Identification and characterization of decision-making factors over industrial energy efficiency measures in electric motor systems

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Abstract

Energy efficiency measures in electric motor systems are scarcely implemented, and previous literature has largely overlooked the characterizing factors responsible for their adoption in industrial operations. The present study, after a comprehensive literature review, aims at supporting research by offering a framework for the identification of the factors that should be assessed when considering the adoption of electric motor systems' energy efficiency measures. The proposed factors are clustered in ten categories, namely: contextual factors, compatibility, economy, energy savings, production-related factors, operations-related factors, synergies, complexity, personnel and additional technical factors. After a preliminary empirical validation, the proposed framework has been applied in a selected sample of manufacturing firms. Findings show that factors more closely related to the firm's production and operations result most critical for the adoption of energy efficiency measures. However, the adoption process is also deeply influenced by their complexity or compatibility to the specific context application, therefore calling for an exhaustive assessment. The adoption of the framework would have reversed some firm's decisions over the initial uptake of EEMs that proved to have critical issues for their implementation. Therefore, the proposed framework provides additional support and further value to decision-makers especially for non-energy intensive firms, where the impact on non-energy production resources becomes more important, and SME usually present greater difficulties for a holistic assessment of EEMs. The study concludes with main implications for research and policy-making from the present study as well as suggestions for future research.

Highlights

- Novel framework of characterizing factors for electric motor systems in industry.
- Thorough assessment of energy efficiency measures in electric motor systems.
- Decision-making factors for the adoption of energy efficiency measures.
- Impacts of energy efficiency on firms' production resources and operations.

Keywords

Energy Efficiency; Electric Motor Systems; Energy Efficiency Measures; Non-Energy Benefits; Decision Making; Characterizing factors.

Word Count: 5571 words

List of Abbreviations	
EMS	Electric motor systems
EEMs	Energy efficiency measures
NEBs	Non-energy benefits

1. Introduction

With energy consumption projected to grow by about 50% between 2018 and 2050 [1], the commitment towards industrial energy efficiency plays a critical role [2,3]. A major share of electric energy consumption is attributable to electric motor systems (EMS) [4,5] thanks to their widespread diffusion in a number of industrial applications and purposes. Despite the existence of minimum efficiency mandatory standards in most of the Countries for new motors, about 70% of the total energy consumed by motors comes from unregulated (IE0) or low-efficiency devices (IE1) [2]. Moreover, reviews show that EMS are broader than the motor itself, with a variety of energy efficiency measures (EEMs) [6], still presenting a largely untapped energy efficiency potential [7]. Despite EEMs in EMS can be easily implemented and with high estimated investment returns [2,8], their implementation rate is still low [9]. Therefore, what could appear at first sight as a low hanging fruit may hide the understanding of a much more complex situation, where the lack of information and specific characteristics of EEMs – together with the potential disruption coming from their adoption – could represent higher barriers jeopardizing their implementation [10,11]. Hence, a mere techno-economic feasibility analysis is insufficient to capture the implications of effectively placing an EEM into the operations. Further, research has been so far limited to highlight some relevant characteristics of EEMs in general (e.g., the knowledge required for the planning and implementation of a general EEM or its diffusion progress and sectorial applicability [12,13]). However, considering EEMs within EMS, the necessary detail to effectively guide decision-makers in the understanding of the distinctive features driving the adoption [14,15] is still lacking. Unfortunately, literature has just preliminarily explored the impacts generated by the adoption of EEMs on a firm's production resources and activities, such as the variations of productivity and production quality. Yet, research has not sufficiently disentangled the multiple impacts on the operations and the working environment.

To contribute to the discussion by addressing the aforementioned research gaps, a novel framework has been specifically designed. The framework could also guide industrial decision-makers and policy-makers in selecting the most appropriate means to promote EEMs in EMS. The remainder of the paper is structured as follows: in Section 2, the extant literature on factors crucial for decision-making over EEMs in EMS is extensively reviewed, followed by the presentation of the new framework (Section 3). In Section 4, the research method used to empirically validate the framework is detailed and the results are explained in Section 5. After the discussion (Section 6), concluding remarks are provided in Section 7.

2. Literature background

Previous research has investigated the characteristics of EEMs in general terms. Fleiter et al. [12] designed a framework of factors characterising EEMs organized according to the categories of relative advantage, technical context and information context. By considering aspects such as the relative advantage or the complexity of an EEM [16], the study represents one of the first attempts to encompass into the analysis of EEMs some elements referring to the diffusion of innovation [17]. Complexity has been acknowledged as an important element that is an essential characteristic linked to the type of investment [18]; similarly, Sandberg and Söderstrom [19] have distinguished between replacements and development investments, the latter being characterized by a good level of profitability but also with a higher risk of greater losses. Fleiter et al. [12] have addressed complexity through the factor type of modification and scope of impact, also taking inspiration from earlier literature [20]. Mills et al. [21] have pointed out the inverse relationship between technical complexity of EEMs, thus uncertainty on the results and their adoption rate, confirming earlier findings by Tornatzky and Klein [17]. The complexity of an EEM is also related to the expertise required during the various stages of the adoption [12], thus on training activities, considered critical also for improving the awareness towards energy efficiency [22,23]. Nonetheless, given the wide skill range required, firms often lack adequate personnel [24,25].

Several studies elaborated on Fleiter et al. [12], reviewing their framework and proposing novel sets of factors. Trianni et al. [13] have kept information regarding the complexity of an EEM including e.g., the ease of implementation, the likelihood of success/acceptance and the corporate involvement required for the adoption. Regarding the economic dimension, implementation costs are deemed as crucial especially in the case of small and medium-sized enterprises (SMEs) [26,27] and potentially more critical than the payback period for EEMs adoption rate [28]. The payback period has been acknowledged as a common indicator to assess investments profitability [29,30]. Cooremans [31] has highlighted the importance of analysing EEMs not only at the operations level but from a strategic perspective. On the other hand, Roberts and Ball [32] have focused on time-related technical characteristics, i.e., implementation time and implementation pace, as well as considering some basic contextual information, such as the physical location where the sustainable manufacturing practices is placed.

Other scholars have enriched the analysis by offering additional information related to consequences on the production and the firms' operations stemming from the adoption of EEMs. In some cases, energy savings are not the most valuable result according to the final users (e.g., [33,34]) and therefore should just be part of the equation rather than the ultimate objective [35]. In literature, such advantages (e.g., lower maintenance requirements, increased productivity, reduced waste and emissions) are generally known as non-energy benefits

(NEBs) [13]. Likewise, EEMs may also have negative impacts on the system, i.e., non-energy disbenefits or losses [36] (e.g., production disruption [37]). Hence, both benefits and losses should be equally acknowledged for wise decision-making [38].

Among NEBs, production and productivity improvements are generally a strong driver for the adoption of EEMs [35]. Despite being usually perceived as a direct benefit of EEMs [39,40] productivity may also be enhanced indirectly, e.g., through improved working conditions positively stimulating operators [39]. On the other hand, unnecessary downtimes should be avoided [19] as potentially leading to disruptions in production [37], particularly critical for heavy capital-intensive sectors and energy-intensive sectors based on continuing production [10,41]. The adoption of an EEM may also bring improved product quality [42,43], measurable by the scraps and reworks reduction [33,44], leading in turn to improved customer satisfaction [35] which may be even more important than a reduction in production costs for decision-makers [23].

Moreover, productivity could be affected by variations in process control [45,46] and equipment conditions and reliability [39,42]. The latter, in turn, may be strongly affected by the adoption of EEMs, together with the lifetime of the devices [47,48]. Referring to the operation and maintenance dimension, many authors pointed out a reduction in motor size [38] or the number of needed devices [49], with a consequent cut in labour requirements and engineering controls [39], but an increase in capacity may occur as well [50,51]. However, authors note the importance of thoroughly assessing the amount of additional indirect costs such as production losses arisen due to production shutdowns [52,53]

The benefits of adopting EEMs can extend to the entire working environment, e.g., by improving the internal temperature [52,54], air quality [45,55] or lighting [56,57], or even by reducing the noise level [58,59], with increased workers' productivity [39], comfort [38], health and safety [60,61]. The impact on the external environment may be important as well, in terms of emissions and waste [13,20] with a potential improvement of firm's image [62] and its public relations [35, also in light of current or future compliance with regulations and environmental targets [13,63].

Among a variety of technologies, EMS are extensively adopted in industrial firms in a countless range of both core production and ancillary processes and have been widely investigated by research (e.g., [13,64,65]). Despite a wealth of industrial literature, previous contributions are mostly limited to an analysis of their technical features (e.g., [66,67]), with just little research exploring a limited number of NEBs stemming from the adoption of EEMs in EMS, by addressing motor units and control systems [35].

As summarised in Table 1, earlier research describing EEMs' features [13,68] has not accounted for the entirety of factors potentially relevant for decision-making purposes. Furthermore, the focus on specific technologies and EEMs is crucial since it allows relevant factors to emerge, as shown by previous research on EEMs in compressed air systems [69]. It is therefore clear that a study encompassing the complete set of factors that might influence the adoption of EMS EEMs is lacking. In fact, the contextual dimensions in which EMS are called to operate remain still unexplored, both in terms of business-related factors (such as firm size and sector [41,70]), operating context, as well as its interactions with the surrounding environment.

