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Analisi di metodologie per il calcolo della domanda termica industriale e applicazione al caso italiano

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Summary

Introduction

One of the main challenges of the 21st century is certainly the reduction of greenhouse gas emissions (in particular CO_2); to achieve this, the decarbonisation of the energy system is necessary.

In Italy in 2018 the industrial sector accounts for the 21% of the total final energy consumption [1] equal to 24.2 Mtoe, with 406.3 ktoe coming from renewable sources (1.7% of the industrial energy consumption). A key point is to establish how this energy is used, in particular the share that is used for heat production and the temperature levels of it.

To date, the decarbonization of the industry is mainly based on the electrification of production processes, which combined with the production of electricity through renewable technologies such as photovoltaic and wind power, allow to reduce carbon dioxide emissions. However, this strategy has several limitations, linked both to the renewable sources used and to the production processes to be decarbonised. A first problem is linked to the discontinuous production of energy from renewable technologies such as photovoltaics, due to meteorological, geographical and seasonal conditions.

There are processes that require large amounts of thermal energy at high temperatures; then the high-temperature heat demand can be a limit to the industrial thermal processes decarbonisation with classical renewable energy sources such as geothermal energy or (non-concentrating) solar thermal, which cannot provide thermal energy at the required temperatures. An example is the steel production, for which temperatures above 1,500°C are required inside the blast furnace. In this process coke is generally used, which performs two fundamental tasks: in addition to providing the necessary heat, it serves to reduce the raw mineral used to produce cast iron. This poses a further problem for the replacement of fossil fuel. Therefore, specific information on required temperature levels is of the essence.

The purpose of this thesis is the evaluation of the industrial thermal energy demand in Italy; in particular, thermal energy consumptions of the different sectors and the associated temperature levels will be calculated. The assessment of the thermal energy demand of the Italian industrial sector is based on methodologies illustrated by [2]. The study aims to estimate the final industrial thermal energy demand for all member states of the European Union using 2 calculation approaches based on different datasets, which allow to evaluate the thermal demand divided by different temperature ranges. Both approaches are based on thermal energy consumption data in German industry sectors: therefore, the hypothesis behind the evaluation is that the estimates for the share of thermal energy for the different sectors and temperature levels are equal (or at least comparable) to those found in Italian industry.

With reference to the Italian industry, data on global energy consumption for the main industrial sectors are used to estimate Italian industrial thermal consumption and temperature levels. These data are obtained from Eurostat analysis [3].

SECTOR	PJ
Iron & Steel	151.7844
Chemical & petrochemical	137.2171
Non-ferreous metal	29.88385
Non-metallic minerals	179.952
Transport equipment	17.14167
Machinery	145.5472
Mining & Quarrying	5.010642
Food, beverages & tobacco	117.2206
Paper, pulp & printing	86.26927
Wood & wood products	20.68721
Construction	14.99844
Textile & leather	47.16366
Not elsewhere specified (industry)	64.41417
Total	1,017.29

Table 1: Italian industrial energy consumption in 2018, Eurostat

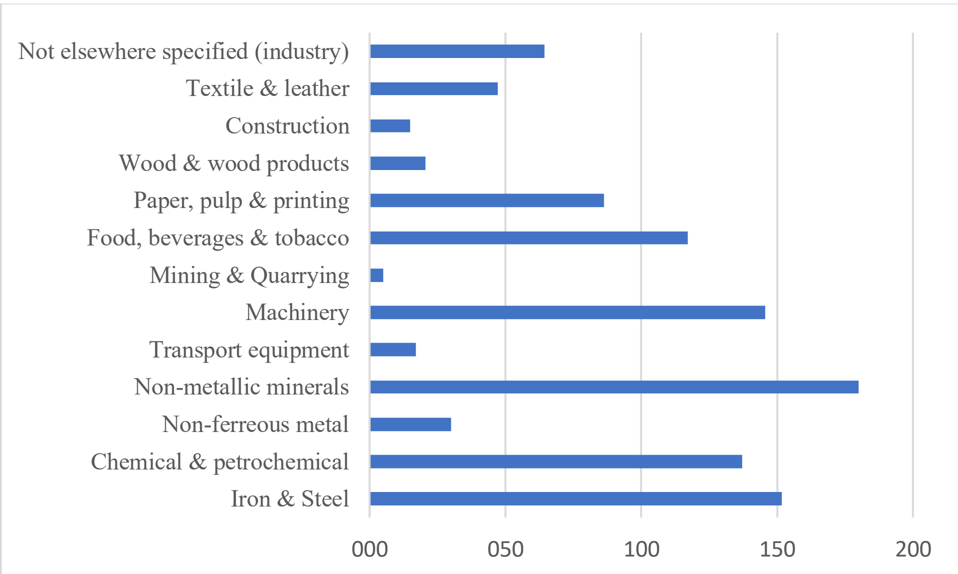

Figure 1: Italian industrial energy consumption in 2018, Eurostat

From the analysis carried out in this thesis using the two approaches, it is obtained that the total estimated thermal energy consumption is 713.44 PJ (approach 1) and 617.48 PJ (approach 2), respectively 70% and 61% of the total consumption.

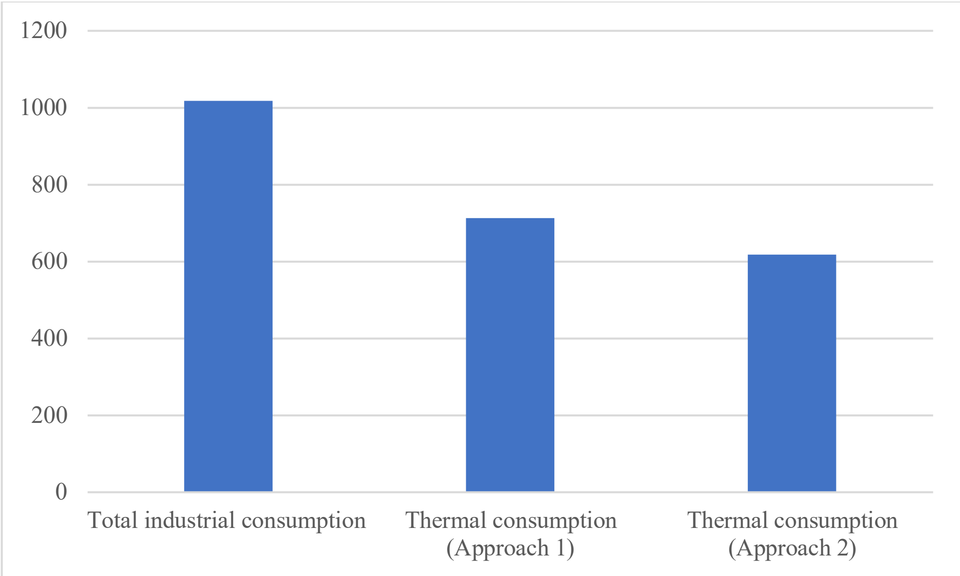

Figure 2: Total industrial consumption and calculated thermal consumption (approach 1 & 2) for the Italian industry

As for consumption by temperature level, the differences in the results are given by the different temperature levels and datasets used, but also because the definition of the industrial branches varies in the different datasets.

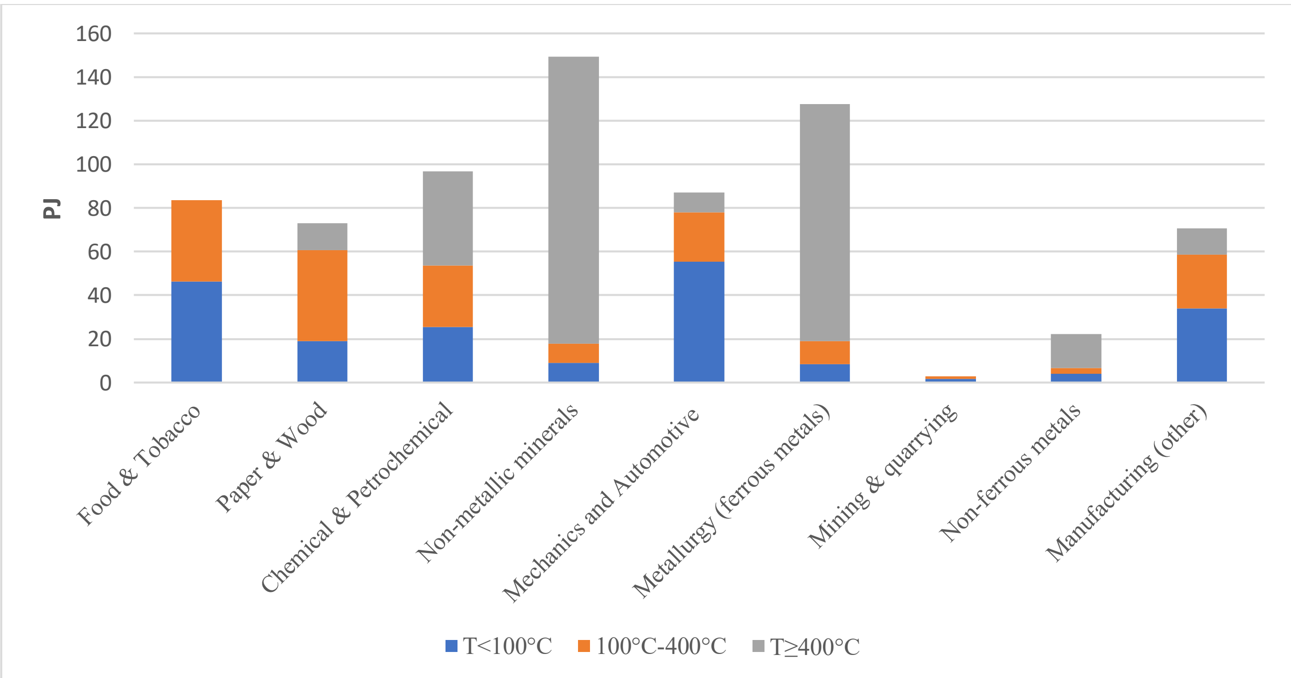

Figure 3: Approach 1 - Italian industrial thermal consumption by sector and 3 temperature ranges

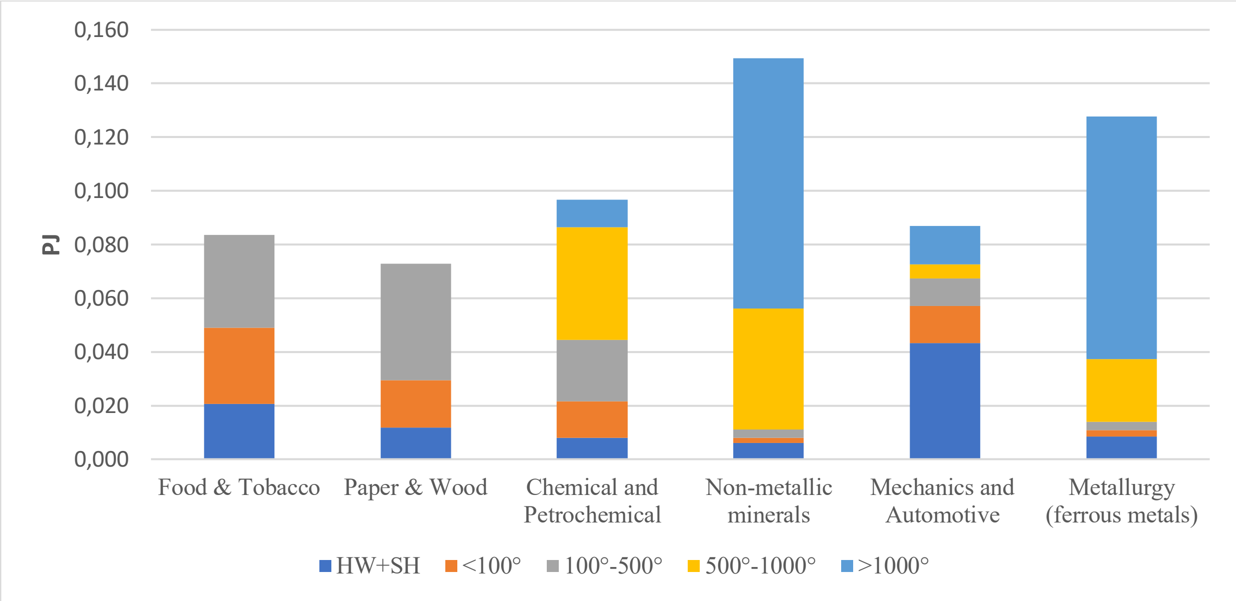

Figure 4: Approach 2 - Italian industrial thermal consumption by sector and 5 temperature ranges

Subsequently, a specific analysis is carried out on 3 Italian industrial sectors: steel industry (Metallurgy), paper (Paper & Wood) and cement (Non-metallic minerals). The choice of these 3 sectors is made first because they are part of macro-sectors analyzed which are characterized by the high consumption of heat and fossil fuels, especially for the production of cement (Non-metallic minerals) and steel (Metallurgy).

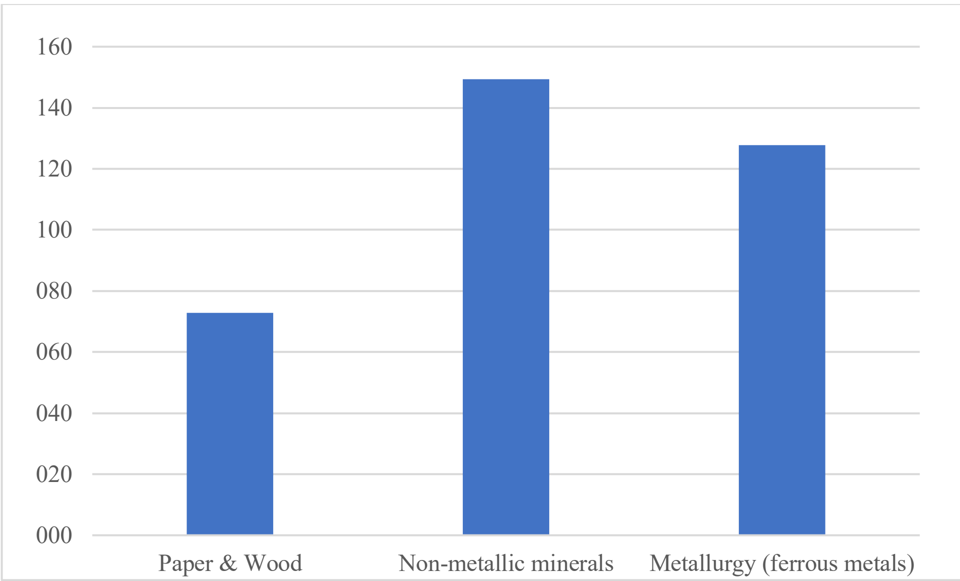

Figure 5: Thermal consumption for Paper & Wood, Non-metallic minerals and Metallurgy sectors (approach 1 & 2 results)

Another point is the presence of a good amount of data provided both by individual companies and by trade associations (eg Assocarta for paper companies), thanks to which it is possible to obtain an estimate of the thermal energy consumption for individual plants, in in order to geographically locate such consumption.
Finally, these sectors are characterized by mature and widespread technologies. In the case of steel, Federacciai's data shows that 82% of steel production in Italy in 2019 came from electric arc furnaces (EAF) and 18% from blast furnace (BF), which allows the use of specific thermal consumptions referred to the technologies-processes considered and therefore more accurate results.

The methodology used to calculate the thermal energy per plant depends on the data provided by the companies, and therefore is based, for example, on the actual production and specific thermal consumption provided by the company or obtained from the trade associations, or aggregate thermal energy consumption supplied by the company are divided among the various plants according to their production capacity.

Motivation of the study and analysis of the context

An analysis of industrial energy consumption, their evolution and the type of fuels used in the various sectors is essential to understand the context in which we operate; furthermore, the indication of the temperature ranges of some production processes can make it clear how an analysis of thermal consumption by temperature ranges is useful for dealing with the decarbonisation of production processes.

Italian industrial energy consumption in 2019 fell by 14% compared to 2010, with a relative stabilization from 2014 (fig.6); considering Europe (EU28), industrial energy consumption fell to a minimum in 2014, to then have a tendency to rise (fig.7).

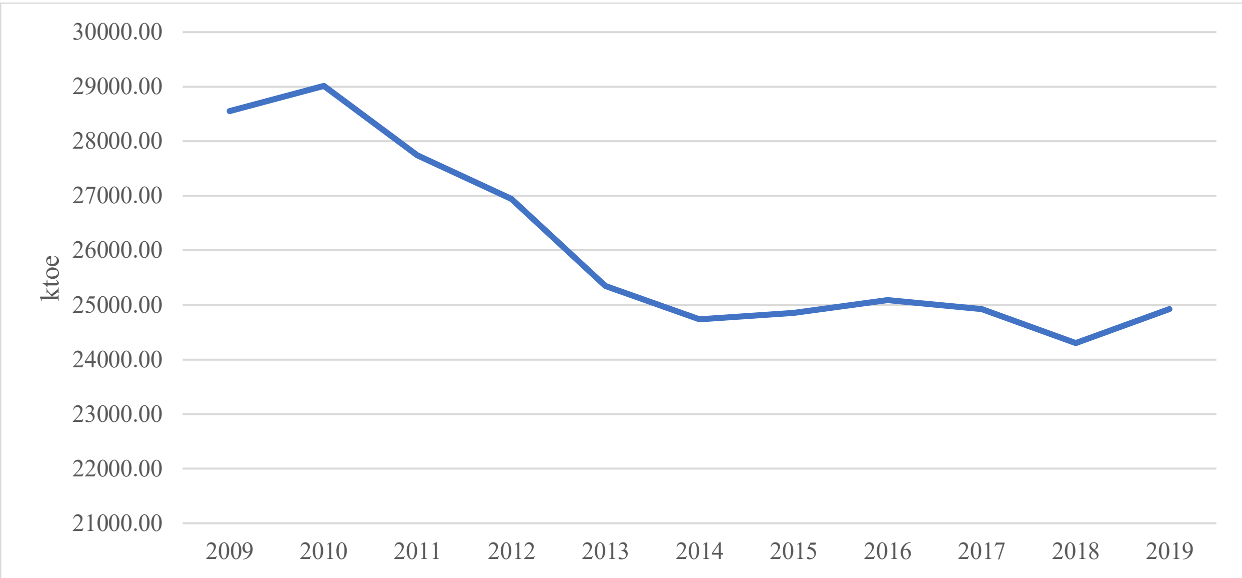

Figure 6: Trend of Italian industrial consumption from 2009 to 2019, Eurostat

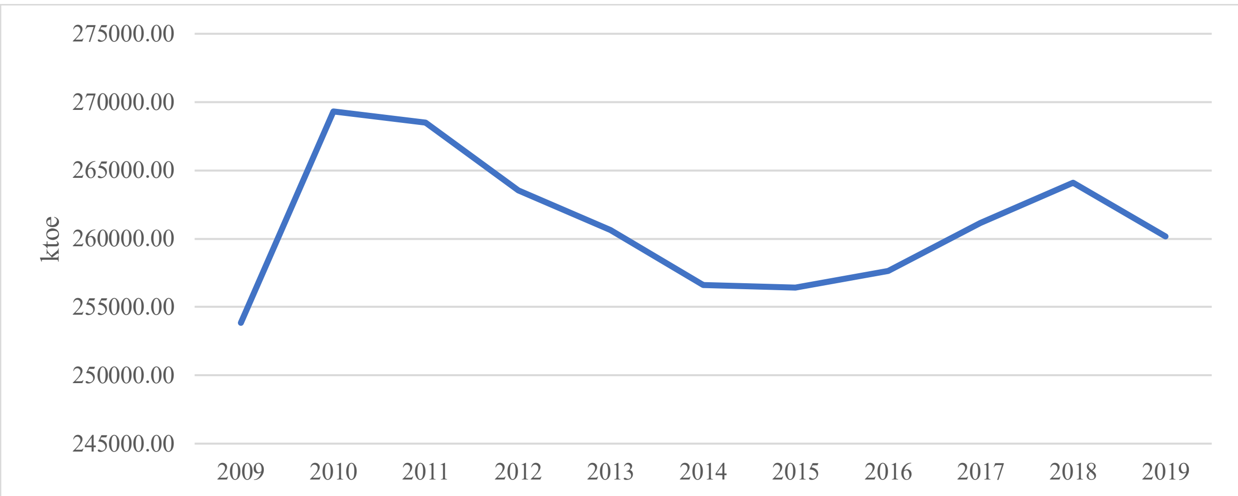

Figure 7: Trend of European (EU28) industrial consumption from 2009 to 2019 (Source: Eurostat)

The reduction in industrial energy consumption has also led to a reduction in fossil fuels used in the industrial sector, which, however, in 2019 in Italy still cover approximately 79.6% of industrial energy needs (fig.8), against a European average of 69.3 %.

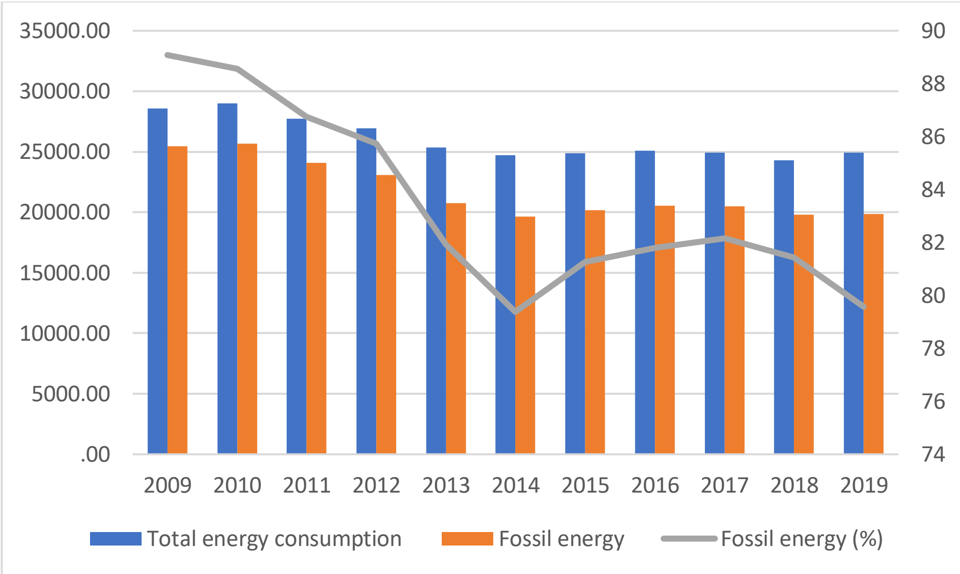

Figure 8: Total energy consumption, energy consumption from fossils and relative share for the Italian industry (Source: Eurostat)

By analyzing energy consumption by individual sector and by type of fuel used, marked differences can be seen in the percentages of energy from fossils. Comparing the different Italian sectors, it can be seen that most industrial branches have percentages of fossil fuel use higher than 70%, with Non-ferrous metals and Non-metallic minerals sectors reaching respectively 89.3% and 88.9%, while the lowest value is relative to Wood & wood products sector with 44.1% (tab.2).

