A framework to characterize energy efficiency measures

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1. Introduction

Energy efficiency has been widely recognized as a very promising means to tackle environmental issues. Indeed, as shown by the recent revision of the European energy targets [1], a strong boost towards the reduction of energy consumption is needed. This means that future policies should be shaped to obtain a wider dissemination of the so called Energy Efficiency Measures (EEMs) in any sector. In particular, policy-makers should focus much more in promoting energy efficiency within the industrial sector, which covers a consistent share of the delivered energy [2], and is starting to look at energy efficiency as a factor to gain a competitive edge towards developing economies with lower labor costs, as noted by recent research [3].

Unfortunately, the implementation rate of EEMs is so far still very low, as shown by recent research from the Industrial Assessment Center database [4,5], due to the existence of various barriers, some of them, beside the economic ones, related to the information about the EEM, to the organization in which the investment is being made, to the effective implementation phase of an EEM, as widely analyzed by the literature (for most recent contributions, see e.g. [6–9]). The existence of such barriers shows that, beside the very well-known perspectives largely presented when considering EEMs (i.e., energy, environmental, as well as economic ones), some other relevant attributes of EEMs are not sufficiently transferred to industrial decision-makers. In brief, it seems apparent that much greater attention should be paid in providing industrial decision-makers a more comprehensive and helpful view on EEMs, thus presenting the major perspectives characterizing them. This means to show also sufficient indications related to the impact that an EEM has on the production system, its issues related to the effective implementation, as well as its interactions (if any) with other parts of the production system.

For this reason, the present study aims at providing a proposal for the characterization of EEMs, highlighting the most relevant perspectives, then detailed into single characteristics, industrial

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Nomenclature

AC	alternating current
AFD	adjustable frequency drive
ARC	assessment recommendation code
CSC	conservation supply curve
EEM	energy efficiency measure
ESM	energy saving measure
GHG	green house gases
HVAC	heating, ventilation and air conditioning
IAC	industrial assessment center
SME	small- and medium-sized enterprise
VSD	variable speed drive

decision-makers account for when considering an investment in energy efficiency. Moreover, a structured characterization of EEMs also contributes to reduce the mismatch between perceived and real barriers, as greater knowledge would place the industrial decision-maker in facing clearly the effective opportunities and threats. Additionally, the study could result of particular interest also for policy-making purposes, as a greater knowledge on EEMs' characteristics – just the ones industrial decision-makers consider as relevant when undertaking an investment in an EEM – represents a basis for the promotion of most effective policies to increase the adoption of EEMs.

In the next section we will review the literature on existing frameworks to characterize EEMs, highlighting the scientific gaps that we aim to fulfill with the present study. Then we will present the novel framework and discuss the results from the application in an extensive range of EEMs within selected cross-cutting technologies. We conclude our paper with suggestions for further research.

2. Literature review of attributes to characterize energy efficiency measures

This section provides an extensive review of key studies and results on characterization of EEMs. Much of the literature in this area generally focuses on economic features, while few efforts have been made to describe and evaluate topics that might be qualified as other-than-economic attributes. Most of the authors have either itemized lists of attributes or parenthetically noted individual features to promote a particular type of EEMs [10], but very few have taken a comprehensive view. Further complicating the matter, other-than-economic attributes may defy researchers to provide even quantitative estimation of their values. As a result, relatively few have unfortunately stepped beyond the conceptual level and have assigned specific quantitative estimates [11].

Among the studies attempting to characterize EEMs through simple lists of recognized attributes, we can appreciate the contributes of Pye and McKane in 2000 and of Skumatz in 1997 and 2005.

Pye and McKane [12] recognize that quantifying the total benefits of energy efficiency projects helps companies understand thoroughly the financial opportunities of investments in EEMs. They argue that energy savings alone are not primary drivers in industrial decision-making and therefore energy savings should be viewed more correctly as part of the total benefits of an energy-efficiency project, rather than the focus of the results. Unfortunately, Pye and McKane do not provide a rationale behind the choice of these potential benefits beyond energy savings and they simply itemize features such as increased productivity, reduced costs of environmental compliance, reduced production costs (including labor, operations and maintenance, raw materials), reduced waste disposal costs, improved product quality (reduced scrap/rework costs, improved customer satisfaction), improved capacity utilization, improved reliability and improved worker safety. By means of this broader set of parameters and some empirical evidence, the authors believe that energy-efficiency advocates will certainly gain more credibility with the industrial sector, yet it is critical to support the claims with quantitative results of the effective potential. Furthermore, in order to make a more compelling case for energy efficiency and pollution prevention, it is also critical to understand the decision-making process of business management which, in turn, means to "understand the interrelationships of various forms of efficiency, and measuring costs and benefits so that the financial ramifications of our proposals are fully understood and can be communicated to management in terms with which they can identify" [12].

Skumatz has long been studying methodologies for a formal evaluation of "hard-to-measures" attributes of EEMs [11,13]. Based on the results of several dozen of projects completed over the last decades, the author has developed and pioneered methods for measuring non-energy impacts – both positive and negative – from commercial and industrial energy efficiency programs. Unlike the work presented earlier, it is worth noting that, not only the author does address quantitative benefits as perceived by customer/participants, but also recognizes that non-energy benefits accrue to three different "perspective" or groups, including: (1) utility, ratepayer, and shareholder perspective; (2) societal perspective; (3) customer or participant perspective. In particular, focusing on the "commercial and industrial participants" category, Skumatz [13] lists about 20 non-energy benefits: water/wastewater bill savings, operating costs, equipment maintenance, equipment performance, equipment lifetime, productivity, tenant satisfaction/fewer tenant complaints, comfort, aesthetics/appearance, lighting/quality of light, noise, safety, etc. Regardless of the length of the list, the author acknowledges that the list is not comprehensive and suggests that, perhaps, it should be refined case by case depending on which measures are to be considered. As aforementioned, Skumatz [13] has examined a number of different approaches to measure non-energy benefits from the participant perspective. Nonetheless, for the vast majority of participant impacts, the surveys methodology is needed. Through nearly a decade of research, the author has tested and refined several approaches, such as willingness to pay, willingness to accept and relative scaling questions. The empirical findings clearly show that, even if utilities may run energy conservation programs to reduce energy use, and the commercial/industrial sector may adopt EEMs, the energy savings alone may not be, and appear not to be, the highest valued outcome to adopters.

The second stream of literature about characterization of EEMs is made of studies trying to take a step beyond the presentation of list of attributes, thus providing a framework able to incorporate a more general set of attributes.

Mills and Rosenfeld [10] study the role of "additional benefits" for building EEMs, and provide a framework for understanding the many benefits of energy efficiency investments that extend beyond the energy bill savings alone. Although they recognize the national-level benefits (e.g., improved competitiveness, energy security, net job creation, and environmental protection) as important, the authors provide a detailed description of user benefits made possible by EEMs. The following seven categories are identified: improved indoor environment, noise reduction, labor and time savings, improved process control, increased amenity or convenience, water savings and waste minimization, and direct and indirect economic benefits from downsizing or elimination of equipment. The authors note that these non-energy benefits play a key role in consumer decision-making. In fact, they point out a crucial factor: efficient technologies provide equivalent services at lower costs, but non-energy benefits add value or enhance services from efficient technologies. As a result, where certain market segments are not sensitive to economic arguments (e.g., as shown in the split-incentives dynamics, [14–16]), non-energy benefits can assume a special importance. Therefore, efforts to incorporate them in program design and marketing will help accelerate the uptake of EEMs.

In 2003, Worrell et al. [17] argue for including "productivity benefits" explicitly in the assessments of EEMs as this would double their cost-effectiveness and economic evaluation. Still, Worrell et al. point out the widespread omission of these benefits in most studies of EEMs. The authors rearrange the attributes, proposed by Mills and Rosenfeld [10] into five main categories: reduced waste, lower emissions, improved maintenance and operating costs, increased production and product quality, and improved working environment. It should be noted that Worrell et al. add an "other" category in order to identify those benefits that are outside the other categories but still worthy of noting. Some examples are decreased liability, improved public image, delaying/reducing capital expenditures, additional space, and improved worker morale. Once the categories are established, the authors put forward a standard framework for analyzing the productivity benefits through the use of energy conservation supply curves (CSC). However, Worrell et al. recognize that, while including these productivity benefits is important, and CSC provide an effective means for including them in an analysis, estimating the magnitude of these benefits can be difficult. Consequently, they are confident that, by following a standard framework, the cost evaluation of productivity benefits is formalized and transparent. All in all, the transparency of this evaluation framework is important both to give credibility to calculation and to provide flexibility to a user looking to apply the CSC framework to another scenario.

