Understanding the impacts on the industrial operations from the adoption of energy efficiency measures: lessons learnt from Italian case studies

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Abstract

Energy efficiency is a key driver to decarbonize industry, improving its sustainability and competitiveness. Nevertheless, the adoption of well-known energy efficiency measures (EEMs) is in many cases hindered by the lack of information about them. Unfortunately, EEMs are usually assessed with a simplistic energy and cost effectiveness analysis, neglecting however other characteristics that should be carefully encompassed, since they can deeply affect the EEMs performance during their implementation and service phases. Among others, the impact EEMs could have on surrounding production activities plays a critical role, especially when embedded in the core business of a company. So far, too little literature has highlighted such impacts, mainly referring to the existence of the so-called non-energy benefits, while research linking the impacts to the key performance indicators of industrial operations is still scarce. Therefore, the present study is intended as a preliminary exploration giving contribution to this discussion, trying to highlight intrinsic features of the EEMs and connect them with their potential impacts in terms of performance indicators once implemented. Results show the need to create a framework linking, e.g., pure production and operations-related information to raw material consumptions and emissions, in order to provide an extensive and integrated vision of the impacts of EEMs adoption. The conceptual framework, to be further developed as an assessment tool in support of decision-makers and energy managers, could represent a valuable support for policymakers and technology suppliers in highlighting the real implications of adopting EEMs.

Introduction

Global energy consumptions are projected to increase by 50 % within the period 2018–2050, with the greatest share of the demand coming from non-OECD countries, characterized by a constantly growing population and enhanced living conditions [1]. Among the potential solutions, energy efficiency is considered the single most powerful remedy, playing the lion's share in the energy policies worldwide [2]. Industry represents the most consuming sector for what concerns delivered energy (about 40 %) [1]. Despite non-negligible efforts have been spent trying to optimize industrial energy efficiency, a huge potential remains still untouched, up to 35 % according to IEA [2]. Indeed, regardless of a series of available energy efficiency measures (EEMs), usually characterized by a short pay-back time, their adoption rate is still low [3]. The mismatch between the theoretically achievable level of efficiency and the implemented one is called *energy efficiency gap* [4]. Thus, what on a first sight seems a low hanging fruit, may be on the contrary a much more complex picture, deeply investigated in literature through the analysis of barriers (e.g. [5]). Literature has noted a large variety of factors acting as barriers, ranging from cost and difficulties in accessing capital up to technical risk and potential disruption in the system, from poor information regarding EEMs to lack of time or different prioritization [6], [7], [8]. The adoption rate of EEMs is even lower if contextualized in small and medium companies (SME), as defined by [9], intrinsically characterized by lack of a rigorous structure as well as internal resources and competences [10]. A different approach aiming at reducing the limited, and in some cases misleading, information regarding EEMs was followed by a number of authors who pointed out the non-energy benefits (NEBs) of EEMs, i.e. all the benefits not directly related to the energy savings [11], [12], as well as the non-energy losses potentially deriving from the adoption of interventions, providing decision-makers with a clearer picture regarding EEMs [13]. As these interventions are carried out in industrial plants, their impacts end up influencing the overall performance of the company, in turn described, at least partially, by specific key performance indicators (KPIs). Nevertheless, at the moment too little research has deeply analyzed the impacts of EEMs adoption on a company KPIs. Therefore, the present study represents a preliminary investigation in this direction, based on a multiple-case study analysis of three companies interested by the recent adoption of EEMs.

The remainder of the paper is as follows: in the next section we perform a brief literature review, followed by the definition of the methodology exploited to conduct the interviews. Subsequently, we describe the empirical investigation of the selected EEMs, while discussions of results and conclusions are provided in the final section.

