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Real Adoption of Industrial Energy Efficiency Measures: Need for Empirical Evidence and an Adoption Framework

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ABSTRACT

The lack of information concerning industrial energy efficiency measures represents a critical obstacle towards their adoption, which may be further exacerbated by the presence of additional barriers of an economic nature. The evaluation of energy efficiency measures should therefore be expanded with respect to the techno-economic analysis of energy savings, ~~to be inclusive of~~ by including ~~a series of~~ several other characteristics that ~~serve~~ support the industrial decision-maker ~~to~~ in better understanding their adoption, also in light of the various non-energy impacts they could have on firms' performance. ~~It is o~~Frequently~~ften~~, the identification of ~~deemed that~~ such impacts~~, once identified,~~ may justify the decision on their adoption, especially when referring to critical dimensions for companies, e.g., ~~variations~~ changes in core production processes ~~close to their core business~~. Nevertheless, the investigation of the energy efficiency measures characteristics and their consequent impacts remains ~~still~~ yet unexplored, together with the analysis of the latter as a function of firms' performance, and the present study represents ~~. Therefore, this study should be understood as~~ an exploratory investigation in this direction. From the analysis of the results, ~~it emerges~~ the need to develop a structured framework emerges, designed on theoretical foundations and capable of providing a complete characterization of energy efficiency measures as well as an assessment of all their impacts on firms' performance, identified at the shop floor level. This framework, providing the complete picture of adoption, could represent a valid support for industrial decision-makers as well as ~~for~~ technology suppliers and policy-makers.~~.~~

Keywords: industrial energy efficiency measures, characteristics, impacts, performance.

NOMENCLATURE

Abbreviations	
EEMs	Energy efficiency measures
NEBs	Non-energy benefits
PMS	Performance measurement systems
KPIs	Key performance indicators
ATEX	Potentially explosive atmosphere

1. INTRODUCTION

Despite the first-rate role unanimously attributed to industrial energy efficiency [1], ~~the interventions developed to ensure an appropriate level, called~~ energy efficiency measures (EEMs), are poorly adopted even if at first glance ~~convenient~~ cost-effective [2], leading to the well-known energy efficiency gap [3]. Literature explains this phenomenon through the existence of barriers [4]. They extend over different areas (e.g. lack of skills, technical barriers, behavioural barriers), but the main ones are ~~always~~ often of an informative or economic nature [5].

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To address ~~To face the informative~~ information barriers that are frequently expressed through a ~~, responsible for the~~ higher risk perception ~~of risk~~ and uncertainty ~~often linked to the term of energy efficiency~~, literature has

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highlighted a series of characteristics to better define the EEMs (e.g., type of modification, diffusion progress, lifetime, etc.) [6]. Further, ~~On the other hand,~~ literature has identified the non-energy benefits (NEBs) of EEMs, shedding light ~~have been identified to shed more light~~ on the impacts of their adoption as well as to improve their economic profitability~~, aiming at overcoming both the informative and the economic barrier~~. ~~For instance,~~ To name a few, a structured classification of NEBs was proposed by Laitner et al. [7] and adopted by many other authors (e.g., [8])~~, [9])~~, which identified benefits deriving from the adoption of EEMs in the areas of waste, emissions, operations and maintenance, production and working environment. ~~On the other hand~~However, ~~if the purpose is~~ in order to provide a complete view of the adoption of EEMs, ~~in addition to the benefits,~~ the ~~losses~~ negative impacts coming from the adoption should also be considered [9]; preliminary analyses ~~to this effect~~ have been carried out (e.g., [6]), although a structured study is still ~~absent~~lacking. Since EEMs are implemented within an ~~in~~ industrial ~~environments~~context, ~~the~~ such impacts ~~generated by their adoption~~ should be analysed as a function of the ~~impacted~~ affected performance. The latter, in turn, is usually measured through the development of appropriate performance measurement systems (PMS), including a series of key performance indicators (KPIs) tracked by companies and useful in ~~evaluating~~ assessing the effectiveness of the actions ~~they have~~ undertaken (e.g., [10], [11]). However, although NEBs can be considered as representative of the impacts of the EEMs adoption, their analysis was conducted in parallel with the study of PMS, and ~~no connection~~a link between the two concepts has not been ~~developed yet~~thoroughly explored. Moreover, a complete PMS defined at shop floor level, i.e. first the level at which the impacts coming from the adoption of EEMs are perceivable – and thus on which the decision is made -, is still lacking.~~–~~

More recently, literature moved towards a more integrated analysis of the adoption of EEMs, e.g., by considering impacts and EEMs characteristics at the same time [12]. Despite this, any cause-effect relationships that could link the characteristics to the respective impacts on corporate KPIs have not been highlighted.