The framework is intended to facilitate the complex process of industrial decision-making over EEMs in EMS. The need for such a tool comes from the complexity of the task to be performed, influenced by both the surrounding working environment, with its multiple and varying dynamics and constraints, and the subjectivity and capabilities of the single decision-maker [71,72], whose perspective filter the entire study.

Table 1

Synthesis of factors used in literary studies to describe EEMs.

Factors	References	Factors	References
Corporate involvement	[13,43,73,74]	Perception, collaboration with clients, suppliers, competitors	[36,43]
Nature	[36]	Increased communication between department and levels within the firm	[74]
Activity type	[12,13,32,75]	Workers' productivity	[53,76–80]
Scope of impact	[12]	Labour savings (or labour cost)	[33–35,37,42,47,49,51,53,55,57,61,64,77,81–84]
Targeted area	[36]	Reduction in labour requirement	[31,34,38,39,45–47,49,50,69,77,83–88]
Extension of impact	[36]	Indirect effects	[13]
Independency from other components or EEMs	[75]	Larger product range	[53]
EEM location	[32]	Flexibility in production	[50,53,80,87]
Accessibility	[75]	Material handling and movement	[61,85]
Diffusion progress	[12,32,43,73]	Raw material and fuel	[13,31,33–35,42,46,47,50–53,55,59,61,65,69,73,80–83,85–93]
Check-up frequency	[13]	Reduced water consumption	[37,38,42,47,48,53,55,57,58,61,77,78,83–85,89,94,95]
Complexity	[16,17,75]	Reliability in production	[31,33–35,39,42,45–49,51–53,55,64,69,81,83,84,86,96–99]
Trialability	[16,17]	Availability	[98]
Duration of the impacts	[32,36]	Unscheduled downtime	[50,53,59,80,87,98]
Resilience	[36]	Reduced cost of production disruption	[82]
Maintainability of the impacts	[36]	Length of implementation	[32]
Stability of the impacts	[36]	Sourcing strategy	[32]
Timescale (peak and frequency of exploitation of the impacts)	[36]	Lower or different maintenance (or maintenance cost)	[13,34,35,37,42,46–53,55,57–61,64,65,69,74–87,89,91,94–96,100–103]
Knowledge for planning, implementation and use	[12,13,32,43,75,77,85,104]	Wear and tear on equipment	[31,39,45,47,51–53,65,74–76,81,83,84,89]
Increased knowledge of the process or operation	[74]	Extended lifetime of the equipment	[12,34,37,46–48,51,53,57,60,61,64,69,76,79,81–84,86,89,94,98,102,103]
Additional space	[31,39,45,47,49–51,53,79,81,83,84,87,101]	Improved process control	[31,38,39,45–47,51,53,81,83,96]
Likelihood of success	[13,105]	Reduced operational cost	[13,34,35,47,51,52,60,61,64,65,73,74,76,78,79,81,83,85,89,91,94–96]
Compatibility	[16,17,75,98]	Logistic benefits	[47,82]
Adaptability to different conditions	[75]	Real time data	[59]
Synergies	[36,75]	Generation of KPI for comparison within the firm	[74]
Distance to the core process	[12,13,31,80,91,98]	Simplification or automation of customs procedures	[53]
Sectoral applicability (process-related, cross-cutting)	[12]	New contracts and design processes	[79]
Firm size	[49,53,60,73,99]	New service provider	[79]

Factors	References	Factors	References
Energy intensity	[81,99]	Obtain sustainability or energy certification	[43,79]
Sector	[53,61,73,95]	Increased sales levels	[34,43,46,53,61,64,74,85,91,103]
Motor numerosity	[89]	Improved public image, brand reputation	[39,43,45–47,50,51,53,61,64,69,73,77,81–84,86–88,90,98,99,104]
Motor size	[49,98]	Improved competitiveness	[43,47,50,51,73,74,81,83,84,87,91–93,96,99]
Motor type	[98]	Increased market share	[61,64,91,104]
Working hours	[98]	New markets	[43,104]
Torque and speed requirements	[98]	Contribution to the firm's vision or strategy	[53]
Saving strategy	[13]	Reduced currency risk	[47,82]
Amount of saved energy	[13,33,51,53,57,65,75,81,83,89,98,105]	Reduced risk (legal, energy, CO2, water price, energy supply, commercial)	[31,44,53,77,78,80,81,83,98,99,104]
Improve energy management	[74,103]	Future change of energy price (volatility)	[61,79,88,92,93,104]
Improved lighting	[34,37,39,45–48,50–53,56,57,60,81–84,87,102]	Reduced volatility of business results	[61]
Improved air quality	[31,34,37,39,42,45–48,50–53,55–57,60,64,69,74–76,78,79,81–84,86–89,92,93,96,106]	Decreased liability	[31,39,45,47,51,53,81,83,90,106]
Better air flow (production, ancillary)	[37,47,53,57,59]	Implementation cost	[12,13,17,32,43,60,75,94,98]
Vibration (and cavitation)	[59,76,89]	Premium price	[61]
Reduced noise level	[31,34,37–39,42,45–48,50–53,55,56,58,59,69,74–76,81–84,87,95,101,102,107]	Transaction cost	[12,32]
Improved temperature control (of working environment)	[31,39,45–47,50,52–54,65,74,76,79,82–84,87,106]	Acquisition of complementary technology	[43]
Reduced need for cooling	[31,37,39,42,45–47,51,53,55,57,65,69,81–84,86,89,96,99]	Reduced interest cost on capital investment	[31,34,39,42,45,47,49,51,53,55,61,69,77,81,83,84,86,88,105]
Better aesthetics	[34,37,47,48,57,60,83,101,102,107]	Reduced or eliminated rental equipment cost (or increased renting revenue)	[33,42,48,49,53,55,61,79,80,85,106,108]
Reduced ancillary operations	[77,83]	Reduced or eliminated demand charges	[34,42,48,55,61,77]
Reduced operating units	[54]	Increased facility or asset value	[44,47,48,50,51,53,61,64,77,79,81,83,87,88,92,93,103,108]
Reduced backup units	[49]	Pay-back	[12,13,17,32,43,53,61,65,75,91,94,97]
Improved ease of system operation	[49]	IRR	[32]
Improved worker morale	[31,39,45–47,50,51,53,57,61,64,69,79,81–84,86,87,104]	Cash-flow	[36]
Increased workers safety (reduced incidents)	[31,33–35,37,38,42,44,46–53,55–58,60,61,64,69,75,76,79–84,87,94,95,104,106,108,109]	Shareholder return	[61]
Greater comfort	[13,31,34,37,38,42,44,46–48,50–53,55–58,60,61,64,74,76–79,81–84,87,88,92–96,99,101,103,104,106–110]	Taxes	[33,43,48,56,77,79,99,100,107]
Vapor, moisture, mould (working environment)	[50,87]	Reduced fines related to emission exceedances	[33,35,43,47,51–53,61,65,77,79,81,83–85,88,94]
Reduced smell (from leaking oil)	[50,64,87]	Achieved rebate, incentives, subsidies	[31,42,55,77,79,90,99]
Reduced CO, CO2, NOX, SOX emissions	[31,34,39,42,45–48,50,52,53,55,60,64,65,69,73,79–82,84,86–93,95,100,105,108–111]	Lower cost of treatment chemicals	[42,47,55,61,89]
Reduced dust emissions (and ashes)	[31,39,42,45–48,50–53,55,69,83,84,87,100,110]	Reduced planning, legal, administrative, procurement cost	[77,85]
Reduced waste	[31,34,35,37–39,42,45–48,50–53,55,58,64,69,74,77,78,80–84,86,87]	Stimulate economic development	[48,60,61,78,88,91–93,95,100,107,109]
Use of waste heat, fuel, gas	[31,39,45,47,52,53,82,83]	Turnover of energy efficiency goods	[92,93]
Environmental	[13,38,42,48,50,55,57,58,61,74,78,87,90,92–94,102,103]	Renewable energy sources target	[92,93]
Production, productivity	[13,16,17,31,33–35,37,39,42,44–49,51,53,55–57,59–61,64,65,69,73,79–84,86,88–96,99,101–104,112]	Rebound effect	[88]

Factors	References	Factors	References
Increased capacity	[33,35,47,50,51,53,81,83,87,91]	Infrastructure	[48,100]
Shorter process cycle time	[31,39,42,45–47,51–53,55,57,61,69,74,80,81,83,86,105]	Create jobs, employment	[37,44,48,60,61,74,77,88,91–93,95,100,107–109]
Stock and lead time	[98]	Poverty alleviation	[44,61,88,92–94,100,106–109]
Changes in the organization of production	[43]	Innovation	[92,93,104]
Product quality	[31,33–35,37,39,42,45–47,50–53,55,57,59,61,64,65,69,73,74,76,80–87,89,96,98,99,105]	Consumer surplus	[44]
Service quality	[98]	Climate change	[44,90,91]
Improved customer satisfaction, change orders, warranty claim	[33–35,37,47,48,51,53,57,58,60,64,76,80,81,83,90,108]	Energy security	[31,44,48,50,61,73,78,83,87,88,90,92,93,99]
Reduced customer service cost (for better quality)	[53]	Public budgets	[88,91–93]

3. A novel framework for decision-making factors on EEMs in EMS

To design a complete framework targeting EEMs in EMS, common features have been identified through the technical description of EEMs in EMS, as recent research suggests [113]. By taking inspiration from the extant literature, features have been clustered to define a novel set of factors through a synthesis process. The approach aims at offering a holistic perspective over the analysis, by encompassing the broad set of impacts on the operations and the other production resources of a firm as well as the contextual dimension in which EEMs are embedded. The definition of the factors is followed by a process of clustering into categories and sub-categories, strongly enhancing the applicability of the framework, also for a potential deployment as an assessment tool (Cagno et al. [114]). A total of 57 factors have been defined and organized in 10 categories, namely: (i) contextual factors, (ii) compatibility, (iii) economy, (iv) energy savings, (v) production-related factors, (vi) operations-related factors, (vii) synergies, (viii) complexity, (ix) personnel and (x) additional technical factors.