Literature background

The adoption of EEMs has been analyzed by a number of studies in the last decades and defined using a range of terms, from non-energy benefits (NEBs) [14] to productivity benefits [11], or ancillary benefits [15]. Pioneering research in this domain, Mills and Rosenfeld [14] have described different cross-cutting technologies and devices through the range of their potential impacts. In particular, they referred to the perceived consequences on the indoor environment, noise level, labor and time savings, process control, amenity or convenience, water savings and waste minimization, direct and indirect economic benefits (downsizing). By taking a different perspective, i.e. the one of the CFO willing to increase shareholders value, Pye and Mckane [16] identified and quantified, through a multiple case study analysis, a list of NEBs associated to specific EEMs. In this case, NEBs were covering different areas, from the increase of production to improvements in production quality, up to considerations regarding operations, savings in materials or enhanced internal conditions. After the analysis, the authors pointed out how in many cases these benefits exceed the pure energy savings. A more structured approach was introduced throughout the classification of single NEBs into categories, such as the distinction among waste, emission, operation and maintenance, production, working environment and other, before quantifying them [11]. Differently, Skumatz and Dickerson [17] analyzed NEBs through the lens of multiple observers, that are utility or ratepayer, participant and society, extending the research far beyond the boundaries of the single industrial firm. Nonetheless, as suggested by their names, i.e. non-energy benefits, the limit in these approaches is represented by the biased result of the analysis, pointing out only the positive implications of the adoption of EEMs, i.e. benefits, removing any consideration related to potential losses that a company may incur in during the adoption process. Working on this bias, Cagno et al. [13] designed a framework inclusive of any kind of impacts, providing a more neutral and objective representation of the adoption process. The same study casts the light on a second literature bias, represented by limiting the analysis exclusively to the service (also known as operating) phase, rarely than extending the focus to include the implementation phase of the EEM.

More recently, the focus of the analysis has been shifted from the impacts of EEMs to their description through a list of characteristics, with studies adopting more neutral definitions of such impacts, such as attributes [12] or factors [18]. Within these studies, new characterizing features of the EEMs found a place among the traditional description of NEBs, such as the implementation related attributes by [12], comprising saving strategy, activity type, ease of implementation, likelihood of success/acceptance, corporate involvement, distance to core process and check-up frequency. Following that stream, research has recently reviewed EEMs in electric motor systems highlighting specifically several important features to be considered at shop floor when adopting them, in particular with respect to the surrounding environment [18].

On the other hand, performance measurement systems, defined as the set of metrics used to quantify both the efficiency and effectiveness of actions [19], are widespread in industry due to the increasing complexity of firms and organizations. For the purpose of the present study, we will limit our scope exclusively to manufacturing performance indicators, widely accepted in literature to be defined in terms of quality, speed, dependability, cost and flexibility (see, e.g., [20]). More recently, literature has broadened towards the field of industrial sustainability KPIs, with authors [21] highlighting the need to include them in the analysis regarding the adoption of interventions. Garbie [22] and later Cagno et al. [23], designed novel frameworks for KPIs following the economic, social and environmental sustainability pillars. The former [22] operated an extensive literature review introducing in the analysis 79 KPIs clustered in order to cover the three aforementioned pillars. However, despite the innovativeness of the analysis, the resulting framework seems not always able to cover all the pillars and their intersections [23]. To close this gap, Cagno et al. [23] provided three Industrial Sustainability Performance Measurement Systems (ISPMSs), with a decreasing number of indicators, from 104 to 44, to suit different contexts of application, able to cover different areas, ranging from investments to suppliers (economic pillar), from community to health and safety (social pillar), and from water, material or energy to environmental management (environment pillar).

Combining and closely analyzing these frameworks, it appears clear how factors, or even KPIs, despite being intended to describe interventions and their impacts once adopted in any plant, are not always independent one from another, but on the contrary they can be strictly bounded by a cause-effect relationship, which however has not been previously investigated by literature. The present work is intended as a preliminary exploration in this direction, with the aim of shedding the light on these relationships through six case studies performed directly on the field with industrial decision-makers.

Research methods

Considered the difficulties naturally embedded in the process, providing more information may prove to be essential to decision-makers in order to make sound decisions; the first step toward this direction is thus to explore the consequences of the adoption of the interventions in a specific sample of three companies, analyzing criticalities and lessons learned as reported by the decision-makers themselves.

