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Energy-Saving Technology Opportunities and Investments of the Italian Foundry Industry

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Abstract: The foundry industry is regarded as one of the most energy-intensive industrial sector due to its energy consumption up to 9 MWh/ton of produced metal. As a result, many companies are trying to increase the energy efficiency of their foundry plants. Since many energy-saving technologies are proposed by manufacturers and the literature, choosing the most appropriate one is a difficult task. Moreover, being updated with the available energy-saving solutions is complicated because of the quick technology advances. Consequently, this paper aims at investigating the recent and future opportunities and investments for reducing the energy consumptions of the technologies of Italian foundry companies. Additionally, it aims at presenting a list of available technological solutions validated by Italian experts. To this end, the Energy Audits developed by 231 plants were analyzed to extract the implemented and planned interventions. Furthermore, the economic data available within the Energy Audits were studied to determine the advantages of a given technological solutions compared to the others. It emerged that the companies are strongly investing in increasing the efficiency of the auxiliary systems such as compressors and motors. The outcomes of this study can assist both researchers and energy managers in choosing the most appropriate energy-saving solutions.

Keywords: energy-saving technologies; foundry manufacturing plant; Italian overview; energy efficiency improvements

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1. Introduction

The foundry industry is among the most energy demanding industrial sectors [1] because of its energy consumption that can reach 9 MWh/ton of metal produced [2]. Indeed, the energy cost of a typical foundry plant could cover up to 7% of the total operating costs [3] and up to 15% of the added value [4]. Given the foregoing considerations, along with the introduction of new legislations [5], the importance of energy management in the foundry plants have been progressively cleared up [6]. This fundamental vision has driven the foundry companies to implement more sustainable and energy efficient solutions.

To attain a higher efficiency, it is possible to either adopt new managerial policies or replace existing old technologies with more modern and energy-saving ones [7]. Particularly, the adoption of innovative technologies could help reducing the cost of production, while coping with the rising energy cost [8]. Considering the foundry process, it is possible to act on a technological level in one of the four main phases, which are: melting, molding, casting, and finishing [9,10]. Technological improvements on auxiliary systems (e.g., compressors or motors) and heat recovery systems (e.g., installation of a Rankine turbine) are viable options as well.

Even though the foundry process could vary based on the kind of metal, which could be ferrous or nonferrous, and depending on company policies, there is a common backbone for all the processes. Indeed, the metal is melted by a furnace, which could be an electric or a fuel furnace. The melting phase is the most energy-intensive phase of the foundry process since it accounts for 70% of the total energy consumption [11]. Specifically, the energy consumption of an electric furnace is between 500 and 700 kWh/ton of metal melted, while the energy consumption related to a furnace fueled by coke is in the range of 90–120 kg/ton of metal melted [12]. With regards to the fuel furnace, the adopted fuel could be coke or methane, which is the most common for nonferrous metals. In parallel with the melting phase, the foundry process is characterized by the molding phase, which consists in the preparation of the molds. A mold is the negative of the realized pieces, and it could include cores to create cavities. Moreover, a mold could be made by sand, or it could be permanent. In case sand molding is adopted, a distinct mold must be created for each produced piece. The materials composing a sand mold are usually silica, olivine sand, and sodium silica, along with other substances such as red mud and blast furnace slag [13]. By contrary, a permanent mold could be used for multiple pieces. Indeed, the mold is made out of metal, and it can be coated with graphite or TO_2-based coatings [14]. Downstream the melting and molding phase, the casting phase occurs. The molten metal is poured into the mold, where it solidifies through the heat exchange with the colder mold. For a sand mold, the molten metal is poured through gravity, while, for a permanent mold, a die-casting or a centrifugal casting could also be adopted to let the metal spread within the mold. During this phase, the melted metal must fill all the mold cavity without creating any holes that would be present in the final product. Finally, the solidified metal is extracted from the mold, and it is sent to the finishing phase, which is tasked with the removal of all the risers, feeders, burrs, and superficial sand inclusion, along with improving the surface roughness. The finishing phase could also include thermal or chemical treatments. A schematic representation of the four main phases characterizing the foundry process is illustrated in Figure 1.

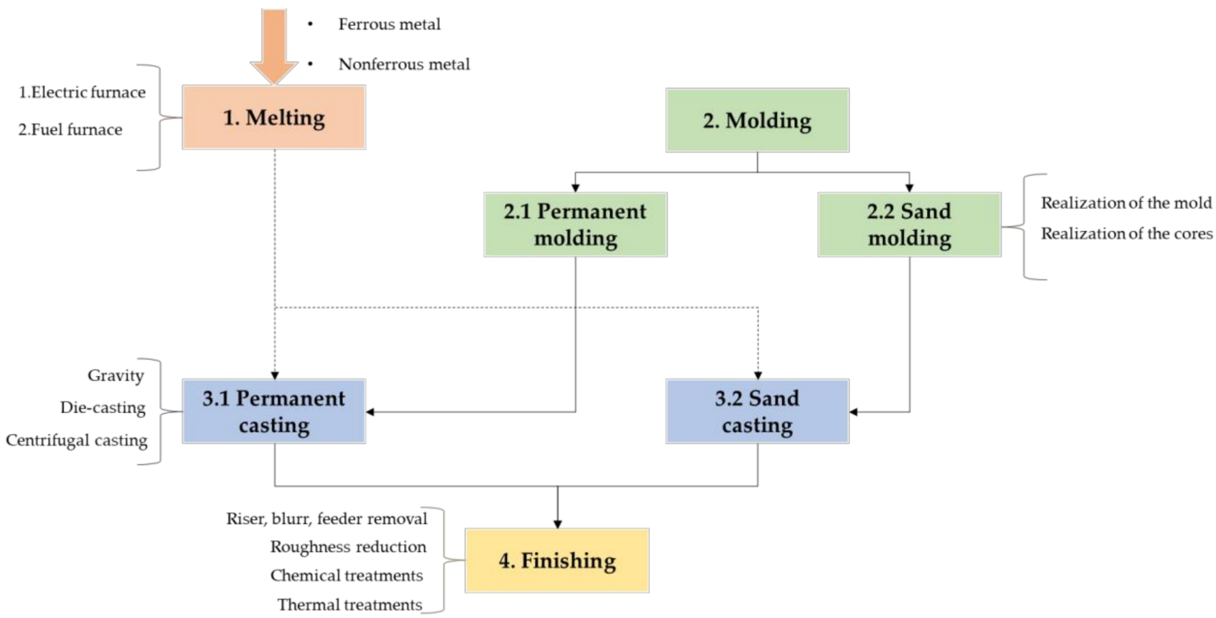

Figure 1. Main phases of the foundry production process.

Within the context of the foundry industry, the reference document to pursue a greater energy efficiency is the Best Available Techniques Reference Documents (BREFs) related to metal foundry [12]. The BREFs are documents realized by the European Union with the aim to provide a guideline for improving energy efficiency. In addition to the BREFs, several energy-efficient technological solutions are reported in the literature. For instance, technologies related to the molding and casting phase could be found in References [15–19], respectively. Specifically, the application of additive manufacturing in the foundry process is found in References [15–17].

Since reaching a higher degree of energy efficiency and environmental sustainability have become crucial requirements, there are several works on this topic for the foundry and the iron and steel industries of distinct countries. Relevant examples were Reference [20] for the foundry industry of India, while References [21–27] were related to the iron and steel industries of China, Mexico, and Taiwan, respectively. Similar studies have been conducted for the Italian foundry industry as well [1,28,29]. Both References [1,29] presented energy efficiency opportunities extracted from the analysis of Energy Audits (EAs), reporting information related to the adopted technologies, along with some relevant energy consumption data. Specifically, both of the aforementioned works underline how energy recovery could be accounted as a difficult task in a foundry plant but nevertheless, if possible, may lead to a 20% energy saving. Installing recuperative burners was also described as an effective energy-saving technology. Reference [28] was also based on an extensive analysis on the EAs of five foundry plants; however, it was more focused on auxiliary systems such as lightening, compressors, pumps, and electric motors.

Despite many researchers have been focusing their efforts on the improvements of energy consumption of energy-intensive processes, industrial technology is constantly developing [30]; thus, keeping up with the technological advances could be regarded as a tough task. Accordingly, some technologies could become obsolete and the available technological solutions for energy-saving purposes should be continuously updated. Moreover, there could be a gap between the technologies proposed by the literature and the technologies that the companies are currently investing on. In this context, this paper aims to provide an overview of the current Italian scenario and near future developments related to technological energy-saving opportunities and investments in the foundry industry, leading to an update of previous studies. Moreover, this work tries to determine the economic reasons that drive the companies towards a given solution instead of other viable options. The data required for the present study are extracted from the EAs of 231 distinct Italian foundry manufacturing sites, carried out by companies in the foundry sector to comply with Article 8 of Legislative Decree 102/2014, Italian implementation of the Energy Efficiency Directive (EED) 2012/27/EU. Indeed, consulting companies working on the field is a common practice to gather useful information and relevant feedbacks [31], along with obtaining an overview of the real situation. Finally, compared to previous similar research carried out for the Italian foundry industry [1,28,29], the present study exploits a higher number of Eas, assuring a much consistent sample. Furthermore, the same studies were mainly focused on presenting the available technologies along with some cost and energy-saving data, while an extensive analysis of all the planned and implemented interventions is neglected. This last aspect is fundamental to grasp the past and future investment trends.

It is worth mentioning that only the technological solutions are considered within this study, while the managerial solutions are disregarded. Moreover, this work does not account for the solution related to lightning, installation of sensors, and heating of the offices. By contrary, technological solutions related to heat recovery systems and auxiliary systems are considered for their pivotal role within a foundry plant. Moreover, even though the terms intervention and solution could be regarded as synonyms, the first is used for referring to something that has been implemented or planned by an Italian company, while the latter is a general word that identifies something that has been found in the literature or in the EAs.

The remainder of the present paper is organized as follows. Section 2 defines the steps of the methodology and describes the available data. Section 3 describes the obtained results related to the analysis. Subsequently, Section 4 provides a discussion on the results, and finally, in Section 5, the conclusions are presented.

