Energy efficiency opportunities in the service plants of cast iron foundries in Italy

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Abstract

Though in a foundry most of the energy is used in the process plants and particularly in energizing furnaces, service plants require absolutely large amounts of energy, above all as electricity. The most energy-consuming service is compressed air preparation, but large amounts are due to lighting, heating, ventilation and air conditioning, pumps and fans. These energy users are common to most of the industrial branches with different weights both in absolute and relative terms. This article reports on the experience of some energy audits carried out in five Italian cast iron foundries allowing to identify the relative importance of different services in this industrial branch. The analysis is based on real data measured during the audits. Energy saving actions were then conceived, comparing the results of new technologies applied in some factory sectors and the energy usage of the previous equipment.

Keywords: service plant; compressor; lighting; electricity supply; ORC; electric motor

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1 INTRODUCTION

Industrial processes are highly energy intensive and currently account for one-third of global energy use [1]. Around 70% of this energy is supplied by fossil fuels. CO_2 emissions from industry make up 40% of total CO_2 emissions worldwide. A number of authors gave an overview of the technologies for reducing emissions from industrial processes by collating information from a wide range of sources [2–5].

Several studies have been published on energy audit and energy analysis results for different industries and in different countries. Akash Bilal and Mohsen Mousa [6] presented the situation of energy consumption in the Jordanian industry; in a previous work, the same authors focused in identifying heat losses of the main components of steel making industry in Jordan [7]. Muller *et al.* [8] presented a method aimed at tracking energy saving opportunities in the food-processing industry through a combination of top-down and bottom-up approaches. An in-depth energy efficiency study of a privatized trailer plant in the Urals was performed by Fromme showing that energy savings of 47% of the current demand can be achieved [9]. De Monte *et al.* [10] defined the thermo and fluid dynamic operating parameters of a coffee roasting plant also with the support of an experimental measuring campaign, evaluating energy recovery possibilities also from the economic point of view. Using the Basque Country industrial database and thermodynamic properties databases, the energy and exergy of waste heat were determined for 10 industrial sectors of the Basque Country by López *et al.* [11]. Other similar works on energy audit and energy analysis results for different industries and in different countries are reported [12–17].

In particular, some studies were previously made concerning energy in the foundry sector. Ozawa *et al.* presented trends in activity, primary energy and carbon dioxide emissions of the Mexican iron and steel industry [18]. Price *et al.* [19], Worrell *et al.* [20] and Yih-Liang Chan *et al.* [21] made similar analyses for the Chinese, USA and Taiwanese iron and steel industry, respectively. Thollander concentrated in the Swedish iron foundry studying the effect of rising electricity prices and quantifying an energy efficiency potential for a medium-sized Swedish iron foundry resulting from a thorough industrial energy audit [14]; other studies of the same author ([22, 23]) provided an insight into barriers to energy efficiency in European foundries, considering several firm's characteristics (size, technologies adopted, country) and studied energy management practices and the driving forces for improved energy efficiency in the European foundry industry (FoundryBench project within the Intelligent Energy Europe program). The same author again presented the use of methods for optimization of dynamic industrial energy systems, studying how they

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can provide energy-intensive small- and medium-sized enterprises like cast iron foundries with additional information when strategic investments are going to be made [24]. Anyway, very few works investigated consumption of the service plants and none in the cast iron foundry sector to the best of authors' knowledge.

This study comes from the field work on single factories where the authors during energy audits had the opportunity to collect real data on production and energy consumption in the individual processes in various factory branches. The cooperation between the University of Padua and the Centro Produttività Veneto provided energy audits in five cast iron foundries located in the Vicenza province (North Italy).

In a previous article [25], first results of the energy audits, considering mainly the energy usage in the production process, were reported by the authors. The analysis highlighted that much of the energy usage in this industrial branch is due to production process and above all in metal melting, obtained by induction furnaces and by blast cupolas. Induction furnaces are responsible up to 80% of the whole energy consumption of the factory (almost entirely electricity), whereas mold making requires about 10% (part electricity, part natural gas (NG)). Blast cupolas account instead about 50% of the energy demand, followed by mold and core making with a weight of 20–30% (half of electricity and half of NG). Minor fractions of energy demand are due to deburring, painting, sand treatment, etc.

A more detailed analysis (than that reported by the authors in reference [25]) of the energy consumption in the production process of the audited foundries is given in another article [26]. In this article, the authors report on the results of the surveys of service plants of the cast iron foundries, in particular concerning:

- compressed air preparation and distribution
- lighting
- electricity supply
- pumps and fans
- heating, ventilation and air conditioning (HVAC)
- water supply
- possible use of renewables.

For the audited cast iron foundries, the services demand accounts from 5 to 10% of the whole energy demand, mainly electricity. For one of the audited foundries whose annual production is 30 000 ton of cast iron, this means about 2 GWh of electricity.

Practically all the previously listed services are common to other industrial branches. The major difference for cast iron industries is the huge demand of compressed air (of the order of 10–20 $MSm^3\,y^{-1}$ for a factory of <200 employees and a revenue of 40 M€). Another particular feature in this branch is the requirement of high-capacity extraction systems (the capacity of each may be well >100 000 $m^3\,h^{-1}$ – 30 $m^3\,s^{-1}$). Finally, a foundry requires huge quantities of water (>30 000 $m^3\,y^{-1}$ for the previously considered foundry, mainly for sand treatment and for cooling). Equally other services with similar characteristics to other industries such as lighting or HVAC will be dealt with as the auditing experience allowed to effectively compare different technologies or possible heat recovery.

Direct production of electricity for internal usage will be analyzed above all for exploiting high and medium temperature heat recovery. As two of the foundries had installed a PV plant an energy and economic balance will be proposed.

2 COMPRESSED AIR SYSTEM

Compressed air is really an energy expensive utility. A foundry makes a widespread use of compressed air for its pneumatically operated production lines, molds forming and many machine tools. A rough evaluation indicates a fraction of about 5% for the electricity usage in the compressed air system on the whole foundry electricity consumption.

It is known that only around 7–10% of the electrical energy for producing compressed air is available as mechanical energy for the user. Flexibility, ease of use, safety, low weight of pneumatic tools equally recommend its use.

The study of the energy flow from the input to the end user (Figure 1) can be a first drive toward possible energy savings. The first inefficiency is due to the electric motor that drives the compressor. A traditional induction motor can operate at 90% top efficiency with diminishing values when departing from nominal speed. A modern permanent magnet motor offers a 95% efficiency over a wide operative speed interval.

The second large inefficiency is due just to the very process of compression. In a traditional compression system, around 70 of the original 100 units of energy input are turned into heat (Figure 1), that is the conversion efficiency from the mechanical energy offered by the electric motor shaft to the potential compressed air energy is only something >20% [27].

This behavior is somehow intrinsic to the compression process: when a gas is compressed, its temperature increases if it is not cooled during compression. However, the compression can be realized in two or three stages with intermediate cooling. In the past two stages, compression was resorted for relatively

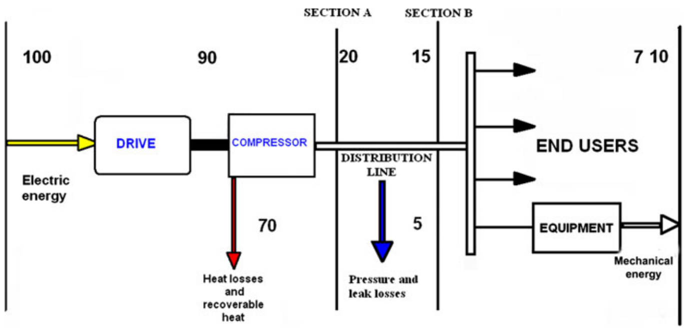

Figure 1. *Energy flow from input section to mechanical energy end-user section in a compressed air system (adapted from Petrecca [27]).*

high final pressure, say 1.5–2 MPa or more. In a foundry, compressed air is usually requested at 0.7–0.8 MPa.