The chosen sample is heterogeneous in terms of i) number of employees, i.e. from small to large firms are considered, ii) energy usage, thus energy cost, including both energy intensive (EI) and non-energy intensive (NEI[1]) firms and iii) sector, analyzing firms belonging to the plastic, the chemical and the wood sectors. This heterogeneity is related to the explorative nature of the study and the willingness to picture the situation with the broader achievable perspective. Regarding the geographic location of the plants, Italy has been chosen, being the second manufacturing country in the EU [24].

As of the EEMs to investigate, a primary distinction should be made between interventions targeting a specific sector and those other applicable in each and every sector, the so-called cross-cutting EEMs [25], referring to four main technologies, that are i) electric motor systems; ii) compressed air; iii) lighting and iv) HVAC. Once more, in order to be able to analyze relationships among different situations, the widest range of available conditions was considered, thus including both type of interventions.

The interviews were conducted following the multiple-case study approach, as described by Voss et al. [26]. Moreover, being the study an exploratory analysis, a structured protocol is almost completely missing in favor of an open discussion, where the interview is faced with wide and open questions.

Each interview is supposed to start from a general introduction, where the interviewee has the possibility to provide a brief description of the company, the status of energy efficiency in the corporate culture, coupled with the presence of certifications, if present, and the role covered. Hence, the EEMs adopted in the past are investigated; interventions that were currently planned for future implementation, even if analyzed in detail by decision-makers, were not considered in the study, given its purpose to describe only impacts empirically verified. In particular, the interviews, after a brief technical description of the performed EEM, moves into the analysis of KPIs, looking at which features are measured, or at least taken into consideration by decision-makers with respect to the specific intervention. Moreover, variations of KPIs, i.e. the impacts coming from the adoption of interventions, are required to the interviewee. Once the performance indicators and their variations are assessed, the discussion turns back to the specific EEM, embedded in the specific context. The purpose is to drive the interviewee in explaining which characteristics, or descriptive features of the EEMs, and which contextual elements, implied that specific impacts on the system as an outcome.

Results from case studies

COMPANY A

Company A is a medium sized plastic manufacturing company (190 employees and an annual turnover lower than 50 million euros), representing the Italian branch of a large multinational company; in particular, they realize plastic medical components through injection molding in controlled environment (cleanroom applications). The main activities performed in the plant are the production, structured in a Job-Shop layout, and stock of finished products. Energy represents a non-negligible share of total costs, higher than 2 %, making the company energy intensive. We have interviewed two key roles for EEM decision-making, such as the energy manager and the maintenance manager. The company also has an Energy and Environmental office with qualified personnel entirely dedicated to these aspects. The company is subject to mandatory energy audits every four years (according to [27]) and is ISO 14001 certified. Nonetheless, their interest in energy efficiency is more related to business motivation rather than environmental conservation, leading to the adoption of a series of EEMs in the last few years, among which:

- Utilize higher efficiency lamps and/or ballasts
- Replacing hydraulic injection molding machines with electric injection molding machines

Utilize higher efficiency lamps and/or ballasts

This EEM consists in replacing existing lamps with more efficient ones, generally compatible with the existing fixtures, characterized by a longer rated life and reduce wattage [28] and no additional maintenance requirements [29]. In case of wide replacement, literature strongly advises to change also the ballasts, reducing the chance of flicker of the strobe effects [30].

