Linking energy efficiency and innovation practices: Empirical evidence from the foundry sector

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1. Introduction

According to the European Council for an Energy Efficient Economy, since the 1970s, energy efficiency has contributed more to European economic prosperity than any other single source of energy supply (ECEEE, 2014). This fact indicates that proper policies focusing on energy sustainability and energy efficiency targets are of vital importance for society, governments, and industry. Conversely, industry involvement is a keystone to achieving these targets because it is responsible for a considerable share of the final energy consumption in society. For instance, in the EU alone, industry accounts for 26% of the final energy consumption (European Commission, 2013a). Nevertheless, industry involvement is often inhibited by the existence of market failures and barriers

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Abbreviations: AE, association expert; BEE, barrier to energy efficiency; BEE-H, high level of barriers to energy efficiency; BEE-L, low level of barriers to energy efficiency; BAT, best available technology; BAT-H, high level of adoption of best available technologies; BAT-L, low level of adoption of best available technologies; EEI, energy efficiency indicator; EM, energy manager; INB, inbound Open Innovation; IP, intellectual property; IRD, internal R&D; OI, Open Innovation; OUT, outbound Open Innovation; SEC, specific energy consumption; SEC-H, high level of performance in specific energy consumption i.e. more energy efficient; SEC-L, low level of performance in specific energy consumption i.e. less energy efficient; SME, small- and medium-sized enterprise

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that drive the intervention of public policies and initiatives (Brown, 2001). Therefore, it seems that to encourage better en-gagement of the industrial sector towards achieving higher energy efficiency, it is necessary to promote additional initiatives that help decrease these barriers but, at the same time, drive compe-titiveness and growth in firms. One possible option could be fo-cusing on innovation, first, because promoting innovation and R&D rather than energy efficiency *per se* is likely to be an especially effective way of improving efficiency (Reddy, 1991), and second, because innovation is an initiative that, together with energy-re-lated efforts, has been notably included in the agendas of firms and governments in the last decade.

A clear example is the Europe 2020 strategy (European Commission, 2010), a central guideline for European Union growth in which two of the key targets translate into flagship initiatives such as promoting R&D and energy efficiency (European Commission, 2013b). Despite this type of policy helping firms to realise the need for both, driving profitable growth through innovation and being environmentally sustainable (Smith et al., 2010), there has been little discussion about understanding the impact of innovation practices on energy efficiency. Addressing this gap is of paramount importance because traditional literature has overlooked the opportunity to use interdisciplinary approaches to propose how to foster more innovative and energy-efficient firms. Even more, this is particularly relevant for firms operating in energy-intensive sectors with moderate level of innovation, such as foundries, where energy efficiency is strictly related to industrial and com-pany performance.

Thus, to empirically explore the link between innovation practices and energy efficiency, we borrow the idea of Open Innovation (Chesbrough, 2003) to measure the innovativeness of a firm in terms of its innovation practices, rather than focusing on product, process, or service innovation. Open Innovation (OI) is a model for managing innovation based on leveraging the firm's R&D through the purposive inflows and outflows of knowledge to accelerate internal innovation (the inbound process) and to expand the markets for external use of innovation (the outbound process) (Chesbrough et al., 2006). One advantage of this model is encompassing, connecting and integrating of internal R&D with other existing innovation activities and previous innovation theories (Huizingh, 2011). In addition, evidence shows that OI can help organisations, including small- and medium-sized en-terprises (SMEs), innovate, even with limited resources and mar-ket reach (Brunswicker and Ehrenmann, 2013; Van de Vrande et al., 2009; Xiaobao et al., 2013). We then explore a possible link between innovation practices and energy efficiency under the premise that because OI can support the introduction of new technologies to a firm (West and Bogers, 2013), it could also support the addition of the best energy-efficient technologies. Consequently, this paper explores whether the combination of internal R&D with Open Innovation practices is beneficial to firms in terms of energy efficiency, measured by three different indicators.

To accomplish this task, being this a first and exploratory attempt, a multiple case study was conducted with 30 foundries located in Northern Italy producing four different types of alloys: aluminium, steel, grey cast iron and ductile cast iron. Through a self-reported questionnaire, we estimated six main indicators. On one side, we evaluated the firms' innovation level through the adoption of practices related to internal R&D (IRD), inbound Open Innovation (INB), and outbound Open Innovation (OUT). On the other side, we measured three different but related energy efficiency indicators (EEIs), namely the firms' specific energy consumption (SEC), the adoption of energy-efficient best available technologies (BATs), and the perception of barriers to energy efficiency (BEEs). Based on these variables, we analysed the impact of combining different innovation practices on foundries' efficiency levels as measured by the three EEIs. In particular, each indicator allowed us to examine the effect between different levels of adoption of innovation activities and (i) a common and objective measure of energy efficiency, i.e., SEC; (ii) the viewpoint of technology adoption as a direct enabler of energy efficiency, i.e., BATs; and (iii) considering perceived obstacles on the decision-making process acting on energy efficiency, i.e., BEEs. Moreover, we examined the relationship between the three EEIs to provide further evidence of innovation practices as an enabler of energy efficiency.

The rest of the paper is organised as follows. Section 2 reviews major literature on the concepts and measurement of Open Innovation and industrial energy efficiency, together with a suggestion of their link and the study framework. Section 3 explains the research method. Section 4 shows and discusses the main results of our analysis. Section 5 provides conclusions of this study with potential policy implications, limitations, and opportunities for future research.

2. Combining innovation and energy efficiency

Historically, people have used innovation as a way to increase efficiency in energy-related applications, with several well-known examples in the industrial sector (see, e.g., Geels, 2002). These events indicate that continuous innovation, R&D, the development of new technologies, and other types of innovation practices could have a direct effect on energy efficiency and industrial performance. Although literature combining innovation practices and energy efficiency is scarce, a few previous studies have provided some initial indications for understanding the relationship between these two concepts.

One of these first studies was from Lutzenhiser (1994), who investigated industrial energy efficiency with a model derived from social sciences literature on technology and organisational change. This model proposed the role of organisational networks in shaping and constraining innovation, and the topic was studied using data on barriers to energy efficiency in the US industry. Another interesting study revealing energy efficiency as an out-come of using a different innovation perspective was conducted by Christensen et al. (2005). Although the main purpose of their study was investigating the industrial dynamics of OI, their ana-lysis provided some hints about the connection between industrial innovation and energy efficiency. More specifically, his in-depth case study revealed that in the consumer electronics innovation system, open and collaborative innovation was needed to achieve better energy efficiency performance in audio amplifiers, which later created a new technological regime.

Following the Open Innovation research trend observed in the last decade, Hakkim and Heidrick (2008) used the OI model to explore the energy sector in Canada. Although this study was useful for advancing the role of OI in the energy sector, it did not provide insights about the relationship between innovation practices and energy efficiency performance. To the best of our knowledge, the only recent study that has proposed to understand the role of innovation in energy efficiency was done by Trianni et al. (2013b). This study examined how some innovation factors may affect the adoption of energy-efficient technologies in energy-intensive industries based on the barriers affecting the adoption of such technologies. This study provided valuable evidence on the role of market, product, and process innovativeness in the adoption of energy-efficient technologies; however, the study did not focus on the different types of collaborative innovation practices used currently by many firms. Thus, a different perspective for evaluating the role of present innovation practices and processes within firms could provide complementary results.

Indeed, there is a vast range of perspectives and models that have been proposed to describe the way in which firms innovate. However, choosing one of these models does not necessarily mean that it is better than the others, only that it could be more convenient for firms' current practices. Seeing that current stronger global competition has created greater knowledge sharing and collaboration in the innovation processes in firms (Gassmann, 2006), using the OI model could be an appropriate option to manage innovation. The main idea of the OI model (Chesbrough, 2003) is that the innovation processes of a firm need to be opened outside its boundaries to enable innovation to move more easily between the external environment and the internal R&D processes. Likewise, the model assumes that not all knowledge and ideas will come from inside the firm and not all ideas will be successfully marketed internally (Chesbrough and Crowther, 2006).

Although previous innovation models have proposed similar ideas on the use of external knowledge by firms, the OI model has some notable differences. An interesting example is Kline and Rosenberg's (1986) 'chain-linked model', which depicts the innovation process inside a firm where the innovator occasionally takes ideas from a common pool of knowledge to try to solve an internal design problem. However, in OI, the knowledge can come from different actors who can help the firm not only explore new knowledge but also exploit it. This exploitation usually takes the form of the commercialisation of an unused innovation to expand the market or create new ones (Chesbrough et al., 2006). This highlights the difference that in the chain-linked model, as in other models, innovation materialises only if a market already exists for it, whereas in OI, a market-push strategy is not needed to profit from innovations. In addition, the use of external actors for innovation could also resemble models, such as collaborative R&D networks where universities, large companies, and government labs build links to create and enforce intellectual property (IP) rights (Wen and Kobayashi, 2001). However, the use of several actors in the OI model has wider applicability because it is also useful for small firms, where formal protection methods to capture value, e.g., IP rights such as patents, are less feasible (De Backer and Cervantes, 2008; Huizingh, 2011).