Starting from the highlighted research gaps, ~~The~~ the present ~~analysis~~ study ~~fits into these gaps as~~ aims at offering a contribution to the discussion by providing a preliminary and exploratory study to analyse which EEMs characteristics~~, descriptive of the EEMs~~, their application and the industrial context, may have an impact on firms' shop floor KPIs~~, considered at shop floor level~~.

2. METHODS

To consider the variety of contextual facets inherent in the adoption of industrial ~~energy efficiency measures~~EEMs, multiple case studies have been conducted~~, in line with what was theorized by Yin~~ [13]. The preliminary nature of the investigation, together with the aforementioned lack of theoretical frameworks, requires the use of exploratory case studies. They were conducted within a sample of three companies located in the northern part of Italy, heterogeneous concerning sector, energy intensity, as well as size. Indeed, given the exploratory nature of the case studies ~~are explorative~~, the whole set of situations that could potentially be found in industry should be allowed. For the same reason, no limits have been ~~imposed~~ set on the EEMs type, therefore both cross-cutting EEMs, transversal to several sectors, and EEMs specific for particular processes have been considered; moreover, the EEMs involved both production and ancillary processes.

The absence of a theoretical framework led to conducting interviews through open questions rather than through structured or semi-structured analysis. Nevertheless, the interviews were organized to cover a well-defined set of topics in a certain order. Therefore, the introductory section used to describe the company and the interviewee's role is followed by the energy analysis, with a particular focus on energy efficiency. Finally, the most substantial part of the interviews concerns the EEMs adoption and the resulting impacts on firms' performance. The causal links between these impacts and the specific characteristics of the EEMs as well as the context and specific application are then sought.

3. RESULTS

3.1 Company A

Company A is a large metalworking manufacturing company (automatic machines assembly and test) ~~company~~ and it is the national branch of a multinational ~~company~~firm. ~~It belongs to the metal manufacturing sector since they assemble and test automatic machines~~. Despite the high total power installed of about 9 GW, energy ~~consumption is~~ expenditures are lower than 2% of the total annual turnover. Neither energy managers nor an Energy and Environmental office are present in the plant, and the energetic and environmental issues

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are delegated to the facility managerrespondent, who is also the respondent facility manager. Nevertheless, a budget is allocated annually to perform EEMs to keep a good image with the stakeholders.–

Among other EEMs, the firm recently replaced two old air treatment units with newer ones. The EEM was carried out mainly because of the under-sizing of the old systemsunit, which was not always often unable to provide the required amount of air flow, also moreover, suffering from the stratification of air due to the high roof of the plant. The EEM consisted of the replacement of the old air treatment chambers and electric motors with more efficient and correctly sized ones, also equipped with variable speed drives (VSD) to enable the variation of their speed, hence omodulate f the flux of airair flow to be treated and sent to the working environment. The nature of the intervention, i.e. energy efficiency, led to a reduction in electricity consumption, hence indirectly of the CO_2 and GHG emissions. Additionally, due to the new and more performant system, the respondent noticed a reduction in the natural gas used by the boilers to heat the working environment during the winter season.–

However, the greatest improvement made possibleallowed by the increased flux air flowof available air was found observed during the summer season. Indeed, given the massive presence of workers and machines in the working area, the cooling requirements have always been considered more critical than the heating ones. Therefore, the EEM greatly affected also the perceived comfort in the working area, both in terms of temperature and of dust level (i.e., . Indeed, before carrying out the EEM they were forced to keep the doors open to improve the circulation of air, which however was leading to the entrance of dust from the external environment). According to the respondent, the improvement of the working environment and the comfort level positively affected the productivity of workers, with possible impacts, despite hardly quantifiable, on production throughput, manufacturing time, inspection operations and process quality.–