Comparing the situation of the Italian sectors with the European average for each industrial branch (tab.3), it is noted that the percentage consumption of fossil fuels in Italy is generally higher, for example for Non-ferrous metals (+22,3%), Non-metallic minerals (+3,9%), Paper, pulp & printing (+41,1%) and Wood & wood products (+18,7%).

	Solid fossil fuels	**Manufactured gases**	**Oil and petroleum products**	**Natural gas**	**Renewables and biofuels**	**Non renewable waste**	**Heat**	**Electricity**	**Fossil energy**	**%**
Iron & steel	381.8	109.4	68.6	1,264.4	0.0	0.0	167.8	1,628.1	2,934.8	81.1
Chemical & petrochemical	0.7	0.0	327.4	931.4	6.8	81.3	973.7	1,174.7	2,840.1	81.2
Non-ferrous metals	27.8	0.0	62.7	396.6	0.0	0.0	1.3	175.1	592.6	89.3

Non-metallic minerals	172.3	0.0	826.7	2,016.1	134.1	163.4	159.0	765.5	3,765.2	88.9
Transport equipment	0.0	0.0	0.0	0.0	0.0	0.0	94.9	315.0	266.1	64.9
Machinery	0.0	0.0	222.8	1,325.2	2.8	2.7	81.5	1,860.7	2,729.8	78.1
Mining & quarrying	0.0	0.0	34.3	33.5	0.0	0.0	3.1	53.9	102.5	82.1
Food, beverages & tobacco	0.0	0.0	99.9	1,126.2	46.0	0.0	358.4	1,157.0	2,211.0	79.3
Paper, pulp & printing	0.0	0.0	33.8	617.3	0.4	0.0	658.3	748.0	1,637.1	79.6
Wood & wood products	0.0	0.0	0.0	28.0	158.2	3.7	26.6	267.5	213.6	44.1
Construction	0.0	0.0	18.4	210.4	1.7	0.0	2.4	157.1	324.6	83.3
Textile & leather	12.6	0.0	45.0	568.8	0.2	0.0	37.2	453.9	928.0	83.0
Not elsewhere specified (industry)	0.0	0.0	16.3	22.5	73.2	32.4	378.4	1,521.8	1,291.4	63.2

Table 2: Energy consumption by sector and type of energy carrier, Italy (Source: Eurostat)

EU28 2019	**Solid fossil fuels**	**Manufactured gases**	**Oil and petroleum products**	**Natural gas**	**Renewables and biofuels**	**Non renewable waste**	**Heat**	**Electricity**	**Fossil energy**	**%**
Iron & steel	2,837.9	4,650.5	457.7	7,757.2	10.8	2.6	484.3	9,484.6	19,999.0	77.9
Chemical & petrochemical	2,463.1	82.5	7,525.5	19,540.4	381.6	454.0	8,056.3	15,568.3	42,955.5	79.4
Non-ferrous metals	332.1	31.6	393.8	3,705.3	1.9	6.7	142.2	5,539.2	6,798.0	67.0
Non-metallic minerals	4,098.0	65.7	5,621.5	13,826.7	1,845.0	3,655.1	279.4	6,036.3	30,144.4	85.0
Transport equipment	231.2	27.2	374.1	2,732.3	23.3	0.1	571.9	4,575.0	5,737.7	67.2
Machinery	77.2	8.8	879.3	6,767.7	106.6	14.1	609.8	10,599.5	12,848.2	67.4
Mining & quarrying	170.6	3.2	843.7	749.5	78.2	1.1	147.3	1,653.1	2,488.8	68.2
Food, beverages & tobacco	1,197.0	0.0	1,555.9	14,239.9	1,160.6	6.9	1,432.4	10,574.4	22,388.8	74.2
Paper, pulp & printing	740.6	0.0	628.2	6,399.9	13,794.1	239.2	2,199.7	9,801.0	13,066.3	38.5
Wood & wood products	33.5	0.0	224.2	556.9	4,872.0	20.7	613.6	2,275.0	2,185.0	25.4
Construction	39.8	0.0	5,429.8	2,461.3	281.0	0.5	34.0	2,221.1	8,822.0	84.3
Textile & leather	62.8	0.0	181.7	1,988.5	26.3	1.2	150.7	1,782.2	3,182.4	75.9
Not elsewhere specified (industry)	374.1	0.3	1,767.1	2,766.6	1,037.8	38.5	1,693.6	8,117.0	9,724.7	61.6

Table 3: Energy consumption by sector and type of energy carrier, EU28 (Source: Eurostat)

So, Italian industrial energy consumption has decreased in recent years, and the use of fossil fuels has also decreased, which is however still above the European average; this indicates that there is still the possibility of significantly reducing the use of fossil fuels in Italian industry through the decarbonisation of production processes.

Knowledge of the temperature levels for the various sectors is important to establish which renewable technologies can be used for the decarbonisation of industrial production processes. In [4], for example, a table is presented with the temperature ranges of some processes identified as suitable for the use of heat supplied by low temperature solar thermal systems (fig.9). It can be noted that in certain sectors there are processes that are compatible or not with technologies such as solar thermal, as in the case of the paper sector where the drying process requires temperatures even higher than 200°C.

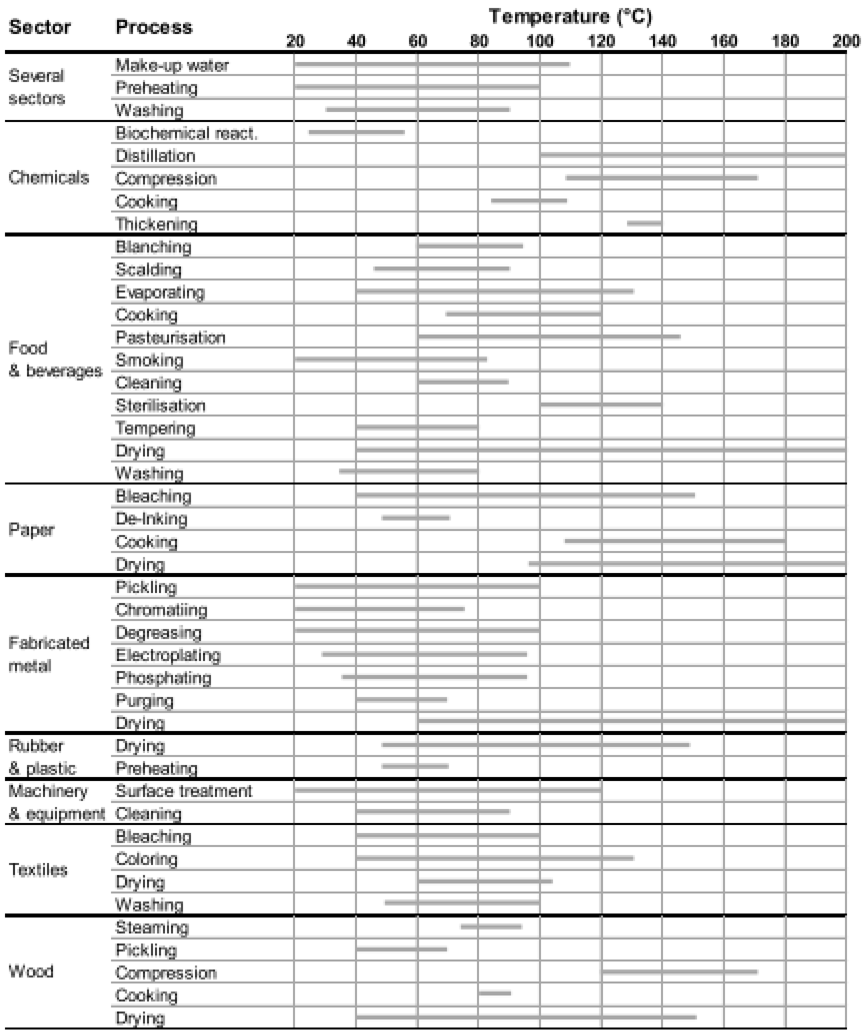

Figure 9: Temperature range for some industrial processes (source: [4])

There are also other processes that require even higher temperatures. [5] presents some processes that require high temperature thermal energy, such as the melting process of non-metallic materials, which requires temperatures up to 3,000°C (fig.10).

Process heating operation	Description/example applications	Typical temperature range (F)
Fluid heating, boiling, and distillation	Distillation, reforming, cracking, hydrotreating; chemicals production, food preparation	150–1000°
Drying	Water and organic compound removal	200–700°
Metal smelting and melting	Ore smelting, steelmaking, and other metals production	800–3000°
Calcining	Lime calcining	1500–2000°
Metal heat treating and reheating	Hardening, annealing, tempering	200–2500°
Non-metal melting	Glass, ceramics, and inorganics manufacturing	1500–3000°
Curing and forming	Polymer production, molding, extrusion	300–2500°
Coking	Cokemaking for iron and steel production	700–2000°
Other	Preheating; catalysis, thermal oxidation, incineration, softening, and warming	200–3000°

Figure 10: High temperature industrial processes (source: [5])

In this case, the classic renewable technologies cannot provide energy at such a high temperature (solar thermal or geothermal energy); it is therefore essential to know the temperature levels and the necessary quantity of thermal energy for the production processes, in order to understand which technologies are most suitable for decarbonisation.

Industrial sectors description

The subdivision of the different industrial sectors is one of the critical points of this thesis work. In fact, the datasets used have different classifications of the industrial sectors, which makes it necessary to reclassify the industrial branches in order to combine the different datasets. The sectors considered are presented below, with the indication of the NACE codes (statistical classification of economic activities in the European Community) where possible.

Sector	NACE code	Description
Food & Tobacco	C.10 – C.11 – C.12	Manufacture of food and tobacco products
Paper & Wood	C.16 – C.17	Manufacture of paper and paper products; manufacture of wood and of products of

		wood and cork (except furniture); manufacture of articles of straw and plaiting materials
Chemical & Petrochemical	C.19 – C.20 – C.22	Manufacture of chemicals (eg. Basic chemicals) and chemical products; manufacture of coke and refined petroleum products
Non-metallic minerals	C.23	Manufacture of non-metallic mineral products (eg. cement production, manufacture of glass and glass products)
Mechanics and Automotive	C.28 – C.29 – C.30	Manufacture of machinery and equipment; manufacture of motor vehicles, trailers and semi-trailers; manufacture of other transport equipment
Metallurgy	C.24.1 – C.24.2 - C.24.3 – C.24.5	Manufacture of basic iron and steel and of ferro-alloys and relative products (eg. pipes, tubes);
Mining & Quarrying	B	Mining of coal, lignite, metal ores; extraction of crude petroleum and natural gas
Non-ferrous metals	C.24.4	Manufacture of basic precious and other non-ferrous metals
Manufacturing (other)	C.13 – C.14 – C.15	Manufacture of textiles, wearing apparel, leather and related products; other manufacturing (eg. jewellery, musical instruments).

Table 4: Description of industrial sectors and indication of NACE codes

The sectors indicated are all present in the analysis of approach 1, while in approach 2 the Mining & Quarrying, Non-ferrous metals and Manufacturing (other) branches are not present due to lack of data correspondence between the datasets used.

Methodology analysis and dataset description

In this part of the thesis the use of two approaches presented by [2] is presented and applied. The two approaches allow to calculate the thermal consumption by sector and temperature band, using datasets obtained from various sources.

The approach 1 allows to obtain the industrial thermal energy demand divided into 3 temperature ranges: <100°C, 100–400°C, >400°C.

The approach 2 allows to obtain the thermal energy consumptions for 5 temperature ranges: SH+HW, <100°C, 100°C-500°C, 500°C-1000°C, >1000°C.

Study [2] calculates the thermal energy consumption by temperature range for the industrial sectors of the different European countries using 3 datasets for approach 1 (DS1-1, DS1-2, DS1-3) and 3 for approach 2 (DS2-1, DS2-2, DS2-3).

Approach 1

- DS1-1: German industrial heat consumption for 3 temperature ranges (<100°C, 100–400°C, >400°C); (AGFW - Germany 2001)
- DS1-2: EU 28 states industrial energy consumption (IEA – 2012)
- DS1-3: Energy demand divided by industrial sector and by type of final use (ISI - Germany 2012)

Approach 2

- DS2-1: German industrial heat consumption for 5 temperature ranges (SH+HW, <100°C, 100°C-500°C, 500°C-1000°C, >1000°C); (Germany 2006)
- DS2-2: EU 28 states industrial energy consumption (Eurostat - 2012)
- DS2-3: Energy demand divided by industrial sector and by type of final use (ISI - Germany 2012)

Figure 11: Approach 1 & 2 - dataset used by [2]

Considering approach 1 (same process for approach 2), the dataset DS1-3 (DS2-3) is used to obtain coefficients (called α in this thesis) which are multiplied by the dataset DS1-2 (DS2 -2), in order to obtain thermal consumption by industrial sector; the thermal consumptions are then multiplied by coefficients (here called β) obtained from the dataset DS1-1 (DS2-1) to obtain the subdivision of the thermal consumptions by temperature bands. A diagram with the different steps is presented below.

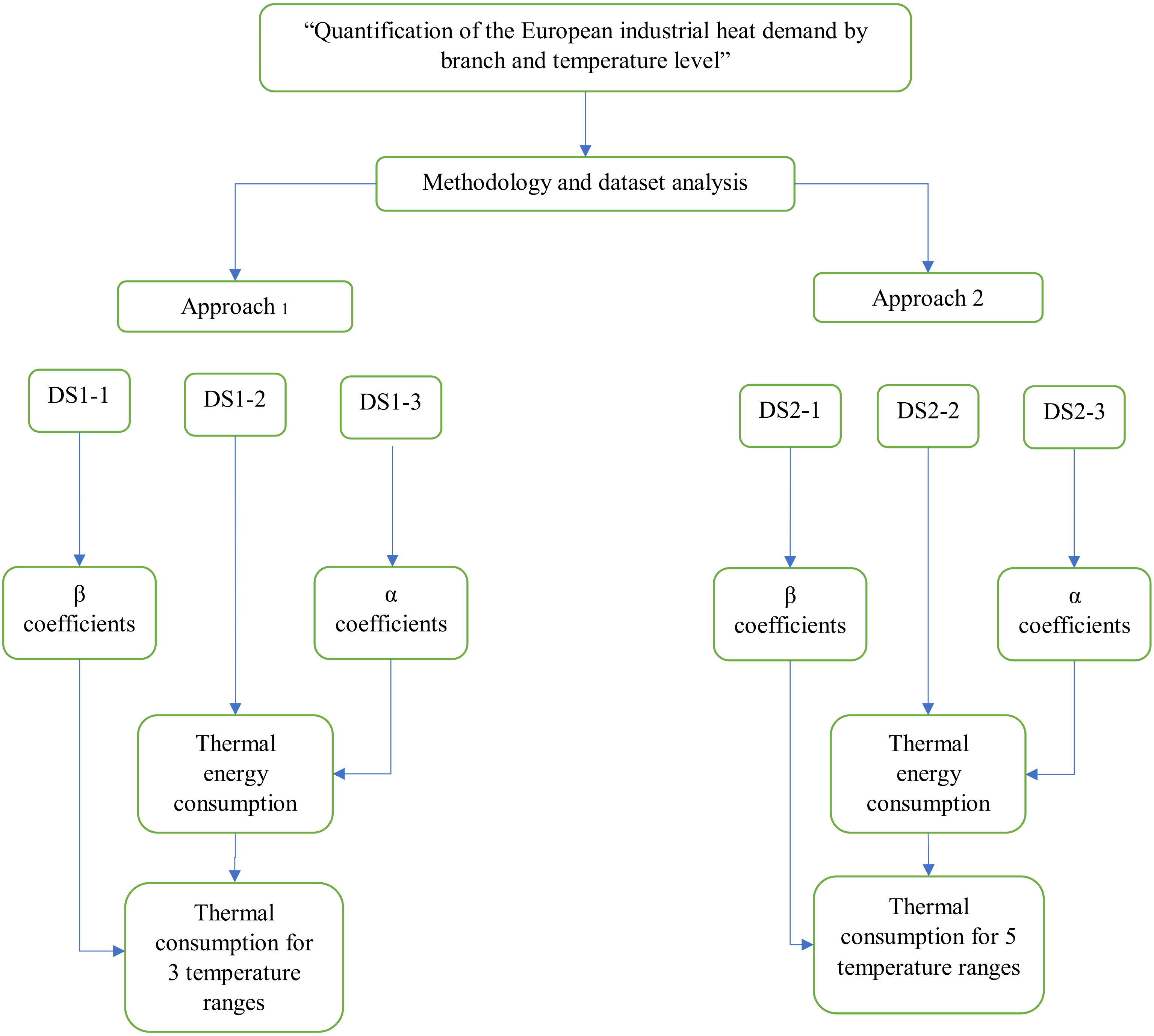

Figure 12: Scheme of the methodology and datasets used by Naegler et al. [2]

The procedure used by [2] is taken up again in this thesis, explaining the different passages. This thesis, however, focuses on the calculation of Italian industrial consumption, and also different datasets are used, in order to have more updated data. The datasets used are called A1-1, A1-2, A1-3 (approach 1) and A2-1, A2-2, A2-3 (approach 2) which will be presented later (the data for A2-2 and A2-3 are the same as for A1-2 and A1-3, so only the A2-1 dataset will be shown for approach 2).

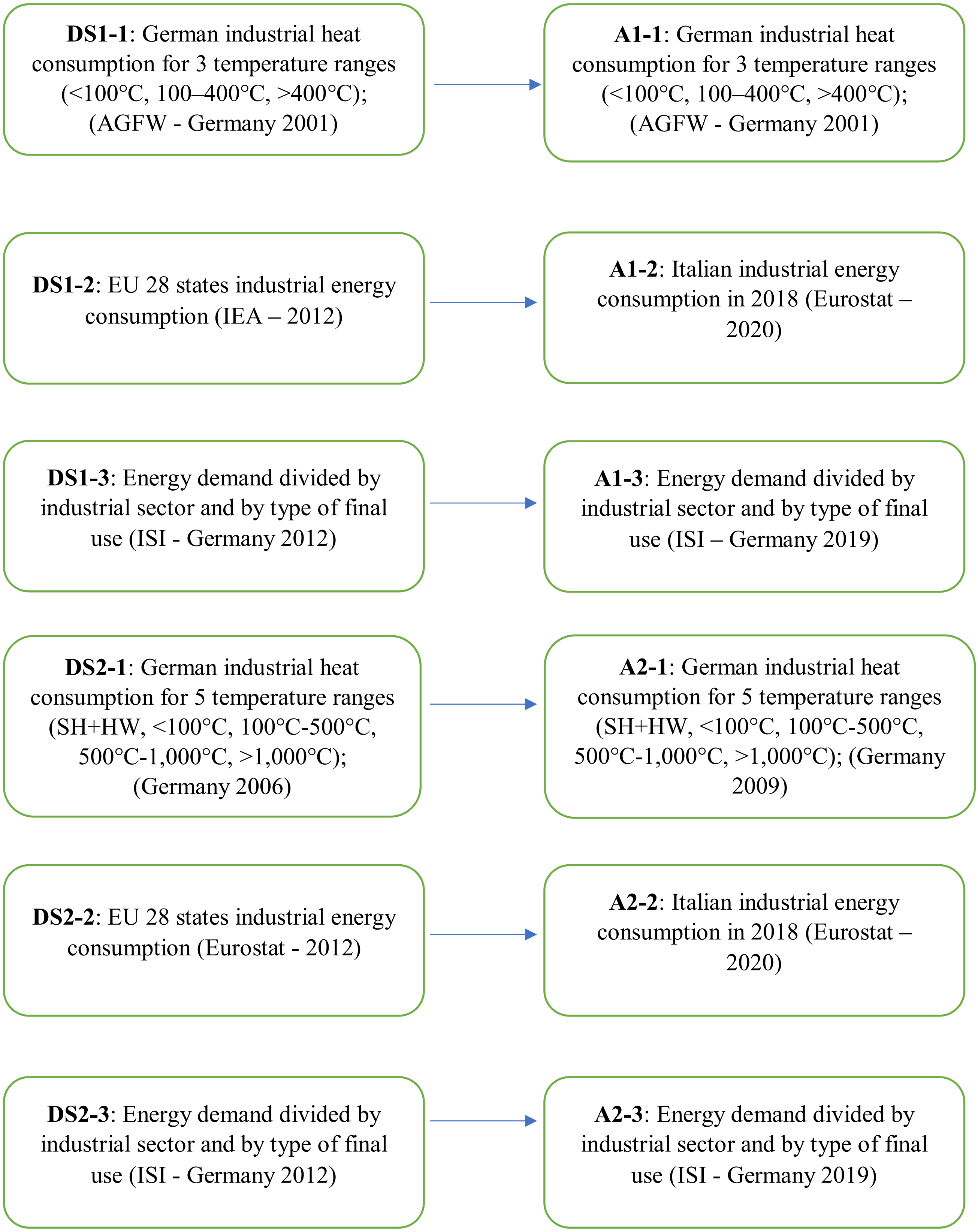

Figure 13: Datasets used by [2] and datasets used in the thesis work

German industrial heat consumption for 3 temperature ranges - Dataset A1-1

It represents the total thermal energy demand divided by industrial sector and temperature range (<100°C, 100°C–400°C, ≥400°C) relative to Germany in 2001. These data are used by [6], a study on the combined generation of electricity and heat, where economic and technological feasibility in the residential and industrial sector are assessed. To get a general picture of the heat demand distributed in space in Germany the study used this dataset, which is mainly based on existing statistical documents, combined with the use of GIS tools (even if these only for limited geographical areas). For the mapping of the heating market for the industrial sector, different temperature ranges are taken into consideration, since heat is required both for production processes and for space heating, with temperature ranges ranging from below 100°C to well over 400°C. For this reason, the study divides the heat requirement of the industry into three temperature ranges: low temperature (T<100°C), medium temperature (100°C≤T<400°C) and high temperature (T≥400°C). The values are indicated in tab.6.