2. Materials and Methods

The main objective of the present study is to investigate the actual trend of opportunities and investments in energy-saving technologies related to the Italian foundry industry. Indeed, the foundry industry is regarded as a highly energy-intensive sector; therefore, reducing energy consumption is a pivotal task to assure a sustainable and forward-looking management of the production process.

2.1. Background

In October 2012, the EED was published by the European Parliament and Council with the purpose of reaching 20% energy savings before 2020 [32]. The EED reports several legal obligations that the large companies (all companies that are not considered as small and medium enterprises) must follow to fulfill the required energy efficiency increase. Within the developed framework, Article 8 obliges the affected enterprises to produce EAs. As stated by Cantini et al. [31], an EA is a systematic document that is required to assess the current energy consumption profile and evaluate future energy-saving investments. In Italy, the EAs are collected by an agency named ENEA (Italian National Agency for New Technologies, Energy, and the Sustainable Economic Development), which is tasked with the management and control of the application of the EED's framework on Italian soil. The EAs are uploaded by the companies on the ENEA Audit 102 portal (https://audit102.enea.it/, accessed on 23 December 2019). In Italy, not only large companies but also energy-intensive enterprises are subject to the EA obligation. Energy-intensive companies are those that consume more than 1 GWh of electricity per year, that have tax relief on the electricity bill, and that are registered in the Environmental Energy Services Fund (CSEA) lists.

The EAs, which were received by ENEA in December 2019 (first expiry of the second cycle of mandatory diagnoses after 2015), contain a lot of interesting information, such as the plant location, the plant type, the type of adopted raw material, and the type of finished products manufactured by the companies. However, for the actual work, the most useful information regarded the interventions implemented by the Italian companies between 2015 and 2019, and the interventions that the companies planned to realize between 2019 and 2022. Indeed, the listed energy-saving solutions are essential to define an overview of the Italian most common opportunities and investments to limit energy consumption in the foundry sector.

To pursue the objective of the present paper, three main phases are identified as described by the following subsections.

2.2. Available Technological Solutions for Energy-Saving Purposes

At first, a literature screening on the technologies adopted by the foundry industry is conducted. Then, the obtained list is integrated with the implemented in the last five years and planned interventions found in the EAs. This activity is of prominent importance to define a comprehensive list of possible energy-saving solutions through the integration of real company information and academic studies. Subsequently, the developed list was shared with the experts of the Italian Foundry Trade Association (Assofond) to obtain valuable comments on the applicability of the listed technological solutions. To consider expert observations, the list of detected technologies was presented to the experts during a brainstorming session. The technological solutions were screened one by one and when an expert determined as necessary to add an observation, a discussion started until a common opinion by all the experts was reached. Accordingly, the developed lists of technological opportunities and investments represent a synthetic, yet useful, tool to facilitate companies in choosing appropriate energy-saving solutions.

2.3. Analysis of the Implemented and Planned Interventions in Italy

Within the context of Italian EAs, a given intervention could be proposed by more companies. Thus, to grasp a better understanding of the Italian foundry sector, the frequencies of the energy-saving technologies extracted through the EAs are estimated. Indeed, the adoption of relevant statistical parameters is pivotal to point out the most popular interventions, along with determining possible past and future trends. Denoting by *SD*, the total number of manufacturing sites that produced the EA and the frequencies of the implemented and planned interventions are computed through Equations (1) and (2), respectively.

$$f_{i,\,i} = \frac{n_{i,i}}{SD}, \tag{1}$$

$$f_{p,\,i} = \frac{n_{p,i}}{SD}, \tag{2}$$

where $n_{i,i}$ identifies the number of companies that implemented the *i*th intervention between 2015 and 2019, while $n_{p,i}$ denotes the number of companies that proposed the *i*th intervention as a future development. Finally, $f_{i,\,i}$ and $f_{p,\,i}$ represents the frequency of implementation and planning associated with the *i*th intervention.

It is worth mentioning that the foundry process could be characterized by an electric or by a fuel furnace. Moreover, the casting phase could occur through the adoption of a permanent or a sand mold. Accordingly, some of the detected interventions could have some applicability limitations. For instance, some technologies could be related to the permanent mold casting; thus, they cannot be adopted by a plant that exploits sand casting. In light of this, new frequencies are defined to get a more truthful and accurate description of the Italian foundry industry. Particularly, given an intervention extracted from the EAs, the new frequencies consider as a sample the number of plants where the aforementioned intervention is implementable (i.e., just a portion of the original sample). Consequently, the more truthful frequencies of the implemented and planned interventions are estimated through Equations (3) and (4), respectively.

$$f_{relevant\_i,\,i} = \frac{n_{i,i}}{reference\_SD}, \tag{3}$$

$$f_{relevant\_p,\,i} = \frac{n_{p,i}}{reference\_SD}, \tag{4}$$

where $n_{i,i}$ and $n_{p,i}$ still identify the number of companies that, respectively, implemented and planned the *i*th intervention, while $reference\_SD$ is the reduced sample size representing all the companies that could adopt the *i*th intervention. Finally, $f_{relevant\_i,\,i}$ and $f_{relevant\_p,\,i}$ denote the new frequencies related to the implementation and the planning.

The estimated frequencies could be useful to detect a trend and underline the most popular interventions in the Italian foundry industry, but they are not sufficient to justify whether an intervention is better than another one.

2.4. Quantitative Economic Analysis of the Gathered Eneregy Saving Interventions

Some of the EAs included data regarding cost, energy savings, and payback period related to the most relevant interventions. Thus, these data were collected and analyzed to determine the reasons that led the companies to adopt a specific energy-saving solution rather than others. Compared to Section 2.2, this phase allows to analyze the adopted interventions from an economic point of view, considering both the investment cost and the expected energy savings associated with each considered intervention. Specifically, a cost-effectiveness indicator is estimated as illustrated by Equation (5)

$$cost - effectiveness\ indicator = \frac{Euro\ invested\ [€]}{\text{Ton of Oil Equivalent (toe)of energy saved [ton]}}, \tag{5}$$

3. Results

The EAs were provided by 231 different manufacturing sites scattered around all Italy, with a higher density in the Lombardy Region with a total amount of 104 plants (see Figure 2). Moreover, the northern regions contain 204 sites, while 22 sites belong to the central regions, and finally, just 5 plants are located in the South of Italy. Finally, 23% of the 231 plants are considered as big enterprises, while the remaining ones are regarded as small and medium enterprises. All 231 plants are required to procure an EA.

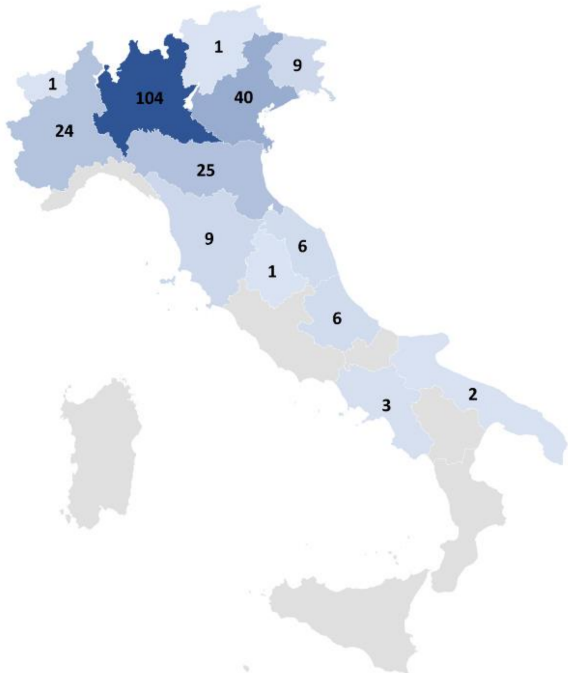

Figure 2. Geographical distribution of the 231 Italian foundry plants constituting the investigated sample.

Considering the Nomenclature of Economic Activities (NACE), the analyzed manufacturing processes comprehend the following class: (i) Casting of iron (NACE code 24.51), (ii) Casting of steel (NACE code 24.52), (iii) Casting of light material (NACE code 24.53), and (iv) Casting of non-iron ferrous material (NACE code 24.54). However, a coarser classification has been adopted for the present study by distinguish between ferrous metal casting and nonferrous metal casting, which can be identified, respectively, by the first two and the last two NACE codes.

By analyzing the 231 EAs, it emerged that 89 manufacturing sites work with ferrous metal (mainly cast iron), while 134 plants are devoted to nonferrous metal casting (mainly aluminum). Finally, seven plants realize artifacts with both ferrous and nonferrous metals. A summary of the aforementioned classification is reported by Table 1.

Table 1. Types of casted metal of the 231 manufacturing sites.

Type of Casted Metal	Manufacturing Sites	Percentage of the Sample
Ferrous	89	39%
Nonferrous	134	58%
Both	7	3%

As previously mentioned, a foundry plant could work with an electric or a fuel furnace based on management policies and choices. Accordingly, the 231 plants were classified based on the exploited type of furnace as well. It was found that 78 foundry sites operate with an electric furnace, while a fuel furnace is adopted by 132 processes. The remaining 21 sites comprehend both an electric and a gas furnace. These findings are listed by Table 2. It is worth mentioning that the analyzed steel foundries adopt only electric furnace, while 60% of the cast-iron production sites exploit an electric furnace. Half of the remaining cast-iron plants (20%) use a coke furnace, while the other half are characterized by a gas furnace. Finally, the majority of nonferrous manufacturing sites have a gas furnace.

Table 2. Types of adopted furnace by the 231 manufacturing sites.

Type of Furnace	Manufacturing Sites	Percentage of the Sample
Electric	78	33.8%
Fuel	132	57.1%
Both	21	9.1%

Finally, the last division has been identified between sites that adopt permanent casting and sites that use sand casting. Particularly, among the 231 production plants, 130 exploit permanent casting, while 91 have implemented side casting. Additionally, 10 manufacturing processes includes both permanent and side casting, as revealed by Table 3.

Table 3. Types of adopted casting by the 231 manufacturing sites.