No other impacts were observed concerning production-related KPIs, since the EEM interested concerned the ventilation system, hence an ancillary process. Moreover, the installation did not create any disruption in the production level since the air treatment units are located in special rooms, far from the working area, and exploiting the availability of overtime. The time required for the implementation was approximately two weeks for each unit, including the time necessary for the removal of the old systems. To avoid a complete lack of air, the upgrade of the two units was performed in sequence and during springtime, to avoid extreme weather conditions which would require the entire capacity of the air treatment units. The maintenance team was required To to perform the installation the maintenance workforce was required, moreover affected in with terms of additional training required to carry out the maintenance tasks. In fact, preventive maintenance was scheduled with the aim of reducing wear and tear of the equipment, in turn improving its availability and utilization rate. On the other hand, the design phase required engineering personnel to correctly size the new motors and the expertise of an external consultancy firm to redesign the shape of the air treatment chambers. Overall, a limited corporate involvement was required to carry out the EEMs, given its impact was limited and far from the core business of the firm, and was obtained outsourcing part of the activities.

The presence of the VSD coupled with the motors acted synergically with the facility automated management system which, thanks to sensors embedded in the plant, allows the automatic setting of the right level of air flow. Therefore, if should a greater air flow is be required, this can be achieved simply by regulating accordingly the speed of the motors. Before the VSD installation of the VSD, the amount of air flow could be varied only through mechanical valves which, beside consuming much more energy, needed the intervention of technical staff. Moreover, since motors were undersized and always operating at full capacity, the higher amount of air required by one user could only be obtained by reducing the request of other users, to keep the total air flow constant.

3.2 Company B

Company B is a medium company belonging to the plastic sector. Being Organized organized into a Job shop layout, it produces plastic components and devices through injection moulding. The company, with a ratio of energy costs expenditures over the total annual turnover higher than 2%, is classified as energy-intensive and has a total power installed of 850 KW. Despite the interview was performed with the production manager, the company employs an energy manager who is entirely dedicated to the monitoring of consumptions and environmental impacts.

Few years ago, the company started a campaign to replace the old hydraulic injection moulding machines

with ~~the~~ new electric and hybrid ones, and every year three~~3~~ to six~~6~~ machines are replaced. More than the necessity to reduce the energy consumption, the main factors supporting the choice are related to the cleanness of these machines and their precision due to the servo motors actuation. Therefore, the focus is kept mainly on the business needs rather than on the energy savings.

Nevertheless, the intervention is classified as an EEM, since both electric and hybrid machines are characterized by the reduction of the energetic input compared to the hydraulic ones. Beside the reduction of electricity consumption, the new devices also allow a reduction in the total material use and the consequent waste. In particular, a huge difference is made by the absence of oil, which according to the interviewee represented a critical factor both in terms of expenses and storage capacity. This reduction has direct implications on the amount of waste, therefore on the disposal activities to them connected, and on the water usage for the oil cooling.

The type of activity, ~~that is~~ i.e. the installation of new devices, allowed for an improvement in the production quality. This was achieved for two main reasons: on the one hand, the new machines were able to improve the precision as well as the repeatability and accuracy of operations thanks to the usage of servo motors. On the other hand, the lack of oil prevents oil leaks from dirtying the pieces which, once thrown into the collector, risk dirtying the entire production and the machines themselves. Consequently, since the time wasted for the production and the quality control of defective parts is reduced, the ~~manufacturing~~ machining time is in turn increased. Moreover, the usage of high-speed servo motors might reduce the cycle time of the products, in turn affecting the production throughput and the amount of work ~~in~~ process. The interviewee also noticed a reduction in the set-up times, with a consequent improvement of the maximum production capacity and the utilized level of production capacity. Moreover, the availability of the machines was improved, therefore reducing the probability of production disruption, given the strict ~~dependence~~ impact ~~these~~ of machines ~~have with~~ on the company's core business ~~of the company~~. Consequently, the frequency of corrective but also preventive maintenance operations was reduced. Eventually, replacing the hydraulic machines allowed to drastically reduce the cleaning operations, thanks to the absence of oil.