Since the framework is designed to support industrial decision-makers, an additional advantage is provided by the indication of the adoption phase addressed by each factor. The distinction between implementation (I) and service (S) phase [36] can give more accurate insights, enabling the optimization of the resources available for the firms. Details over the categories, the sub-categories and factors are reported in Table 2.

3.1 Contextual factors

Contextual factors provide a broader picture of the applications in which the EEMs may operate. Indeed, the built-in motors' characteristics and the operating context influence the possible impacts of EEMs on the system and may direct the choice on the most appropriate EEMs, by limiting the number of opportunities. This category includes 6 factors, namely: (i) motor model, (ii) motor size, (iii) motors number, (iv) working hours, (v) process focus and (vi) application load.

3.2 Compatibility

Taking inspiration from Rogers [16], compatibility defines the capability for EEMs to adapt in an already organized system and to establish a positive engagement with existing operating conditions and devices. This category is structured with two sub-categories, namely: (i) load and (ii) system. The *load* sub-category refers to the compatibility of EEMs to the specific application requirements, by including load compatibility and adaptability to different conditions. The *system* sub-category refers to (i) the compatibility of an EEM to the physical environment in which it operates; and (ii) the possible reduction in layout flexibility.

3.3 Economy

The economy category encompasses several common factors for the assessment of EEMs' economic figures, by including: (i) initial implementation costs; (ii) total adoption costs; (iii) adoption costs of mandatory secondary devices; (iv) adoption cost of additional optimisation devices; (v) financial exposure; (vi) monetary savings and (vii) pay-back time.

3.4 Energy savings

Reduced energy consumption is the first perceivable impact coming from the adoption of an EEM [18,35].

3.5 Production-related factors

This category describes the production-related impacts on a firm stemming from the EEMs adoption, including variations in ancillary processes with indirect impact on productivity (e.g., operators productivity improved thanks to improved working conditions [39] obtained through the optimization of an ancillary system such as air conditioning). The same holds also for production processes, whose variations may have a dual impact on the production area, both direct and indirect. This category is organized into global and local sub-categories. The *global* sub-category analyses through six factors how the total of EMS installed in a plant affects its production-related activities, directly and indirectly, in terms of: (i) productivity; (ii) production quality and (iii) production costs. The *local* sub-category rather focuses on single EMS, describing its performance variation and condition with potential impact on production-related factors, by including: (i) setup time; (ii) reliability of the equipment; (iii) downtime for maintenance and repairs; (iv) downtime for implementation; (v) equipment lifetime and (vi) process control.

3.6 Operations-related factors

The category describes the impact EEMs may have on factors related to operations. Different perspectives are introduced, shifting the focus from the conditions of the single EMS to a holistic analysis of the working and the broader external environment. This includes three sub-categories: (i) motor conditions, (ii) working environment and (iii) external environment. Concerning *motor conditions*, the impacts coming from the adoption of EEMs are perceived by analysing the operating parameters of the equipment, including: (i) temperature; (ii) vibrations; (iii) power quality; and (iv) air quality. Further, the impacts coming from the adoption of EEMs on the *working environment* are assessed in terms of: (i) noise; (ii) environmental temperature; (iii) environmental vibrations; (iv) health and safety; and (v) air quality. Impacts on the *external environment* are assessed through changes in (i) waste; and (ii) emissions.

3.7 Synergies

During the adoption, industrial decision-makers may identify synergies between different EEMs and coordinate their action to gain advantages [36] (e.g., avoiding multiple shutdowns of the plant by scheduling the implementation of several EEMs during maintenance activities).

3.8 Complexity

By adapting the definition of complexity as “the degree to which an innovation is perceived as difficult to understand and use” [16] to EEMs, this category includes a number of factors as follows: (i) training; (ii) dependency from other components/EEMs; (iii) physical placement inside motor system; (iv) activity type; (v) technical maturity and technology market diffusion and (vi) accessibility.

3.9 Personnel

This category refers to the roles impacted by the EEMs adoption and the magnitude in terms of employees involved. The analysis on the roles may provide knowledge regarding the authority and the skills required to successfully adopt an EEM, supporting firms in designing a better strategy [19]. Also, this category may indirectly refer to the ease of implementation, given that the involvement of multiple departments within a firm and personnel with different roles usually implies greater difficulties for the implementation [17]. The factors grouped in the role sub-category differentiate between *actively engaged* (or required) personnel in the adoption of EEMs from personnel passively undergoing the change (*passive*). Additionally, despite top management exercise a considerable degree of control, this may be insufficient to transform the firm into a conscious entity with a unitary will [115]. Therefore, the corporate involvement sub-category addresses the extension of the involvement required for any role, i.e., the number of impacted employees, either actively or passively.

3.10 Additional technical factors

The category provides further insights into the technical description of EEMs applied to EMS. It includes: (i) implementation type; (ii) check-up frequency; (iii) secondary devices necessary; (iv) additional optimisation devices; and (v) automation.

Table 2

Novel framework composed of categories, sub-categories and factors to support industrial decision-makers in the assessment of industrial EEMs.

Category	Sub-category	Factors	Description	Phase	References
Contextual factors		Motor model	Model of the motors where EEMs will be applied in terms of efficiency (thus indirectly of age). Among others, it may provide information regarding compliance with local rules.	I +S	[113,116–120]
		Motor size	Motor size (power) for EEMs considerations.	I+S	[49,113,116,120,121]
		Motors number	Number of motors affected by the EEM.	I+S	[89,116]
		Working hours	Working hours of the motors where the EEMs will be applied. It is strongly related to the activity performed by	I+S	[15,116,120,122]

Category	Sub-category	Factors	Description	Phase	References
			the firms and to the role of the motors.		
		Process focus	Distinction between process-core and non-process core activities. Excluding some rare exceptions (see e.g. [88]), it coincides with the division between production and ancillary activities.	I+S	[12,13,31,80, 91,116]
		Application load	Load applied: constant torque load, variable torque load and constant power load applications.	I+S	[113,120]
Compatibility	Load	Load compatibility	EEM suitability and compatibility with technologies embedded in the EEM or existing system. Particularly important for EMS working in critical conditions (e.g., very high or low-speed applications, high torque or shock load applications).	S	[98,113]
		Adaptability to different conditions	EEM flexibility in case of changes to the system.	S	/
	System	Adaptability in every environment	Adequacy of use in the chosen location.	S	[113,123]
		Reduced layout flexibility	The implementation of EEMs could lead to a reduction in the degree of freedom in designing the configuration of the plant, because of built-in technological constraints, especially when layout modifications are not allowed.	I	[113]
Economy		Initial implementation cost	Implementation costs at "time 0" (e.g., equipment purchases, engineering/contractor fees and adaptation costs). In the case of technology upgrade, only the marginal costs should be considered.	I	[12,13,23,26–28,98,116]
		Total adoption cost	Total investment expenditure throughout the project life (particularly important in case of repeated implementation).	I	/
		Adoption cost of mandatory secondary devices	Costs of other secondary devices necessary/mandatory to fully benefit from the adoption of the EEM.	I+S	[113]
		Adoption cost of additional optimization devices	Costs for additional devices (not mandatory), that could optimize the benefits of the interventions (e.g., control devices).	I+S	[113]
		Financial exposure	The factor describes whether an EEM could grant a firm more freedom in managing its finance.	I+S	/
		Monetary savings	Monetised energy savings.	S	[13,98,120,124]
		Pay-back time	Pay-back time of the investment, defined as the ratio between implementation costs and monetised energy savings.	S	[12,13,26,29, 30,120,125,126]
Energy savings			Energy savings in energy units (MJ or kWh).	S	[13,18,35]
Production-related factors	Global	Productivity - direct	Direct impacts on the productivity of a firm.	S	[13,19,34,35, 39,40,42,44]
		Productivity - indirect	Indirect impacts on the productivity of a firm (e.g., due to improved working conditions which positively affect the personnel).	S	[39]
		Production Quality - direct	Direct variations in production quality (e.g., reductions in scraps and reworks).	S	[23,35,39,42–44,98]
		Production Quality - indirect	Indirect variations in production quality.	S	/
		Production costs – direct	Direct variations in production cost (e.g., labour, operations and maintenance, raw materials, waste or production disruptions).	S	[35,37,39,44]
		Production costs - indirect	Indirect variations in production cost.	S	/
	Local	Set-up time	Variations in the time needed to change configuration when different operating conditions are required.	S	[113]
		Reliability of the equipment	Changes in the reliability of the equipment through the mean time to failure (MTTF).	S	[35,39,42,98]
		Downtime for maintenance and repairs	Changes in the downtime for maintenance and repair through the mean time to repair (MTTR). Comprehensive of both the planned and unplanned downtimes.	S	[34,35,98]