Other comparisons could be possible, but the main idea here is that the essence of OI, and thus one key difference with other innovation models, is that it connects the processes of acquiring external knowledge and exploiting internal knowledge externally. Although OI novelty has been questioned for being conceived using previous theories, the reality is that currently, in terms of innovation management, it is considered 'the umbrella that encompasses, connects, and integrates a range of already existing activities' (Huizingh, 2011; p. 3). Researchers of OI have acknowledged that this concept uses traditional management ideas such as absorptive capacity (Cohen and Levinthal, 1990), exploration versus exploitation (March, 1991), and complementary assets (Teece, 1986) but also that OI represents modern innovation practices by firms (Van der Meer, 2007). Hence, a common way to operationalise OI is through different types of activities, mainly grouped as Inbound and Outbound (Gassmann and Enkel, 2004).

The adoption of these practices does not imply that a firm should stop its established internal innovation process (Huizingh, 2011); instead, OI suggests that internal R&D should be complemented and leveraged with other sources of technology and knowledge (Schroll and Mild, 2012). However, before a firm can look for innovative solutions and technologies outside its organisational boundaries, it must have a strong R&D capacity (Veugelers, 1997; Xiaobao et al., 2013). Weak internal R&D (IRD) would be an obstacle for a firm towards being innovative even with the support of external sources of knowledge (Negassi, 2004); therefore, IRD is a key element in Open Innovation (Xiaobao et al., 2013). Moreover, many recent studies have shown that OI as-sumptions are also valid for contexts such as medium-tech man-ufacturing SMEs in mature industries, including the automotive industry (see, e.g., Brunswicker and Ehrenmann, 2013; Chiaroni et al., 2010; De Massis et al., 2012; Ili et al., 2010; Lazzarotti et al., 2010, 2011; Van de Vrande et al., 2009; Xiaobao et al., 2013). Certainly, some challenges exist when adopting OI, such as ob-jectively measuring its impact on firms due to the lack of a widely accepted indicator to proxy OI (De Backer and Cervantes, 2008). However, researchers seem to agree that OI can be evaluated through scales for each OI practice (Cheng and Huizingh, 2014), by the type and number of activities and collaborations (Laursen and Salter, 2006) or with a mix of them to understand the level of openness in a firm (Dahlander and Gann, 2010).

Regarding the level of energy efficiency in a firm, a similar approach can be used because energy efficiency implies several different indicators (Patterson, 1996). One of these indicators could be the assessment of energy efficiency measures (Fleiter et al., 2012a), such as the most efficient technology or new process-specific technologies in a firm (Trianni et al., 2013a). The practice of comparing and adopting these innovations and technologies, including the BATs in an industry, can improve the firm's overall energy efficiency performance (Norup and Taylor, 2005; The Institute for Industrial Productivity, 2013a). Similarly, the implementation of BATs by a firm relates directly to the existing barriers that may inhibit investments in these energy-efficient technologies and consequently limit industrial energy efficiency (Sorrell et al., 2000; Trianni et al., 2013c). Thus, the perception of the barriers that a firm could have can also be used as a complementary indicator of its level of energy efficiency (Cagno et al., 2013). This idea has been recently studied with large firms in the foundry sector (Trianni et al., 2013a) but also with SMEs (Cagno and Trianni, 2012; Trianni and Cagno, 2012).

Considering the aforementioned ideas, Fig. 1 depicts how they all relate in our study. In this framework, linking innovation practices with energy efficiency is done under the assumption that because OI can support the introduction of new technologies to a firm (West and Bogers, 2013), it could also support the addition of energy-efficient BATs. More specifically, there are three clearly differentiated types of innovation practices (IRD, INB and OUT) that a firm uses to benefit from external knowledge and technol-ogy as aligned to the central idea of the OI 'funnel' (Chesbrough, 2006). Interaction between these innovation practices

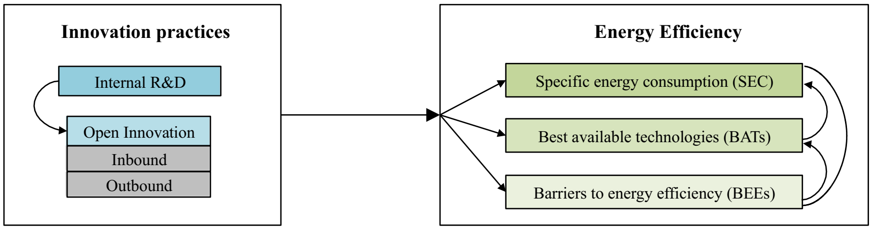

Fig. 1. The conceptual framework.

demonstrates the precondition of internal R&D being essential in the firm (Xiaobao et al., 2013) together with a different concurrent influence of INB and OUT practices (Mazzola et al., 2012) to achieve higher levels of energy efficiency. In particular, we see this first with SEC, which is an actual and objective measure of how energy efficient the main production process of a foundry is; second, with the rate of adoption of the BATs in each foundry sector, which are deemed as direct enablers of energy efficiency and therefore probably having an effect on SEC; and third, with a measure of the perceived barriers, i.e., BEEs, which can affect the decision-making process of adopting energy-efficient BATs and consequently also have an impact on the level of SEC.

Moreover, analysing the link between the three energy efficiency indicators could be helpful for understanding the result of adopting more or less innovation practices on better energy efficiency performance. Finally, it should be noticed from the framework that the scope of our study is to explore these relationships first at the firm level, which means that external drivers of innovation in energy efficiency, such as economic, social and, institutional regulations, are not currently included. Nevertheless, we acknowledge that regulations have a major impact on in-novation, e.g., the creation of innovation-based alliances (Firth and Mellor, 1999), and also on energy efficiency, e.g., the relocation of energy-intensive firms (Martin et al., 2014). Regrettably, because in this study it was not possible to collect data to measure the effect of policies and regulations, we limit our discussion to linking our findings with suggestions and implications for policy in a general sense.

3. Methodological approach

3.1. Measured indicators

To explore the relationship between firms' levels of innovativeness and energy efficiency, we focused on measuring six indicators, which are described next. In regards to a firm's innovativeness, the measurement is not straightforward. For instance, despite the process of harmonisation based on the Oslo Manual, general innovation indicators still have significant differences (OECD, 2013a). A similar challenge exists with OI measures, which are subjective and only marginally comparable (Cheng and Huizingh, 2014; Schroll and Mild, 2012). Nevertheless, a widespread approach to measure the level of innovativeness of a firm is focusing on the perceived ability to innovate through innovation practices (OECD, 2005). As justified before, in this study we chose to measure innovation practices related to internal R&D (IRD), inbound OI (INB), and outbound OI (OUT).

To provide objectivity to our study, we adapted the items used to measure IRD and OI practices, either from innovation questionnaires or from the innovation management literature. From the first group of sources, we took items directly associated with IRD activities mainly from the latest public Community Innovation Survey (Eurostat, 2013). We then added more focused questions on open and collaborative innovation from the IMP3rove assess-ment (Brunswicker and Vanhaverbeke, 2011) and the Open2-In-nova8ion Tool (Caird et al., 2013). Later, we reinforced these questions using concepts overlapping in the literature relevant to the context of the studied firms, i.e., manufacturing firms in ma-ture industries (Chiaroni et al., 2010; Ili et al., 2010; Laursen and Salter, 2006; Lazzarotti et al., 2010). Finally, we conducted an ad-ditional confirmation of the questions related to IRD and OI by matching them with empirical measures obtained from recent studies and reports (Cheng and Huizingh, 2014; European Com-mission, 2013c; OECD, 2008). We included all these steps to guarantee that the questionnaire contained well-known items used to measure a firm's level of innovativeness (Table 1).

All the innovation practices were evaluated through multiple direct questions using a 1–4 Likert scale (1 – not adopted to 4 – extensively adopted) for the level of adoption within the firm. In addition, to show the results in a clear-cut way, we considered useful defining a practice as having a low adoption level if it was rated with a value of 1 or 2 and having a high adoption level if it was rated with a value of 3 or 4. Using the same logic, we defined a foundry having low or high adoption levels for each group of innovation practices (i.e., IRD, INB, and OUT) by calculating an average of all the scores in each group. It should be clarified that using an average was the best option to show the results in an aggregated way because performing a factor analysis was not possible due to the low values of the Kaiser–Meyer–Olkin measure, mainly caused by the limited size of our sample.

On the other side, to measure the energy efficiency performance of a firm, we used an interdisciplinary approach (Thollander and Palm, 2013) consisting of three different EEIs. First, from the different measures for energy efficiency performance stressed by the International Energy Agency (Tanaka, 2008), we chose the energy consumption index, i.e., the total amount of energy required to produce a tonne of a certain material measured in kilowatt-hours per tonne. In our study, we labelled this in-dicator as Specific Energy Consumption (SEC) to align with the term used in industrial energy efficiency benchmarks (UNIDO, 2010). Additional advantages of choosing this physical-thermo-dynamic indicator include its objective measurement, reflecting what it is required in terms of the end user unit (Patterson, 1996), avoiding market value fluctuations, and its relation to process operations and technology choices (IEA, 2013). It is important to clarify that in this study, we focus on measuring the SEC value of the melting process in the foundries because it can account for up to 84% of the total final energy use (UNIDO, 2010).

Because each sector has different industry standards for energy efficiency (Patterson, 1996), each alloy foundry has its own benchmark SEC values for considering a process energy efficient. Therefore, we coded the SEC value on a scale from 1 (poor) through 4 (excellent) using different thresholds for each alloy (Table 2). Such thresholds were derived based on theoretical, practical minimum, and benchmark values taken from the litera-ture, primarily from industry reports (Backlund et al., 2011; Choate and Green, 2003; EPA, 2012, 2008; European Commission, 2012, 2005; Helber and Steinhäuser, 2011; Remus et al., 2013; The In-stitute for Industrial Productivity, 2013a; U.S. Department of En-ergy, 2005; UNIDO, 2010). The foundry associations and their ex-perts, with whom we collaborated on this project, helped us to confirm these thresholds while we prepared the questionnaire. Later, based on the built scales and the experts' estimation, we decided to have clear-cut criteria for presenting results related to SEC as well. Accordingly, we categorised foundries as having poor (1) and good (2) levels as being less efficient and thus having a low performance level of SEC (SEC-L). In contrast, foundries with very good (3) and excellent (4) levels were considered to be more energy efficient and thus have a high performance level of SEC (SEC-H).