Nevertheless, the modern installed screw compressors work in two stages with a water cooling system. Consider a schematic of the system in Figure 2. At the top, the air is sucked from the outside and after filtering it is compressed in the first stage by a screw compressor. The air at an intermediate pressure is refrigerated by circulating the water necessary also to cool the lubricating oil. Some water vapor in the air condenses, and it is discharged by a trap. The air is then compressed in the second stage to the final pressure and again it is refrigerated before being supplied to the distribution lines. Another trap discharges the condensate that separates from the air as at the higher pressure the air becomes saturated at temperatures well above the ambient. A further cooling is provided on the screw compressor casing as well as some cooling is allowed by the lubricating oil. Consequently the compression is not perfectly adiabatic; the process can be approximated by a polytropic exponent n which is lower than the adiabatic exponent k that for air is set at 1.4: n can be as low as 1.3. As a result an energy saving of about 15–20% is obtainable.

In the audited foundries, many old compressors were still operating. The 'simple' equipment replacement allowed significant energy savings. An example illustrates the possible advantages of a renovation of the compressor station.

In Foundry A, cast iron production is ~35 000 ton y^{-1}. In the previous situation of compressed air, four different stations were located not far from the utilization. The compressed air required an installed power of 912 kW, as specified in Table 1. The renovation considered a careful inspection of the compressed air leaks, reducing the stations to only two, limiting the upper pressure of 1 MPa (required by the mold forming department) to only one compressor and keeping the old 55 kW compressor. As regards the other compressors, two new 250 kW compressors (one of them for backup only), one 132 kW and another 250 kW inverter-equipped compressor were installed. The choice of one variable speed compressor allows to operate supplying just the demanded flow rate improving system efficiency. A total engaged power for compressed air is now of 687 kW, that is 25% less of the previous situation.

Two different surveys before and after the renovation are summarized in Table 2 (flow rates in the compressed air sector are usually expressed in $m^3\ min^{-1}$).The overall energetic and economic saving is of about 18% with a yearly saving of about 70 000 €.

The renovation of the compressors sometimes looks not so necessary because some auxiliary services are not considered. This is the case of Foundry B where the air compression station was equipped with two reciprocating two-stage compressors of 132 kW (volumetric flow rate 24.780 $m^3\ min^{-1}$ each) and one reciprocating two-stage compressor of 60 kW (volumetric flow rate 9.480 $m^3\ min^{-1}$). All the compressors were water cooled and operated at 0.7 MPa gauge. The renovation provided one 200 kW

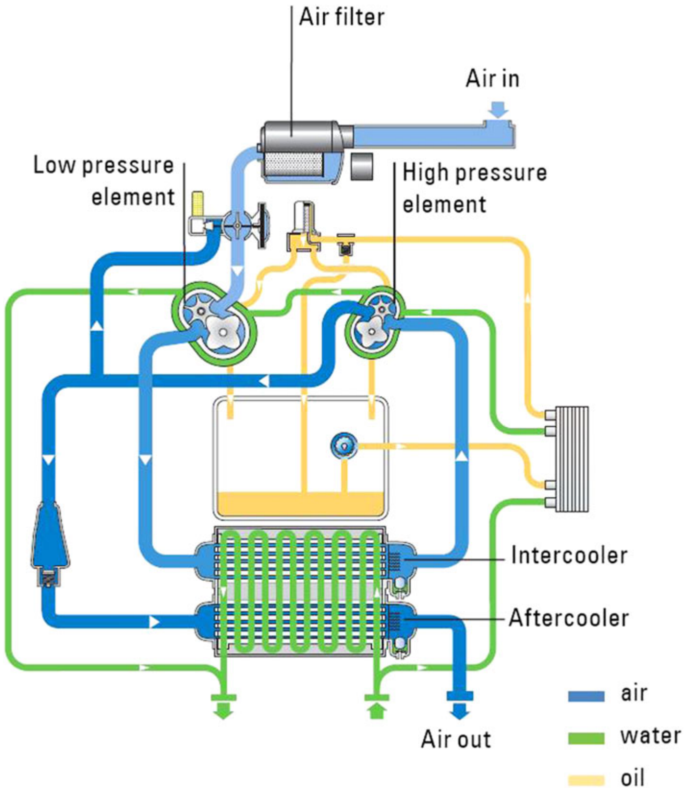

Figure 2. *Two-stage screw compressor with water cooling system (courtesy of Atlas Copco) [28].*

Table 1. *Installed compressors in one of the audited foundries before renovation.*

Number of compressors	Unitary power (kW)	Total power (kW)	Pressure (bar)	
Foundry compressed air station				
2	110	220	7	
2	75	150	7	Operating according to the demand
Mold forming compression air station				
3	75	225	10	
1	55	55	10	Always operating
Fettling operation station				
1	132	132	7	
Sand blasting equipment				
1	130	130	7	
Total power		912		

Table 2. *Comparison of the compressed air stations before and after renovation in the audited foundry.*

	Before renovation	After renovation	Saving %
Maximum engaged power (kW)	912	687	25
Flow rate ($m^3\ min^{-1}$)	136	111.4	18
Electrical consumption (kWh)	2 620 848	2 154 897	18
Cost of electricity (€)	393 127	323 234	18
Specific power ($kW\ m^{-3}$ min)	6.70	6.16	8
Specific cost (€ m^{-3})	0.0167	0.0154	8

constant speed screw compressor (flow rate 41.5 $m^3 min^{-1}$) and one 160 kW variable speed screw compressor (maximum flow rate 31.1 $m^3 min^{-1}$), both air cooled. Two typical weeks were surveyed before and after the renovation. Before renovation the electricity required to drive the compressors was of 14 671 kWh against 90 210 m^3; after renovation the electricity was 16 116 kWh against 121 376 m^3. The specific consumption was then decreased by 18%. However, the cost saving resulted almost double than that. In fact, the water-cooled compressors required electricity for pumps and cooling tower, a continuous consumption of lubricating oil and a consumption of water with additives for the cooling circuit. Moreover, some labor had to be considered for daily check and topping up the oil. The yearly evaluation gives a saving of 22 600 € for the more efficient compressors, but a similar figure of cost (22 700 €) was attributed to the elimination of the auxiliary services of the previous compressed air station.

The careful inspection of the lines to eliminate possible leaks and the selection of the really requested pressure are both very important items in the energy auditing of the compressed air system as demonstrated in the previous example. Some figures can highlight the possible impact of these measures. Usual leaks are surveyed arriving at 10% of the pipe air flow. Leakage is often found at the connections of the lines with the pneumatic tools. Automatic disconnectors applied on every single machine that shut off the compressed air connections when the machine is not operating can halve the leaks. Flow leaks from an orifice of an equivalent diameter of 6.35 mm (1/4") at a pressure of 0.8 MPa absolute can be evaluated in 50 $g s^{-1}$ with a compression power of 17 kW.

To prepare compressed air at 1 MPa gauge requires a specific power of about 8 $kW m^{-3}$ min, whereas the compression to 0.7 MPa wants about 6 $kW m^{-3}$ min. Hence, the really necessary compressed air pressure must be firstly investigated.

