energies

Article

Identification and Categorization of Factors Affecting the Adoption of Energy Efficiency Measures within Compressed Air Systems

Andrea Trianni [1], Davide Accordini [2],* and Enrico Cagno [2]

[1] Faculty of Engineering and IT, University of Technology Sydney, Ultimo, NSW 2007, Australia; Andrea.Trianni@uts.edu.au
[2] Department of Management, Economics & Industrial Engineering, Politecnico di Milano, 20133 Milano, Italy; enrico.cagno@polimi.it
* Correspondence: davide.accordini@polimi.it; Tel.: +39-348-148-0926

Received: 11 August 2020; Accepted: 22 September 2020; Published: 1 October 2020

Abstract: Understanding the factors driving the implementation of energy efficiency measures in compressed air systems is crucial to improve industrial energy efficiency, given their low implementation rate. Starting from a thorough review of the literature, it is thus clear the need to support companies in the decision-making process by offering an innovative framework encompassing the most relevant factors to be considered when adopting energy efficiency measures in compressed air systems, inclusive of the impacts on the production resources and the operations of a company. The framework, designed following the perspective of the industrial decision-makers, has been validated, both theoretically and empirically, and preliminarily applied to a heterogeneous cluster of manufacturing industries. Results show that, beside operational, energetic, and economic factors, in particular contextual factors such as complexity, compatibility, and observability may highlight critical features of energy efficiency measures whose absence may change the outcome of a decision-making process. Further, greater awareness and knowledge over the important factors given by the implementation of the framework could play an important role in fostering the implementation of energy efficiency measures in compressed air systems. The paper concludes with further research avenues to further promote energy efficiency and sustainability oriented practices in the industrial sector.

Keywords: energy efficiency; compressed air systems; energy efficiency measures; nonenergy benefits; assessment factors

1. Introduction

Industrial energy efficiency is widely recognized as crucial means to mitigate the growing final energy consumption (by more than 25% in the 2018–2040 time span [1]), given that industry is responsible for 35% of global total final energy use [2]. Energy efficiency can also lead to other benefits, such as enhanced security of the energy production systems and a healthier and more comfortable environment [3], plus strategic advantages connected to a less volatile energy market [4], especially in countries strongly dependent on energy imports [5,6]. As discussed by [7,8], previous research has mainly focused on sector-specific energy efficiency measures (EEMs). However, the extreme heterogeneity of the industrial sectors calls for a different approach aimed at promoting specific cross-cutting technologies. Among others, the Compressed Air System (CAS) looks particularly interesting, being widely diffused as ancillary technology within many industrial processes [9] due to its cleanness, practicality, and ease of use [10]. Usually, industrial compressed air (CA) is generated by using electricity as energy source and can account for about 10% of the total electricity bill in some contexts [10]. By taking a life-cycle costs perspective on CAS, the largest portion of costs is covered by operating costs (almost 80% [11]). Therefore, improved energy efficiency in CAS by implementing EEMs (both implying both technological and behavioral changes [12]) should be abundantly cost-effective, and lead to other benefits, such as reduced scrap rates, greater capacity utilization, enhanced safety, and many others [13].

Nonetheless, despite the huge potentials for energy efficiency gains (up to 20% [11,14]) and continuous development in the field [15], EEMs are not diffused as expected, leading to the so-called energy efficiency gap [16,17], particularly critical for small and medium-sized enterprises (SMEs), which everywhere represent the vast majority of companies and are responsible for the largest share of consumption [18,19]. Previous research noted that SMEs particularly suffer from a lack of internal competences as well as standard procedures hindering EEMs adoption [20–22]. This is also confirmed by studies on barriers to energy efficiency [17,20,23], which only partially refers to costs, rather pointing the attention on the lack of awareness and specific knowledge [22–24] as well as unperfect information and irrational behavior [25], therefore suggesting that it is of primary importance to highlight the single factors driving the decision-making process over EEMs. The literature has so far identified assessment factors for EEMs (e.g., [26]); however, they are referred to other technologies other than CAS. Since different technologies are characterized by different EEMs [27], different factors should be analyzed as well.

Classifications of interventions in CAS have been proposed by literature [11,28,29]; nevertheless, a mere technical EEM description does not sufficiently pinpoint some relevant factors, such as specific implications at the operational level that, beyond energy and monetary savings, are crucial for wise decision-making, representing a major research gap. Therefore, starting from an overview of CAS (Section 2) and literature review in Section 3, we offered a novel framework encompassing the most important factors for decision-making over industrial CAS EEMs (Section 4). The framework, which includes the specific EEMs description, broadens the effects of their implementation beyond energy and economic considerations, offering a genuine and innovative contribution to the academic discussion over the impacts of EEMs on industrial operations. Further, the proposed framework also aims to effectively contribute to supporting decision-makers and policymakers in fostering the adoption of EEMs in CAS, as well as technology and service providers in tailoring their services. A validation and preliminary application of the framework was conducted in several manufacturing enterprises (Sections 5 and 6, respectively), giving valuable insights and opening further research avenues (Section 7).

2. EEMs in CAS: An Overview

Overall, CAS are usually characterized by reduced energy efficiency [10,30]. However, CAS energy efficiency can be improved through well-known EEMs, in terms of technologies and practices available in the market. Understanding the characteristics of CAS EEMs is of primary importance to shed light on the factors driving their adoption and foster their implementation.

A valuable source for the analysis of EEMs in CAS is represented by the US DOE Industrial Assessment Center (IAC) [31], which identified 16 EEMs labelled with an Assessment Recommendation Code (ARC). Such EEMs, as noted by previous literature [7,26,32], represent a broad range of activities to improve the energy efficiency of CAS, including (as summarized in Table 1):

- installation of new equipment (e.g., ARC 2,4226 “Use/purchase optimum sized compressors”, 2,4224 “Upgrade control compressors”, 2,4225 “Install common header on compressors”);
- optimization of existing equipment (e.g., ARC 2,4231 “Reduce the pressure of compressed air to the minimum required”, 2,4235 “Remove or close off unneeded compressed air lines”);
- recovery of extant working conditions (e.g., ARC 2,4236 “Eliminate leaks in inert gas and compressed air lines/valves”);
- replacement of compressed air medium (e.g., ARC 2,4232 “Eliminate or reduce the compressed air used for cooling, agitating liquids, moving products or drying”, 2,4233 “Eliminate permanently the use of compressed air”);

- energy recovery (e.g., ARC 2,2434 from either compressors or ARC 2,2435 from air dryers).

Moreover, efficiency in CAS may be reached following three directions: preventing energy losses, minimizing energy input, and recovering energy [33]. The IAC database covers the first two areas, however, the latter is partially lacking since the database only refers to the recovery of thermal energy. Hence, to cover the gap, an additional EEM related to the adoption of energy harvesting units was added to Table 1.

Table 1. Industrial Assessment Center (IAC) classification of EEMs in CAS.

ARC Code	EEMs	Type of EEM	Description	Important Characteristics for the Adoption	References
2,4221	Install compressor air intakes in the coolest location	Installation of new equipment	Aspiring from the coolest location [34], may they be outside [35] or inside the plant [36], could provide multiple benefits, ranging from efficiency up to the regulation range, passing by avoidance of shutdowns, according to the type of compressor installed [37,38].	• The location may be difficult to access with a consequent negative impact on maintenance practices [37,38]; • continuous air monitoring required (external installation) [36]; • the installation of an additional ventilation system may be required (internal installation) [36].	[34–43]

2,4222	Install adequate dryers on air lines to eliminate blowdown	Installation of new equipment	Applications of compressed air or wear requirements of the components need a certain level of air dryness [44], usually guaranteed by refrigerated dryers, coupled with a moisture separator and condensate traps.	• Cycling or noncycling refrigerated dryers are usually adopted, characterized by different implementation and operation costs [45–47]; • periodic maintenance required [30].	[30,42,44–52]
2,4224	Upgrade controls on compressors	Installation of new equipment	The control system ensures high efficiency by matching the supplied compressed air to meet the demand, ensuring that the minimum required pressure is maintained. Control can be achieved for a single unit or the entire system to optimize the operations [29].	• Different control systems exist, with the optimal one depending on the specific application (e.g., see [29,45,53]); • a reduction in the required number of compressors may be achieved through a central control system [29]; • if a monitoring system is installed with the central control system, benefits in terms of maintenance and unscheduled downtimes may be obtained.	[29,34,39,42,44,45,47–59]

2,4225	Install common header on compressors	Installation of new equipment	The closed-loop configuration represents the best air distribution system layout, saving up to 12% of power requirements [42,48,57]. Moreover, the installation of a common header enables compressors to work together, taking advantage of load sharing.	• Higher bore improves air storage capacity, which enables operations with a higher output of compressors and avoidance of unexpected switching on or off [42,52]; • installation must be performed by CA experts [60]; • there may be accessibility issues.	[30,42,44,48–52,57,60,61]
2,4226	Use/purchase optimum sized compressors	Installation of new equipment	Use a compressor able to handle the demand of the system at any time with efficient operation, since oversizing is one of the major problems in the supply side of compressed air systems [48].	• High efficiency units must be preferred [11,50,57,62,63]; • noise may be reduced; • space requirements may be reduced; • installation must be performed by CA experts.	[11,29,34,35,39,42,45,48–50,55,57,62–64]

2,4227	Use compressor air filter	Installation of new equipment	A filtering system may be necessary to provide air of the right quality, designed considering (i) extraction efficiency, (ii) air flow rate, and (iii) dust capacity.	• Noise may be reduced; • useful life of compressors may be increased, and unplanned downtimes reduced; • filters should be inspected and replaced regularly [51,65]; • simple installation and maintenance practices.	[39,42,44,45,47,48,50,51,57,65–69]
2,4231	Reduce the pressure of compressed air to the minimum required	Optimization of existing equipment	Pressure should be minimized according to the requirements of end-users [30,51,70], proceeding then backward in the identification of losses [29,71].	• The number of working compressors [68] may be reduced; • end-use pressure should be reached avoiding losses rather than increasing the generated pressure [42,72,73].	[29,30,34,40,42,47,51,55,58,69–74]

2,4232	Eliminate or reduce the compressed air used for cooling, agitating liquids, moving products or drying	Replacement of compressed air medium	CA is a simple and readily available form of energy, but it is often used inappropriately; many operations in a plant, such as agitating liquids, moving product, aspirating, atomizing, padding, can be accomplished more economically through alternative technologies [29].	• The alternatives to CA are vast, ranging from blowers to air amplification high-performance nozzles [29,39,75], each of them characterized by different features; • blowers, for instance, require more space but are easy to implement [76] and are much more efficient for high volume low-pressure applications [50,77].	[29,30,39,40,45,47–51,70,75–79]
2,4233	Eliminate permanently the use of compressed air	Replacement of compressed air medium	When the wrong use of CA is discovered, it should be converted to other types of equipment (e.g., electric driven equipment for vacuum pump [29,79])	• Specific characteristics depend on the alternative solution chosen.	[29,30,39,40,45,47–51,70,75–79]

2,4234	Cool compressor air intake with heat exchanger	Installation of new equipment	Lowering the inlet temperature may provide multiple benefits to CAS (see ARC 2,4221). Beside moving the compressor air intake, it is possible to obtain a cooling effect of inlet air using a heat exchanger [37,38].	• Heat exchangers are easier to install with respect to a change in the compressor air intake, but they require more space [37,38].	[37,38,57]
2,4235	Remove or close off unneeded compressed air lines	Optimization of existing equipment	Compressed air lines should be removed in case of permanent disuse or temporarily closed, e.g., through shut-off valves, when they remain idle for a certain time during the production cycle [50,80,81].	• The disconnection may reduce noise, enhance safety, and save space once occupied by the equipment itself [29,82]; • there may be issues in the accessibility of pipes with consequent hidden costs.	[29,42,50,80–82]

2,4236	Eliminate leaks in inert gas and compressed air lines/valves	Recovery of extant working conditions	Leaks are the major single sources of consumption in compressed air systems [35,70]. They can be reduced following operational good practices [49,83] and performing maintenance activities, beside introducing a leak management program [29].	• Leak reduction may enhance the equipment lifetime reducing the pressure of operating time [29]; • experienced personnel are required to design and carry out the activity [84]; • accessibility may represent an issue.	[29,30,35,39,42,44,47,49,56,57,59,70,83–85]
2,4237	Substitute compressed air cooling with water or air cooling	Replacement of compressed air medium	Cooling air at the compressor outlet enables the blowdown collection and the avoidance of heat exchangers in the points of use; different cooling system exists, with the optimal fit depending on the specific case (e.g., see [86,87]).	• Maintenance, operating costs, and installation costs depend on the specific choice; • water usage costs and water waste management costs should be considered when dealing with a cooling system where water is the main medium [88]; • noise may be reduced after the replacement [88].	[39,86–89]

2,4238	Do not use compressed air for personal cooling	Replacement of compressed air medium	Personnel cooling describes the self-application, made by operators, of compressed air for ventilation purposes. An efficient and secure alternative is provided by electrical fans [29].	• Enhance personnel safety since the flow of compressed air can inject particles into the human skin [29].	[29]
2,2434	Recover heat from air compressor	Energy recovery	Up to 93% of the electrical energy used by an industrial air compressor is converted into heat, which can be mostly recovered with a properly designed heat recovery unit [27,42,90]	• Maintenance efforts are higher due to the requirements of the added equipment [39,91]; • equipment lifetime may be improved [36].	[27,29,34,36,39,40,42,44,45,51,57,90,91]
2,2435	Recover heat from compressed air dryers	Energy recovery	As for air compressors, heat can be recovered from dryers. This intervention is one of the most convenient concerning energy efficiency, since the source of energy is often waste [34].	• Maintenance efforts are higher due to the requirements of the added equipment [39,91]; • equipment lifetime may be improved [36].	[27,29,34,36,39,40,42,44,45,51,57,90,91]

/	Install energy harvesting units	Energy recovery	Energy can be recovered from the wasted pressurized air when discharged in the environment or from the presence of moving masses (kinetic energy) [92,93]. It can be transformed into electricity [93] or directly used to power other devices [94].	• Maintenance requirements increase [92]; • energy-saving circuits might be difficult to implement and might affect system performance [33,95].	[33,92–98]

With respect to other literature addressing EEMs in CAS (e.g., Nehler [11]), the IAC has been preferred, given that Nehler [11] has clustered EEMs according to their physical local location to recognize the effect on the system and their interrelations, however leading to a significant overlapping, since multiple EEMs seem to target the same energy efficiency issue. Rather, IAC classification allows assessing EEMs with an industrial decision-maker perspective. In fact, as reported in Table 1, the implementation of those EEMs should consider several additional operational issues (e.g., accessibility, location, noise) and impacts on other production resources (e.g., labor through an impact on maintenance activities and/or safety) that are important for industrial decision-makers and other literature, industrial and scientific. Interestingly, the existence of such implications seems to show the need for academic literature to more thoroughly and systematically address the factors that should be considered when adopting an EEM in CAS.