In the specific, the intervention also implied a wide replacement for the cleanrooms, while for external areas and other zones of the plant the old lamps were replaced with LED only when exhausted; differently from the industrial suggestion, the original ballasts were kept, being perfectly compatible with the new lamps. Once adopted, the first visible outcome has been a non-negligible reduction in energy consumption, since the lamps in the cleanroom work on a continuing basis, with a forecasted pay-back time of just few years. Consequently, emissions of CO_2 and other GHG gases were reduced as well. The installation of the lamps in the cleanroom was performed during the shutdown of the plant, to avoid disruption in the production. Otherwise, it would be impossible to replace the lamps directly on the operating molding machines with personnel operating on them, as well as the following mandatory cleaning operations. Moreover, as a consequence of the absence of any productive stop, the available overtime remains untouched, together with the utilized level of production capacity. Regarding the type of implementation and the need to carry out frequency check, the interviewees stated that the EEM is a single initial installation with no more checks (except from ordinary maintenance required during its lifetime). The area interested by the replacement of the old and inefficient lamps was quite large, as the number of replaced lamps, explaining why the firm turned to an external supplier for the installation; this choice, in turn, reduced the involvement of internal personnel in the implementation, as well as the technical competences required, which was thus limited to the workforce for cleaning operations (but also maintenance personnel for future activities). The cleanroom applications, characterized by a high level of automation, require only few manual operations, limited to

1. Non-energy intensive firms are those whose energy cost does not exceed 2 % of their turnover [6].

the inspection of finished products before the final packaging. In this regard, the interviewees pointed out an appreciable improvement in lighting which reflected in increased comfort for operators, also enhanced by a reduction in the environmental temperature as a consequence of the adoption of high efficiency cold lamps. Furthermore, company remarked a possible increase of workers productivity, but was lacking to have a thorough measurement or clear feedbacks from the production department. Moreover, the interviewees might agree on the potential avoidance of health or safety issues thanks to the new installation. On the contrary, when asked about eventual variations in the process quality or manufacturing time, the negative answer could be easily explained by the high level of automation and the lack of human's interference in the production processes. Regarding the layout of the lamps, no changes were registered, maintaining the same number of devices despite the better performance, in order to improve the lighting.

Replacing hydraulic injection molding machines with electric injection molding machines

Injection-molding machines represent the most crucial plastic processing machinery, constituting the main energy consuming equipment of plastic processing plants [31]. They are classified primarily by the type of driving system: hydraulic, all-electric, or hybrid, with the first characterized by higher injection rates, larger drive torque and longer hold time, hence are mainly used in high-power and ultra-high-power loads [32], [33]. All-electric machines instead use only high-speed servo motors, resulting in lower energy consumption, shorter cycle time and higher precision, as well as higher repeatability and accuracy of operations and reduced start-up times [33], [34]. Moreover, they do not require oil, thus avoiding leakages and reducing maintenance and cleaning requirements, making these devices optimal for cleanroom applications [34]; However, all-electric injection-molding machines application is restricted due to servo motor power and the cost of large-power machines [32], [34], [35], besides being subjected to higher wear and tear rates [33].

Despite the huge potential energy savings, in the specific case the main driver for the adoption of this EEM was the cleanliness required by the cleanroom applications; indeed, the old hydraulic equipment was connected to episodes of disruption in the cleaning operations due to oil leakages. Nevertheless, the interviewees recognized the efficiency gains not only in terms of energy savings (and related avoided CO_2 and other GHG emissions), but also a reduction in total material use and waste. This was apparent regarding oil, a critical factor with high expenses both for purchase, replacement in the machines, as well as for disposal. Moreover, the interviewees noted that the new machines – due to their higher precision – improved the process quality. This in turn led to an increase of first pass yield and scrap rate reduction, together with the reduction of inspection and control times, and consequently the waste of raw material. Therefore, the adoption of this EEM brought relevant economic and environmental benefits.

Furthermore, company managers noted the improvement in equipment yield and availability, reducing the downtimes and the maintenance operations (especially oil replacement ones, as aforementioned), thus increasing the effective manufacturing time. The cleaning operation has been drastically reduced, with consequent impact on the good production time and production throughput. Dealing with the installation of a new device, the interviewees considered the implementation time required by injection molding machine, including the removal of the old device and the installation of the new one, but also the cleaning of the cleanroom and its consequent re-validation process conducted by the quality department. For the specific case, only limited downtimes in the production were registered, since the EEM was performed during winter shutdown. The scheduling was driven by the long implementation time (about one week), that was deemed unbearable from a company operating on a continuing basis.