	T≥400°C	**100°≤T<400°**	**T<100°**	**Total**
SECTOR	PJ	PJ	PJ	PJ
Mining & quarrying	0	11.8	14.8	26.6
Food & tobacco	0	69.6	86.7	156.3
Paper & Pulp	22.9	78.2	35.8	136.9
Basic chemical industry	139.8	81.4	66.5	287.7
Other chemical industry	45.4	26.4	20	91.8
Rubber & plastics	0.9	14.1	23.1	38.1
Glass & ceramics	66.2	7.4	3.8	77.4
Non-metallic mineral products	134.8	5.9	10.1	150.8
Metal production (iron & steel)	455.3	24	8.8	488.1
Non-ferrous metals	33.2	5.9	8.5	47.6
Metal processing	12.6	20.9	27.8	61.3
Mechanical sector (Machinery)	6.3	15.8	43.9	66
Automotive	7.9	19.8	42.8	70.5
Manufacturing (other)	21.2	42.5	59.2	122.9
Total	946.5	423.7	451.8	1,822

Table 5: Dataset A1-1 - Thermal energy consumption by industrial sector and temperature range (<100°C, 100°C–400°C, ≥400°C), Germany 2001 (Source: [6])

It can be seen that the study differentiates the thermal energy used by temperature range, but it says nothing about the intended use of this energy (i.e. process heat, heating and hot water production).

Italian industrial consumption - Dataset A1-2

It represents the total industrial energy consumption in Italy in 2018, divided by industrial sector. The data are derived from Eurostat analysis [3], which provides statistical annual data (for EU states) on quantities for crude oil, petroleum products, natural gas and manufactures gases, electricity and derived heat, solid fossil fuels, renewables and wastes covering the full spectrum of the energy sector from supply through transformation to final consumption by sector and fuel type [7]. Data on annual statistics are collected by standard questionnaires compiled by National Administrations competent for energy statistics (for Italy is the Ministry of Economic Development); there is no information regarding the statistical sample used to collect data on Italian industrial consumption.

SECTOR	PJ
Iron & Steel	151.7844
Chemical & petrochemical	137.2171
Non-ferreous metal	29.88385
Non-metallic minerals	179.952
Transport equipment	17.14167
Machinery	145.5472
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Food, beverages & tobacco	117.2206
Paper, pulp & printing	86.26927
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Construction	14.99844
Textile & leather	47.16366
Not elsewhere specified (industry)	64.41417
Total	1,017.29

Table 6: Total energy consumption by industrial sector, Italy 2018 (Source: [3])

In this case, only the total consumption is indicated, with no indication of how much of this energy is used in thermal and power applications.

German industrial consumption by type of final use - Dataset A1-3

The data on final energy consumption of this dataset are divided by industrial sector (indicated as consumption of electricity and fuels, whether they are fossil or renewable) and by type of final use (heating, hot water, process heat, lighting, etc.). The data refer to Germany for the year 2019 [8].

The study considers the energy consumption of the year as the basis for the assessment. To obtain plausible results, energy demands are initially classified into two groups.

The first group includes all applications that are more related to buildings and employees like air conditioning, lighting, ICT (Information and Communication Technologies), space heating and hot water, therefore those technologies that hardly differ between the branches of industry. Consumptions are calculated using specific consumption parameters referring to the built-up area or the number of employees; in particular, to obtain an analysis that is more in line with reality, employees are divided into two groups: office employees and production employees.

The second group is set up to consider the great heterogeneity of industrial processes and includes the applications most associated with the production process. Given the difference between the various processes and their large number, consumptions are estimated only for those energy intensive processes, while others are derived using literature information.

The data obtained from the study are shown in tables 7 and 8, which respectively represent the consumption of electricity and fuel divided by industrial sector and by intended use.

ELECTRICITY CONSUMPTION [PJ]	Lighting	Mechanical energy	Information & Communication	Air conditioning	Process cooling	Process heat (PH)	Heating & Hot water	Total
Mining & quarrying	0.2	5.5	0.1	0.1	0	0.3	0	6.2
Food & tobacco	2.9	39	2.1	2.8	12.5	9	0.3	68.6
Paper & Pulp	0.8	61	0.5	1.1	0.6	0	0.1	64.1
Basic chemical industry	0.8	100	1.1	1	20.4	39.5	0.1	162.9
Other chemical industry	1.2	18.2	2	1.5	1.2	0.2	0.2	24.5
Rubber & plastics	2.4	40.9	1.4	2	0.4	2.4	0.3	49.8
Glass & ceramics	0.5	14.9	0.3	0.2	0.3	0	0.1	16.3
Non-metallic mineral products	0.6	27.1	0.6	0.3	0	0	0.1	28.7
Metal production (iron & steel)	0.5	44.6	0.3	0.2	0	23.2	0.1	68.9
Non-ferrous metals	0.9	29	0.4	0.4	0	38.2	0.1	69
Metal processing	4.5	38	2.4	2.2	0	5	0.5	52.6
Mechanical sector (Machinery)	5.4	21	6	1.8	0.7	3.7	0.7	39.3
Automotive	5.5	39.6	4.7	1.8	0	5.6	0.6	57.8

Manufacturing (other)	7.5	47.8	9.5	2.4	0.7	7.3	0.9	76.1
Total	33.7	526.6	31.4	17.8	36.8	134.4	4.1	784.8

Table 7: Electricity consumption divided by industrial sector and by type of final use, Germany 2019 (Source: [8])

FUEL CONSUMPTION [PJ]	Mechanical energy	Process heat (PH)	Heating	Hot water	Total
Mining & quarrying	0.1	7.8	0.6	0.1	8.6
Food & tobacco	1.9	127.1	14.8	1.5	145.3
Paper & Pulp	1.4	136.6	3.1	0.3	141.4
Basic chemical industry	6.5	347.9	3.9	0.4	358.7
Other chemical industry	1	53.7	5.6	0.6	60.9
Rubber & plastics	0.4	18.8	9.8	1	30
Glass & ceramics	0.9	62.8	2	0.2	65.9
Non-metallic mineral products	3.2	171.2	2.6	0.3	177.3
Metal production (iron & steel)	6	447.7	1.8	0.2	455.7
Non-ferrous metals	0.8	49.8	3.4	0.3	54.3
Metal processing	0.6	27.7	18	1.8	48.1
Mechanical sector (Machinery)	0.5	6.9	23.2	2.7	33.3
Automotive	0.7	32.8	22.4	2.2	58.1
Manufacturing (other)	1.5	76.1	32.4	3.5	113.5
Total	25.5	1,566.9	143.6	15.1	1,751.1

Table 8: Fuel consumption divided by industrial sector and by type of final use, Germany 2019 (Source: [8])

German industrial heat consumption for 5 temperature ranges - Dataset A2-1

It represents the total thermal energy demand by industrial sector in Germany in 2009, distinguishing the process heat by temperature range (<100°C, 100°C-500°C, 500°C-1,000°C, >1,000°C) and the heat used for the heating (SH) and hot water production (HW).

The data are derived from [4], a study whose purpose is to determine the theoretical potential for low-temperature solar process heat systems in industrial processes; for this it was necessary to analyze the industrial heat demand and its temperature levels.

Sector	HW [PJ]	SH [PJ]	<100°C [PJ]	100°C -500°C [PJ]	500°C - 1000°C [PJ]	>1000°C [PJ]	Total [PJ]
Food, beverages & tobacco	1.08	29.88	42.84	52.56	0	0	126.36
Textiles	0.36	4.32	7.2	0	0	0	11.88
Wearing apparel	0	0.36	0.72	0	0	0	1.08
Leather and related products	0	0.36	0.72	0	0	0	1.08
Wood and wood products	0	1.08	5.4	1.44	0	0	7.92
Paper and paper products	0.36	8.64	9.72	35.64	0	0	54.36
Printing and reprod. of recording media	0	1.44	0.72	9.72	0	0	11.88
Chemicals and chemical products	0.72	24.12	48.6	75.24	160.92	39.6	349.2
Rubber and plastic products	0.36	5.76	3.24	12.6	0	0	21.96
Non-metallic mineral products	0.36	12.6	4.32	6.48	96.84	200.88	321.48
Basic metals	0.72	15.84	3.24	9.72	113.4	444.6	587.52
Fabricated metal products	3.24	22.68	8.28	6.48	3.6	8.64	52.92
Computer, electronic, optical products	0.36	3.24	1.08	0.72	0.36	1.08	6.84
Electrical equipment	1.08	8.64	3.24	3.96	1.08	2.88	20.88
Machinery and equipment	2.16	16.2	5.76	4.32	2.16	6.12	36.72
Motor vehichles and trailers	3.6	26.28	9.72	7.2	3.6	10.08	60.48
Other transport equipment	0.36	3.24	1.08	0.72	0.36	1.08	6.84
Furniture and other goods	0	2.52	1.44	3.6	0	0.36	7.92
Total	14.76	187.2	157.32	230.4	382.32	715.32	1,687.32

Table 9: Thermal energy consumption divided by industrial sector and temperature range (HW, SH, <100°C, 100°C-500°C, 500°C-1000°C, >1000°C), Germany 2009 (Source: [4])

The tab.9 shows the industrial heat demand in Germany for 2009 sorted by temperature level. This data was calculated by using employee-specific heat demand, which have been determined by investigating about 150 representative energy consumers and about 90 typical buildings. Given that the number of businesses and buildings analyzed is quite high, the study states that employee-specific heat demand figures are reasonably reliable.

Calculation of Italian industrial thermal consumption for 3 temperature ranges - Approach 1

To obtain the thermal energy consumption and temperature bands, coefficients are obtained from the datasets illustrated above. These coefficients are used in study [2], and here they are recalculated using the new datasets. The α coefficients represent the shares of heat from A1-3 for the calculation of the thermal energy by industrial sector, while the β coefficients are the shares for each temperature level from A1-1 for the subdivision of the thermal consumption by temperature range.

Considering A1-3 (tab. 7, 8), all common items between fuel and electricity consumption are summed. All the thermal energy consumptions are then added together, to obtain the share of thermal energy with respect to the global energy demand, for each industrial sector.

SECTOR	Lighting	Information & Communication	Process cooling	Air conditioning	Mechanical energy	Process heat (PH)	Heating & Hot water	Total	
Mining & quarrying	0.2	0.1	0	0.1	5.6	8.1	0.7	14.8	PJ
Food & tobacco	2.9	2.1	12.5	2.8	40.9	136.1	16.6	213.9	PJ
Paper & Pulp	0.8	0.5	0.6	1.1	62.4	136.6	3.5	205.5	PJ
Basic chemical industry	0.8	1.1	20.4	1	106.5	387.4	4.4	521.6	PJ
Other chemical industry	1.2	2	1.2	1.5	19.2	53.9	6.4	85.4	PJ
Rubber & plastics	2.4	1.4	0.4	2	41.3	21.2	11.1	79.8	PJ
Glass & ceramics	0.5	0.3	0.3	0.2	15.8	62.8	2.3	82.2	PJ
Non-metallic mineral products	0.6	0.6	0	0.3	30.3	171.2	3	206	PJ
Metal production (iron & steel)	0.5	0.3	0	0.2	50.6	470.9	2.1	524.6	PJ
Non-ferrous metals	0.9	0.4	0	0.4	29.8	88	3.8	123.3	PJ
Metal processing	4.5	2.4	0	2.2	38.6	32.7	20.3	100.7	PJ
Mechanical sector (Machinery)	5.4	6	0.7	1.8	21.5	10.6	26.6	72.6	PJ
Automotive	5.5	4.7	0	1.8	40.3	38.4	25.2	115.9	PJ
Manufacturing (other)	7.5	9.5	0.7	2.4	49.3	83.4	36.8	189.6	PJ
Total	33.7	31.4	36.8	17.8	552.1	1,701.3	162.8	2,535.9	PJ

Table 10: Energy consumption divided by industrial sector and by type of final use, Germany 2019

Since the data of A1-1 and A1-3 are classified differently from A1-2 (Italian industrial energy consumption), a reclassification is necessary to proceed with a homogeneous analysis; so, sectors that may have similar processes or use the same raw materials are aggregated (for example "Basic chemical" and "Other chemical industry").

Sector	**T≥400°** E_3	**100°≤T<400°** E_2	**T<100°** E_1	**Total** **E**	
Food & Tobacco	0	69.6	86.7	156.3	PJ
Paper & Wood	22.9	78.2	35.8	136.9	PJ
Chemical and Petrochemical	186.1	121.9	109.6	417.6	PJ
Non-metallic minerals	201	13.3	13.9	228.2	PJ
Mechanics and Automotive	14.2	35.6	86.7	136.5	PJ
Metallurgy (ferrous metals)	467.9	44.9	36.6	549.4	PJ
Mining & quarrying	0	11.8	14.8	26.6	PJ
Non-ferrous metals	33.2	5.9	8.5	47.6	PJ
Manufacturing (other)	21.2	42.5	59.2	122.9	PJ

Table 11: Reclassification 1 - thermal energy consumption by industrial sector and temperature range (<100°C, 100°C–400°C, ≥400°C), Germany 2001.

Sector	**Lighting**	**Information & Comunication**	**Process cooling**	**Air conditioning**	**Mechanical energy**	**Process heat (PH)** E_{PH}	**Heating & Hot water** E_{HW-H}	E_{tot}	**Tot. Heat**	
Food & Tobacco	2.9	2.1	12.5	2.8	40.9	136.1	16.6	213.9	152.7	PJ
Paper & Wood	0.8	0.5	0.6	1.1	62.4	136.6	3.5	205.5	140.1	PJ
Chemical and Petrochemical	4.4	4.5	22	4.5	167	462.5	21.9	686.8	484.4	PJ
Non-metallic minerals	1.1	0.9	0.3	0.5	46.1	234	5.3	288.2	239.3	PJ
Mechanics and Automotive	10.9	10.7	0.7	3.6	61.8	49	51.8	188.5	100.8	PJ
Metallurgy (ferrous metals)	5	2.7	0	2.4	89.2	503.6	22.4	625.3	526	PJ

Mining & quarrying	0.2	0.1	0	0.1	5.6	8.1	0.7	14.8	8.8	PJ
Non-ferrous metals	0.9	0.4	0	0.4	29.8	88	3.8	123.3	91.8	PJ
Manufacturing (other)	7.5	9.5	0.7	2.4	49.3	83.4	36.8	189.6	120.2	PJ
Total	33.7	31.4	36.8	17.8	552.1	1,701.3	162.8	2,535.9	1,864.1	PJ

Table 12: Reclassification 1 - Total energy consumption divided by industrial sector and by type of final use, Germany 2019.

Sector	PJ
Food & Tobacco	117.220558
Paper & Wood	106.956486
Chemical and Petrochemical	137.21708
Non-metallic minerals	179.951954
Mechanics and Automotive	162.68889
Metallurgy (ferrous metals)	151.78436
Mining & quarrying	5.010642
Non-ferrous metals	29.883854
Manufacturing (other)	111.57783

Table 13: Reclassification 1 - Total energy consumption by industrial sector, Italy 2018

To establish the thermal energy consumption by sector, coefficients are calculated starting from the data in table 12; the results are shown in table 14.

$$\alpha_i = \frac{E_{PH,i} + E_{HW-H,i}}{E_{tot,i}}$$

α_i: share of thermal energy on total consumption for sector i;

$E_{PH,i}$: process heat consumption for sector i;

$E_{HW-H,i}$: consumption for hot water and heating for sector i;

$E_{tot,i}$: total energy consumption for sector i;

SECTOR	α
Food & Tobacco	0.713885
Paper & Wood	0.681752
Chemical and Petrochemical	0.7053
Non-metallic minerals	0.830326
Mechanics and Automotive	0.534748
Metallurgy (ferrous metals)	0.841196
Mining & quarrying	0.594595
Non-ferrous metals	0.744526
Manufacturing (other)	0.633966

Table 14: Approach 1 - Share of thermal energy on total consumption, Germany 2019

The next step is to establish the "quality" of this energy, therefore in which temperature ranges these consumptions are placed. For this purpose, coefficients are calculated starting from the data in table 11, which allow to obtain the thermal energy consumption for the 3 temperature ranges considered. The results are shown in table 15.

$$\beta_{1,i} = \frac{E_{1,i}}{E_i} \qquad \beta_{2,i} = \frac{E_{2,i}}{E_i} \qquad \beta_{3,i} = \frac{E_{3,i}}{E_i}$$

$\beta_{1,i}$: share of thermal energy for the temperature range T<100°C for the sector i;

$\beta_{2,i}$: share of thermal energy for the temperature range 100°C ≤T<400°C for the sector i;

$\beta_{3,i}$: share of thermal energy for the temperature range T≥400°C for the sector i;

$E_{1,i}$: thermal energy in the temperature range T <100°C for sector i;

$E_{2,i}$: thermal energy in the temperature range 100°C≤T<400°C for sector i;

$E_{3,i}$: thermal energy in the temperature range T≥400°C for sector i;

$E_i = E_{1,i} + E_{2,i} + E_{3,i}$: total thermal energy consumption for sector i;

	$\beta_{1,}$	β_2	β_3
Food & Tobacco	0.554702495	0.445298	0
Paper & Wood	0.261504748	0.57122	0.167275
Chemical and Petrochemical	0.262452107	0.291906	0.445642
Non-metallic minerals	0.060911481	0.058282	0.880806
Mechanics and Automotive	0.635164835	0.260806	0.104029
Metallurgy (ferrous metals)	0.066618129	0.081726	0.851656
Mining & quarrying	0.556390977	0.443609	0
Non-ferrous metals	0.178571429	0.12395	0.697479
Manufacturing (other)	0.481692433	0.34581	0.172498

Table 15: Approach 1 - Share of thermal energy for the 3 temperature ranges (<100°C, 100°C–400°C, ≥400°C), Germany 2001

At this point we can proceed with the calculation of the thermal energy consumption by industrial sector in Italy, multiplying the values on the Italian industrial consumption of tab.13 and the previously obtained α coefficients (tab.14). The results are indicated in tab.16.

$$C_{th,i} = \alpha_i * C_i$$

$C_{th,i}$: thermal energy consumption for the Italian sector i;

C_i: total energy consumption for the Italian sector i;

α_i: share of thermal energy on total consumption for sector i;

	THERMAL ENERGY C_{th} [PJ]
Food & Tobacco	83.68199723
Paper & Wood	72.91777951
Chemical and Petrochemical	96.77919853
Non-metallic minerals	149.4188154
Mechanics and Automotive	86.99756028
Metallurgy (ferrous metals)	127.6804308
Mining & quarrying	2.979300649
Non-ferrous metals	22.24929276
Manufacturing (other)	70.73657788
Total	713.440953

Table 16: Approach 1 - Thermal energy consumption by industrial sector, Italy 2018

Finally, once the thermal energy consumption has been calculated, the thermal energy consumption values divided by temperature ranges can be obtained, using the coefficients β (tab.15) and thermal energy consumption by sector (tab.16). The results are indicated in tab.17.

$$C_{1,i} = \beta_{1,i} * C_{th,i} \qquad C_{2,i} = \beta_{2,i} * C_{th,i} \qquad C_{3,i} = \beta_{3,i} * C_{th,i}$$

$C_{1,i}$: thermal energy in the temperature range T<100°C for Italian sector i;

$C_{2,i}$: thermal energy in the temperature range 100°C≤T<400°C for Italian sector i;

$C_{3,i}$: thermal energy in the temperature range T≥400°C for Italian sector i;

	T<100°C	**100°C≤T<400°C**	**T≥400°C**	
	C_1	C_2	C_3	
Food & Tobacco	46.41861266	37.26338	0	PJ
Paper & Wood	19.06834555	41.65208	12.19734953	PJ
Chemical and Petrochemical	25.3999046	28.25044	43.1288526	PJ
Non-metallic minerals	9.101321357	8.708459	131.6090355	PJ
Mechanics and Automotive	55.25779103	22.68947	9.050295648	PJ
Metallurgy (ferrous metals)	8.505831391	10.43475	108.7398499	PJ
Mining & quarrying	1.657656	1.321645	0	PJ
Non-ferrous metals	3.973087993	2.75779	15.51841428	PJ
Manufacturing (other)	34.07327429	24.46139	12.20191579	PJ
Total	203.4558249	177.5394	332.4457132	PJ

Table 17: Approach 1 - Thermal energy consumption by industrial sector and temperature range (<100°C, 100°C–400°C, ≥400°C), Italy 2018.

From the results obtained, three industrial sectors (Chemical & Petrochemical, Non-metallic minerals, Metallurgy) dominate the demand for industrial thermal energy in Italy (fig.14), with a share of 52.4% of thermal energy demand in 2018.