Similarly, Lung et al. [18] examine the importance of "ancillary savings" resulting from EEMs adoption in industrial facilities through the use of energy CSC. The term "ancillary saving", somewhat different from the "non-energy benefit", refers to "all quantifiable cost savings that result from an ESM (energy saving measure, i.e. EEM) that are not part of the energy savings from that improvement" [18]. Nonetheless, beside this slightly different terminology, Lung et al. apply the same approach proposed by Worrell et al. [17] to a large dataset of energy-efficiency projects. The EEMs' attributes are reduced to five categories, one of which is still the "other" category. These include: operations and maintenance, production, work environment, environment, and other (such as achieved rebate/incentive, reduced/eliminated demand charges, reduced/eliminated rental equipment costs, avoided/delayed costs).

The most recent contribution in categorizing EEMs is provided by Fleiter et al. [19], who, starting from a thorough review of the previous contributions in the literature, have provided a first rationale behind the categorization of the EEMs attributes, considering, as selection criteria: relevance, applicability, specificity, independence and distinctness. The authors then list twelve attributes grouping them into three areas: relative advantage (internal rate of return, payback period, initial expenditure and non-energy benefits), technical context (distance of core process, type of modification, scope of impact and EEM lifetime) and information context (existence of transaction costs, needed knowledge for planning and implementation, diffusion progress, and sector applicability). Table 1 summarizes the relevant features of each contribution in chronological order.

The review of both previous studies on EEMs benefits, as well as earlier characterization frameworks suggests some interesting considerations. Firstly, from a methodological point of view, a discordance about how to group the attributes within categories there exists. In fact, the same attributes, grouped in a certain category by an author, are sometimes split up and then aggregate again within other categories by another author. For instance, regarding indirect benefits, Mills and Rosenfeld [10] define two distinct categories for "improved indoor environment" and "reduced noise", whereas Worrell et al. [17] cite "reduced noise level" as pertinent to the "working environment" group. Moreover, Lung et al. [18] aggregate "waste" and "emission" reduction, proposed by Worrell et al. [17] within "environmental" benefits. Moreover, only Fleiter et al. [19] started to provide in an explicit form a rationale behind the selection of the attributes.

Secondly, none of the studies have clearly identified who might be responsible and involved in the decision-making process. This characteristic is very relevant since it might affect the effective success from the implementation of an investment in a given EEM.

Thirdly, we should start at noting that all the studies agree on the importance of encompassing all possible EEMs' impacts. In fact, including non-energy attributes explicitly in the modeling parameters would double the cost-effective potential for energy-efficiency improvement, compared to an analysis excluding those benefits [17]. Therefore, an omission of these features results in an incomplete understanding of the benefits that are derived from energy efficiency initiatives and of the impact of energy efficiency on firm's profitability [12]. Nonetheless, even the most recent contribution in the literature by Fleiter et al. [19] does not provide a detail of the non-energy benefits, limiting to pointing out their possible existence.

Fourthly, the authors also agree that giving any reliable evaluation of some attributes is an extremely critical aspect. For instance, attributes such as improved working conditions, better worker safety/morale, reduced noise levels, or improved air quality benefit are not easily quantified [20]. Hence, assumptions will be needed to translate the benefits into a comparable cost figure and thus the evaluation turns out to be rather subjective [17]. In addition, as noted by Lung et al. [18], some attributes are not achieved consistently. That is, while such benefits often accrue in the wake of an energy-efficiency improvement, the same benefits may not be obtained each time a project is implemented.

Fifthly, the efforts attempt to quantify non-energy attributes in the literature seem to be dispersed. Indeed, Mills and Rosenfeld [10] clearly limit their analysis to the identification of possible non-energy attributes without making any attempt to quantify them. Pye and McKane [12], instead, try to evaluate the avoided non-energy costs brought by the adoption of some EEMs. A remarkable approach is provided by Worrell et al. [17] who pioneer the path toward a mathematical procedure to include productivity benefits into energy CSC, rather than providing a methodology to quantify the benefits. Likewise, Lung et al. [18] provide other evidences favoring the integration of ancillary benefits in the construction of energy CSC. Skumatz [20] refines four different techniques (i.e., willingness-to-pay/accept, contingent evaluation, relative valuations as well as scaled valuations) for measuring non-energy benefits though surveys dedicated to participant of demand-side management programs. Finally, Fleiter et al. [19] interestingly adopt a morphological box to attempt to provide an evaluation of the attributes.

Sixthly, we can observe that so far the perspectives industrial decision-makers consider as relevant when evaluating an EEM are not fully represented in any of the previous literature contributions. For instance, if we should acknowledge the valuable contribution offered by Worrell et al. [17] in detailing the productivity benefits, nonetheless we should also recognize that the study does not focus sufficiently on other relevant perspectives, e.g. the implementation one. Again, other authors group attributes according to "areas" (Fleiter et al., [19]), but, if on the one hand they tend to present the "policy-making" perspective, on the other hand they do not consider very relevant perspectives, such as the energy and environmental-related ones.

In summary, many valuable contributions in the literature can be found, but an all-encompassing characterization framework is still needed, since the previous works are missing some features spotted in other studies.

3. A novel framework to characterize EEMs

Taking the suggestions from the literature, the following section presents a thorough description of the perspectives, then detailed into attributes, upon which the characterization framework is built.

In selecting and describing the attributes, we have followed the selection criteria proposed by Fleiter et al. [19]. Indeed, it should be noted that our categories have not been created simply by a random aggregation of basic attributes. Instead, we have tried to comply with some assumptions proper of the knowledge-representation science [21,22]. In this regard, we may define the characterization framework proposed in this study as an attribute-value system. For instance, our categories were firstly intended to deal with the broadest array of attributes characterizing any EEM. In doing that, we have referred to the perspectives industrial decision-makers consider as most relevant when undertaking an investment in an EEM. In fact, beside energy, environmental and economic issues, industrial decision-makers necessarily require adequate detail on the impact an investment has on the existing production system, on the effective implementation issues to be addressed, as well as the interaction an EEM might have with other parts of the production system. Secondly, our categories were borne from an aggregation process of simple attributes. Thirdly, we attempted to minimize the degree at which categories overlap with each other. Fourthly, the list of categories is neither lengthy nor short in order to provide a right balance between, in turn, not being redundant or conflicting.

Nonetheless, it is apparent that some attributes might present some common elements. Indeed, we want to point out that the choice of such attributes has been made to point out the perspectives deemed as most relevant by industrial decision-makers when evaluating an EEM. In this regard, the categories in which we have grouped the attributes represent such perspectives. In fact, it is clear that attributes expressed differently (e.g., amount of energy saved expressed in physical units versus monetary energy savings), although reflecting the same phenomenon, i.e. an energy saving, might have different impact on different decision-makers, according to their attitudes and mindset.

In the following, we will provide the description of our framework, grouping the attributes according to six categories: economic, energy, environmental, production-related, implementation-related and indirect attributes.

3.1. Economic attributes

Payback time: the payback criterion continues to be widely used in industry since it is regarded as simple, easy to communicate and intuitive [23]. Hein and Blok [24] report that all the 50 firms, surveyed in their study, used the simple payback criterion. Moreover, Alhourani and Saxena [25] conducted a logistic regression analysis on 147 reported energy efficiency projects and they found that the probability of implementing a suggested EEM is mainly dependent on the payback period.

Implementation costs: as noticed in Martin et al. [26], the most promising technologies are characterized by lower initial costs. Implementation costs, such as adaptation costs, engineering/contractor fees, equipment purchases, might be particularly critical for SMEs. In fact, Woodruff et al. [27] found that first costs appear to be even more important than payback periods on implementation rates. They also explain that SMEs are likely to be more capital constrained than larger establishments and are thus less able to invest in even those higher cost measures that have very short payback periods.

3.2. Energy attributes

Resource stream: if industrial enterprises are assumed to choose the cheapest energy sources (and thus, fuels) available to them, the knowledge of which type of energy, either directly employed or indirectly influenced by an EEM, is essential in order to predict possible responses to changing fuel prices. Moreover, the type of energy employed shapes the mix of fuel consumption in the industrial sector and thus the related air pollutant emissions [28].

Amount of saved energy: Anderson and Newell [5], through a statistical analysis of a large database containing information on energy audit recommendations, bring some evidences that firms seem to be more responsive to energy savings based on the quantity of energy conserved than to energy prices. At this point, redundancy may be claimed since the payback time is mathematically linked both to the energy savings and the implementation costs. Nonetheless, from a bounded rationality perspective which implies non-perfectly rational behaviors [23], the three attributes might have different impacts on energy efficiency investments.

