspective	Theoretical barrier
Economic non-market failure	Heterogeneity
	Hidden costs
	Access to capital
	Risk
Economic market failure	Imperfect information
	Split incentives
	Adverse selection
	Principal-agent relationships
Behavioural	Bounded rationality
	Form of information
	Credibility and trust
	Inertia
	Values
Organisational	Power
	Culture

for CASs, Cagno and Trianni (2014) found that the following barriers were highly ranked by the Italian SMEs studied; lack of information on costs and benefits, information not clear by technology providers, and trustworthiness of the information source.

DRIVERS

Drivers for industrial energy efficiency have not been subject to that intense study as the barriers, anyhow, the knowledge on drivers play an important role in the adoption of energy efficiency measures. In most of the empirical studies on drivers for industrial energy efficiency, people with real ambition, long-term energy strategy and threat of rising energy prices, have been shown to be important drivers (e.g. Apeaning and Thollander (2013), Hasanbeigi et al. (2010), Cagno and Trianni (2013), Thollander and Ottosson (2008) and Rohdin et al. (2007)).

In applying their classification scheme for energy efficiency measures, Fleiter et al. (2012) found that it is not the energy efficiency measure itself that hinders the adoption of it, it is rather the characteristics of the measure that hinder the implementation of it. Hence, the adoption of energy efficiency measures faces different obstacles depending on the characteristics of the specific measure. The same applies for possible drivers for energy efficiency; measures associated with higher adoption rates probably have characteristics that act as sufficiently good drivers which drive the adoption and implementation of them (Fleiter et al., 2012).

The importance of the characteristics of energy efficiency measures in relation to the adoption of them has also been stressed by Trianni et al. (2014) in developing a framework for characterization of energy efficiency measures. The authors conclude that characteristic attributes of energy efficiency measures with higher adoption rates may act as drivers for energy efficiency. Hence, to study the drivers for energy efficiency from different perspectives and on different levels, will deepen the understanding and as stated by Fleiter et al. (2012) and Trianni et al. (2014), it will guide decision-makers as well as policy-makers in implementing and promoting energy efficiency measures.

Non-energy benefits

Industrial energy efficiency is often stressed as an important means to reach climate and energy targets, but in addition to that, energy efficiency might bring other positive side-effects as well, so-called non-energy benefits. Energy efficiency improvements measures in industry may yield a number of potential outcomes beyond energy savings and energy cost savings, for instance increased productivity, improved product quality, reduced waste and reduced maintenance (Lilly and Pearson, 1999, Pye and McKane, 2000, Finman and Laitner, 2001, Laitner et al., 2001, Hall and Roth, 2003, Worrell et al., 2003, Lung et al., 2005). Most industrial non-energy benefits may be classified into following categories; production, operation and maintenance, working environment, waste, and emissions and there is also a category consisting of other benefits not fitting the categories mentioned above (Lilly and Pearson, 1999, Pye and McKane, 2000, Finman and Laitner, 2001, Laitner et al., 2001, Hall and Roth, 2003, Worrell et al., 2003, Lung et al., 2005).

Pye and McKane (2000) stated that if non-energy benefits are monetized and included in the investment calculation regarding industrial energy efficiency projects, the financial aspect of investments in energy efficiency improvements will be enhanced. This was later acknowledged by Finman and Laitner (2001) addressing that non-energy benefits have to be considered and assigned monetary values (if possible) in order to increase the potential for energy efficiency investments. Finman and Laitner (2001) studied non-energy benefits within 77 case studies and in 52 of the cases the benefits could be quantified and monetized resulting in halving the payback time for the projects. The energy savings in the 52 cases were also compared to the monetized value of the non-energy benefits and according to the authors, for more than half of the 52 cases the value of the non-energy benefits were equal to or greater than the energy savings. Businesses studied by Hall and Roth (2003) estimated that 3.27 non-energy benefits (of ten given) could on average be quantified and monetized for every energy-efficient technology measure installed and in particular benefits within the maintenance and waste category were quantified. Laitner et al. (2001) present several examples of non-energy benefits together with comments about the opportunity to quantify the benefits. Non-energy benefits related to production, operating and maintenance, waste and emissions could be quantified according to the authors. On the other hand, non-energy benefits improving the working environment may be more difficult to quantify and monetise.