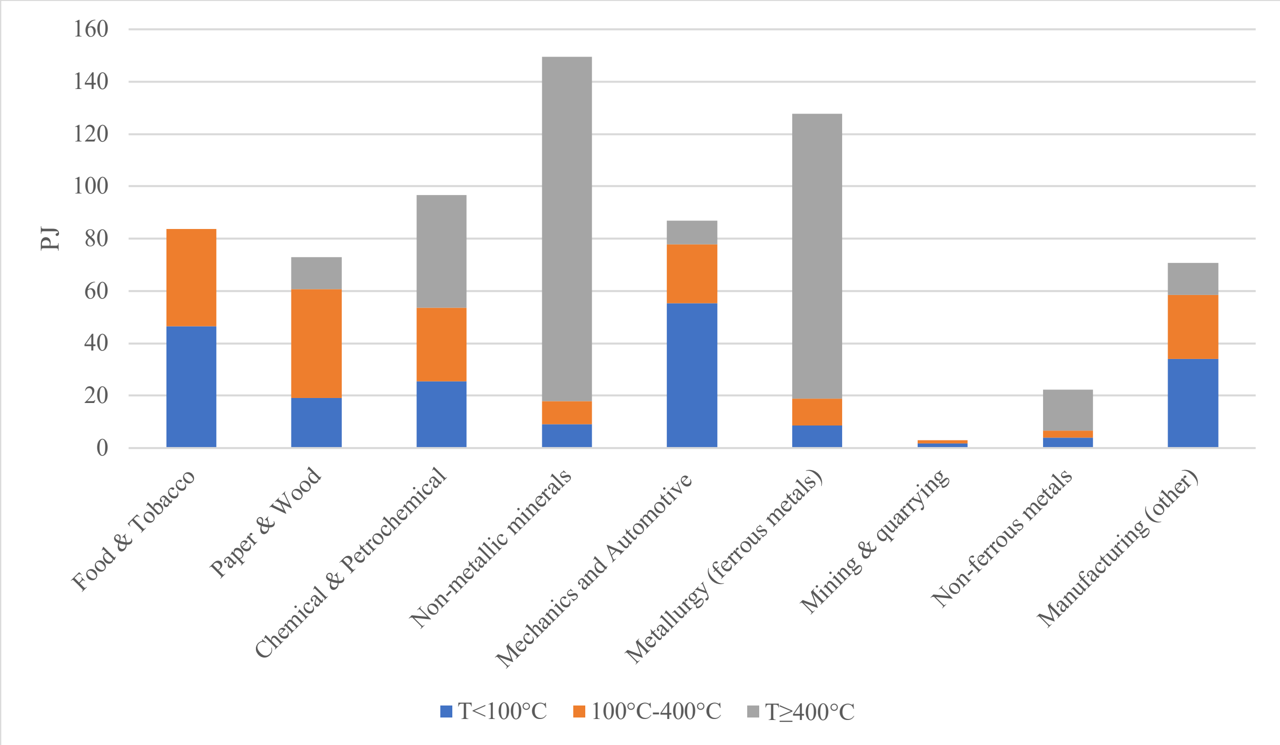

Figure 14: Approach 1 - Thermal energy consumption by industrial sector and temperature range (<100°C, 100°C–400°C, ≥400°C), Italy 2018.

Regarding the subdivision by temperature range, the highest consumptions are in the interval T> 400°C, which represent about 46.6% of the total thermal consumptions (fig.15). This is a very important point, because it gives a first indication of the limits of industry decarbonisation with classic renewable energy sources (for example solar thermal), which can provide energy at a relatively low temperature. On the other hand, there are other renewable technologies that provide thermal energy at high temperatures, such as concentrated solar thermal that provides thermal energy at temperatures around 550°C [9].

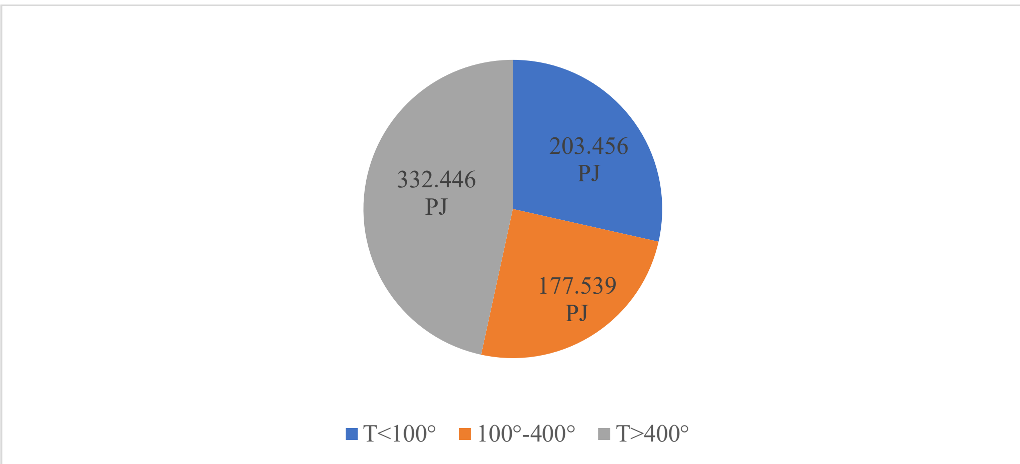

Figure 15: Approach 1 - Thermal energy consumption by temperature range (<100°C, 100°C–400°C, ≥400°C), Italy 2018.

High temperature processes are found mainly in heavy industry such as Non-metallic minerals (cooking of raw materials up to 1,450°C in the rotary kiln for the production of clinker – cement) and Metallurgy (temperatures up to 1,800°C in the blast furnace for the production of cast iron - steel), where the share of heat consumption over 400°C is the dominant part (88% and 85% respectively, fig.16), while in other sectors there is no consumption in this range or very limited like in Food & Tobacco and Paper & Pulp (0% and 16.7%).

The sector with the highest heat consumption in the range T>400°C is Non-metallic minerals (131.61 PJ), followed by sectors Metallurgy (108.74 PJ) and Chemical & Petrochemical (43.13 PJ). Therefore, the sectors characterized by the highest thermal consumption are also those that require energy at the highest temperature.

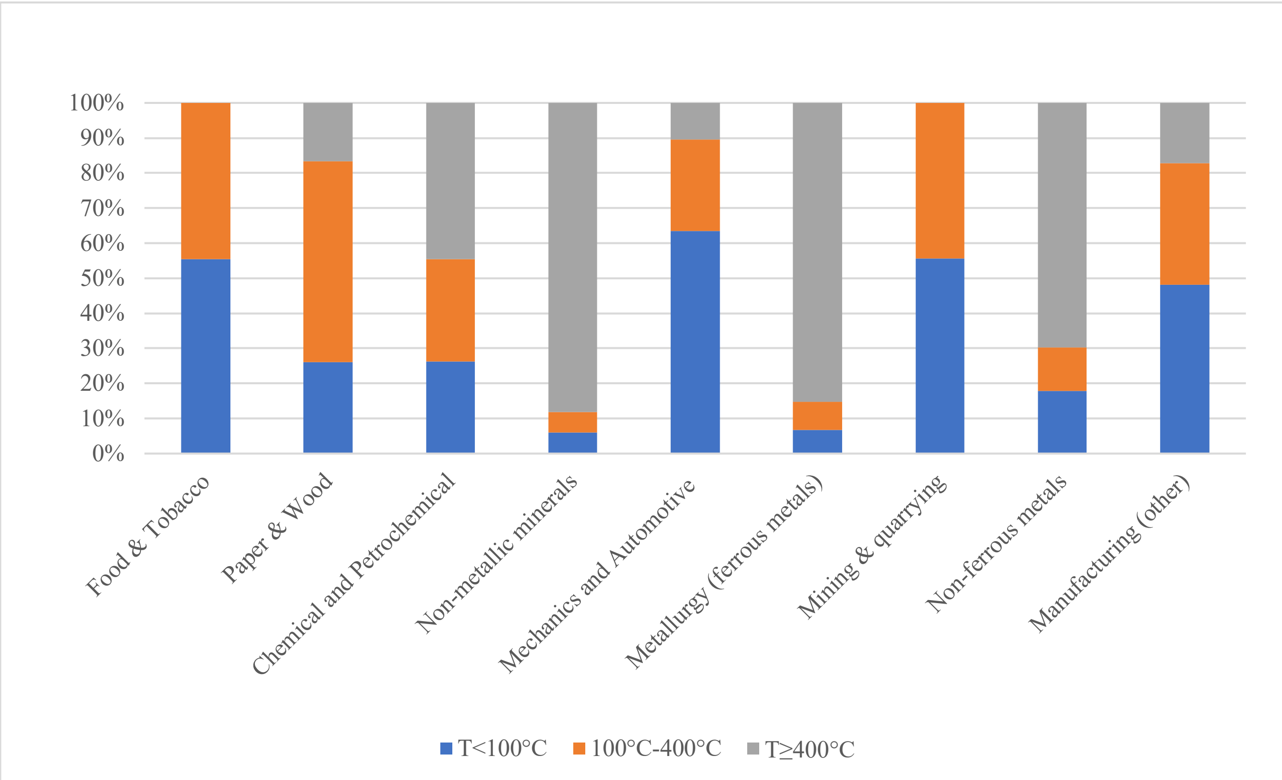

Figure 16: Approach 1 - Heat shares by temperature level, for each industrial branch

Calculation of Italian industrial thermal consumption for 5 temperature ranges - Approach 2

The second approach provides the thermal energy consumptions for 5 temperature ranges (HW+SH, <100°C, 100°C-500°C, 500°C-1,000°C, >1,000°C), therefore a more precise characterization of the thermal consumptions for each industrial branch. A finer subdivision of the temperature levels is useful to better understand how thermal consumption is distributed, and therefore which renewable technologies can be adopted for decarbonisation.

Regarding the energy used for heating (SH) and hot water (HW), a single temperature range will be considered for these two items: in fact, for SH, temperatures ranging from 25°C to 70°C are generally required (depending on the technologies used), while for the production of HW the temperature ranges from 45°C to 55°C. Therefore, it is a "low temperature" range, which differs from the <100°C range as the latter refers more specifically to the production processes.

The procedure adopted is equivalent to that of approach 1, partly also regarding the data used, with the only difference on the dataset necessary for the calculation of the temperature ranges. Also in this case the coefficients are calculated as in approach 1, and in particular the α coefficients represent the shares of heat from A2-3 for the calculation of the thermal energy by industrial sector, while the β coefficients are the shares for each temperature level from A2-1 for the subdivision of the thermal consumption by temperature range.

As in approach 1 it is necessary to reclassify the industrial sectors to obtain a homogeneous analysis; then we proceed in the same way as approach 1, considering the datasets A2-1, A2-3 and A2-2 (tab. 9, 10, 6). The reclassified data are shown in tables 18, 19, 20.

Sector	HW	SH	<100°C	100°C-500°C	500°C-1000°C	>1000°C	Total	
Food & Tobacco	1.08	29.88	42.84	52.56	0	0	126.36	PJ
Paper & Wood	0.36	9.72	15.12	37.08	0	0	62.28	PJ
Chemical and Petrochemical	1.08	29.88	51.84	87.84	160.92	39.6	371.16	PJ
Non-metallic minerals	0.36	12.6	4.32	6.48	96.84	200.88	321.48	PJ

Mechanics and Automotive	6.12	45.72	16.56	12.24	6.12	17.28	104.04	PJ
Metallurgy (ferrous metals)	3.96	38.52	11.52	16.2	117	453.24	640.44	PJ

Table 18: Reclassification 2 - Thermal energy consumption divided by industrial sector and temperature range (HW, SH, <100°C, 100°C-500°C, 500°C-1000°C, >1000°C), Germany 2009.

Sector	**Lighting**	**Information & Comunication**	**Process cooling**	**Air conditioning**	**Mechanical energy**	**Process heat (PH) E_{PH}**	**Heating & Hot water E_{HW-H}**	E_{tot}	
Food & Tobacco	2.9	2.1	12.5	2.8	40.9	136.1	16.6	213.9	PJ
Paper & Wood	0.8	0.5	0.6	1.1	62.4	136.6	3.5	205.5	PJ
Chemical and Petrochemical	4.4	4.5	22	4.5	167	462.5	21.9	686.8	PJ
Non-metallic minerals	1.1	0.9	0.3	0.5	46.1	234	5.3	288.2	PJ
Mechanics and Automotive	10.9	10.7	0.7	3.6	61.8	49	51.8	188.5	PJ
Metallurgy (ferrous metals)	5	2.7	0	2.4	89.2	503.6	22.4	625.3	PJ

Table 19: Reclassification 2 - Total energy consumption divided by industrial sector and by type of final use, Germany 2019

Sector	**[PJ]**
Food & Tobacco	117.2206
Paper & Wood	106.9565
Chemical and Petrochemical	137.2171
Non-metallic minerals	179.952
Mechanics and Automotive	162.6889
Metallurgy (ferrous metals)	151.7844

Table 20: Reclassification 2 - Total energy consumption by industrial sector, Italy 2018.

At this point we proceed with the calculation of the coefficients necessary for the calculation of thermal consumption by industrial sector (α) and by temperature range (again by industrial sector, β). As approach 1, these coefficients are used in study [2], and here they are recalculated using the new datasets.

For the computation of α, the equation used is the same as in approach 1, while the data used are those reported in tab.19

$$\alpha_i = \frac{E_{PH,i} + E_{HW-H,i}}{E_{tot,i}}$$

α_i: share of thermal energy on total consumption for sector i;

$E_{PH,i}$: process heat consumption for sector i;

$E_{HW-H,i}$: consumption for hot water and heating for sector i;

$E_{tot,i}$: total energy consumption for sector i;

Sector	α
Food & Tobacco	0.713885
Paper & Wood	0.681752
Chemical and Petrochemical	0.7053
Non-metallic minerals	0.830326
Mechanics and Automotive	0.534748
Metallurgy (ferrous metals)	0.841196

Table 21: Approach 2 - Share of thermal energy on total consumption, Germany 2019

The data in table 18 are used to calculate the β coefficients, considering that the HW and SH items will be added together to obtain a single temperature range.

$$\beta_{1,i} = \frac{E_{1,i}}{E_i} \qquad \beta_{2,i} = \frac{E_{2,i}}{E_i} \qquad \beta_{3,i} = \frac{E_{3,i}}{E_i} \qquad \beta_{4,i} = \frac{E_{4,i}}{E_i} \qquad \beta_{5,i} = \frac{E_{5,i}}{E_i}$$

$\beta_{1,i}$: share of thermal energy for SH+HW range for the sector i;

$\beta_{2,i}$: share of thermal energy for the temperature range T<100°C for the sector i;

$\beta_{3,i}$: share of thermal energy for the temperature range 100°C≤T<500°C for the sector i;

$\beta_{4,i}$: share of thermal energy for the temperature range 500°C≤T<1,000°C for the sector i;

$\beta_{5,i}$: share of thermal energy for the temperature range T≥1,000°C for the sector i;

$E_{1,i}$: thermal energy in SH+HW range for sector i;

$E_{2,i}$: thermal energy in the temperature range T<100°C for sector i;

$E_{3,i}$: thermal energy in the temperature range 100°C≤T<500°C for sector i;

$E_{4,i}$: thermal energy in the temperature range 500°C≤T<1,000°C for sector i;

$E_{5,i}$: thermal energy in the temperature range T≥1,000°C for sector i;

$E_i = E_{1,i} + E_{2,i} + E_{3,i} + E_{4,i} + E_{5,i}$: total thermal energy consumption for sector i;

Sector	**β_1 HW, SH**	**β_2 <100°**	**β_3 100°-500°**	**β_4 500°-1000°**	**β_5 >1000°**
Food & Tobacco	0.245014	0.339031339	0.415954416	0	0
Paper & Wood	0.16185	0.242774566	0.595375723	0	0
Chemical and Petrochemical	0.083414	0.139670223	0.236663434	0.433559651	0.106692532
Non-metallic minerals	0.040314	0.01343785	0.020156775	0.301231803	0.624860022
Mechanics and Automotive	0.49827	0.15916955	0.117647059	0.058823529	0.166089965

Metallurgy (ferrous metals)	0.066329	0.017987634	0.02529511	0.182686903	0.707700956

Table 22: Approach 2 - Share of thermal energy for the 5 temperature ranges (HW+SH, <100°C, 100°C-500°C, 500°C-1000°C, >1000°C), Germany 2009

It is now possible to proceed with the calculation of thermal consumption by industrial sector in Italy, using the coefficients α of tab.21 and the data on Italian industrial consumption in tab.20. The equation used is the following:

$$C_{th,i} = \alpha_i * C_i$$

$C_{th,i}$: thermal energy consumption for the Italian sector i;

C_i: total energy consumption for the Italian sector i;

α_i: share of thermal energy on total consumption for sector i;

The results are shown in the following tab.23.

Sector	Thermal energy C_{th} [PJ]
Food & Tobacco	83.68199723
Paper & Wood	72.91777951
Chemical and Petrochemical	96.77919853
Non-metallic minerals	149.4188154
Mechanics and Automotive	86.99756028
Metallurgy (ferrous metals)	127.6804308
Total	617.4757817

Table 23: Approach 2 - Thermal energy consumption by industrial sector, Italy 2018

Using the coefficients β (tab.22) and the data on heat consumption by industrial sector just calculated (tab.23), it is possible to trace the heat consumption for the 5 temperature ranges considered. The formulas used and the results obtained are indicated below (table 20).

$$C_{1,i} = \beta_{1,i} * C_{th,i} \quad C_{2,i} = \beta_{2,i} * C_{th,i} \quad C_{3,i} = \beta_{3,i} * C_{th,i} \quad C_{4,i} = \beta_{4,i} * C_{th,i} \quad C_{5,i} = \beta_{5,i} * C_{th,i}$$

$C_{1,i}$: thermal energy in SH+HW range for Italian sector i;

$C_{2,i}$: thermal energy in the temperature range T<100°C for Italian sector i;

$C_{3,i}$: thermal energy in the temperature range 100°C≤T<500°C for Italian sector i;

$C_{4,i}$: thermal energy in the temperature range 500°C≤T<1,000°C for Italian sector i;

$C_{5,i}$: thermal energy in the temperature range T≥1,000°C for Italian sector i;

Sector	**HW+SH**	**<100°C**	**100°C-500°C**	**500°C-1000°C**	**>1000°C**	
Food & Tobacco	20.50328	28.37082	34.8079	0	0	PJ
Paper & Wood	11.80172	17.70258	43.41348	0	0	PJ
Chemical and Petrochemical	8.072756	13.51717	22.9041	41.95956	10.32562	PJ
Non-metallic minerals	6.023603	2.007868	3.011801	45.0097	93.36584	PJ
Mechanics and Automotive	43.34827	13.84736	10.23501	5.117504	14.44942	PJ
Metallurgy (ferrous metals)	8.468966	2.296669	3.22969	23.32554	90.35956	PJ
Total	98.21859	77.74247	117.602	115.4123	208.5004	PJ

Table 24: Approach 2 - Thermal energy consumption by industrial sector and temperature range ranges (HW+SH, <100°C, 100°C-500°C, 500°C-1000°C, >1000°C), Italy 2018

The sectors with the highest thermal energy consumption are Non-metallic minerals (149.42 PJ) and Metallurgy (127.68 PJ), equal to 44,9% of total thermal consumption (fig.17).

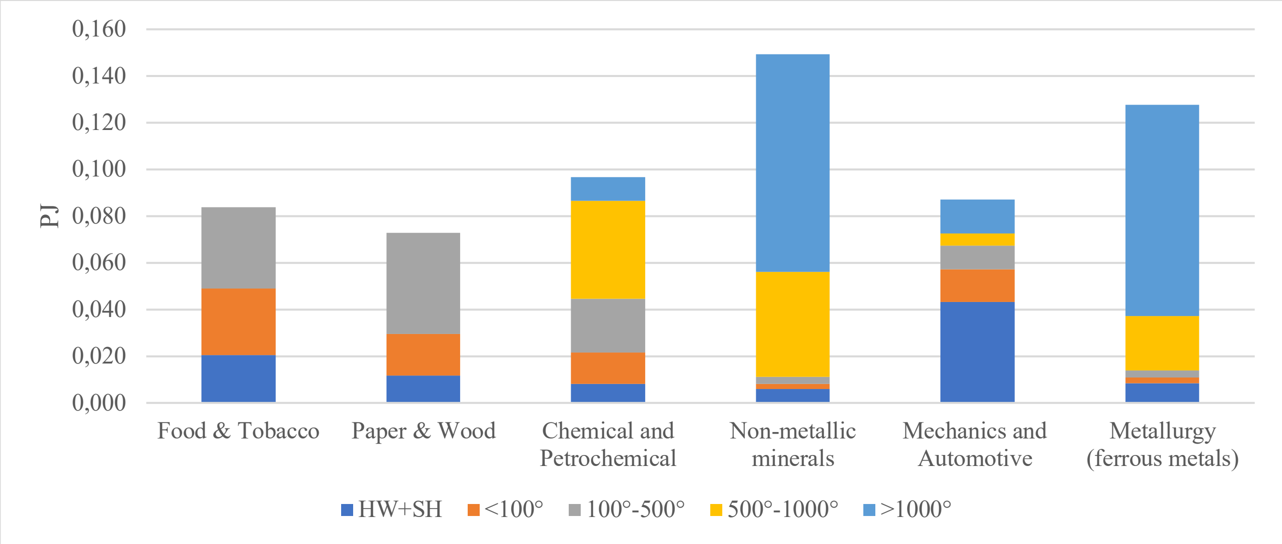

Figure 17: Approach 2 - Thermal energy consumption by industrial sector and temperature range (HW+SH, <100°C, 100°C-500°C, 500°C-1000°C, >1000°C), Italy 2018

As regards the temperature ranges, there is a concentration of thermal consumption for higher temperatures, in particular for T>1,000°C which with 208.50 PJ represents about 33.8% of total thermal consumption (fig.18); considering the consumption in the range 500°C-1,000°C and >1,000°C, we arrive at 323.9 PJ of thermal energy, that is 52.5% of the total thermal consumption. This indicates that for the decarbonization of industrial thermal processes, in addition to classic renewable sources (e.g., solar thermal), other technologies are also needed to cover the energy demand at higher temperatures.