3.3. Environmental attributes

Environmental attributes refer to reduction in either air emissions or in waste streams that result from the adoption of EEMs [26]. As noted by Atkins in an assessment of UK small business [29], when asked to consider the association between good environmental practice and real business benefits, the majority of participants believe that environmental good practice and business success are linked. Therefore, smaller businesses are clearly asking for more information and advice on environmental issues in order to make positive changes.

Emission reduction: given the present need to meet the Kyoto targets, it is straightforward to highlight whether an EEM will help a firm to comply with or anticipate GHG emission regulations. The cost of complying with environmental regulation can be an important driver in the decision to invest in particular EEMs, especially in the non-attainment areas [26]. A part form GHG emissions, following Worrell et al. [17], dust emission reduction is also included here.

Waste reduction: Ilomaki and Melanen [30], in a study focused on waste minimization practices of 41 Finnish SMEs, argue that improvement of the company image as a result of waste reduction practices are generally seen as an asset. Hence, if an EEM yields to decreased waste amounts it is actually adding value to the firm.

3.4. Production-related attributes

Productivity: manufacturers' primary motivation is to keep their production operating because this generates their income and increases shareholders' value. Anything, including a seemingly simple EEM, that can be perceived as threatening this primary motivation needs to be carefully brought to the decision-maker [31]. Porter and van der Linde [32] claim that it is a common occurrence that the search for energy efficiency leads to productivity improvements. Furthermore, Boyd and Pang [33] provide

Table 1
Synthesis of the literature review on earlier characterization frameworks.

Source	Type	Framework		
Mills and Rosenfeld [10]	Grouped	Improved indoor environment	Reduced noise	Labor and time savings
		Reduce indoor air pollution, enhance thermal comfort, or improve factors associated with health or safety, such as the ability of exhaust heat recovery systems to decrease the likelihood of insufficient ventilation rates	Reduced noise levels, such as the sound-insulating value of highly-efficient windows	Lower maintenance costs, improve productivity because workers have an improved environment, or reduce the amount of time required to do a task, exemplified by the more rapid cooking time offered by microwave ovens
		Improved process control	Increased amenity or convenience	Water savings and waste minimization
		Enhance the control of a process, such as the use of variable-speed motors to improve the quality and uniformity of a manufacturing procedure or halogen-lamp cooktops to improve control over cooking	Enhance the quality of energy services or the functionality of the end-use device, such as, electronic ballasts eliminate flicker and noise from lighting systems	Less water use, such as horizontal-axis clothes washers, which require less water and detergent
		Direct and indirect economic benefits from downsizing of equipment		
		Measures such as HVAC equipment (direct) and distribution system (indirect) downsizing made possible as a result of reduced solar gain through windows, from lights and plug loads, etc.		
Skumatz [11,13]	Listed	Water/wastewater bill savings; Operating costs (non-energy); Equipment maintenance; Equipment performance (push air better, etc.); Equipment lifetime; Productivity; Tenant satisfaction/fewer tenant complaints; Comfort; Aesthetics/appearance; Lighting/quality of light; Noise; Safety; Ease of selling/leasing; Product losses (mostly refrigeration at grocery); Labor requirements; Indoor air quality; Health/lost days at work; Doing good for environment; Reliability of service/power quality; Savings in other fuels or services (as relevant)		
Pye and McKane [12]	Listed	Increased productivity, reduced costs of environmental compliance, reduced production costs (including labor, operations and maintenance, raw materials), reduced waste disposal costs, improved product quality (reduced scrap/rework costs, improved customer satisfaction), improved capacity utilization, improved reliability and improved worker safety		
Worrell et al. [17]	Grouped	Waste	Emission	Operations and maintenance
		Use of waste fuels, heat, gas Reduced product waste Reduced waste water Reduced hazardous waste Materials reduction	Reduced dust emissions; Reduced need for engineering controls Reduced CO, CO2, NOx, SOx emissions	Reduced need for engineering controls; Lowered cooling requirements; Increased facility reliability; Reduced wear/tear on equipment; Reductions in labor requirements
		Production	Working environment	Other
		Increased product output/yields Improved equipment performance Shorter process cycle times Improved product quality/purity Increased reliability in production	Reduced need for personal protective equipment;Improved lighting; Reduced noise level; Improved temperature control; Improved air quality	Decreased liability; Improved public image; Delaying or Reducing capital expenditures; Additional space; Improved worker morale
Lung et al. [18]	Grouped	Operations and maintenance	Production	Work environment
		Reduced maintenance costs; Reduced purchases of ancillary materials Reduced water consumption; Lower cooling requirements; Reduced labor costs Lower costs of treatment chemicals	Reduced product waste Increased production Improved product quality Increased production reliability Shorter process/cycle time	Increased worker safety Reduced noise levels Improved workstation air quality
		Environmental	Other	
		Reduced hazardous waste; Reduced dust emissions; Reduced waste water output; Reduced CO, CO_2, NOx, SOx emissions	Achieved rebate/incentive (one-time) Reduced/eliminated demand charges Reduced/eliminated rental equipment costs Avoided/delayed costs (one-time)	
Fleiter et al. [19]	Grouped	Relative advantage	Technical context	Information context
		Internal rate of return Payback time period Initial expenditure Non-energy benefits	Distance to core process Time of modification Scope of impact Lifetime	Transaction costs Knowledge for planning and implementation Diffusion progress Sectorial applicability

statistical support that energy intensity and productivity have at least a proportional link.

Operation and maintenance: as it emerges from Lilly and Pearson [34] who analyzed a set of industrial energy efficiency projects, the uptake of EEMs led to lower maintenance costs and replacement costs of related components. Most of the quantified ancillary savings are recorded in situations in which less equipment and machinery are in use after an EEM is adopted [18].

Working environment: occupants who are satisfied with the overall environmental quality of their workspace are widely assumed to be more productive [35]. In accordance with Abrahamsson [36], working environment issues should be regarded as production-related since there is a strategic advantage: it becomes natural to regard the expenditure as investment rather than "working environment costs" and to question and modify the conditions that give rise to working environment problems.

3.5. Implementation-related attributes

Saving strategy: as suggested by Vidmar [37], it should be distinguished between "pure energy efficiency" and "energy conservation". He points out that an important way to view the difference is what happens to the ratio useful output over energy input: conservation achieves reduction in energy use by reducing both the output and input of the system, while pure efficiency reduces consumption while having the same result from the system.

Activity type: this feature distinguishes if an EEMs (intended either as technology or practice) constitutes: (i) a simple refurbishment or recovery of the existing functions; (ii) an optimization in the use of an existing technology; (iii) an equipment retrofitting; (iv) a new energy-efficient equipment installation. According to Worrell and Biermans [38], the knowledge of such a feature is important to differentiate the decision-making behavior. For instance, Sandberg [31] suggests that simple refurbishment or pure retrofit investments may be easier to make, respect to new equipment purchase, because the conditions remain almost the same. Finally, taking suggestion from previous research of Cagno and Trianni [6], and Cagno et al. [39], it is important to distinguish between recovery, optimization, and innovation EEMs, due to their different impact within the production system.

Ease of implementation: this attributes indicates how easy it is for the people involved to accomplish the EEM properly. As described in [40], the implementation may be: (i) easy, when the implementation requires only minimal effort, no extra skill are need, does not present tricky factors; (ii) routine, when still not much effort or skill required, however operators may need to learn a new procedure in order to install correctly the measure; (iii) difficult, if it needs major staff effort since the procedure may be tricky, or it could be even hard just to find reliable contractors. (iv) very challenging, when the implementation can be unpleasant, and even likely to be resisted.

Likelihood of success/acceptance: Martin et al. [26] point out that it is difficult to predict how likely a technology is to be successful since certain technologies reach different efficiency levels depending on local conditions, including the quality of inputs and style of operation (e.g., plant availability and maintenance methods). Therefore this attribute indicates the likelihood that an EEM will remain effective throughout its promised service life.

Corporate involvement: successful adoption of EEMs means in some cases more than just installing few pieces of equipment, as it may require to make people at all levels aware of efficiency goals [41], thus with a wider corporate involvement of the whole production unit. Whilst, in some cases only few people could be involved (e.g. the maintenance staff). Hence, it is important to identify the people affected by the establishment of an EEM, since it will help the company to design a better strategy toward a successful implementation [31].

Distance to core processes: as described by Fleiter et al. [19] and empirically pointed out by Thollander and Ottosson [42] and Dieperink et al. [43], the distance to the core process might be a major factor influencing the adoption of an EEM from a technical perspective, in particular related to its effective implementation.