Second, the achievement of benchmark values in the foundry sectors is highly dependent on the best energy management practices and new technologies (BCS, 2007). Considering this, as well as the relevance of the most effective process-specific technologies to promote energy efficiency (Worrell and Biermans, 2005), we evaluated the implementation of energy saving technologies labelled as BATs. As with the SEC values, the BATs for each alloy were obtained with the support of the association experts (AEs), industry databases and reports (listed in the last column of Table 2). When several BATs were available in the literature, we considered the ones with the highest impact on energy efficiency

Table 1
Items used to measure internal R&D and Open Innovation practices.

Construct	Concept	Code	Practices and activities	Sources
Perceived innovation capacity	*Internal innovation (R&D)*	In1	Introducing innovative products related with the firm's core business	Community Innovation Survey Questionnaire (Eurostat, 2013), IMP3rove assessment (Brunswicker and Vanhaverbeke, 2011)
		In2	Introducing innovative processes related with the firm's core business	
		In3	Investing of resources in internal R&D	
		In4	Operating at the forefront of developing new technologies	
		In5	Producing intellectual property inside the firm	
		In6	Engaging in org. innovation to improve operations and efficiencies	
	Inbound Open Innovation	Ib1	Accessing to external funding to develop innovative ideas	Open2-Innova8ion Tool (Caird et al., 2013), Empirical measures of Open Innovation (OECD, 2008), Open Innovation 2.0 Yearbook (European Commission, 2013c), Laursen and Salter (2006), Lazzarotti et al. (2010)
		Ib2	Using new methods of organising relations with other organisations	
		Ib3	Conducting trend and technology scouting	
		Ib4	Consuming external R&D to increase knowledge and expertise stock	
		Ib5	Innovating through reverse engineering	
		Ib6	Purchasing technical or scientific services	
		Ib7	Acquiring advanced machinery, equipment or software to innovate	
		Ib8	Licensing-in patents or purchasing external IP knowledge	
		Ib9	Adapting information on customer requirements into valuable IP	
		Ib10	External training of personnel to improve the innovation process	
		Ib11	Engaging in activities to get innovative ideas from atypical sources	
		Ib12	Using different entities as collaboration partners to innovate	
	Outbound Open Innovation	Ob1	Selling innovation projects developed inside the firm	Chiaroni et al. (2010), Ili et al. (2010), Cheng and Huizingh (2014)
		Ob2	Supporting the formation of spin-off companies	
		Ob3	Using licensing-out schemes (*technology, patents, and trademarks*)	
		Ob4	Selling technical or scientific services to other organisations	
		Ob5	Creating valuable intellectual property to sell it to other organisations	
		Ob6	Commercialising technology developed or improved inside the firm	

Table 2
Ranges of specific energy consumption (SEC) for different alloys.

Alloy	SEC [kWh/ton]				Sources of information
	Poor (1)	Good (2)	Very good (3)	Excellent (4)	
Steel	Higher than 2530	2530–2205	2205–1075	1075–730	BAT Reference Document for Iron and Steel Production BAT Conclusions for Iron and Steel Production
Aluminium	Higher than 830	830–705	705–490	490–390	Industrial Efficiency Technology Database: Iron and Steel BAT Guidance Note for the Non-Ferrous Metals US Aluminum Production Energy Requirements
Ductile cast iron	Higher than 1200	1200–1000	1000–800	800–750	BAT Guidance Note for Ferrous Metals Foundries Energy Saving Opportunities for the Metal Casting Industry Global Industrial Energy Efficiency Benchmarking
Grey cast iron	Higher than 1100	1100–900	900–700	700–650	Foundrybench D19 and D16 The Smitheries and Foundries BREF

and the most used BATs in the industry according to the AEs (Table 3). For each implemented BAT, we assigned a score of 1 to the foundry (and 0 otherwise). This allowed us to analyse which BATs were adopted and build an aggregate indicator of BAT adoption by summing the single BATs scores, providing informa-tion on the percentage of adopted BATs for each alloy. It should be noted that with the support of the AEs, we first identified which BATs were applicable in each firm out of the total list of BATs for each foundry sector. Then, from the number of applicable BATs, the AEs assessed the ones that were actually implemented in each firm. We used the ratio of this value as a fair approximation of the adoption level of BATs, which could be compared between the sampled foundries despite their foundry sector. We also estab-lished together with the AEs that when a foundry adopted less than 50% of the applicable BATs, it was considered to have a low adoption level (BAT-L), and when it adopted more than 50%, it was classified as having a high adoption level (BAT-H).

The third EEI evaluated was the level of barriers to energy efficiency (BEEs). These are directly associated with the obstacles hindering the adoption of energy-efficient technologies (Trianni and Cagno, 2012). These BEEs were measured using the novel taxonomy by Cagno et al. (2013), focusing on the perceived barriers by a firm and their effect on its decision-making process in favour of energy efficiency. One advantage of using this taxonomy is that it comprises previous classifications of barriers that include market and nonmarket failures (e.g., Sorrell et al., 2004). In addition, recent studies have demonstrated the usefulness of adapting this taxonomy when examining barriers in single firms (e.g., Kostka et al., 2013). Therefore, we used the same approach and adapted the seven main categories of barriers (Table 4) studied by Trianni et al. (2013a, 2013b). We measured the perceived im-portance of BEEs through multiple direct questions on a seven-item four-point Likert scale ranging from 1, 'not important', to 4, 'very important', as previously used in literature (see, e.g., Ha-sanbeigi et al. (2010) or Trianni et al. (2013a)). Similarly as before, to show the results in a clear-cut way, we defined a BEE as not significant if it was rated with a value of 1 or 2 and as very sig-nificant if it was rated with a value of 3 or 4. In addition, to see how each foundry perceived the barriers in general, we calculated an overall BEE index with the average of all the BEEs scores in each firm. For the overall BEE index, if the value was lower than 2.5, the foundry had a low level of barriers (BEE-L), and if it was higher than 2.5, the foundry had a high level of barriers (BEE-H).

3.2. *Sample and data collection process*

To collect the data to measure the aforementioned six indicators, we used a multiple case study methodology with 30 Italian foundries. We selected the foundry sector due to the large amount of energy used in it. It is considered one of the most important energy-intensive sectors (The Institute for Industrial Productivity, 2013a). For instance, the foundry sector of iron, steel, and non-ferrous metals together with the chemical and petrochemical sectors accounted for 60% of industrial energy used

Table 3
List of best available technologies (BATs) most used in the steel, aluminium and cast iron foundry sectors.

Alloy	Code	BATs	Alloy	Code	BATs
Steel	S1	State of the Art Power Plant	Cast Iron (Ductile and Grey)	CI1	State of the Art Power Plant
	S2	Coke Dry Quenching (CDQ)		CI2	Recovery Heat Solution
	S3	BOF Waste Heat and Gas Recovery		CI3	Continuous Melting
	S4	Continuous Casting		CI4	Scraps Pre-heating or Drying of raw materials
	S5	Scrap Pre-heating		CI5	Sinter Plant Waste Gas Heat Recovery
	S6	Sinter Plant Waste Gas Heat Recovery		CI6	Optimised melting process for Cupola Furnace
	S7	Optimised sinter pellet ratio		CI7	Optimised melting process for Induction Furnace
	S8	Oxy-fuel Burners		CI8	Optimised melting process for Rotatory Furnace
	S9	Pulverised Coal Injection (PCI)		CI9	Change from main to medium frequency furnace
	S10	Top Gas Recovery Turbine (TRT)		CI10	Oxy-fuel Burners (oven, preheat, vessel, other)
Aluminium	A1	Drying of raw materials		CI11	Pulverised Coal Injection (PCI) and others
	A2	Space heating and hot water supply		CI12	Top Gas Recovery Turbine (TRT)
	A3	Hood and sealed furnace door		CI13	Space heating and hot water supply
	A4	Unburned hydrocarbons		CI14	Indicators on fans
	A5	Indicators on fans		CI15	Oxygen enriched air in the furnaces and burners
	A6	Oxygen enriched air or oxygen in burners		CI16	CO burning
	A7	Plastic used as fuel			
	A8	CO burning			

Table 4
Taxonomy of barriers to energy efficiency.
Adapted from Cagno et al. (2013).

Category	Description of the associated barriers
Economic barriers	Low capital availability, investment costs, hidden costs, intervention-related risks, external risks, intervention not sufficiently profitable.
Organisational barriers	Complex decision chain, lack of time and other priorities of top management, issues on energy contracts, lack of internal control, divergent interests
Information barriers	Issues on energy contracts, lack of information on benefits, trustworthiness of the information source, unclear information by technology suppliers
Behavioural barriers	Inertia, lack of sharing the objectives and interest in energy efficiency topic, imperfect evaluation criteria other priorities.
Barriers related to competences	Difficulties in gathering external skills to identify inefficiencies and opportunities in order to implement interventions.
Barriers related to awareness	Lack of personal environmental/energy concern, ignorance about energy efficiency topic
Technology-related barriers	Technology not adequate or compatible, and technology not available.

worldwide in 2010 (UNIDO, 2010). In the European Union, these industrial sectors accounted for almost 16% of its total final energy consumption in 2011. Moreover, our studied context is relevant because in 2011, Italy had the second highest consumption of final energy in these sectors in the EU, only trailing Germany (European Commission, 2013a).