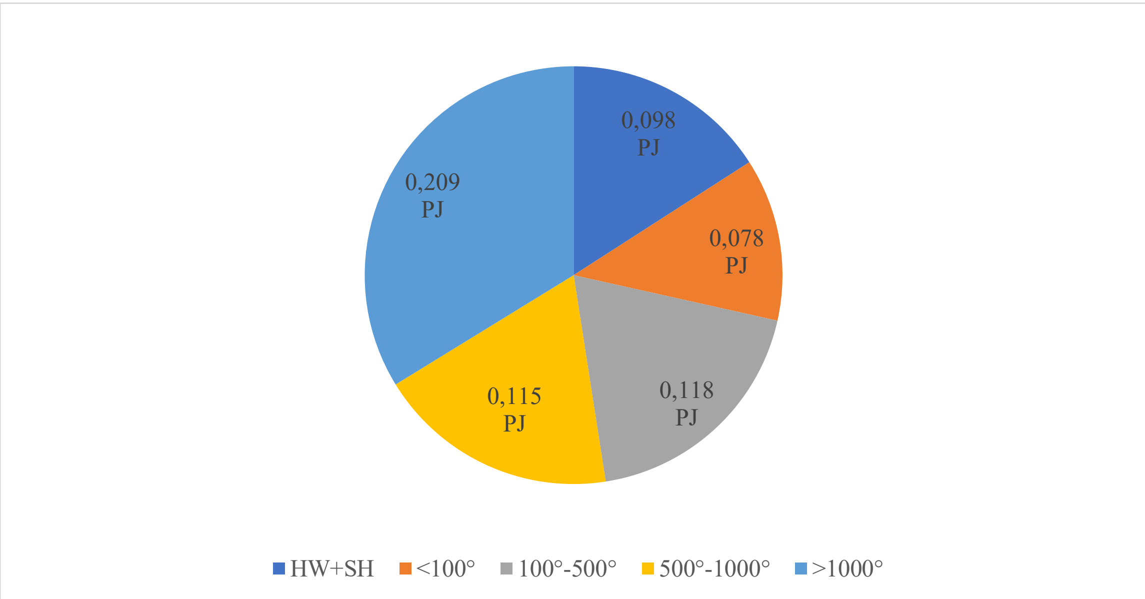

Figure 18: Approach 2 - Thermal energy consumption by temperature range (HW+SH, <100°C, 100°C-500°C, 500°C-1000°C, >1000°C), Italy 2018

With regard to the subdivision of consumption by temperature range for each sector, it is noted that in the heavy industry sectors there is a clear prevalence of thermal energy in the ranges 500°C-1,000°C and >1,000°C: for the Non-metallic minerals sector the consumption in the 500°C -1,000°C and >1000°C ranges respectively represent 62.5% and 30.1% of total heat consumption (overall 92.6%), while in the Metallurgy sector percentages of 18.3% and 70.8% (fig.19). Furthermore, these two sectors also have the highest consumption in the range >1,000°C (93.37 PJ for Non-metallic minerals and 90.36 PJ for Metallurgy), while in the 500°C-1,000°C range are the Non-metallic minerals and Chemical & Petrochemical with the highest consumption, equal to 45.01 PJ and 41.96 PJ respectively (fig.20).

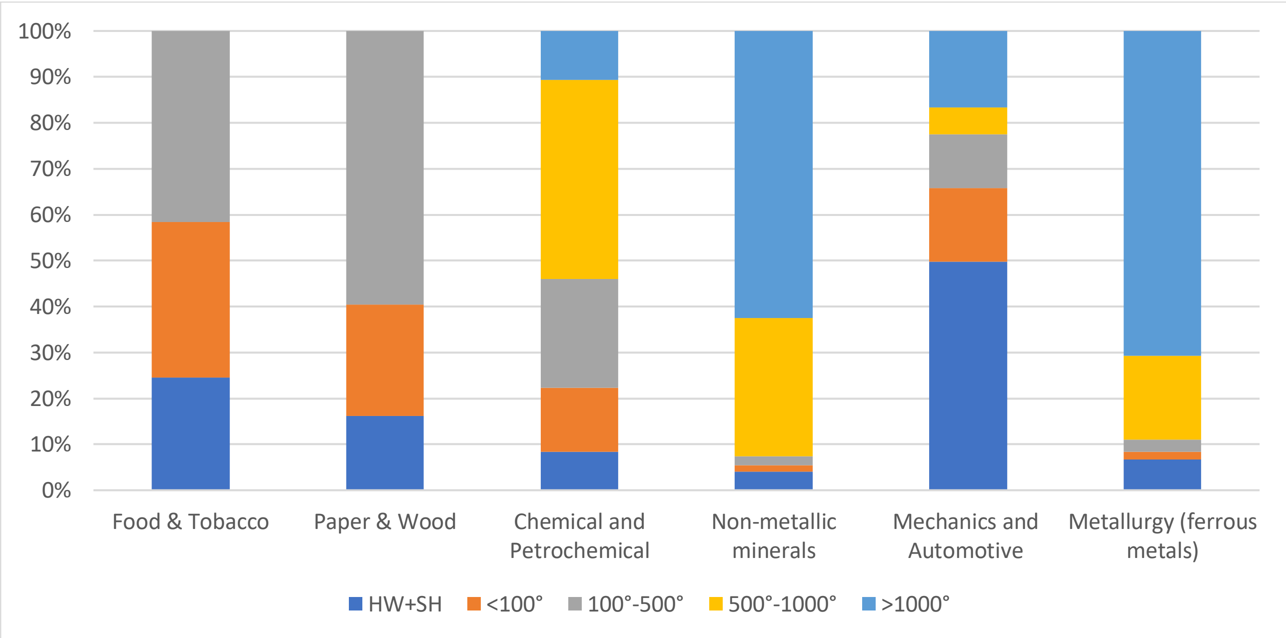

Figure 19: Approach 2 - Heat shares by temperature level, for each industrial branch

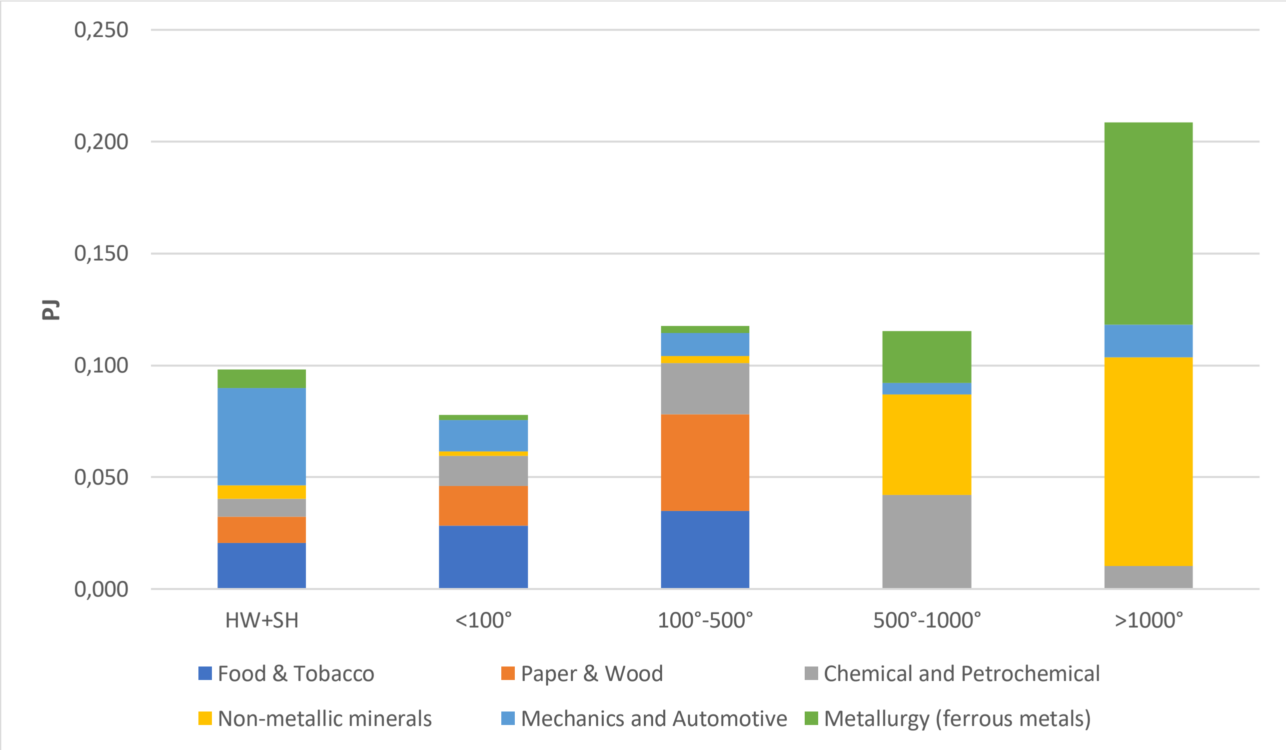

Figure 20: Approach 2 - Thermal energy consumption by temperature range, highlighting thermal consumption of each industrial branch

Conclusions and comparison between the two approaches

In comparing the two methods, it must be pointed out that the thermal energy consumptions obtained (without considering the temperature ranges) for the sectors analyzed are the same for both approaches, given that the datasets used for the calculation (A1-2, A1- 3, A2-2, A2-3) are the same. Furthermore, some sectors analyzed in approach 1 are not present in approach 2, due to the lack of data for the subdivision into temperature ranges; therefore, the comparison will be only between the sectors common to both approaches. However, it can be considered a negligible problem: in fact, considering the results of approach 1, the thermal consumption of the 3 sectors not considered (Mining & Quarrying, Non-Ferrous metals, Manufacturing) have relatively low consumption, and represent only 13.4 % of total industrial thermal consumption. Furthermore, the sectors of greatest interest, both for absolute consumption and for how they are divided into the temperature ranges, are present in both analysis.

		APPROACH 1					APPROACH 2			
[PJ]	**Thermal energy**	**T<100°C**	**100°C-400°C**	**T>400°C**	**HW+SH**	**<100°C**	**100°C-500°C**	**500°C-1000°C**	**>1000°C**	
Food & Tobacco	83.68	46.42	37.26	0.00	20.50	28.37	34.81	0.00	0.00	PJ
Paper & Wood	72.92	19.07	41.65	12.20	11.80	17.70	43.41	0.00	0.00	PJ
Chemical & Petrochemical	96.78	25.40	28.25	43.13	8.07	13.52	22.90	41.96	10.33	PJ
Non-metallic minerals	149.42	9.10	8.71	131.61	6.02	2.01	3.01	45.01	93.37	PJ
Mechanics and Automotive	87.00	55.26	22.69	9.05	43.35	13.85	10.24	5.12	14.45	PJ
Metallurgy (ferrous metals)	127.68	8.51	10.43	108.74	8.47	2.30	3.23	23.33	90.36	PJ
Mining & quarrying	2.98	1.66	1.32	0.00						PJ
Non-ferrous metals	22.25	3.97	2.76	15.52						PJ
Manufacturing (other)	70.74	34.07	24.46	12.20						PJ

Table 25: Comparison between approach 1 and approach 2 results

As approach 1 and approach 2 aggregate at different temperature levels, a precise comparison of the results from both approaches at the temperature level cannot be performed; but a comparative analysis giving indications on the reliability of the results can be carried out. In particular the sum of PH <100°C and SH/HW from approach 2 can be compared with SH, HW, PH<100°C from approach 1.

Considering the Metallurgy sector, at level T<100°C there is a difference of 21% of approach 1 compared to approach 2; at the high temperature level (>400°C for approach 1, >500°C for approach 2) the difference between the two approaches is 7%. These results reveal systematic uncertainties in the estimation of the distribution of consumption by temperature range of [6] and [4], as it would be expected that the thermal energy in the range >400°C (approach 1) is higher than that in the range >500° (approach 2); however, for both approaches, consumption at high temperature levels represents the highest share of total heat consumption, with 85.2% for approach 1 (>400°C) and 89% for approach 2 (>500°C).

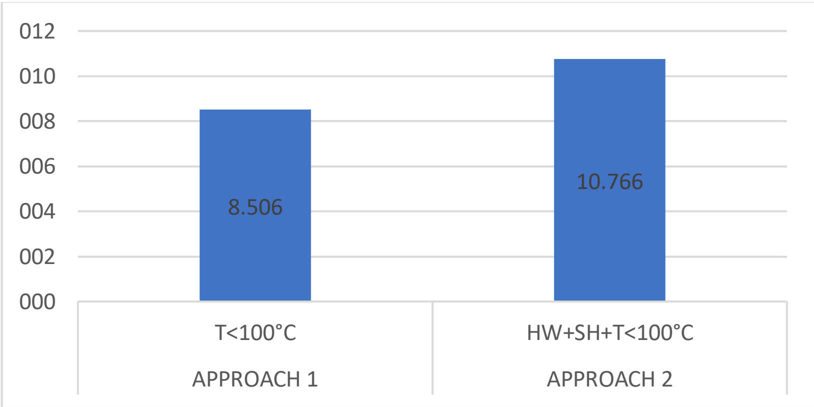

Figure 21: Metallurgical sector results, comparison of low temperature levels

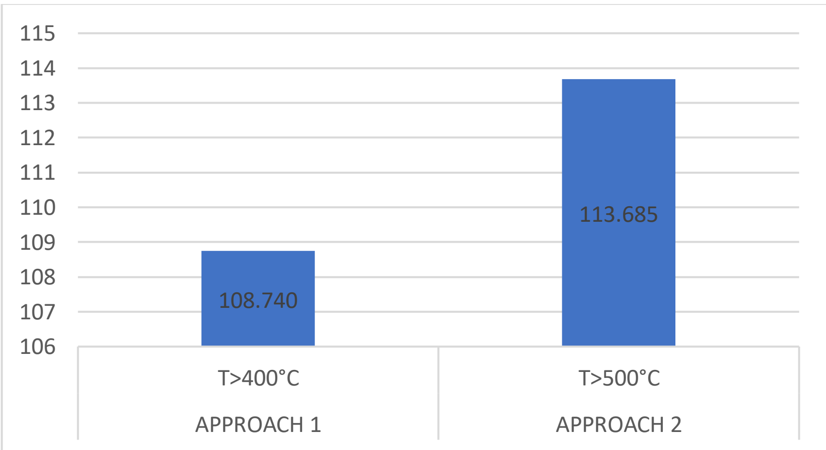

Figure 22: Metallurgical sector results, comparison of high temperature levels

For the Non-metallic minerals sector, at level T<100°C there is a difference of 13.3% of approach 1 compared to approach 2; considering the higher temperature level, the difference is reduced, with the consumption obtained from approach 1 lower by 4% compared to approach 2; also in this case there is a systematic uncertainty due to the starting datasets, given that the consumptions in the range T>400°C (approach 1) are lower than those in the range T>500°C (approach 2).

For both approaches, the share of consumption at high temperature levels is the predominant one, with 88.1% for approach 1 (T>400°C) and 92.6% for approach 2 (T>500°C).

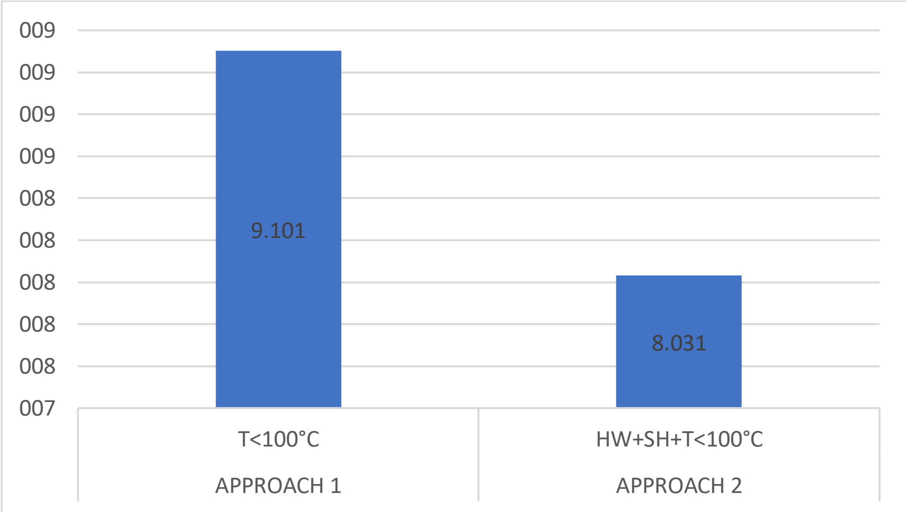

Figure 23: Non-metallic minerals sector results, comparison of low temperature levels

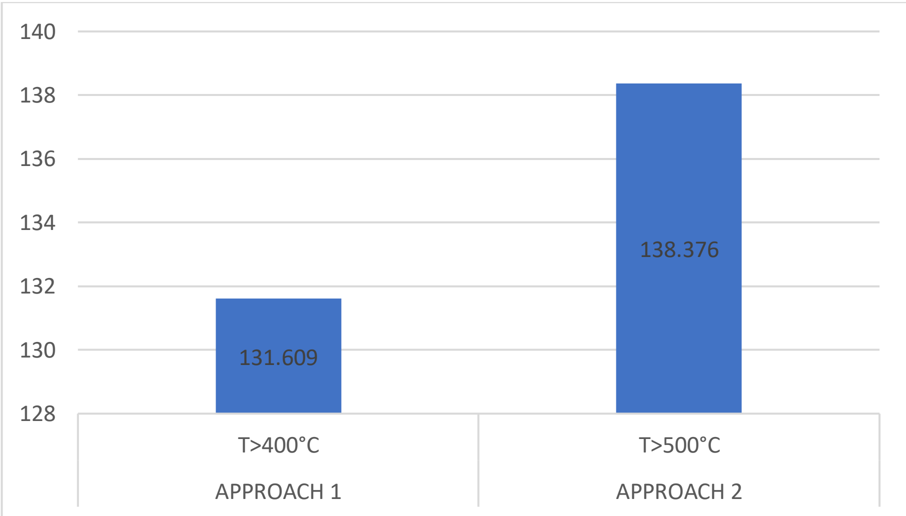

Figure 24: Non-metallic minerals sector results, comparison of high temperature levels

In conclusion, the work done in this first part of the thesis was to reconstruct the methodologies presented by [2] and to use more updated datasets, and to apply these methodologies to the Italian case. The differences between the results of the two approaches reveal systematic uncertainties in the estimation of the temperature levels in the datasets used, but they still give good indications.

This methodology certainly has limitations, but there are also possibilities for improvement in order to have a subdivision of thermal consumption by temperature range closer to reality.

The main limitation concerns the hypothesis that the temperature ranges characteristic of the German industry are also applicable to the Italian case. Even if Italy and Germany are among the most economically and technologically developed states, there will certainly be differences in production processes (even if small) or in production efficiency that can change the relative shares of thermal energy for the various ranges of temperature.

The results obtained are then based on [6] and [4], datasets with statistical data referring respectively to 2001 and 2009, which therefore reflect a situation that may have changed in recent years, for example with greater energy efficiency, or with a variation in the type of production processes used which may have changed the shares of thermal energy associated with the various temperature ranges. However, the physical and chemical requirements of different processes are not expected to change drastically, which means that changes over time are expected to occur slowly, and therefore do not affect the goodness of the results. However, this limit can be overcome by using more recent datasets, and therefore closer to today's industrial reality.

Another problem is the definition of the various industrial branches in the datasets used, which is not clear and varies in the different datasets; consequently, the reclassification carried out is a source of systematic errors. The solution may be to use data collectors of a unique classification of industrial sectors (for example using the NACE classification).

Thermal analysis for the Italian production of steel, cement and paper

In the second part of this thesis, three industrial branches are specifically analyzed: steel, cement and paper industry. The choice of these 3 sectors is made first because they are part of macro-sectors analyzed which are characterized by the high consumption of heat and fossil fuels, especially for the production of cement (Non-metallic minerals) and steel (Metallurgy).
Another point is the presence of a good amount of data provided both by individual companies and by trade associations (e.g. Assocarta for paper companies), thanks to which it is possible to obtain an estimate of the thermal energy consumption for individual plants, in in order to geographically locate such consumption.
These sectors are also characterized by mature and widespread technologies, which allows the use of specific thermal consumptions (where needed) referred to the technologies-processes considered and therefore more accurate results.

The methodology used to calculate the thermal energy per plant depends on the data provided by the companies, and therefore is based, for example, on the actual production and specific thermal consumption provided by the company or obtained from the trade associations, or aggregate thermal energy consumption supplied by the company are divided among the various plants according to their production capacity.

Siderurgy

The metallurgical sector represents 14.9% of total italian industrial consumption [3] and from the previous analysis 17.9% of total industrial thermal consumption; therefore a more in-depth analysis of this sector may be interesting. In particular, the steel sector is analyzed, which from the analyzes of FEDERACCIAI represents over 60% of the production of the metallurgical sector [10].

The study starts from the analysis of the current production processes, identifying the technologies currently in use and the most critical phases for the consumption of thermal energy and the required levels of temperature then statistical and literature data are used to obtain an estimate of thermal consumption and temperature ranges. In particular, statistical data on the national steel production provided by FEDERACCIAI and specific thermal consumption values provided by [11] will be used to obtain an estimate of the sector's thermal consumption. Subsequently, the individual plants with production from blast furnaces will be specifically analyzed and thermal consumption calculated, using the production values provided by the companies and the specific thermal consumption obtained from [11].

Production processes

Steel is defined as any iron alloy that has a carbon content not exceeding 2% by weight [12]. Above this we will speak of cast iron and no longer of steel. The production of steel, therefore, is closely linked to the control of the carbon in the alloy, as well as to that of the other elements that make it up and to which the properties of the alloy itself are attributable. Currently, Italian steel production is basically obtained with two manufacturing cycles [13]: **integral cycle** and **electric furnace cycle**. Another process that is starting to be used is the directed reduced iron (DRI) process, in which iron ore is reduced to iron without melting typically using natural gas or coal. This system could be equipped with chemical absorption-based CO_2 capture, a common process operation based on the reaction between CO_2 and a chemical solvent (e.g., amine-based). The CO_2 is released at temperatures typically in the range 120°C to 150°C and the solvent regenerated for further operation [14]. From the information gathered, however, this type of technology seems not yet to be used in the Italian steel industry.

Integral cycle

In the integral cycle, steel production starts from the processing of iron ore (Fe_2O_3 or FeO_4) which is melted in the **blast furnace (BF)**, in order to separate the iron from the starting rock material.

Inside the blast furnace there is a descending charge of solid substances, consisting of iron oxide, coke, and limestone ($CaCO_3$), and an ascending current of reducing hot gases, which are essentially composed of CO, CO_2, N_2, with limited content by H_2. The reducing gas originates in the lower part of the furnace, at the height of the tubes, for the combustion of the coke; the limestone transforms

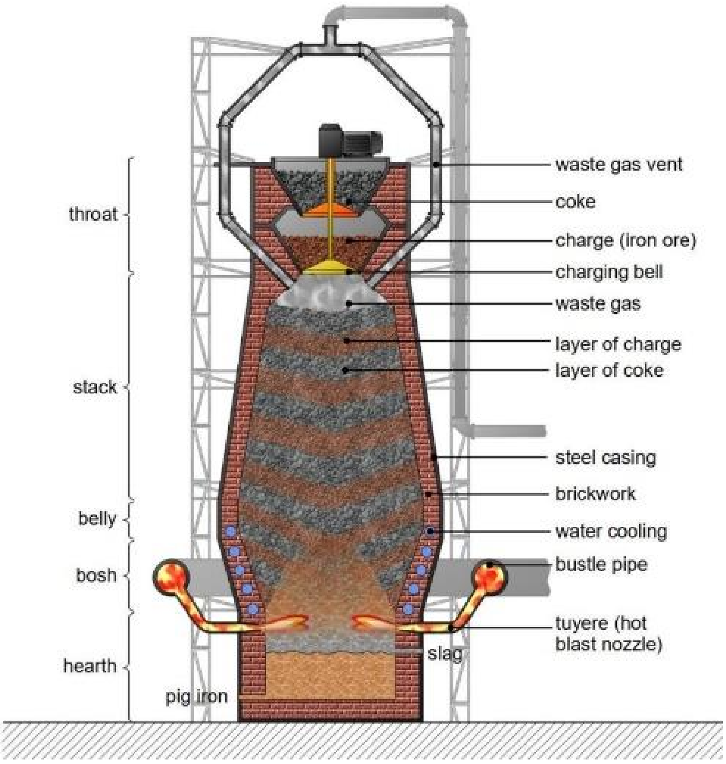

Figure 25: Blast furnace (BF) scheme (Source: tec-science.com)

into quicklime, favors the melting of iron and combines with the impurities present in the mineral, giving rise to the gangue.