3. Literature Review, Critiques, and Needs

Section 2 highlighted several EEMs characteristics helpful to identify technical and operative factors that should be assessed when dealing with the adoption of EEMs in CAS. Similarly, assessment factors have been discussed by previous academic literature. A breakthrough contribution is represented by the study by Fleiter et al. [26], who developed a framework based on 12 factors grouped into three categories, namely relative advantage, technical context, and information context. Interestingly, the factors considered refer to the profitability side of the EEMs, but point also toward their complexity, with thus some links to research by Rogers focused on the adoption of innovation into industry [99]. The relative advantage and the complexity indeed represent the only factors, among the ones considered by Rogers [99], which are statistically related to the adoption of interventions, together with the compatibility of an innovation [100], considered however as a "rather broad and subjective characteristic that is heavily dependent on the potential adopter", thus neglected in the analysis by Fleiter et al. [26]. Roberts and Ball [101], referring more generally to sustainability practices (thus with a broader focus than energy efficiency), encompassed most of the aforementioned considerations, defining a framework that also pointed out the importance of including the time dimension in the analysis, which was not included by Fleiter et al. [26]. Similarly, factors for the characterization of EEM were considered by Trianni et al. [7], who maintained the profitability dimension but also the description of the complexity of an EEMs, as suggested by Fleiter et al. [26], through factors such as the activity type, the ease of implementation, and the likelihood of success/acceptance. Noteworthy, both Roberts and Ball [101] and Trianni et al. [7] made a further step preliminarily suggesting to include among the assessment factors also the nonenergy benefits (NEBs), i.e., all the benefits coming from the adoption of an EEM beyond the energy savings, as defined by Mills and Rosenfeld [102], but not explicitly.

However, NEBs represent the positive impacts that EEMs have on the operations and the other production resources. They were considered mainly as additional benefits to stimulate the implementation of industrial energy efficiency, since their value may exceed that of the energy savings [7,103]. However, recent research has pointed out that there may be also negative implications stemming from the adoption (e.g., [103,104]), which should likewise be included in the assessment also as a necessary acknowledgement to gain credibility with the industrial sector [102]. In a nutshell, regardless of being positive or negative, NEBs describe impacts stemming from the EEMs adoption and, as such, they should be assessed during the decision-making process to make a sound decision.

Literature identified NEBs stemming from the adoption of a variety of technologies and EEMs, referring them to a set of categories according to their nature and targeted area (e.g., relative advantage, technical context, information context [26]; complexity, compatibility, observability [99,100]; waste, emission, operation and maintenance, production, working environment, and other [105,106]). In this regard, Table 2 shows the most significant contributions (NEBs encompassed by literature are indicated with an "X"; the green background helps to graphically highlight the areas most frequently covered by the past studies). Unfortunately, the majority of literature over NEBs does look to specific technologies not including CAS (e.g., [107–109]), or considers CAS together with other technologies [11]. To the best of our knowledge, only very few studies were conducted targeting CAS specifically. Gordon et al. [49] first attempted to analyze NEBs referring to CAS exclusively, listing a variety of NEBs, ranging from maintenance and insurance and labor costs to improved system performance and workers' safety conditions. More recently, Nehler et al. [27] highlighted a simple list of 34 specific NEBs for CAS, ranked according to their importance as perceived by users and experts, with the top positions occupied by organizational related factors (e.g., commitment from top management; people with real ambition), energy-related factors (cost-reductions resulting from lowered energy use; energy management system; the threat of rising energy prices), and strategic factors (long-term energy strategy). Doyle and Cosgrove [110] further delved into this issue by identifying the benefits stemming from one EEM, i.e., compressed air leaks repair, in terms of reduction of the required working units and the consequent drop in the plant room temperature, which in turn improve the efficiency of CAS. Interestingly, Table 2 shows that, despite referring specifically to CAS, these studies consider about the same NEBs already defined by Worrell et al. [105]. The only exception is represented by the improvements in system performance, which address improved pressure levels, consistency of pressure, and the ability to address spikes in usage [49], which are indeed specific of the technology. On the other hand, if many manuals deal with CAS technology (e.g., [29,39,111]) they refer solely to technical aspects, such as the impact on parameters like pressure or temperature, which are critical for the adoption of the technology, nonetheless representing a limited perspective, not even naming the wider concepts of assessment factor nor NEBs.

Table 2. Factors used in literature to describe EEMs.

Categories	Factors	CAS (Specific)						CAS (Among other Technologies)								Other Technologies/innovations			
		[49]	[110]	[27]	[105]	[112]	[106]	[7]	[107]	[113]	[108]	[109]	[114]	[26]	[115]	[100]	[99]	[102]	[116]
Relative advantage/ economic	IRR													X		X (relative advantage)	X (relative advantage)		
	Pay-back	X						X				X		X					
	Increased sales										X								
	Initial expenditure/implementation cost	X						X						X					
	Interest cost on capital investment	X																	
Technical context	Distance to core process							X						X					
	Type of modification													X					
	Scope of impact													X					
	Lifetime (of the measure)													X					
Complexity														X		X	X		
Compatibility																X	X		
Informational context	Transaction cost													X					
	Knowledge for planning and implementation													X					
	Diffusion progress													X					
	Sectoral applicability													X					
Trialability																	X	X	
Observability																	X	X	
Communicability																	X		
Divisibility																	X		
Social approval																	X		
	Saving strategy							X											

Categories	**Factors**	**CAS (Specific)**						**CAS (Among other Technologies)**								**Other Technologies/innovations**			
		[49]	[110]	[27]	[105]	[112]	[106]	[7]	[107]	[113]	[108]	[109]	[114]	[26]	[115]	[100]	[99]	[102]	[116]
Implementation related	Activity type							X											
	Ease of implementation							X											
	Likelihood of success/acceptance							X											
	Corporate involvement							X											
	Check-up frequency							X											
Waste	Use of waste fuel, heat, gas				X	X		X (waste)	X									X (waste)	
	Reduced product waste			X	X	X	X				X		X		X				
	Reduced wastewater			X	X	X	X		X				X		X				
	Reduced hazardous waste (and hazardous water)			X	X	X	X		X						X				
	Waste disposal cost									X									
	Material reduction (raw material)			X	X	X			X	X		X			X				
Emissions	Reduced dust emission (ashes)			X	X	X	X	X (emission)	X (emission)	X (emission)									X (emission)
	Reduced CO, CO2, NOX, SOX emissions			X	X	X	X					X							
	Reduced cost of environmental compliance (fines included)											X							
Operations and maintenance	Reduced need for engineering control				X	X		X (operations and											

Categories	**Factors**	**CAS (Specific)**						**CAS (Among other Technologies)**								**Other Technologies/innovations**			
		[49]	[110]	[27]	[105]	[112]	[106]	[7]	[107]	[113]	[108]	[109]	[114]	[26]	[115]	[100]	[99]	[102]	[116]
	Better control/ improved process control							maintenance)					X					X	
	Lowered cooling requirements			X	X	X	X		X			X			X				
	Increased facility reliability				X	X													
	Reduced wear and tear on equipment				X	X						X							
	Increased lifetime			X					X	X	X		X		X				
	Reduced labor requirements (cost, savings)	X		X	X	X	X			X			X		X			X	
	Reduced maintenance (maintenance cost)	X		X			X		X	X		X	X		X				
	Reduced water consumption						X												
	Lower cost of treatment chemicals						X												
	Reduced operating time									X									
	Reduced purchases of ancillary materials						X												
	Reduced non-energy operational cost										X	X							
	Improved ease of system operations	X																	
Production	Productivity							X	X	X	X								
	Increased product output/yield			X	X	X	X		X		X	X	X		X				X (production)
	Improved	X			X	X													

Categories	**Factors**	**CAS (Specific)**						**CAS (Among other Technologies)**								**Other Technologies/innovations**			
		[49]	[110]	[27]	[105]	[112]	[106]	[7]	[107]	[113]	[108]	[109]	[114]	[26]	[115]	[100]	[99]	[102]	[116]
	equipment performance																		
	Shorter process cycle time			X	X	X	X												
	Improved product quality/ decrease scrap			X	X	X	X		X	X	X	X			X				
	Increased system capacity									X									
	Reduced cost of production disruption								X										
	Increased reliability in production	X		X	X	X	X			X					X				
Working environment	Reduced need for PPE/increased safety/reduced illness or injuries	X		X	X	X	X	X (working environment)	X (working environment)	X	X		X					X (working environment)	X (working environment)
	Decreased personnel needs										X								
	Improved lighting				X	X							X						
	Improved noise level			X	X	X	X			X			X						
	Improved temperature control/reduced temperature		X	X	X	X						X	X						
	Better aesthetics												X						
	Comfort												X						
	Reduced glare, eyestrain												X						
	Improved air quality			X	X	X	X						X		X				
Other	Decreased liability				X	X													
	Improved public image			X	X	X			X						X				X
	Delay/reduce	X		X	X	X	X								X				

Categories	**Factors**	**CAS (Specific)**						**CAS (Among other Technologies)**								**Other Technologies/innovations**			
		[49]	[110]	[27]	[105]	[112]	[106]	[7]	[107]	[113]	[108]	[109]	[114]	[26]	[115]	[100]	[99]	[102]	[116]
	capital expenditure																		
	Achieved rebate/incentives						X												
	Reduced/ eliminated demand charges						X												
	Reduced/eliminated rental equipment cost						X												
	Additional space				X	X													
	Improved workers morale (satisfaction)			X	X	X			X		X				X				
	Direct and indirect economic benefits (downsizing)																	x	
	Reduced currency risk								X										
	Reduced number of devices required	X	X																
	Reduced insurance cost from fewer compressors	X																	

By analyzing the literature, and in particular the area surrounded by the red line in Table 2, the main literary gap is clearly represented by the lack of study encompassing for the entire range of factors that should be considered by decision-makers during the assessment of EEMs, especially when dealing with CAS. Referring to a single technology is necessary since different technologies require different EEMs, which might provide different NEBs [27] and be characterized by different assessment factors. Moreover, without this specificity, the work might lose the practical interest by decision-makers because it is too general to describe the broadest set of possible industrial contexts where to consider the adoption of EEMs on CAS. Furthermore, it is clear how most studies dealing with assessment factors on CAS, regardless from the addressed technology, do not address the context in which the technology is called to operate, therefore missing a (potentially) crucial element for a complete decision-making. Moreover, it should be noted that most studies are focused on NEBs from the service phase of the equipment, whilst both the drawbacks stemming from the adoption and the implementation phase itself of the EEM have been rarely considered in the analysis [117].

4. A Novel Framework of Factors for Decision-Making Over CAS EEMs

The framework, designed to provide a holistic perspective for decision-making purposes, has been created by tailoring factors and the broader categories to the specific features of CAS EEMs. The factors, which should be relevant to the adoption of EEMs and, if possible, should avoid overlaps, derive from either a thorough review of the industrial literature about the technology behind single EEMs (Table 1) or from the scientific literature on EEMs characteristic. This dual perspective guarantees the completeness of the analysis, being therefore inclusive of the impacts on the operations and the other productive resources of a company. This completeness was maintained during the following synthesis process, which made it possible to obtain a synthetic framework thanks to the grouping of factors into categories and subcategories. Furthermore, the grouping process was carried out in such a way that the framework obtained corresponds to the perspective adopted by decision-makers regarding the adoption of EEMs to CAS. As summarized in Table 3, 22 factors were identified and organized in three categories, respectively: (i) operative factors, (ii) economic-energetic factors, and (iii) contextual factors, which in turn were divided into three further subcategories, i.e., (i) complexity, (ii) compatibility, and (iii) observability.

4.1. Operational Factors

The need for compressed air is primarily defined by end-users' requirements in terms of:

- *air flow rate* [29];
- *pressure level* [29];
- *air temperature* [39].

The CAS performance and efficiency do not rely exclusively on such primary factors. Yet, primary factors are strictly interconnected to several secondary ones: among these, we can find heat and thermal capacity, linked to the air temperature, power, work, but also volume, density and mass flow rate of air, directly connected to its pressure and flow rate.

4.2. Economic and Energetic Factors

Pay-back time. Pay-back time has been widely recognized as an easy yet indicative factor supporting industrial decision-makers with limited resources [7,118].

Initial expenditure. Regardless of the type of investment [119], the initial expenditure is a crucial factor and may represent a major hurdle hindering EEMs adoption, especially among SMEs, due to their limited capital availability [120,121].

Energy savings. The amount of saved energy is a critical indicator of savings stemming from the adoption of an EEM [7] and it refers to monetary quantification of the physical energy source (either primary or secondary).

4.3. Contextual Factors

Other than considering operative and economic-energetic factors, CAS EEMs can be characterized by many factors strongly dependent on the specific industrial context for which they are considered. We took inspiration from the study conducted by Rogers [99] who broadly reviewed the characteristics of innovation in general. Since the adoption of EEMs into a specific context can represent a process innovation, those characteristics were transferred and adapted to CAS EEMs, as detailed in the following.

4.3.1. Complexity Factor

Complexity describes the difficulty one might encounter when adopting an EEM, inversely proportional to the adoption rate of the measure itself [99]. Understanding in which cases the adoption is revealed to be complex is a fundamental passage to characterize it. Literature on innovation refers to the radicalness as an index of complexity, since it is correlated to the degree of change required for the adopters [122]. This is a rather vague definition for the specific study and a potential source of misunderstanding [26,123]. Hence, we decomposed the complexity into factors whose definitions are specifically intended for the analysis of EEMs.

Activity type distinguishes if an EEM constitutes a simple refurbishment or recovery of the existing functions, an optimization in the use of an existing technology, a retrofitting of the equipment or a new energy-efficient equipment installation [7]. Indeed, a simple retrofit is easier than a new investment in equipment [124].

Expertise required refers to the range of skills required for the correct implementation of an EEM. Since different levels of expertise are required for each EEM and considering their variety, the skill range can be wide enough to be hard for firms in finding technology experts, especially for SMEs, where CAS is used almost exclusively as a service [125].

Independency from other components/EEMs refers to the influence of the implementation of an EEM on the existing system, to underline the nature of the impact [26,100,126]. The possible impacts can influence CAS equipment working conditions, other systems or can generate cause–effect relationships with other EEMs, with the magnitude of the influence being inversely proportional to the easiness of understanding the consequences of the installation and predicting the total savings.

Change in maintenance effort. The variation of maintenance requirements as a consequence of the adoption of EEMs has been often considered an important factor by previous literature [102,105,106].

Accessibility. Difficulties in accessing equipment may require higher efforts from personnel or a greater amount of technological resources to carry out operations; this can be even harder for CAS, in which the distribution system is usually difficult to access. Moreover, accessibility may also refer to space unavailability for maintenance procedures when technology add-on measures are installed.

4.3.2. Compatibility Factors

Compatibility explains to which degree EEMs can be adapted to the existing system. According to Rogers [99], it can be referred, among others, to the compatibility with previously introduced ideas, that can be translated into technological compatibility, as suggested by Tornatzky and Klein [100], or to layout features or operating conditions that difficultly fits in the existing system. Nonetheless, despite being relevant for the adoption, compatibility and related factors have not been adequately considered in EEMs literature, being strongly dependent on the adopters' contextual characteristics [26].