Because foundries are energy-intensive firms, it is reasonable to assume that energy efficiency has a strong and direct influence on industrial and company performance, making this research context relevant for the purpose of this study. It is worth mentioning that we noticed some common characteristics for the chosen firms, which we are not highlighting in this study but could be important to mention. First, according to the EU definition, most foundries in Italy are SMEs (Trianni et al., 2013a). Second, the selected foundries are often tier-2 suppliers[1] to the automotive industry, which allowed the firms to be stable given the pressures of a major supplied manufacturing industry in terms of cost optimisation, R&D efficiency, and competition (Wyman, 2007). Moreover, the main markets served by foundries in Europe are the automotive (50%), general engineering (30%) and construction (10%) sectors, which could also be sources of innovation from an OI perspective. Third, all firms are equally influenced by the same European regulations for the foundry sectors, thus making it difficult to consider these regulations as relevant differentiators. For instance, all the sampled foundries should follow the European emissions trading scheme (EU ETS) regardless of which foundry sector they belong to. Fourth, as we previously mentioned, the foundries produce four different types of alloys: steel, aluminium, grey cast iron, and ductile cast iron. This distinction is important because it relates directly to the benchmark values of SEC and the specific BATs for each alloy and process. Nevertheless, the focus of this study is not on the alloy process itself but on the relationship between the level of adoption of certain BATs and the perceived BEEs, among others.

For this study, we chose 30 firms with the support of different Italian foundries' associations. These associations provide foundries with continuous assistance related to technical, regulatory and environmental information; therefore, having their support was vital to collecting and confirming data. All of the studied foundries are located in Northern Italy, which provided consistency to the firms analysed in our study because this region is marked by a particular diffusion of innovative activities among firms (Conte, 2002; Lazzarotti et al., 2011). It should be noted that from more than 40 foundries contacted randomly, very few chose to participate. Therefore, we requested the foundry associations provide the names of firms known for being more cooperative and proactive. This strategy helped us obtain information for more firms; however, a side effect was that the foundries suggested by the associations were also known for being relatively innovative. Therefore, it can be said that the firm selection process was partially influenced by the associations' participation; however, their participation helped us reach our goal of studying firms with certain levels of R&D and innovation intensity. We acknowledge that our sample is not representative of all foundries in the region, including the least innovative foundries. However, the case study approach is judged on its theoretical generalisability rather than its statistical generalisability (Eisenhardt and Graebner, 2007). Therefore, the sample of 30 firms, including foundries deemed as relatively innovative, was judged to be appropriate.

We collected and analysed the data with a multiple case study methodology (see Yin (2013)), used in similar studies focusing on energy management (Thollander and Ottosson, 2010), industrial energy efficiency (Thollander et al., 2007), barriers to energy efficiency (Trianni et al., 2013b), and innovation management (Lazzarotti and Manzini, 2009). The multiple case study approach included a visit to each foundry to apply semi-structured interviews and a self-reported questionnaire that was designed according to literature suggestions (Bryman and Bell, 2007; Fink, 2003). This questionnaire was the result of refining a larger set of items through a pilot study (Ramirez-Portilla et al., 2014), yielding 65 relevant questions for this study. Testing the preliminary measurement instrument in the aforesaid study helped in providing consistency (firms answering in the same way to the same question) and validity (items correctly measuring the investigated indicators) to this larger study. Likewise, to increase the reliability of our study, we followed a rigorous case study protocol as well as a structured database created for the analysis of the empirical evidence from the cases.

It should be acknowledged that a self-reporting method for collecting data, such as our questionnaire, could have some disadvantages in terms of validity and respondent bias. We tried to offset these drawbacks by teaming up with the foundry associations and their experts before and during the visits to the firms. For instance, the AEs reviewed preliminary versions of the questionnaire with a special emphasis on verifying items related to the benchmark levels of energy consumption per alloy sector and the lists of the state-of-the-art energy-efficient technologies for each alloy. Similarly, the team of AEs also supported us during the data collection process. Together with the AEs, we spent around half a day per case, four to six hours in each firm, evaluating the different indicators by each party. This means that on the one side was that the AEs led the objective assessment of the technologies applied in each firm and measuring the energy efficiency of the main foundry process. In contrast, we led the evaluation of the perceived BEEs and the innovation practices adopted by firms through interviews with managers.

To ensure respondents in the Italian foundries fully understood the constructs and indicators originally formulated in English, we

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[1] A tier-2 or second-tier supplier is a company that supplies materials or parts to another company, which then supplies them to a manufacturer.

used a double back translation procedure (see, e.g., Cheng and Huizingh, 2014). We conducted the semi-structured interviews and the questionnaire with top management selected as key respondents due to their direct role in the strategy and operations of the firms, e.g., the general director, the operations director, the plant manager and other specialised managers if available. This approach was appropriate because it is common in Italian SMEs that these types of key employees are deeply involved with strategic firm decisions, such as innovation, technology and efficiency topics (Lazzarotti et al., 2010).

4. Results and discussion

The results of this study are discussed in different ways. First, we describe some general aspects from the sample such as its mix, the existence of specialised managers and the types of collaboration partners used for innovation projects (Section 4.1). Later we analyse the innovation indicators and groups of firms with different adoption levels of innovation practices (Section 4.2) to better understand their influence on foundries' SEC (Section 4.3), the adoption rate of energy-efficient BATs (Section 4.4), and the perceived BEEs (Section 4.5). In all sections, a discussion of the relationships between the different innovation levels is included, and, when appropriate, the relationship between the three EEIs is discussed.

4.1. *General analysis of the sample*

When examining the general characteristics of the sample, we can see a similar mix of SMEs in terms of annual turnover and number of employees (Table 5). This mix is similar to the size of firms in the European foundry industry, in which 80% of firms employ less than 250 people (European Commission, 2005). Regarding the proportion of foundries, even though we wanted to study an equal number of SMEs per each foundry sector, the amount of firms in the studied region varied greatly between them. It is recognised that the size of the sample for each type of alloy is not equal and statistically representative in all cases; nevertheless, this study covered a fair proportion of the foundries in the region, with 20%, 80% and 32% for steel, aluminium and cast iron foundries, respectively (ASSOFOND, 2013; ASSOMET, 2014; FEDERACCIAI, 2014). Therefore, this sample is relevant for the purpose of exploring the link between innovation practices and energy efficiency.

An interesting observation is that only two firms in the sample have an innovation manager, in comparison to the existence of 12 energy managers (EM). This difference suggests that although managers in these foundries coordinate some innovation activities, they are not focused on innovation alone; they support other activities and areas inside the foundries. It is also clear that the number of EMs, 12, is similar to the 11 firms conducting energy audits in the last three years, suggesting an analogous relation between energy-focused staff and energy-focused activities. Nevertheless, after a closer evaluation, we observed that the relationship between having an EM and conducting energy audits is not correspondent in our sample (Table 6). For instance, only 2 foundries (C4 and C5) employ EMs and at the same time conduct energy audits. However, the other 19 foundries also marked with a dot in the table do not show simultaneous employment of an EM and conducting of energy audits. We believe this unexpected trend could be explained by two different strategies that some top managers expressed during the visits and interviews. The first is when a firm chooses an approach focused on managing energy issues, it clearly identifies in an EM an opportunity to improve the firm's energy performance, control internal energy indicators and thus decrease external audits. The second is a more conservative approach in which firms do not hire a full-time EM but delegate part of this role to other employees to execute energy-related activities periodically, such as energy audits. This result is interesting because the studied foundries do not need to appoint a certified energy manager according to Italian national laws, derived from the Act of the Rational Use of Energy since their energy consumption is lower than 10,000 toe/year (The Institute for Industrial Productivity, 2013b). This finding suggests, as expressed by some top managers, that most foundries in our sample are already aware of energy management practices and the importance of energy efficiency actions due to the role of industrial associations in communicating local and regional policies. Similarly, it suggests that some of these foundries pursue different strategies to be energy efficient even though they are all guided by the same regulations such as the EU ETS or not requiring a certified energy manager.

On the innovation side, an additional and preliminary analysis of the information sources and collaboration partners that the sampled foundries use to innovate is reported in Table 7. From this table, we can see that for the 30 foundries, all of them indicated that they collaborate or obtain information useful for innovation from suppliers, and 27 firms did so from clients. Two other sources of information or forms of collaboration highly mentioned were industry associations, mentioned by 26 firms, and technical or scientific publications, mentioned by 25 firms. In contrast, the less mentioned sources of knowledge or collaboration for innovation used by foundries are start-up firms, public research institutes, and other industries. These results are aligned with previous studies on the impact of different types of innovation collaborations and innovation sources, which found that horizontal collaborations (e.g., with competitors) and science-based collaborations (e.g., with government research institutions) are not adopted by many firms in the manufacturing sector. Instead, it is more usual that vertical collaboration (e.g., with suppliers and clients) can positively influence innovation capacity and performance in this type of firms (Ebersberger et al., 2012). For instance, one of the owners stated that it was common to periodically invite suppliers and clients to the foundry premises to talk about possible joint projects. Conversely, he said that they would probably never invite a competitor or a start-up because they were not sure which types of collaborations could be done with them. All these findings suggest that regional policies could be better framed to promote collaboration networks between universities, government and

Table 5
General characteristics of the studied firms.