The implementation time of the machines did not lead to substantial production disruption, since the installation was performed during the period of plant closure. However, this choice strongly affected the availability of overtime, since a huge amount of workforce was required to carry out the installation, also considering the removal of the old equipment and the efforts required for the layout reconfiguration which follows the replacements. Moreover, some electric injection moulding machines were equipped with additional devices, i.e. braking regenerative systems, which however had no further impacts if not referring to the higher reduction in electricity consumption through the energy recovery. Since the installation is not performed in multiple phases, all the effort and impacts are cumulated in the initial operation. Furthermore, the adoption of the EEM was performed using a mixed approach, with some activities outsourced while others conducted by internal personnel. Therefore, if engineers were required to support the design and implementation phases, mainly outsourced, workers and maintenance personnel were involved more extensively and required to take a specific training program. Overall, the corporate involvement was however limited to the people working in the production department.

Eventually, employees were also positively impacted by the improvement in the working environment, since with the new machines noise and vibration levels reported a significative reduction, together with the working temperature thanks to the avoidance of oil heating. Moreover, the safety and health condition of the employees were improved by the reduction of hazardous substances coming from the oil leaks. According to the interviewee, these impacts positively affected labour productivity, despite he was not able to quantify the impact.

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3.3 Company C

Company C is a large company belonging to the chemical sector, with a core business consisting of the production of painting starting. With a total power installed of 2600 KW, with a ratio of energy ~~costs~~ expenditures over total annual turnover ~~are~~ slightly below ~~the~~ 2% ~~of the total annual turnover~~. Every year, part of the budget is used to carry out EEMs and the environmental impact of the firm is monitored by recording energy consumption and the amount of waste produced. An energy manager or an energy and environmental office are ~~not present~~lacking, and the adoption of EEMs is supervised by the

respondent, who is the manager in charge for the continuous improvement of the firm.

In 2019 company C decided to replace the old lamps and ballasts with more efficient ones. Therefore, the EEMs consisted of a wide replacement in two departments and a progressive substitution of the external neon lamps with led lamps. Beside reducing the energy consumption, the firm was willing to improve the lighting level, especially in the potentially explosive atmosphere (ATEX) areas where the number of lamps was also increased. Despite the higher number of lamps, the firm was still able to register an energy consumption reduction. Furthermore, considering that the type of activity was a replacement of the old lamps with new and more reliable ones, characterized by a longer useful life, the firm was expecting to reduce the future number of lamps replacement with respect to the past conditions. This, in turn, would have a positive impact on corrective maintenance, hence on the labour requirements of maintenance personnel.

The improved lighting, especially in the ATEX areas, led to enhanced safety conditions due to increased visibility, which could theoretically reduce the number of accidents in the working place. Moreover, better lighting increased the perceived level of comfort in the working environment; therefore, they would expect benefits in terms of labour productivity, despite they were still not able to identify nor quantify them because the recent adoption of the EEM.

Before the installation, a lighting study was conducted by an external firm to define the position of the new additional lamps. Concerning the installation, it was performed during weekends or exploiting the availability of overtime when dealing with critical production areas. Indeed, despite the distance to the core process, the EEM could have brought disturbances to the production. Differently, the installation in the warehouse was performed during working days by delimiting and making inaccessible the affected areas, however coordinating the activity with the production department to avoid emergencies during the installation. The replacement activity was completely outsourced, not involving personnel of the firm except for maintenance personnel, required for the supervision and the cleaning operations. Therefore, even the corporate involvement required to carry out the intervention was very limited.

~~The relationships between the EEMs characteristics and their impacts on firms' performance which emerged from the case studies have been reported in Fig 1. Knowing the characteristics of the EEMs, decision-makers could have a preliminary idea on which KPIs could be impacted by the adoption.~~

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~~5.~~4. DISCUSSION

The relationships between the EEMs characteristics and their impacts on firms' performance discussed in the previous section have been reported in Fig 1. By knowing the characteristics of the EEMs, decision-makers could have a preliminary idea on which KPIs could be impacted by the adoption.

			EEMs characteristics									
			EEM-related				Application-related			Business-related		
			Objective and type of EEM	Implementation related	Personnel related	Secondary devices	Distance to core process	Extension of the EEM	Sourcing strategy	Sector	Firm size	Energy importance
Impacts on firms' KPIs	Production	Productivity	X				X	X				
		Production quality	X									
		Flexibility	X									
		Production time		X			X	X				
		Downtimes		X			X	X				
	Social	Employees involvement			X			X	X		X	
		Training			X				X		X	
		Working conditions			X							
		Health&safety			X							
	Environment	Water	X							X		
		Material	X							X		
		Energy	X			X				X		X
		Emissions	X							X		
		Waste	X							X		

Fig 1 Exploratory relationships between EEMs characteristics and their impacts on firms' performance.