Category	Sub-category	Factors	Description	Phase	References
		Downtime for implementation	Time interval including the installation, testing and the start-up of the new equipment as well as the decommissioning of the existing equipment (in case of substitution). When dealing with a practice, it can be considered as the time to effectively implement it.	I	[34,36]
		Equipment lifetime	Variations in the equipment lifetime as a consequence of EEMs adoption. It may be affected by the different conditions of wear and tear to which the equipment is subjected.	S	[12,34,35,39,98]
		Process control	Variations in the level of process control.	S	[38]
Operations-related factors	Motor conditions	Equipment temperature	Variations in the equipment temperature (cooling requirements).	S	[8,39,98]
		Equipment vibrations	Variations in the vibrations to which the equipment is subjected.	S	[59,76,89,98]
		Equipment power quality	Variations in power quality (e.g., power factor, voltage unbalance, off-design voltages and harmonic distortion).	S	[98,113]
		Equipment air quality	Variations in the air quality that reaches the physical devices.	S	[113]
	Working environment	Noise	Variations in the noise within the working environment.	S	[34,35,38,39,42,58]
		Environmental temperature	Variations in the temperature of the working environment.	S	[39]
		Environmental vibrations	Variations in the vibrations perceived by operators within the working environment.	S	/
		Health and Safety	Variations in the health and safety conditions for the operators within the working environment, including the avoided need for personal protective equipment.	S	[34,35,38,42,58]
		Air quality	Variations in the air quality of the working environment after the adoption of EEMs.	S	[34,38,39,42]
	External environment	Waste	Variations in the amount of waste generated.	S	[13,20,34,35,38–40,42,62]
		Emissions	Variations in the amount of GHG and dust emissions. It may affect firm compliance with local regulations.	S	[13,34,35,39,42,44,63,127,128]
Synergies			Synergies between different EEMs which could be exploited to gain advantages.	I+S	[36]
Complexity		Training	Level of training required to adopt an EEM.	I+S	[22–24,72,125,129]
		Dependency from other components/EEMs	Magnitude of influence of an EEM, distinguishing between interventions impacting the specific devices, sub-systems or the wider surrounding system.	S	[12,17]
		Physical placement inside motor system	EMS area addressed by the EEM (location of installation for physical devices or targeted area for procedures). The intervention may be related to a single component of the motor system or the connection between systems (component wide variation) or the entire motor system (architectural innovation). The installation of a new component could also lead to an architectural innovation by shifting the importance of other components in the system.	I	[20,32]
		Activity type	Nature of an EEM, distinguishing between a procedure, a new equipment installation, an optimization in the use of existing technology or an equipment retrofitting.	I	[12,13,19,68,130]
		Technical maturity and diffusion of the technology in the market	Technical maturity of an EEM and its level of diffusion in the market.	/	[12,72,131–133]
		Accessibility	Difficulty to access the location where the EMS is installed.	I+S	[75]
Personnel	Role	Active personnel	Personnel actively engaged during the adoption.	I+S	[8,12,19]
		Passive personnel	Personnel who passively undergoes the adoption.	I+S	/
	Corporate involvement	Active corporate involvement	Extent of involvement by personnel actively engaged.	I	[13]

Category	Sub-category	Factors	Description	Phase	References
		Passive corporate involvement	Extent of involvement by personnel who passively undergoes the adoption.	I	[13]
Additional technical factors		Implementation type	Single-step or multiple times installation, thus providing information about how the effort is distributed along the lifetime of the measure.	I	/
		Check-up frequency	One-time effort or periodic check.	S	[13,134]
		Secondary devices necessary	Technical needs of mandatory secondary devices to benefits from EEMs adoption.	I+S	/
		Additional optimization devices	Technical needs of suggested secondary devices to benefits from EEMs adoption.	I+S	/
		Automation	Eligibility of EEM for automation.	S	/

4. Research methods

The theoretical framework has been tested in the field with industrial decision-makers to verify its completeness and its applicability as an assessment tool, capable of pointing out the major factors driving the adoption of EEMs in EMS. The multiple case study methodology has been adopted following a replication logic, choosing independent cases to obtain similar results, in line with Yin [135] and Voss et al. [136]. Indeed, the differences in the businesses and the environment could deeply influence the perception of factors and categories and, in turn, the approach toward the adoption of EEMs. The selected sample encompasses Italian firms within different sectors, firm size and energy use, thus potentially characterized by different behaviours toward the adoption of EEMs. Indeed, larger firms are usually more structured compared to smaller ones, with a more structured decision-making chain [137]. Moreover, the choice of the sector could lead to different applications of EMS, thus also influencing the adoption rate of EEMs, beyond a different relevance of energy costs and savings. Finally, the six sampled firms (details in Table 3) are located in two large manufacturing regions contributing to about 30% of the Italian GDP [138].

Table 3

Sample of companies and EEMs selected for the validation of the framework.

Firm	Sector	Size [employees]	Turnover [M€]	Energy intensity [EI/NEI][1]	Role of the Interviewee	EEMs	EMS targeted	EEM type	EEM code
1	Boiler construction and carpentry	101 ÷ 150	27	NEI	Plant manager	Use adjustable frequency drive to replace throttling system (ARC 2,4143)	3 KW motor used for equipment testing	Implemented	EEM 1-1
						Use most efficient types of electric motors (ARC 2,4133)	3x1,5 KW motors used for ventilation fans	Implemented	EEM 1-2
2	Food & beverage	10 ÷ 50	19	NEI	Maintenance responsible	Use VSDs	1,5 KW motor used for wine racking	Not implemented	EEM 2-1
						Utilize energy-efficient belts and other improved mechanisms (ARC 2,4111)	7 motors with a power up to 8 KW used for material handling	Implemented	EEM 2-2

Firm	Sector	Size [employees]	Turnover [M€]	Energy intensity [EI/NEI][1]	Role of the Interviewee	EEMs	EMS targeted	EEM type	EEM code
3	Plastic & packaging	151 ÷ 249	90	EI	Deputy Maintenance responsible	Utilize energy-efficient belts and other improved mechanisms (ARC 2,4111)	7x50 KW motors used for a cutting press	Not implemented	EEM 3-1
						Replace DC equipment with AC equipment (ARC 2,3311)	30x3 KW motors used for material handling	Implemented	EEM 3-2
						Use VSDs	140 KW motor used in a screw extruder	Implemented	EEM 3-3
4	Steel rolling	51÷ 100[2]	90	EI	Maintenance responsible	Establish a preventive maintenance program (ARC 2,4156)	900 KW motor used for material handling	Implemented	EEM 4-1
						Replace DC equipment with AC equipment (ARC 2,3311)	6x150 KW motors used for steel lamination	Not implemented	EEM 4-2
5	Machine assembly	51÷ 100	12	NEI	CEO and owner	Use most efficient types of electric motors (ARC 2,4133)	3,5 KW motor used for material handling	Not implemented	EEM 5-1
						Upgrade control on compressors (ARC 2,4224)	17 KW motor used for HVAC	Implemented	EEM 5-2
6	Iron & steel	≥ 250[3]	/	EI	Electrical maintenance responsible	Install isolation transformers	3 motors with a power up to 3,5 MW used for steel lamination	Implemented	EEM 6-1

[1] Firms are labelled as energy-intensive when their energy costs exceed 2% of the total annual turnover [11].

[2] The plant interviewed belongs to a larger corporate employing about 1100 people.

[3] The plant belongs to a larger corporate employing about 6500 people with total revenue of €5 billion.

In-field interviews are carried out following the semi-structured approach [139], to allow the partial customization required by the heterogeneity of situations under analysis.

Each interview has started with a brief description of the firm and its main production processes. The discussion has also explored the relevance and the characteristics of EMS and the required applications. The decision-making process is then investigated, together with the role of the respondents for the adoption of EEMs in EMS, followed by a brief overview of the EEMs implemented in the past.

The second part of the interview has dealt with the preliminary validation of the framework according to a predetermined set of indicators. A Likert scale from one (poor) to four (excellent) is used, similarly to [75]. The features interested by the analysis firstly has encompassed the structure, scope and perspective of the framework, followed by the categories, sub-categories and factors, considered in this step as clusters. After the understanding by the responding of the overarching framework structure, the analysis has moved into the details of the single categories, sub-categories and factors. Table 4 shows the indicators used and their specific role in the validation of each element of the framework.

Table 4

Indicators for the validation of the framework completeness, classification, usefulness and clearness.

Framework	Completeness	Classification	Usefulness	Clearness
Structure				X
Scope			X	X
Perspective				X
Categories	X (cluster)		X	X
Sub-categories	X (cluster)		X	X
Factors	X (cluster)	X (cluster)	X	X

Upon completion of the preliminary validation, the framework has been further validated in terms of completeness and usefulness through the investigation of twelve heterogeneous EEMs selected from [113] among the most implemented in industry [9] (Table 3). The sample includes both EEMs which were successfully adopted by the firms and still in place (*implemented EEMs)*, those considered for adoption but not implemented or adopted but then removed (*not implemented EEMs*). Respondents are required to point out which factors were considered and deemed important in order to adopt EMS EEMs. Moreover, in the final phase of the empirical validation, they are asked whether a different decision would have been taken if the framework had been available to support them. The flow chart of the methodology process is described in Fig. 1.