The only losses registered were due to the testing and tuning activities, to be performed after the installation, which required a couple of days, however largely recovered by the increased reliability of the new equipment. Nonetheless, interviewees pointed out a connection between the implementation time and the potential productivity disruption, enforced by the core role of the device for the company processes. The same considerations were drawn regarding availability of overtime and utilized level of production capacity. In turn, the interviewees pointed out how an impact on these performances, all connected to the production timing, would likely influence the expectations and satisfaction of customers due to potential late shipments. The installation of the devices was outsourced, nonetheless internal personnel was involved, from maintenance personnel up to production responsible for supervision. Moreover, the revalidation of the cleanroom, certified by official reports, had to be performed by the quality department after the cleaning activities (undertaken by devoted personnel). Furthermore, despite the outsourcing, the interviewees stated this type of EEMs comes intrinsically with a requirement in terms of knowledge and expertise, particularly important in the design phase (involving especially engineering personnel), but also follows the implementation, with new training courses for maintenance personnel. By more closely considering the service phase of the equipment, the new devices directly impacted the working environment, with improvements in the noise and vibration level; furthermore, the hazardous substances were reduced (due to the lack of oil leakages). These aspects could in turn affect the labor productivity and the inspection and control operations, reducing the returned defective products. Moreover, interviewees pointed out an improvement in the safety conditions, due to the replacement of old devices with new ones, characterized by more sophisticated safety systems with respect to the workers operations. Additionally, such remarkable noise reduction could lead to avoidance of earplugs, i.e. personal protective equipment (PPE), still under verification. From a technical point of view, according to literature [34], new devices could have come equipped with a braking regenerative system; this variation is however not mandatory for running the injection molding machine, as stated by the interviewees, who indeed did not opt for this solution.

COMPANY B

Company B is a large chemical company (transformation of resins into paints, 400 employees, annual turnover higher than 50 million euros), representing the Italian branch of a multinational company, located in the north of the country. The production is non-energy intensive. Further, they do not have an energy manager nor an energy and environmental office, being energy-related tasks divided among personnel in charge of other activities. However, they perform the mandatory audit every four year. Despite the limited energy expenditures, they dedicate almost every year a percentage of the budget to the adoption of EEMs, showing that energy culture and attention are strongly consolidated. We have interviewed the person in charge of assessing investments opportunities for continuous improvement, as well as with the supervision of the EEM adoption and monitoring, once the main investment decisions are taken centrally for the European branch. Main drivers for the adoption are the reduction in energy expenditures but also other reasons, such as the need to improve process control or to replace obsolete devices, plus the green image of the multinational company. For the purpose of the present study, the following EEMs were analyzed:

- Replacement of old compressors with new ones equipped with VSD
- Installation of a more efficient boiler

Replacement of old compressors with new ones equipped with VSD

According to the interviewee, the EEM was undertaken due to the presence of an oversized old system, composed of four compressors controlled by a simple on-off strategy, deeply affecting the energetic performance. After closely monitoring the compressed air requirements, it has been decided to replace all the old devices with two new and better sized units, one of which equipped with a VSD, improving also the control strategy. By introducing a VSD-controlled compressor, the company is able to perfectly match the non-flat demand changing speed or torque of the driving unit, avoiding unnecessary machines overload, leading to considerable energy savings. The installation of this EEM improved the equipment control and information level, allowing to instantaneously monitor the compressed air demand, as well as to manage data for decision-making purposes and/or forecasts. According to the interviewee, the yield, availability and reliability have been proved to be higher, in accordance to what noted by previous literature [36]. The EEM has been implemented during holiday period, using the available overtime, in order to prevent disruptions and losses in terms of good production time. Moreover, being the EEM adopted in one single step, no further time slots were required. Since the installation was fully outsourced to the technology supplier, including the design phase of the intervention, personnel in the company were not involved, except for the supervisor who had to be present during the installation. On the other hand, the interviewee pointed out how an additional job training was needed to operate the machine during its service phase, thus updating the working methods, especially for maintenance. Moreover maintenance, which was reduced also thanks to the reduction in the number of operating units, is generally outsourced by the company to the same technology supplier, with only few extra-ordinary corrective maintenance activities performed internally, usually on holidays in order to exploit the availability of overtime (to limit disruptions and reductions of good production time). This is doable thanks to the presence of a back-up compressor, ready to replace a malfunctioning unit in the plant. The interviewee stated they did not appreciate any difference in the working environment, since the compressors are installed away from the main working area, thus avoiding any direct contact with workers and their performance. Nonetheless, the new compressors are identified as less noisy with respect to the old ones and, because of the lower load, their impact on the environmental temperature is reduced. Eventually, when asked about the relationship with the production side of the plant, the interviewee stated that no direct connection are present, since the compressors are isolated and used for services only, i.e. an ancillary process.