By ~~Analysing~~ analysing the results of the exploratory case studies, major differences emerge with respect to the scientific literature. In particular, we can note the lack of information regarding the adoption of EEM, which fully justifies the analysis of characteristics by Fleiter et al. [14], likewise highlights its limitations, since analysing

the characteristics without the impacts on firms' performance ~~only highlights half of the picture~~is somewhat limited. Likewise, ~~The same is true vice versa,~~ by analysing only the impacts of EEMs regardless of their characteristcs, as in the case of NEBs, does not provide a full picture. On the other hand, just ~~combining~~ linking together characteristics of EEMs and their impacts ~~is~~ does not look correct. Indeed, what emerges from this analysis is the close causal link that connects them, with the characteristics not only specific to EEMs, e.g., the time of adoption or the type of activity, but also the context and the specific application, e.g., the extension of the EEMs in the plant and their relationship with the production process. For instance, the interview with company C clearly shows the different approach kept in managing the EEM adoption when the lamps to be replaced belong to the warehouse rather than the production area.

Even more evidently, the ~~reason~~ motivation driving the adoption seems to be different when EEMs act on the production process rather than on auxiliary processes. Company B, in fact, carried out the replacement of the old equipment with the express purpose of gaining competitiveness, putting the energy consumptions just in the background, despite the importance energy costs have for an energy-intensive company. This also explained the rationale for performing the interview with the production manager, despite being an energy manager present in the company. Otherwise, when targeting ancillary processes (companies A and C), EEMs are intended to reduce energy consumption and to improve the of environmental conditions. The different approaches, resulting from different impacts, are also perceived based on the characteristic describing the extension of the EEMs. Considering the wide area affected by the replacement of the lamps performed by company C, the EEM was carried out in several stages, to avoid a complete stop of the company. This was done even in the case of impacts on areas not directly devolved to production, as connections to the production requirements might exist, e.g., in the case of the warehouse. A similar dynamic is recorded in company A where, although only two~~2~~ air treatment units are replaced, the impact of the EEM is extended since they supply air to the entire production department. Therefore, even in this case, the adoption is staggered. Differently, ~~in the case of~~for ~~–~~company B, where the number of affected devices is limited, the EEMs are performed contemporarily.

By analysing these relationships and the variety of impacts on firms' performance, from consumption to production, from maintenance to safety, it emerges the idea that the responsible for the EEMs adoption should strictly cooperate with all the other firms' decision-makers responsible for managing and monitoring the entire set of firms' performance at ~~the~~ shop floor level. These performance, moreover, are often not independent one from ~~each~~ another but in turn hide a network of relationships (e.g., the possibility of having an indirect impact on the productivity by acting on ancillary EEMs, through the improvement of the working environment), confirming ~~. This~~ the concept of mutual dependence between KPIs ~~is aligned with the~~ as preliminary analysed~~is, e.g.,~~ by Brundage et al. [15], although a complete analysis at the shop floor level ~~is~~ has not yet been provided~~present~~.

Overall, by considering the lack of statistical evidence and of a theoretical framework on which grounding the results, the preliminary framework in Fig 1 should be viewed as the result of an exploratory analysis. It shed light on the existence of relationships between EEMs characteristics and their impacts on firms' performance and on the need to furtherly explore them, rather than being a practical tool capable to support decision-makers.

~~6.~~5. CONCLUSIONS

Knowledge of the impacts on firms' performance resulting from the adoption of EEMs can be critical for overcoming economic and information barriers, allowing industrial decision-makers to take sound decisions and promoting ~~contemporarily~~ at the same time the adoption of EEMs. From the preliminary analysis conducted on three exploratory cases, the connections between few EEMs characteristics and the resulting impacts on firms' performance emerge. The knowledge of these connections would allow decision-makers to have in advance a map of firms' performance possibly ~~impacted~~ affected by the adoption. Nevertheless, a structured framework capable of highlighting these connections and the entire set of ~~impacted~~ affected shop floor KPIs has not yet been designed. Future research should move toward this direction, focusing on the characteristics descriptive of the context and the specific application, beside the ones proper of EEMs. Furthermore, greater efforts should be made in terms of empirical research, still almost totally absent.

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