Technological compatibility analyzes the technological constraints related to EEMs, pointing out the conditions where their implementation is suggested or should be avoided, highlighting a strict connection to the specific context. Indeed, in several cases, more technologies concur for the adoption of the specific EEM, and the best choice depends on their matching with the existing system, as well as their suitability [127]. Without technological compatibility, the EEMs expected performance may not be guaranteed, with also possible lack of trust for future interventions [128].

Presence of difference pressure loads outlines the existence of different pressure levels at the end-use which may be a source of high inefficiencies and incompatibilities in the system [129]. This may be due to (i) the widespread availability of lamination valves that, although can be easily installed, are meant to disperse the pressure generated; (ii) the generation of a high-pressure point, which is recommended only when a considerable amount of air is required at that pressure.

Adaptability to different conditions may be referred to demand needs as well as to different ambient conditions, which can influence, e.g., the air conditions at the compressor intake (e.g., see IAC ARC 2,4221). It represents a critical factor considering the flexibility of use usually required for CAS [29].

Synergy with other activities. During the EEM implementation, synergies among different EEMs may occur, leading to potential benefits coming from the coordination of multiple activities (e.g., similar interventions that are suggested contemporarily, taking advantage of the same downtime of the equipment [130]). Nonetheless, synergies may also be negative for EEMs adoption [131].

Distance to the electric service. The distance of the point of use to the electric service can be a reason for the low adoption rates of EEMs requiring the technology substitution from compressed air-driven to electric driven devices [132].

Presence of thermal loads. The quality level of the fluid delivered by the heat exchangers from heat recovery units represents the major problems for the low diffusion of this solution throughout CAS. Although the EEM can be theoretically installed for each compressor type (both packaged or not), [29,36], its profitability depends on the fluid quantity and temperature. If the compressor load is variable, heat may be delivered discontinuously in time, potentially representing an issue for the end-use application [36].

4.3.3. Observability Factors

Observability, when referred to innovations, relates to their visibility and the communicability of their effects to others [99]. Concerning CAS EEMs, observability can be translated into focus towards the sensible changes detected in both the CAS and the working environment once the EEM is implemented.

Safety. Since difficulties may arise when handling compressed air for high fluid pressure and high-speed rotating parts, safety requirements are tight, aiming at reducing the accident rates [133].

Air quality. Pollution in an indoor environment is one of the more underestimated problems within a production facility. Paying attention to air quality monitoring and improvement is on the one hand related to enhanced health and performance of operators [106,113]; on the other hand, to improved operating conditions for all the parts in contact with the fluid, thanks to lower values of solid and liquid contaminants.

Wear and tear variation of the equipment is widely considered in scientific literature, mostly with a positive meaning [105]. The same factor can be perceived, in turn, as influencing the lifetime of the equipment [103,113]. For the specific case of CAS, a reduction of wear and tear of the equipment may be obtained because of the lower stress impressed by the fluid, attained with the reduction of pressure or through enhanced control capabilities.

Noise coming from the equipment may affect the working environment and possibly the performance of the operators [102,103,105]. Nonetheless, the quantification of noise variation stemming from the implementation of a CAS EEM can be extremely difficult, being related to several parameters such as e.g., cost of absenteeism, accidents, and variation in workers productivity, that are extremely complex and with impacts measurable almost exclusively in the long-term.

Artificial demand. Air flow demand increases at higher pressure, especially when air is open blown to the atmosphere; hence, the sizing of the system based on the maximum pressure creates an over-pressurization that minimizes efficiency [134]. This further demand, defined as artificial demand, is considered one of the major causes of inefficiencies in compressed air systems. On the other hand, each time an EEM entails a reduction of the CAS pressure level or the reduction of its unregulated use, this affects positively the amount of air being delivered, representing a further benefit of the adoption.

Table 3. Categories, subcategories, and factors of the new framework.

Categories	Subcategories	Factors	References
Operational factors		Pressure	[29,49]
		Temperature	[39]
		Flow rate	[29]
Economic-energetic factors		Pay-back time	[7,26,118]
		Initial expenditure	[7,26,119–121]
		Energy savings	[7,135]
Contextual factors	Complexity	Activity type	[7,26,124,136]
		Expertise required	
		Independency from other components/EEMs	[26,100,107,126]
		Change in maintenance effort	[102,105,106,137]
		Accessibility	/
	Compatibility	Technological	[99,127,128]
		Presence of different pressure load	[129]
		Adaptability to different conditions	[29]
		Synergy with other activities	[130,131]
		Distance to the electric service	[132]
		Presence of thermal load	[36]
	Observability	Safety	[102,103,105,106,133]
		Air quality	[103,105–107,113]
		Wear and tear	[103,105,106,113]
		Noise	[72,102,103,105]
		Artificial demand	[29,134]

5. Validation of the Framework

The validation of the model, intended to reach the analytical generalization as defined by Yin [138], is performed following two separate steps: theoretical and empirical. The theoretical validation is based on the assessment of the factors that compose the model and their capacity to describe the selected EEMs through the analysis of literature contributions, both scientific and industrial, as discussed in Section 5.1. On the other hand, the empirical validation, structured according to the case study methodology following Yin [138] and Voss et al. [139], is required to validate with industrial decision-makers the framework and its composing elements, basing the analysis on a set of predetermined indicators (Section 5.2). For the purpose of the present study, i.e., understanding the main factors that rule the adoption rate of EEMs in CAS and their influence on the decision-making process, multiple case study is the most appropriate research methodology. Discrete experiments that serve as replications, contrasts, and extension to the emerging theory [138] are considered so that each of the case-studies gives a contribution to the theory development beside emphasizing the rich real-world context in which the phenomena will occur [140]. The combined approach for validation, successfully undertaken by previous research on similar topics ([7,141]), provides better generalizability of results, avoiding relying uniquely on the data obtained from a limited number of investigations.

5.1. Theoretical Validation

The theoretical validation is used (i) to verify the ability of the developed framework in characterizing the EEMs addressing CAS and (ii) to provide a qualitative evaluation of factors, which could result in interesting insights for decision-makers. The process involves a revision of the EEMs highlighted in Section 2 and it is accomplished thanks to a thorough review of the literature performed following the perspective imposed by the factors considered in the model. The results of the theoretical validation are reported in Table 4. In a nutshell, the framework proved to be able to fully describe EEMs in CAS, also supported by the inclusion of a qualitative evaluation of interventions, intended however to provide general guidelines rather than absolute and specific insights.

Table 4. Theoretical validation of the framework.

Description	Ref. Description	Economic Energetic Fac-			Operative Factors			Contextual Factors																Ref. Factors
								Complexity					Compatibility					Observability						
		Investment Cost [a]	Payback Time [b]	Energy Savings [a]	Pressure [c]	Temperature [c]	Fluid flow Rate [c]	Activity Type [d]	Expertise required [e]	Independency from other Compo-	Change in Maintenance Effort [g]	Accessibility [h]	Technological [i]	Presence of different	Adaptability to dif-	Synergy with other activities [l]	Distance from electric	Presence of different	Safety [n]	Noise [n]	Air Quality [n]	Wear and Tear [n]	Artificial demand [n]	
Install compressor air intakes in coolest location (ARC 2,4221)	[34–43]	L	S	L		X	X	R	H/L	L	N/A	I	H	0	H	H (N/A)	0	0	0	+	I	+	0	[7,37,72,133,142–144]
Install adequate dryers on air lines to eliminate blowdown (ARC 2,4222)	[30,42,44–52]	H	M	N/A		X	X	R	M	L	T	N/A	H	0	0	H; -D	-	0	0	-	+	+	0	[7,29,72,142,145–148]
Upgrade controls on compressors (ARC 2,4224)	[29,34,39,42,44,45,47–59]	M	S/M	M/H	X	X	X	R/N	H/L	L	T	N/A	H	0	+	H (N/A)	0	0	-	+	0	+	+	[7,29,72,133,142,149]
Install common header on compressors (ARC 2,4225)	[30,42,44,48–52,57,60,61]	H	M	N/A	X		X	N	M	L	+	-	H	-	+	H; -D	0	0	0	0	0	+	0	[7,29,129,142,150]

Description	**Ref. Description**	**Economic Energetic Fac-**			**Operative Factors**			**Contextual Factors**																**Ref. Factors**
								Complexity					**Compatibility**					**Observability**						
		Investment Cost [a]	**Payback Time [b]**	**Energy Savings [a]**	**Pressure [c]**	**Temperature [c]**	**Fluid flow Rate [c]**	**Activity Type [d]**	**Expertise required [e]**	**Independency from other Compo-**	**Change in Maintenance Effort [g]**	**Accessibility [h]**	**Technological [i]**	**Presence of different**	**Adaptability to dif-**	**Synergy with other activities [l]**	**Distance from electric**	**Presence of different**	**Safety [n]**	**Noise [n]**	**Air Quality [n]**	**Wear and Tear [n]**	**Artificial demand [n]**	
Use/purchase optimum sized compressor (ARC 2,4226)	[11,29,34,35,39,42,45,48–50,55,57,62–64]	H	M/L	M/H	X	X	X	N	H	L	+	I	H	H	+	H; (+D)	0	0	0	I	0	I	0	[7,29,64,72,129,133,134,142,151]
Use compressor air filter (ARC 2,4227)	[6,9,11,12,14,16,18,19,26,35–39]	L	S	L	X			O	L	H	-	I	L	0	0	M (N/A)	0	0	+	+	+	+	0	[7,133,142,143]
Reduce the pressure of compressed air to the minimum required (ARC 2,4231)	[29,30,34,40,42,47,51,55,58,69–74]	L	S	L	X		X	O	M	L +	-	-	0	H	0	H (N/A)	0	0	+	+	I	+	+	[7,29,72,142,150,152]

Descrip-tion	**Ref. Description**	**Economic Energetic Fac-**			**Operative Factors**			**Contextual Factors**																**Ref. Factors**
								Complexity						**Compatibility**				**Observability**						
		Investment Cost [a]	**Payback Time** [b]	**Energy Savings** [a]	**Pressure** [c]	**Temperature** [c]	**Fluid flow Rate** [c]	**Activity Type** [d]	**Expertise required** [e]	**Independency from other Compo-**	**Change in Maintenance Effort** [g]	**Accessibility** [h]	**Technological** [i]	**Presence of different**	**Adaptability to dif-**	**Synergy with other activities** [l]	**Distance from electric**	**Presence of different**	**Safety** [n]	**Noise** [n]	**Air Quality** [n]	**Wear and Tear** [n]	**Artificial demand** [n]	
Eliminate or reduce the compressed air used for cooling, agitating liquids, moving products, or drying (ARC 2,4232)	[29,30,39,40,45,47–51,70,75–79]	M	S	H	X		X	O	H	L	T	I	H	T	-	L; -D	-	0	+	+	I	+	+	[7,29,142,153–155]
Eliminate permanently the use of compressed air (ARC 2,4233)	[29,30,39,40,45,47–51,70,75–79]	M	S	H			X	O	L	H	0	-	0	0	0	H (N/A)	0	0	0	+	0	0	+	[7,29,142,152,155]
Cool compressor air intake with heat exchanger (ARC 2,4234)	[37,38,57]	M	M	M		X	X	N	L	H	N/A	-	0	0	0	H; +M	0	0	0	0	0	0	0	[7,133,142–144,156–158]

Descrip-tion	Ref. Description	Economic Energetic Fac-			Operative Factors			Contextual Factors: Complexity					Contextual Factors: Compatibility				Contextual Factors: Observability							Ref. Factors
		Investment Cost [a]	Payback Time [b]	Energy Savings [a]	Pressure [c]	Temperature [c]	Fluid flow Rate [c]	Activity Type [d]	Expertise required [e]	Independency from other Compo-	Change in Maintenance Effort [g]	Accessibility [h]	Technological [i]	Presence of different	Adaptability to dif-	Synergy with other activities [l]	Distance from electric	Presence of different	Safety [n]	Noise [n]	Air Quality [n]	Wear and Tear [n]	Artificial demand [n]	
Remove or close off unneeded compressed air lines (ARC 2,4235)	[29,42,50,80–82]	M	S	N/A				O	L	H	+	-	0	0	0	H (N/A)	0	0	-	0	0	+	+	[7,29,142,152,155]
Eliminate leaks in inert gas and compressed air lines/valves (ARC 2,4236)	[29,30,35,39,42,44,47,49,56,57,59,70,83–85]	L	S	H	X		X	Rec	M	L	-	-	0	L	0	H; -D	0	0	+	+	0	+	+	[7,29,72,142]
Substitute compressed air cooling with water or air cooling (ARC 2,4237)	[39,86–89]	M	S	N/A		X	X	N	M	L	-	-	M	0	0	H; +M	0	0	0	I	0	0	0	[7,87,89,133,142,155,157–160]
Do not use compressed air for personal cooling (ARC 2,4238)	[29]	M	S	N/A			X	O	L	M	0	-	0	0	0	H (N/A)	-	0	+	-	+	0	+	[7,29,133,142]

Description	**Ref. Description**	**Economic Energetic Fac-**			**Operative Factors**			**Contextual Factors**																**Ref. Factors**
								Complexity					**Compatibility**					**Observability**						
		Investment Cost [a]	**Payback Time** [b]	**Energy Savings** [a]	**Pressure** [c]	**Temperature** [c]	**Fluid flow Rate** [c]	**Activity Type** [d]	**Expertise required** [e]	**Independency from other Compo-**	**Change in Maintenance Effort** [g]	**Accessibility** [h]	**Technological** [i]	**Presence of different**	**Adaptability to dif-**	**Synergy with other activities** [l]	**Distance from electric**	**Presence of different**	**Safety** [n]	**Noise** [n]	**Air Quality** [n]	**Wear and Tear** [n]	**Artificial demand** [n]	
Recover heat from air compressor (ARC 2,2434)	[27,29,34,36,39,40,42,44,45,51,57,90,91]	M	M	H		X	X	R	H	L	-	-	M	+	-	M (N/A)	0	+	0	0	+	+	0	[7,29,36,39,72,89,142]
Recover heat from compressed air dryers (ARC 2,2435)	[27,29,57,90,91,34,36,39,40,42,44,45,51]	M	M	H		X	X	R	H	L	-	-	M	+	-	M (N/A)	0	+	0	0	0	+	0	[7,29,36,39,72,89,142]
Install energy harvesting units	[33,92–98]	N/A	M	M			X	R	H	L/M -	+	-	H	T	-	N/A	0	0	0	0	0	0	0	[33,92–98]

[a] Low (L) if less than $2.000; medium (M) if between $2.000 and $10.000; high (H) if higher than $10.000; not available (N/A). [b] Short (S) if less than 1 year; medium (M) if between 1 and 2 years; long (L) if more than 2 years. [c] Impacted by the adoption of the EEM: (X); not impacted: ( ). [d] Retrofit (R); new installation (N); optimization (O); procedure of recovery (Rec). [e] Low (L) if the presence of maintenance personnel is enough; Medium (M) if engineering is required; High (H) if the support of a technology expert is needed. [f] Magnitude: Low (L); medium (M); high (H). Orientation: positive (+); negative (-). [g] Changes with technological change (T); maintenance effort is decreased (+); maintenance effort is increased (-); the factor is not influent for the EEM (0); not available (N/A). [h] Accessibility problems negatively influence the EEM adoption (-); the EEM may change accessibility to some point, but the influence is negative or positive depending on the context (I); not available (N/A). [i] High (H); medium (M); low (L); not influencing the EEM (0). [j] If the condition is verified, the factor may: highly influence the adoption (H); have a little influence (L); not influence at all (0). The influence may also depend on the technology (T). Orientation: the influence positively (+) or negatively (-) affects the adoption. [k] The factor may: highly influence the adoption (H); have a little influence (L); not influence at all (0). Orientation: the influence positively (+; ++) or negatively (-) affects the adoption. [l] Possibility of installation with other EEMs: low (L), medium (M), high (H). Orientation: positive (+) or negative (-) influence on the synergy with similar maintenance activities (M) or required shutdown of equipment (D); not available (N/A). [m] The factor may positively (+) or negatively (-

) influence the adoption or may be not influencing at all (0). [n] The factor may positively (+) or negatively (-) influence the adoption. In some cases, the factor is influencing but not in a precise direction (I) or it does not influence at all (0).