Installation of a more efficient boiler

The replacement of the boiler found its justification in the obsolescence of the old device, which was thus replaced by two new and more efficient units, one used at full load to cover the base demand and the other, more flexible, to meet the demand variation along the day. The target of the intervention, i.e. efficiency, was reached, as according to the interviewee they registered reductions in natural gas consumption, although this value should be further analyzed to distinguish the efficiency contribution from the seasonality variations of external temperatures, reflected in the internal heating requirements. The same consideration can be drawn also for CO_2 emissions. Being the new boilers more recent and sophisticated, they are capable of providing higher yield than previous one. As for the aforementioned EEM, the devices are linked to an ancillary process: hence, according to the interviewee, any direct impact on the core process of the plant, i.e. production of paint, is avoided; moreover, indirect impact on personnel performance is missing as well, since the boilers are installed in the technical room, that is separately from the shop floor area. In order to move from a single boiler to a couple of devices, a layout reconfiguration to have larger space might be required: this represented a major concern during the implementation phase. However, in this specific case, the company managed to modify only the expansion vessels and the chimneys, also thanks to the facilitated accessibility to the boilers location, thus not needing more space. Moreover, the layout reconfiguration, performed during overtime as well, implied the involvement of engineers and was deemed as an additional effort that the company had thoroughly considered in advance. Further, the installation of the devices was completely outsourced, therefore avoiding the usage of internal personnel to carry out the task, exception being for the supervision of the work. The interviewee noted that the EEM impacted maintenance with two opposite effects in terms of final results and effort: on the one side, the higher reliability of the new equipment itself enabled them to reduce the frequency of preventive maintenance. On the other side they were forced to increase the corrective maintenance, i.e. the interventions due to unplanned downtimes for breakages, given the higher failures rate due to the additional electronic devices.

COMPANY C

Company C is a small wood manufacturing firm (24 employees and a turnover lower than 10 million euros), located in the North-East of Italy. Its core activity consists in the design and production of buildings and industrial furniture, mainly exploiting local woods and organized according to a job shop layout; they are responsible also for the installation on location. Considering the type of activities performed, the company is classified as non-energy intensive. Furthermore, an energy manager is not present in the plant, nor an Energy and Environmental office with personnel entirely dedicated to these aspects, which on the contrary are managed by the single person interviewed for this case, i.e. the owner himself, who also directly supervised the installation and monitoring of the chosen EEMs. Since the company is neither large (both in terms of people and of revenue) nor energy intensive, an energy audit is not mandatory according to the Italian regulation, and the company has never performed one. Nonetheless, the region in which the company is located places a lot of emphasis on energy efficiency, providing incentives as well as restrictions for the construction of new buildings, both residential and non, and the renovation of the existing ones. The interviewed firm somehow reflect this attitude, investing in energy efficiency when feasible.

Use anti-wear coatings on cutting tools for wood machines

This EEM consists in the substitution of the cutting tools with anti-wear ones. Indeed, the main difficulties in wood machining arise from differences in physical and chemical structures between wood and metals; even if wood has a good machinability, allowing high material removal rate and cutting speed, it contains a considerable amount of water, leading to high corrosion of tools. In order to improve cutting performance, nitrides, carbides and diamond-based coatings have been applied on cutting tools [37], [38], with the optimal solution depending on the specific application.