Type of Casting	Manufacturing Sites	Percentage of the Sample
Permanent	130	56.3%
Sand	91	39.4%
Both	10	4.3%

It is worth mentioning that there is a great difference between a sand casting and a permanent casting process. Indeed, a sand mold is less expensive than a permanent mold, but it is needed to realize a new mold for each produced piece. By contrary, the investment cost related to a permanent mold is higher, but it leads to higher productivity and less finishing requirements of the casted products.

3.1. List of Energy-Saving Technologies Obtained through the Literature and EAs

A literature review was conducted to obtain a preliminary list of available technologies related to the foundry sector. Next, to provide a broader overview of the technologies that could be adopted, the implemented and planned interventions extrapolated from the EAs were integrated with the available literature. Finally, to validate the obtained output, the list of technologies was screened by two foundry experts who provided precious observations regarding the applicability of some technological solutions, along with eliminating unnecessary solutions and adding relevant ones. The two experts that took part in the process belong to the staff of the Italian foundry association and have, respectively, more than 20 and 30 years of experience.

The detected technological solutions were divided by process phases to make them more user-friendly and understandable. As an example, in Table 4, the technologies found for the melting phase are listed, while the tables related to the other phases are reported in Appendix A. In each table, the third column refers to the solution that can be implemented to improve a specific process stage, while the first and the second columns, respectively, identify the machinery and the object associated with the technological solution. Moreover, each technology found in the literature is accompanied by the related bibliographic references (fifth column), while the experts' comments are listed in the sixth column. Finally, the technological alternatives found in the Eas are reported in italics. Therefore, there could be three different types of technologies:

1. Technologies that are reported in italics and characterized by one or more bibliographic references. These technologies are found both in the literature and in the Eas.
2. Technologies that are reported in black. These technologies are only found in the literature
3. Technologies that are reported in italics and characterized by no bibliographic reference. These technologies are only found in the Eas.

To make a meaningful difference an energy hierarchy that specifies the energy approach was introduced in the fourth column. Specifically, the energy hierarchy is based on three levels similarly to what were done by Reference [33], where seven levels were used. The different energy approaches and their hierarchy are as follows:

1. Innovation: introduce a completely new technology for a part of the process or that is tasked with something that was not done before.
2. Replace: replacing a given technology with a more efficient and/or modern ones. Compared to the previous level, it introduces less changes.
3. Recover: recover thermal or electric energy.
4. Resource: change the source of energy.

Table 4. Technological energy-saving solutions for melting obtained from both the literature and Eas.

Melting					
Process Machinery	**Solution Object**	**Energy-Saving Approach**	**Energy-Saving Technological Solution**	**Reference**	**Comments from Sector Experts**
Furnace feeders	Furnace feeders	Recover	*Preheating the row material through the exhaust fumes*	[34,35]	This solution was very common in the past, but it is now less popular due to the high costs. It could be interesting in case the exhaust gas is adopted to preheat the scrap before entry the furnace.
Furnace	Burners	Innovation	*Installing recuperative burners*	[36]	
Furnace	Burners	Innovation	Installing low NO_x burners to reduce the emission	[34]	
Furnace	Burners	Replace	*Replacing the existing burners with more modern and efficient ones*	[34]	
Furnace	Burners	Innovation	*Installing regenerative burners*	[34]	
Furnace	Burners	Innovation	Installing oxy-fuel burners	[37,38]	This solution is mandatory and it is adopted in all the cast iron plants with rotating furnaces.
Furnace	Burners	Innovation	Installing a combustor for a no flame combustion	[34,38]	
Furnace	Furnace	Replace	*Replacing the existing furnace with a more modern and efficient one*	[34]	
Furnace	Furnace	Innovation	*Adopting IGBT technology for electric furnace*	[39]	
Furnace	Furnace	Innovation	Installing Ultra High Power transformer to increase the voltage of the electric arc furnace	[8]	Few companies adopt this solution, which is typical of steel foundry process characterized by smaller furnaces compared to steel production. It should be evaluated if this intervention could be convenient in a foundry plant since the furnace size and its degree of utilization are different compared to the iron and steel industry.
Furnace	Furnace	Re-source	Installing Oxy-oil technology to exploit oil as fuel and reducing the consumption of coke along with the emission	[8]	There is no similar application in Italy
Furnace	Furnace	Replace	Installing an efficient water-cooled furnace	[27]	A water-cooling system is already present.

Table 4. *Cont.*

Melting					
Process Machinery	**Solution Object**	**Energy-Saving Approach**	**Energy-Saving Technological Solution**	**Reference**	**Comments from Sector Experts**
Furnace	Furnace	Replace	*Replacing the refractory material of the furnace with a new one to reduce the heat dispersion*	[27,40]	Increasing the thickness of the refractory material leads to a reduction of the furnace production capacity, even though it assists in reducing the energy consumption. Moreover, increasing the thickness of the refractory material causes less space available for the raw material.
Furnace	Furnace	Innovation	Installing Electron Beam Furnace	[35]	
Furnace	Furnace	Innovation	Installing Solar Furnace	[35]	
Furnace	Furnace	Innovation	Installing Plasma Furnace	[35]	
Furnace	Furnace	Innovation	Installing Immersion Heaters	[35]	
Furnace	Furnace	Innovation	Installing Microwave melting technology	[35]	
Furnace	Recovery system	Innovation	Installing machines to recover metal from slag	[41]	Slag is usually selected depending on the furnace type; thus, its chemical composition is known.
Furnace	Pneumatic powder injector	Innovation	Installing a pneumatic injector to send to the furnace the dust trapped within the air filters	[42]	It leads to higher energy consumption and slag production. It assists in decreasing the environmental impact.
Furnace	Pneumatic injector lance	Innovation	*Installing a pneumatic injector lance to blow away the slag from the combustion area*	[42]	This solution inerts the slag, leading to a reduction of environmental impact. However, it could increase the energy consumption.

3.2. Frequencies of the Interventions Extracted from the Eas

After extracting the implemented and planned interventions from the Eas, the frequencies associated with each intervention was computed as explained in Section 2.3. The results of the calculation are shown in Table 5, where an italic intervention represents an intervention that is found only in the Eas.

Table 5. Number of companies that implement and plan a given intervention, along with its associated frequencies.

Process Stage	**Intervention Object**	**Energy-Saving Approach**	**Intervention**	$n_{i,i}$	$n_{p,i}$	$f_{i,i}$	$f_{p,i}$	$f_{relevant\_i,i}$	$f_{relevant\_p,i}$
Melting	Furnace feeders	Recover	Preheating the row material through the exhaust fumes	2	2	0.0087	0.0087	0.0087	0.0087
Melting	Burners	Innovation	Installing recuperative burners	0	7	0	0.0303	0	0.046
Melting	Burners	Replace	Replacing the existing burners with more modern and efficient ones	0	1	0	0.0043	0	0.0065
Melting	Burners	Innovation	Installing regenerative burners	0	1	0	0.0043	0	0.0065
Melting	Furnace	Replace	Replacing the existing furnace with a more modern and efficient one	6	11	0.026	0.048	0.026	0.048
Melting	Furnace	Innovation	Adopting IGBT technology for electric furnace	0	1	0	0.0043	0	0.01

Table 5. *Cont.*

Process Stage	Intervention Object	Energy-Saving Approach	Intervention	$n_{i,i}$	$n_{p,i}$	$f_{i,i}$	$f_{p,i}$	$f_{relevant\_i,i}$	$f_{relevant\_p,i}$
Melting	Furnace	Replace	Replacing the refractory material of the furnace with a new one to reduce the heat dispersion	2	1	0.0087	0.0043	0.013	0.0065
Melting	Pneumatic injector lance	Innovation	Installing a pneumatic injector lance to blow away the slag from the combustion area	0	1	0	0.0043	0	0.0043
Molding	Sand recovery system	Re-source	*Replacing the electric sand recovery system with a gas one*	0	1	0	0.0043	0	0.0099
Molding	Sand recovery system	Innovation	*Installing a sand recovery system*	1	0	0.0043	0	0.0099	0
Molding	Molding station	Replace	*Replacing the molding stations with more efficient ones*	1	0	0.0043	0	0.0099	0
Molding	Mixer	Replace	*Replacing the mixing systems with a more efficient one*	2	0	0.0087	0	0.02	0
Molding	"Hot box" molding	Innovation	Installing a pre-heating system or regenerative or recuperative burners for the furnace tasked with the production of the sand mold	1	0	0.0043	0	0.0099	0
Molding	Molding machinery	Innovation	*Installing low-pressure casting machine capable of using inorganic cores*	0	1	0	0.0043	0	0.0099
Molding	Molding machinery	Replace	*Installing an efficient filter for the sand molding process*	0	1	0	0.0043	0	0.0099
Molding	Molding machinery	Replace	Replacing the existing machinery with newer and more efficient ones	1	0	0.0043	0	0.0099	0
Casting	Casting furnace	Replace	*Replacing the casting furnace with a more efficient and newer one*	1	0	0.0043	0	0.0043	0
Casting	Cooling system	Innovation	*Installing a forced ventilation cooling system*	1	0	0.0043	0	0.0071	0
Casting	Casting machinery	Replace	Replacing the casting machineries with more efficient and newer ones	4	2	0.017	0.0087	0.029	0.014
Casting	Die-casting machinery	Replace	*Replacing the furnace where the cast waits to be poured in the mold with a more efficient and newer one*	2	3	0.0087	0.013	0.014	0.021
Casting	Die-casting machinery	Replace	*Installing a new efficient die-casting line*	0	3	0	0.0043	0	0.0099
Casting	Sand removal machinery	Replace	Replacing the machinery in charge of the sand removal process with more efficient and newer ones	1	0	0.0043	0	0.0043	0
Casting	Ladle	Innovation	Installing machines capable of scheduling an efficient preheat of the ladle	0	1	0	0.043	0	0.043
Finishing	Finishing station	Replace	*Installing a new efficient finishing line*	2	0	0.0087	0	0.0087	0
Finishing	Finishing station	Replace	*Installing high efficiency nozzles*	0	1	0	0.0043	0	0.0043
Finishing	Finishing station	Replace	Replacing old finishing machineries with more efficient and modern ones	2	1	0.0087	0.0043	0.0087	0.0043
Finishing	Heat Treatment Furnace	Replace	*Replacing the heat electric furnace with a more efficient and modern one*	0	1	0	0.0043	0	0.0043
Auxiliary Systems	Compressors	Replace	Replacing the compressor with more modern and efficient ones	21	33	0.091	0.14	0.091	0.14
Auxiliary Systems	Compressors	Innovation	Installing variable speed compressors (i.e., compressor with inverter)	0	3	0	0.013	0	0.013