Type of alloy	Annual turnover [€M]		No. of employees		No. of firms	Innovation managers	Energy managers	Energy audits
	Min	Max	Min	Max				
Steel	–	235	–	205	1	0	1	1
Alum.	11	100	50	240	4	1	4	1
Cast iron	5	60.5	23	220	25	1	9	9
TOTAL					**30**	**2**	**14**	**11**

Table 6
Relation between energy managers and conducting energy audits.

Firm	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	C13	C14	C15	C16	C17	C18	C19	C20	C21	C22	C23	C24	C25	C26	C27	C28	C29	C30
Energy manager	●	●	●	●	●			●							●		●								●		●		●	●
Energy audit				●	●						●	●	●	●		●		●	●					●				●		

● – Marks when a firm employs an energy manager, or has conducted energy audits in the last 3 years.

firms of all sizes to improve regional innovation systems that can help solve social problems (Wen and Kobayashi, 2001). Because collaboration is only one part of the activities that firms can use to improve their innovation capacity, an in-depth analysis of the investigated innovation practices is shown in the next section.

4.2. Analysis on the adoption level of innovation practices

The next step of the analysis is to understand the extent to which the studied foundries are adopting or not adopting the chosen innovation practices. Table 8 shows the level of adoption of the innovation practices classified into the three innovation practices indicators, internal R&D (IRD), inbound OI (INB), and outbound OI (OUT). The first interesting result is that most firms adopt or extensively adopt IRD practices. This observation, to-gether with the purpose of displaying the scores in a more prac-tical way, motivates us to add two columns combining the scores into low and high adoption. This approach allows us to see clearly which innovation practices are adopted by most foundries in our study. A good example is that 22 out of the 30 foundries are rated as extensively adopting the practice of engaging in organisational innovation to improve operations and achieve different types of efficiencies (In6). However, if categorised by low or high adoption level, this activity is considered favourably adopted by all firms. Similarly, introducing innovative processes (In2) and investing resources in IRD (In3) leads to a high adoption level in 29 and 28 firms, respectively. Conversely, this approach is also useful to see that 18 out of 30 firms do not engage deeply in producing intellectual property rights internally (In5).

These results showing a high general level of Internal R&D in most of the studied foundries somehow contrast with the average measures of R&D expenditures in the foundry sector (OECD, 2013b). However, this difference could be explained by the criteria used in this study to select the foundries in which a certain level of innovativeness was desired to be already present. In fact, these specific results were shared with the associations' managers, who, based on their experiences, confirmed that most of the studied foundries were in general regarded as being reasonably innovative. Similarly, these results could also imply that IRD is not meaningless for all foundries in general, but that indicators used to measure R&D intensity, such as R&D expenditures or activities related to IP, e.g., creating trademarks, patents or publications, could be more conservative in the foundry sector. This could be one of the reasons that firms in mature industries, such as foun-dries, are categorised as not research-intensive firms i.e., firms with ‘low or medium-tech’ profiles (Hirsch-Kreinsen and Jacobson, 2008). Nevertheless, empirical evidence has shown the innovative capacity of low- or medium-tech firms in mature sectors (Robertson and von Tunzelmann, 2009). Therefore, our results align and contribute to the literature showing that foundries can also perceive their internal R&D activities as crucial to increasing the capability to be innovative.

Similarly to the results in the IRD category, INB practices in general are mostly rated as greatly adopted, with some exceptions. Among the most adopted INB practices, acquiring advanced machinery or equipment to improve process or products (Ib7) is being either adopted or extensively adopted by 29 firms. Equally, external training of personnel to improve the innovation process (Ib10) and conducting technology scouting (Ib3) are practices adopted by 22 and 24 firms, respectively. These results are consistent with those of other studies that mention technology scouting as a crucial activity for the innovation process in mature sectors (Parida et al., 2011) or the use of non-R&D activities such as acquiring advanced machinery as vital to enhance the innovation process of any firm (Santamaría et al., 2009). The INB practices less adopted by our sample of foundries are purchasing or license-in

Table 7
Number of information sources and collaboration partners for new innovation projects by foundry.

Firm	Suppliers	Clients	Competitors	Private Research Institutes	Universities	Start-ups	Pubic Research Inst. (Govt.)	Other industries	Conferences, trade fairs, exhibitions	Technical or scientific publications	Industry associations
C1	X	X	X	X	X	X	X	X	X	X	X
C2	X			X	X	X	X	X	X	X	X
C3	X	X		X	X	X	X	X	X	X	X
C4	X	X		X	X	X	X	X	X	X	X
C5	X	X	X	X	X		X	X		X	X
C6	X	X					X		X		X
C7	X	X	X	X				X	X		X
C8	X	X	X	X	X				X	X	X
C9	X	X	X	X	X				X	X	X
C10	X	X	X	X	X				X	X	X
C11	X	X			X					X	X
C12	X	X			X					X	X
C13	X	X		X	X		X			X	X
C14	X	X			X					X	X
C15	X	X	X	X	X	X		X		X	X
C16	X	X	X						X	X	X
C17	X			X	X						X
C18	X	X	X	X				X	X	X	X
C19	X	X	X	X				X	X	X	
C20	X			X	X						X
C21	X	X					X		X		X
C22	X	X	X						X	X	X
C23	X	X	X						X	X	X
C24	X	X	X	X					X	X	
C25	X	X		X	X				X	X	X
C26	X	X	X	X	X		X	X	X	X	X
C27	X	X		X	X	X	X	X	X	X	X
C28	X	X	X	X					X	X	
C29	X	X	X						X	X	X
C30	X	X	X		X		X		X	X	
Σ	30	27	17	20	19	6	11	11	22	25	26

Table 8
Level of adoption of innovation practices by categories for the 30 foundries.

Practices	**Code**	**Not adopted** (1)	**Scarcely adopted** (2)	**Adopted** (3)	**Extensively adopted** (4)	**Low adoption** (1+2)	**High adoption** (3+4)
Internal R&D (IRD)	In1	1	4	11	14	5	25
	In2	0	1	13	16	1	29
	In3	0	2	11	17	2	28
	In4	0	4	19	7	4	26
	In5	2	16	9	3	18	12
	In6	0	0	8	22	0	30
Inbound Open Innovation (INB)	Ib1	0	9	10	11	9	21
	Ib2	0	12	16	2	12	18
	Ib3	1	5	20	4	6	24
	Ib4	1	10	19	0	11	19
	Ib5	5	8	17	0	13	17
	Ib6	0	9	17	4	9	21
	Ib7	0	1	17	12	1	29
	Ib8	0	20	10	0	20	10
	Ib9	2	8	18	2	10	20
	Ib10	0	8	18	4	8	22
	Ib11	9	13	8	0	22	8
Outbound Open Innovation (OUT)	Ob1	13	13	4	0	26	4
	Ob2	17	12	1	0	29	1
	Ob3	17	10	3	0	27	3
	Ob4	12	17	1	0	29	1
	Ob5	17	11	2	0	28	2
	Ob6	21	7	2	0	28	2

patents from other firms (Ib8) and obtaining innovative ideas from atypical sources such as online marketplaces or ideas competitions (Ib11), only adopted by 10 and 8 foundries, respectively.

We can also see that the OUT practices are clearly perceived with a low adoption level in general, being the most adopted form to sell innovation projects developed inside the firm (Ob1) for only four firms. These findings suggest that outbound OI might not be relevant in the foundry sector, which aligns with previous results about the sparse use of outbound practices in mature industries and manufacturing sectors (Laursen and Salter, 2006;

Table 9
Average values of the innovation practices adopted in every firm shown by the innovation sub-categories proposed for the analysis.

Firm	ALL			TIRD	TIRD+TINB	TIRD+TINB+TOUT
	IRD	*INB*	*OUT*			
C1	2.33	1.91	1.00	–	–	–
C2	2.83	2.55	2.00	–	–	–
C3	3.50	3.00	3	3.50	3.25	3.17
C4	3.33	2.45	2.17	3.33	–	–
C5	3.33	2.45	2.17	3.33	–	–
C6	3.67	3.00	2.00	3.67	3.33	–
C7	3.67	3.00	2.00	3.67	3.33	–
C8	3.50	3.27	2.00	3.50	3.39	–
C9	3.67	3.00	2.00	3.67	3.33	–
C10	3.50	2.64	1.00	3.50	–	–
C11	2.33	2.27	2.00	–	–	–
C12	2.83	2.18	2.00	–	–	–
C13	3.33	2.91	1.00	3.33	–	–
C14	3.17	2.82	1.17	3.17	–	–
C15	3.00	2.64	1.33	3.00	–	–
C16	3.17	2.18	1.00	3.17	–	–
C17	3.17	2.09	1.00	3.17	–	–
C18	3.17	2.09	1.20	3.17	–	–
C19	3.00	2.45	2.17	3.00	–	–
C20	4.00	2.82	1.00	4.00	–	–
C21	2.67	2.91	1.17	–	–	–
C22	3.17	2.45	1.33	3.17	–	–
C23	3.33	2.73	1.17	3.33	–	–
C24	3.00	2.27	1.67	3.00	–	–
C25	3.50	3.09	1.83	3.50	3.30	–
C26	3.83	3.18	1.00	3.83	3.51	–
C27	3.67	3.09	1.17	3.67	3.38	–
C28	3.33	3.27	1.17	3.33	3.30	–
C29	3.83	3.27	1.17	3.83	3.55	–
C30	2.83	2.73	1.17	–	–	–
Total firms	30			24	10	1

Lichtenthaler, 2009).