Check-up frequency: as noted by Wulfinghoff [40], the adoption of some measures can be considered as a one-time effort while others require periodic check. EEMs within the former type, once installed, remain fully functional throughout the service life. However, others may requires continuing management attention and periodic check, e.g., in case of reflectors and lamps to be regularly cleaned.

3.6. Interaction-related attributes

Indirect effects: as pointed out by Mills and Rosenfelds [10], e.g. cross-cutting technologies are not stand-alone systems. Some EEMs primary intended to enhance energy efficiency within a particular area may display effect on components belonging to other systems. In fact, a particular measure may enhance the quality of the energy service, improve the functionality of other end-use devices or even effect the load of other systems. Typical examples are the interactions between: (i) electronic ballasts and lamps, (ii) motors and HVAC loads; (iii) variable speed drives and the electricity distribution system.

4. Application of the novel framework

In the following we apply the framework to an extensive range of EEMs in cross-cutting technologies. Before, we will briefly provide explanation of the rationale behind the choice of the selected EEMs and the research to better describe the selected EEMs.

4.1. EEMs in cross-cutting technologies

4.1.1. Selected cross-cutting technologies

Although the approach described in the present study could be applied to any EEMs, we have decided to analyze four cross-cutting technologies, as they are of great interest due to their wide diffusion across industries of different sectors [44], and improvements in such systems are easily replicable among, e.g. SMEs [26], but also as they are accountable for a considerable share of the energy not directly related to the production processes.

In fact, **electric motor systems** account for a considerable proportion of total power consumption, being responsible for about 69% of industrial power consumption in EU [45]. Furthermore, it should be emphasized that a standard motor is already an efficient device with efficiency above 80% over most of the working range, rising over 90% at full load [46]. However, according to estimates [47], adopting existing well-established EEMs would result in savings of approximately 11–18%, and in turn would push down the total environmental cost of electricity generation [48]. Specifically, systems driven by AC induction motor are the focus of the characterization, because they represent more than 90% of the motor electricity consumption [45].

Compressed air is widely used throughout industry, and is often considered as quite relevant in many facilities [49]. It accounts for as much as 10% of industrial electricity consumption in the EU, 10% in US and 9.4% in China [50]. However, it is probably the most expensive form of energy because of its poor efficiency, typically about 10–19% [41,50]. For instance, the cost of electric power operating an air compressor continuously for a year is usually greater than the initial price of the equipment. From this perspective, any effort to reduce energy consumption pays for itself immediately and produces ongoing savings [51].

The importance of **industrial lighting** can be appreciated both in terms of safety (due to the need to provide adequate visibility so that materials can be transformed into finished products without hazards for the operators executing the tasks [52]), but also in terms of energy consumption. In fact, although representing generally a few percentage in the industrial energy consumption, it is a large amount in absolute terms [41]. Nonetheless, only a small part of the energy used in lighting luminaries is for lighting; the remainder is lost as heat [52]. So, even when lighting is a relatively small part of a plant's energy use, it may be possible to find considerable energy savings from using more efficient lighting systems.

Finally, **HVAC systems** can cover a consistent share of the industrial energy consumption due to their primary role both being submitted to the production processes, but also in providing a comfortable environment to the operators. They are also quite relevant for the processes and various cost-effective opportunities for energy saving are widely known [40].

4.1.2. Identification of EEMs in the selected cross-cutting technologies

Although there exists a large volume of literature on EEMs for homes and some categories of public and commercial buildings such as offices, hotels, hospitals, shopping centers, school and college facilities, sports centers and even airports, there exist much fewer comprehensive reviews on EEMs in cross-cutting technologies for the industrial sector [53]. The first step toward a thorough characterization of EEMs was to collect information on a broad "universe" of potential measures. The search was exclusively restricted to the publications which were available in full-text only. Furthermore, the information has been sought according the two principles of quality and recentness. First, in order to ensure the quality of information, the key sources included only academic articles (both peer-reviewed articles and conference proceedings), Government reports and published books. Then, the time span was restricted to the latest 15 years to ensure that our assessment focused only on recent researches. It is, however, important to note that exhaustiveness of our review may not be claimed and some promising technologies might have likely been overlooked.

The review allowed to identify 192 EEMs. The information gathered has been transferred to the same degree of detail, according to the standard defined by the United States Industrial Assessment Center [54], obtaining 88 EEMs. In Table 2 we report the description of the identified EEMs as well as the literature used (respectively in columns 1 and 2).

4.2. Application of the novel framework on EEMs in selected cross-cutting technologies

For the identified EEMs, we have performed an additional literature review of the studies providing qualitative judgments and quantitative evaluations of the attributes associated to each EEM.

The result of this extensive and thorough review has been reported in Table 2 (with the corresponding references in the last column). Nonetheless, some clarifications for the process of evaluating EEMs attributes are needed.

Firstly, attributes such as initial cost, payback time, waste reduction, emission reduction, operation and maintenance, productivity, working conditions and indirect benefits, have been evaluated exclusively when information was supported by quantitative estimations.

Secondly, when available, quantitative and qualitative evaluations considering the other attributes (e.g. ease of implementation and check-up frequency), have been favored and reported.

Thirdly, considering the type of activity, it is apparent that both in terms of technologies and practices (procedures) we can distinguish between recovery and refurbishment, optimization of the existing equipment, retrofit of an existing equipment and complete new installation. Nonetheless, at a first approximation, we have decided to not perform this distinction between procedures, as a greater shading can be found. For example, considering ARC. 2.7311 (Shut off ventilation system when room is not in use), we have no elements to express whether this practice should be introduced from the beginning, or represents the optimization of an already existing procedure, or even if the procedure is in place, but simply not adopted. Considering the technologies, it can be easily claimed to operate a distinction between recovery, optimization, retrofit or complete new installation. It is rather more difficult to distinguish between a refurbishment (e.g. ARC 2.4154, Avoid rewinding motors more than twice) and the needed procedure, as they result strictly related, and from the ARC the distinction does not seem that can be claimed. Therefore, we have decided to mark refurbishment EEMs as procedures. Finally, attributes as corporate involvement, resource saved and distance to core processes have been evaluated upon authors' experience, being aware that might be subject to specific cases. As an example, in case of ARC 2.4111 (Utilize energy-efficiency belts and other improved mechanisms), it is apparent that the distance to core processes might not be clearly evaluated, as it depends whether the less efficient motors are related to production processes or to ancillary systems. Analogously, the level of the needed involvement of the maintenance staff to evaluate some EEMs might depend on many factors, such as firm's size.

In the following we present the application of the novel framework to four EEMs in the selected cross-cutting technologies (extracted from Table 2) and discuss them. Of course, it should be pointed out that the framework has been oriented to provide suggestions to industrial decision-makers as well as policy-makers on the most relevant features of EEMs' characteristics, trying to provide a set of useful perspectives to analyze them. This necessarily implies that, during a proper design phase of an investment in a particular EEM, a more accurate and tailored evaluation about the identified feasible measure is however required.

4.2.1. ARC 2.4143: use AFD to replace throttling system

The replacement of the throttling system through the adoption of an adjustable frequency drive (AFD) can be considered as an efficiency EEM, and represents a retrofit of an existing equipment. It is rather a simple measure, whose implementation requires from 10 to 70 labor hours, depending on system size and complexity [69], and can be either strictly connected to the core production processes or more related to ancillary services. Moreover, as pointed out by Saidur [69], modern variable speed drives (VSD) systems are affordable, reliable, flexible, and offer significant electrical energy savings (37% less energy according to Ferreira,[70]), and with a very high likelihood of success. Furthermore, its return has been estimated from few months to about 3 years [46,69], in any case less than one third of the motor service life, depending on average speed reduction. In addition, it is a one-time EEM that does require a minor corporate involvement, typically the maintenance staff, and presents medium implementation costs. Finally, it can be interestingly noted that the installation of AFD has several environmental benefits: indeed, authors estimate an about 30% reduction in non-hazardous waste, and about 37% of GHG reduction, with a low dependency on the motor rated power [70]. This EEM provides also benefits in terms of reduced wear on mechanical equipment [71] (with consequent reduction of operation and maintenance activities), a tighter control of the process (increased productivity) [71,72], and a reduction of worker noise exposure [17], leading to an improvement in the working environment.

Table 2
Synoptic table: the characterization framework applied to the EEMs in selected cross-cutting technologies.