Table 5. *Cont.*

Process Stage	Intervention Object	Energy-Saving Approach	Intervention	$n_{i,i}$	$n_{p,i}$	$f_{i,i}$	$f_{p,i}$	$f_{relevant\_i,i}$	$f_{relevant\_p,i}$
Auxiliary Systems	Pressure Systems	Innovation	Replacing all the equipment for pressurized air distribution with electric devices (if possible)	1	0	0.0043	0	0.0043	0
Auxiliary Systems	Suction Systems	Replace	Installing high efficiency fans	1	6	0.0043	0.026	0.0043	0.026
Auxiliary Systems	Suction Systems	Innovation	Installing variable speed fans (i.e., fans with inverter)	1	3	0.0043	0.013	0.0043	0.013
Auxiliary Systems	Suction Systems	Innovation	*Installing a forced air suction system for the furnace*	1	0	0.0043	0	0.0043	0
Auxiliary Systems	Forklifts	Replace	Replacing the forklifts with more efficient and modern ones	0	1	0	0.0043	0	0.0043
Auxiliary Systems	Forklits' Batteries	Replace	Replacing the batteries of the forklifts	0	2	0	0.0087	0	0.0087
Auxiliary Systems	Transport Systems	Replace	*Replacing conveyor belts with more efficient and modern ones*	1	0	0.0043	0	0.0043	0
Auxiliary Systems	Transport Systems	Innovation	Installing high efficiency belt and replace V-belts with toothed belts	0	5	0	0.022	0	0.022
Auxiliary Systems	Transport Systems	Innovation	*Replacing V-belts with helicoidal belts*	0	1	0	0.0043	0	0.0043
Auxiliary Systems	Electric Transformers	Replace	*Replacing the electricity transformers with more efficient and modern ones*	1	5	0.0043	0.022	0.0043	0.022
Auxiliary Systems	Inverter	Innovation	Installing inverters on electric motors or replacing the inverters with more efficient and modern ones	11	56	0.048	0.24	0.048	0.24
Auxiliary Systems	Lift Truck	Replace	*Replacing the lift trucks with more efficient and modern ones*	0	1	0	0.0043	0	0.0043
Auxiliary Systems	Crane	Replace	*Replacing the cranes with more efficient and modern ones*	2	1	0.0087	0.0043	0.0087	0.0043
Auxiliary Systems	Passive filter	Innovation	Installing passive filters	0	10	0	0.043	0	0.043
Auxiliary Systems	Engines	Replace	Installing high efficiency electric motors (class IE2, IE3 and IE4)	3	56	0.013	0.24	0.013	0.24
Auxiliary Systems	Engines	Innovation	*Installing regenerative electric motors*	0	2	0	0.0087	0	0.0087
Auxiliary Systems	Engines	Replace	Rewinding electric motors	0	1	0	0.0043	0	0.0043
Auxiliary Systems	Engines	Innovation	Installing variable speed motors (i.e., motors with inverter)	0	2	0	0.0087	0	0.0087
Auxiliary Systems	Fluid Distribution System	Innovation	Optimize the pipelines' design leakage along with installing appropriate seal to minimize air leakage	3	66	0.013	0.29	0.013	0.29
Auxiliary Systems	Pumps	Replace	Replacing the pumps with more efficient and modern ones	2	3	0.0087	0.013	0.0087	0.013
Auxiliary Systems	Cooling Systems	Replace	*Replacing the cooling towers with more efficient and modern ones*	2	2	0.0087	0.0087	0.0087	0.0087
Heat Recovery Systems	Rankine turbine	Recover	Installing a Rankine turbine to generate electric energy through the exhaust gas	0	1	0	0.0043	0	0.0043
Heat Recovery Systems	ORC turbine	Recover	Installing a ORC turbine to generate electric energy through the exhaust gas	0	3	0	0.013	0	0.013
Heat Recovery Systems	Cogeneration	Recover	Installing cogeneration or trigeneration technologies	1	13	0.0043	0.0562	0.0043	0.056
Heat Recovery Systems	Refrigeration cycle	Recover	Installing technologies able to exploits the exhaust gas for a refrigeration cycle	0	1	0	0.0043	0	0.0043
Heat Recovery Systems	Battery	Replace	Replacing the batteries of the heat recovery systems	1	0	0.0043	0	0.0043	0

Table 5. *Cont.*

Process Stage	Intervention Object	Energy-Saving Approach	Intervention	$n_{i,i}$	$n_{p,i}$	$f_{i,i}$	$f_{p,i}$	$f_{relevant\_i,i}$	$f_{relevant\_p,i}$
Heat Recovery Systems	Evaporator	Recover	*Installing an evaporator to retrieve heat from the emulsified water*	1	0	0.0043	0	0.0043	0
Heat Recovery Systems	Sand drying system	Recover	*Installing technologies for the sand drying process*	1	0	0.0043	0	0.0043	0
Heat Recovery Systems	Exchanger	Recover	*Installing an exchanger to retrieve heat from the exhaust gas and generate hot water for the drier*	0	1	0	0.0043	0	0.0043
Heat Recovery Systems	Exchanger	Recover	*Installing an exchanger to retrieve heat from the compressors*	1	13	0.0043	0.056	0.0043	0.056
Heat Recovery Systems	Cooling system	Recover	*Installing a heat recovery system from the cooling process of the molds*	0	1	0	0.0043	0	0.0071
Heat Recovery Systems	Exchanger	Recover	*Installing an exchanger to retrieve heat and preheat the ladle*	0	4	0	0.017	0	0.017
		Total		84	336				

It is possible to state that the estimated frequencies provide a description about the adopted strategies to reduce energy consumption in the Italian foundry industry. Indeed, high values of $f_{relevant\_i,i}$ denote a common intervention exploited by the Italian companies in the last five years for energy-saving purposes. Indeed, since $f_{relevant\_i,i}$ represents the percentage of plants that implemented the ith intervention, the higher the value of $f_{relevant\_i,i}$, the more popular a given intervention has been during the past years. Moreover, $f_{relevant\_p,\ i}$ represents the portion of companies that are willing to adopt a certain technological intervention, giving a hint on possible future developments. Indeed, high values of $f_{relevant\_p,\ i}$ indicates an intervention that could be soon very popular since a high number of Italian foundry plants are planning to implement that intervention in the next future.

Figure 3 illustrates the number of interventions implemented and planned for each process phase, considering the auxiliary and the heat recovery systems as a separate phase.

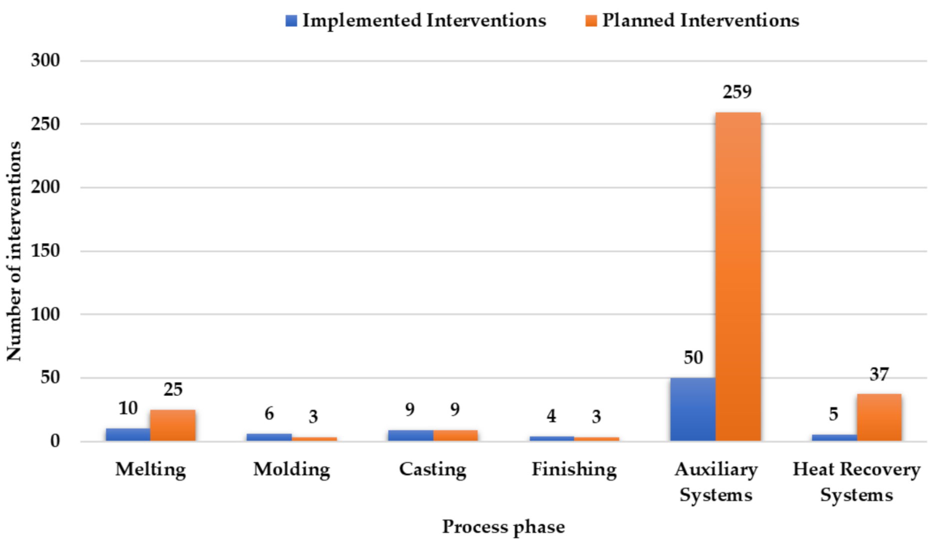

Figure 3. Number of implemented and planned interventions for each process phase.

It emerged that the companies prefer investing in auxiliary systems, which are characterized by 50 implemented interventions and 259 planned interventions. Accordingly, 59% of the implemented interventions and 77% of the planned interventions involve the auxiliary equipment. In contrast, less interest is devoted to the other process phases among which the heat recovery systems result the most considered one, with five implemented interventions and 37 planned interventions. Since the melting phase is the most energy-intensive, many efforts and investments are focused on it. Specifically, the melting phase has seen a total of 10 implemented interventions and 25 planned interventions. Finally, the finishing phase is the most neglected phase, since it is not relevant in all the manufacturing sites. For instance, the plants that adopt permanent mold casting are usually characterized by less effort on the finishing phase.

To illustrate even further the obtained results, the implemented and planned interventions for each intervention object related to the auxiliary systems, the heat recovery systems, and the melting phase are illustrated by Figures 4–6, respectively. Indeed, it is interesting to highlight the distributions of the interventions associated with the three most relevant "phases".