5.2. Empirical Validation

We sampled firms across several sectors, limiting the analysis to SMEs, as discussed in the introduction [161]. In this exploratory phase, different industrial sectors are considered, since the usage of CA may vary according to the application, as well as its energy intensity. Five companies embodying the previously stated criteria were considered for the empirical validation (details provided in Table 5).

Table 5. Heterogeneity of the sample for the framework empirical validation.

Company	Sector	Dimensions (employees)	Turnover [M€]	Energy Intensity (EI/NEI) [a]	Role of the Interviewee
V1	Plastic and packaging	150 ÷ 199	≤20	EI	Site manager
V2	Test and inspection of electric/mechanical components	10 ÷ 49	≤2	EI	Maintenance responsible
V3	Machine design and construction	100 ÷ 149	≤10	EI	Quality and energy responsible
V4	Tires regeneration	10 ÷ 49	≤10	EI	Quality and energy responsible
V5	Food and beverage	100 ÷ 149	≤50	NEI	Quality and energy responsible

[a] The threshold between energy intensive and non-energy intensive companies is defined by the value of energy costs compared to the total turnover; in the present study such value is set at 2% [162].

The interviews followed a semi-structured format [156], to give higher flexibility and customization, being able to encompass a broader set of situations. In each case study, in the first part we collected various information regarding company profile, including sector, size, energy intensity and turnover, the role of the interviewees—ranging from the owner to the maintenance or energy manager—and their status and main responsibilities in the decision-making process over the adoption of CAS EEMs. Moreover, the perceived importance of energy and energy efficiency were investigated, together with the past EEMs implemented. Additionally, the CAS was analyzed to understand the applications and purposes of compressed air usage.

In the second part of the interview, respondents evaluated the proposed set of factors based on four performances, i.e., completeness, usefulness, clearness, and absence of overlapping, exploiting an even Likert scale from 1 (poor) to 4 (excellent) to avoid any neutral output. In particular, the validation process was divided into two separate steps: first, the foundations of the framework were assessed, i.e., its general structure, scope and perspective, as well as categories, subcategories, and factors considered as clusters in their own (top-level analysis). Second, the analysis delved into the investigation of the single elements of the framework, i.e., categories, subcategories, and factors (bottom-level analysis). The dual step process was designed to provide the interviewee with the general picture and only later moving into details, to avoid losing his attention releasing too much information in a single instance. The indicators used for the evaluation are displayed in Table 6, with detailed scores for the five companies reported in Appendix A.

Table 6. Parameters for the framework validation.

Framework		Completeness	Usefulness	Clearness	Absence of Overlapping
	Structure	X		X	
	Scope		X	X	
	Perspective		X		
Categories		X (cluster)	X	X	X
Subcategories		X (cluster)	X	X	X
Factors		X (cluster)	X	X	X

The overall evaluation is extremely positive for each indicator, with no changes in the framework suggested:

- *usefulness:* the framework can provide useful insights to industrial decision-makers when dealing with the adoption of EEMs in CAS;
- *completeness:* all the critical factors are identified, especially those which are usually neglected due to a lack of awareness or specific knowledge about the technology;
- *clearness:* the factors are clearly defined and easy to understand for industrial decision-makers;
- *absence of overlapping:* the framework does not contain any unnecessary repetition.

The importance of pointing out all the consequences stemming from the adoption is moreover stressed by the interviewee of company V4, suggesting that technology providers should also use the framework to highlight the consequences when proposing CAS EEMs. On the other hand, as noted by company V5, such increased knowledge might empower industrial decision-makers, since he recognized that usually service providers lean on a greater set of competences, thus limiting the company to implement suggested EEM, rather than proposing EEMs by themselves.

6. Application of the Model

Multiple case-study with semistructured interviews was selected as research methodology also for the empirical application of the framework into a second sample composed by 11 companies, sampled with the same rationale previously presented in Section 5 (details in Table 7). In order to apply the framework and test its effectiveness, considering the sample heterogeneity, we focused our analysis on the most recommended interventions, by considering the IAC database as reference (Table 8). Considering the timeline of the companies, EEMs are divided into:

(i) past EEMs when recommended and backed up by an investment plan but never implemented;
(ii) present EEMs if recommended and adopted, so the companies experienced the result; and
(iii) future EEMs if not yet recommended or only recently recommended, with no decision about their implementation undertaken.

Table 7. Heterogeneity of the sample for the framework application.

Company	Sector	Dimensions (employees)	Turnover (M€)	Energy Intensity (EI/NEI)	Role of the Interviewee
A1	Plastic and packaging	150 ÷ 199	≤20	EI	Site manager
A2	Test and inspection of electric/mechanical components	10 ÷ 49	≤2	EI	Maintenance responsible
A3	Machine design and construction	100 ÷ 149	≤10	EI	Quality and energy responsible

A4	Tires regeneration	10 ÷ 49	≤10	EI	Quality and energy responsible
A5	Food and beverage	100 ÷ 149	≤50	NEI	Quality and energy responsible
A6	Thermoforming of plastic and PVC materials	10 ÷ 49	≤10	N/A	Quality and energy responsible
A7	Microelectronic components	100 ÷ 149	≤20	EI	Site manager
A8	Plastic manufacture, thermoplastic, and plastic welding	10 ÷ 49	≤2	EI	Owner/site manager
A9	Manufacture and distribution of paints	10 ÷ 49	≤20	NEI	Site manager
A10	Food and beverage	10 ÷ 49	≤10	EI	Owner/site manager
A11	Food and beverage	10 ÷ 49	≤20	N/A	Site manager

Table 8. Synoptic of the most recommended EEMs [142] that will be analyzed for the framework application.

ARC Code	Measure	Recommended	% Implementation
2,4236	Eliminate leaks in inert gas and compressed air lines/vales	8138	80.38
2,4221	Install compressor air intakes in coolest locations	5129	46.5
2,4231	Reduce the pressure of compressed air to the minimum required	4446	49.6
2,2434	Recover heat from air compressor	1626	31.86
2,4232	Eliminate or reduce compressed air used for cooling, agitating liquids, moving products, or drying	1450	46
2,4226	Use/purchase optimum sized compressor	692	42.92
2,4224	Upgrade controls on compressors	639	44.6

The application of the framework is intended to test its ability to work as an assessment tool. Decision-makers are required to indicate the importance factors have in the adoption process, ranging between ‘not important’ and ‘very important’. Eventually, the relevance in using the framework for the decision-making process and the greater awareness gained from it are asked to the respondents, together with the effort required for its usage and its ease of application.

Box 1. Application of the framework to company A5.

Company profile:

- Company A5 is a medium size company, with 105 employees and about €50 million of annual turnover, part of a multinational corporation operating in the food and beverage sector.
- They are specialized in the production and distribution of canned sea food, with six production lines present in the plant. CA is used in the production lines for cleaning activities on the cans, for cutting fish, for the packaging system, and to drive the transportation lines.

Energy profile:

- Energy consumption is around 1% of the total turnover, which makes it a non-energy intensive company [1]. About 15% of the total energy consumption is related to compressed air, with a total power installed of 162 KW, distributed along four compressors located in two separate compressors rooms.
- Company A5 is not certified with ISO 50001.
- The last energy audit was performed in 2016

Interviewee profile:

- The interviewee is the site manager, who is moreover in charge of the energy management inside the plant.
- The decision-making process is performed by the site manager together with his team, composed of four people. They are also responsible for maintaining the correct conditions, aligned with the indications coming from the installed performance measurement system, during the execution of the production and service processes.

EEM profile:

- Company A5 considered the replacement of CA used for the transportation system for cans and aluminum tubes along the production line with a motor driven vacuum system, aiming at enhancing the performance getting rid of a dated technology.
- The EEM belongs to the past cluster since company A5 eventually did not perform the substitution. The reason lies in the high investment cost and the required shutdown of the entire line which would have meant production disruption, thus losses, since they are continuously operating 24 h per day.

Application of the framework:

Operational factors		**Pressure**	The requirements to be satisfied in terms of pressure were considered by the decision-maker.
		Temperature	Temperature was not perceived as a very influencing factor for the replacement of the CA-based transportation system.
		Flow rate	Together with pressure, the flow rate requirement was considered during the decision-making process, being of paramount importance for the operation of the system.
Economic-energetic factors		**Pay-back time**	The importance of the factor was high, although the decision-maker was more susceptible to costs rather than to the extent of the pay-back period.
		Initial expenditure	The high investment cost required for the EEM, together with the losses due to the stop of production which would have been necessary to perform the substitution of the transportation system, were the main reasons that led to the nonadoption decision.
		Energy savings	Energy savings represent an important factor for the adoption of the EEM, with the decision-makers pointing out the possibility to enhance the energetic performance of the system by replacing a dated technology.
Contextual factors	**Complexity**	**Activity type**	The EEM is a new installation.
		Expertise required	The installation of the EEM requires the involvement of experts in the substitution process, negatively affecting the decision according to the decision-maker.
		Independency from other components/EEMs	Considering the pervasive involvement of the transportation system for the proper operation of the production line, the decision-maker pointed out a high dependency for the EEM.
		Change in maintenance effort	No main changes were pointed out by the decision-maker with respect to maintenance efforts.
		Accessibility	For the specific location of the CAS and the transportation system in company A5, the accessibility is not a big issue.
	Compatibility	**Technological**	The measure cannot be applied on all systems; hence the technological compatibility is a very important factor according to the decision-maker.
		Presence of different pressure loads	Generally, the presence of different pressure loads should usually favor the adoption of the vacuum pumps; however, for the specific situation of company A5, pressure loads differences were almost negligible, reducing the weight of the factor.
		Adaptability to different conditions	The capacity of the EEM to adapt to different operating conditions does not influence the adoption for the specific case of company A5 since a single vacuum pressure level is required.
		Synergy with other activities	Through the exploitation of synergies the installation can be performed when the line is down, taking advantage of a planned production stop; this factor is critical, since for no reason the replacement of the actual transportation system would have been performed in a different time slot, with the risk of influencing and stopping the normal activities.
		Distance from the electric service	For the specific situation of company A5 the factor is not critical due to the installation of the compressors in two rooms, close to the electric service.
		Presence of thermal load	No thermal loads are present for the specific application.
	Observability	**Safety**	The factor is not highly influential for the adoption of the specific EEM according to the decision-maker.
		Air quality	The variation in the quality of air was not perceived as a very important factor by the decision-maker.
		Wear and tear	The variation in wear and tear of the equipment does not represent a critical factor for the adoption of the specific EEM.
		Noise	The interviewee proved to be almost unaware of the potential improvement in noise level and assigned a low weight to the factor.
		Artificial demand	The factor is not critical for this EEM according to the decision-maker.

Eventually, the framework proved to be able to outline factors not known to the engineering of company A5, although it should be noted that none of the negative ones had been underestimated. In turn, more aware of the positive consequences of the adoption, the decision-maker could go back to his steps in case of a new stoppage of the line. He admitted that, despite the massive usage of compressed air and its energy consumption, they are not completely aware of the measure which could fit in their context. For this reason, he considered the developed tool as extremely tailored for their case. Moreover, the user-friendliness and the ease of use were positively rated.

In Box 1, we reported the application of the framework to a selected company (A5). In the following, we present the results of the application, displayed in Table 9. By looking at the implementation of the proposed framework, it appears clear how the operational factors are always considered during the assessment, with the only exception represented by the temperature, neglected in the assessment conducted by company A1 for the adoption of a controller, which nonetheless did not compromise the result. Referring to the economic-energetic factors, decision-makers stated how important they are for the correct assessment of EEMs, hence are usually the major set of factors considered in the decision-making process.

Nevertheless, the contextual factors pointed out on multiple occasions their capability to highlight critical features whose absence may change the adoption outcome. Particularly, the type of activity, providing information regarding the complexity of an EEM, was considered of primary importance in all the assessments, pointing out the huge perceived differences between the different nature of EEMs. The installation of a new device, or even a retrofit entailing the addition of new equipment, was indeed perceived as a complex operation by A1, which installed control systems and considered the movement of the compressors air intakes in a cooler place, or even by A5, which considered the replacement of the transportation system based on compressed air. On the other hand, completely different perceptions came from the companies which considered an optimization, e.g., companies A3, A6, A8, and A10, where the EEM relates to the repair of leaks. A2 stated how the type of activity was an important factor in his assessment, since the EEM, i.e., the reduction of the pressure level to the minimum required, is a simple optimization which does not imply any structural change in the system, hence requiring only a low level of involvement.

Similarly, the expertise required to carry out the adoption is assessed as one of the main factors to be taken into consideration by decision-makers, especially for complex EEMs or in case of lack of knowledge, e.g., for the EEM considered by A9, which would imply the elimination of the compressed air used for dense phase transport but would be completely outsourced because of lack of internal competences. The expertise required guides A2 on the choice of simply consulting the compressor technical manual or contacting a technology expert for the adoption of the planned EEM. Further, in the case of A7, one of the main reasons for not adopting the EEM was the high expertise required, similarly to A5.

The independence from other components or EEMs was highly appreciated by the decision-maker of company A5, who was indeed worried about the high involvement of the transportation system in the production processes. Although the same EEM was considered by A9, the decision-maker was at first unaware about the importance of the factor. Rather, he was aware of the high dependency for what concerns the other EEM adopted by the company, i.e., the installation of control systems (two in the specific case), as he recognized how one may influence the proper working of the other. Regarding the repair of leaks in the compressed air lines, the advantage coming from the increased pressure level, which may end up with the reduction of the number of required compressors, was known to A3, A8, and A10. Differently, A6 was sceptic about this potential influence, thus neglected the factor from the analysis and ended up not adopting the EEM. Similarly, the dependency of the considered EEM was not known by A2, which did not take into account the potential risks related to the reduction of the pressure level for other activities to be performed through the same medium. Likewise, the decision-makers within A1 disregarded to resize the air receivers and the possible installation of the central control for the dryers. In both cases, the assessment resulted in the underestimation of the negative sides of the EEMs which could compromise their adoption.

Table 9. Assessment of the factors from the application of the model.