The results on the low level of adoption of OUT practices lead us to use a different approach to continue further analyses. Therefore, to better understand the differences between firms that adopted more or less certain innovation practices, we defined three new categories of firms based on the aggregated level of innovation practices for each firm. To do this, we considered the average value for each group of innovation practices (IRD, INB and OUT). Based on the difference between the top performers and the rest of the firms, we categorise the firms in three groups (Table 9):

- All foundries in the sample (labelled as ALL). This sub-category is used as a baseline and thus includes the 30 firms regardless of their levels for each innovation practice.
- Top performers in internal R&D practices (labelled as TIRD). This sub-category covers only firms that show a mean value of IRD practices higher than 3. We calculated this value as an average of the adoption levels for the six IRD practices.
- Top performers in internal R&D and in inbound OI practices (labelled as TIRD+TINB). This sub-category covers only firms that show a mean value higher than 3 on IRD and on INB practices. Similarly as before, we calculated these values with the average of the adoption levels separately for the six IRD practices and for the 11 practices classified as INB.

It should be noted that in the resulting sub-categories of firms, only one firm fell under a fourth classification of adding up the OUT practices; thus, this sub-category was not considered as relevant. We then compared the overall average of innovation levels between the sub-categories proposed as a further step to confirm relevant differences between the groups. By doing this we observed a difference in the average of 22.9% between the groups ALL and TIRD. Similarly, we saw a difference of 21.8% between the groups ALL and TIRD+TINB. These moderate differences indicated to us that other relevant differences could arise when comparing the groups with the three EEIs.

When analysing in detail which innovation practices have a higher weight in the proposed innovation sub-categories, we notice some similarities and differences with the first analysis of the whole sample. These findings highlighting some of the most adopted innovation practices suggest that the disparity between the innovativeness levels of the sampled foundries could be improved by promoting some specific activities as best practices by the foundry associations. For instance, adopting or developing new technologies (In4) was the only practice showing a higher adoption rate in the TIRD group in comparison to the foundries grouped in ALL. If the comparison is made with the TIRD+TINB group, we see similar adoption rates in this group, with the exception of two additional practices considered both as extensively adopted: introducing innovative products (In1) and accessing to external funding to develop innovative ideas (Ib1). Thus, the adoption of certain innovation practices is crucial for being regarded as highly innovative among the studied foundries, and these practices could be established as a benchmark for the foundry sector.

4.3. Analysis of the level of specific energy consumption (SEC)

In relation to the first EEI, a comparison of the SEC level for the 30 firms showed a fair distribution of this indicator level in our sample. This was concluded because 10 foundries have a poor level, 9 foundries have a good level, and 11 foundries have a very good SEC level. It is worth noting that only the first three levels were obtained from the sampled foundries, and none of them were evaluated with a level of excellent SEC, which could be ex-plained since this level is close to the theoretical value. Although the main purpose of this study is not to provide precise results for each foundry sector, evaluation of the SEC level was possible by type of alloy. Considering that 15 out of the 26 cast iron foundries produce both types of cast iron because their primary process is very similar, together with the association experts, we assessed the SEC values for 45 production processes. Based on this eva-luation, 14 processes were rated as having a poor SEC level, 14 were acceptable, and 17 were energy efficient, which shows a si-milar fair distribution of the SEC levels throughout the studied foundries if analysed by alloy. Moreover, if we consider the SEC levels in the foundry sector (UNIDO, 2010), we can see in our sample that the steel foundry has a slightly less energy-efficient process in comparison to the European benchmark. On the con-trary, the four aluminium foundries can be observed as having energy-efficient production compared with the European and in-ternational benchmark. The rest of the 40 production processes for cast iron foundries are divided between poor, good and very good levels; however, based on the European and international foundry benchmarks, we determined that only 15 of these processes were really energy efficient.

With these views of the SEC levels among the processes of all sampled foundries, it is then also interesting to evaluate the SEC level in the innovation sub-categories previously created. Although the difference of the average SEC level is not very high between the three groups, the relative difference between ALL and TIRD with respect to the TIRD+TINB sub-category looks interesting (Graph A in Fig. 2). More precisely, in this graph, we can see that ALL and TIRD practically have the same SEC mean value – 2.03 and 2.04, respectively – i.e., a good level. Interestingly, however, firms included in the TIRD+TINB group present a higher average SEC value equal to 2.20. This finding provides partial support for the conceptual premise that a higher level of innovativeness based

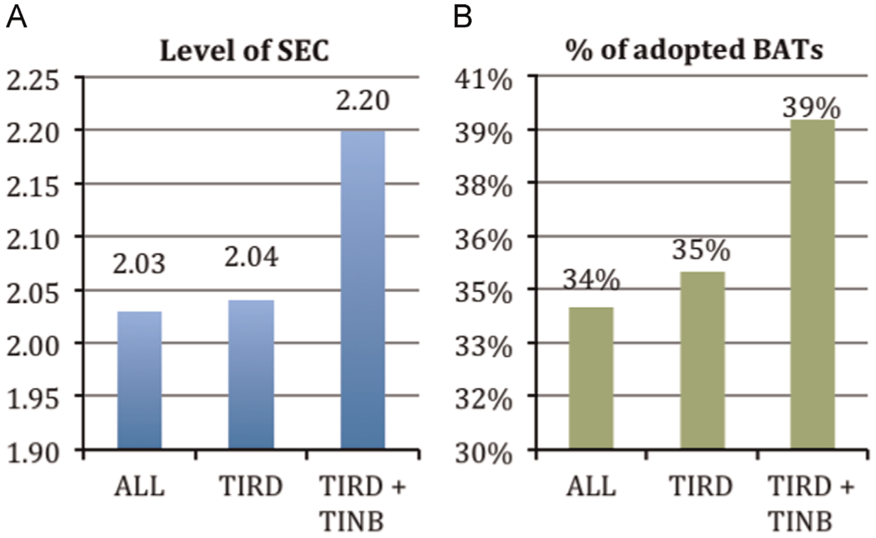

Fig. 2. (A) Average levels of specific energy consumption for the three innovation sub-categories based on different levels of adoption of innovation practices and (B) adoption rate of best available technologies for the same three innovation sub-categories.

on the aggregated innovation practices used by a firm provides slightly better results in terms of the SEC level.

4.4. Analysis of the adoption level of best available technologies (BATs)

For the BATs evaluated in the whole sample, the level of adoption exhibits an average of 34% with a standard deviation of 0.13, demonstrating that this is an average that properly describes the adoption level of the studied foundries. This number contrasts with the 60% adoption level expressed by one of the foundry associations as the desired minimum level in the affiliated foundries. Nevertheless, in general, the level of adoption of BATs is fairly optimistic for the studied firms considering the variety of available technologies in the different foundry sectors (Fig. 3). An important reminder when looking at this graph is that each alloy has different numbers of BATs. Thus, as previously explained in Section 3.1, to compare the levels of adoption between all foundries, we focused on assessing the applicable BATs in each firm and not on the list of all possible BATs for each sector. This approach helps display the general level of BAT adoption in the whole sample on a similar basis.

The difference in the number of BATs used for each alloy production and the number of cases of each alloy makes it difficult to provide a detailed analysis of BATs in an aggregated way. Thus, we centred our further analysis on the BATs specifically on cast iron foundries, which is the largest cluster of our sample. When analysing cast iron foundries, we found that among the most used BATs by the 25 firms, having a state-of-the-art power plant (CI1) was mentioned 13 times. Furthermore, considering that cast iron can be produced with three types of furnaces (cupola, induction and rotary), it is interesting to see that all 12 foundries using induction furnaces implement an optimising melting process (CI7). Similarly, 5 out 6 firms using cupola (CI6), and 6 out of 7 using rotary (CI8) apply this technology. These results seem to show that processes can be equally enhanced in the three types of furnaces, even though in the foundry sector, the induction furnace is preferred as the best option to achieve energy efficiency. Other BATs commonly implemented within the 25 cast iron foundries include using oxy-fuel burners (CI10), operating space heating and hot water supply (CI13), and having indicators on fans (CI14), implemented by 12, 11 and 10 firms, respectively. In contrast, the BATs less employed in this sector include only two firms using recovery heat solutions (CI2) and none of the firms implementing Pulverised Coal Injection – PCI (CI11) or Scraps Pre-heating-SPh (CI4). This preference could be explained by the fact that applying PCI can be costly, especially if a complex layout for the plant increases the installation costs, and operating the SPh process can be inconvenient due to its complex ratio of time spent and energy savings obtained if staff is not trained properly (The Institute for

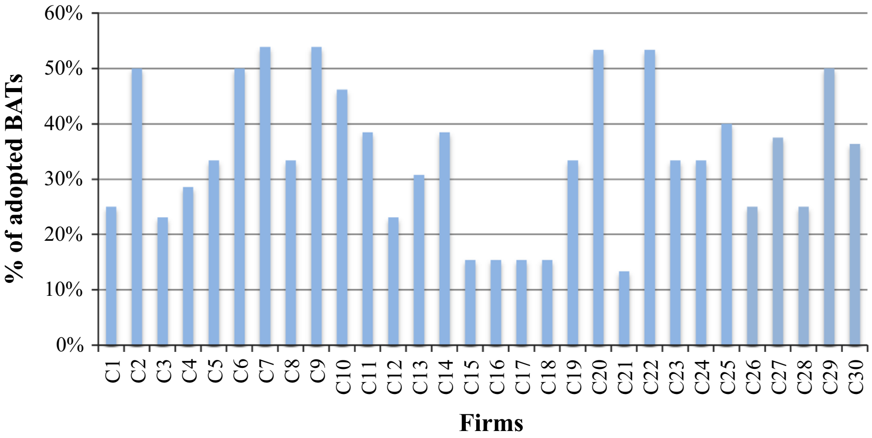

Fig. 3. Adoption rate of best available technologies for the whole sample of foundries.