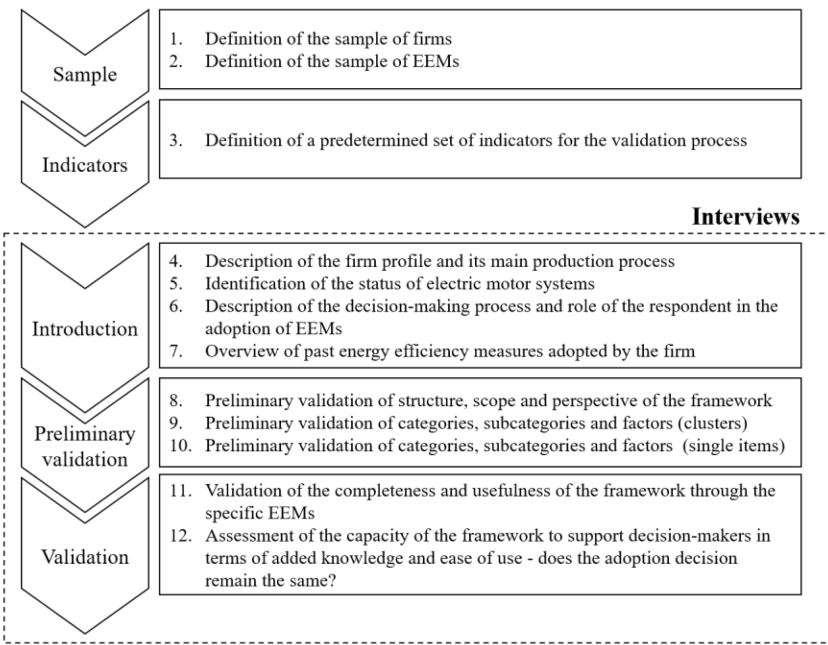

Fig. 1. Flow chart of the methodology process.

5. Results

The preliminary validation has allowed gathering some valuable insights for the framework, with interviewees positively judging all indicators (details reported in Table A1 in the Appendix). In particular, interviewees noted that all the factors potentially affecting the adoption of EEMs in EMS have been included. Further, there were no major concerns regarding the classification into categories and sub-categories. In this regard, the structure has been acknowledged and deemed appropriate, and factors well understood by decision-makers. Finally, the overall evaluation of the usefulness resulted extremely positive.

Regarding the second phase of the validation, Table 5 and Table 6 present the empirical results based on two specific EEMs, EEM 2-1 and EEM 3.2 respectively, followed by more general comments over the general validation.

Table 5

Validation of the framework through EEM 2-1, pointing out: factors considered useful (✓) in the EEMs assessment; factors assessed and eventually driving the adoption decision, both positive (EEM implemented, ✓✓) and negative (EEM not implemented, ✓✓*); factors neglected from the EEMs assessment, both negligible (O), important (X) and potentially reversing the decision (X X) with respect to the outcome.

Validation of the framework: EEM 2-1				
Firm profile				• Small non-energy intensive firm belonging to the food&beverage sector.
Production				• The firm produces wine and the process includes all the phases from the pressing of harvested grapes to the bottling of the final products.
EMS				• More than 200 motors, some of them running continuously 24 hours per day. The maximum power is 10 KW.
Decision-making				• Given the low share of energy cost, about 0,8% of the total turnover, an energy manager is missing. The EEMs are carried out by the respondent (maintenance responsible), supported by external service providers for the most expertise requiring EEMs.
EEM				• Installation of a VSD coupled with a pump actioned by a 1.5 KW motor and used for wine racking from one pool to another (EEM 2-1).
EEM type				• Not implemented (implemented but soon removed).
Framework				**Factors consideration and notes for firm 2**
Descriptive factors		Motor model	✓	• Considered in the analysis as the basis of the assessment
		Motor size	✓	
		Motors numerosity	✓	
		Working hours	✓	
		Process focus	✓	
		Application load	✓	
Compatibility	Load	Load compatibility	X X	• The analysis of the load compatibility was limited to the initial configuration, which unfortunately represented the best scenario with respect to all the different phases of the racking process. To perform a complete racking of wine, the process is stopped multiple time according to the level reached by the wine in the pool. However, with the progressive movement of wine from one pool to another, the static head acting on the pump increased to unbearable levels for the VSD, which was soon removed from the process.
		Adaptability to different conditions	✓	
	System	Adaptability in every environment	✓	• The compatibility of the EEM with the system was considered and no issues were detected.
		Reduced layout flexibility	✓	
Economy		Initial implementation cost	✓✓	• Cost represented a major barrier to the adoption, but the analysis of the benefits led to an acceptable pay-back time. • They were not aware of the potential need to invest in additional devices to improve the power quality against the harmonic distortion introduced by the VSD.
		Total adoption cost	✓✓	
		Adoption cost of secondary devices	X	
		Adoption cost of additional optimization devices	O	
		Financial exposure	O	
		Monetary savings	✓	
		Pay-back time	✓✓	
Energy benefits			✓	• Low energy savings due to the reduced consumption of the motor.
Production related factors	Global	Productivity - direct	✓✓	• Productivity improvement is one of the main reasons driving the adoption of the EEM. • The indirect impacts on productivity were not considered, but their impact would have been negligible since just one small motor was affected by the EEM.
		Productivity - indirect	O	
		Production quality - direct	✓	
		Production quality - indirect	O	
		Production cost - direct	✓	
		Production cost - indirect	O	
	Local	Set-up time	✓	• The improvement in process control was the main reasons driving the adoption of the EEM.
		Reliability	✓	
		Downtime for maintenance and repair	✓	
		Downtime for implementation	✓	
		Equipment lifetime	✓	
		Improved process control	✓✓	
Operations related factors	Motor conditions	Equipment temperature	✓	• Motor conditions were considered but reported only slight variations due to the reduction of speed during the great majority of the operating time.
		Equipment vibrations	✓	
		Equipment power quality	✓	

Validation of the framework: EEM 2-1				
		Equipment air quality	✓	
	Working environment	Air quality	✓	• The conditions of the working environment were considered but did not change due to the single small motor impacted by the EEM, which was moreover placed away from the working area.
		Noise	✓	
		Environmental temperature	✓	
		Environmental vibrations	✓	
		Health and safety	✓	
	External environment	Waste	O	• Variations in the external environment were not considered. They would have not impacted the adoption.
		Emission	O	
Synergies			O	• Synergies were not known by the decision-maker, but even if considered they would have not impacted the adoption.
Complexity		Training	✓	• Complexity factors were considered, especially regarding the required training to maintain the VSD and the reduced level of risk introduced by the activity type.
		Dependency from other components/ EEMs	✓	
		Physical placement inside motor system	✓	
		Activity type	✓	
		Technical maturity and diffusion of the technology in the market	✓	
		Accessibility	✓	
Personnel	Role	Active personnel	✓	• No great variations impacted the personnel beside the additional training, however limited to the maintenance personnel.
		Passive personnel	✓	
	Corporate involvement	Active corporate involvement	✓	• Only the involvement of the respondent was required to carry out the adoption.
		Passive corporate involvement	✓	
Additional technical factors		Implementation type	✓	• They were not aware of the potential need to install additional devices to cope with the power quality issues generated by the VSD.
		Check-up frequency	✓	
		Secondary devices necessary	X	
		Additional optimization devices	X	
		Automation	✓	

Table 6

Validation of the framework through EEM 3-2, pointing out: factors considered useful (✓) in the EEMs assessment; factors assessed and eventually driving the adoption decision, both positive (EEM implemented, ✓✓) and negative (EEM not implemented, ✓✓*); factors neglected from the EEMs assessment, both negligible (O), important (X) and potentially reversing the decision (X X) with respect to the outcome.

Validation of the framework: EEM 3-2				
Firm profile				• Medium energy-intensive firm belonging to the plastic&packaging sector.
Production				• The firm realizes plastic products such as containers or disposable tableware used in the food sector. • 20 lines are installed to carry out the production, each of them divided into two sections: the first is responsible for the creation of plastic sheets from raw powder, while in the second the sheets are heated up, vacuum-formed in a mould and eventually cut through a press.
EMS				• The total power installed is about 5 MW, with motors ranging in size up to 140 KW.
Decision-making				• Despite the high share of energy costs, about 4% of the total turnover, an energy manager is missing, hence EEMs are implemented by the respondent (deputy maintenance responsible) together with the maintenance responsible.
EEM				• Replacement of 30 old 3 KW DC motors powering the material handling system of two production lines with the corresponding AC devices (EEM 3-2).
EEM type				• Implemented.
Framework				**Factors consideration and notes for firm 3**
Descriptive factors		Motor model	✓	• Considered in the analysis as the basis of the assessment
		Motor size	✓	
		Motors numerosity	✓	
		Working hours	✓	
		Process focus	✓	
		Application load	✓	
Compatibility	Load	Load compatibility	✓	• Despite AC devices are usually characterized by a lower torque with respect to their DC counterparts, the analysis of the load compatibility did not highlight problems due to the limited requirements from the load. • To be compatible with the speed modularity required by the material handling system (i.e., compatibility to different conditions), the firm was forced to couple the new devices with VSDs.
		Adaptability to different conditions	✓✓	