		Categories of Factors	**Operational Factors**			**Economic-Energetic Factors**			**Contextual Factors**													
									Complexity						**Compatibility**					**Observability**			
		Factors	**Pressure**	**Temperature**	**Flow Rate**	**Pay-back time**	**Initial Expenditure**	**Energy saving**	**Activity type**	**Expertise Required**	**Independency**	**Change in mainte-**	**Accessibility**	**Technological**	**Presence of Dif-**	**Adaptability to Different**	**Synergy with**	**Distance to the**	**Presence of Ther-**	**Safety**	**Air Quality**	**Wear and tear**	**Noise**	**Artificial Demand**
Company	**EEM**	**EEM status**																						
A1	Install compressor air intakes in coolest location (ARC 2,4221)	past	✓	✓	✓	✓	✓	✓✓	✓	✓						(!!)	✓				(!)			
A1	Upgrade controls on compressors (ARC 2,4224)	present	✓	(!)	✓	✓	✓	✓✓	✓	✓	(!)			✓		✓✓	✓							✓
A2	Reduce the pressure of compressed air to the minimum required (ARC 2,4231)	future	✓		✓	✓	✓	✓	✓	✓	(!!)			✓✓								(!)		(!)
A3	Use/purchase optimum sized compressors (ARC 2,4226)	past	✓		✓	✓	✓✓	✓✓	✓✓	✓	✓				✓									
A3	Eliminate leaks in inert gas and compressed air lines/ valves (ARC 2,4236)	future	✓	✓	✓	✓	✓	✓✓	✓	✓	✓✓	✓	✓✓							✓				✓
A4	Install compressor air intakes in coolest location (ARC 2,4221)	future	✓	✓	✓	✓✓	✓✓	✓✓	✓✓	✓			✓								(!)			
A5	Eliminate or reduce the compressed air used for cooling, agitating liquids, moving products, or drying (ARC 2,4232)	past	✓		✓	✓	✓✓	✓✓	✓	✓	✓			✓✓			✓✓							
A6	Eliminate leaks in inert gas and compressed air lines/ valves (ARC 2,4236)	past	✓		✓	✓✓	✓✓	✓✓	✓	✓	(!)		✓✓							✓				(!)
A7	Recover heat from air compressor (ARC 2,2434)	past		✓	✓	✓✓	✓✓	✓✓	✓	✓✓			✓✓		(!)	✓			✓✓					
A8	Eliminate leaks in inert gas and compressed air lines/valves (ARC 2,4236)	future	✓		✓	✓✓	✓✓	✓✓	✓	✓	✓	✓✓	✓							✓✓				(!)
A9	Upgrade controls on compressors (ARC 2,4224)	present	✓	✓	✓	✓✓	✓✓	✓✓	✓	✓	✓			✓✓		✓✓	✓✓							✓
A9	Eliminate or reduce the compressed air used for cooling, agitating liquids, moving products, or drying (ARC 2,4232)	future	✓		✓	✓✓	✓✓	✓✓	✓	✓✓	(!)		✓	✓			✓✓							
A10	Eliminate leaks in inert gas and compressed air lines/ valves (ARC 2,4236)	present	✓		✓			✓✓	✓		✓		✓✓							✓			✓	✓
A10	Install compressor air intakes in coolest location (ARC 2,4221)	future	✓	✓	✓	✓	✓	✓✓	✓	✓							✓✓							
A11	Use/purchase optimum sized compressors (ARC 2,4226)	present	✓		✓	✓✓	✓✓	✓✓	✓✓	✓✓	✓				(!)							✓		

Factors considered as important (✓) and very important (✓✓) by decision-makers and literature; factors important (!) and very important (!!) that should have been considered by decision-makers according to literature, but which were not considered in the decision to adopt EEMs.

The variation in maintenance effort is considered by almost all the respondents but it was perceived as critical only when the effort would be increased because of the leaks repair activity, i.e., by A3 and A8, which were considering the EEM for the future. Differently, A10, which performs the same EEM regularly, evaluated the effort as manageable.

The accessibility of CAS was widely considered since some companies had issues in the past. A10, e.g., assessed the accessibility as the most critical factor when dealing with the repair of leaks, together with A6 and A8, since parts of their compressed air lines can either be hard to reach or inaccessible (underground). The criticality of the factor was also pointed out by company A9, where the transport system to be replaced is integrated into the process lines, and A4 and A7.

Moving to the compatibility subcategory, technological compatibility was considered a critical factor by many companies. The choice of the controller, for instance, was strictly constrained by the type of compressor installed, as highlighted by A1 and A9. Technological compatibility was also rated as very important by A2, dealing with the reduction of pressure level of the CAS, since the variation in performance depends on the type of compressor. Eventually, A5 and A9 pointed out how the elimination of compressed air from the transportation system is an EEM which cannot be always applied because of technological constraints.

The presence of different pressure loads was considered of utmost importance by A3 when dealing with the correct sizing of compressors, since it may influence the decision regarding the number of devices required. However, for the same EEM, A11 did not perceive the criticality of the factor, despite the effective presence of different pressure levels in their lines. The explanation should be researched in the number of pressure reducers installed in the system. Eventually, if the factor had been properly considered, the company would have probably opted for a different and more efficient configuration. Similarly, in A2 the factor was not considered, despite the influence the pressure level has on the heat recovery potential.

The adaptability to different conditions was considered as the most important factor by A1 and A9, both dealing with the adoption of controllers on compressors, which were indeed installed with the specific purpose of changing the operating conditions of the equipment when needed. The factor was, however, underestimated by A1 regarding the assessment of the second EEM, i.e., the displacement of the compressors air intakes in the coolest location, because of a lack of awareness, and this was one of the main reasons hindering the adoption. Moreover, as stated by the decision-maker of company A7, the adaptability to different conditions, related to the variability of requirements in the demand side, is a very important factor when considering the recovery of heat from the compressors.

It should be assessed, however, together with the factor describing the presence of thermal loads, which refers to the availability of the right amount of heat to match the demand side. These are the most important factors to be considered when dealing with that type of EEM according to A7.

The possibility to take advantage of synergies to carry out the installation when the production line is down was considered as a very important point by both A5 and A9 when deciding about the replacement of the old air compressed transportation system with a more efficient technology. Otherwise, this would lead to an additional plant shutdown with related production losses, hence supporting the non-adoption of the EEM. The same factor was rated as critical for the adoption of controllers on compressors carried out by A1 and A9. In particular, the decision-maker of company A1 pointed out that the activity requires a long time to be performed, thus it was done during the summertime when the plant was closed. The synergy is also reported by A1 and A10 considering the displacement of the compressors air intakes in cooler locations.

Regarding the observability factors, all the respondents whose companies performed the repair of leaks in compressed air lines recognized the importance the activity has on the safety.

The air quality was generally not acknowledged as a critical factor, although other authors pointed out its relevance [29]. Companies A1 and A4 considered the displacement of the compressors air inlets from the external environment to the internal one, in a cooler location. Beside a difference in temperature however, the quality of the internal air is usually better: the moisture content is lower, and this may lower the wear of the compressors, extending their lifetime. Differently, for A10 there would be no variation in the air quality but only in air temperature since the EEM would just imply to shift the air inlet indoor.

The variation of CAS wear and tear was considered by A11 in terms of the extended lifetime of the equipment embedded in the installation of the new and correctly sized compressor and, according to the respondents, was a very important factor. Differently, A9 was unaware of the factor when referring to the adoption of a controller, nor A2 when thinking about the reduction of pressure level, although in both cases they agreed on the importance this could have on the decision-making process.

Noise was considered critical by A10 to foster the repair of leaks. A3, A6, and A8, who assessed the same EEM, did not deem the factor important. However, they claimed to perform repair activities as soon as a noise is perceived to limit its effect on the surroundings.

The artificial demand was known and considered very influential only by A3 and A10, both dealing with the repair of leaks. For the same EEM, A6 and A8 did not perceive the criticality. Initially, the decision-maker within A2 did not give much importance to the factor. However, he pointed out that the actual compressed air flow was higher than required because of a poorly sized compressor, and the artificial demand phenomenon was further increasing the gap between supply and demand. Therefore, the consideration of this factor could significantly increase the possibilities of a future adoption of the EEM. Moreover, the influence of the artificial demand also affects the adoption of controllers, as pointed out by the decision-makers of companies A1 and A9.

Overall, regardless of the nature of the EEM, i.e., past, present, or future, the framework proved to be able to provide additional information to industrial decision-makers. For instance, the respondent within A1 pointed out that the increased awareness resulting from the framework application would be probably enough to reconsider in the future the displacement of the compressors air intakes in the coolest location. Moreover, using the framework, the decision-maker of company A9 assessed an EEM he was not aware of. The framework resulted effective in A5 to highlight factors unknown to the decision-maker. However, none of the negatives were underestimated, and ultimately the decision not to adopt was due to the high investment costs and the production disruption to carry out the installation. Similarly, A7 acquired more insights from the framework, but the low amount of achievable savings drove the decision not to implement the considered EEM.

Furthermore, all the respondents particularly appreciated the ease of use of the framework and the low efforts required for its application, in particular for being able to completely define the EEMs encompassing only a limited number of factors.

7. Discussion

Comparing the result with the existing models, similarities can be found only regarding energetic and economic factors, since the most widespread and universally accepted indicators are utilized (e.g., pay-back time [26,112,163]) to evaluate the investment from an economic point of view, thus making the tool more user-friendly for the final adopters. On the other hand, differences can be found if considering operative factors, although technical information is widely covered by past literature [39]. The reason lies in the restricted focus of this work, i.e., CAS, being specific enough to enable the analysis of specific characteristics of the technology, which has been rarely investigated to this level of detail concerning characterizing factors. As confirmation of the previous statement, Nehler and Rasmussen [107] indicate that the characteristics of factors may depend on the type of EEMs, as already pointed out by Cagno and Trianni [22] referring to barriers to specific EEMs. Less detailed results come from a variety of studies considering compressed air through a multitechnology analysis [103,106], in many cases not even providing a clustering framework of factors [108,109,113]. Differently, more specific focus is provided by the study conducted by Nehler et al. [27], focused on CAS, which includes among the NEBs an improvement in temperature control, hence indicating the criticality of this factor. Moreover, considerations about pressure and flow rate are listed among the impacts perceived by suppliers concerning specific EEMs, as documented by a wealth of technical manuals and industrial literature extensively covering these aspects, despite neither categorizing the factors into an operative framework nor providing additional insights with respect to the mere technical ones. During the interviews conducted on field, these factors were highly appreciated by industrial decision-makers, given the practicality they confer to the tool; it would be indeed unfeasible to discuss the implementation of EEMs within CAS without taking into account such information. Other differences can be found analyzing those factors which introduce the contextual dimension, making the framework flexible enough to be exploited in all the different situations where the industrial decision-maker is required to operate. The first step toward this path was made by Rogers [99], followed by Tornatzky and Klein [100]; both the studies, however, treat compatibility referring to innovation, thus dealing with society in its entireness rather than a specific technology or field. Although the definition of the category can be adapted to the industrial environment, the details depicted by the single factors are here included for the first time. An exception is represented by the observability factors, i.e., safety, air quality, wear and tear, and noise, which are commonly considered in literature [105,106,164], sometimes clustered in a single element describing the whole working environment [7], given the strict relation with many EEMs, regardless of the technology considered. Industrial respondents were generally aware of such characteristics, despite the fact that they were never considered as the most critical elements leading the adoption of EEMs, with the exception being for A4; however, here compressed air belongs to the production process, which may act as a discriminant for the perceived importance of the role of compressed air. This is aligned with the perspective provided by Nehler et al. [27], where the importance of NEBs as a driver for the decision-making process is evaluated: enhancements of the working environment and safety conditions are considered. However, they are perceived as of secondary importance with respect to other advantages, e.g., those directly connected to the reliability and lifetime of the equipment. One reason could be the difficulty of their evaluation and monetization, thus the impossibility to include these considerations in the economic assessment of any investment, which represents a critical step of the decision-making process [165]. Nevertheless, according to Nehler and Rasmussen [107] those characteristics that cannot be evaluated from a monetary perspective, may be considered alongside the proposal in the form of comments. Regarding the remaining operational factor, i.e., artificial demand, given the strict dependency with the specific CA technology, it cannot be found in frameworks related to a broader cluster, such as by Trianni et al. [7]. Nevertheless, it should be noted that almost all the interviewees were aware of this phenomenon, despite the technical nature and difficulty of observation make it hard to be recognized by users without deep expertise in CAS.

Apart from observability factors, the complexity ones are partly included in previous literature, despite being categorized differently (e.g., [26,105,126]). Activity type, for instance, is included by Trianni et al. [7], who confined the definition by Rogers [99] and Tornatzky and Klein [100] to a limited field, i.e., industry, to make it practically exploitable. On the other hand, the willingness to focus on more than a single technology prevented them from analyzing all single factors related to compressed air solely. Interestingly, the present framework specifically included for the first time the difficulty in accessing the distribution system (accessibility factor), despite being deemed as important by any decision-maker interviewed. Further, compatibility issues, except for synergies [131], represent a neglected dimension in scientific literature, despite the fact that they are widely recognized in technical manuals or industrial sources (e.g., [29,127,129]). Once more, since the framework is intended for a practical application into companies, these considerations should be encompassed in the decision-making process, as revealed from the investigation where decision-makers acknowledged that some important factors were not always taken into account. This capability was embedded in the design of the framework, thanks to its focus on the single technology of CAS.

The need of a more specific funneled knowledge over relevant factors for EEMs adoption is partially aligned with the specificity of the characteristics but also to the applicability property discussed by Fleiter et al. [26], provided that the efficiency interventions remain confined to CAS. On the other hand, as demonstrated by the different importance attributed to the observability factors during the interviews, the selected factors should not be independent of the context and the adopting company, as stated by [26], but should include the information; the category contextual factors is considered in the present study to fulfil this necessity. In this regard, future research could explore whether such interdependency could be modulated by the different relationships between CA and the core process of the firms. Relationships may also exist among the various factors included in the framework, which are not completely disconnected from each other, confirming the close interactions CAS have with the operations of a company. For instance, the repair of leakages (ARC 2,4236) would lead to a reduction in pressure requirements, which in turn would affect the noise level and the wear and tear of the equipment. Interestingly, preliminary results of the analysis (e.g., Table 4) may suggest that some relationships exist, although more research is needed to shed some light on this. Indeed, an in-depth study of the impacts between factors could make a further contribution to the discussion about impacts on the operations and the other productive resources of a company.

8. Conclusions

The willingness to understand the main factors that rule the adoption of EEMs on CAS represents the driver that pushed toward the definition of the present framework. Aiming at providing a systemic view of the adoption, factors referring to the complexity, compatibility, and observability of the results coming from the adoption of EEMs were included in the model, encompassing, among others, the impacts on the operations and the other productive resources of an industrial firm, together with more traditional considerations regarding the operational and the economic and energetic factors. Results from the empirical application show how these features might prove critical in the path for the adoption, sometimes even capable of reversing the outcome, hence confirming the added knowledge brought by the framework. In this regard, future longitudinal research could explore the change of awareness in decision-makers when assessing EEMs in CAS and other sustainability practices within industrial operations. Moreover, the focus kept on the specific technology of CAS enabled to point out peculiar factors that might be lost approaching the problem through a more holistic perspective, e.g., difficulties in accessing CAS, which was a recurrent topic in the empirical investigations. Nonetheless, despite its non-negligible importance according to the interviewed decision-makers, the factor has never been approached by previous studies.