Given the findings above, it seems clear that omitting non-energy benefits from evaluations regarding investments or measures in energy-efficient improvements measures may result in an underestimation of the financial potential for an energy efficiency investment or measure. Moreover, these findings also stress the importance of monetising the non-energy benefits in order to incorporate the benefits into the investment calculation. However, as concluded by Nehler and Rasmussen (2016), non-energy benefits are not commonly included in investment calculations, but to communicate the benefits as costs and revenues might be a way to ease the incorporation of the benefits into the calculation. Of course, in order to make energy efficiency investment evaluations and calculations as correct as possible, negative impacts should be to be considered as well. Even benefits that cannot be monetised might play an important role in investment decisions qualitatively depending on the role and magnitude of the benefits (Nehler and Rasmussen, 2016).

Method

This study is based on a combined approach using both interviews and a questionnaire. Interviews with industrial energy managers as well as independent energy audit experts for CASs were carried out to gain understanding of the barriers to and drivers for energy efficiency measures for CASs. The research design hence includes not only the energy managers as respondents to information on CAS, it also covers the auditors' or the field experts' perspective in their role as information providers. Viewing the problem from more than one perspective enables a deeper understanding, but it also contributes to data triangulation in combining two data sets. As regards the NEBs part, a questionnaire was sent out to the energy audit experts

Table 2. Background information including description of the interviewees' position in the company.

	Position	Type of business	Number of employees
Interviewee 1	Global energy manager	Meat casing	>5,000
Interviewee 2	Region project manager, Bellevue OH, US (former energy manager)	PET beverage containers	>37,800
Interviewee 3	Region engineering director, US (former energy manager)	Paints and coatings	>28,000
Interviewee 4	Global energy manager, Europe	Chemical company	>40,000
Interviewee 5	Region energy and sustainability manager, US	Food packaging	>11,000

Table 3. Background information of the CAS energy auditor experts.

	Position	Company	Affiliated to equipment suppliers	Records of audits
Interviewee 1	System auditor/owner	Crowsnest Ltda.	No	<50
Interviewee 2	System auditor	IZ Systems LLC	No	<100
Interviewee 3	System auditor/ general manager	IZ Systems LLC	No	>300
Interviewee 4	System auditor	Southern Corporation of SC	No	>300
Interviewee 5	System auditor/owner	Compressed Air Consultants	No	>200

in order to capture their view on perceived NEBs in relation to energy efficiency improvement measures for CASs. In previous studies of barriers, drivers and NEBs, the unit of analysis has been the decision of cost-effective energy efficiency measures. Accordingly, in this study the unit of analysis is the decision of cost-effective energy efficiency CAS measures.

In total ten interviews were carried through and half of them were conducted with representatives on corporate level from global companies. The chosen companies were industrial manufacturing companies whose energy costs for CASs represented a significant share of the total conversion costs for the production of products or services. All of the interviewees had, or have had positions as energy managers, which in this case is considered to be a suitable choice of respondents due to their experiences in energy efficiency improvement measures. Moreover, the role of energy managers as such includes having a comprehensive perspective on energy-related issues within the company combined with more specific knowledge on the energy using processes within the company's production, which also make these respondents suitable in studies regarding specific energy using processes like CAS. The name of the interviewees and the companies have all been anonymised. In Table 2 the position of the interviewees, the type of business of the companies and the number of employees are displayed.

The other five interviews were conducted with independent energy audit experts for CASs from different consultancy firms in the US. The choice of interviewing energy audit expert for CASs, and not energy audit experts in general, was due to their focus on both the supply-side and the demand-side. Energy audit experts in general or auditors not specialised in CASs would probably focus too much on the supply-side. Table 3[1] shows position of the audit interviewees, the companies and the number of undertaken energy audits.

The data collection for the interviews were based on an interview guide including open questions and ended with a more structured part. Hence, in the first part the respondents could speak freely about aspects of energy efficiency related to CASs across the corporation and how information on energy efficiency improvement measures for CASs was retrieved. In the structured part of the guide the respondents were asked to rank the drivers' and barriers' impact on the implementation of cost-effective energy efficiency improvement measures for CASs. The choice of barriers and drivers included in the structured part were influenced by previous research by Rohdin and Thollander (2006) and Brunke et al. (2014). Furthermore, the respondents were also asked to rank the usefulness of information sources regarding energy efficiency improvement measures for CASs. This was followed by the respondents' valuation of an existing potential for profitable (according to the companies' investment criteria) cost-effective energy efficiency improvement measures for demand-side CASs. This part ended with general background information of the company and which financial capital budgeting tools the companies generally applied in investment decisions. As suggested by Yin (2009), the interviewed guide was reviewed by senior staff.