Industrial Productivity, 2013a).

Similarly as before, we analysed the evaluation of the adoption rate of BATs by each of the innovation sub-categories. By doing this breakdown, it is possible to see that the 10 foundries grouped in TIRD+TINB had slightly higher adoption rates of BATs of 4% and 5% with respect to the ALL and TIRD categories (Graph B in Fig. 2). This result seems to suggest that combining inbound OI practices with internal R&D practices could lead to a greater adoption level of energy efficiency BATs than focusing only on internal innovation practices. It was also noticed that, when looking at the details of the most and less used BATs, we did not find a major difference between the ALL, TIRD or TIRD+TINB sub-categories. This could be explained by the fact that the mix of alloy foundries comprising the ALL group remains alike for the TIRD group (20 cast iron and 4 aluminium) and different but still comparable for TIRD+TINB (6 cast iron and 4 aluminium). Although these different mixes could imply that aluminium foundries are more likely to combine different innovation practices, due to our limited number of cases for this alloy, it is difficult to provide such a conclusion. In contrast, the detailed analysis on BATs adopted by the sampled cast iron foundries can provide more precise insights. For instance, it seems that these foundries, independently of their innovation levels, can implement some energy-efficient technologies, such as CI1, CI10, CI13 and CI14. In fact, we shared this suggestion with the managers of the foundry association, who concurred that these BATs should be adopted as the minimum level in the cast iron foundry sector in Italy and in Europe.

To explore the influence of different adoption levels of BATs on other EEI, we further assessed the effect of adopting more or fewer BATs on the foundry's level of SEC. Based on this idea, we analysed 23 foundries considered BAT-L and 7 as BAT-H because the difference of 0.33 in their mean SEC values was considered relevant (BAT-L=1.96 and BAT-H=2.29). This result shows that having a higher adoption level of BATs also seems to have a slight but relatively significant influence on the level of energy efficiency in terms of the SEC value. This finding, while preliminary, seems to suggest that the studied foundries having better technology and innovation management techniques and tools (e.g., see Hidalgo and Albors (2008)) benefit not only in terms of the quality of the technologies being used but also in terms of the efforts towards being energy efficient.

The most adopted BATs by foundries grouped as BAT-H include using a state-of-the-art power plant (CI1), oxy fuel burners in ovens and vessels (CI10), space heating and having a hot water supply (CI13), and indicators on fans (CI14). These BATs affect the 34% adoption level of BATs for all foundries assessed on site by the authors and association experts, in comparison to the average 32% adoption rate of new energy-efficient technologies self-reported by top management during the interviews. This minimal differ-ence suggests a high awareness by the studied foundries on the technologies and energy saving opportunities for reducing energy consumption (Cagno and Trianni, 2012), which, if addressed by local authorities through proper policies, could further diffuse the adoption of specific energy-efficient BATs, as previously mentioned.

4.5. *Analysis of the level of perceived barriers (BEEs)*

The general analysis of perceived BEEs has shown an overall average value of 2.32. Nonetheless, with a closer look into each barrier category and taking into account the whole sample, Table 10 shows the frequencies of barriers by its perceived im-portance and significance. Economic and technological barriers emerged as most critical, rated as important and very important by 25 and 19 firms, respectively, similar to what was found in previous studies (see, e.g., Fleiter et al., 2012b; Rohdin et al., 2007; Trianni et al., 2013b). This analysis highlighted the relevance of information barriers, considered important by 12 firms. This finding confirms previous results on Chinese manufacturing SMEs (e.g., Kostka et al., 2013), suggesting that currently in the foundry sector in Italy, information issues represent a critical problem that should be properly addressed by sectoral policies using more ef-fective communication strategies.

Only one firm rated barriers related to awareness as being important. Most of the foundries considered them scarcely important, similar to most assessments given to barriers related to organisational, behavioural, and competences issues (see, e.g., Trianni and Cagno, 2012). These results show that although more than one-third of the firms, 12 out of 30, consider information obstacles, such as issues on energy contracts, important, most of them declare to be aware of energy efficiency relevance currently. It is possible, therefore, that even though the studied foundries are conscious about the challenges related to energy efficiency, they might not always pursue actions to mitigate related issues. This inertia in firms could be explained by market failures such as split incentives and imperfect and asymmetric information, and by nonmarket failures such as hidden costs, risk and limited access to capital (Sorrell et al., 2004; Thollander and Palm, 2013) in the Italian foundry sector. This paradox towards knowing a relevant problem related to sustainability but not doing something precise to solve it could be addressed with the support of clear programs provided by policymakers (Giddens, 2009). In our case, because foundries seem to be aware of energy efficiency challenges, information campaigns about specific energy saving actions might represent a precise effort for policymakers to reduce market failures. In consequence, this type of effort could directly support the increase in energy efficiency in the foundry sector (Thollander and Palm, 2013; Trianni et al., 2013a).

Moreover, comparing the average level of barriers perceived by foundries according to the three innovation level sub-categories can be helpful for having a better view of these EEIs. Despite the fact that the average barrier levels in foundries grouped in TIRD are fairly aligned with firms in ALL (respectively, 2.32 and 2.34), interestingly, firms grouped in TIRD+TINB seem to show a slightly lower value of BEEs at 2.16. To make this statement more robust, a detailed comparison of the seven barriers categories according to

Table 10
Frequencies of barriers to energy efficiency by categories ad by perceived importance for the 30 foundries.

Categories	**Not important** (1)	**Scarcely important** (2)	**Important** (3)	**Very important** (4)	**Not significant** (1+2)	**Very significant** (3+4)
Economic	0	5	15	10	5	25
Organisational	5	19	4	2	24	6
Information	5	13	12	0	18	12
Behavioural	8	18	4	0	26	4
Competences	3	20	7	0	23	7
Awareness	3	26	1	0	29	1
Technology	0	11	13	6	11	19

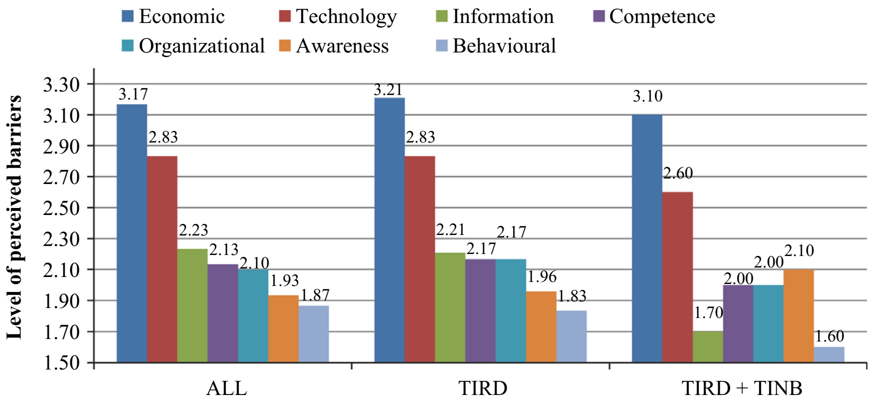

Fig. 4. Level of perceived barriers to energy efficiency for the three innovation sub-categories.

the three innovation sub-groups is shown in Fig. 4. When comparing the average barrier levels in the TIRD+TINB group, it is possible to notice some differences, e.g., information barriers showing similar scores between firms in the ALL and TIRD groups. In particular, all barriers seem to have a decreasing slope from the two groups ALL and TIRD to the TIRD+TINB group. The only exception is barriers related to awareness, which increases its value in the group of more innovative firms. This finding could be justified because using more inbound OI activities would inherently expose foundries to more external knowledge, making it possible for them to be exposed to technologies and practices of which they were not aware before. However, it is probable that foundries, as found by literature for other traditional industries, might need assistance in building absorptive capacity to use this external knowledge in the best possible way (Spithoven et al., 2010), and using collective research centres supported by local authorities could be an option.

Among other interesting differences, we can see that the levels of information and behavioural barriers seem to drop when the studied foundries adopt more INB practices, which can be explained by the fact that one of the basic notions of the Open Innovation model is the inflow and outflow of information and knowledge, which in turn could influence the behaviour of the whole organisation (Chesbrough, 2003). Less profoundly but still interestingly, organisational and competences barriers seem to decrease for foundries adopting INB practices in addition to IRD practices i.e., firms in the TIRD+TINB group. In fact, according to our previous results, certain INB practices with high adoption levels in our sample of foundries, such as external training of personnel to improve the innovation process (Ib10) and conducting technology scouting (Ib3), could support the gathering of external skills to identify opportunities for energy savings.

In addition, we have assessed the relationship of barriers with the level of adoption of BATs. Thus, to be consistent with previous criteria, we considered relevant making a comparison between the 22 BEE-L foundries and the 8 BEE-H foundries because the difference of 12% between their BAT adoption rates, i.e., 37% and 25%, respectively, is substantial. This preliminary result shows that foundries that perceive lower BEEs adopt more BATs. Conversely, the more barriers perceived by a firm, the lower its BAT adoption level is. To reinforce this finding and provide additional evidence, we added an analysis of the BAT adoption level among foundries with high (BEE-H) and low (BEE-L) average levels of barriers (Graph A in Fig. 5).