ARC	Cross-cutting technologya	Description	Ref. description	Economic		Energy		Environmental		Production-related			Implementation-related							Inter.	
				Pay-back time[b]	Implementation Costs[c]	Resource Stream[d]	Amount of Saved Energy[d]	Emission reduction[e]	Waste reduction[e]	Productivity[e]	Operation and Maintenance[f]	Working Environment[f]	Saving strategy[g]	Activity Type[h]	Ease of Implementation[i]	Likelihood of success/ acceptance[c]	Corporate Involvement[j]	Distance to core processes[k]	Check-up frequency[l]	Indirect effects[e]	Ref. attributes
2.4111	M	Utilize energy-efficient belts and other improved mechanisms	[55–58]	S	M*	E	L*	N/A	P*	P*	I*	I*	E	R	Dep*	H	L	C/D	O	N/A	[55,58–60]
2.4112	M	Install soft-start to eliminate nuisanse trips	[54–56]	L*	H	E	L*	N/A	N/A	P*	D*	I*	E	N	Diff*	M*	L	C/D	O	P*	[17,59,61]
2.4113	M	Install motor voltage controller on lightly loaded motors	[41,54,56,62]	L*	M	E	L*	N/A	P	P*	D*	I*	E	N	Diff*	L*	L	C/D	O	P*	[17,55,59,61]
2.4131	M	Replace over-sized motors and pumps with optimum size	[57,63]	M	H	E	M*	N/A	N/A	P*	D*	I*	E	R	Diff*	M*	L	C/D	P	P*	[41,47,63,64]
2.4132	M	Size electric motors for peak operating efficiency	[55–57,62]	M	M	E	M*	N/A	N/A	P*	D*	I*	E	R	Diff*	M*	L	C/D	P	P*	[17,41,47,63,64]
2.4133	M	Use most efficient type of electric motors	[41,57,63,65]	M*	M*	E	L*	P*	N/A	P*	D*	I*	E	R	Easy*	H*	L	C/D	P*	P*	[17,40,45–47,59]
2.4134	M	Replace electric motor with fossil fuel engine	[55,57,66,67]	M	M	E	N/A	N/A	N/A	N/A	N/A	N/A	E	N	Diff	M	L	C/D	O	N/A	
2.4141	M	Use multiple speed motors or adjustable frequency drive (afd) for variable pump, blower and compressor loads	[41,55–57,65–68]	M*	M*	E	H*	P*	N/A	P*	D*	I*	E	R	Easy*	H*	L	C/D	O	P*	[17,46,69–72]
2.4142	M	Use afd to replace motor-generator set	[41,55–57,65,68]	M*	M*	E	M*	P*	N/A	P*	D*	I*	E	R	Diff*	H*	L	C/D	O	P*	[17,41,46,69–72]
2.4143	M	Use afd to replace throttling system	[41,55–57,65,68]	M*	M*	E	M*	P*	P*	P*	D*	I*	E	R	Diff*	H**	L	C/D	O	P*	[17,46,69–72]
2.4144	M	Use afd to replace mechanical drive	[41,55–57,65,68]	M*	M*	E	M*	P*	N/A	P*	D*	I*	E	R	Diff*	H*	L	C/D	O	P*	[17,41,46,69–72]
2.4145	M	Install isolation transformer on afd	[57]	L	H*	E	N/A	N/A	N/A	N/A	D*	N/A	E	R	Diff*	H*	L	C/D	O	P*	[69]
2.4151	M	Develop a repair/replace policy	[57]	M	H	E	N/A	N/A	N/A	N/A	N/A	N/A	E/C	P	Dep*	M	W	C/D	P	N/A	[59]
2.4152	M	Use only certified motor repair shops	[57]	N/A	N/A	E	L*	N/A	N/A	N/A	N/A	N/A	E	P	Dep*	M	L	C/D	P	N/A	[59,63]
2.4153	M	Avoid emergency rewind of motors	[57,63]	M/L	H	E	L*	N/A	N/A	N/A	N/A	N/A	E	P	Dep*	H	L	C/D	P	N/A	[59,63]
2.4154	M	Avoid rewinding motors more than twice	[55,57,63,66,67]	M	L	E	L*	N/A	N/A	N/A	N/A	N/A	E	P	Dep*	H	L	C/D	P	N/A	[59,63]
2.4155	M	Standardize motor inventory	[57]	S	L	E	N/A	N/A	P	N/A	N/A	N/A	E	P	Dep*	M	L	C/D	P	N/A	[54,59]
2.4156	M	Establish a preventative maintenance program	[57]	S	L	E	M*	N/A	P	P*	D*	N/A	E	P	Dep*	M	L	C/D	P	P*	[54,59,63]
2.4157	M	Establish a predictive maintenance program	[57]	S	L	E	M*	N/A	N/A	P*	D*	N/A	E	P	Dep*	M	L	C/D	P	P*	[59,63]
2.4221	C	Install compressor air intakes in coolest locations	[41,47,51,57,63,65,73]	M*	L	E	L*	N/A	N/A	N/A	N/A	N/A	E	N	Dep*	M*	L	D	O	N/A	[41,47,51,74–76]
2.4222	C	Install adequate dryers on air lines to eliminate blowdown	[57]	M	H	E	N/A	N/A	N/A	N/A	N/A	N/A	E	R	Dep*	M*	L	D	O	N/A	
2.4223	C	Install direct acting units in place of compressed air pressure system in safety system	[57]	M	M	E	N/A	N/A	N/A	N/A	N/A	N/A	E	N	Dep*	M*	L	D	O	N/A	
2.4224	C	Upgrade controls on compressors	[41,49,57,63,65,77]	M*	M	E	M*	N/A	N/A	P*	N/A	N/A	E	R	Dep*	M*	L	D	O	P*	[41,47,73,78]
2.4225	C	Install common header on compressors	[57]	M	H	E	N/A	N/A	N/A	N/A	N/A	N/A	E	N	Dep*	M*	L	D	O	N/A	
2.4226	C	Use / purchase optimum sized compressor	[57,63]	M/L*	H	E	L*	N/A	N/A	N/A	N/A	N/A	E	R	Dep*	M*	L	D	O	N/A	[41,51,77,78]
2.4227	C	Use compressor air filters	[57]	M*	L	E	L*	N/A	N/A	N/A	D*	N/A	E	R	Easy	M	L	D	P	P*	[41,47,77,78]
2.4231	C	Reduce the pressure of compressed air to the minimum required	[41,55,57,63,65]	S*	L	E	L*	N/A	N/A	N/A	D*	N/A	E/C	O	Easy*	H	L	C/D	P	P*	[41,47,49,75,76]
2.4232	C	Eliminate or reduce compressed air used for cooling, agitating liquids, moving product, or drying	[57]	S*	M	E	H*	N/A	N/A	N/A	N/A	N/A	E/C	O	Dep	M*	W	C	P	P*	[41,49,74]
2.4233	C	Eliminate permanently the use of compressed air	[57]	S*	M	E	H*	N/A	N/A	N/A	N/A	N/A	E/C	O	Dep	M*	W	C/D	O	P*	[41,49,74]
2.4234	C	Cool compressor air intake with heat exchanger	[57]	M	M	E	L*	N/A	N/A	N/A	N/A	N/A	E	N	Diff	H	L	D	O	N/A	[41,47,75,76]
2.4235	C	Remove or close off unneeded compressed air lines	[41,55,57,65,73]	S	M	E	N/A	N/A	N/A	N/A	N/A	N/A	E/C	O	Dep	M	L	C/D	P	P*	[49]