Moreover, the distribution lines are usually some hundreds of meters long. Consider a flow rate of 100 $m^3 min^{-1}$ of compressed air at 0.7 MPa along a pipe of 100 m: if the nominal bore is 100 mm the air speed is of about 26 $m s^{-1}$. The pressure drop can be evaluated in 0.04 MPa, whereas a nominal bore of 150 mm would have limited the drop to 0.01 MPa and a more generous bore of 200 mm would have produced a pressure drop of 0.004 MPa. These differences look seemingly modest, but the energy over cost for the smallest bore is 200 $W m^{-3} min^{-1}$, that means 20 kW of additional power for the compressor for the above flow rate; for the middle bore and for the largest diameter the same figure would have been 2 kW and 200 W, respectively. As it is not unusual to observe 500 m of lines in a foundry, it is apparent how the right selection of the lines bore strongly influences the cost of this service.

Even if in a foundry many opportunities of heat recovery are available (whereas low temperature heat is of limited value), compressors require adequate cooling, so that recoverable heat is often directly provided in the equipment at temperatures between 60 and 80°C at the extent of 70–80% of the electrical input to the compressor. This easily recovered heat can be used for building heating.

3 LIGHTING

Lighting in foundries is not a particularly challenging task. The required illumination is between 200 and 500 lux in work areas with lower values in warehouses or outdoor. However, the extension of an average size foundry is so large that the fraction of electricity due to lighting is often of the order of 2% of the total electricity consumption of the factory. As a foundry energy need is very high, even that low fraction produces appreciable absolute values.

The audited Foundry C required 9 735 673 kWh electricity on the whole in 2013, of which 193 664 for lighting. Moreover this service can benefit the latest development of lighting technology regarding lighting efficiency (expressed in lumen of lighting flux per watt of electricity supplied), color rendering and average life. According to the Directive 2005/32/CE EuP, all the lamps containing mercury or without sufficient performance regarding efficiency, lamp lumen maintenance factor or lamp survival factor are going to be banned in two phases: the first within April 2015 and the other within April 2017. Therefore, a scrutiny about new available products is extremely useful.

The most widespread lamps have been fluorescent till now with increasing diffusion of high-intensity discharge (HID): all these lamps present a similar lifetime of ~8–10 000 hours with a sort of conflicting behavior between lighting efficiency and color rendering. In fact, the most efficient lamps (the low pressure sodium) feature 200 $lm W^{-1}$ efficiency with the lowest color rendering; they are often used in parking areas where no colors are detectable as everything appears yellowish. Metal halide HID lamps produce a fair color rendering (they are used for sports lighting), but the lighting efficiency is less than one-third with respect to the previous one (even if the latest developments in these lamps have improved that performance).

Alternatives are at hand with good color rendering, high lighting efficiency and a by far longer lifetime: induction lamps and light emission diode (LED). Table 3 gives an overview of lamps that can be considered for replacement in a foundry. As in some departments an acceptable color rendering is welcome, only lamps with a color rendering index >90 have been considered. By comparison, data regarding the old metal halide HID lamps and the fluorescent tube lamps are reported.

The new metal halide HID lamps and new fluorescent tube lamps are quite comparable with induction lamps and LEDs in terms of efficacy and even color rendering, whereas a strong difference can be easily noticed regarding lifetime, more than double for LEDs and even 5-fold higher for induction lamps. While metal halide and fluorescent lamps seem to have reached complete maturity and no further developments are waited, LEDs are continuously improving so that Table 3 should be modified within next 12 months. Other factors of comparison are difficult to be evaluated, for example the lumen depreciation for LEDs is strongly dependent on the fixture and on its ability to keep the lamp temperature below a set value.

Table 3. *Comparison of lamps actually operating in foundries and possible new technology replacement.*

	Old metal halide HID	New metal halide HID	Old fluorescent lamps	New fluorescent lamps	Induction lamps	LEDs
Efficacy (lm W^{-1})	60	95	75	90	85	95
Color rendering index	65	90	58	85	98	92
Lifetime (hours)	6000	10 000–20 000	9000	20 000	100 000	50 000

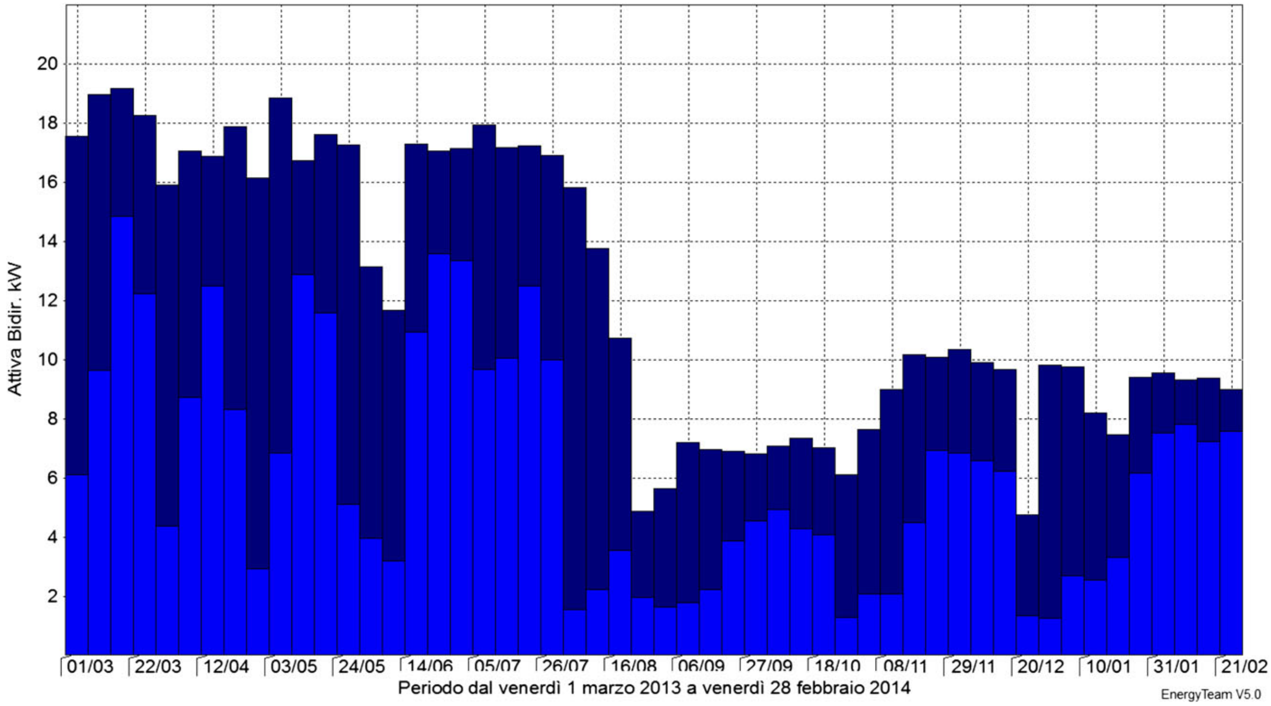

Figure 3. *Comparison between the weekly electricity required by the old (in dark) and the renovated lighting plant in Foundry D during a year (1 March 2012 to 28 February 2013 for the old plant and the following year for the new plant).*

The comparison between the existing lamps in the audited foundries with the new available products suggested to analyze the lamps' replacement at least in some departments. The case study of the audited Foundry D is reported. Existing fluorescent tube and compact lamps (about 120) and metal halide lamps (high wattage lamps, 430 W each) were replaced by LEDs with the due shape and size to provide the same or even higher illumination in the departments and outside. The renovated lighting plant started on 7 March 2013. Figure 3 reports the comparison of the first year of operation of the new plant with the consumption of the old plant in the same period of the previous year. The survey in the same month before and after replacement gave a reduction from 9008 to 5157 kWh (7 February–7 March 2013, or 2014). The annual saving can then be evaluated in 40 000 kWh with an investment of 27 000 €.