Validation of the framework: EEM 3-2				
				• With this EEM the firm moved toward the standardization of the equipment, with the aim of increasing the compatibility of the devices in terms of adaptability to different conditions.
	System	Adaptability in every environment	O	• The adaptability of the devices in the environment was not considered, but no problems would arise because of the strict environmental standards the firm is subjected to due to the collaboration with the food sector.
		Reduced layout flexibility	✓	• The limited layout flexibility of a rigid system such as a production line could have been a problem with the installation of VSD, which must be placed not too far from the control centre. However, no problems arose.
Economy		Initial implementation cost	✓✓	• The adoption of new AC devices consistently reduced the high costs in which the firm was incurring to find spare parts for the old DC devices, no longer widely diffused in the market. • Further additional devices, i.e., passive filters, were required to deal with the power quality issues, mainly harmonics, generated by the extensive adoption of VSDs in the plant. The cost of these additional devices is added to the non-negligible cost of the EEM. • Despite a rather long pay-back time according to the firm evaluation, the economic assessment was positive.
		Total adoption cost	✓✓	
		Adoption cost of secondary devices	✓✓	
		Adoption cost of additional optimization devices	✓	
		Financial exposure	O	
		Monetary savings	✓	
		Pay-back time	✓	
Energy benefits			✓	• High energy consumption reduction.
Production related factors	Global	Productivity - direct	✓✓	• Productivity improvement is one of the main reasons driving the adoption of the EEM. • The indirect impacts on productivity were not considered by the decision-maker.
		Productivity - indirect	X	
		Production quality - direct	O	
		Production quality - indirect	X	
		Production cost - direct	✓	
		Production cost - indirect	X	
	Local	Set-up time	✓	• The improvement in productivity derived from the increased reliability and equipment lifetime, mainly due to the absence of brushes in the new devices, was considered very important. • The downtimes of the production for maintenance and repairs are reduced thanks to the creation of an internal standard spare parts warehouse with standard spare motors immediately available for use.
		Reliability	✓✓	
		Downtime for maintenance and repair	✓✓	
		Downtime for implementation	✓	
		Equipment lifetime	✓✓	
		Improved process control	✓	
Operations related factors	Motor conditions	Equipment temperature	✓	• The operations factors were considered, given their proximity to the reliability of the equipment. In particular, the decision-maker noticed an improvement in the air quality due to the absence of dust created by the DC motors brushes degradation.
		Equipment vibrations	✓	
		Equipment power quality	✓	
		Equipment air quality	✓	
	Working environment	Air quality	✓	• Except for the aforementioned air quality, the decision-maker did not take into account variations in the working environment, nor the positive impact this could have on the workers and on the conditions in which they are called to operate, potentially indirectly fostering their productivity.
		Noise	X	
		Environmental temperature	X	
		Environmental vibrations	X	
		Health and safety	X	
	External environment	Waste	O	• Variations in the external environment were not considered, despite the willingness of the firm to be perceived as sustainable and efficient, as testified by the certificates they own and the events they organize.
		Emission	O	
Synergies			✓	• Synergies were considered
Complexity		Training	✓	• Complexity was mainly taken into account considering the dependency of the EEM from other components, carefully analysed because of the potentially disruptive effect it could have on a rigid system based on production lines configuration. • The complexity of the EEM required additional training for the operators. • No accessibility issues were detected, despite AC motors are generally larger with respect to DC ones and additional VSD had to be installed.
		Dependency from other components/ EEMs	✓	
		Physical placement inside motor system	✓	
		Activity type	✓	
		Technical maturity and diffusion of the technology in the market	✓	
		Accessibility	✓	
Personnel	Role	Active personnel	✓	• Personnel was considered when dealing with the reduction in maintenance and referring to the additional training activities required by the EEM. • The impacts on personnel who passively underwent changes in the conditions of the working environment after the adoption of the EEM were not considered.
		Passive personnel	X	
	Corporate involvement	Active corporate involvement	✓	• Considering the investment and the extension of the EEM on 30 motors, the adoption needed to be supported by higher management levels. • A large number of employees was involved in the adoption of the EEM.
		Passive corporate involvement	✓	
Additional technical factors		Implementation type	✓	• The additional technical factors were considered by the decision-maker.
		Check-up frequency	✓	
		Secondary devices necessary	✓	
		Additional optimization devices	✓	
		Automation	✓	

In both the cases discussed in Table 5 and Table 6, the framework proved to be complete, being able to highlight all the important factors to be considered for the adoption of the EEMs. Interestingly, some of them were not always considered by the decision-makers of the two firms. Concerning EEM 2-1, many important factors that would support its adoption were assessed, however missing the most critical one highlighted in the present framework, i.e., lack of load compatibility, that effectively led to the EEM removal after its adoption. On the other hand, firm 3 was more aware of the adoption and, as the use of the framework showed, the large majority of factors that should have been considered were already assessed by their decision-maker. Nonetheless, the framework proved to shed light on some additional benefits which were overlooked by the firm (e.g., positive impacts on the working environment, thus on the personnel). While this addition would not change the outcome of the adoption, it could give a decision-maker a more realistic picture of the EEM adoption and its consequences. Therefore, the validation of the framework was successful in both cases.

Considering the whole sample of twelve EEMs, useful insights came from the validation process (Table 7). Firstly, the importance of all the categories and factors for in-depth decision-making about EEMs in EMS is confirmed. Regardless of the outcome of the adoption, by using the framework decision-makers confirmed they could undertake the assessment with additional valuable information on all the major factors. In particular, interviewees have appreciated the level of detail achieved by the framework that allowed for thorough decision-making over the specific EEMs. The efficacy of the approach has been shown multiple times during the interviews, e.g., in the case of firm 2 (EEM 2-1), where EEMs were not adopted because of the lack of compatibility with the existing system (see Table 5 for more details). However, the relevance of EEMs compatibility with the system in which they are adopted varies according to the specific technology; for instance, the compatibility with the applied load should be assessed for EMS but it might be less interesting for other technologies, e.g., lighting. As confirmed by respondents, with just a general framework to support decision-makers, such specific implications could not be grasped. Moreover, the user-friendliness and ease of use of the framework, thanks to a perspective focused on the decision-maker, were particularly appreciated.

Secondly, the preliminary investigation revealed that the application of the framework would not have changed the decision of adopting the implemented EEMs: all the factors potentially driving the adoption were recognised by companies or, when not considered, they were mainly related to additional benefits (thus further corroborating the decision).

Thirdly, interviewees offered interesting insights and comments regarding not-implemented EEMs. As observed in many companies (e.g., Firm 5), firms could have implemented more valuable EEMs by using the framework, thus further improving their sustainability.

Table 7

Validation of the framework, pointing out: factors considered useful (✓) in the EEMs assessment; factors assessed and eventually driving the adoption decision, both positive (EEM implemented, ✓✓) and negative

(EEM not implemented, ✓✓*); factors neglected from the EEMs assessment, both negligible (O), important (X) and potentially reversing the decision (X X) with respect to the outcome.