2.4236	C	Eliminate leaks in inert gas and compressed air lines / valves	[41,47,49,51,55, 57,63,65,73,77]	S*	L	E	H*	N/A	N/A	P*	D*	I*	E	P	Easy	H	W	C/D	P	N/A	[41,47,51,73]
2.4237	C	Substitute compressed air cooling with water or air cooling	[57]	S	M	E	N/A	N/A	P	N/A	N/A	N/A	E	N	Dep	M	L	D	O	N/A	[54]
2.4238	C	Do not use compressed air for personal cooling	[57]	S	L	E	N/A	N/A	N/A	N/A	N/A	N/A	E/C	P	Easy	H	W	C/D	P	N/A	
2.7111	L	Reduce illumination to minimum necessary levels	[40,57]	S*	L*	E	H*	N/A	N/A	N/A	D*	I*	E/C	O	Easy*	M*	W	C/D	P	N/A	[40,79,80]
2.7112	L	Reduce exterior illumination to minimum safe level	[40,57]	S*	L*	E	H*	N/A	N/A	N/A	D*	I**	E/C	O	Easy*	M*	L	D	P	N/A	[40,80]
2.7121	L	Utilize daylight whenever possible in lieu of artificial light	[40,57,81,82]	M	M	E	H*	N/A	N/A	P*	N/A	I*	E/C	O	Dep*	M*	W	C/D	P	P*	[40,41,83–86]
2.7122	L	Disconnect ballasts	[40,57]	S*	L	E	L*	N/A	N/A	N/A	N/A	N/A	E/C	O	Easy*	H	L	C/D	O*	N/A	[40]
2.7123	L	Keep lamps and reflectors clean	[40,57]	S	L	E	M*	N/A	N/A	N/A	I*	I*	E	P	Easy*	H	L	C/D	P*	P*	[40]
2.7124	L	Make a practice of turning off lights when not needed	[40,57]	S	L	E	N/A	N/A	N/A	N/A	I*	N/A	E/C	P	Easy	M	W	C/D	P	N/A	[83]
2.7131	L	Add area lighting switches	[40,57,81]	M	L	E	N/A	N/A	N/A	N/A	N/A	N/A	E	N	Easy	M	L	D	O	N/A	
2.7132	L	Install timers on light switches in little used areas	[40,57]	S	L	E	H*	N/A	N/A	N/A	I*	D*	E/C	N	Easy	M*	L	D	O	N/A	[83,87]
2.7133	L	Install separate switches on perimeter lighting which may be turned off when natural light is available	[57]	S	L	E	H*	N/A	N/A	P*	I*	I*	E/C	N	Easy	M*	L	D	O	P*	[83,86,88]
2.7134	L	Use photocell controls (photosensor)	[40,57,82]	S	L	E	H*	N/A	N/A	P*	I*	I*	E	N	Easy*	H*	L	C/D	O*	P*	[83,86–88]
2.7135	L	Install occupancy sensors	[40,57,82,89]	M*	M*	E	H*	N/A	N/A	N/A	I*	D*	E	N	Easy*	H*	L	C/D	O*	P*	[41,83,87]
2.7141	L	Lower light fixtures in high ceiling areas	[57]	M/L	H	E	N/A	N/A	N/A	N/A	N/A	N/A	E	N	Dep	H	L	C/D	O	N/A	
2.7142	L	Utilize higher efficiency lamps and/or ballasts	[40,57,81,82,89]	M*	M*	E	H*	N/A	P*	N/A	D*	I*	E	R	Easy	H	L	C/D	O	P*	[90–93]
2.7143	L	Use more efficient light source: HIF replacements for high bay HID	[57]	M*	M*	E	H*	N/A	P*	P*	I*	I*	E	R	Diff*	M*	L	C/D	O	P*	[17,41,94,95]
2.7144	L	Install spectral reflectors / delamp	[40,57]	L*	M	E	H*	N/A	N/A	N/A	N/A	I*	E	N	Easy*	H*	L	C/D	O	N/A	[40,79]
2.7145	L	Install skylights	[57]	M/L	H	E	H*	N/A	N/A	P*	N/A	I*	E	N	Diff*	M*	L	C/D	O	P*	[40,83,84,86]
2.7211	H	Clean and maintain refrigerant condensers and towers	[57]	S*	M	E	L*	N/A	N/A	N/A	N/A	N/A	E	P	Easy*	M*	L	D	P	N/A	[40]
2.7212	H	Install or upgrade insulation on HVAC distribution systems	[53,57]	M	M*	E/T	H*	N/A	N/A	N/A	N/A	N/A	E	N	Diff*	H*	L	D	O	N/A	[40,41]
2.7221	H	Lower temperature during the winter season and vice-versa	[41,57]	S*	H	E/T	L*	N/A	N/A	N/A	N/A	N/A	C	O	Easy*	M*	W	C/D	P	N/A	[40,96–98]
2.7222	H	Air condition only space in use	[53,57,66]	S	M	E/T	N/A	N/A	N/A	N/A	N/A	N/A	E/C	O	Dep	M	W	C/D	P	N/A	
2.7223	H	Condition smallest space necessary	[57]	S	H	E/T	N/A	N/A	N/A	N/A	N/A	N/A	E/C	O	Dep	M	W	C/D	P	N/A	
2.7224	H	Reduce space conditioning during non-working hours	[57]	S	L	E/T	L*	N/A	N/A	N/A	N/A	N/A	C	O	Easy*	M*	W	C/D	P	P*	[40]
2.7225	H	Close outdoor air dampers during warm-up / cool-down periods	[57]	L	H	E/T	N/A	N/A	N/A	N/A	N/A	N/A	E	O	Dep	M	L	D	P	N/A	
2.7226	H	Use computer programs to optimize HVAC performance	[41,53,57,66,99]	M*	H	E/T	M*	N/A	N/A	N/A	D*	N/A	E	O	Diff	H	L	D	O	P*	[41,96,100]
2.7227	H	Use water on air conditioning exchanger to improve heat transfer and increase air conditioner efficiency	[57]	M	M	E/T	N/A	N/A	P	N/A	N/A	N/A	E	N	Diff	H	L	D	O	N/A	[54]
2.7228	H	Avoid introducing hot, humid, or dirty air into HVAC system	[57]	M	M	E/T	N/A	N/A	N/A	N/A	N/A	N/A	E	R	Diff	H	L	D	O	N/A	
2.7231	H	Use radiant heater for spot heating	[57]	M	L	E/T	N/A	N/A	N/A	N/A	N/A	N/A	E/C	N	Easy	H	W	C/D	O	N/A	
2.7232	H	Replace existing HVAC unit with high efficiency model	[57]	M*	H*	E/T	H*	N/A	N/A	N/A	N/A	N/A	E	R	Diff	M*	L	D	O	N/A	[99,101]
2.7233	H	Use properly designed and sized HVAC equipment	[57]	M/L	H	E/T	H*	N/A	N/A	N/A	N/A	N/A	E	R	Diff	M*	L	D	O	P*	[102]
2.7234	H	Use heat pump for space conditioning	[57]	M/L*	H	E/T	L*	N/A	N/A	N/A	N/A	I*	E	N	Diff	M*	L	C/D	O	N/A	
2.7235	H	Install fossil fuel make-up air unit	[57]	M	H	E	N/A	N/A	N/A	N/A	N/A	N/A	E	N	Diff	M*	L	C/D	O	N/A	
2.7241	H	Install outside air damper / economizer on HVAC unit	[41,57,103]	M/L*	H	E/T	H*	N/A	N/A	N/A	I*	I*	E	N	Diff	M*	L	D	O	P*	[40]
2.7242	H	Change zone reheat coils to variable air volume boxes	[41,57]	L*	H*	E/T	L*	N/A	N/A	N/A	I*	I*	E	N	Diff	M*	L	C/D	O	P*	[40]
2.7243	H	Improve air circulation with destratification fans/other methods	[41,57,96]	M*	H	E/T	M*	N/A	N/A	P*	N/A	I*	E	N	Diff	M*	L	C/D	O	P*	[41,96,100,104]

(*continued on next page*)

Table 2 (*continued*)