The data collection regarding the NEBs part of this study were conducted via a questionnaire that was distributed to independent energy audit experts (see Table 3). The rationale of choosing the respondents among these was due to their aggregated experience of auditing and implementing energy efficiency projects in CASs of all sizes and characteristics as well as experience of evaluations of energy efficiency CASs projects. The respondents were first asked to rank possible NEBs perceived after implementation of energy efficiency projects. The NEBs considered in the questionnaire were common industrial NEBs stated in literature (e.g. Lilly and Pearson, 1999, Pye and

1. For the NEBs questionnaire, one auditor was replaced for another with a similar profile, and from the same firm, due to availability issues.

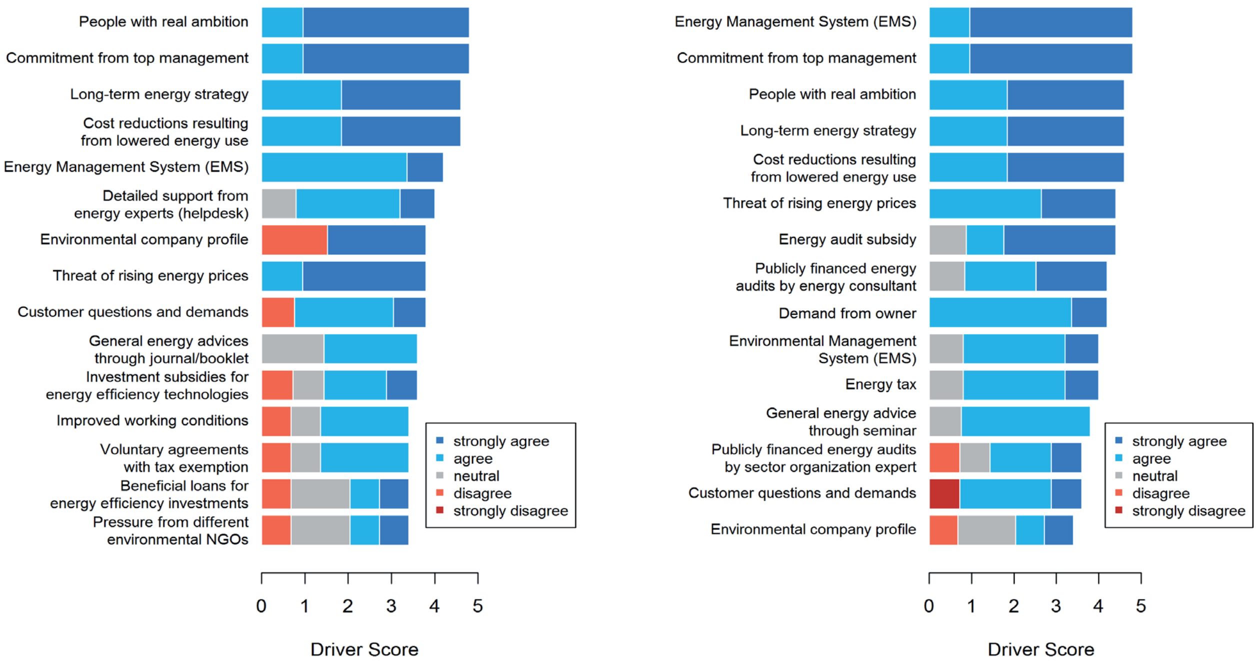

Figure 2. Top 15 drivers for the implementation of cost effective energy efficiency measures in CAS from users (left) and experts (right).

McKane, 2000, Finman and Laitner, 2001, Laitner et al., 2001, Hall and Roth, 2003, Worrell et al., 2003, Lung et al., 2005). Capital avoidance (if a company cancels its plans to acquire new equipment after implementing an energy savings project that resulted in turning off air compressors) was also included as a NEB in the questionnaire. The decision to include this benefit is based on experiences from several CAS energy audits conducted by independent auditors. In addition to that there was an opportunity to mention other benefits not included in the questionnaire. In order to address the role of NEBs as drivers, a question was asked on NEBs possible contribution in the decision making process for energy efficiency projects. Before sent out to the respondents, the questionnaire was reviewed by senior staff.