The oven temperature gradually increases from the loading mouth where it is about 400°C to the belly where it reaches a temperature of 1,800°C [15]. The solid charge, on its downward path, meets the upward current of the preheated compressed air introduced by the high-speed nozzles. The oxygen contained in the air reacts with coal (C) generating carbon monoxide (CO), carbon dioxide (CO_2) and developing heat. The spongy iron continues to descend and enters the bosh where, finding an even higher temperature, it reacts with a part of the carbon (which cannot yet burn because the nozzles are lower) and forms cementite (or iron carbide); the cementite melts and forms the cast iron which continues to descend in the hottest areas, and having a lower melting temperature than the spongy iron, it melts and drips into the crucible (heart).

In this process, coke performs 3 tasks:

- provides thermal energy.
- reduces iron oxide into spongy iron.
- transforms the spongy iron into cast iron.

The blast furnaces operate in a continuous cycle, for a period ranging from a minimum of three years to a maximum of seven to eight: if the combustion stopped, the partially melted mass would solidify, and the furnace would have to be demolished prematurely.

The refining of the cast iron to obtain steel takes place through the removal of excess carbon and the control of the desired alloy elements. The most important refining process for cast iron , and also more widespread in the world, is the **Linz-Donawitz process** (**LD process**), which achieves the aforementioned oxidation by introducing pure oxygen into the molten cast iron, using the so-called **Basic Oxygen Furnace** (**BOF**), thanks to which the elements such as carbon, silicon, phosphorus and manganese are completely or partially oxidized, through the insufflation of pure oxygen through a lance introduced from above, while the exothermic oxidation reactions provide the process with the heat necessary to bring the bath of liquid cast iron at the temperature required for subsequent operations (the so-called out-of-oven treatments and solidification by casting). The charge of the BOF is balanced with the addition of small quantities of scrap, as well as components (e.g., limestone) that allow to obtain the desired degree of hardness and resistance.

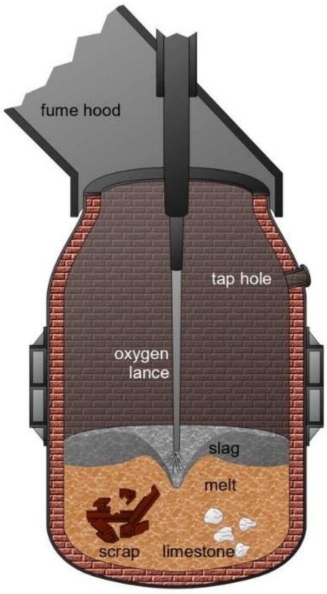

Figure 26: Basic oxygen furnace (BOF) scheme (Source: tec-science.com)

Electric furnace cycle

The steel production cycle through the electric furnace is more compact than the integral cycle since steel scrap is used directly without the use of plants and machinery necessary for the production of cast iron and its transformation into steel. Consequently, the electric furnace technology has spread thanks to the lower complexity of the production cycle, the ability to adapt quickly and flexibly to market trends, as well as the increased availability of steel scrap, following the development of the industrial era. Steel production takes place through the melting of suitably prepared and selected scrap which takes place in the electric furnace [16].

Electric Arc Furnace (EAF) is usually used, where scrap steel and solid cast iron are melted using an electric arc. Electric current passes through the steel, bringing it to a high temperature. Since electricity is used to heat the metal, the new steel can be created entirely from scrap steel. Once created, liquid steel can be cooled, rolled, cast and formed into a wide variety of products. This technology is characterized by high consumption of electricity but has several advantages such as the speed of commissioning, the greater possibility of controlling the chemical transformation processes, and the independence of the plant from ports or other important goods sorting stations.

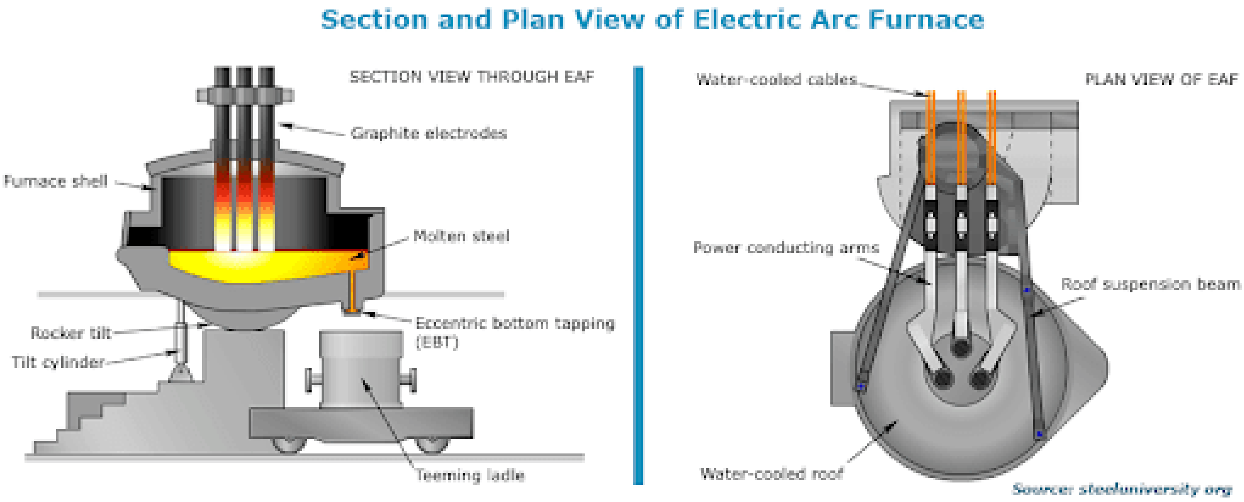

Figure 27: Electric arc furnace (EAF) (source: steeluniversity.com)

Calculation of thermal consumption for steel production in Italy

Here an overview of the Italian steel industry is initially presented, with relative production data provided by FEDERACCIAI and the different production rates from blast furnaces and electric arc furnaces; using these data and the specific consumption of thermal energy provided by [11], the thermal energy consumption is obtained, divided by integral cycle (BF + BOF) and electric arc furnace.

As already mentioned, steel production in Italy is one of the most energy-intensive sectors. From Federacciai analysis, steel production was 24.5 t in 2018 and 23.2 in 2019 [17], with a reduction of 5.3% compared to the previous year; despite the decline, Italy is the second largest producer of steel in the European Union after Germany (there are no production data in 2020 yet, but a significant reduction due to the pandemic is conceivable).

Produzione acciaio nell'Unione Europea (28) e quota sul totale nel 2019

M.t.	2015	2016	2017	2018	2019	var.% 19/18	quota 2019
Germania	42,7	42,1	43,3	42,4	39,7	-6,5%	25,0%
Italia	22,0	23,3	24,0	24,5	23,2	-5,3%	14,6%
Francia	15,0	14,4	15,5	15,4	14,4	-6,1%	9,1%
Spagna	14,8	13,6	14,4	14,3	13,5	-5,7%	8,5%
Polonia	9,2	9,0	10,3	10,2	9,0	-11,5%	5,7%
Belgio	7,3	7,7	7,8	8,0	7,8	-2,8%	4,9%
Altri	55,3	52,1	53,0	52,8	51,2	-3,0%	32,2%
Unione Europea (28)	**166,2**	**162,2**	**168,5**	**167,5**	**158,7**	**-5,3%**	**100,0%**

Elaborazioni su dati Federacciai e worldsteel

Table 26: Steel production in Italy and in the European Union (28), (Source: [13])

Figure 28: Steel production plants in Italy (Source: [13])

Currently in Italy there are 39 sites (42 sites including non-operational ones) for the production of steel, of which 3 are based on the production of steel through a blast furnace (integral cycle) and 37 that use electric furnaces [13]. The sites are located largely in central-northern Italy in the Po Valley area, while in southern Italy there are few plants like that of Taranto, which however has considerable importance given its large production capacity.

Federacciai's data shows that 82% of steel production in Italy in 2019 came from electric furnaces [10]; using this information and the data on the total production indicated in fig.28 it is possible to make a division on the quantity of steel produced both by electric furnace and by blast furnace, with the hypothesis that production is linked only to these two processes (tab.26).

$$K_{el} = K_{tot} * k_{el}$$

$$K_{int} = K_{tot} - K_{el}$$

$$k_{el} = 0.82$$

K_{tot}: total steel production.

K_{el}: production from electric furnace.

K_{int}: production from integral cycle (BF–BOF).

	2018	2019	
Total Production	24,500,000	23,200,000	t
EAF	20,090,000	19,024,000	t
Integral Cycle (BF-BOF)	4,410,000	4,176,000	t

Table 27: Steel production by EAF and integral cycle

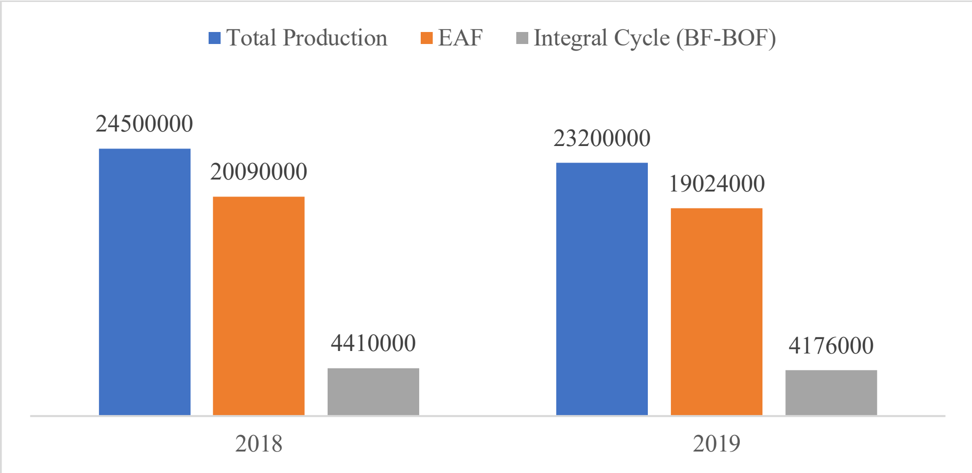

Figure 29: Steel production by EAF and integral cycle

The specific consumption indicated by Harvey et al. [11] is used to calculate the heat consumption relating to the various processes; the purpose of this paper is to calculate the practical and theoretical energy needs for the production of hot metal (pig iron) in a blast furnace (BF), and the transformation of hot metal into crude steel in a basic oxygen furnace (BOF) or electric arc furnace (EAF) with the addition of scrap iron or scrap steel of varying purity. In the study there are both theoretical minimum energy requirements that take into account various factors (e.g., amount and type of impurities in iron), and real world observed energy use.

Blast furnace (GJ/t)		DRI (GJ/t)			
		C fraction	Metallization		
Pure Fe from hematite, all credits	7.19		1.00	0.97	0.94
Hot metal, minimum					
With offgas and sensible heat credits, no energy loss	9.21[a]	0.000	9.93	9.68	9.44
Add minimal heat loss (0.40 GJ/t)	9.61	0.025	10.70	10.46	10.22
Without offgas credit	11.36	0.050	11.47	11.24	11.01
And without sensible heat capture	16.20				
Observed		Observed			
Efficient	11.72		9.96 to 10.55 total		
US average	13.71		10.5 to 18.9 GJ NG/t and 93 to 100 kWh elec/t		
EU average	13.65				
BOF (GJ/t)		**EAF (GJ/t)**			
			2%C DRI	5%C DRI	0.36%C scrap
Cold hot metal, no offgas credit	0.889	Feed oxidation	0.187	0.547	0.157
Cold hot metal, full offgas credit	0.159	Offgas energy	0.357	0.892	0.152
		Total	0.544	1.439	0.309
		Reduction heat sink	− 0.179	− 0.053	− 0.049
		Net supply	0.491	1.389	0.220
Observed		Observed			
External energy input	0.91 to 1.21	Feed oxidation	0.792		0.680
Steam production	0.12 to 0.34	Offgas energy	0.432		0.428
Offgas energy	0.35 to 0.70	Reduction heat sink	− 0.374		0.000
Net	0.44 to 0.17	Net supply	0.850		1.109

Table 28: Specific thermal energy consumption for different processes and different working conditions for steel production (Source: [11])

Since the purpose of this chapter is to obtain an estimate of the heat consumption of the Italian steel industry, the values relating to the real operating conditions of the production plants will be used for the calculation of energy consumption: this is because the paper provides specific consumption values related to specific operating conditions, which change from plant to plant.

For the blast furnace the index of tab.28 relative to the EU average is used, while for the BOF and the EAF an average value relative to the minimum and maximum energy input is calculated.

The values used are indicated in tab.29.

	e_{sp}	**Lower value**	**Upper value**	
BF	13.65			GJ/t_{steel}
BOF	1.06	0.91	1.21	GJ/t_{steel}
EAF	0.9795	0.85	1.109	GJ/t_{steel}

Table 29: Specific thermal energy consumption used for the calculation

Using the specific thermal energy consumption indicated in table 25 and the values of italian steel production for 2019 of table 23, an estimate of the thermal energy consumption for the BF, BOF and EAF can be obtained.

$$E_{BF} = e_{sp,BF} * K_{int}$$

$$E_{BOF} = e_{sp,BOF} * K_{int}$$

$$E_{EAF} = e_{sp,EAF} * K_{el}$$

E_{BF}: BF energy consumption.

E_{BOF}: BOF energy consumption.

E_{EAF} : EAF energy consumption.

2019	Energy consumption	
BF	57.0024	PJ
BOF	4.42656	PJ
EAF	18.63401	PJ
Total	80.06297	PJ

Table 30: Thermal energy consumption for BF, BOF and EAF processes

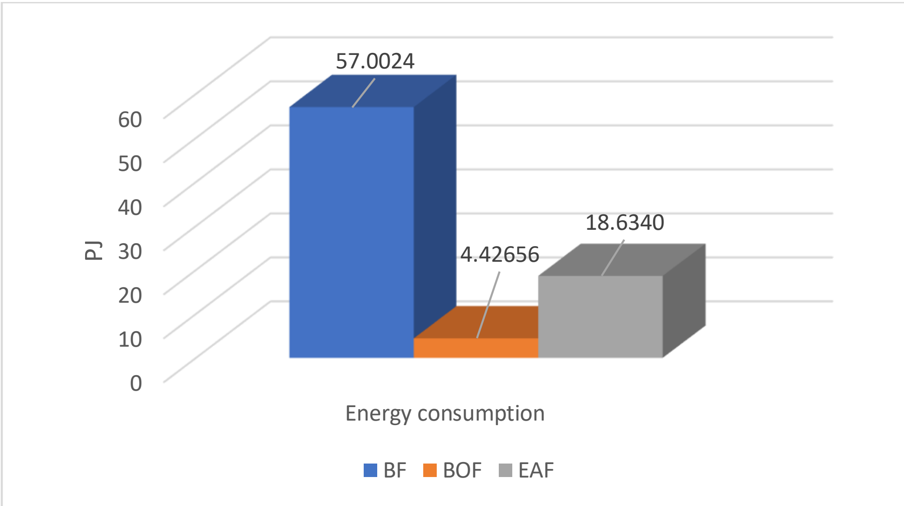

Figure 30: Thermal energy consumption for BF, BOF and EAF processes

The production of steel with integrated cycle (BF-BOF) involves thermal energy consumption of 61.429 PJ, against the 18.634 PJ of energy spent for steel production by EAF; therefore, the energy consumption of the integrated cycle is much greater than that of the EAF, with only 18% of the steel production obtained through BF-BOF. In particular, the most energy-intensive process is the production of cast iron through BF with 57.003 PJ.

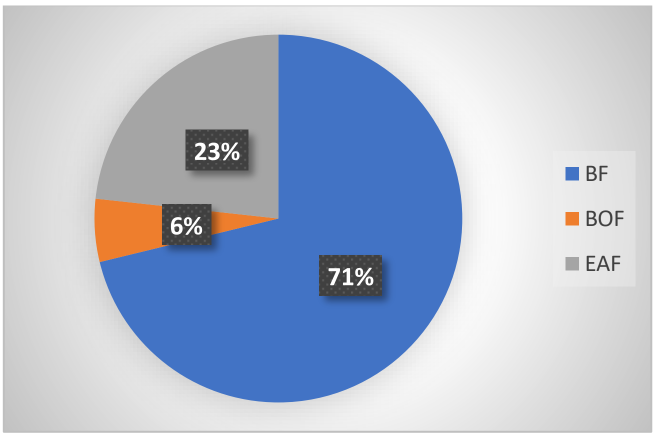

Figure 31: Share of thermal consumption with respect to the total consumption of thermal energy for BF, BOF and EAF

Thermal energy analysis for blast furnace steel production plants

This paragraph analyzes the thermal energy consumption associated with the individual blast furnace steel production plants. This choice was made because the blast furnace systems have high thermal specific consumption and are powered almost exclusively by fossil fuels (coke).

Focusing on single plants allows both to have more precise data and to locate the energy demand from a geographical point of view. For this purpose, a search was carried out to identify the plants (and related company) present in Italy, and subsequently a search was carried out for each plant, in order to obtain information on production, production capacity and energy consumption.

Federacciai indicates that in 2019 there are 3 plants that produce blast furnace steel in Italy: the plants in Taranto (ArcelorMittal), Trieste (Arvedi) and Piombino (JSW Steel). Below in tab.31 the plants considered are shown, with information on geographic location (latitude and longitude), data obtained by the companies (annual production), and thermal energy values obtained.

Plant	Company	Region	Latitude	Longitude	Production			Thermal consumption		
					2020	2019	2017	2020	2019	2017
					t	t	t	PJ	PJ	PJ
Taranto	ArcelorMittal	Puglia	40.508993	17.207589	3,400,000	4,300,000	\	50.014	63.253	\
Trieste	Arvedi	Friuli Venezia Giulia	45.6249882	13.7767049	\	\	378,674	\	\	5.1689
Piombino	JSW Steel	Toscana	42.930055	10.531811	\	\	\	\	\	\

Table 31: Thermal energy production and consumption data for blast furnace steel

The single plants will be analyzed below.

Piombino – JSW Steel

The Piombino steel plant has been managed since 2018 by JSW steel Italy, which is part of the multinational JSW steel. The plant is equipped with a blast furnace which, however, has been shut down since 2014 [18] , and today it operates only as a processing center; for this reason it will not be considered in the analysis.

Trieste – Arvedi group

The Trieste steel plant is owned by the Arvedi group, a steel company that operates mainly in Italy, with a small production presence abroad (Poland and Brazil). In the plant, the raw material is processed through the blast furnace to obtain cast iron in blocks, which is then sent to the other plant of the group (located in Cremona) to obtain the finished steel [19]; therefore the plant is not complete cycle, but has only the blast furnace for the production of cast iron.

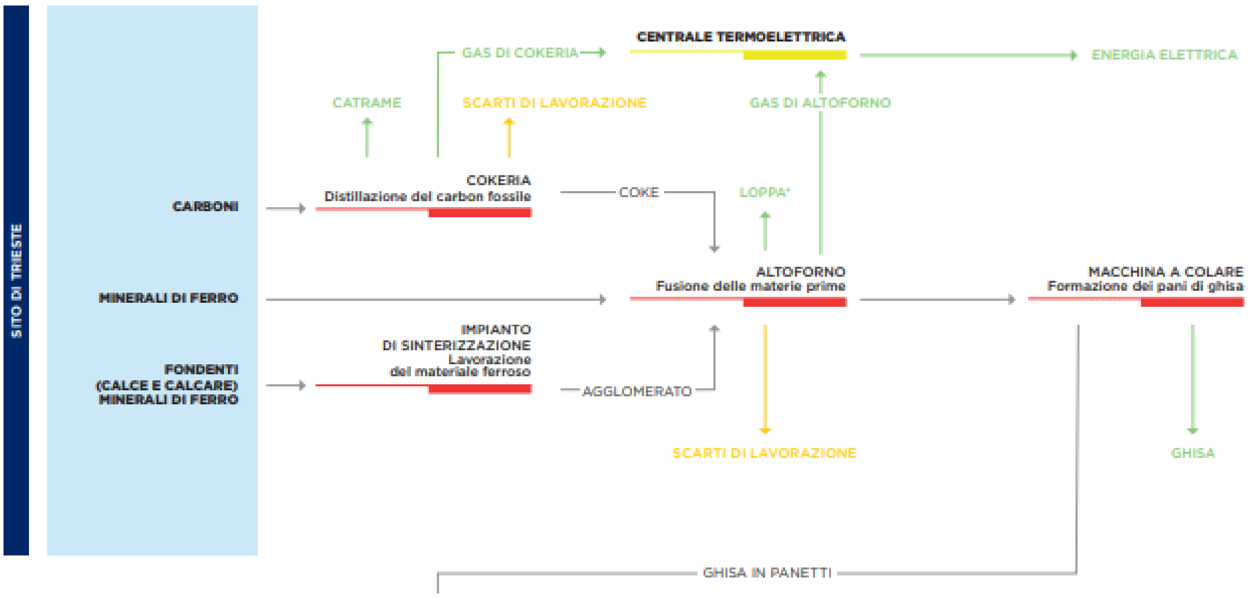

Figure 32: Trieste (Arvedi group) - production process scheme

Following a series of meetings at the end of 2019 and at the formal request of local institutions, Acciaieria Arvedi proceeded, in coordination with the MISE (Ministry of Economic Development), to initiate a process of decarbonisation and industrial reconversion of the Trieste site, which resulted in the cessation of the production activity of the hot area (coking plant and blast furnace) in April 2020 [20]; therefore today the Trieste site is a transformation center only.