An economic analysis of the investment is carried out in Figure 4 where the cash flow for a 10-year period is reported, comparing the new lamps with the existing at the actual cost of electricity for the company (0.16 € kWh^{-1}) at a discount rate of 2% and an inflation rate for energy of 7% per year. According to this evaluation the payback time of the investment is between 3 and 4 years without considering the cost of the periodic replacement of the previous lamps.

Another experience was carried out in Foundry C where a department of finishing (cutting, flattening, grinding, welding) of 4000 m^2, equipped with 51 metal halide lamps (nominal power 400 W each, but measured power about 480 W) operated 2600 hours per year with a recorded electricity requirement of 63 648 kWh. The average life of these lamps was about 6000 hours. The illuminance was 250 lux. Two different alternatives were considered for replacement: LEDs and induction lamps. The main characteristics of the various lamps are listed on Table 4.

Figure 5 gives the economic comparison on a 15-year period with the same assumptions of Figure 4. The company preferred the induction lamps not only for the lower investment cost but also for the very long lifetime. The return time of the two investments without considering the periodic replacement of the old model lamps is between 3 and 4 years for the induction lamps and about 7 years for the LEDs. The longer payback of LEDs if compared to the application in the other foundry previously considered is due to the different annual working hours of the lamps that in the previous foundry is almost double.

In the future, significant cost reductions are waited for LED lamps that might reverse the company's conclusions.

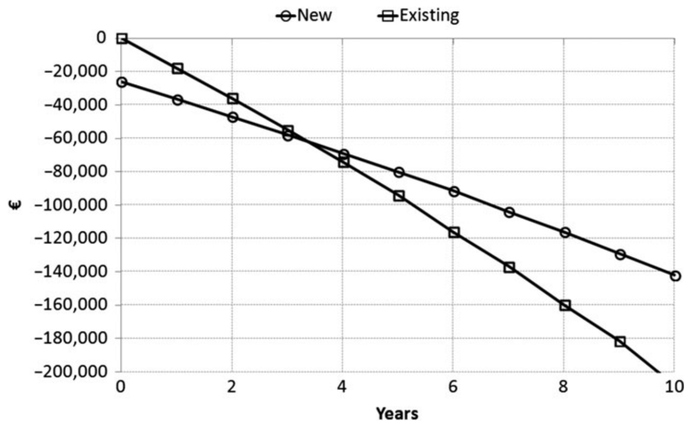

Figure 4. *Economical comparison between the old lighting plant and the new one through the flux diagram, considering a discount rate of 2% with an inflation rate for energy of 7% and an investment for the renovation of 27 000 € (electricity cost at the starting date 0.16 € kWh^{-1}).*

Table 4. *Comparison of characteristics and cost of the lamps considered for replacement in Foundry C.*

	Existing halide lamps	LEDs	Induction
Nominal power (W)	400	170	250
Number of lamps	51	76	58
Lifetime (h)	6000	50 000	100 000
Efficacy (lm W^{-1})	60	95	85
Unitary cost (€)		470	250
Investment cost (€)		35 720	14 500
Annual consumption (kWh)	63 648	33 592	37 700
Annual cost (€)	10 184	5375	6032
Annual saving (€)		4809	4152

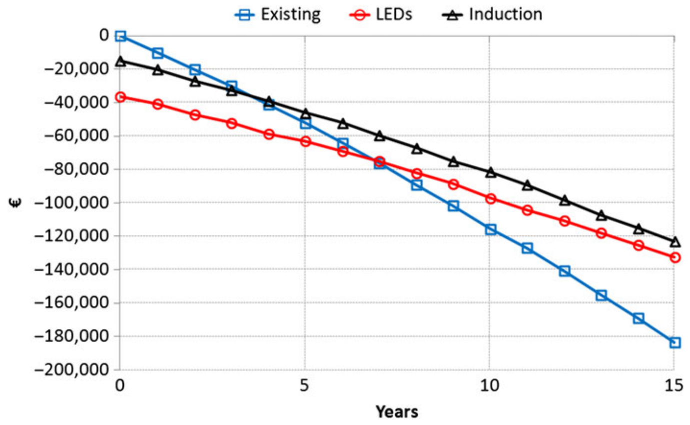

Figure 5. *Economical comparison between the old lighting plant and two alternative solutions through the flux diagram, considering a discount rate of 2% with an inflation rate for energy of 7%. The initial investment is 14 500 € for induction lamps and 35 720 € for LEDs (electricity cost at the starting date 0.16 € kWh^{-1}).*

4 ELECTRICITY SUPPLY AND MANAGEMENT

The performance assessment of foundries electric power system has two distinctive aspects: the supply side and the demand side. In this section, we concentrate on the former and on the next section the latter. For these considerations, we refer mainly to one of the audited foundry (named Foundry E), the only equipped with induction furnaces (five) and so with the largest electric power supply (10 MW) [25].

4.1 Electricity supply and distributed generation: an economic viability analysis

On the supply side, both the commercial and technical aspects should be concerned. From the commercial point of view, monthly bills were analyzed in order to establish the amounts paid for active and reactive energy and for power demand charge. Such analyses and considerations may result in identifying the opportunities to reduce the costs for electricity even before taking a look at the technical aspects of the electricity use. In this case, no opportunities for changing the electricity supplier were possible as the foundry recently joined an electricity consortium, but the bills' analysis is informative as well. It started from the construction of the electric load and the load duration diagrams, measuring the 'instant' power (time step of 15 minutes) globally demanded by the foundry during the 3 weeks of February 2014. From these data the 'typical week' curves were deduced (Figure 6 and Figure 7).

The foundry works on two work shifts per 5 days a week (Saturday only one work shift), 47 weeks per year. The value calculated in Equation (1) can be considered satisfactory, taking into account that the curve depicted in Figure 6 is quite difficult to be smoothed due to the kind of the production process (use of the induction furnaces, the shake-out and take-out equipment to get the casting separated by the molding box and the sand, etc.) but above all due to the material handling equipment (e.g. the bridge cranes consume hundreds of kilowatts even if

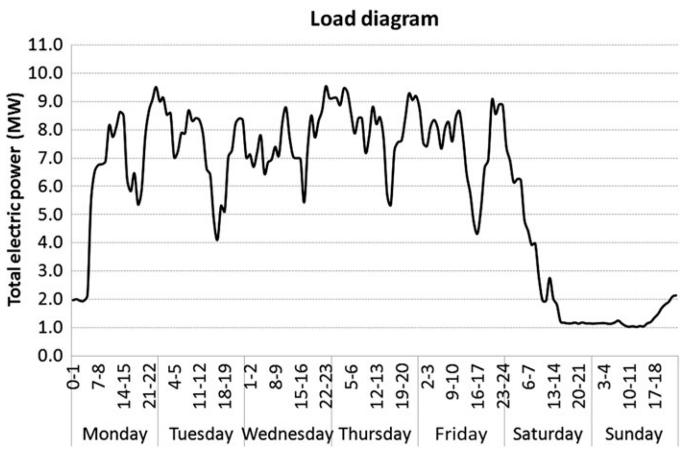

Figure 6. *Electric load diagram of a 'typical week' for the audited Foundry E.*

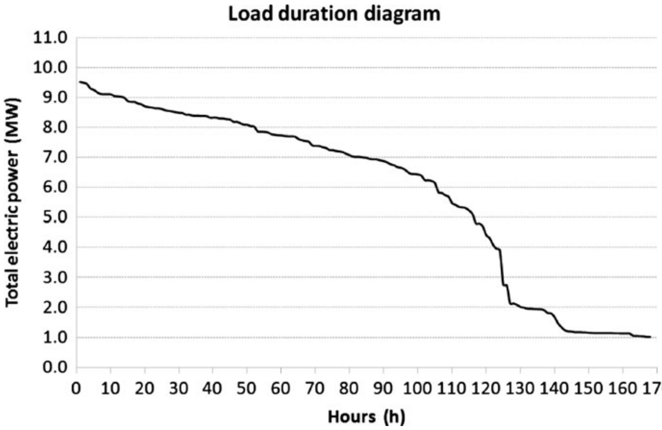

Figure 7. *Electric load duration diagram with reference to Figure 6.*

they operate, randomly, few seconds a time). Concerning the five induction furnaces, the use of PLCs and intelligent control systems could reduce significant electrical power demand and annual costs. Such systems record the demand and power consumption and saves the data, building up a characteristic curve on which the process controller synchronizes all the furnaces' separate cycle times to create a balanced load profile with no peaks in consumption. This could limit the demand charge due across the year as a whole. Furthermore, such intelligent control systems could increase energy saving as well with respect to traditional 'in series' disconnection furnaces management; in fact, they do not disconnect furnaces in series (for the first furnace in the series to be disconnected, the melting times would rise noticeably) but merely reduce their demand simultaneously for a brief time.