Results and discussion

DRIVERS

Results show a high importance on organizational aspects as drivers to energy efficiency and economic incentives to energy-efficient technology. Figure 2[2] shows the top 15 (out of 43) drivers to energy efficiency in CASs as per users (energy managers), and experts (CAS auditors). We see that the level of agreement on what are the main drivers is high, this can be explained by the fact that often the interlocutor for auditors at large corporations are energy managers. Energy managers are measured against, among many other factors, achieved energy efficiency; opposed to a maintenance manager in charge of energy efficiency, the latest will always be driven by reliability, uptime, among other factors.

2. Score is calculated from the grade given to each statement (1 Strongly Disagree; 2 Disagree; 3 Neutral; 4 Agree; 5 Strongly Agree).

The majority of the respondents agreed that compressed air makes an excellent target for energy efficiency because it is easy to identify savings and paybacks are often attractive. Commitment from top management is also ranked high, corroborated by experts. Often energy managers need to fight against the perception that compressed air is cost free when there is a lack of sub-metering. Only one contestant, from an energy intensive company, stated that CAS was not a strategic objective for energy savings nor they had a commitment from management towards savings in this area.

Cost reduction is ranked second; three out of five contestants stated receiving a lot of pressure from top management to reduce costs and energy management systems also play an important role. Having any sort of sub-metering helping energy managers accurately show the level of costs involved in CASs, is advantageous to raise capital for energy efficiency projects. Incentives, while relevant, scored low. This can be explained by the hurdles that need to be overcome to materialize those incentives. One contestant, from a global paint company, said that often those incentives were promised by the local authorities, and at the end they didn't get the funds, which might be a reason why the corporation decided, at a global level, not to take advantage of these incentives.

As can be seen in Figure 2, main drivers (people with real ambition, long-term energy strategy and threat of rising energy prices) for energy efficiency stated in previous literature (e.g. Apeaning and Thollander (2013), Thollander et al. (2013), Hasanbeigi et al. (2010), Cagno and Trianni (2013), Thollander and Ottosson (2008) and Rohdin et al. (2007) are highly ranked for CAS energy efficiency by the users as well as by the audit experts. Moreover, many highly ranked drivers in this study seem to be related to organisational aspects in the company.

In summary, energy managers need to operate in a nourishing environment, where they not only count with the capital to fund retrofitting projects, but also to obtain complete informa-