In the report the company states that the plant produces about 400,000 tons of pig iron per year, so it can be assumed that production until 2019 does not differ much from this value; however, the company provides the precise value of production in 2017 (which does not differ much from the value indicated above).

	2017
Crude steel production Q_{steel} (t)	378,674

Table 32: Trieste (Arvedi group) - crude steel production

Using the specific energy consumption indicated in tab.29 and the production value of tab.32, it is possible to obtain an estimate of the heat consumption, which in this case refers only to the blast furnace (BF). The result is shown below.

$$E_{th} = e_{sp,BF} * Q_{steel} \text{ (PJ)}$$

$e_{sp,BF}$: thermal specific consumption for blast furnace

Q_{steel}: crude steel production (t)

Site	Company	Region	Latitude	Longitude	Thermal consumption (PJ)
Trieste	Arvedi	Friuli-Venezia Giulia	45.62498817	13.77670491	5.1689

Table 33: Trieste (Arvedi group) - Plant information and thermal energy consumption

Taranto - ArcelorMittal

The ArcelorMittal Italia's Taranto steel plant is, according to the European Commission, the largest steel plant in Italy and in the EU.

Site	Company	Region	Latitude	Longitude
Taranto	ArcelorMittal	Puglia	40.508993	17.207589

Table 34: Taranto (ArcelorMittal) - Plant information about company and location

It has a capacity to produce 10 million tons of steel annually, which corresponds to 40% of Italian steel production [21]. To date, it is the only full-cycle plant operating in Italy (BF+BOF), even if production is limited to below 50% of its capacity [22] due to legal issues.

Figure 33: Taranto (ArcelorMittal) - Top view of the plant

The production data from [23] [24] is shown below:

	2020	2019
Production $\boldsymbol{Q_{steel}}$ (t)	3,400,000	4,300,000

Table 35: Taranto (ArcelorMittal) - Steel production

Using the specific energy consumption indicated in tab.29 and the production value of tab.35, it is possible to obtain an estimate of the heat consumption for the years 2019 and 2020.

$$E_{BF} = e_{sp,BF} * Q_{steel} \text{ (PJ)}$$

$$E_{BOF} = e_{sp,BOF} * Q_{steel} \text{ (PJ)}$$

E_{BF}: BF energy consumption.

E_{BOF}: BOF energy consumption.

$e_{sp,BF}$: thermal specific consumption for blast furnace

$e_{sp,BOF}$: thermal specific consumption for basic oxygen furnace

Q_{steel}: steel production (t)

	2020	2019	
BF	46.41	58.695	PJ
BOF	3.604	4.558	PJ
Thermal Consumption	50.014	63.253	PJ

Table 36: Taranto (ArcelorMittal) - Thermal energy consumption

Cement industry

From the analysis carried out it in this thesis emerges that Non-metallic minerals sector is the one characterized by the highest thermal consumption in absolute terms, with 149.419 PJ of thermal energy used; for this we proceed with an analysis of the cement industry, which represents an important part of the Non-metallic minerals macro sector.

The study starts from the analysis of the current production processes, identifying the technologies currently in use and the most critical phases for the consumption of thermal energy, both in quantitative and qualitative terms (i.e. required temperatures); then statistical and literature data are used to obtain an estimate of thermal consumption and temperature ranges.

Production process

Cement is a hydraulic binder that comes in the form of a finely ground powder, which, when mixed with water, forms a paste that sets and hardens. This hydraulic hardening is mainly due to the formation of hydrated calcium silicates following the reaction between the water added for the mixture and the components of the cement. The hydraulically active component of a cement is the so-called "Portland Clinker". Cement, produced industrially since the mid-19th century, still remains one of the main building materials because, thanks to its characteristics of flexibility and high performance, it finds application in various building sectors[25].

For the manufacture of cement, both minerals of natural origin and mineral and / or industrial products or waste can be used, which can be used in the production cycle to replace natural raw materials. Considering the natural raw materials, they are extracted and initially crushed to reduce their size, in order to facilitate their handling and storage [26].

The crushed and stored raw materials are previously ground before cooking in order to obtain the so-called raw meal, that is a homogeneous mixture with adequate fineness that ensures the best conditions for the subsequent cooking process. The grinding is called raw (precisely because it precedes cooking), obtained using the raw mill [27].

Then we move on to cooking the flour using the cooking system, which consists of 3 main parts [28]:

- **Cyclone tower**: it is made up of different stages (generally from 4 to 6) where the flour undergoes a progressive heating thanks to the heat exchange with the hot gases leaving the oven. During its passage in the tower, the temperature of the flour goes from 100°C to 900°C, in order to obtain the decarbonation of the limestone (which occurs around 900°C), i.e. the separation of the CO_2 contained in the raw materials (in the form of carbonates) from the oxides necessary for processing ($CaCO_3 \rightarrow CaO + CO_2$). About 60% of the fuel can be consumed at this stage, as decarbonation is an extremely endothermic process.

- **Rotary kiln**: clinker is obtained by cooking the flour, which is a semi-finished product in the form of spherical particles with a diameter of 3-25 mm. To obtain this result, it is necessary to raise the temperature inside the rotary kiln up to about 1,450°C (with a flame temperature close to 2,000°C).
- **Grid cooler**: the clinker leaving the kiln must be cooled rapidly to stabilize its molecular structure and chemical composition. The grid cooler, to convey the passage of cold air, consists of a series of superimposed perforated plates that move alternately to transport the clinker out of the kiln.

After the clinker has cooled, it is ground in ball mills together with small quantities of gypsum (3-4%) until a powder smaller than 100 micrometers is obtained, or the so-called cement.

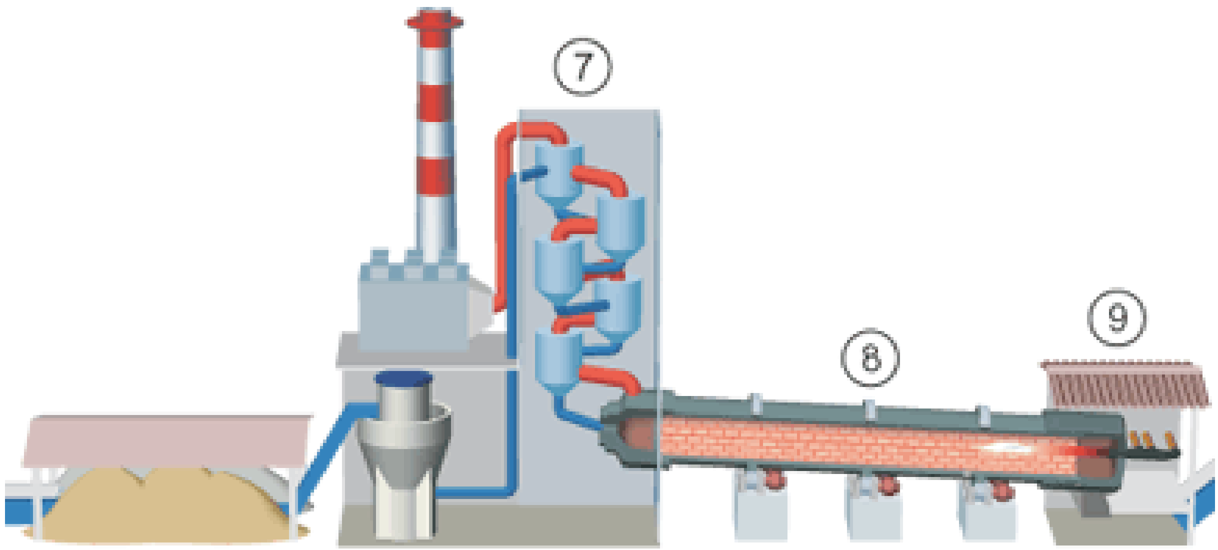

Figure 34: Cement production plant scheme, with cyclone tower (7), rotary kiln (8), grid cooler (9); (Source: holcim.it)

Calculation of thermal consumption for cement production in Italy

To assess the thermal energy demand, we start by listing the national cement production. According to data obtained by Federbeton, cement production was 16,393,539 tons in 2018 and 16,430,882 tons in 2019, with a slight decrease of 0.2% [29].

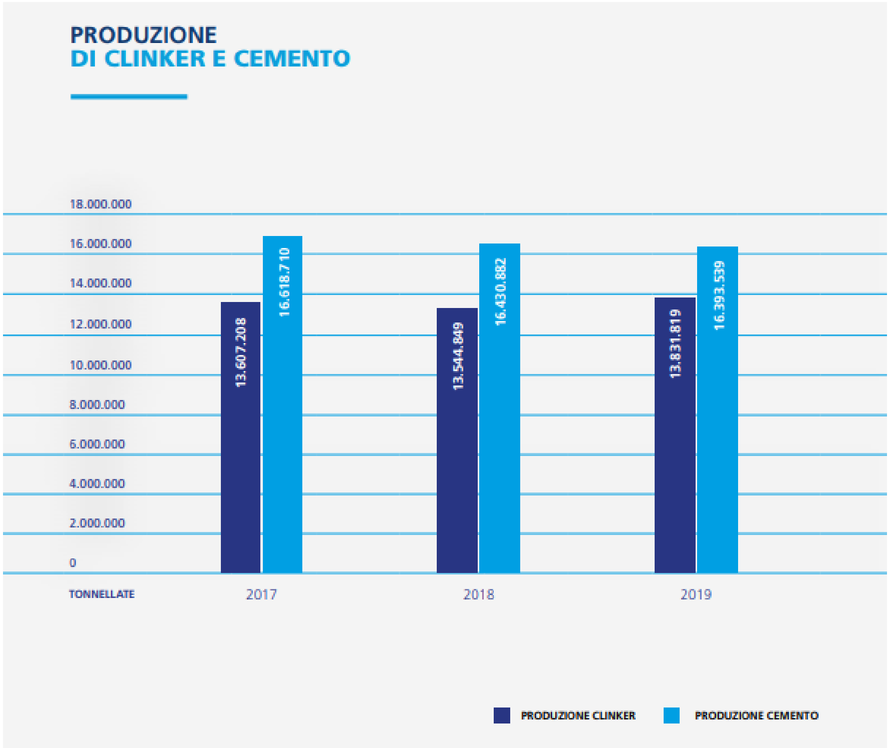

Figure 35: Cement and clinker production of AITEC member companies

However, the production data indicated refer only to AITEC member companies, which represent 85% of the total national production; then we proceed to obtain an estimate of the total national production.

$$G = \frac{G_{AITEC}}{g_{AITEC}}$$

$$g_{AITEC} = 0.85$$

G: total national production of cement \ clinker

G_{AITEC}: production of cement \ clinker by AITEC member companies

For the calculation of clinker production, it was decided to adopt the same coefficient used for the cement (0.85), The results are shown in the following tab.37.

	Cement (t)	**Clinker (t)**
2018	19,330,449.41	15,935,116.47
2019	19,286,516.47	16,272,728.24

Table 37: Total Italian production of cement and clinker

From [29] we obtain the specific consumption of thermal energy per ton of clinker produced; as can be seen, the specific consumption of thermal energy remains almost constant, with a small increase from 2017 to 2019 probably due to the lower saturation of the plants.

	Thermal energy specific consumption q_{th} [GJ/tn clinker]
2017	3.56
2018	3.58
2019	3.61

Table 38: Thermal energy specific consumption for clinker production (Source: [29])

Figure 36: Thermal energy specific consumption for clinker production (Source: [29])

Using the clinker production data from tab.37 and the specific consumption of thermal energy in tab. 38 the thermal energy consumption is obtained; the results are shown in tab.37.

$$Q_{th} = G_{clinker} * q_{th}$$

Q_{th}: thermal energy consumption for clinker production

$G_{clinker}$: clinker production

q_{th}: specific consumption of thermal energy to produce clinker

	Q_{th} [PJ]
2018	57.048
2019	58.745

Table 39: Cement sector thermal consumption

The thermal consumption of the cement sector thus calculated represents 38.2% and 31.7% respectively of the thermal consumption of the non-metallic minerals sector obtained through the 1 & 2 approach (149.42 PJ) and of the total consumption of the non-metallic minerals sector (179.95 PJ).

At this point, literature and statistical information can be used to estimate the temperature ranges associated with the thermal energy used. According to [30], 99% of the thermal energy required for cement production is used in the cyclone tower and in the rotary kiln. Inside the cyclone tower the raw meal passes through a precalcination stage which serves to optimize the heat exchange between the material and the hot gases, and to complete the decarbonation of the limestone, which occurs at around 900°C. **About 60% of the fuel can be consumed at this stage**, as decarbonation is an extremely endothermic process [28].

	T_{min} [°C]	T_{max} [°C]
Cyclone tower	100	900
Rotary kiln	900	1,450

Table 40: Temperature range for cyclone tower and rotary kiln

Using these data, it is possible to obtain the energy consumption associated with the cyclone tower and the rotary kiln, as well as a subdivision by temperature range. Thermal consumption is calculated as follows:

$$Q_{cyclone} = Q_{th} * \alpha_{cyclone}$$

$$Q_{kiln} = Q_{th} - Q_{cyclone}$$

$$\alpha_{cyclone} = 0{,}60$$

Q_{th}: thermal energy consumption for clinker production.

$Q_{cyclone}$: thermal energy associated with the cyclone tower.

Q_{kiln}: thermal energy associated with the rotary kiln.

	2018	**2019**	
Cyclone tower	34.229	35.247	PJ
Rotary kiln	22.819	23.498	PJ

Table 41: Cyclone tower and rotary kiln thermal consumption

Regarding the subdivision by temperature range, given the characteristics of the production process in question, two temperature ranges are considered 100°C<T≤900°C and 900°C<T≤1450°C, which correspond to the minimum and maximum temperature which is reached in the cyclone tower and in the rotary kiln (tab.42).

	2018	**2019**	
100°C<T≤900°C	34.229	35.247	PJ
900°C<T≤1,450°C	22.819	23.498	PJ

Table 42: Cement production - Consumption divided by temperature range (100°C<T≤900°C and 900°C<T≤1450°C)

Thermal energy analysis for cement production plants

This chapter analyzes the energy consumption associated with the individual cement production plants. This allows both to have more precise data and to be able to locate the energy demand from a geographical point of view. For this purpose, a search was carried out to identify the plants (and related company) present in Italy, and subsequently a search was carried out for each plant, in order to obtain information on production, production capacity and energy consumption.

The number of active plants and related companies is provided by AITEC (Italian Economic Technical Association of Cement): in January 2020 in Italy there are a total of 32 full-cycle plants and 23 grinding centers, managed from different companies. For the analysis of thermal consumption, only the complete cycle plants are considered since the thermal energy consumption of the grinding centers is negligible. The data collected by the companies allowed the evaluation of thermal energy consumption for 26 full cycle plants out of 32, that is 81% of the plants in Italy.

The plants considered are shown in tab., with information on geographic location (latitude and longitude) and thermal energy consumption calculated. Below will be indicated the various cement manufacturing companies with their relative plants, and the information made available by the companies themselves.

Plant	Company	Region	Latitude	Longitude	Thermal consumption
					2019
					PJ
Robilante	Buzzi Unicem	Piemonte	44.30179007	7.505859185	2.12513
Fanna	Buzzi Unicem	Friuli Venezia Giulia	46.17673662	12.74269275	1.25008
Monselice	Buzzi Unicem	Veneto	45.2533971	11.75173335	1.00006
Vernasca	Buzzi Unicem	Emilia Romagna	44.79385298	9.810111851	1.62510
Greve in Chianti	Buzzi Unicem	Toscana	43.61603953	11.28469446	0.68754
Guidonia	Buzzi Unicem	Lazio	42.00364085	12.71584332	2.37514
Siniscola	Buzzi Unicem	Sardegna	40.55660653	9.674058693	0.68754
Barletta	Buzzi Unicem	Puglia	41.31470058	16.28917001	1.37508
Augusta	Buzzi Unicem	Sicilia	37.1944724	15.18209149	2.37514
Gubbio	C. A. Barbetti	Umbria	43.36295296	12.54449241	/

Barile	C. Costantinopoli	Basilicata	40.95253601	15.67051652	/
Marcellinara	Cal.me	Calabria	38.91422326	16.44870861	/
Pederobba	Cementi G. Rossi	Veneto	45.87997901	11.96349609	/
Piacenza	Cementi G. Rossi	Emilia Romagna	45.04799037	9.716515864	/
Caravate	Colacem	Lombardia	45.88627423	8.667569216	1.509324625
Rassina	Colacem	Toscana	43.65908156	11.83678292	1.509324625
Gubbio	Colacem	Umbria	43.28792919	12.61533695	1.509324625
Spoleto	Colacem	Umbria	43.28794852	12.61546462	1.509324625
Sesto Campano	Colacem	Molise	41.44391314	14.06339921	1.509324625
Maddaloni	Colacem	Campania	41.06012219	14.37496226	1.509324625
Galatina	Colacem	Puglia	40.16884638	18.20092081	1.509324625
Ragusa	Colacem	Sicilia	36.90405463	14.72796285	1.509324625
Ternate	Holcim Italia	Lombardia	45.78308117	8.68153176	/
Calusco D'Adda	Italcementi	Lombardia	45.68691544	9.468258659	2.549087811
Rezzato	Italcementi	Lombardia	45.51490426	10.34411333	2.209209436
Colleferro	Italcementi	Lazio	41.73609919	13.00585344	2.955338892
Samatzai	Italcementi	Sardegna	39.4664115	9.027902452	1.773203335
Guardiaregia	Italcementi	Molise	41.45608747	14.55226696	0.295533889
Matera	Italcementi	Basilicata	40.67661041	16.65631295	1.529452687
Isola delle Femmine	Italcementi	Sicilia	38.19272962	13.24916682	1.600808566
Tavernola	Italsacci	Lombardia	45.71588581	10.04731366	1.477669446
Cagnano	Italsacci	Abruzzo	42.46342171	13.2592207	0.849695937
Total					40.81542

Table 43: Information about cement production plant location and relative calculated thermal energy consumption

The total thermal energy value calculated for the individual plants represents 71.5% of the total thermal energy for the cement sector calculated using AITEC and Federbeton data, 27.3% compared to the thermal consumption of the non-metallic minerals sector (approach 1 & 2) and 22.7% of the total consumption of the same sector. No data were found on the total consumption of the cement sector.

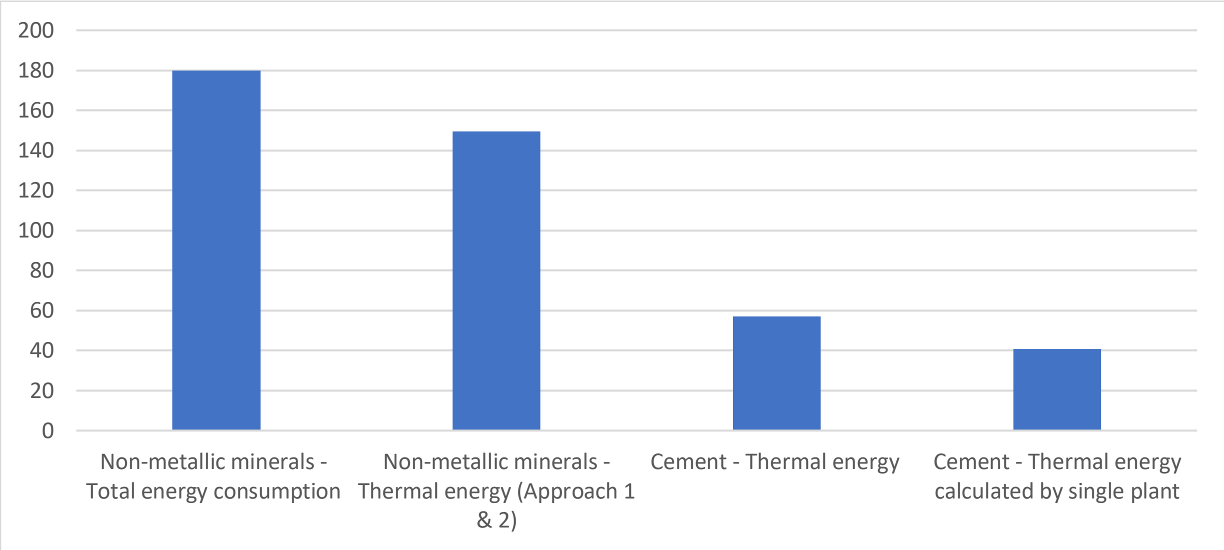

Figure 37: Thermal energy consumption for Non-metallic minerals and cement sectors

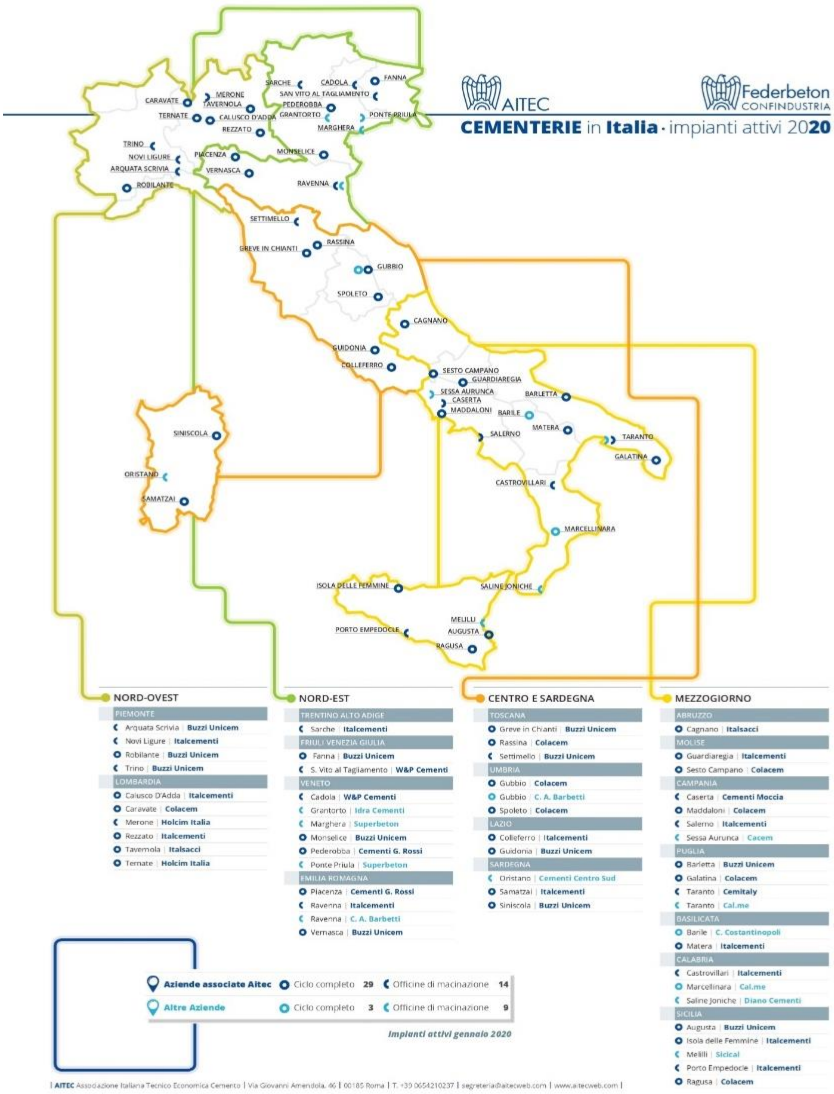

Figure 38: Cement production plant in Italy

Buzzi – Unicem

Buzzi Unicem is an international group, focused on the production of cement, concrete and natural aggregates. In Italy they have 9 full cycle plants and 4 grinding centers. The geographical position of the complete cycle plants (latitude and longitude) is indicated below, which will be indicated with the name of the city where they are located.