Using the framework, industrial decision-makers could tackle the perception of uncertainty they have concerning EEMs, beside finding valuable support to overcome the barriers related to risk, imperfect evaluation criteria, and lack of information, which might represent critical issues preventing a sound decision-making process. These barriers might be particularly present in SMEs, generally characterized by less trained or less skilled decision-makers, who may moreover face difficulties in the use of complex or overly detailed models. However, the structuring resulting from the synthesis process to which the framework was subjected made it possible to obtain a complete framework regarding the factors to be considered in the adoption of CAS EEMs, characterized at the same time by a high ease of use. Indeed, as pointed out by the empirical application, the evaluation of the user-friendliness and the effort required for the usage were overall positive, despite the fact that the greatest share of companies in the sample were SMEs. Policy makers, on the other hand, could take advantage of the framework to design tailored policies for enhancing the efficiency of CAS. Moreover, the assessment of the factors that rule the adoption of EEMs on CAS could lead to a deeper understanding of the specific barriers that affect the technology, which might move away with respect to the issue preventing the adoption of other technologies, assigned to different roles in a plant, e.g., electric motor systems. This deeper knowledge would, in turn, create solid foundations on which to lay the basis for the definition of drivers to overcome these barriers, improving the overall efficiency.

In conclusion, we would like to acknowledge some study limitations, starting from the narrowness of the application sample and its heterogeneity with respect to the industrial sectors. Besides, not all sectors are encompassed in the present study, e.g., textile or metal manufacturing are missing. Moreover, limiting the analysis to the technology of CAS did not enable to consider the entire set of impacts the adoption of an EEM has on the other productive resources or on the operations of a firm. Accordingly, future research could move towards this direction, furtherly extending the analysis to include a broader set of heterogeneous EEMs to better assess the impacts of their adoption. Additionally, further research could effectively develop approaches to measure such impacts more quantitatively, linking the impacts on production and operations performance. Furthermore, research could explore what synergies may be explored by integrating the developed framework into a broader set of tools to improve the sustainability performance of industrial enterprises, also connecting it with assessment tools, maturity models, etc.

Author Contributions: Conceptualization, D.A., A.T. and E.C.; methodology, E.C. and D.A.; validation, A.T., E.C. and D.A.; formal analysis, A.T., D.A. and E.C.; investigation, A.T., E.C. and D.A.; resources, A.T., D.A. and E.C.; data curation, D.A.; writing—original draft preparation, D.A., A.T. and E.C.; writing—review and editing, A.T., E.C. and D.A.; visualization, D.A.; supervision, A.T.; All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

Appendix A. Scores for the theoretical validation of the framework [a].

			Company V1				Company V2				Company V3				Company V4				Company V5			
			Usefulness	Completeness	Clearness	Absence of overlapping	Usefulness	Completeness	Clearness	Absence of overlapping	Usefulness	Completeness	Clearness	Absence of overlapping	Usefulness	Completeness	Clearness	Absence of overlapping	Usefulness	Completeness	Clearness	Absence of overlapping
Top-level analysis	Framework	Structure		4	4			4	4			4	4			4	4			4	4	
		Scope	4		4		4		4		3		4		4		4		4		4	
		Perspective	4				4				4				3				4			
	Categories			4				4				4				4				4		
	Subcategories			4				4				4				4				4		
	Factors			4				4				4				4				3		
Bottom-level analysis	Categories	Operational parameters	3		4	4	3		4	4	4		4	4	4		4	4	4		4	4
		Economic-energetic parameters	4		4	4	4		4	4	4		4	4	4		4	4	4		4	4
		Contextual parameters	4		4	4	4		4	4	4		4	3	4		4	4	4		4	4
	Subcategories	Compatibility	4		4	4	4		4	4	4		4	4	4		4	4	4		4	4
		Complexity	4		4	4	4		4	4	4		4	4	4		4	4	4		4	4
		Observability	4		4	4	4		4	4	4		4	4	4		4	4	4		4	4
	Operational parameters	Pressure	4		4	4	4		4	4	4		4	4	4		4	4	4		4	4
		Temperature	4		4	4	4		4	4	4		4	4	4		4	4	4		4	4
		Flow rate	4		4	4	4		4	4	4		4	4	4		4	4	4		4	4
	Economic-energetic parameters	Pay-back time	4		4	4	4		4	4	4		4	4	4		4	4	4		4	4
		Initial expenditure	4		4	4	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	4		4	4
	Complexity	Activity type	4		4	3	4		4	4	4		4	4	4		4	4	4		4	4
		Expertise	4		4	4	4		4	4	4		4	4	4		4	4	4		4	4
		Independency from other components/EEMs	4		4	4	4		4	4	4		4	3	4		4	4	4		4	4
		Change in maintenance effort	4		4	4	4		4	4	4		4	3	4		4	4	4		4	4
		Accessibility	4		4	4	4		4	4	4		4	4	4		4	4	4		4	4
	Compatibility	Technological	3		4	4	4		4	4	4		4	4	4		4	4	4		4	4
		Presence of different pressure loads	4		4	4	4		4	4	4		4	4	4		4	4	4		4	4
		Adaptability to different conditions	4		4	4	4		4	4	4		4	4	4		4	4	4		4	4

			Company V1				**Company V2**				**Company V3**				**Company V4**				**Company V5**			
			Usefulness	**Completeness**	**Clearness**	**Absence of overlapping**	**Usefulness**	**Completeness**	**Clearness**	**Absence of overlapping**	**Usefulness**	**Completeness**	**Clearness**	**Absence of overlapping**	**Usefulness**	**Completeness**	**Clearness**	**Absence of overlapping**	**Usefulness**	**Completeness**	**Clearness**	**Absence of overlapping**
		Synergy with other activities	4	/	3	3	4	/	4	4	4	/	4	3	4	/	4	4	4	/	4	4
		Distance to the electric service	4	/	4	4	3	/	4	4	4	/	4	4	4	/	4	4	4	/	4	4
		Presence of thermal loads	4	/	4	4	4	/	4	4	4	/	4	4	4	/	4	4	4	/	4	4
	Observability	Safety	4	/	4	4	4	/	4	4	4	/	4	4	4	/	4	4	4	/	4	4
		Air quality	4	/	4	4	4	/	4	4	4	/	4	4	4	/	4	4	4	/	4	4
		Wear and tear	4	/	4	4	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	4	/	4	4
		Artificial demand	4	/	3	4	4	/	4	4	4	/	4	4	4	/	3	4	4	/	4	4

[a] The green background represents an excellent rating (4 on the Likert scale); the orange background represent a good rating (3 on the Likert scale); no mediocre or poor ratings are present.

References

1. International Energy Agency IEA. *2018 World Energy Outlook—Executive Summary*; OECD/IEA: Paris, France, 2018; pp. 11.
2. U.S. Department of Energy. *International Energy Outlook 2019 with projections to 2050*; U.S. Department of Energy: Washington, DC, USA, 2019; pp. 85.
3. Berardi, U.; Tronchin, L.; Manfren, M.; Nastasi, B. On the effects of variation of thermal conductivity in buildings in the Italian construction sector. *Energies* **2018**, *11*, 1–17, doi:10.3390/en11040872.
4. Medved, M.; Ristovic, I.; Roser, J.; Vulic, M. An overview of two years of continuous energy optimization at the Velenje coal mine. *Energies* **2012**, *5*, 2017–2029, doi:10.3390/en5062017.
5. International Energy Agency IEA. *Energy Policies of IEA Countries: Italy 2016 Review*. OECD/IEA: Paris, France, 2016; pp. 214, doi:10.1787/9789264266698-en.
6. ENEA. *Rapporto Annuale Efficienza Energetica. Analisi e Risultati delle Policy di Efficienza Energetica del nostro Paese*; ENEA, Rome, Italy, 2018; pp. 292.
7. Trianni, A.; Cagno, E.; De Donatis, A. A framework to characterize energy efficiency measures. *Appl. Energy* **2014**, *118*, 207–220, doi:10.1016/j.apenergy.2013.12.042.
8. Cagno, E.; Trianni, A. Analysis of the most effective energy efficiency opportunities in manufacturing primary metals, plastics, and textiles small- and medium-sized enterprises. *J. Energy Resour. Technol. Trans. ASME* **2012**, *134*, 1–9, doi:10.1115/1.4006043.
9. Worrell, E.; Martin, N.; Price, L.; Ruth, M.; Elliott, N.; Shipley, A.M.; Thorn, J. Emerging energy-efficient technologies for industry. *Energy Eng.* **2002**, *99*, 36–55, doi:10.1080/01998590209509345.
10. European Commission. *Reference Document on Best Available Techniques for Energy Efficiency;* European Commission: Bruxelles, Belgium, 2009; pp. 430.
11. Nehler, T. Linking energy efficiency measures in industrial compressed air systems with non-energy benefits—A review. *Renew. Sustain. Energy Rev.* **2018**, *89*, 72–87, doi:10.1016/j.rser.2018.02.018.
12. Fleiter, T.; Fehrenbach, D.; Worrell, E.; Eichhammer, W. Energy efficiency in the German pulp and paper industry—A model-based assessment of saving potentials. *Energy* **2012**, *40*, 84–99, doi:10.1016/j.energy.2012.02.025.
13. Russell, C.H. Energy management pathfinding: Understanding manufacturers' ability and desire to implement energy efficiency. *Strateg. Plan. Energy Environ* **2009**, *25*, 20–54, doi:10.1080/10485230509509690.
14. Wheeler, G.M.; Bessey, E.G.; McGill, R.D.; Vischer, K. Compressed air system audit software. Proceedings of the ACEEE Summer Study on Energy Efficiency in Industry, New York, USA, 1997; 343-353.
15. International Energy Agency IEA. *Energy Efficiency 2O18—Analysis and outlooks to 2040; Market Report Series*; OECD/IEA: Paris, France, 2018; pp.174.
16. Weber, L. Some reflections on barriers to the efficient use of energy. *Energy Policy* **1997**, *25*, 833–835.
17. Backlund, S.; Thollander, P.; Palm, J.; Ottosson, M. Extending the energy efficiency gap. *Energy Policy* **2012**, *51*, 392–396, doi:10.1016/j.enpol.2012.08.042.
18. Trianni, A.; Cagno, E.; Farnè, S. An empirical investigation of barriers, drivers and practices for energy efficiency in primary metals manufacturing SMEs. Proceedings of the 6th International Conference on Applied Energy, Taipei, Taiwan, 30 May–2 June 2014; *61*, 1252–1255, doi:10.1016/j.egypro.2014.11.1071.
19. Cagno, E.; Trianni, A.; Spallina, G.; Marchesani, F. Drivers for energy efficiency and their effect on barriers: Empirical evidence from Italian manufacturing enterprises. *Energy Effic.* **2017**, *10*, 855–869, doi:10.1007/s12053-016-9488-x.
20. Trianni, A.; Cagno, E.; Worrell, E.; Pugliese, G. Empirical investigation of energy efficiency barriers in Italian manufacturing SMEs. *Energy* **2013**, *49*, 444–458, doi:10.1016/j.energy.2012.10.012.
21. Johansson, I.; Mardan, N.; Cornelis, E.; Kimura, O.; Thollander, P. Designing policies and programmes for improved energy efficiency in industrial SMEs. *Energies* **2019**, *12*, 1338, doi:10.3390/en12071338.
22. Cagno, E.; Trianni, A. Evaluating the barriers to specific industrial energy efficiency measures: An exploratory study in small and medium-sized enterprises. *J. Clean. Prod.* **2014**, *82*, 70–83, doi:10.1016/j.jclepro.2014.06.057.
23. Trianni, A.; Cagno, E.; Farné, S. Barriers, drivers and decision-making process for industrial energy efficiency: A broad study among manufacturing small and medium-sized enterprises. *Appl. Energy* **2016**, *162*, 1537–1551, doi:10.1016/j.apenergy.2015.02.078.

24. Sorrell, S.; Mallett, A.; Nye, S. *Barriers to Industrial Energy Efficiency: A Literature Review*; United Nations Industrial Development Organization: Vienna, Austria, 2011; pp.98.
25. DeCanio, S.J. Barriers within firms to energy-efficient investments. *Energy Policy* **1993**, *21*, 906–914, doi:10.1016/0301-4215(93)90178-I.
26. Fleiter, T.; Hirzel, S.; Worrell, E. The characteristics of energy-efficiency measures - a neglected dimension. *Energy Policy* **2012**, *51*, 502–513, doi:10.1016/j.enpol.2012.08.054.
27. Nehler, T.; Parra, R.; Thollander, P. Implementation of energy efficiency measures in compressed air systems: Barriers, drivers and non-energy benefits. *Energy Effic.* **2018**, *11*, 1281–1302, doi:10.1007/s12053-018-9647-3.
28. Unger, M.; Radger, P. Energy Efficiency in Compressed Air Systems – A review of energy efficiency potentials, technological development, energy policy actions and future importance. Proceedings of the 10th International Conference on Energy Efficiency in Motor Driven Systems, Rome, Italy, 6-8 September 2017; 207–233.
29. U.S. Department of Energy. *Improving Compressed Air System Performance. A Sourcebook for Industry*; U.S. Department of Energy: Washington, DC, USA, 2003; pp.128.
30. Barbieri, D.; Jacobson, D. Operations and maintenance in the glass container industry. Proceedings of the 3rd ACEEE Summer Study on Energy Efficiency in Industry: Industry and Innovation in the 21st Century, New York, USA, 15-18 June 1999; 655–665.
31. Muller, M.R.; Pasi, S.; Baber, K.; Landis, S. *Industrial Assessment Center—Assessment Recommendation Code*; U.S. Department of Energy: Washington, DC, USA, 2019; pp.44.
32. Cagno, E.; Trucco, P.; Trianni, A.; Sala, G. Quick-E-scan: A methodology for the energy scan of SMEs. *Energy* **2010**, *35*, 1916–1926, doi:10.1016/j.energy.2010.01.003.
33. Harris, P.; Nolan, S.; O'Donnell, G.E. Energy optimisation of pneumatic actuator systems in manufacturing. *J. Clean. Prod.* **2014**, *72*, 35–45, doi:10.1016/j.jclepro.2014.03.011.
34. Beyene, A. Energy efficiency and industrial classification. *Energy Eng.* **2005**, *102*, 59–80, doi:10.1080/01998590509509426.
35. Kaya, D.; Phelan, P.; Chau, D.; Sarac, H.I. Energy conservation in compressed-air systems. *Int. J. Energy Res.* **2002**, *26*, 837–849, doi:10.1002/er.823.
36. Heat Recovery and Compressed Air Systems. Available online: https://www.airbestpractices.com/technology/air-compressors/heat-recovery-and-compressed-air-systems (accessed 31 July 2020).
37. Inlet Air Temperature Impacts on Air Compressor Performance. Available online: https://www.airbestpractices.com/system-assessments/compressor-controls/inlet-air-temperature-impacts-air-compressor-performance (accessed on 31 July 2020).
38. Ming, H.C. Experimental Investigation of Inlet Air Temperature on Input Power in an Oil-Flooded Rotary Screw Air Compressor. M.Sc Thesis, The University of Alabama, Tuscaloosa, AL, USA, 2015.
39. Saidur, R.; Rahim, N.A.; Hasanuzzaman, M. A review on compressed-air energy use and energy savings. *Renew. Sustain. Energy Rev.* **2010**, *14*, 1135–1153, doi:10.1016/j.rser.2009.11.013.
40. Saidur, R.; Mekhilef, S. Energy use, energy savings and emission analysis in the Malaysian rubber producing industries. *Appl. Energy* **2010**, *87*, 2746–2758, doi:10.1016/j.apenergy.2009.12.018.
41. Zhang, Y.; Cai, M.; Kong, D. Overall energy efficiency of lubricant-injected rotary screw compressors and aftercoolers. Proceedings of the Asia Pacific Power and Energy Engineering Conference, Wuhan, China, 28-31 March 2009; 1-5, doi:10.1109/APPEEC.2009.4918581.
42. Dindorf, R. Estimating potential energy savings in compressed air systems. Proceedings of the XIIIth International Scientific and Engineering Conference on Hermetic Sealing, Vibration Reliability and Ecological Safety of Pump and Compressor Machinery, Sumy, Ukraine, 6–9 September 2011; *39*, 204–211, doi:10.1016/j.proeng.2012.07.026.
43. Alavi, S.; Alavi, S.; Gholami, S. Investigation of compression power in a three-stage centrifugal compressor by thermodynamic modeling and neural network modeling algorithm. *Indian J.Sci.Res.* **2014**, *1*, 866–879.
44. La, T. Don't Let Compressed Air Blow Away Your Profits. *Energy Eng.* **2013**, *111*, 7–15, doi:10.1080/01998595.2013.10769725.
45. Terrell, R.E. Improving compressed air system efficiency—Know what you really need. *Energy Eng.* **1999**, *96*, 7–15, doi:10.1080/01998595.1999.10530444.