The curves allow to calculate the load factor (LF) that is a measure of the ability of using the total installed capacity during the time:

$$\begin{aligned} \mathrm{LF} &= \frac{\text{Average load}}{\text{Maximum load}} \\ &= \frac{\text{Energy consumed during the period}}{\text{Maximum demand} \times \text{time under consideration}} \\ &= \frac{990.32\,[\mathrm{MWh}]}{9.5449\,[\mathrm{MW}] \times 24\,[\mathrm{h\,d^{-1}}] \times 7\,[\mathrm{d\,w^{-1}}]} = 61.8\% \end{aligned} \tag{1}$$

However, a large part of the electricity consumption is not easily foreseeable (e.g. the above-mentioned bridge cranes) so that it is difficult to further enhance the LF value. For the LF calculated in Equation (1), the actual electricity bill structure can be considered good enough, as the total cost of electrical energy is in the flat part of the curve (Table 5, Figure 8).

A possible alternative to decrease peak demand and to increase reliability of the electric supply (due to the possibility of fewer interruptions in electric service) is the distributed generation.

A first possibility for electricity self-generation was examined in a previous article regarding the analysis of energy in process plants in foundries [26]. It concerned the utilization of waste heat for electricity generation. Strictly speaking, the heat of flue gases at the cupola exhaust should not be defined as waste heat even if it is usually simply dissipated to the environment. As clearly outlined by Bending *et al.* [29] a fraction of this heat can be recycled within the process, whereas another fraction can be recovered to a secondary process producing electricity. In fact the proposal was first a transfer of heat of the flue gases outside the cupolas to the combustion air and then the residual enthalpy was exploited in a steam generator or an Organic Rankine Cycle (ORC) in small foundries with discontinuous utilization of the cupolas.

In the past, these operations were prevented by the high temperatures and corrosive environment due to the flue gas. Recent availability of special alloy heat exchangers allows to face both the aspects. Kilkovsky *et al.* [30] illustrate how to face the problems of fouling due to solid particles contained in the flue gas as in the cupola exhaust. Aquaro and Pieve [31] give an overview of recent high-temperature heat exchangers technology developments.

Table 5. *The monthly electrical bill components structure.*

Energy charges	Energy	F1	€ kWh^{-1}	0.08238
		F2-F3	€ kWh^{-1}	0.06533
	Grid losses[a]	F1	€ kWh^{-1}	0.08238
		F2-F3	€ kWh^{-1}	0.06533
Dispatch charges	Fixed		€	1.55
	Variable		€ kWh^{-1}	0.0108
Transport charges	Distribution	Fixed	€	34.7091
		Power	€ kW^{-1}	2.3598
		Variable	€ kWh^{-1}	0.00048
	Transmission		€ kWh^{-1}	0.00568
	Measurement	Fixed	€	22.1377
	A/UC/MCT charges	Fixed	€	19.19
		Variable	€ kWh^{-1}	0.05226
VAT		10%		

[a] The energy charges due to grid losses have to be imposed on the 4% of the energy consumed per each time period slot (F1, F2, F3).

A/UC/MCT charges are connected to general costs of the national electricity generation and transport system (e.g. costs for the incentive of renewable energy sources, costs for the casting off of the nuclear plants, etc.). F1 is the peak hours time slot, F2 the intermediate hours time slot and F3 the off-peak time slot.

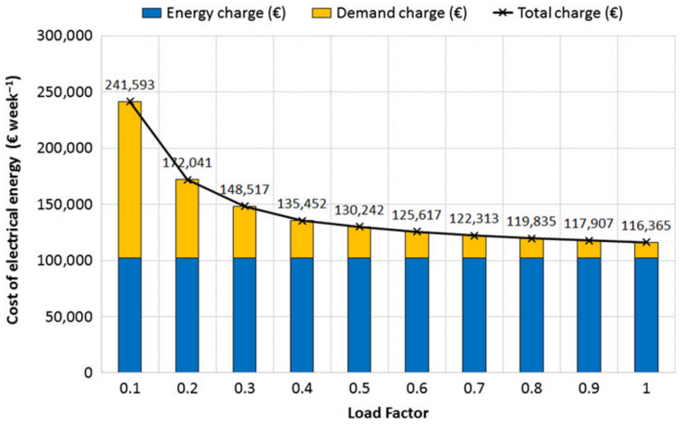

Figure 8. *Total cost vs LF for the rate structure reported in Table 5.*

Table 6. *Technical characteristics of the generators considered for 1 MW electric power.*

	P_{el} (kW)	P_{th} (kW)	P_{in} (kW)	η_{el} (%)	Investment cost (€ kW^{-1})	Availability (%)	Maintenance cost (€ kWh^{-1})
RESI	1000	1050	2500	40.0	900	95	0.009
GT	1000	1222	2778	36.0	700	95	0.0045
ORC	500		2632	19.0	1400	95	0.009
	400		2260	17.7			
	350		2059	17.0			
	300		1875	16.0			
	250		1724	14.5			
	200		1538	13.0			
	150		1304	11.5			
	100		1000	10.0			
	50		556	9.0			

P_{el} = electric rated power; P_{th} = thermal rated power; P_{in} = input rated power. Concerning ORC, characteristics of different sizes (compatible with the thermal power recovered by RESI and GT) are reported. Availability is a factor multiplying the power to calculate the yearly energy that can be effectively produced.

Table 7. *The monthly NG bill components structure.*

Fixed cost (€)	32		
Variable cost (€ Sm^{-3})	0.28		
Consume tax (€ Sm^{-3})	0.012498	Discounted Consume tax (€ Sm^{-3})	0.0001348
Regional tax (€ Sm^{-3})	0.006249	Discounted Regional tax (€ Sm^{-3})	0
VAT	10%		

Table 8. *Economic valorization of the electricity sold to the distributor for the North Italy zone (where the foundry considered is located).*

	North Italy		
	F1	F2	F3
€ kWh^{-1}	0.06123	0.06261	0.04987

An additional possibility is the direct self-producing part of the electrical demand of the foundry driving prime motors. Note that cogeneration is not considered here as the heat demand of the foundry is mainly satisfied by the heat recovery from various processes such as from air compressors or the induction furnaces (see Section 5).

The analysis here proposed is based on the previously described load curves (Figures 6 and 7) and considers two kinds of technologies: Reciprocating Engine Spark Ignition (RESI) and Gas Turbine (GT), whose technical characteristics are reported in Table 6. For each technology, two typical sizes of the generator (1 and 2 MW electric power) and two possibilities (buying one generator or three generators) were considered. Equipment were considered to be operated at full power in all the time slots (F1, F2 and F3).