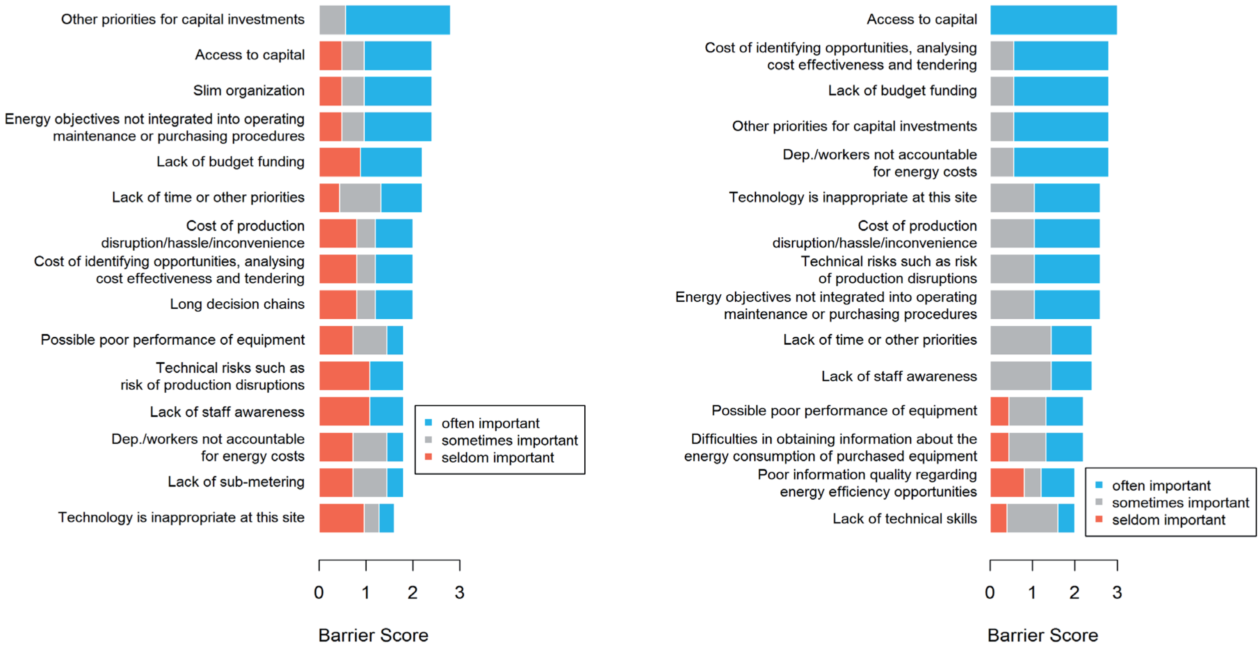

Figure 3. Top 15 Barriers to the implementation of cost effective energy efficiency measures in CAS from users (left) and experts (right).

tion, which often does not guarantee that opportunities exist, but at least offer an impartial analysis. Hence, to address the importance of organisational aspects such as well-functioning in-house energy management practices might be one way create the basis and further build-up of a company's energy efficiency routines within CASs.

BARRIERS

Figure 3[3] shows the key barriers to energy efficiency in CASs. Main barriers are related to investment; the main one for users is other priorities for capital investments and the second access to capital. Experts agree with this notion to a certain extent. In the interviews one of the respondents mentioned that projects of this nature go to a pool, and only those with a better payback get selected, not considering any other benefit or externality. Another respondent said that even using independent auditors, saving figures were difficult to realise by the controlling department in the company. From the top 15 barriers, five are related to capital or the cost associated to risks involved in new technology. On the expert side, a tool developed to overcome this barrier is to offer performance guarantees covering the cost of auditing against identification of savings, and the cost of the implementation against savings realised.

The main barriers for energy efficiency improvement measures in CASs ranked by the respondents (both users and audit experts) are thus related to economic non-market failures, for instance access to capital. These results differ from findings from Cagno and Trianni (2014), who found that main barriers in CASs were related to information (e.g. lack of information, information not clear). However, it should be pointed out that this study is limited.

Barriers inside the organization are often significant; often the improvement of the supply side translates in changes in the delivery of compressed air (e.g. lowered pressure, eliminate unnecessary lower pressure dew points), this likely creates resistance from production.

INFORMATION

As part of the study, different sources of information concerning opportunities for energy savings in CASs were evaluated by interviewees. All respondents agreed on that information coming from independent sources is better than the one coming from manufacturers. Four out of five respondents stated in the interviews that manufacturers (of air compressors) limit their analysis to the compressor room as it often provides enough savings to justify the purchase of new equipment, and that most of the time the solutions are a new compressor, and not necessarily optimization of the demand. On the other hand, by optimizing the supply side of a CAS, users agree that often the result is turning off compressors, creating backup, and avoiding the purchase of new equipment. Figure 4[4] shows how users and experts rate the different sources of information for energy savings in compressed air systems.

NEBS

NEBs after implementation

As can be seen from Figure 5 which presents the results from the questionnaire. More reliable production, was the highest ranked benefit as perceived by the respondents.

Sealing of leakages is an energy-efficient improvement measure that apart from the energy saved also lead to the avoidance of operating losses; e.g. lower system pressure, air tools

3. Score is calculated from the grade given to each statement (1 Seldom Important; 2 Sometimes Important; 3 Often Important).