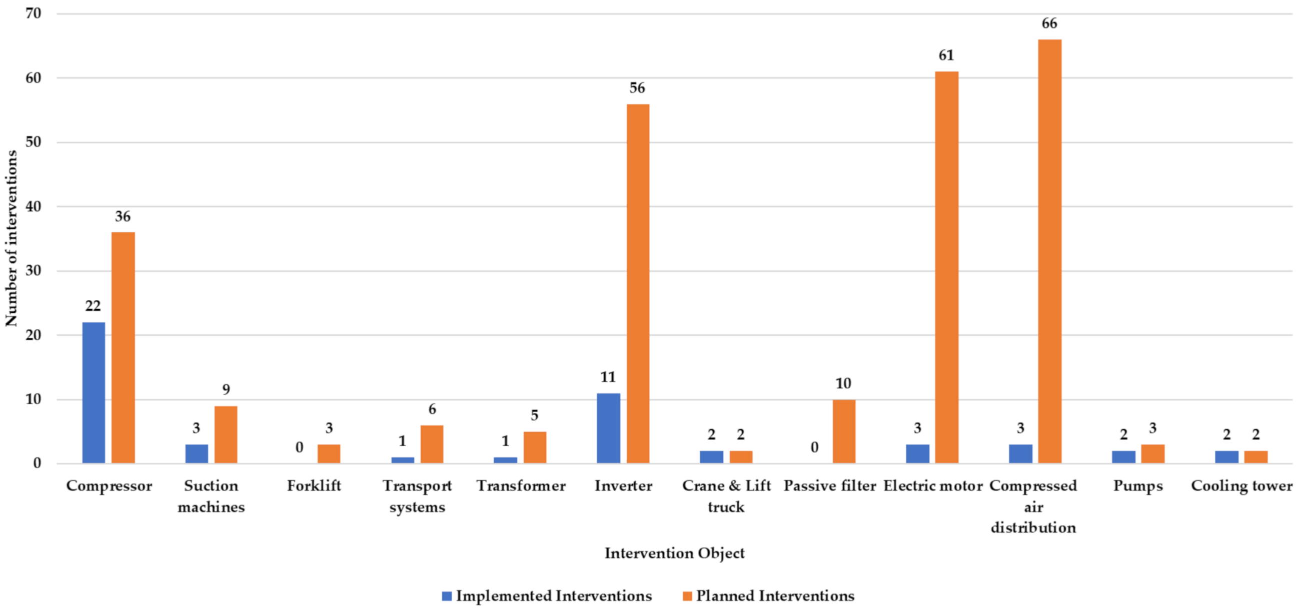

Figure 4. Number of implemented and planned interventions for the auxiliary systems.

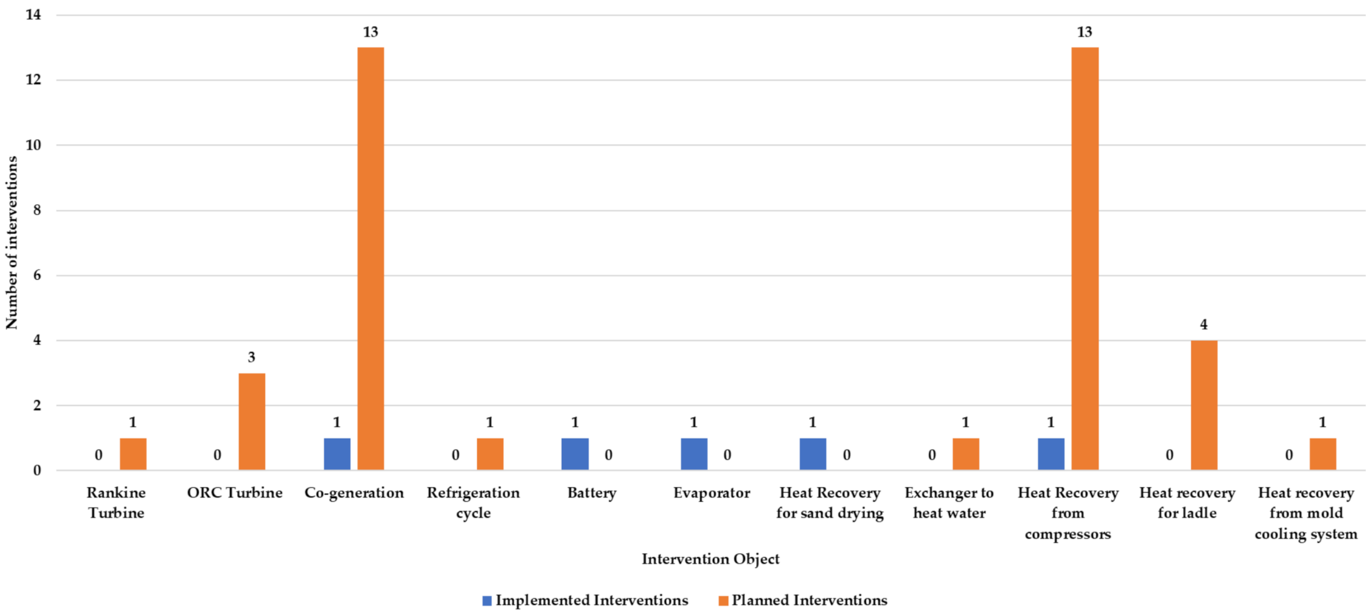

Figure 5. Number of implemented and planned interventions for the heat recovery systems.

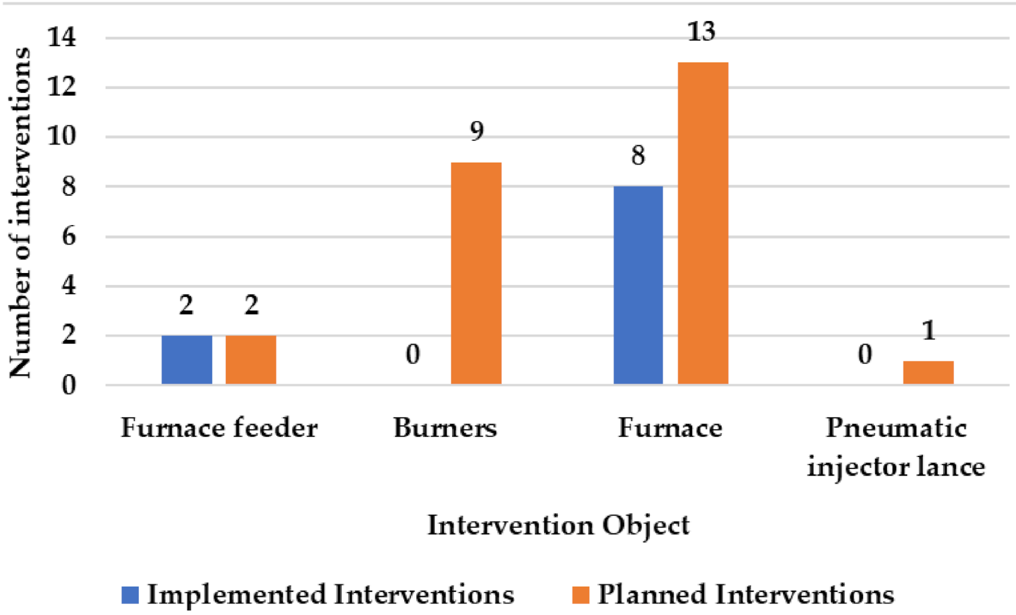

Figure 6. Number of implemented and planned interventions for the melting phase.

Considering the auxiliary systems, the most interventions were adopted for the compressors, which are characterized by 22 implemented interventions; among which, 21 interventions were regarded the replacement of old compressor with newer and more efficient ones (see Table 5). Indeed, the aforementioned intervention is associated with the highest $f_{relevant\_i,i}$, which is estimated at 0.09. This value identifies a trend of the implemented interventions, since almost 9% of the companies replaced the compressors between 2015 and 2019. Moreover, the replacement of compressors with more efficient ones has been planned by 33 enterprises, leading to a $f_{relevant\_p,i}$ equal to 0.14. Accordingly, this intervention is still regarded as one of the most beneficial. Finally, 56, 61, and 66 companies planned an intervention related to inverters, electric motors, and air distribution systems, respectively. Thus, it is expected to see an increase of the number of interventions associated with the three aforementioned intervention objects during the next years. Considering the inverters, 56 companies are willing to install new ones or replace the old ones, leading to a $f_{relevant\_p,i}$ of 0.24. However, the highest values of $f_{relevant\_p,i}$ are associated with the reduction of leaks in the air distribution systems (66 planned interventions) and the replacement of electric motors with more efficient ones (56 planned interventions). Indeed, the last two interventions yield a $f_{relevant\_p,i}$ of 0.29 and 0.24, respectively.

The heat recovery systems are mostly characterized by planned interventions; among which, the most popular one consists in installing a heat recovery system to retrieve heat from the compressor. This intervention is associated with a $f_{relevant\_p,i}$ equal to 0.056, which identifies the possibility that 6% of the companies will adopt this intervention during the next years. The installation of a cogeneration system could also become a common intervention during the next years, since it yields a $f_{relevant\_p,i}$ of 0.056 as well.

Finally, with regards to the melting phase, most of the implemented interventions is related to the furnace, which has seen eight interventions; among which, six interventions consisted of replacing the old furnace with a more efficient one, leading to a $f_{relevant\_i,i}$ of 0.026. Installing a more efficient furnace has also been planned by 11 companies, resulting in a $f_{relevant\_p,i}$ equal to 0.045.

3.3. Cost–Benefit Quantitative Analysis

Companies also reported quantitative data on the savings achieved by implementing technological interventions. A total of 84 implemented interventions with quantitative information were listed in the analyzed 231 EAs. Among them, the focus in this article is on technological areas of intervention related to the production process, auxiliary systems and heat recovery systems: they are summarized in Tables 6 and 7. In the tables, toe stands for ton of oil equivalent, and savings are in terms of final energy. (The column "Other savings" refers to a mix of electric and thermal savings for which the disaggregation in the two components was not available in the energy audit or to savings of other energy vectors.) Production lines determine large energy savings and the largest economic investments (both total and average). Interventions on electric or fuel furnaces are included in this area, coherently with the technological interventions shown in Table 7, and these are largely represented by replacing the existing furnace with a more modern and efficient one. Pressure systems are the second area both in terms of savings and total investment, whereas thermal power plant and heat recovery systems are the second area in terms of average investment. The average quantitative data shown in Tables 6 and 7 was computed as average of the number of production sites that reported quantitative information.

Table 6. Energy savings produced by the implemented technological interventions in the various areas of intervention. The total annual savings are calculated as the sum of thermal energy, electricity, and fuel savings.