After the adoption, the company noted a reduction in the electricity consumption, despite not being the main driver for the adoption. Moreover, he pointed out how this reduction could positively affect the company emissions of CO_2 and GHG gases, although the company was not subject to any restriction. On the contrary, the improvement of wear, tear and yield performance were highly appreciated. These, in turn, positively affected other performance: among others, improvements for the first pass yield and reducing scrap rate, defective rate and consequently returned products. Additionally, the reduction of scrap and defective rates implied a reduction in raw materials input and waste disposal. Due to type of production, i.e. on demand, they implemented an internal 100 % control on finished products. However, since the furniture are assembled and installed directly on location, such variations affect an internal performance, but not directly the customer satisfaction. Furthermore, the extension of the useful life of the tools reduced the related inventory levels and tools changeover, and provided enhancement in terms of availability and reliability, which in turn implied a reduction in maintenance requirements. Since the EEM was performed on a core process of the company, a direct impact on the production of the plant was noticed: indeed, the interviewee pointed out a visible improvement in the cutting performance, hence positively affecting the manufacturing time (in terms of increased good production time and reduced set-up time), but also the production throughput.

Beside the direct impact on the production, an interesting consideration was made regarding an increase in productivity due to the improved internal environment, i.e. indirectly obtained from the EEM. After the installation, noise, vibrations and dust level in the air were reduced, improving the working conditions. Moreover, the reduction of vibrations from machines also led to a further increase in process quality, summing this benefit to the quality enhancement aforementioned. Considering the need to periodically revise internally the EEM, based on the wear status, an optimization study has been commissioned in order to find the best compromise between the cost of replacing tools and time for replacing them, which heavily impacts tools performance and maintenance operations, since the replacement of a tool due to wear deterioration is classified as a preventive maintenance operation. Moreover, regarding the knowledge and personnel required for the adoption, the interviewee stated that maintenance personnel alone was enough for the task, i.e. both installation and periodic check of the conditions, exception being for the optimization analysis that required the intervention of qualified engineers.

Eliminate leaks in inert gas and compressed air lines/valves

This EEM consists in detecting and fixing the air leakages in the compressed air system, due to wear and tear for the utilization (or to natural deterioration). One of the major factors driving the issue is the lack of maintenance operations and control of the system status: as noted by literature, holes sharply grow in size and with increasing speed once the leak starts [39]. This EEM is designed in two steps: the leaks detection (e.g. using an ultrasonic acoustic detector or simply listening for noise when the system is in pressure and unloaded) and the leaks repair [39].

This EEM was performed in the past and already re-scheduled for the near future, given the massive use of compressed air in the company, both for operating the machines and for the cleaning operations on the semi-finished products before finishing and assembling them. Leaks were detected through a noise analysis: however, the noisy working environment prevented leaks noise from pipes and joints from being heard; it was in fact the noise heard from the end-user tools, especially when not used, that drove the decision-maker to take action. The first and appreciable consequence from the adoption was the impact in terms of energy consumptions, reduced for both production and ancillary activities. Moreover, as already discussed when considering the previous EEM, such reduction was intrinsically linked to reduction of CO_2 and GHG emissions. Compressed air, despite being an ancillary process, is necessary for operating the machines, thus the adoption of this intervention had an impact on the good production time, despite limited since the leaks repair was mainly performed exploiting available overtime and within a low demand period. Nonetheless, the interviewee pointed out the relationship between these type of interventions with the possibility of production disruption, as they suffered from it, albeit with very limited consequences. The interviewee also argued about the possibility that the EEM implementation could negatively affect delivery due dates if done during a peak demand season, hence leading to customers complaints. Furthermore, he highlighted how the intervention had impact on the production throughput, as well as on manufacturing time and process quality. Being compressed air widely used to actuate production machines, a reduction in its supply would lead to production disruption, with product damage should the stoppage occurred during its machining.