4. Score is calculated from the grade given to the quality of each source (1 Poor; 2 Average; 3 Good; 4 Excellent).

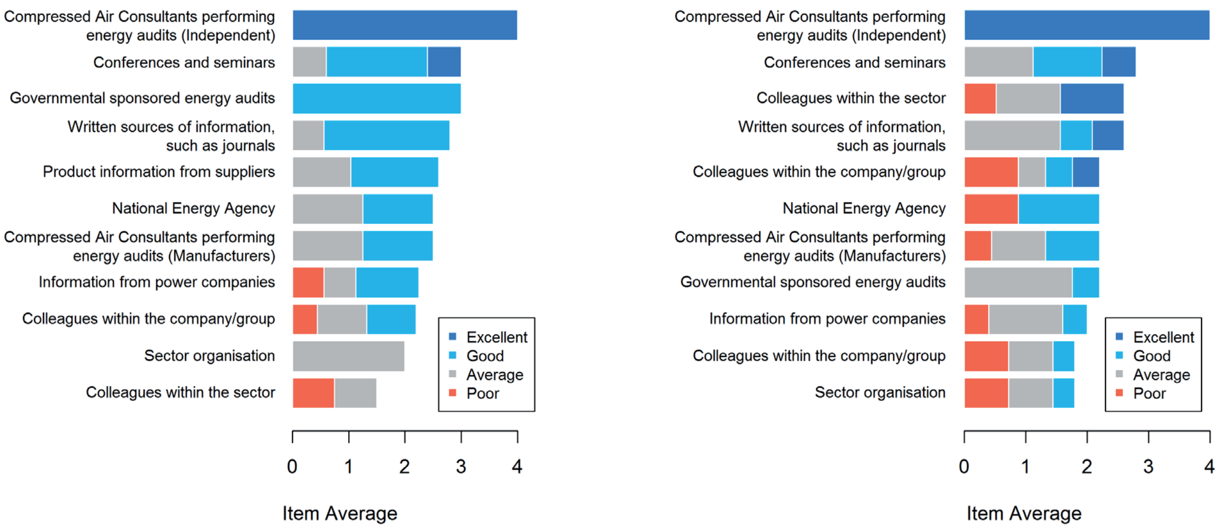

Figure 4. Quality of information sources on energy efficiency in CAS according to users (left) and experts (right).

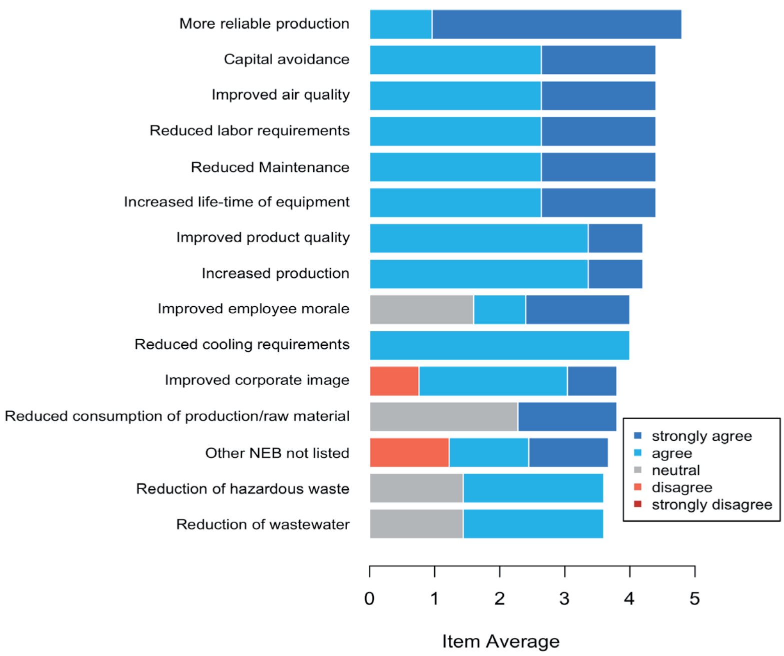

Figure 5. Ranked NEBs after implementation as perceived by the respondents.

function less efficiently, production is affected, shorter life time for equipment, and increase of maintenance. These operating losses might direct or indirect affect the compressed air-related production within a company. So, by avoiding these losses, a company might experience effects that positively affects the production where a *More reliable production* might be one of them. This might also explain why *Improved product quality* and *Increased production* are high-ranked by the respondents.

Capital avoidance was ranked as the second highest NEB by the respondents. The use of compressed air in companies' production can be analysed by documenting the production routines and processes in order to match the use to the load on the compressor(s). Use of air that is not related to a company's production should be avoided or minimised, e.g. leakages and incorrect use. As these factors relate to the working pressure of the CAS; sealing of leaks and avoidance of incorrect use will lead to lower working pressures and thereby a decreased energy use. Hence, optimisation of the CAS combined with energy efficiency improvement measures can thus be a way to handle the work load on the compressors, instead of investing in new compressors. This might have contributed to why *Capital avoidance* was ranked as a very high NEB. In addition, interviewees agreed that in many cases rental costs are also part of NEB after implementing a retrofit project. Often companies get rentals to support the production during a machine breakdown, and due to concerns from production, they remain running.