Area of Intervention	Production Sites Reporting Quantitative Information	Electricity Savings (Toe/Year)	Thermal Energy Savings (Toe/Year)	Other Savings (Toe/Year)	Annual Savings (Toe/Year)	Annual Savings (%)	Average Annual Savings (Toe/Year)
Pressure systems	14	326	0	13	339	19%	24
Intake system	8	117	0	0	117	7%	15
Thermal power plant and heat recovery systems	3	0	59	44	103	6%	34
Engines, inverters, and other electrical installations	3	9	0	0	9	0%	3
Production lines and machines	14	348	258	610	1217	68%	87
Total	42	801	317	667	1784	100%	-

Table 7. Investments required to apply technological interventions in the various areas of intervention.

Area of Intervention	# Production Sites Reporting Quantitative Information	Total Investment (€)	Total Investment (%)	Average Investment (€)
Pressure systems	19	1,791,068	17%	94,267
Intake system	9	666,428	6%	74,487
Thermal power plant and heat recovery systems	3	615,500	6%	205,166
Engines, inverters, and other electrical installations	7	430,620	4%	71,770
Production lines and machines	20	7,347,956	68%	367,398
Total	58	10,851,572	100%	-

A cost-effectiveness indicator was calculated for each intervention, measured as Euros invested per Ton of Oil Equivalent (toe) of energy saved (see Table 8). The available information allowed to calculate it only on 11 interventions, reporting both information on energy saved and costs. The area of "Engines, inverters, and other electrical installations" shows an advantageous value of the indicator, confirming that this is a type of intervention with a large applicability, also in different industrial sectors.

Table 8. Cost-effectiveness indicator for each area of intervention.

Area of Intervention	Production Sites Reporting Quantitative Information	Cost-Effectiveness Indicator (€/toe)
Pressure systems	14	6821
Intake system	7	15,340
Thermal power plant and heat recovery systems	0	-
Engines, inverters, and other electrical installations	3	3101
Production lines and machines	11	13,900

A total of 840 planned interventions with quantitative information were identified in the EAs examined. For the purpose of this analysis, as already explained for implemented interventions, we disregard solutions related to areas of intervention not related to production process and auxiliary systems such as, for example, lighting, managerial interventions, and production from renewable sources. Tables 9 and 10 summarize the savings of final energy and investment cost indicated by those companies that proposed a feasibility study. Table 11 reports the cost-effectiveness indicators calculated for the planned interventions. Feasibility studies estimated electrical savings in all areas and thermal savings to be significant in "Thermal power plant and heat recovery systems" and "Production lines and machines" one. As in the applied interventions, also in the planned interventions the highest energy saving was associated with the production lines area, accompanied, however, by a significant investment cost (Table 10). This area shows a high cost-effectiveness indicator, and as shown in Table 4, most technological interventions are applied to furnaces; additionally, in this case, a furnace substitution represents a high share of interventions in this area. Thermal power plant and heat recovery systems have the best value of cost-effectiveness, followed by pressure systems (Table 11).

Table 9. Energy savings assessed for the planned technological interventions in the various areas of intervention. The total annual savings are calculated as the sum of thermal energy, electricity, and fuel savings.

Area of Intervention	Production Sites Reporting Quantitative Information	Annual Electricity Savings (Toe/Year)	Annual Thermal Energy Savings (Toe/Year)	Other Savings (Toe/Year)	Annual Savings (Toe/Year)	Annual Savings (%)	Average Annual Savings (Toe/Year)
Pressure systems	142	1316	47	64	1427	14%	10
Intake system	71	569	0	0	569	6%	8
Thermal power plant and heat recovery systems	56	741	917	1264	2922	29%	52
Engines, inverters, and other electrical installations	149	1072	0	128	1200	12%	600
Production lines and machines	65	2075	1380	437	3892	39%	3892
Total	483	10,009	2344	1893	14,246	100%	-

Table 10. Investments assessed for the planned interventions for distinct areas of intervention.

Area of Intervention	# Production Sites Reporting Quantitative Information	Total Investment (€)	Total Investment (%)	Average Investment (€)
Pressure systems	135	3,549,176	11%	26,290
Intake system	73	2,662,437	8%	36,472
Thermal power plant and heat recovery systems	53	7,023,606	21%	132,521
Engines, inverters, and other electrical installations	148	5,646,496	17%	48,872
Production lines and machines	68	14,568,165	44%	214,238
Total	477	30,787,442	100%	-

Table 11. Cost-effectiveness indicator for each area of intervention.

Area of Intervention	# Production Sites Reporting Quantitative Information	Cost-Effectiveness Indicator (€/toe)	Pay-Back Time (Years)
Pressure systems	133	3252	2.6
Vacuum system	71	6232	4.9
Thermal power plant and heat recovery systems	52	1935	3.4
Engines, inverters, and other electrical installations	143	6622	5.2
Production lines and machines	61	10,089	5.6

Planned technological interventions can also be analyzed distinguishing for their Payback Time class (PBT; Figure 7). In this case, 421 interventions report quantitative information: interventions with PBT between one and two years represent 8% (2.1 ktoe/year) of the total annual potential saving. Further, 26% of the potential savings is associated with interventions, having a PBT between 2 and 3 years (2.3 ktoe/year).

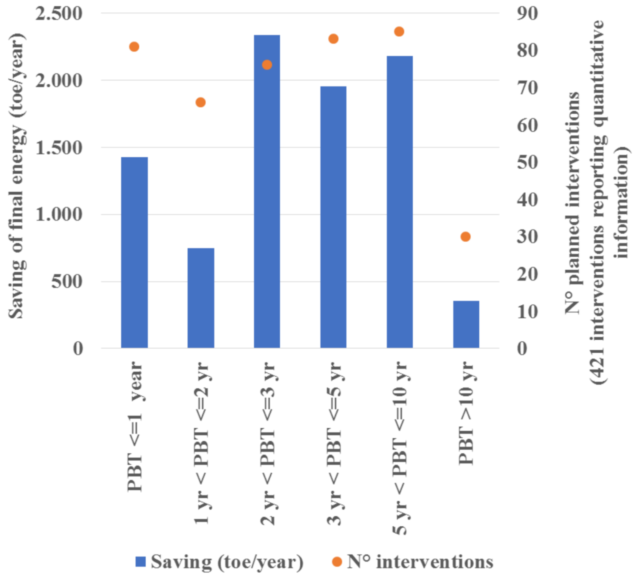

Figure 7. Annual saving and planned interventions according to the PBT classes.

4. Discussion

As depicted by Figure 3, the auxiliary systems are characterized by the highest number of implemented and planned interventions. This peculiar trend is related to the low investment cost, which results in decent values for the cost-effectiveness indicator and short payback period. Indeed, auxiliary machines are characterized by the lowest investment costs (see Table 10). Moreover, the compressors and pressure systems are associated with the lowest PBT, which is estimated at 2.6 years, and the second cost-effectiveness indicator evaluated at 3252 €/toe (see Table 11) for the planned intervention and 6821 €/toe for the implemented intervention. Furthermore, replacing old compressors with more efficient ones is regarded by the association expert as a very good strategy to reduce energy consumption. On the other side, vacuum systems and electric motors have a PBT of approximately 5 years and a cost-effectiveness indicator estimated at about 6000 €/toe for the planned intervention. Additionally, the engine sector is characterized by the best cost-effectiveness indicator among the implemented interventions (about 3000 €/toe). Another advantage of the interventions related to the auxiliary systems is the easiness of implementation, since the process remains unchanged, and the interventions are mostly characterized by the replacement of an old machine with a more efficient and modern one.

The interventions that act on the heat recovery systems are also quite popular due to the lowest cost-effectiveness indicator of 1935 €/toe (among the planned interventions). Compared to the interventions on auxiliary systems, which are always possible, the interventions related to the heat recovery systems could not always represent a viable option. Indeed, the ability to retrieve heat is limited because of the low temperature characterizing the exhaust gas, leading to some applicability restrictions. For instance, the installation of a cogeneration system is considered by the experts as difficult to implement in a foundry plant. Saying that, the installation of an Organic Rankine Cycle (ORC) turbine and the heat recovery from compressors could become popular interventions in the next future. The ORC turbine exploits lower temperature compared to the more common Rankine turbine, while the heat recovery from compressors is regarded by the experts as an emerging technology which advantages, related to energy-saving indicators, must be evaluated during the next years. Among the interventions concerning heat recovery systems, the installation of an exchanger to retrieve heat and preheat the ladle is worth mentioning. Indeed, the Italian foundry experts state that it is not a common technology, but it has great potential and margin of rationalization. It is worth mentioning that cogeneration and trigeneration interventions are not included in the heat recovery system category, but they are examined as a separate category: planned interventions reporting quantitative information are 10 and correspond to 17,586 toe/year of primary energy saving. The average cost-effectiveness indicator is 1536 €/toe of primary energy; the average PBT is 4 years, thus showing a similar value to heat recovery systems (3.4 years).

Considering the process phases, most of the interventions are implemented and planned for the melting phase, which is the most energy-intensive one. The interventions related to this area are among the most expensive ones, but they assure higher annual energy savings compared to more popular interventions. Furthermore, these kinds of interventions are usually more complex and invasive compared to the interventions related to the auxiliary systems. For instance, replacing the furnace could be very impactful on production schedule and could also lead to more strict requirements with regards to layout and spacing within the plant. However, there are some interventions that are easier to implement, such as the installation of regenerative burners, which is now mandatory and adopted by all the cast iron foundry plants, as stated by the experts.

To make a meaningful difference and resume the previous findings, Figure 8 shows that half of potential saving (4.5 ktoe/year) can be achieved by adopting interventions with PBT lower than 3 years and by mobilizing 20% of total investment associated with suggested interventions (around 5.9 million Euro). This highlights that relatively less expensive interventions are associated with a high saving potential, and such a trend appears even more significant when considering that the existing incentive mechanisms are not included within the PBT calculations.