46. Energy Savings Result from Compressed Air Dryer Selection. Available online: https://www.airbestpractices.com/technology/air-treatment/n2/energy-savings-result-compressed-air-dryer-selection (accessed 31 July 2020).
47. Marshall, R.C. Optimization of Single-unit Compressed Air Systems. *10 Energy Eng.* **2012**, *109*, 10–35, doi:10.1080/01998595.2012.1043657.
48. Neale, J.R.; Kamp, P.J.J. Compressed air system best practice programmes: What needs to change to secure long-term energy savings for New Zealand? *Energy Policy* **2009**, *37*, 3400–3408, doi:10.1016/j.enpol.2009.04.047.
49. Gordon, F.; Peters, J.; Harris, J.; Scales, B. Why is the treasure still buried? Breaching the barriers to compressed air system efficiency. Proceedings of the 3rd ACEEE Summer Study on Energy Efficiency in Industry: Industry and Innovation in the 21st Century, New York, USA, 15–18 June 1999; 709–718.
50. Scot Foss, R. Optimizing the compressed air system. *Energy Eng.* **2005**, *102*, 49–60, doi:10.1080/01998590509509419.
51. Yang, M. Air compressor efficiency in a Vietnamese enterprise. *Energy Policy* **2009**, *37*, 2327–2337, doi:10.1016/j.enpol.2009.02.019.
52. Anderson, K.J.; Collins, B.; Cortese, A.; Ekman, A. Summary of Results for Six Industrial Market Transformation Projects. Funded by the Northwest Energy Efficiency Alliance. Proceedings of the ACEEE Summer Study on Energy Efficiency in Industry, New York, USA, 24-27 July 2001; *1*, 255–266.
53. Carbon Trust. *Variable speed drives. Introducing energy saving opportunities for business*; The Carbon Trust: London, UK, 2011; p 27. Available online: https://www.academia.edu/15350420/Variable_speed_drives_Introducing_energy_saving_opportunities_for_business_Technology_guide (accessed 23 September 2020).
54. De Almeida, A.T.; Ferreira, F.J.T.E.; Fonseca, P.; Chretien, B.; Falkner, H.; Reichert, J.C.C.; West, M.; Nielsen, S.B.; Both, D. *VSDs for Electric Motor Systems*; European Commission: Bruxelles, Belgium, 2000; pp. 109. Available online: https://silo.tips/download/vsds-for-electric-motor-systems (accessed 23 September 2020).
55. Barringer, F.L.; Woodbury, K.A.; Middleton, B. *Efficiency improvements for compressed air systems*. SAE International: Troy, USA, 2012, pp. 9, doi:10.4271/2012-01-0327.
56. AlQdah, K.S. Prospects of energy savings in the national meat processing factory. *Int. J. Sustain. Energy* **2013**, *32*, 670–681, doi:10.1080/14786451.2013.790035.
57. Galvão, J.; Moreira, L.; Leitão, S.; Silva, É.; Neto, M. Sustainable energy for plastic industry plant. Proceedings of the 4th International Youth Conference on Energy, Siófok, Hungary, 6–8 June 2013; doi:10.1109/IYCE.2013.6604193.
58. Widayati, E.; Nuzahar, H. Compressed Air System Optimization: Case Study Food Industry in Indonesia. Proceedings of the International Conference on Engineering and Technology for Sustainable Development, Yogyakarta, Indonesia, 11–12 November 2015; *105*, doi:10.1088/1757-899X/105/1/012018.
59. Abdelaziz, E.A.; Saidur, R.; Mekhilef, S. A review on energy saving strategies in industrial sector. *Renew. Sustain. Energy Rev.* **2011**, *15*, 150–168, doi:10.1016/j.rser.2010.09.003.
60. Šešlija, D.; Ignjatovi, I.; Dudi, S.; Lagod, B. Potential energy savings in compressed air systems in Serbia. *Afr. J. Bus. Manag.* **2011**, *5*, 5637–5645, doi:10.5897/AJBM10.1340.
61. Energy efficiency best practice program. *Compressing Air Costs. Good Practice Guide N126*, 1th ed.; 1997; pp. 51. Available online: http://air-safe.org.uk/pdf/carbontrust/GPG126.pdf (accessed Jul 31, 2020).
62. L.Capehart, B.; C.Turner, W.; J.Kennedy, W. *Guide to Energy Management, 7*th ed.; The Fairmont Press: Lilburn, GA, USA, 2012; pp. 659, ISBN 0881736724.
63. Akbaba, M. Energy conservation by using energy efficient electric motors. *Appl. Energy* **1999**, *64*, 149–158, doi:10.1016/S0306-2619(99)00051-3.
64. How to size and select an air compressor. Available online: https://www.quincycompressor.com/images/pdf/how to size and select an air compressor.pdf (accessed on 31 July 2020).
65. Rotary screw air compressor basics. Available online: https://www.plantengineering.com/articles/rotary-screw-air-compressor-basics/ (accessed on 31 July 2020).
66. Petracca, G. *Energy conversion and management. Principles and Applications*; Springer: Berlin/Heidelberg, Germany, 2016; pp. 356.
67. Air Compressor Guide. Available online: https://www.air-compressor-guide.com/articles/the-air-compressor-inlet-filter-more-important-than-you-think/ (accessed 23 September 2020).
68. U.S. Department of Energy. *DOE Assessment of the Market for Compressed Air Efficiency Services*; U.S. Department of Energy: Washington, DC, USA, 2001; pp. 63.

69. CEA Technologies Inc. *(CEATI) Compressed Air. Energy Efficiency Reference Guide*; CEA Technologies Inc.: Fyshwick, Australia, 2007; pp.118.
70. D'Antonio, M.; Epstein, G.; Bergeron, P. Compressed air load reduction approaches and innovations. Proceedings of the ACEEE Summer Study on Energy Efficiency in Industry, New York, USA, 24–27 July 2001; *2*, 317–327.
71. Technical Brief on Pressure Loss. Available online: https://cagi.org/news/assets/PressureLossTechnicalBrief.pdf (accessed 31 July 2020).
72. ATLAS COPCO. *Compressed Air Manual*; ATLAS COPCO: Wilrijk, Belgium, 2015; pp.146, ISBN 9789081535809.
73. OEM machine design. Pneumatics: Sizing Demand Users. Available online: https://www.airbestpractices.com/system-assessments/end-uses/oem-machine-design (accessed 31 July 2020).
74. Systems Approach Cuts Fabric Mill Energy Costs. Available online: https://www.airbestpractices.com/system-assessments/end-uses/systems-approach-cuts-fabric-mill-energy-costs (accessed 31 July 2020).
75. A Kroger Company Bakery Saves Energy. Available online: https://www.airbestpractices.com/technology/blowers/kroger-company-bakery-saves-energy (accessed 31 July 2020).
76. Compressed air versus blowers—The Real Truth. Available online: http://2015pdfs.s3.amazonaws.com/Nexflow Air/compressed_air_vs_blowers.pdf (accessed 31 July 2020).
77. Food Industry Factory Saves $154,000 in Annual Energy Costs. Available online: https://www.airbestpractices.com/system-assessments/vacuum/blowers/food-industry-factory-saves-154000-annual-energy-costs (accessed 31 July 2020).
78. Laouar, S.; Molodtsof, Y. Experimental characterization of the pressure drop in dense phase pneumatic transport at very low velocity. *Powder Technol.* **1998**, *95*, 165–173, doi:10.1016/S0032-5910(97)03338-X.
79. Pump or Venturi? Available online: https://fluidpowerjournal.com/pump-or-venturi/ (accessed 31 July 2020).
80. Seslija, D.; Milenkovic, I.M.; Dudic, S.P.; Sulc, J.I. Improving energy efficiency in compressed air systems - practical experiences. *Therm. Sci.* **2016**, *20*, 22-22, doi:10.2298/TSCI151110022S.
81. Bottler Best Practices in California. Available online: https://www.airbestpractices.com/industries/plastics/bottler-best-practices-california (accessed 31 July 2020).
82. U.S. Department of Energy. *Industrial Technologies Program. Eliminate Inappropriate Uses of Compressed Air*; U.S. Department of Energy: Washington, DC, 2004; pp.2. DOE/GO-102004-1963. Available online: https://iac.tamu.edu/files/doe/2_-_Inappropriate_Uses.pdf (accessed 23 September 2020).
83. Reduce energy costs in compressed air systems by up to 60%. Available online: https://www.festo.com/net/SupportPortal/Files/300860/WhitePaper_EnergySavingServices_EN.pdf (accessed 23 September 2020)
84. Are Compressed Air Leaks Worth Fixing? Available online: https://www.airbestpractices.com/system-assessments/leaks/are-compressed-air-leaks-worth-fixing (accessed on 23 September 2020).
85. U.S. Department of Energy. I*ndustrial Technologies Program Minimize Compressed Air Leaks*; U.S. Department of Energy: Washington, DC, 2004; pp. 2. DOE/GO-102004-1964. Available online: https://www.energy.gov/sites/prod/files/2014/05/f16/compressed_air3.pdf (accessed 23 September 2020).
86. Specifying an Air Compressor Cooling System. Available online: https://www.airbestpractices.com/technology/cooling-systems/specifying-air-compressor-cooling-system (accessed 31 July 2020).
87. Control Panel Cooling Change Saves Compressed Air Electrical Costs. Available online: https://www.airbestpractices.com/technology/cooling-systems/control-panel-cooling-change-saves-compressed-air-electrical-costs (accessed 31 July 2020).
88. Calculating the Water Costs of Water-Cooled Air Compressors. Available online: https://www.airbestpractices.com/technology/air-compressors/calculating-water-costs-water-cooled-air-compressors-part-1 (accessed 31 July 2020).
89. Turning Air Compressors into an Energy Source. Available online: https://www.kaeser-knowhow.co.nz/turn-your-compressors-into-an-energy-source-with-heat-recovery/ (accessed 24 September 2020).
90. Carbon Trust. *How to Recover Heat from a Compressed Air System*; The Carbon Trust: London, UK; pp. 4. Available online: https://www.carbontrust.com/?id=GPG238 (accessed 23 September 2020).
91. Recupero del Calore dall'Aria Compressa: Quanto Conviene. Available online: http://www.progettoenergiaefficiente.it/recupero-del-calore-dallaria-compressa-quanto-conviene/ (accessed 31 July 2020).

92. Hepke, J.; Weber, J. Energy saving measures on pneumatic drive systems. Proceedings of the 13th Scandinavian International Conference on Fluid Power, Linköping, Sweden, 3–5 June 2013; 475–483, doi:10.3384/ecp1392a47.
93. Gryboś, D.; Leszczyski, J.S. Implementation of Energy Harvesting System of Wastes of Compressed Air Wastes for Electrical Steel Cutting Line. Proceedings of the E3S Web of Conference - Energy and fuel, Krakow, Poland, 19–21 September 2018; *108*, doi:10.1051/e3sconf/201910801005.
94. Cummins, J.J.; Nash, C.J.; Thomas, S.; Justice, A.; Mahadevan, S.; Adams, D.E.; Barth, E.J. Energy conservation in industrial pneumatics: A state model for predicting energetic savings using a novel pneumatic strain energy accumulator. *Appl. Energy* **2017**, *198*, 239–249, doi:10.1016/j.apenergy.2017.04.036.
95. Ferraresi, C.; Franco, W.; Quaglia, G.; Scopesi, M. Energy Saving in Pneumatic Drives: An Experimental Analysis. In Proceedings of the 9th International Workshop on Research and Education in Mechatronics, Bergamo, Italy, 18–19 September 2008.
96. Trujillo, A. Energy Efficiency of High Pressure Pneumatic Systems. Ph.D. Thesis, Polytechnic University of Catalonia, Barcelona, Spain, 2015.
97. Leszczynski, J.S.; Kastelik, K.; Kaminski, R.; Tomasiak, B.; Grybos, D.; Olszewski, M.; Plewa, A.; Mermer, P.; Rygal, R.; Soinski, M. Some harvesting system transforming energy wastes of compressed air to electricity. Proceedings of the E3S Web of Conference - Energy and fuel, Krakow, Poland, 21–23 September 2016; *14*, doi:10.1051/e3sconf/20171401036.
98. Doll, M.; Neumann, R.; Sawodny, O. Energy efficient use of compressed air in pneumatic drive systems for motion tasks. Proceedings of the 2011 International Conference on Fluid Power and Mechatronics, Beijing China, 17–20 August 2011; 340–345, doi:10.1109/FPM.2011.6045785.
99. Rogers, E.M. *Diffusion of Innovation*, 3rd ed.; Collier Macmillan Publishers: New York, NY, USA, 1983; pp. 512.
100. Tornatzky, L.G.; Klein, K.J. Innovation Characteristics and Innovation Adoption- Implementation : A Meta-Analysis of Findings. *IEEE Trans. Eng. Manag.* **1982**, *29*, 28–45, doi:10.1109/TEM.1982.6447463.
101. Roberts, S.J.F.; Ball, P.D. Developing a library of sustainable manufacturing practices. Proceedings of the 5th CIRP Conference on Assembly Technologies and Systems, Dresden, Germany, 13–14 November 2014; *15*, 159–164, doi:10.1016/j.procir.2014.06.054.
102. Mills, E.; Rosenfelds, A.R.T. Consumer non-energy benefits as a motivation for making energy-efficiency improvements. *Energy* **1996**, *21*, 707–720. doi.org/10.1016/0360-5442(96)00005-9.
103. Skumatz, L.A.; Gardner, J. Methods and results for measuring non-energy benefits in the commercial and industrial sectors. Proceedings of the ACEEE Summer Study on Energy Efficiency in Industry: Cutting the High Cost of Energy. West Point, New York, 2005; *6*, 163–176.
104. Piette, M.A.; Nordman, B. Costs and Benefits from Utility- Funded Commissioning of Energy- Efficiency Measures in 16 Buildings. Proceedings of the ASHRAE Winter Meeting, Atlanta, GA, USA, 17–21 February 1996.
105. Worrell, E.; Laitner, J.A.; Ruth, M.; Finman, H. Productivity benefits of industrial energy efficiency measures. *Energy* **2003**, *28*, 1081–1098, doi:10.1016/S0360-5442(03)00091-4.
106. Lung, R.B.; Mckane, A.; Leach, R.; Marsh, D. Ancillary Savings and Production Benefits in the Evaluation of Industrial Energy Efficiency Measures. Proceedings of the *ACEEE* Summer Study on Energy Efficiency in Industry: Cutting the High Cost of Energy. West Point, New York, 2005; *6*, 103–114.
107. Nehler, T.; Rasmussen, J. How do firms consider non-energy benefits? Empirical findings on energy efficiency investments in Swedish industry. *J. Clean. Prod.* **2016**, *113*, 472–482, doi:10.1016/j.jclepro.2015.11.070.
108. Hall, N.; Roth, J. Non-Energy Benefits from Commercial & Industrial Programs: What Are the Benefits and Why Are They Important to Participants? In Proceedings of the ACEEE Summer Study on Energy Efficiency in Buildings: Breaking out of the box. 2004; *4*, 123-135.
109. Lilly, P.; Pearson, D. Determining the full value of industrial efficiency programs. Proceedings of the 3rd ACEEE Summer Study on Energy Efficiency in Industry: Industry and Innovation in the 21st Century, New York, USA, 15–18 June 1999; 349–362.
110. Doyle, F.; Cosgrove, J. An approach to optimising compressed air systems in production operations. *Int. J. Ambient Energy* **2018**, *39*, 194–201, doi:10.1080/01430750.2016.1269685.