Except from *Improved air quality*, the benefits *Reduced labour requirements, Reduced maintenance, and Increased life time of equipment* are in one way or another related to the operation and maintenance of the equipment. Compressed air can contain water, oil and different type of particles and to achieve required air quality, the air passes through various types of filters and dryers. To a more or less extent, all filters give rise to pressure drop in CAS which often causes a higher energy use. Hence, energy efficiency improvement measures related to different air treatments will thus not only lead to improved energy efficiency, it will also give a well-functioning CAS. This might have contributed to the high rankings for *Reduced labour requirements, Reduced maintenance, and Increased life time of equipment*. Indirectly, this might also have impact on the production; a well-functioning CAS supports a stable production, which might be a contributory factor to that *More reliable production* was the highest ranked barrier. And clearly, energy efficiency improvement subject to air treatments in various ways, will not only affect energy use, but also the air quality as such, which might have impacted on *Improved air quality* as the third highest ranked NEB.

CASs are complex systems consisting of sub-systems and related parts that are interdependent and linked to one another. Energy efficiency improvements will thus have impacts on more than one part of a CAS and NEBs as outcomes of energy efficiency improvements in CASs will thus be interrelated and affect one another.

Among the highest ranked barriers for energy efficiency measures for CASs found in this study, several are related to economic non-market failures. Hence, acknowledging benefits such as Capital avoidance and production-related NEBs might be one step up in climbing over the barriers.

NEBs as drivers to implementation

The respondents were also asked about their view on NEBs' in decisions of implementing energy efficiency projects; in what degree do NEBs complement energy savings in the decisions making process. In Figure 6, the 15 highest ranked NEBs as drivers for energy savings projects are displayed.

All respondents agreed on that the five highest ranked NEBs; *More reliable production, Capital avoidance, Improved product quality, Increased production* and *Reduced maintenance*, could complement in the decision making process for energy savings projects, i.e. the stated NEBs could act as drivers for energy efficiency improvement projects. At the same time, these five NEBs have also been ranked as major NEBs perceived after implementation of energy efficiency CAS project. Three of highest ranked NEBs; *More reliable production, Improved product quality,* and *Increased production* are directly related the company's production, i.e. the core business. The absence of linkage between energy efficiency and core business has been stresses as a reason for the non-implementation of energy efficiency improvement investments (Cooremans, 2012). Hence, to stress that energy efficiency improvement measures not only lowers energy use, but also positively affects a company's production, might ease the implementation of energy efficiency measures for CASs.

The respondents further agreed on that *Capital avoidance* and *Reduced maintenance*, ranked as number two and number five, as major drivers for energy efficiency improvement measures for CASs. Both of these benefits relate to financial aspects, i.e. reduced costs or reduced expenditures, which is of great importance for companies in their persistent strivings to be competitive. This connects to what previous has been addressed (e.g. Pye and McKane (2000); Finman and Laitner (2001)); the inclusion of quantified and monetised non-energy benefits will contribute enhanced investment proposals for energy efficiency investments. Thus, avoided or delayed expenditures and reduced cost are impelling to the managerial board, which might aid in positive decisions regarding implementation of energy efficiency measures for CASs. However, both *Capital avoidance* and *Reduced maintenance* are effects that might become apparent in a longer time-frame, compared to the production-related NEBs discussed above. This probably applies for some of the

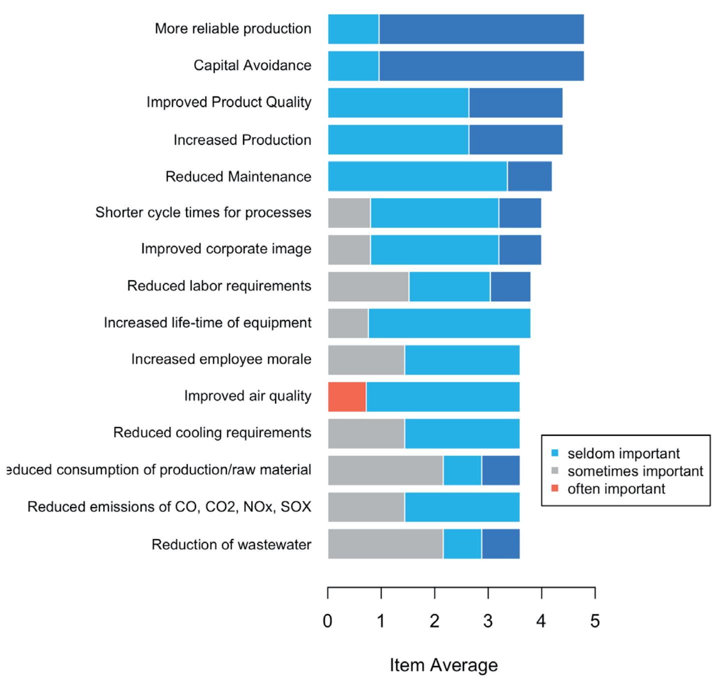

Figure 6. Ranked NEBs as drivers to implement energy efficiency CAS projects.

benefits which were lower ranked, for instance, *Improved corporate image* and *Increased employee morale*.