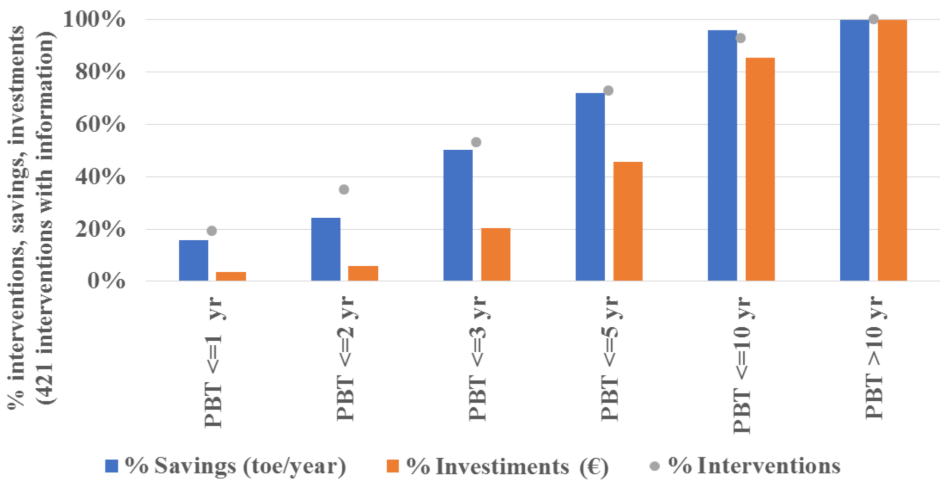

Figure 8. Cumulative saving and investment according to PBT classes.

Finally, it is worth mentioning that some technological solutions are found in the literature, but they are not currently implemented or planned by Italian companies. There could be different reasons that leads to this behavior. For instance, some technologies are emerging (e.g., 3D printing for core and mold making), which leads to uncertainty related to their application. Indeed, the costs and benefits of the emerging technology are not always clear, or the companies could be reluctant to implement a technology that is not well-known. Another reason for a low application level could be that a given technological solution is obsolete; thus, companies are not considering it anymore. Another possible reason for a scarce implementation could be that certain technologies could be disruptive for the process and could lead to major changing. As a result, there could be a quite strong resistance to change. Finally, the existing energy efficiency incentive schemes are very likely to have a role in influencing what technological solutions are more often adopted or planned: the policy coverage would evolve over time, including more promising technologies.

5. Conclusions

Given the uncertainties and difficulties that arise when planning energy-saving investments in a foundry plant, a comprehensive analysis on the interventions implemented and planned by 231 Italian manufacturing sites was conducted in this study. The in-depth study involved the EAs provided by the Italian foundry companies, along with foundry expert judgements, leading to obtain an overview of the current Italian developments on energy-saving investments. Indeed, the frequencies related to the implemented interventions provide the past trends, while the frequencies associated with the planned interventions give a hint on future trends. Moreover, as a further step of analysis, the economic data reported by the EAs were examined to determine whether there is a relationship between the adopted technological interventions and economic indicators.

The results of this study pointed out that the companies lean towards investments on the auxiliary systems and the heat recovery systems, while the melting phase has attracted most of the efforts among the process phases. Specifically, the most adopted intervention was the replacement of compressors with more efficient ones, while the most planned intervention is reducing the leakages of the air distribution systems. Among the most popular interventions that the companies are willing to implement, it is worth mentioning the following ones: replacing electric motors and furnaces with more efficient ones, installing cogeneration systems and installing or replacing the inverters. From an economic and energy-efficiency perspectives, it is possible to state that the companies prefer investing in technologies characterized by a short PBT and a decent cost-effectiveness indicator. The cost-effectiveness indicator represents the investment cost for each toe of energy saved; thus, it is strongly related to the reduction of energy consumption. The aforementioned trend is also related to the easiness of implementation of some solutions compared to others. Indeed, considering the interventions related to the heat recovery systems, it is possible to state that they guarantee the best cost-effectiveness indicators and generally higher energy-savings compared to the interventions related to pressure systems, compressors and engines. However, they are characterized by some limitations with regards to implementation.

Another fundamental outcome of this paper is the list of technologies, which have been validated by Italian foundry experts. Indeed, this output represents an up-to-date guideline for companies who are conducting a screening analysis of the possible energy-saving solutions. In other words, the aforementioned list could be exploited as a preliminary decision support tool.

During this work, energy-efficiency strategies related to lighting, heating of offices, and installation of sensors, along with the adoption of proper managerial practices, were not considered. Thus, the presented study could not account for all the possible solutions that can be adopted in a foundry plant to reduce energy consumption.

Further developments could include the analysis of other industrial sectors subjected to the EED, along with duplicating the analysis for the foundry industry of other countries. Indeed, different types of manufacturing plant could have distinct needs, leading to different choices related to energy-saving investments. Additionally, both the prices of electric energy and fuels could vary from nation to nation, resulting in diverse economic opportunities. Finally, another interesting future development could be repeating the study when the next EAs are produced to check whether the companies adopted the planned interventions and point out whether new opportunities have been identified.

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

Appendix A

Table A1. Technological energy-saving solutions for molding obtained from both the literature and EAs.

Molding					
Process Machinery	**Solution Object**	**Energy-Saving Approach**	**Energy-Saving Technological Solution**	**Reference**	**Comments from Sector Experts**
Molding machinery	Sand recovery system	Innovation	Installing machine capable of retrieving slag from furnace and using it as sand mold.	[43]	
Molding machinery	Sand recovery system	Re-source	*Replacing the electric sand recovery system with a gas one*	Energy Audits	This solution is in total contrast with the decarbonization requirments.
Molding machinery	Sand recovery system	Innovation	*Installing a sand recovery system*	Energy Audits	This solution generates an increase of the energy consumption; however, it could help mitigating the environmental impact. Indeed, recovering sand leads to lower level of sand waste and disposal.
Molding machinery	Molding station	Replace	*Replacing the molding stations with more efficient ones*	Energy Audits	
Molding machinery	Mixer	Replace	*Replacing the mixing systems with a more efficient one*	Energy Audits	
Molding machinery	"Hot box" molding	Innovation	*Installing a preheating system or regenerative or recuperative burners for the furnace tasked with the production of the sand mold*	[29]	
Molding machinery	Molding machinery	Replace	*Installing an efficient filter for the sand molding process*	Energy Audits	The benefits of this solution should be evaluated considering the compressed air required to clean the filter
Molding machinery	Molding machinery	Innovation	Installing a infrared system for drying the mold	[8,17]	This solution is adopted by some Italian foundry plants. It is exploited for both the refractory material of the mold and the coating of the sand mold
Molding machinery	Molding machinery	Innovation	*Installing low-pressure casting machine capable of using inorganic cores*	Energy Audits	
Molding machinery	Molding machinery	Replace	*Replacing the existing machinery with newer and more efficient ones*	[8]	
Molding machinery	3D Printer	Innovation	Installing a 3D Printer (Jet Binding) for making molds	[15,44]	
Molding machinery	3D Printer	Innovation	Installing a 3D Binder Jetting Printer for making cores. The 3D Printer blends the sand through a binder agent	[16]	Emerging techology; thus, its energy consumption should be evaluated more in-depth. More benefits for low production volumes.
Molding machinery	3D Printer	Innovation	Installing 3D Printer for making cores	[16]	Emerging techology; thus, its energy consumption should be evaluated more in-depth. More benefits for low production volumes.

Table A2. Technological energy-saving solutions for casting obtained from both the literature and EAs.

Casting					
Process Machinery	**Solution Object**	**Eenergy-Saving Approach**	**Energy-Saving Technological Solution**	**Reference**	**Comments from Sector Experts**
Casting machinery	Casting machinery	Innovation	Installing a Vacuum Suction Casting Technology	[15]	This solution allows to obtain a better surface roughness, leading to a lower energy consumption during the finishing phase. However, it is an emerging technology and it could lead to high energy consumption due to the requirments of mantaining the vaccum conditions. Before implementing this solution it is recommended to evaluate the energy consumption increase during the casting phase and the energy consumption decrease of the finishing phase.
Casting machinery	Cooling system	Innovation	Adopting the "quench casting" technique for cooling the cast	[18]	
Casting machinery	Cooling system	Innovation	Adopting the "splash casting" technique for cooling the cast	[18]	
Casting machinery	Cooling system	Innovation	*Installing a forced ventilation cooling system*	Energy Audits	
Casting machinery	Ladle	Innovation	*Installing machines capable of scheduling an efficient preheat of the ladle*	[8,38]	It is usually performed without considering energy-saving opportunities. Large margin of potential and rationalization.
Casting machinery	Ladle	Innovation	Using lid for ladle to reduce the heat loss	[8]	It is a very useful solution with large margin of potential and rationalization.
Casting machinery	Ladle	Innovation	Adopting coating material for the ladle to reduce the heat loss	[8]	It is a very useful solution with large margin of potential and rationalization
Casting machinery	Ladle	Replace	Installing ladle with a more pointed outled to reduce the porosity of the cast. It also assures a lower thermal dispersion.	[45]	It is not a common technological solution
Casting machinery	Ladle	Innovation	Installing an automatic ladle pouring system	[35]	
Casting machinery	Casting furnace	Replace	*Replacing the casting furnace with a more efficient and newer one*	Energy Audits	
Casting machinery	Casting machinery	Replace	*Replacing the casting machineries with more efficient and newer ones*	[46]	
Casting machinery	Die-casting machinery	Replace	*Installing a new efficient die-casting line*	Energy Audits	
Casting machinery	Die-casting machinery	Replace	*Replacing the furnace where the cast waits to be poured in the mold with a more efficient and newer one*	Energy Audits	
Sand removal machinery	Sand removal machinery	Replace	*Replacing the machinery in charge of the sand removal process with more efficient and newer ones*	[8]	

Table A3. Technological energy-saving solutions for finishing obtained from both the literature and EAs.

Finishing					
Process Machinery	**Solution Object**	**Energy-Saving Approach**	**Energy-Saving Technological Solution**	**Reference**	**Comments from Sector Experts**
Finishing station	Robot	Innovation	Installing a robot for finishing	[47]	The automatic operations allows to both reduce cost and save time. Moreover, they limit human interventions leading to a safer process.
Finishing station	Finishing station	Replace	*Installing a new efficient finishing line*	Energy Audits	
Finishing station	Finishing station	Replace	*Replacing old finishing machineries with more efficient and modern ones*	[8,24]	
Finishing station	Finishing station	Replace	*Installing high efficiency nozzles*	Energy Audits	
Heat Treatment Furnace	Heat Treatment Furnace	Replace	*Replacing the heat tratment furnace with a more efficient and modern one*	Energy Audits	

Table A4. Technological energy-saving solutions for auxiliary systems obtained from both the literature and EAs.