ARC	Cross-cutting technology[a]	Description	Ref. description	Economic		Energy		Environmental		Production-related			Implementation-related							Inter.	
				Pay-back time[b]	Implementation Costs[c]	Resource Stream[d]	Amount of Saved Energy[d]	Emission reduction[e]	Waste reduction[e]	Productivity[e]	Operation and Maintenance[f]	Working Environment[f]	Saving strategy[g]	Activity Type[h]	Ease of Implementation[i]	Likelihood of success/ acceptance[c]	Corporate Involvement[j]	Distance to core processes[k]	Check-up frequency[l]	Indirect effects[e]	Ref. attributes
2.7244	H	Revise smoke cleanup from operations	[57]	M	M	E/T	N/A	N/A	N/A	N/A	N/A	N/A	E/C	N	Diff	M	L	C	O	N/A	
2.7245	H	Use direct air supply to exhaust hoods	[57]	M	M	E/T	N/A	N/A	N/A	N/A	N/A	N/A	E/C	N	Dep	M	L	C	O	N/A	
2.7251	H	Reduce air conditioning load by evaporating water from roof	[57]	M/L	H	E/T	N/A	N/A	N/A	N/A	N/A	N/A	E/C	N	Diff	M	L	D	O	P*	
2.7252	H	Utilize an evaporative air pre-cooler or other heat exchanger in ac system	[57]	M	H	E/T	N/A	N/A	P	N/A	N/A	N/A	E	N	Diff	M*	L	D	O	N/A	[54]
2.7261	H	Install timers and/or thermostats	[53,57]	S	L	E/T	L*	N/A	N/A	N/A	N/A	N/A	E	N	Dep	M*	W	C/D	O	N/A	[100]
2.7262	H	Separate controls of air handlers from ac / heating systems	[57]	L	L	E/T	L*	N/A	N/A	N/A	N/A	N/A	E	R	Diff	M*	L	C/D	O	N/A	[47,49,75,76]
2.7263	H	Lower compressor pressure through a/c system modification	[57]	M	H	E/T	N/A	N/A	N/A	N/A	N/A	N/A	E	R	Dep*	H	L	C/D	O	N/A	[49]
2.7264	H	Interlock heating and air conditioning systems to prevent simultaneous operation	[57]	S	M	E/T	H*	N/A	N/A	N/A	N/A	N/A	E	R	Diff	M*	L	C/D	O	N/A	[40]
2.7271	H	Replace electric reheat with heat pipes	[57]	M*	M*	E/T	M*	N/A	N/A	N/A	D*	I*	E	N	Diff	M*	L	C/D	O	P*	
2.7272	H	Install heat pipes / raise cooling setpoint	[57]	M*	M*	E/T	M*	N/A	N/A	N/A	D*	I*	E	N	Diff	M	L	C/D	O	P*	
2.7273	H	Install desiccant humidity control system	[57]	L*	H*	E/T	M*	N/A	N/A	N/A	D*	I*	E	N	Diff	H	L	D	O	P*	[54,105,106]
2.7291	H	Reschedule and rearrange multiple-source heating systems	[57]	S	L	E/T	N/A	N/A	N/A	N/A	N/A	N/A	E	O	Dep	L	L	D	P	N/A	
2.7292	H	Lower ceiling to reduce conditioned space	[57]	M	M	E/T	N/A	N/A	N/A	N/A	N/A	N/A	E	N	Dep	H	L	C/D	O	N/A	
2.7293	H	Install dry sprinkler system to reduce heating requirements	[57]	M	H	E/T	N/A	N/A	N/A	N/A	N/A	N/A	E	N	Diff	H	L	C/D	O	N/A	
2.7311	H	Shut off ventilation system when room is not in use	[57]	S	M	E/T	M*	N/A	N/A	N/A	N/A	N/A	E/C	P	Easy	M*	W	C/D	P	N/A	[40,98]
2.7312	H	Minimize use of outside make-up air for ventilation	[57]	S	M	E/T	L*	N/A	N/A	N/A	N/A	I*	E	O	Easy*	M*	L	C/D	P	P*	[40]
2.7313	H	Recycle air for heating, ventilation and air conditioning	[57]	M	H	E/T	N/A	N/A	N/A	N/A	N/A	N/A	E	R	Diff	H	L	C/D	O	N/A	
2.7314	H	Reduce ventilation air	[57]	S	M	E/T	N/A	N/A	N/A	N/A	N/A	N/A	E/C	O	Easy	H	W	C/D	P	N/A	
2.7315	H	Reduce building ventilation air to minimum safe levels	[57]	S	M	E/T	N/A	N/A	N/A	N/A	N/A	N/A	E/C	O	Easy	H	W	C/D	P	N/A	
2.7316	H	Centralize control of exhaust fans to ensure their shutdown, or establish program to ensure manual shutdown	[57]	S	L	E	N/A	N/A	N/A	N/A	N/A	N/A	E	P	Diff	M	L	D	P	N/A	

With "*" we mark values supported by literature studies.
When not marked with "*", the columns referring to pay-back time and implementation costs have been supported by values from the Industrial Assessment Center database [57].

(a) Motors (M); Compressed Air (C); Lighting (L); HVAC (H).
(b) Short (S); Medium (M); Large (L).
(c) Low (L); Medium (M); High (H).
(d) Electricity (E); Thermal (T).
(e) Proven (P); Not Available (N/A).
(f) Increase (I); Decrease (D); Not Available (N/A).
(g) Efficiency (E); Conservation (C).
(h) Procedure or recovery (P); Optimization (O); Retrofit (R); New Installation (N).
(i) Easy (Easy); Dependent (Dep); Difficult (Diff).
(j) Limited (L); Wide (W).
(k) Close (C); Distant (D).
(l) One-time intervention(O); Periodic check required (P).

4.2.2. ARC 2.4231: reduce the pressure of compressed air to the minimum required

The presented EEM, related to the optimization of the existing equipment, can be either classified as an energy efficiency and conservation measure that can be either referred to some equipment particularly close to the core activities, or distant from them. It has been evaluated as easy to be implemented and with high likelihood of success, as the unique drawback to be taken into account is the possible pressure fall of the point-of-use below the minimum requirements [49] which can be easily managed. Moreover, it requires a periodic check and an involvement of the maintenance staff, but its implementation requires no direct implementation costs, and is able to bring a moderate saving, in terms of a few percentage of the specific energy consumption by each half bar reduced [47,49,75,76]. Nonetheless, it should be pointed out that operating at a too high pressure increases maintenance costs [41,50], and decreases the system life. Therefore, this measure has a proven effect in terms of reduction of operating and maintenance costs, and an indirect benefit on the whole compressed air system.

4.2.3. ARC 2.7123: keep lamps and reflectors clean

This procedure can be easily implemented [40] and with a very high likelihood of success, and can be either close or distant to the core production activities. According to the Energy Efficiency Manual [40] can bring even 10% of less energy used for lighting, and according to estimates from the IAC database presents a very low payback time. Although requires an increase in the operation and maintenance activities (as a routine of the maintenance), it can substantially increase the conditions of the working environment. Finally, as dirt also traps heat, keeping lamps and reflectors clean can thereby increase lamps and ballasts life [40].

4.2.4. ARC 2.7243: improve air circulation with destratification fans/ other methods

This new installation EEM belonging to the HVAC system shows a higher difficulty in the implementation, and might also refer to an EEM to be implemented close or distant from the core production activities. Moreover, it presents a medium likelihood of success, as its success is highly dependent on climate, latitude, and orientation [101]. Nonetheless, it is a measure that requires a minor corporate involvement, and with a medium payback time (about 2 years, according to Balaras [96]). As acknowledged by some authors, the savings are relevant (up to 60% less electric energy [100], and about 3% of less energy [96]). Moreover, we can appreciate improvement of the system productivity [104] and several authors highlight an improved indoor comfort condition and reduced thermal stratification [41,96], and improved occupant's health [104]. Finally, this EEM is evaluated to provide a reduced AC load, and a 17–48% cooling load reduction [104].

5. Discussion

We should acknowledge that, although from a theoretical viewpoint the EEMs characteristics are independent, nonetheless, in some cases, they appear concurrently. By looking at the structure of the IAC database, the distribution of the considered EEMs by areas is: 19 about Motors, 15 on Compressed Air, 16 about Lighting and 38 about HVAC systems.

Firstly, we can appreciate that 32 out of 88 present a relevant likelihood of success, 47 medium, and only 9 a low one (about 10% of the total).

Considering those with low likelihood of success, 6 refer to the HVAC area. Indeed, considering that HVAC system could even represent in some cases an effective system within a production system, it is reasonable to be more subject to customization and consequent variations in its performance.

Only in 5 cases we have found in the literature a proven emission reduction, and only in 10 a proven waste reduction. By looking at this small cluster, we have not found any relationship between the two attributes (with just one exception). For what concerns the GHG emission reduction, in all cases are related to motor systems presenting also an increase of the productivity, medium implementation costs, retrofit or installation of new equipment, and increased working conditions. Moreover, in all cases, they present also indirect benefits, only in one case the need to be checked-up regularly there exists, and with one exception the corporate involvement is limited. Regarding EEMs with proven waste reduction, 5 out of 10 belong to motors, and 5 seem to be related to increased working conditions, present a high likelihood of success, 8 out of 10 should be implemented once and are related to a retrofit or a new installation.

With respect to implementation costs and payback times, the EEMs seem to be distributed with a preponderance towards low (32) and medium (39) payback times. Motors and HVAC seem to present higher payback times, possibly to the disruption of the production activities, and the precise setting needed to be operated. When looking at EEMs with lower implementation costs (24), 18 of them present a low payback time: as they are mostly optimization or procedures EEMs (only in 4 cases they represent a new installation). Nonetheless, we can appreciate that those EEMs are still able to lead to relevant savings, and thus should not be overlooked both by entrepreneurs but also by policy-makers. In 20 cases out of 88 we have observed a proven increased of productivity.