Anyhow, the benefits in the role as drivers might be a means to overcome the barriers to energy efficiency improvement measures in CASs. As presented and discussed above in the section which concerns perceived barriers for energy efficiency improvement measures for CASs, most of the main barriers (both for users and auditing experts) were related to the investment, for instance *Other priorities for capital investments* and *Access to capital*. To stress and acknowledge NEBs like *Capital avoidance* and *Reduced maintenance* might help to overcome investment-related barriers such as *Other priorities for capital investments* and *Access to capital* and thereby increase the adoption and implementation of energy efficiency improvement measures for CASs. The same applies for the barriers found that were related to the production and equipment, for instance *Cost of production disruption/hassle/inconvenience, Possible poor performance of equipment* and *Technical risks such as risk of production disruptions*. If information on production-related benefits, e.g. *More reliable production* and *Improved product quality,* as possible outcomes of energy efficiency improvement measures for CASs, is presented to concerned departments that are in charge of production and related investments and measures, might aid in overcoming these obstacles.

Concluding remarks

There seems to be a hidden potential for energy savings in industrial CASs and the understanding of existing barriers to and drivers for energy efficiency improvement measures for CASs as well as related NEBs might ease in unlocking the potential. This paper contributes with the view of users of CASs in large global companies as well as the view of auditing experts on CASs in large global companies in order understand what drives and what hinders the implementation of energy efficiency improvement measures for CASs.

Despite that projects in energy efficiency applied to CASs easily can pass the cost-benefit test due to large opportunities on the supply side, efforts should address the demand side too. Vested interests is a justification that is by itself significant to revise the alliances between authorities and agencies and the private sector. Savings in both supply- and demand-side represent a big opportunity for companies to achieve energy savings at attractive conditions. Since the major barriers found in this study were related to the investments of energy efficiency measures for CASs, an increased focus on behavioural and operational measures on the demand-side might be a way to tackle and go around the barriers because these measures tend to have lower investment costs as well as lower payback periods. This further relates to organisational aspects and setting up routines for energy efficiency in industrial equipment, for instance CASs, which was stated to be a major driver for energy efficiency improvement measures in CASs.

Overcoming barriers is a combination of empowering energy managers, allocate funding to implement, but also to obtain valuable information. The market of compressed air is dominated mostly by manufacturers of air compressors, these are few and barriers of entry are high. Some auditors claim that it is sometimes difficult for energy managers to get the funds to conduct an audit when a manufacturer would do it for free. Previous research has focused on market failures of information nature (imperfect information and asymmetric information), however, imperfect competition, if proven, could trigger changes in how the private sector gets involved in energy efficiency matters. Research in this area will require an understanding of how market is shared in different regions, how do manufacturers weigh sustainability goals connected to energy efficiency at the different sites they have contracts and their own performance. An oligopolistic market structure, combined with vested interests, could eventually prove to be against the goals in energy efficiency set globally. Despite possible differences in how users approach energy efficiency in CASs, and how authorities and agencies aid in the efforts of energy efficiency, the problem related to vested interests, and the incomplete information coming from auditors from the manufacturer of equipment side, seems to be common across all countries. Awareness of CAS-related NEBs and their role as drivers would aid in overcoming the barriers to energy efficiency improvement measures for CASs and thereby positively impact the adoption rate of the measures.

It is important to mention that these conclusions are based on a limited sample which limits generalisations. Still, answers from the energy audit experts are based on knowledge retrieved by conducting several energy audits for CASs in large global companies and answers from energy managers are based on experiences in handling energy issues in large global companies in which CASs are an important support process for industrial applications. Conclusions can indeed be seen as indications of explorative nature in a field where further research in needed. The resources of the present research were limited, but the results presented could guide in which direction further research should be conducted, e.g. studies on the effect of vested interests in the effectiveness of energy efficiency initiatives that address technology rather than optimization of use and the implementation of good practices.

This paper has investigated the barriers to, drivers for and related NEBs for energy efficiency improvement measures for CAS in general. Further research should also emphasize these aspects for other support processes, such as ventilation and lighting, as well as for the related specific energy efficiency improvement measures.

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