The activity to detect and repair leaks was performed internally, involving only maintenance personnel, who nevertheless gained a direct advantage from this intervention, with reduced maintenance requirements (especially corrective maintenance) for the compressed air system. In this regard, the interviewee noted that the necessary knowledge and expertise to undertake the EEM were already almost completely owned by the maintenance personnel, who only received a short additional training. After the adoption, the interviewee observed a general improvement in the working environment, with a reduction in noise and vibration, but also dust level in the air; he stated that this enhancement might positively impact the labor productivity of the workers. However, due to the low volumes, he was unable to links these improvements to the production performance. All in all, he had good feedbacks for the EEM, and he was already considering about a follow-up; despite according to literature the optimal solution can be obtained through the adoption of a leaks detection maintenance program [39], the interviewee admitted that the company could not afford it in terms of time requirements, so that a repeated implementation was the only feasible possibility.

Discussions and conclusions

Understanding the implications of the adoption of EEMs and their impact on the performance of industrial companies is of critical importance. Such knowledge can be extremely useful for industrial decision-makers, enabling the knowledge of the potential implications of an EEM before implementing it. Further, this knowledge could represent a driver to overcome some of the most influencing barriers highlighted by previous research, such as lack or distorted information or, even more critical, potential risk of disruption when dealing with production processes [7]. Our interviews confirmed the need to consider among the information the distance from the core process, given the different considerations that derived from that, not only in terms of technical risk and fear of production disruption – that play an important role in the decision-making – , but also in terms of motivation and drivers leading managers and responsible to take action. Indeed, while ancillary interventions, such as the ones related to lighting or to the compressed air, were mainly pushed by the willingness to reduce energy consumption taking advantage from a short pay-back time, the EEM in the core process was rather driven by the possibility to improve production through the optimization or replacement of already existing and obsolete equipment. Our preliminary investigation allowed to note that the presence of an energy manager and an Energy and Environmental office with dedicated personnel makes a remarkable difference when it came to discuss about energetic and environmental issues. Consequences regarding the impacts on the environment were strongly perceived in Company A, where indeed the interviewee was responsible for this area; interestingly, they were always correlated by an economic evaluation and the compliance with existing regulations. Moreover, the presence of an energy manager offers to the company a series of advantages related to the exploitation of incentives to perform the installation of EEMs. When considering the difference in company size, smaller companies are usually characterized by greater lack of resources than larger ones [40]. Moreover, most of the performance measurement systems are designed for large enterprises and it has been proved to be difficultly applied to SME [41]. Hence, if the consequences of the adoption of EEMs are not identified and measured through KPIs, the information can be lost, leading to incorrect investment assessments (both in terms of benefits and losses). Differently from literature, the present analysis did not show large differences between smaller and larger companies, but being the sample of limited dimensions, any consideration cannot be generalized. Moreover, the reason may also connect to the fact that a complete list of performance at shop floor level is still missing from literature, thus preventing a comprehensive check of what is considered and what is not. In all cases, a higher interest towards energy efficiency, as well as more specific competences, can be perceived when dealing with production or productivity-related information.

In conclusion, we can point out an important take out from the investigation: what is missing is a tool showcasing impacts from the adoption of EEMs with respect to their specific characteristics, i.e. a framework highlighting on the one side the distinctive features of EEMs and, on the other side, the actual impacts they have on the measured KPIs of a company, taking into account the contextual dimension in which they are embedded. In turn, these KPIs should be extensively analyzed and explained in order to cover all the meaningful areas of the companies, since this information is still missing, as proved by the case studies previously reported, especially when dealing with shop floor performance. This system would prove extremely useful in case of companies with limited internal competence and resources to perform a sound analysis of the interventions, such as SMEs. Moreover, the interest for such a tool would be even greater for non-energy intensive companies, where energy expenditures is just one of the many cost factors of the company, and not necessarily one of the major ones. Thus, providing indication regarding other benefits (and losses) which may be perceived as more critical to the company, could help decision-makers to have the complete picture around the EEM, thus enabling better and more conscious decisions.

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