Auxiliary Systems					
Process Machinery	**Solution Object**	**Energy-Saving Approach**	**Energy-Saving Technological Solution**	**Reference**	**Comments from Sector Experts**
Compressors	Compressors	Replace	*Replacing the compressor with more modern and efficient ones*	[28]	It is a very good technological solution to reduce energy consumption
Compressors	Exchanger	Innovation	Improving the air quality through the introduction of an exchanger located at the compressor outlets	[48]	
Compressors	Filter	Innovation	Improving the air quality through the introduction of a filter located at the compressor outlets to remove volatile substances	[48]	
Compressors	Filter	Innovation	Improving the air quality through the introduction of a filter to remove oil from compressed air	[48]	
Compressors	Injection pump	Innovation	Installing a pump for better injecting and sparing the lubrificant	[48]	
Compressors	Compressors	Innovation	Installing technologies capable of isolating some sections of the system that requires specific values for the pressure of the air	[49]	
Compressors	Compressors	Replace	Optimize the size of the compressors	[49]	
Compressors	Compressors	Innovation	Installing an intercooler for the compressors	[28,50]	
Compressors	Compressors	Innovation	*Installing variable speed compressors (i.e., compressor with inverter)*	[49]	
Compressors	Compressors	Replace	Installing efficient induction motors	[49]	

Table A4. *Cont.*

Auxiliary Systems					
Process Machinery	**Solution Object**	**Energy-Saving Approach**	**Energy-Saving Technological Solution**	**Reference**	**Comments from Sector Experts**
Compressors	Compressors	Innovation	Replacing the compressors needed for creating vacuum with vacuum pumps	[49]	It is a very good technological solution to reduce energy consumption
Pressure systems	Pressure systems	Innovation	*Replacing all the equipment for pressurized air distribution with electric or idraulic devices (if possible)*	[49]	
Pressure systems	Pressure systems	Innovation	Replacing the compressor with fans, blowers or other alternative solutions (if possible)	[51]	
Lubrification system	Lubrification system		Installing technologies for electrostatic lubrification to decrease the oil contained in the air	[34]	
Suction Systems	Suction Systems	Innovation	Placed the suction systems as close as possible to the sources	[34]	It is a very good technological solution to reduce energy consumption
Suction Systems	Suction Systems	Innovation	Installing defrosters to remove condensation drops	[34]	
Suction Systems	Suction Systems	Innovation	Installing electrostatic precipitator to remove dust	[34]	
Suction Systems	Suction Systems	Innovation	Installing appropriate systes to reduce the emissions	[36]	
Suction Systems	Suction Systems	Replace	*Installing high efficiency fans*	[8]	
Suction Systems	Suction Systems	Replace	Installing fans with proper size and power	[8]	
Suction Systems	Suction Systems	Innovation	*Installing variable speed fans (i.e., fans with inverter)*	[8]	
Suction Systems	Suction Systems	Innovation	*Installing a forced air suction system for the furnace*	Energy Audits	
Transport Systems	Forklift	Replace	*Replacing the forklifts with more efficient and modern ones*	[52]	
Transport Systems	Forklift's battery	Replace	*Replacing the batteries of the forklifts*	[52]	
Transport Systems	Transport Systems	Replace	*Replacing conveyor belts with more efficient and modern ones*	Energy Audits	
Transport Systems	Transport Systems	Innovation	Installing appropriate covers and roofings for the material transportation systems	[36]	
Transport Systems	Transport Systems	Innovation	Installing frequency converters with controlled speed for the transportation systems	[53]	
Transport Systems	Transport Systems	Innovation	Replacing pneumatic, chain and screw transport systems with belt conveying systems	[53]	
Transport Systems	Transport Systems	Replace	Replacing poly-v belts with more efficient and modern ones	[54]	
Transport Systems	Transport Systems	Innovation	*Installing high efficiency belt and replace V-belts with toothed belts*	[8]	
Transport Systems	Transport Systems	Innovation	*Replacing V-belts with helicoidal belts*	Energy Audits	

Table A4. *Cont.*

Auxiliary Systems					
Process Machinery	**Solution Object**	**Energy-Saving Approach**	**Energy-Saving Technological Solution**	**Reference**	**Comments from Sector Experts**
Transport Systems	Lift truck	Replace	*Replacing the lift trucks with more efficient and modern ones*	Energy Audits	
Transport Systems	Crane	Replace	*Replacing the cranes with more efficient and modern ones*	Energy Audits	
Electricity Transformers	Electricity Transformers	Replace	*Replacing the electricity transformers with more efficient and modern ones*	Energy Audits	
Inverters	Inverters	Innovation	*Installing inverters on eletric motors or replacing the inverters with more efficient and modern ones*	[1]	
Electric Plant	Electric Plant	Innovation	*Installing passive filters*	[34]	
Engines	Engines	Replace	*Installing high efficiency electric motors (class IE2, IE3 and IE4)*	[28,54]	It is recommended for all the motors with high working hours.
Engines	Engines	Replace	Installing electric motors correctly sized in relation to the power required by the system	[54]	
Engines	Engines	Innovation	*Installing regenerative electric motors*	Energy Audits	
Engines	Engines	Innovation	Installing motors with low starting current	[55]	It assures lower consumption and less dependence on the electricity network.
Engines	Engines	Replace	*Rewinding electric motors*	[8,55]	
Engines	Engines	Replace	Rewiring the engines	[8]	
Engines	Engines	Innovation	*Installing variable speed motors (i.e., motors with inverter)*	[55]	
Fluid distribution systems	Fluid distribution systems	Replace	Installing a closed circuit cooling system	[36]	
Fluid distribution systems	Fluid distribution systems	Innovation	*Optimize the pipelines' design leakage along with installing appropriate seal to minimize air leakage*	[49,56]	
Fluid distribution systems	Fluid distribution systems	Replace	Installing a proper insulation for the fluid distribution system to reduce heat loss	[8]	
Pumps	Pumps	Replace	*Replacing the pumps with more efficient and modern ones*	[8]	
Pumps	Pumps	Replace	Installing pumps correctly sized	[8]	
Pumps	Pumps	Replace	Trim the impellers of the pumps to reduce the energy consumption	[8]	
Pumps	Pumps	Innovation	Installing variable speed pumps (i.e., pumps with inverter)	[8]	
Cooling Systems	Cooling Systems	Replace	*Replacing the cooling towers with more efficient and modern ones*	Energy Audits	
Cooling Systems	Cooling Systems	Innovation	Installing technologies able to reuse the condensation of the cooling towers	[8]	

Table A5. Technological energy-saving solutions for heat recovery systems obtained from both the literature and EAs.

Heat Recovery Systems					
Process Machinery	**Solution Object**	**Energy-Saving Approach**	**Energy-Saving Technological Solution**	**Reference**	**Comments from Sector Experts**
Furnace	Heat Recovery Systems	Recover	Installing a heat recovery system to retrieve heat from the slag	[57]	
Furnace	Heat Recovery Systems	Recover	Installing a preheater for the combustion air	[36]	
Furnace	Heat Recovery Systems	Recover	Installing a regenerator to retrieve heat from exhaust gas	[35]	
Furnace	Heat Recovery Systems	Recover	Installing a recuperator to retrieve heat from exhaust gas	[35]	
Furnace	Heat Recovery Systems	Innovation	Installing Carbon Capture and Utilization (CCU) technology for capturing the CO_2 contained in the exhaust gas and exploit it for other purposes	[58]	This is an emerging solution; thus, it is not easily implementable for small and medium enterprises
Rankine turbine	Heat Recovery Systems	Recover	*Installing a Rankine turbine to generate electric energy through the exhaust gas*	[34,38]	
Combined cycle	Heat Recovery Systems	Recover	Installing technologies able to exploits exhaust gas to produce electric energy through a combined cycle	[59]	It is usually adopted for gas cupola furnace
ORC turbine	Heat Recovery Systems	Recover	*Installing a ORC turbine to generate electric energy through the exhaust gas*	[8,38,56]	It could be adopted for medium cupola furnaces, which are exploited for at least two shifts
Burner	Heat Recovery Systems	Innovation	Installing a burner able to capture organic volatile substances to burn them and produce heat	[5]	This is an interesting technology in case the post-combustion could be totally fueled with the volatile substances, otherwise methane is required, leading to economic unsustainability
Cogeneration	Heat Recovery Systems	Recover	*Installing cogeneration or trigeneration technologies*	[8]	This solution is not easily implementable in a foundry plant
Refrigeration cycle	Heat Recovery Systems	Recover	*Installing technologies able to exploits the exhaust gas for a refrigeration cycle*	[60]	
Battery	Heat Recovery Systems	Replace	*Replacing the batteries of the heat recovery systems*	[61]	
Evaporator	Heat Recovery Systems	Recover	*Installing an evaporator to retrieve heat from the emulsified water*	Energy Audits	It is adopted for the nonferrous metals produced through die-casting
Sand drying system	Heat Recovery Systems	Recover	*Installing technologies for the sand drying process*	Energy Audits	
Furnace	Heat Recovery Systems	Recover	*Installing an exchanger to retrieve heat from the exhaust gas and generate hot water for the drier*	Energy Audits	

Table A5. *Cont.*

Heat Recovery Systems					
Process Machinery	**Solution Object**	**Energy-Saving Approach**	**Energy-Saving Technological Solution**	**Reference**	**Comments from Sector Experts**
Furnace	Heat Recovery Systems	Recover	Installing a turbine to retrieve heat from the high pressure of the furnace	[24,57]	
Storage Tank	Heat Recovery Systems	Recover	Installing a heat storage tank	[56]	
Compressor	Exchanger	Recover	*Installing an exchanger to retrieve heat from the compressors*	[49,56]	
Ladle	Exchanger	Recover	*Installing an exchanger to retrieve heat and preheat the ladle*	[51]	It is not a common technology; however, it has a large margin of potential and rationalization
Casting machinery	Cooling system	Recover	*Installing a heat recovery system from the cooling process of the molds*	Energy Audits	

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