A likely limit to the economic viability of the solutions here proposed is because the heat available from the motors is of no use in the foundry. A possible alternative to recover heat from the exhaust of the RESI and the GT is coupling an ORC. It uses organic fluids (e.g. polysiloxane) that evaporate at lower pressures than water giving the possibility of lower maintenance costs and greater automation level of the plant. ORCs are competitive when the heat source is at medium or low temperature (say below 400°C) because they have a thermodynamic efficiency not far from Rankine cycles with no condensation in the expansion and lower thermo-mechanical stress of the turbine.

So, the same solutions mentioned earlier were considered with an ORC coupled as well, considering a coupling heat exchanger with an efficiency of 80%. These solutions were investigated also considering a different operation strategy that is stopping the generators from Saturday 3 pm to Monday 5 am (when there are not work shifts and so the electric load demand is at the lowest values, Figure 6).

Table 7 reports the NG bill components for the economic evaluation of the generators consumption: it is worth to stress that in Italy NG used for self-producing electricity has a reduction in the consume tax and a cancellation in the regional tax. Table 8 reports the economic evaluation of the surplus electricity sold to the grid by the 'dedicated withdrawal' (the company can sell the produced electricity to the local distributor): the sell price is a function of the zone of Italy where there is the grid of the distributor to which the self-producer is connected and it is a function of the time slot as well.

Furthermore it is worth to stress that a recent Italian Government law (Decree 91/2014) establishes that for the case here considered (self-generation system not based on renewable energy sources or cogeneration), the so-called electric system charges (the extent of which is of the order of 5 c€ kWh^{-1}) have to be paid for all the 'consumed but not from the grid' electricity (that is for the self-produced electrical energy). So the analysis was conducted both considering and not considering the decree (strongly challenged by Italian trade associations) in order to appreciate the strong effect of such a law in distributed generation economic viability and so in its potential diffusion.

For the sake of brevity, Table 9 reports the results for the 'extreme' cases only: one generator of 1 MW and three generators of 2 MW electric power each, both considering and not considering the effect of the Decree 91/2014. The period of the analysis is 10 years, and the real interest rate is 4.1% (7% annual energy inflation rate and 2.8% discount rate). From the economic point of view, RESI and GT behave quite similarly. All

Table 9. *NPW and DPB in the period of the economic analysis for the alternatives considered: only generator (RESI, GT), generator + ORC (RESI_ORC, GT_ORC), generator + ORC not operating from Saturday 3 pm to Monday 5 am (RESI_ORC2, GT_ORC2).*

		NPW (€)		DPB (years)	
		Decree 91/14 not considered	Decree 91/14 considered	Decree 91/14 not considered	Decree 91/14 considered
P_{el} = 1 MW (1)	RESI	3 386 384	−75 119	1.8	11.1
	GT	3 317 080	−144 424	1.5	13.4
	RESI_ORC	4 020 715	275 780	1.7	7.5
	GT_ORC	3 988 603	171 949	1.5	8.0
	RESI_ORC2	2 906 850	114 373	2.2	8.8
	GT_ORC2	2 930 917	84 962	1.9	8.9
P_{el} = 2 MW (3)	RESI	12 210 829	−8 558 191	2.7	
	GT	11 795 001	−8 974 019	2.3	
	RESI_ORC	16 045 686	−7 216 785	2.5	
	GT_ORC	15 986 208	−7 987 993	2.2	
	RESI_ORC2	16 827 414	−518 659	2.4	11.1
	GT_ORC2	17 217 161	−659 626	2.1	11.7

Cases with one generator of 1 MW and three generators of 2 MW electric power each, both considering and not considering the effect of the Decree 91/2014.

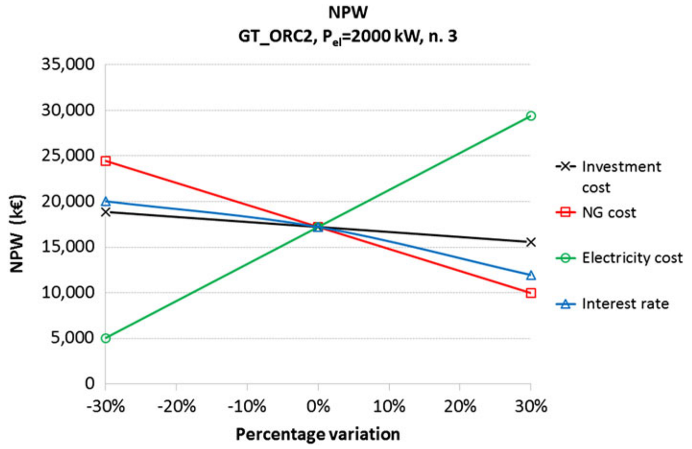

Figure 9. *Sensitivity analysis for the best case of Table 9 (GT_ORC2): NPW as a function of the investment cost, the NG cost, the electricity cost and the interest rate variation with respect to the value used in the economic analysis.*

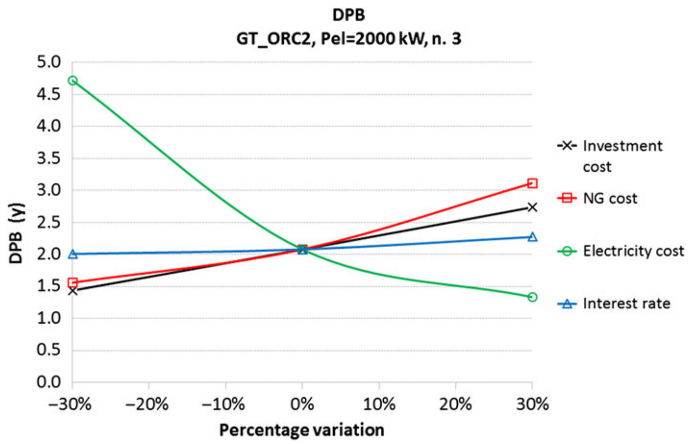

Figure 10. *Sensitivity analysis for the best case of Table 9 (GT_ORC2): DPB as a function of the investment cost, the NG cost, the electricity cost and the interest rate variation with respect to the value used in the economic analysis.*

the solutions have a discounted payback (DPB) around 2 years (between 1.5 and 2.7 years). Generally speaking, coupling the ORC has a positive effect as the electricity self-production increases. The most profitable solution is a plant constituted by three GT generators coupled to ORCs operating 24 hours per day except from Saturday 3 pm to Monday 5 am (GT_ORC2): it features a Net Present Worth (NPW) around 17.2 M€.

The new legislation has very important effect on the economic viability of the investments: comparing the columns of Table 9 it is worth to note the impressive increase of the DPBs and the decrease of the NPWs. Only the solutions with one generator coupled to ORC maintain a DPB around 7.5 years. All the other solutions have a DPB around or greater than 10 years; the solutions with three generators are not profitable at all as the investment cost is never counterbalanced by the annual electricity savings (except the solutions with the ORC not operating during weekends).

Results depend on the previous assumptions concerning the initial investment cost, the cost of electricity and NG and the interest rate of the economic analysis. A sensitivity analysis was developed varying these parameters in order to assess the economic viability of the investment. The results for the best case (three GT generators coupled to ORCs operating 24 hours per day except from Saturday 3 pm to Monday 5 am, not considering the effect of the new Decree 91/14) are reported in Figures 9 and 10. The economic viability of the investment in distributed generation for the foundry is strongly affected by the cost of energy supply: an increase till 30% of the cost of electricity can bring the NPW of the most profitable solutions near 30 M€ and the DPB around 1.5 years. Similar results were obtained in case of decreasing the NG cost till 30%. The reduction of the investment cost has instead a lower effect, while developing the analysis considering the very low inflation rate and interest rate of the actual period can further improve the economic results.