Differences between foundries having low and high levels of BEE are visible, but the most notable ones mainly pertain to two barriers. First, the BAT adoption rate increases by 9% when foundries perceive lower information-related barriers. This trend could be explained, as noticed during the visits to the foundries, by the fact that managers perceiving lower obstacles to obtaining information from different sources often increase their interest in energy efficiency, benefit from discovering new technologies, and

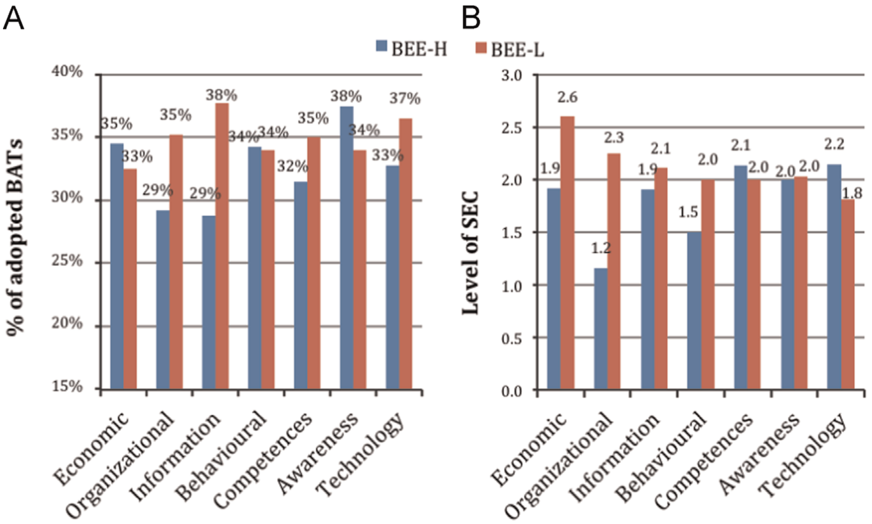

Fig. 5. (A) Adoption rate of best available technologies according to foundries with high and low levels of barriers to energy efficiency. (B) Level of specific energy consumption according to foundries with high and low levels of barriers to energy efficiency. *BEE-H*: Firms that have an average level of perceived barriers higher than or equal to 2.5. *BEE-L*: Firms that have an average level of perceived barriers lower than 2.5.

can help to gather externals skills to implement energy saving interventions. However, lowering these types of obstacles can be challenging for the sampled foundries; therefore, most of them recognised the importance of belonging to industry associations that could inform them regularly about local and regional programs focused on supporting foundries in being energy efficient. Second, although the difference is smaller, it seems that perceiving low organisational barriers increases the adoption rate of BATs from 29% to 35%. The result seems reasonable because with, e.g., a complex decision chain or divergent interests, the decision-making process of investing in a BAT might not be as straightforward and thus energy efficiency opportunities are missed.

Finally, we considered the relation of high and low barrier levels with respect to SEC levels. The variance of SEC between BEE-L and BEE-H foundries was noteworthy because the first group has a mean SEC level of 2.32 whereas the second has a mean SEC level of 1.25. Although a premature result, these numbers indicate that the analysed foundries with lower levels of perceived BEEs could be slightly more energy efficient in terms of energy consumption in their processes. To extend the examination on SEC levels, we considered the variations on each category of barriers (Graph B in Fig. 5). Notably, a great difference in SEC levels is visible for foundries with lower organisational and economic barriers, at 0.9 and 0.7, respectively. Similarly, SEC levels increase by 0.5 when foundries perceive lower behavioural barriers. These preliminary findings confirm previous studies highlighting the importance of economic (Fleiter et al., 2012b) and organisational barriers (Trianni et al., 2013a) in energy-intensive SMEs in Europe. Nevertheless, most of the interviewed managers mentioned that even though resources could be allocated to improve energy efficiency, they still see support from associations and government as critical to truly achieving it. Thus, it seems that for most of the studied foundries, more policies and programs related to energy efficiency are needed.

5. Conclusions and further research

Current policies to reduce energy consumption and fostering innovation are part of the key targets of the Europe 2020 strategy. Nevertheless, further policies at the local and regional levels are required to promote industrial energy efficiency by different means and drivers that can be viably exploitable by SMEs (Trianni et al., 2013a). Similarly, programs targeting different energy-in-tensive sectors to address energy efficiency and innovation chal-lenges should be prioritised because overcoming these issues can directly influence overall sustainable performance in industries (Smith et al., 2010). Therefore, in this study, we explored the re-lationship between different innovation practices and different indicators of energy efficiency performance in foundries, sug-gesting a framework to better interpret the reality of firms in energy-intensive industrial sectors.

In particular, this study contributes to knowledge and extends the literature in different ways. First, one novelty of this study is that we considered multiple indicators to measure and operationalise the innovativeness of a firm as well as its level of energy efficiency. For instance, we measured the innovation level based on Open Innovation practices rather than differentiating product and service innovation. Similarly, in addition to using the tradi-tional index for energy consumption to measure energy efficiency, we also considered the level of adoption of energy-efficient technologies and barriers to energy efficiency. Second, our results show that within the studied sample, foundries that are more innovative, i.e., having both a higher level of adoption of internal R&D and inbound OI practices (the TIRD+TINB group), are also more energy efficient in terms of the level of adoption of energy-efficient BATs, which in turn seems to drive a subtle, but relevant efficiency level in terms of SEC. Third, our evidence indicates that more innovative and 'open' foundries seem to perceive lower barriers to energy efficiency, particularly with relation to technology, behaviour and information, suggesting that these firms have greater potential to achieve energy efficiency with the current structure, processes and systems than less innovative foundries. Therefore, in general, it appears that even though not all innovation practices have a relationship with energy efficiency, some of them have an indirect influence as enablers of it through few but specific BATs used in the foundry sector.

The derived results from this study can be used as a reference to recommend to SMEs and policy makers in support of innovation initiatives, including OI practices, as a mean to increase results in energy management and overall industrial performance. Similarly, our findings can be used to identify opportunities and promote mechanisms that allow foundries to share innovative practices and technologies to increase energy efficiency in their processes. For instance, findings about the most used innovation practices in this sector could be helpful in developing appropriate regulatory mechanisms for collaborative forms of innovation that enable an exchange of information and may lower the perceived barriers to innovation and energy efficiency. Moreover, this study contributes by showing some of the specific innovation practices and technologies that are currently adopted by foundries, which in turn could also be used by policymakers to create local and regional policy frameworks focused on creating the conditions to improve knowledge and technology transfer between foundries with the reward of energy efficiency and innovation initiatives.

Nonetheless, it is important to mention a number of limitations in our study. First, we used a subjective self-reported assessment to measure some variables in our study. SEC and BAT were objectively measured with the support of the association experts, whereas innovation practices and barriers to energy efficiency were measured based on top management responses. This method can cause the data to be idiosyncratic because we obtained respondents' own views. However, these views are also valuable because firms' investments to overcome energy efficiency barriers are driven by both the real and the perceived values, as assessed by the firms' decision-makers (Cagno et al., 2013). Second, due to the case study methodology used, our study considers a limited and non-representative sample of innovative firms that does not allow for full statistical analyses or the use of factor analysis to aggregate variables. Nevertheless, we believe it is useful as a starting point for future studies linking interdisciplinary research dealing with relevant challenges related to managing energy and innovation. Thus, we suggest future research could use other re-search methodologies, such as more quantitative approaches with larger samples, in different sectors, and in other countries. Simi-larly, it could be interesting to include larger and representative samples firms with all levels of innovativeness, from the least to the most innovative.

Third, we acknowledge this study has focused only on exploring the relationship between innovation practices and energy efficiency. Therefore, future research should also focus on understanding what factors effectively drive firms to adopt more BATs and if such drivers may also have an impact on the implementation of OI practices. This could be done by continuing to borrow ideas from management disciplines, such as methodologies enabling OI (Bianchi et al., 2010) or the notion of firms using ambidexterity as a dynamic capability (O'Reilly III and Tushman, 2008) to achieve both energy efficiency and innovation performance. Likewise, in this study, we did not focus on the role of regulations as a driver of energy efficiency; therefore, it could be interesting to analyse the simultaneous influence or moderating effect of different regulatory frameworks on both innovation and energy efficiency efforts. In this sense, investigating the influence of organisational structure in energy-intensive SMEs, e.g., the presence or absence of energy managers due to regulations, could provide an interesting vein of further research.

Finally, we also noted that most of the examined foundries do not measure their energy consumption levels and targets in tonnes of oil equivalent [toe] but rather in kilowatt-hours, in contrast to guidelines suggested in the Energy Efficiency Directive approved in 2012. This situation, together with our main findings, suggests the need for local and regional policy makers to support and monitor larger policies, programs and frameworks to enhance positive expectations towards energy efficiency and increase innovation (Foxon et al., 2005). We have taken a small but steady step towards understanding the link between innovation practices and energy efficiency, but more research is still needed. Likewise, policies and regulatory frameworks that separately stimulate energy efficiency and R&D are currently in place, but more can be done. Therefore, we encourage further involvement from researchers and policymakers to find the right coactive strategies that can support the achievement of the challenging targets set on innovation and energy efficiency that are still ahead of us.

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