For what concerns the saving strategy, the EEMs considered are almost exclusively related to efficiency (64), with about 25% (22) of both efficiency and conservation, and 2 of just conservation. This seems reasonable, as it is apparent, in the industrial context, to find more efficiency EEMs than conservation ones, as the latter could affect the production throughput. In this regard, it is noteworthy that motors and compressed air systems are usually more related to the specific production processes, whilst lighting and HVAC to the working conditions. Nonetheless, it is apparent that in many contests HVAC is strictly related to specific production process conditions (e.g. clean rooms). Therefore, considering that, at least partially, the way the EEMs are implemented might affect their evaluation with respect to the saving strategy (therefore being either efficiency or conservation), we might expect to find few conservation EEMs, in particular for motors and air compressed systems. In fact, in the aforementioned cross-cutting technologies, a reduction of both input (energy) and output (service offered) would deeply affect the production. For example, eliminating or reducing compressed air used for cooling, agitating liquids, moving product, or drying might be critical in case of moving, e.g., aluminum cans (that are paramagnetic), or plastic bottles. When looking at lighting and HVAC systems, instead, conservation EEMs might affect the service provided (at least perceived by a worker, in terms of safety and well-being). For instance, reducing the illumination to minimum necessary levels (ARC 2.7111) should be surely implemented considering the safety requirements for the operators. Nonetheless, it can be foregone concluded that operators would perceive a reduction in the comfort.

The vast majority of EEMs (71) does not seem to affect deeply the organization, as the decision about their investments requires a limited corporate involvement. Indeed, only in 17 cases we have pointed out the need to involve the whole organization. It is remarkable that in 55 out of 88 EEMs we have one-time investments, thus without the need to be checked-up regularly. Moreover, in 37 out of 88 EEMs we have observed indirect benefits from the interaction with other systems.

By considering the distance from the core production activities, only 3 out of the considered 88 EEMs can be primarily referred to be as close, since the EEM has been specifically described as dealing with production activities. In 27 cases we have EEMs far from the core activities. The vast majority of them (58) are either close or distant from the core activities. Although in real cases it is quite easy to operate a clear distinction between distant and close from core processes, by considering the ARC, that presents a lower detail, it has not been always possible to further characterize the distance of an EEM from the core activities.

5.1. Analysis by cross-cutting technologies

Motor systems: 18 out of 19 motors EEMs require a limited corporate involvement, and in only one case the whole organization needs to be involved. This results in a lower difficulty to be implemented, as it is requires in general the involvement of the maintenance staff. Nonetheless, it seems relevant to point out that motor systems, although quite often being a standard component, are widely diffused in production processes, thus possibly affecting the operating performance. Indeed, it can be interestingly noted that in 16 cases they are evaluated as with a high or medium likelihood of success.

Moreover, all the 9 EEMs with high likelihood of success require a limited corporate involvement. Additionally, only two out of 19 are evaluated as being easy to be implemented (and all with a high success likelihood): this might imply that, although their general low implementation costs (and the possible incentives to further reduce their costs), to be most effectively diffused a technical support might be necessary, due to their hidden costs.

In the majority of cases (12) the considered EEMs imply a retrofit or a new installation of the equipment (and 7 of them are related to a procedure): this might be interesting, as it has an impact on the avoided need to frequent check-ups (only half of them). Finally, as aforementioned, motors are by their nature either close or distant from core production activities.

Compressed air: Only 4 out of 15 compressed air EEMs in this area required the involvement of the whole organization. As pointed out before for the motor systems, also in the compressed air the EEMs are of a greater difficulty to be implemented, as they refer to a system strictly connected to the production activities. Nonetheless, considering the 4 EEMs being easy to be implemented, in all cases they present a low implementation costs, and usually low payback times.

Moreover, all EEMs present a medium or high likelihood of success, and in 2 cases we have found a proven effect in decreasing the operation and maintenance activities.

Lighting systems: in the greater majority (13) of the considered lighting EEMs (16) the investments require a limited corporate involvement (and almost all of them being one-time interventions), with just three cases of involvement of the whole organization required. Moreover, 10 out of those 13 EEMs can be easily implemented, with a high (or medium) likelihood of success (none of them being difficult). Additionally, 7 out of 10 are related to a retrofit or new installation. If we also consider that 10 out of 13 present low or medium payback times, and in 7 out of 10 also high savings, these EEMs seem very promising to be exploited for an increased energy efficiency. Indeed, although lighting does not usually cover a significant portion of the energy consumption (and related costs), the achievable savings from the implementation of such EEMs are considered as very interesting.

By looking at the two EEMs with a difficulty to be implemented, we can reasonably note that they are related to the existing building and envelope configuration, whose modification might result to be difficult (e.g. in ARC 2.7145, Installing skylights).

Moreover, considering that are in the vast majority standard components, the implementation costs of lighting EEMs result to be usually low or medium, with just two exceptions.

In 10 out of 16 lighting EEMs we have found a proven increase of the working consideration, and, among them, in 7 cases also an effect from the indirect interaction with other systems (e.g., the total electrical load).

HVAC systems: the HVAC systems is by far the most complex cross-cutting technology among those considered in this study, and quite often at least partially customized. This can result in greater implementation costs (17 out of 39 EEMs with high implementation costs, only 6 present low values). Nonetheless, the achievable savings are in general relevant, thus leading to low or medium payback times (only in 8 cases large or medium-large).

Customization also related to a greater difficulty of implementation, with only 8 cases being easy. This might also result in a greater (than estimated) payback, in case detailed data and information would be required, thus increasing the so-called hidden costs.

Nonetheless, from our preliminary analysis the need to further explores the characteristics of HVAC EEMs clearly emerges, as it can be reasonably assumed that a relevant reduction in the emission, as well as an increase of the working environment can be achieved (now proven in just 8 cases), considering the huge impact of such cross-cutting technology on the workers' comfort.

6. Conclusions and future research

Firstly, developing an innovative framework to characterize EEMs is crucial to the structuring and the sharing of knowledge on EEMs both for decision-makers and policy-makers. Indeed, thanks to an increased knowledge on EEM, policy-makers could be better supported in developing the most effective policies to promote industrial energy efficiency. Moreover, improving the knowledge about EEMs characteristics could drive a deeper comprehension of the barriers currently hindering their adoption, which is again an additional interesting issue for decision-makers as well as policy-makers. Indeed, our novel classification scheme might provide a useful support to point out the punctual differences in the barriers to specific EEMs, e.g. when considering the hidden costs related to their adoption. In fact, in many cases, a proven easiness of implementation, the existence of productivity benefits, as well as reduction of operation and maintenance costs, should represent relevant elements to be considered when evaluating EEMs, in addition to their low payback times. In particular, it would be interesting to see how different barriers seem to tackle different EEMs in the, e.g. lighting with the respect to the, e.g. HVAC cross-cutting technologies: here, beyond the mere considerations about the different implementation costs and related pay-back times, a more thorough investigation, with a full spectrum of EEMs' characteristics, could serve to systematically understand which different barriers, e.g. economic, competence-related or information-related, might hinder the adoption of such EEMs.

In detail, the presented framework starts from an encompassing review of the previous literature contributions, that has highlighted the need to come up with a novel approach to the characterization of EEMs, as in most cases even the rationale behind the selection of the attributes is not discussed.

In addition to that, the framework has provided a comprehensive view on EEMs, presenting the most relevant perspectives industrial decision-makers consider as most relevant when undertaking an investment in energy efficiency. This has implied a large effort in detailing, beside the energy, environmental as well as economic perspectives (well-known in the literature), also the impact on the existing production system, the implementation issues, as well as the interaction with other systems of EEMs.

Moreover, and notable for a practical application of the framework, none of previous studies has highlighted attributes such as "corporate involvement", that is particularly critical for industrial decision-makers, and, in turn, also for policy making purposes, as a wider corporate involvement represents a critical barrier hindering the adoption of an EEM. Additionally, another crucial element of novelty is represented by having pointed out the need to analyze EEMs according to different perspectives. In particular, having grouped the attributes in categories allows to provide a comprehensive view of the most relevant perspectives characterizing the EEMs and resulting to be particularly useful for the selection of the most promising EEMs to be promoted. This has been obtained also by recovering in the framework a structured set of attributes related to the non-energy benefits that had been neglected in the most recent literature contributions.

This opens the research to a better understanding of the drivers to promote industrial energy efficiency, that has, since now, received too little attention by the research. In this field in fact only a few empirical studies have been developed [107–110], but, and more critical, still a lack in a comprehensive theoretical classification there exists, as the existing contributions seem to be more a list of potential drivers than taxonomies [3,42,111]. Future research should thus detail more deeply, e.g., which is the impact of the drivers on the decision-making process, i.e. to which step of the decision-making process appears to be most tackled by the different drivers, and which are the barriers behind each decision-making process step. Moreover, starting from a feature of our classification scheme, it seems interesting to explore which phases of the decision-making needs the involvement of different actors, and how drivers could better improve their involvement.

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