Other minor energy and economic saving opportunities from the electricity supply side can be related to:

- Increasing power factor: cast iron foundries, above all the ones with electric induction melting furnaces, are very 'inductive' electric users because all the industrial users (motors, power electronic devices, lighting and furnaces) absorb very high inductive reactive power. As it is well known, this causes the power factor (that is the cosine of the phase angle between voltage and current) to be quite lower than 1, causing different drawbacks all linked to the higher current intensity absorbed by the electric users for a given real power. In all the audited foundries, no penalties in the electric bills for power factor lower than 0.9 were detected as large capacitive reactive power was installed;
- Optimizing electrical transformers size: electric transformers used in industry are typically medium/low voltage (MV/LV) or high/medium voltage (HV/MV), and they have very high efficiency, typically above 95–96%. Also for this reason, generally energy efficiency optimization is not the main issue faced during the design phase of a transformer station, but plant and safety issues are. Once the latter are completely satisfied, it is a good rule selecting the transformer size to obtain the highest efficiency, that is operating it at a partial LF that allows the maximum efficiency for its 'load losses at rated power to no-load losses' ratio (even if the different partial load conditions differ typically for <1%).

5 ELECTRICITY DEMAND: FANS, PUMPS AND MOTORS

From the electricity demand point of view, the electric motors are used as source of power for driving a number of mechanical devices in foundries, which in turn provide mechanical work. It is usual to refer to the set of an electric motor and the attached mechanical device (fan, pump, conveyer belt, other cast iron production process equipment) as an electric motor drive. So energy efficiency can be faced considering this entire system: the motor, its control and the connection between the motor and the driven equipment.

5.1 Electric motors

According to de Alemeida *et al.* [32] 'pumps, fans and compressors are by far the most important loads in industry and in the services sectors'. Electricity consumption by end use in industrial sector can be attributed 18% to air compressors, 16% to fans and 21% to pumps. Even if Saidur [33] gives a different distribution in electricity use (that is only 8% to air compressors, 23% to fans and 32% to pumps), these three utilities are by sure the most important electricity consumers in the industrial sector. A similar estimate can be applied also to foundries using blast cupolas.

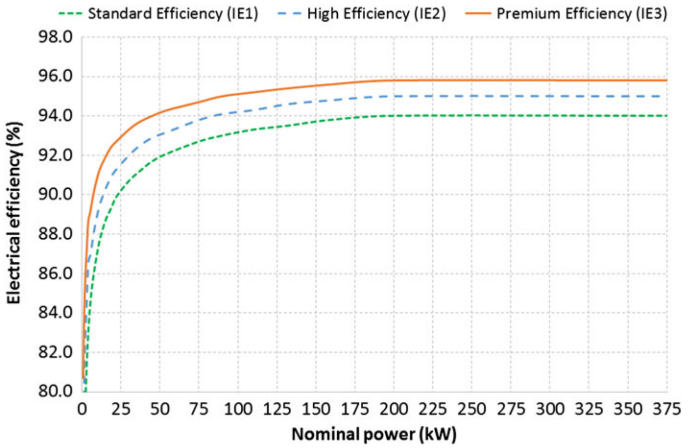

Figure 11. *Electrical efficiency classes as defined in IEC 60 034-30:2008 standard (two-pole motors).*

In cast iron foundries, electric motors are largely diffused in all the departments: coupled to fans for the exhaust extraction from the furnaces or for the air supply in cupolas or for the transportation of sand, coupled to pumps or inside other production process equipment. In this last case, users have no influence on the motors' power as the motors have been delivered together with the equipment.

A first obvious way to get energy efficiency is to buy high efficiency motors instead of standard ones. For three-phase asynchronous one-speed motors (the most widespread in industry), the IEC 60 034–30:2008 standard defines the energy efficiency classes as reported in Figure 11. High efficiency IE2 motors feature an improvement in efficiency ranging from 0.5 to 1.5% at a cost increase of ~15–25% with respect to standard efficiency ones [34].

Hasanuzzaman *et al.* estimate that by introducing high efficiency motors into the industrial sector, 5.5% of energy could be saved [35]. The efficiency improvement typically comes from an increased use of laminated steel, increase core length, use of more copper in stator windings and rotor bars and more rigid quality control measures. For example, for the Foundry E considered in Section 4.1, the substitution of the existing IE1 motors coupled to the pumps of the cooling water circuit and the evaporative tower circuit connected to the electric induction furnaces could produce an appreciable energy saving (Table 10); as the investment cost of the motors is between 40 and 60 € kW^{-1} in the range of power here considered, the payback period may be ~2–7 years according to the motor size.

Another aspect that affects the efficiency is the oversizing of motors. Motors operating at partial load decrease not only their efficiency (typically constant till 75% of the full load, then falling by around 5% at a load of 50%, then declining dramatically) but also they increase their demand of inductive reactive power (that is they decrease power factor even faster than efficiency). So, when considering the substitution of an old or damaged electric motor, it is worth to estimate the effective needs in mechanical work in order to eventually buy a smaller size one.

Table 10. *Data for the example in the text.*

	Number of pumps operating simultaneously	Nominal power (kW)	Operating time (h y^{-1})	Nominal efficiency IE1 (%)	Nominal efficiency IE2 (%)	Energy saving (kWh y^{-1})	Energy saving (€ y^{-1})
Cooling tower	3	11	3360	87.6	89.4	2232	338
Cooling water induction furnaces	1	22	3360	89.9	91.3	1133	172
Cooling water induction furnaces[a]	1	75	7900	92.7	94.0	8194	1242
Total						11 560	1753

[a] Four-pole motor.Operating hours of the pumps consider that the induction furnace cooling water circuit is always operating (24 hours per day, 47 weeks per year), while the cooling tower circuit is operating only during 'no heating' weeks (24 hours per day, 20 weeks per year) when the heat gained by the cooling water has to be dissipated. Cost of electrical energy was assumed to be the one reported in Table 5.

5.2 Variable speed drives

Increasing the efficiency of electric motors is only the first step. The key to achieve peak efficiency of the system is running only when necessary and at the capacity needed to meet the demand, operating in a stable and precise control range that matches system demand. Also in foundries, variable speed drives applications represent a great potential for reducing electric energy consumption by replacing the traditional regulation of pressure and fluids flows obtained by throttling, by adjusting vanes and blades of pumps and fans and bypassing lines. Electric motors have to be fed by a controlled speed drive unit typically constituted by four main components: an alternate/direct current (AC/DC) converter, a DC link circuit to electronically recreating the wave form with necessary voltage and frequency, a DC/AC inverter and the control unit to correctly feed the motor. Reducing the speed of electric motors when no nominal value is requested decreases the power demand with the cube of the speed (theoretically) or with something between the cube and the square (practically).

Hundreds of electric motors are present in each of the audited foundries, some already driven by variable speed inverter-based systems.

As an example, Foundry C installed two inverters to the two fans that provide the exhaust extraction from a furnace: power of the fans 2 × 132 kW, flow rate 130 000 $m^3 h^{-1}$ (36 $m^3 s^{-1}$), working 230 days y^{-1}, 12 hours d^{-1}, 2760 hours y^{-1}. The electricity demand during the year before the improvement was of 728 640 kWh. After the renovation, 1380 hours were surveyed at 50% capacity with an electricity rate of only 60 kW, whereas for the left time the average rate was 200 kW. Consequently, the recorded electricity consumption was of 358 800 kWh with an energy saving of 369 840 kWh.

The economic result can be immediately appreciated comparing the investment of 15 000 € with an annual saving of more than 50 000 €.