Framework			**Firms and EEMs**											
Categories	**Sub-categories**	**Factors**	EEM 1-1	EEM 1-2	EEM 2-1	EEM 2-2	EEM 3-1	EEM 3-2	EEM 3-3	EEM 4-1	EEM 4-2	EEM 5-1	EEM 5-2	EEM 6-1
Descriptive factors		Motor model	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Motor size	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Motors numerosity	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Working hours	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Process focus	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
		Application load	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Compatibility	Load	Load compatibility	✓	✓	X X	✓	✓✓*	✓	✓	✓	✓	✓	✓	✓
		Adaptability to different conditions	✓✓	✓	✓	✓	✓	✓✓	✓	✓	✓	✓	✓	✓
	System	Adaptability in every environment	✓	✓	✓	✓	O	O	O	✓	X	✓	✓	✓✓
		Reduced layout flexibility	O	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	O
Economy		Initial implementation cost	✓	✓✓	✓✓	✓✓	✓	✓✓	✓✓	✓	✓✓*	✓✓	✓✓	✓✓
		Total adoption cost	✓	✓✓	✓✓	✓✓	✓	✓✓	✓✓	✓	✓✓*	✓✓	✓✓	✓✓
		Adoption cost of secondary devices	X	O	X	✓	✓	✓✓	✓	✓	✓✓	X	O	✓
		Adoption cost of additional optimization devices	X	O	O	✓	✓	✓	✓	✓	✓	X	O	✓
		Financial exposure	X	O	O	O	O	O	O	✓	✓	O	O	O
		Monetary savings	✓✓	✓✓	✓	✓	✓✓	✓	✓✓	✓	✓	✓✓*	✓✓	✓✓
		Pay-back time	✓	✓	✓✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Energy savings			✓✓	✓✓	✓	✓	✓✓	✓	✓✓	✓	✓	✓✓	✓✓	✓✓
Production related factors	Global	Productivity - direct	✓	✓	✓✓	✓	✓✓	✓✓	✓	✓✓	✓✓	✓	✓	✓✓
		Productivity - indirect	O	O	O	X	O	X	X	✓	X	O	O	✓
		Production quality - direct	✓	✓	✓	✓	✓	O	O	O	O	✓	✓	✓✓
		Production quality - indirect	O	O	O	X	O	X	X	✓	X	O	O	✓
		Production cost - direct	✓	✓	✓	✓	✓	✓	✓	✓	✓✓	✓	✓	✓✓
		Production cost - indirect	O	O	O	X	O	X	X	✓✓	X	O	O	✓
	Local	Set-up time	✓	✓	✓	✓	O	✓	✓	✓	✓	✓	✓	✓
		Reliability of the equipment	✓	✓✓	✓	✓✓	✓✓	✓✓	✓	✓✓	✓✓	✓	✓	✓
		Downtime for maintenance and repair	O	O	✓	✓✓	✓✓	✓✓	✓	✓	✓	✓	✓	✓
		Downtime for implementation	✓	✓	✓	✓	O	✓	✓	✓	✓	✓	✓	✓
		Equipment lifetime	✓	✓✓	✓	✓	O	✓✓	✓	✓✓	✓✓	✓	✓	✓
		Process control	✓✓	✓	✓✓	O	O	✓	✓✓	O	O	✓	✓	✓
Operations related factors	Motor conditions	Equipment temperature	✓	✓	✓	✓	O	✓	✓	✓	X	✓	✓	✓✓
		Equipment vibrations	✓	✓	✓	✓	O	✓	✓	✓	X	✓	✓	✓
		Equipment power quality	X	O	✓	✓	O	✓	✓	✓	X	✓	✓	✓
		Equipment air quality	O	✓	✓	✓	O	✓	✓	O	X	✓	✓	✓
	Working environment	Air quality	O	✓	✓	✓	O	✓	✓	O	X	O	✓	✓
		Noise	O	✓	✓	✓	O	X	X	✓	X	O	✓	✓
		Environmental temperature	O	✓	✓	✓	O	X	X	✓	X	O	✓	✓
		Environmental vibrations	O	✓	✓	✓	O	X	X	✓	X	O	✓	✓
		Health and safety	O	O	✓	✓	O	X	X	✓	X	O	✓	✓
	External environment	Waste	O	O	O	O	O	O	O	✓	O	✓	✓	✓
		Emission	O	O	O	O	O	O	O	✓	O	✓	✓	✓
Synergies			X	✓	O	O	O	✓	✓	O	O	✓	✓	O
Complexity		Training	✓	✓	✓	✓	O	✓	✓	✓✓	✓✓*	✓	✓	✓✓
		Dependency from other components/ EEMs	✓	✓	✓	✓	O	✓✓	✓✓	✓	✓	✓	✓	✓✓
		Physical placement inside motor system	✓	✓	✓	✓	O	✓	✓	✓	✓	✓	✓	✓
		Activity type	✓	✓	✓	✓	O	✓	✓	✓	✓	✓	✓	✓
		Technical maturity and diffusion of the technology in the market	✓	✓	✓	✓	O	✓✓	✓	✓	✓	✓	✓	O
		Accessibility	O	O	✓	✓	O	✓	✓	✓✓	✓✓	✓	✓	✓
Personnel	Role	Active personnel	✓	✓	✓	✓	O	✓	✓	✓	✓	✓	✓	✓✓
		Passive personnel	✓	✓	✓	X	O	X	X	✓	X	O	✓	✓
	Corporate involvement	Active corporate involvement	✓	✓	✓	✓	O	X	X	✓	✓	✓	✓	✓
		Passive corporate involvement	✓	✓	✓	X	O	X	X	✓	X	O	✓	✓
Additional technical factors		Implementation type	✓	✓	✓	✓	O	✓	✓	✓	✓	✓	✓	✓
		Check-up frequency	✓	✓	✓	✓	O	✓	✓	✓	✓	✓	✓	✓
		Secondary devices necessary	X	O	X	✓	O	✓	✓	✓	✓	X	O	✓
		Additional optimization devices	X	O	X	✓	O	✓	✓	✓	✓	X	O	✓
		Automation	✓	✓	✓	✓	O	✓	✓	O	✓	O	O	O

6. Discussion

The empirical analysis performed in the present study confirmed the criticality played by some of the factors previously identified by literature and summarised in Table 1. Productivity improvements, achieved through the higher reliability of the new equipment, drove the adoption of EEM 1-2 and EEM 2-2, confirming findings from previous works that linked the adoption of EEMs to increased productivity [39,112]. Productivity and process control improvements also led firm 2 to the consideration of a VSD (EEM 2-1), confirming the finding of Saidur et al. [141]. In Firm 4, reliability represented the main driver for the EEMs considered by firm 4, confirming the importance attributed to the factor by previous research (e.g., Gordon et al. [49]). In accordance, the literature demonstrated how reliability is important for both increasing the value offered by a firm and decreasing its operational risk [31,53]. Furthermore, operations related factors were assessed by all decision-makers interviewed, especially in the case of EEM 6-1, where the equipment temperature was a factor of primary importance. Indeed, impacts on factors such as air quality, vibrations and temperature show a strict connection with the equipment performance. Such finding looks aligned with those of Piette and Nordman [76], who highlighted a degradation in both the production quality and the reliability of the equipment as a consequence of the variation of those factors. Furthermore, earlier literature greatly supported the role of EEMs as a means to affect the working environment, with a consequent impact on workers comfort, health and safety, and indirectly on their productivity [39]. From the interviews performed in the present study, these factors were not always assessed by decision-makers, which however acknowledged their relevance by using the framework. Also, our preliminary investigation showed that the external environment, encompassing emissions and waste factors, was either largely neglected or barely relevant for the adoption. However, when dealing with environmental topics, respondents clearly pointed out their firms were fully compliant with local regulations, and this could explain the relatively lower importance attributed to these factors. Our findings differ from other research where the impact on the external environment was crucial for the decision [64,82], in particular when dealing with industrial firms subjected to environmental regulations. Lilly and Pearson [65] showed how the evaluation of emissions is different depending on whether firms may incur fines, whilst Elliott et al. [33] pointed out that emissions could be even more important than any enhancement in reliability or production since unfulfilled regulations could lead to a complete shutdown of the firms' operations.

Nevertheless, despite the great importance attributed to the aforementioned categories of factors, the present research shows additional categories and factors playing a key role in the adoption of EEMs in EMS. The present investigation revealed how some additional factors, specific for EMS, should be pinpointed for more effective decision-making, critical since often neglected by literature and sometimes even by decision-makers. This the case of e.g., the factors related to the compatibility or the complexity dimensions of an EEM, especially when EEMs in EMS may affect the core production processes. According to our results (e.g., EEM 2.1 and EEM 3.1), compatibility issues might prevent decision-makers from implementing those EEMs, regardless of any further consideration or achievable benefits. Our empirical findings corroborate previous works linking complexity and compatibility of innovation and the respective level of adoption [16,17]. However, referring to the broad concept of innovation, previous analyses lack the level of detail necessary for an empirical assessment of EMS EEMs, being rather focused on compressed air systems [75]. Nevertheless, being the compressed air systems an ancillary service, important considerations that might play a critical role for EMS were not captured (e.g., the need to adapt to the variation of production conditions, as shown by EEM 1-1 or EEM 3-2). Likewise, our investigation broad new knowledge about other important factors (e.g., synergies, the impacts on personnel or the additional technical factors) previously mostly overlooked by research [36].

Earlier literature gave limited importance to the specific context of application of the EEMs (e.g., the location [32] or the distance to the core process [12,13,31]). Rather, the investigated case studies revealed that the EMS EEMs should be analysed within their specific context of application. As noted in firm 2, the lack of compatibility identified was due to both the technical characteristics of the EEM [113] and the context in which the EEM was meant to operate.

Moreover, the case studies made it possible to observe the impact of contextual factors. For instance, motors' size and numerosity seem to have a moderating function (similarly to what observed by Aguinis et al. [142]) on other factors, e.g., the investment cost. For firm 4, e.g., the higher cost due to large motor size and high number represented one of the main issues hindering the replacement of the old DC motors. Furthermore, the same contextual factors might affect the importance attributed to the external and working environment, since these may not be significantly affected in the case of just a few small motors installed. As observed in firm 5 (EEM 5-1), despite the great importance of the working environment conditions, this feature was overlooked because of the limited size of the motor proposed for the intervention (3.5 KW) and its limited number of working hours. Furthermore, the preliminary investigation seems to point out that the type of load may also have a moderating function on monetary energy savings – when the EEM refers to a controller [143,144] –, and decision-makers seemed particularly sensitive to this effect every time a VSD was considered for application. Differently, the process centrality seems to be characterized by a mediating nature [142], particularly evident when looking at the different critical elements by analysing core versus ancillary processes. Core processes represent the main activity of the plant, therefore extremely connected to revenues and market competitiveness: hence, it is reasonable to expect the adoption of EMS EEMs to be primarily led by productivity enhancement and the related factors, e.g., reliability [31,61]. Rather, similar patterns cannot be clearly identified for ancillary processes. Likewise, energy intensity plays an important role in affecting firms' behaviour [53]. According to the literature, given the high share of energy costs, energy-intensive firms are usually more concerned about energy savings [96,99]. The findings of the present study show that earlier approaches limited on technical and cost-effectiveness analyses of EEMs (e.g., [145,146]) are not sufficient to justify the adoption in, e.g., non-energy intensive firms [53], where the influence on the production and the operations shall be carefully analysed. Our study also confirms earlier findings referring to the impact of the firm size on the adoption process due to the lack of procedures and internal competencies [147,148]. Indeed, in the greatest majority of case studies regarding SMEs, the analysis performed by the interviewees did not include all the factors that should be taken into account for thorough decision-making (see Table 6). On the other hand, in larger sampled firms a higher degree of awareness was observed, possibly related to the lower level of energy management and interest in energy issues that generally characterize smaller firms [99], which in turn is reflected in lower expertise when it comes to adopting EEMs. Consequently, the proposed framework appears particularly suitable for SMEs to support them in identifying the major factors when adopting EEMs in EMS.