111. Sustainability Victoria. *Energy efficiency Best Practice Guide. Compressed Air Systems*. Sustainability Victoria: Melbourne, Australia, 2009; pp. 27. Available online: https://www.sustainability.vic.gov.au/Business/Energy-efficiency-for-business/Business-energy-efficiency/Energy-efficiency-best-practice-guidelines (accessed 23 September 2020).
112. Finman, H.; Laitner, J.A. Industry, Energy Efficiency and Productivity Improvement. Proceedings of the ACEEE Summer Study on Energy Efficiency in Industry, New York, USA, 24–27 July 2001; *1*, 561–570.
113. Pye, M.; McKane, A. Making a stronger case for industrial energy efficiency by quantifying non-energy benefits. *Resour. Conserv. Recycl.* **2000**, *28*, 171–183, doi:10.1016/S0921-3449(99)00042-7.
114. Skumatz, L.A.; Dickerson, C.A.; Coates, B. Non-energy benefits in the residential and non-residential sectors: Innovative measurements and results for participant benefits. Proceedings of the ACEEE Summer Study on Energy Efficiency in Buildings: Energy Efficiency & Sustainability, Pacific Grove, CA, USA, 17-21 August 2000; *8*, 353–364.
115. Parra, R.; Thollander, P.; Nehler, T. Barriers to, drivers for and non-energy benefits for industrial energy efficiency improvement measures in compressed air systems. Proceedings of the *E*ceee Industrial Summer Study: Going beyond energy efficiency to deliver savings, competitiveness and a circular economy, Berlin, Germany, 12–14 September 2016; *2*, 293–304.
116. Rasmussen, J. The additional benefits of energy efficiency investments—A systematic literature review and a framework for categorisation. *Energy Effic.* **2017**, *10*, 1401–1418, doi:10.1007/s12053-017-9528-1.
117. Cagno, E.; Moschetta, D.; Trianni, A. Only non-energy benefits when adopting an EEM? Cases from industry. Proceedings of the *E*ceee Industrial Summer Study: Going beyond energy efficiency to deliver savings, competitiveness and a circular economy, Berlin, Germany, 12–14 September 2016; *2*, 281-292.
118. Thollander, P.; Ottosson, M. Energy management practices in Swedish energy-intensive industries. *J. Clean. Prod.* **2010**, *18*, 1125–1133, doi:10.1016/j.jclepro.2010.04.011.
119. Kemp, R.; Volpi, M. The diffusion of clean technologies: A review with suggestions for future diffusion analysis. *J. Clean. Prod.* **2008**, *16S1*, S14–S21, doi:10.1016/j.jclepro.2007.10.019.
120. Cagno, E.; Worrell, E.; Trianni, A.; Pugliese, G. A novel approach for barriers to industrial energy efficiency. *Renew. Sustain. Energy Rev.* **2013**, *19*, 290–308, doi:10.1016/j.rser.2012.11.007.
121. Millar, H.H.; Russell, S.N. The adoption of sustainable manufacturing practices in the Caribbean. *Bus. Strateg. Environ.* **2011**, *20*, 512–526, doi:10.1002/bse.707.
122. Damanpour, F. Innovation type, radicalness, and the adoption process. *Communic. Res.* **1988**, *15*, 545–567, doi:10.1177%2F009365088015005003.
123. Dahlin, K.B.; Behrens, D.M. When is an invention really radical? Defining and measuring technological radicalness. *Res. Policy* **2005**, *34*, 717–737, doi:10.1016/j.respol.2005.03.009.
124. Sandberg, P.; Soderstrom, M. Industrial energy efficiency: The need for investment decision support from a manager perspective. *Energy Policy* **2003**, *31*, 1623–1634, doi:10.1016/S0301-4215(02)00228-8.
125. Thollander, P.; Palm, J. *Improving Energy Efficiency in Industrial Energy Systems. An Interdisciplinary Perspective on Barriers, Energy Audits, Energy Management, Policies and Programs*; Springer: Berlin/Heidelberg, Germany, 2013; pp. 151. ISBN 144714161X.
126. Hellström, T. Dimensions of Environmentally Sustainable Innovation: The Structure of Eco-Innovation Concepts. *Sustain. Dev.* **2007**, *15*, 148–159, doi:10.1002/sd.309.
127. Request for Proposals: Resource Assessment, Emerging Technology, Measure Characterization. Available online: https://www.energytrust.org/wp-content/uploads/2017/08/Resource-Assessment-Emerging-Technologies-RFP-FINAL.pdf (accessed 31 July 2020).
128. Arensberg, C.M.; Niehoff, A.H. Introducing Social Change: A Manual for American Overseas. *Science* **1968**, *147*, 500, doi:10.1126/science.147.3661.1027-a.
129. Designing your compressed air system. How to determine the system you need. Available online: https://pdf.directindustry.com/pdf/kaeser-compressors/designing-your-compressed-air-system-guide-3/68092-177031.html (accessed 31 July 2020).
130. Pascual, R.; Meruane, V.; Rey, P.A. On the effect of downtime costs and budget constraint on preventive and replacement policies. *Reliab. Eng. Syst. Saf.* **2008**, *93*, 144–151, doi:10.1016/j.ress.2006.12.002.
131. Cagno, E.; Moschetta, D.; Trianni, A. Only non-energy benefits from the adoption of energy efficiency measures? A novel framework. *J. Clean. Prod.* **2019**, *212*, 1319–1333, doi:10.1016/j.jclepro.2018.12.049.
132. The Ins and Outs of Vacuum Generators. Available online: https://www.airbestpractices.com/technology/vacuum/ins-and-outs-vacuum-generators (accessed 31 July 2020).

133. Health and Safety Executive, HSE. *Compressed Air Safety* (HSG39), *2nd edition.*; HSE: Bootle, UK, **1998**; pp. 50. Available online: https://www.hse.gov.uk/pubns/books/hsg39.htm (accessed 23 September 2020).
134. Technical Brief - Sizing Compressed Air Equipment. Available online: https://www.cagi.org/pdfs/Sizing-Technical-Brief-Final.pdf (accessed 31 July 2020).
135. Sorrell, S.; Schleich, J.; Scott, S.; O'Malley, E.; Trace, F.; Bode, U.; Kowener, D.; Mannsbart, W.; Ostertag, K.; Radgen, P. *Reducing Barriers to Energy Efficiency in Private and Public Organisations*; Science Policy Research Unit SPRU: University of Sussex, Falmer, UK, 2000; p 197.
136. Worrell, E.; Biermans, G. Move over! Stock turnover, retrofit and industrial energy efficiency. *Energy Policy* **2005**, *33*, 949–962, doi:10.1016/j.enpol.2003.10.017.
137. Matasniemi, T. *Operational Decision Making in the Process Industry. Multidisciplinary Approach*; VTT Technical Research Centre of Finland: Espoo, Finland, 2008; pp. 143.
138. Yin, R. *Case Study Research: Design and Methods*, 5th ed.; Sage: London, UK, 2014; pp. 219.
139. Voss, C.; Tsikriktsis, N.; Frohlich, M. Case research in operations management. *Int. J. Oper. Prod. Manag.* **2002**, *22*, 195–219, doi:10.1108/01443570210414329.
140. Eisenhardt, K.M.; Graebner, M.E. Theory building from cases: Opportunities and challenges. *Acad. Manag. J.* **2007**, *50*, 25–32.
141. Trianni, A.; Cagno, E.; Bertolotti, M.; Thollander, P.; Andersson, E. Energy management: A practice-based assessment model. *Appl. Energy* **2019**, *235*, 1614–1636, doi:10.1016/j.apenergy.2018.11.032.
142. Industrial Assessment Center (IAC) Database. Available online: https://iac.university/download (accessed 23 August 2020).
143. U.S. Department of Energy. *Effect of Intake on Compressor Performance*; U.S. Department of Energy: Washington, DC, USA, 2004; pp.2. DOE/GO-102004-1933.
144. Testing and Troubleshooting Drain Traps on Compressed Air Systems, 1996; Available online: https://www.armstronginternational.com/sites/default/files/resources/documents/testingandtrouble-shootingdraintrapsoncompressedairsystems11-96.pdf (accessed 23 September 2020).
145. Compressed Air Dryer Efficiency. 2015. Available online: https://fluidpowerjournal.com/compressed-air-dryer-efficiency/ (Accessed 23 September 2020)
146. Cycling Refrigerated Air Dryers—Are Savings Significant? Available online: https://www.compressedair-challenge.org/data/sites/1/media/library/articles/2011-11-CABP.pdf (accessed 31 July 2020).
147. Seven Rules for Improving the Quality of Compressed Air. Available online: https://www.hydraulicspneumatics.com/technologies/air-filters-and-frls/article/21883468/seven-rules-for-improving-the-quality-of-compressed-air (accessed 31 July 2020).
148. Reliable Operation of High Purity Desiccant Compressed Air Dryers. Available online: https://www.airbestpractices.com/technology/air-treatment/n2/reliable-operation-high-purity-desiccant-compressed-air-dryers (accessed 31 July 2020).
149. Controls increase compressor efficiency. Available online: https://www.plantengineering.com/articles/controls-increase-compressor-efficiency/ (accessed 31 July 2020).
150. Qin, H.; McKane, A. *Improving Energy Efficiency of Compressed Air System Based on System Audit*; Lawrence Berkeley National Laboratory: Berkeley, CA, USA, 2008; pp. 10. Available online: https://escholarship.org/uc/item/13w7f2fc (accessed 23 September 2020).
151. Neelis, N; Worrell, E.; Masanet, E.R. *Energy Efficiency Improvement and Cost Saving Opportunities for the Petrochemical Industry*; Lawrence Berkeley National Laboratory: Berkeley, CA, USA, 2008; pp. 151.Available online: https://ies.lbl.gov/publications/energy-efficiency-improvement-and-8 (accessed 23 September 2020).
152. Compressed Air System Design, 2016. Available online: https://compressedair.net.au/wp-content/uploads/2016/02/003_CAAA_Fact-Sheet-Copy_Compressed-Air-System-Design_290416.pdf (accessed 23 September 2020)
153. U.S. Department of Energy. *Evaluation of the compressed air challenge training program.*; U.S. Department of Energy: Washington, DC, USA, 2004; pp. 98. DOE/GO-102004-1919. Available online: https://www.energy.gov/sites/prod/files/2014/05/f16/eval_cactp_cd.pdf (accessed 23 September 2020).
154. Compressed Air Versus Blower Systems. Available online: https://www.stanmech.com/articles/compressed-air-versus-blower-systems (accessed 31 July 2020).

155. Optimize a Compressed Air System with Highly Fluctuating Air Demand. Available online: https://www.airbestpractices.com/system-assessments/end-uses/optimize-compressed-air-system-highly-fluctuating-air-demand (accessed 31 July 2020).
156. Bernard, H.R. *Research Methods in Anthropology: Qualitative and Quantitative Approaches*, 4th ed; Rowman Altamira; Lanham, MD, 2006; pp. 680. ISBN 0759108692, 9780759108691.
157. Evaluating Air Compressor Cooling System. Available online: https://www.airbestpractices.com/sustainability-projects/cooling-systems/evaluating-air-compressor-cooling-systems (accessed 31 July 2020).
158. U.S. Department of Energy. *Maintenance of Compressed Air Systems for Peak Performance*; U.S. Department of Energy: Washington, DC, USA, 1998; pp. 3.
159. Air Compressors—Care & Maintenance Tips, 2009. Available online: https://www.mobil.com.de/de-de/industrial/lubricant-expertise/resources/air-compressor-maintenance-tips (accessed 23 September 2020).
160. Vortex A/C. Available online: https://www.vortextube.co.uk/pdf/Vortex-AC-VT.pdf (accessed 31 July 2020).
161. European Commission. *Observatory of European SMEs Analytical Report*; European Commission: Bruxelles, Belgium, 2007; pp. 267.
162. Trianni, A.; Cagno, E. Dealing with barriers to energy efficiency and SMEs: Some empirical evidences. *Energy* **2012**, *37*, 494–504, doi:10.1016/j.energy.2011.11.005.
163. Cooremans, C. Investment in energy efficiency: Do the characteristics of investments matter? *Energy Effic.* **2012**, *5*, 497–518, doi:10.1007/s12053-012-9154-x.
164. Nehler, T.; Thollander, P.; Ottosson, M.; Dahlgren, M. Including non-energy benefits in investment calculations in industry—Empirical findings from Sweden. Proceedings of the Eceee Industrial Summer Study: Retool for a competitive and sustainable industry, Arnhem, the Netherlands, 2-5 June 2014; *2*, 711–719.
165. Skumatz, L.A. *Non-Energy Benefits/Non-Energy Impacts (NEBs/NEIs) and their Role & values in Cost-Effectiveness Tests: State of Maryland*; Skumatz Economic Research Associates, Inc: Superior, CO, USA, 2014; p. 71. Available online: https://www.energyefficiencyforall.org/resources/non-energy-benefits-non-energy-impacts-nebs-neis-and-their-role-and-values/ (accessed 23 September 2020)

© 2020 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/).