6 HEATING, VENTILATION AND AIR CONDITIONING

HVAC in foundries calls for a minor percentage of the total energy consumption; for example for the induction furnaces foundry already considered in the previous sections (Foundry E), the audit established that HVAC calls for <30% of the thermal energy consumption and only 4% of the electricity consumption. In this case, as the greatest part of the furnace energy losses (~70%) is in the inductive coils and they have to be cooled typically to a temperature around 40–45°C, a useful heat recovery is easily obtainable. In effect, the audited foundry actuated a thermal heat recovery by the five induction furnaces, producing 432 000 kWh of thermal energy during 2013 used to heat offices (by means of low temperature ceiling fan coils) and molding department (by means of unit heaters). Measured data concerning the thermal power recovered and the furnaces' electric consumption linked to suitable assumptions on average work LFs and average monthly work hours of the furnaces give an estimation of the thermal energy recovered for heating purpose; this results in the order of 5% of the total furnaces cooling energy and 1.4% of the melting electrical energy consumed by the furnaces.

Most of industrial buildings, differently from commercial and residential ones, are characterized by:

- The large size of the conditioned air volume with respect to the working area [36]. The large part of the factory sheds are >4 m high (50% are >6 m high), that causes a strong stratification effect (air is considerably and uselessly warmer near the ceiling). Furthermore, the big dimensions in plant can cause irregular heat distribution as a function of the type of heating system. This, together with the frequent opening of large doors and receiving/shipping bay doors, can cause great energy cost and drawbacks in reaching rapidly the right indoor thermal conditions;
- In all the audited foundries the manufacturing departments were heated only (as it is very usual in factory sheds). Air temperature and humidity control was provided in none of the foundries. Instead, due to the dusty atmosphere and sometimes high carbon monoxide (CO) content, foundries are equipped with ample sizing of exhaust stacks. Excessive air exhaust may result in under-pressure in the building and draught problems. In production areas inside the foundries, the existence of too many exhaust points and the lack of a system for air supply may create this negative

pressure, also increasing the heating needs due to the fresh makeup air being brought in from outside in winter. Replacing the general ventilation of the entire area with locally situated, hooded exhausts from areas that need to be ventilated (e.g. over bake-core making machines, furnaces, ladles and pouring stations) was a viable solution to limit energy cost of ventilation detected in some of the audited foundries;

- Relating to all this, the heating systems used in the audited foundries were substantially of two types: direct air heating (typically unit heaters and floor standing air heaters) and radiant heating (radiant tubes and radiant strips);
- Near the manufacturing buildings, also office (administration, design, logistic) and laboratory (testing and inspection, research and development) buildings are situated. These need typically all-year air-conditioning and are served by more traditional HVAC plants (boilers + air conditioners or reversible air to water heat pumps/chillers).

7 WATER SUPPLY

Even if water is not directly connected to energy use, the possible reduction of water utilization is always pursued in an energy auditing both for environmental and economic reasons. In the past, water was directly provided by factory water wells at the only cost of pumping. Costs today are due above all to sewer charges that differ from one municipality to another with an overall cost of not <0.2 € m^{-3} for process water to 2.5 € m^{-3} for potable water.

The main water utilization in foundries is for cooling purposes, particularly:

- for induction furnaces to cool the coils;
- for cupolas to protect the refractory;
- for a first cooling of the very hot exhaust from the cupola before filtering;
- to cool the castings;
- to cool the compressed air during compressed air refrigeration.

Another important water utilization is the molds and core preparation to humidify the sand.

Of course like other factories, potable water is required for the kitchen use of the canteen and for the workers' showers.

As far as the last use is concerned, the recorded consumption of one of the audited foundry was of 5939 $m^3\,y^{-1}$, about a half for showers and a half for kitchens: the consumption does not look so notable but consider that it is mainly hot water. The increasing cost of sewer charge had already obliged the foundries to adopt water conservation measures. Previous requirements up to 500 000 $m^3\,y^{-1}$ were reduced to figures from 15 000 to 100 000 by avoiding disposable water cooling or by air cooling. Where cooling temperature strongly influences process efficiency, evaporative cooling was used. These actions not only favored the reduction of the sewer bill but also the consumption of the well pumps. In one of the audited foundry, a 14 kW well lift pump withdraws water from a 54 m deep well. The halving of energy use, withdrawing only the really needed water, allowed an electricity saving of about 30 000 kWh y^{-1}.

Whereas many different actions can be undertaken to save water in cooling, no possibilities are available to save water in molds and core preparation.

An audited foundry realized a plant for recovery of rain water. This action was made compulsory as the authority responsible for the control of sewers obliged to the depuration of the first rain water on the whole factory area. The first rain is defined as water deriving from a strong rainfall in the first 15 minutes. In this case, the affected area is of 54 000 m^2, which is 21 000 m^2 of building roof, 17 000 m^2 of impervious and 16 000 m^2 of ground yard. The first rain water was evaluated in 7.5 mm water per m^2. Therefore, a concrete collecting tank of 460 m^3 was provided, slightly more than the 405 m^3 strictly required. A second tank was also provided for sedimentation and oil extraction of 740 m^3 capacity.

If the rain ceases before the filling of the first tank, a submersible pump sends directly the water to the second tank and from there directly to the process utilization where the requirement is evaluated in about 40–50 $m^3\,d^{-1}$. If the rain goes on till the filling of Tank 1, water overflows from Tank 1 to Tank 2 where it can be treated before being discharged in the sewer. A third tank of 600 m^3 capacity is for the storage of treated water and from there to the production for period of scarce rainfall.

According to rainfall reports at the locality of the factory, the described system can supply practically all the process water. It should be noted that the high investment (~600 000 €) was justified by the legal obligation rather than on economical basis.

8 PV PLANTS

Some considerations are here presented on the possible use of renewable energy in foundries.

Solar thermal is not suitable, as it could be of use for producing hot service water, but plenty of heat is available in a foundry by heat recovery from various processes.

Probably the only possibility is a PV plant, whose capacity is anyhow very small comparing the electricity requirements with the available area for PV modules.

Two of the audited foundries installed a PV plant on the roof of the factory. The former had a plant with a 220 kW peak power of polycrystalline silicon. The plant gave 187 040 kWh in 2013. The latter had 643.4 kW peak power, 2681 panels on an area of 4290 m^2. The produced electricity was 701 974 kWh in 2012 and 662 726 in 2013. In this case, the investment was of 1.6 M€ and the DPB is estimated in 7 years with the incentives provided at the time of the investment with a grant of about 22 c€ for every kilowatt-hour even if used inside the factory.

9 CONCLUSIONS

As anticipated, the energy need for service plants represents in a foundry a minor fraction of the whole energy consumption. Nevertheless, the amounts are absolutely outstanding, particularly concerning electricity, often of the order of hundreds of megawatt-hours per year for the audited foundries. The conducted analysis on the various services was meaningful. First of all, it concentrated on the most energy intensive services within a cast iron foundry such as compressed air and electric motors for fans and pumps. Secondly, even for those services that are common and of similar importance in other industrial branches such as lighting or electricity management or HVAC. The survey of actions really undertaken allowed to produce some quantitative pictures of energy and economic balance. Experience of replacement of compressors or of lighting system or resorting to variable speed motors has been reported. Some of the described interventions demonstrated DPB from <1 year to 3–4 years at the actual discount rates.

Self-producing of part of the electricity demand might return the investment as well in 3–4 years even without heat cogeneration. Higher payback times are reached operating the RESI or the GT with an ORC in a combined cycle but with better NPW in longer periods. This is true also for steam or ORC cycles driven by recovered heat from the metal melting process, as reported in previous articles [25, 26]. Unfortunately, an unwise recent Italian Government law charges the self-produced electricity even if directly consumed by the factory with the electric system general charges at the actual disproportionate burden of about $4\,\text{c€}\,\text{kWh}^{-1}$. Consequently, the payback period exceeds 7–8 years, so that no such actions are advisable in Italy.

Finally, the possibility of reducing the water consumption by collecting and storing rain water must be considered a good solution for the environment even if economically very expensive.

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