7. Conclusions

The present study aims at offering a contribution to the discussion over industrial energy efficiency by offering an innovative framework for the identification and assessment of the major factors driving the adoption of EEMs in EMS. Besides assessing the technical, economic and energy-related characteristics of EEMs [113], the framework has been designed to encompass their specific context of application and their impacts on the production resources and the firm's operations. The framework thus obtained is inclusive of fifty-four factors, organized into ten categories, representing the minimum information to take sound decisions regarding the adoption of EEMs in EMS. The preliminary investigation in a set of manufacturing enterprises operating in various contexts demonstrated the capability to provide increased knowledge to industrial decision-makers. In particular, decision-makers belonging to non-energy intensive firms could make valuable use of the framework, given its capability to pinpoint interesting impacts across the energy dimension to provide a more comprehensive view of the adoption. Similarly, the framework emerged particularly suitable for SMEs, which may experience greater difficulties in gathering information about EEMs. In addition, the proposed framework could support policy-makers in identifying the major barriers preventing the adoption of EEMs in EMS. In fact, by highlighting the major factors, more specific and tailored policies could address the specific issues at the backbone of the decision-making process of adopting an EEM. Nevertheless, more research is needed in this direction.

In conclusion, a limitation of the study should be acknowledged referring to the size of the validation sample, which prevents a statistical generalization of findings. Future research should test the framework on a wider set of firms and their respective sectors, to allow for the statistical significance of the findings. Similarly, the number of tested EEMs should be increased to better understand how they impact different areas of an industrial firm. Furthermore, the moderating and mediating role [142] of some factors was just preliminarily observed (e.g., firm size or energy intensity), but future research should more thoroughly and more extensively shed light on these relationships. Also, another interesting yet challenging research avenue stemming from the study is represented by the quantification of the impacts deriving from the adoption of EEMs in EMS.

Appendix

Table A.1

Preliminary validation of the framework in terms of usefulness, completeness, clearness and classification, evaluated through a Likert scale from one(poor) to four (excellent).

			Firm 1				Firm 2				Firm 3				Firm 4				Firm 5				Firm 6			
			Usefulness	Completeness	Clearness	Classification	Usefulness	Completeness	Clearness	Classification	Usefulness	Completeness	Clearness	Classification	Usefulness	Completeness	Clearness	Classification	Usefulness	Completeness	Clearness	Classification	Usefulness	Completeness	Clearness	Classification
Framework	Structure		4		4		4		4		4		4		4		4		4		4		4		4	
Framework	Scope		4		4		4		4		4		4		4		4		4		4		4		4	
Framework	Perspective				4				4				4				4				4				4	
Categories				4				4				4				4				4				4		
Sub-categories				4				4				4				4				4				4		
Factors				4		4		4		4		4		4		4		4		4		4		4		4
Contextual factors			4		4		4		4		4		4		4		4		4		4		4		4	
Compatibility			4		4		4		4		4		4		4		4		4		4		4		4	
	Load		4		4		4		4		4		4		4		4		4		4		4		4	
	System		4		4		4		4		4		4		4		4		4		4		4		4	
Economy			4		4		4		4		4		4		4		4		4		4		4		4	
Energy savings			4		4		4		4		4		4		4		4		4		4		4		4	
Production-related factors			4		4		4		4		4		4		4		4		4		4		4		4	
	Global		4		4		4		4		4		4		4		4		4		4		4		4	
	Local		4		4		4		4		4		4		4		4		4		4		4		4	
Operations-related factors			4		4		4		4		4		4		4		4		4		4		4		4	
	Motor conditions		4		4		4		4		4		4		4		4		4		4		4		4	
	Working environment		4		4		4		4		3		4		4		4		4		4		4		4	
	External environment		3		4		3		4		4		4		4		4		4		4		4		4	
Synergies			4		4		4		4		4		4		3		4		4		4		4		4	
Complexity			4		4		4		4		4		4		4		4		4		4		4		4	
Personnel			4		4		4		4		4		4		4		4		4		4		4		4	
	Role involved		4		4		4		4		4		4		4		4		4		4		4		4	
	Corporate involvement		4		4		4		4		4		4		4		4		4		4		4		4	
Additional technical factors			4		4		4		4		4		4		4		4		4		4		4		4	
Contextual factors		Motor model	4		4		4		4		4		4		4		4		4		4		4		4	
Contextual factors		Motor size	4		4		4		4		4		4		4		4		4		4		4		4	
Contextual factors		Motors numerosity	4		4		4		4		4		4		4		4		4		4		4		4	
Contextual factors		Working hours	4		4		4		4		4		4		4		4		4		4		4		4	
Contextual factors		Process centrality	4		4		4		4		4		4		4		4		4		4		4		4	
Contextual factors		Application load	4		4		4		4		4		4		4		4		4		4		4		4	
Compatibility	Load	Load compatibility	4		4		4		4		4		4		4		4		4		4		4		4	
Compatibility	Load	Adaptability to different conditions	4		4		4		4		4		4		4		4		4		4		4		4	
Compatibility	System	Adaptability in every environment	4		4		4		4		3		4		4		4		4		4		4		4	
Compatibility	System	Reduced layout flexibility	4		4		4		4		4		4		4		4		4		4		4		4	
Economy		Initial implementation cost	4		4		4		4		4		4		4		4		4		4		4		4	
Economy		Total adoption cost	4		4		4		4		4		4		4		4		4		4		4		4	
Economy		Adoption cost of secondary devices	4		4		4		4		4		4		4		4		4		4		4		4	
Economy		Adoption cost of additional optimization devices	4		4		4		4		4		4		4		4		4		4		4		4	
Economy		Financial flexibility	4		4		4		4		3		4		4		4		4		4		4		4	
Economy		Savings	4		4		4		4		4		4		4		4		4		4		4		4	
Economy		Pay-back time	4		4		4		4		4		4		4		4		4		4		4		4	
Production-related factors	Global	Productivity - direct	4		4		4		4		4		4		4		4		4		4		4		4	
Production-related factors	Global	Productivity - indirect	4		4		4		4		4		4		4		4		4		4		4		4	
Production-related factors	Global	Production quality - direct	4		4		4		4		4		4		4		4		4		4		4		4	
Production-related factors	Global	Production quality - indirect	4		4		4		4		4		4		4		4		4		4		4		4	
Production-related factors	Global	Production cost - direct	4		4		4		4		4		4		4		4		4		4		4		4	
Production-related factors	Global	Production cost - indirect	4		4		4		4		4		4		4		4		4		4		4		4	

			Firm 1				Firm 2				Firm 3				Firm 4				Firm 5				Firm 6			
			Usefulness	Completeness	Clearness	Classification	Usefulness	Completeness	Clearness	Classification	Usefulness	Completeness	Clearness	Classification	Usefulness	Completeness	Clearness	Classification	Usefulness	Completeness	Clearness	Classification	Usefulness	Completeness	Clearness	Classification
	Local	Set-up time	4		4		4		4		4		4		4		4		4		4		4		4	
		Reliability of the equipment	4		4		4		4		4		4		4		4		4		4		4		4	
		Downtime for maintenance and repair	4		4		4		4		4		4		4		4		4		4		4		4	
		Downtime for implementation	4		4		4		4		4		4		4		4		4		4		4		4	
		Equipment lifetime	4		4		4		4		4		4		4		4		4		4		4		4	
		Process control	4		4		4		4		4		4		4		4		4		4		4		4	
Operations-related factors	Motor conditions	Equipment temperature	4		4		4		4		3		4		4		4		4		4		4		4	
		Equipment vibrations	4		4		4		4		3		4		4		4		4		4		4		4	
		Equipment power quality	4		4		4		4		3		4		4		4		4		4		4		4	
		Equipment air quality	4		4		4		4		3		4		4		4		4		4		4		4	
	Working environment	Air quality - personnel health	4		4		4		4		4		4		4		4		4		4		4		4	
		Noise	4		4		4		4		4		4		4		4		4		4		4		4	
		Environmental temperature	4		4		4		4		4		4		4		4		4		4		4		4	
		Environmental vibrations	4		4		4		4		4		4		4		4		4		4		4		4	
		Health and safety	4		4		4		4		4		4		4		4		4		4		4		4	
	External environment	Waste	3		4		3		4		4		4		4		4		4		4		4		4	
		Emission	3		4		3		4		4		4		4		4		4		4		4		4	
Complexity		Training	4		4		4		4		4		4		4		4		4		4		4		4	
		Dependency from other components/ EEMs	4		4		4		4		4		4		4		4		4		4		4		4	
		Physical placement inside motor system	4		4		4		4		4		4		4		4		4		4		4		4	
		Activity type	4		4		4		4		4		4		4		4		4		4		4		4	
		Technical maturity and diffusion of the technology in the market	4		4		4		4		4		4		4		4		4		4		3		4	
		Accessibility	3		4		4		4		4		4		4		4		4		4		4		4	
Personnel	Role	Active personnel	4		4		4		4		4		4		4		4		4		4		4		4	
		Passive personnel	4		4		4		4		4		4		4		4		4		4		4		4	
	Corporate involvement	Active corporate involvement	4		4		4		4		4		4		4		4		4		4		4		4	
		Passive corporate involvement	4		4		4		4		4		4		4		4		4		4		4		4	
Additional technical factors		Implementation type	4		4		4		4		4		4		4		4		4		4		4		4	
		Check-up frequency	4		4		4		4		4		4		4		4		4		4		4		4	
		Secondary devices necessary	4		4		3		4		4		4		4		4		4		4		4		4	
		Additional optimization devices	4		4		3		4		4		4		4		4		4		4		4		4	
		Automation	4		4		4		4		4		4		4		4		3		4		4		4	

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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