Full cycle plants	Company	Region	Latitude	Longitude
Robilante	Buzzi Unicem	Piemonte	44.301790079	7.5058591855
Fanna	Buzzi Unicem	Friuli-Venezia Giulia	46.17673662	12.74269275
Monselice	Buzzi Unicem	Veneto	45.2533971	11.75173335
Vernasca	Buzzi Unicem	Emilia-Romagna	44.79385298	9.810111851
Greve in Chianti	Buzzi Unicem	Toscana	43.61603953	11.28469446
Guidonia	Buzzi Unicem	Lazio	42.00364085	12.71584332
Siniscola	Buzzi Unicem	Sardegna	40.55660653	9.674058693
Barletta	Buzzi Unicem	Puglia	41.31470058	16.28917001
Augusta	Buzzi Unicem	Sicilia	37.1944724	15.18209149

Table 44: Buzzi Unicem - Plants location

The 2020 sustainability report published by the company [31] provides various information on energy consumption and cement production. However, the data provided is aggregated by country (Italy), and not by single production plant.

	2020	2019
Cement production $\mathbf{p_{tot}}$ (tn)	4,616,000	4,708,000
Specific thermal consumption $(\mathbf{MJ}/\mathbf{tn_{clinker}})$	4,138	4,109
Production capacity $(\mathbf{tn_{cement}}/\mathbf{year})$	10,800,000	

Clinker production factor ($^{tn_{clinker}}/_{tn_{cement}}$)	0.693

Table 45: Buzzi Unicem - data on production and specific thermal consumption

Buzzi Unicem provides further data on the production capacity of the individual plants (not actual production). For the Greve in Chianti plant this information was not found, therefore the production capacity is obtained by subtracting the values relating to the individual plants from the aggregate value of production capacity.

	Production capacity ($^{\mathbf{t_{cement}}}/_{\mathbf{year}}$)
Robilante	1,700,000
Fanna	1,000,000
Monselice	800,000
Vernasca	1,300,000
Greve in Chianti	550,000
Guidonia	1,900,000
Siniscola	550,000
Barletta	1,100,000
Augusta	1,900,000

Table 46: Buzzi Unicem - Production capacity for each plant

In the absence of other information, to calculate the actual production of the individual plant it is assumed that it is proportional to the production capacity of the plant itself.

$$n_i = \frac{c_i}{c_{tot}}$$

n_i: production factor of plant i;

c_i:production capacity of plant i;

c_{tot}: total production capacity;

Now is possible to calculate the cement production for each plant.

$$p_i = p_{tot} * n_i$$

p_i: cement production of plant i;

p_{tot}: total cement production;

Using these data, the clinker production can be calculated:

$$b_i = p_i * \beta_{clinker}$$

b_i: clinker production of plant i;

$\beta_{clinker}$: clinker production factor ($^{\mathrm{tn_{clinker}}}/_{\mathrm{tn_{cement}}}$);

The results are shown in the following table:

	Production factor $\boldsymbol{n_i}$	***Cement production (tn)***	***Clinker production (tn)***
Robilante	0.157407407	741,074	513,564
Fanna	0.092592593	435,925	302,096
Monselice	0.074074074	348,740	241,677
Vernasca	0.12037037	566,703	392,725
Greve in Chianti	0.050925926	239,759	166,153
Guidonia	0.175925926	828,259	573,983
Siniscola	0.050925926	239,759	166,153
Barletta	0.101851852	479,518	332,306
Augusta	0.175925926	828,259	573,983

Table 47: Buzzi Unicem - cement and clinker production for each plant calculated by using production factor $\boldsymbol{n_i}$

For the calculation of thermal energy consumption, the clinker production values just calculated and the specific consumption of thermal energy supplied by the company are used.

$$q_i = b_i * \alpha_{th}$$

q_i: thermal energy consumption of plant i;

b_i: clinker production of plant i;

α_{th}: specific thermal consumption ($^{\mathrm{MJ}}/_{\mathrm{tn_{clinker}}}$);

Thermal energy consumption (PJ)	2019
Robilante	2.12512921
Fanna	1.25007601
Monselice	1.00006081
Vernasca	1.62509881
Greve in Chianti	0.68754180
Guidonia	2.37514441
Siniscola	0.68754180
Barletta	1.37508361
Augusta	2.37514441
Total	13.50082087

Table 48: Buzzi Unicem - Thermal energy consumption for each plant

Italcementi – Italsacci

Italcementi - Italsacci is a cement and concrete manufacturing company operating in Italy, and part of the Heidelbergcement group, which operates in more than 50 states. It operates 9 full-cycle plants and 7 grinding centers.

Figure 39: Italcementi - Map of company plants

Full cycle plants	Company	Region	Latitude	Longitude
Calusco D'Adda	Italcementi	Lombardia	45.68691544	9.468258659
Rezzato	Italcementi	Lombardia	45.51490426	10.34411333
Colleferro	Italcementi	Lazio	41.73609919	13.00585344
Samatzai	Italcementi	Sardegna	39.4664115	9.027902452
Guardiaregia	Italcementi	Molise	41.45608747	14.55226696
Matera	Italcementi	Basilicata	40.67661041	16.65631295
Isola delle Femmine	Italcementi	Sicilia	38.19272962	13.24916682
Tavernola	Italsacci	Lombardia	45.71588581	10.04731366
Cagnano	Italsacci	Abruzzo	42.46342171	13.2592207

Figure 40: Italcementi - plant location

The 2019 Sustainability report [32] gives some information about energy consumption and specific energy consumption for cement and clinker production. The clinker (cement) production value is obtained dividing energy consumption for clinker (cement) by specific energy consumption for clinker (cement).

	2019	2018
Energy consumption – cement (TJ)	15,338	15,451
Energy consumption – clinker (TJ)	15,240	15,365
Specific energy consumption – cement ($^{\mathbf{MJ}}/_{\mathbf{tn}}$)	2,733	2,631
Specific energy consumption – clinker ($^{\mathbf{MJ}}/_{\mathbf{tn}}$)	3,497	3,451
Clnker production (t)	4,358,021	4,452,332
Cement production (t)	5,612,147	5,872,671

Table 49: Italcementi - aggregated data provided by the company

Italcementi provides further data on the cement/clinker production capacity of some of the individual plants (not actual production).

	$tn_{cement}/_{year}$	$tn_{clinker}/_{year}$
Calusco D'Adda	1,500,000	-
Rezzato	1,300,000	-
Tavernola	-	600,000
Colleferro	1,500,000	1,200,000
Samatzai	950,000	720,000
Cagnano	500,000	-
Guardiaregia	250,000	120,000
Matera	900,000	-
Isola delle Femmine	900,000	650,000

Table 50: Italcementi - data about plants production capacity (clinker-cement)

To obtain the missing values of clinker production capacity, a clinker/cement ratio is calculated by averaging the clinker/cement ratios of the plants for which both production capacities are known. In this way it is possible to go back to an estimate of the clinker production capacity of the other plants.

$$\varepsilon_i = \frac{clinker\ production\ capacity}{cement\ production\ capacity}$$

ε_i*: clinker/cement ratio of the plant i (*$^{tn_{clinker}}/_{tn_{cement}}$*);*

	$\boldsymbol{\varepsilon_i}$
Colleferro	0.8
Samatzai	0.757894737
Guardiaregia	0.48
Isola delle Femmine	0.722222222

Table 51: Italcementi - clinker/cement ratio $\boldsymbol{\varepsilon_i}$

The average value of the clinker / cement ratio will be:

$$\varepsilon = \frac{\sum_i \varepsilon_i}{4} = 0{,}69 \ (^{tn_{clinker}}/_{tn_{cement}})$$

At this point the clinker production capacity can be calculated by multiplying the value of the cement production capacity of the single plant by ε. The results are shown in the following table.

	$tn_{clinker}/_{year}$
Calusco D'Adda	1,035,043
Rezzato	897,038
Tavernola	600,000
Colleferro	1,200,000
Samatzai	720,000
Cagnano	345,014
Guardiaregia	120,000
Matera	621,026
Isola delle Femmine	650,000
Total	6,188,122

Table 52: Italcementi - clinker production capacity for each plant

In the absence of other information, to calculate the actual clinker production of the individual plant it is assumed that it is proportional to the production capacity of the plant itself.

$$n_i = \frac{c_i}{c_{tot}}$$

n_i: production factor of plant i;

c_i: clinker production capacity of plant i;

c_{tot}: total clinker production capacity;

	Production factor n_i
Calusco D'Adda	0.16726298
Rezzato	0.144961249
Tavernola	0.096959937
Colleferro	0.193919875
Samatzai	0.116351925
Cagnano	0.055754327
Guardiaregia	0.019391987
Matera	0.100357788
Isola delle Femmine	0.105039932

Table 53: Italcementi - production factor n_i

Now is possible to calculate the clinker production for each plant.

$$p_i = p_{tot} * n_i$$

p_i: clinker production of plant i;

p_{tot}: total clinker production;

Clinker production (tn)	2019	2018
Calusco D'Adda	744,710.427	728,935.6051
Rezzato	645,415.7034	631,744.1911
Tavernola	431,697.8957	422,553.459
Colleferro	863,395.7915	845,106.9179
Samatzai	518,037.4749	507,064.1508
Cagnano	248,236.809	242,978.535
Guardiaregia	86,339.57915	84,510.69179
Matera	446,826.2562	437,361.3631
Isola delle Femmine	467,672.7204	457,766.2472

Table 54: Italcementi - Clinker production for each plant

For the calculation of thermal energy consumption, the clinker production values just calculated and the specific consumption of thermal energy supplied by the company are used.

$$q_i = b_i * \alpha_{th}$$

q_i: thermal energy consumption of plant i;

b_i: clinker production of plant i;

α_{th}: specific thermal consumption ($^{\mathrm{MJ}}/_{\mathrm{tn_{clinker}}}$);

Thermal energy consumption (PJ)	2019	2018
Calusco D'Adda	2.549087811	2.569995684
Rezzato	2.209209436	2.227329592
Tavernola	1.477669446	1.489789438
Colleferro	2.955338892	2.979578876
Samatzai	1.773203335	1.787747326
Cagnano	0.849695937	0.856665228
Guardiaregia	0.295533889	0.297957888
Matera	1.529452687	1.54199741
Isola delle Femmine	1.600808566	1.613938558
Total	15.24	15.365

Table 55: Italcementi - thermal energy consumption calculated for each plant

Colacem

Colacem S.p.A. is the main company of the Financo Group, whose core business is the production of cement and concrete. Colacem in Italy manages 8 full cycle plants.

Full cycle plants	Company	Region	Latitude	Longitude
Caravate	Colacem	Lombardia	45.88627423	8.667569216
Rassina	Colacem	Toscana	43.65908156	11.83678292
Gubbio	Colacem	Umbria	43.28792919	12.61533695
Spoleto	Colacem	Umbria	43.28794852	12.61546462
Sesto Campano	Colacem	Molise	41.44391314	14.06339921
Maddaloni	Colacem	Campania	41.06012219	14.37496226
Galatina	Colacem	Puglia	40.16884638	18.20092081
Ragusa	Colacem	Sicilia	36.90405463	14.72796285
Caravate	Colacem	Lombardia	45.88627423	8.667569216

Table 56: Colacem - plants location

The 2019 sustainability report published by the company provides information on energy consumption, in particular the aggregate heat consumption is indicated.

	2018	2019
Clinker production $\left({}^{\mathbf{tn_{clinker}}}/_{\mathbf{year}}\right)$	2,936,934	3,309,638
Cement production $\left({}^{\mathbf{tn_{clinker}}}/_{\mathbf{year}}\right)$	3,174,475	3,791,604
Total energy consumption $\left({}^{\mathbf{GJ}}/_{\mathbf{year}}\right)$	12,209,227	13,819,652
Thermal energy consumption $\left({}^{\mathbf{GJ}}/_{\mathbf{year}}\right)$	10,682,348	12,074,597
Specific thermal energy $\left({}^{\mathbf{GJ}}/_{\mathbf{tn_{clinker}}}\right)$	3.64	3.64

Table 57: Colacem - aggregated data provided by the company

However, the company does not provide the consumption of the individual plants, nor does it provide information on the production or production capacity of the individual plants. For this reason it is not possible to make a weighted subdivision of the thermal consumption, but the thermal consumption is equally divided among the various plants.

Thermal energy consumption	***2019***	***2018***
Caravate	1.509324625	1.3352935
Rassina	1.509324625	1.3352935
Gubbio	1.509324625	1.3352935
Spoleto	1.509324625	1.3352935
Sesto Campano	1.509324625	1.3352935
Maddaloni	1.509324625	1.3352935
Galatina	1.509324625	1.3352935
Ragusa	1.509324625	1.3352935
Caravate	1.509324625	1.3352935

Table 58: Colacem - thermal energy consumption calculated for each plant

Other plants

For the plants indicated here it was not possible to obtain information regarding thermal consumption, or data regarding production that could allow us to trace the energy consumption of the plants. Below we indicate the plants and companies that manage them, as well as their geographical position.

Full cycle plants	***Company***	***Region***	***Latitude***	***Longitude***
Gubbio	C. A. Barbetti	Umbria	43.36295296	12.54449241
Barile	C. Costantinopoli	Basilicata	40.95253601	15.67051652
Marcellinara	Cal.me	Calabria	38.91422326	16.44870861
Pederobba	Cementi G. Rossi	Veneto	45.87997901	11.96349609
Piacenza	Cementi G. Rossi	Emilia Romagna	45.04799037	9.716515864
Ternate	Holcim Italia	Lombardia	45.78308117	8.68153176

Table 59: Other cement production plants - plants location

Paper industry

The paper industry is very diversified, using many types of raw materials to produce different kinds of paper by different methods in mills of all sizes, but the paper production is basically a two-step process in which a fibrous raw material is first converted into pulp, and then the pulp is converted into paper. Pulp and paper are manufactured from raw materials containing cellulose fibers, generally wood, recycled paper, and agricultural residues. The paper manufacturing process has several stages: raw material preparation, pulp manufacturing, pulp washing and screening, chemical recovery, bleaching, stock preparation, and papermaking.

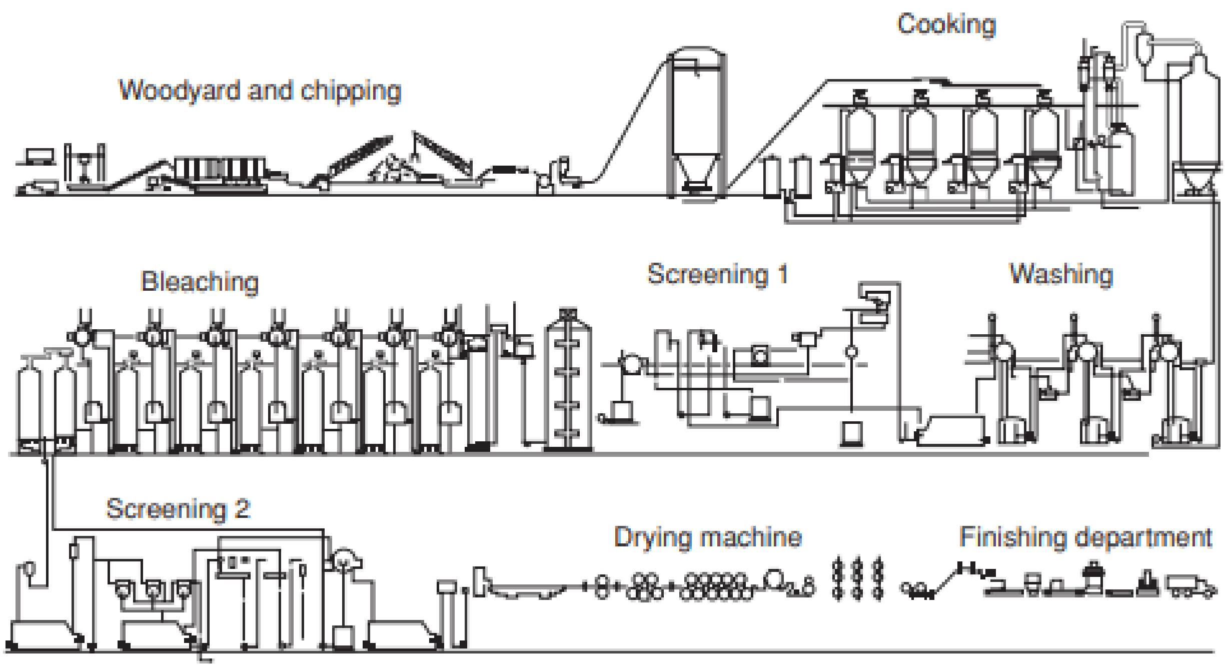

Figure 41: Paper production scheme

The harvested wood is first processed so that the fibers are separated from the unusable fraction of the wood, the lignin. Pulp making can be done mechanically or chemically. The pulp is then bleached and further processed, depending on the type and grade of paper that is to be produced. In the paper factory, the pulp is dried and pressed to produce paper sheets. Postuse, an increasing fraction of paper and paper products is recycled. Nonrecycled paper is either landfilled or incinerated [33].

The actual papermaking process consists of two primary processes: dry-end and wet-end operations. In wet-end operations, the cleaned and bleached pulp is formed into wet paper sheets. In the dry-end operations, those wet sheets are dried and various surface treatments are applied to the paper.

Paper drying section is usually the most expensive section of a paper mill, both for energy consumption and capital cost: in particular, this section consumes about 85% of the heat energy used in papermaking [34]. The classical method for paper drying is the conventional drying cylinder (figure 42), where steam at saturation temperature is supplied to the cylinders as heat the source. As steam condenses in the inner surface of the cylinder, latent heat of vaporization is released, and heat is transferred to the paper. In a typical modern machine, 1.3 kg of steam is usually required to evaporate 1 kg of water from the wet paper. Steam pressure generally does not exceed 11 bar, with relative steam temperature around 150°C.

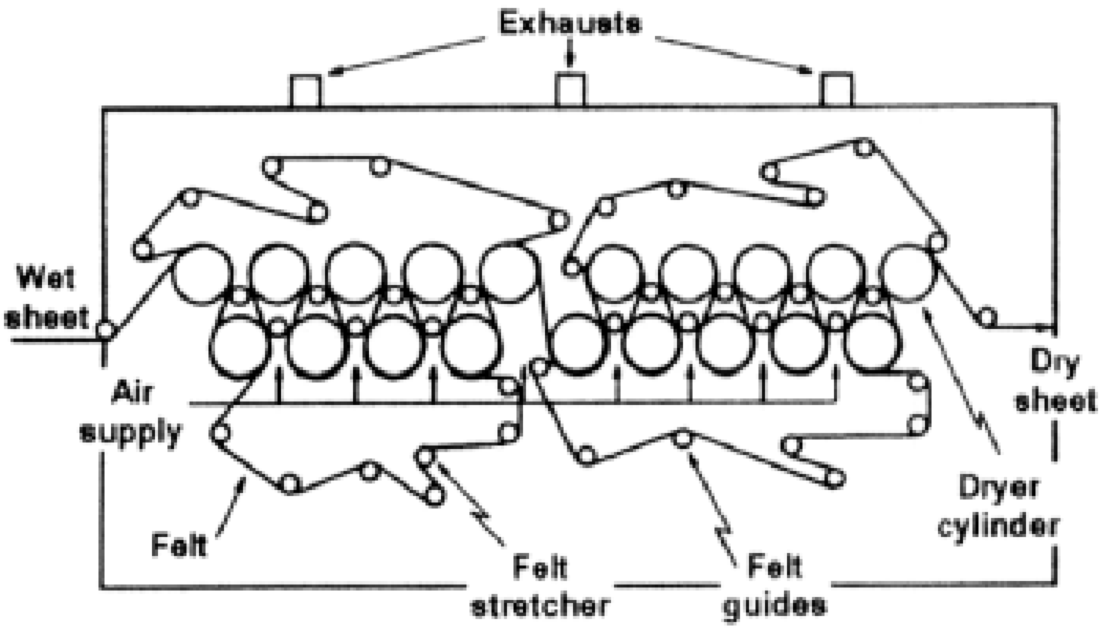

Figure 42: Paper drying - scheme conventional drying cylinder

Calculation of thermal consumption for paper production in Italy

In 2018 the Italian paper industry had an energy consumption of 86,269 PJ, which represents 8.5% of the total Italian industrial energy consumption [3]. For the analysis of thermal consumption, reference is made to the sector association Assocarta, which in addition to providing information regarding the annual production of paper, also provides the value of the process heat used [35][36].

	2019	2018
Production (tn)	8,900,900	9,091,000
Process heat (TJ)	42,900	43,100

Table 60: Data on total Italian paper production and related thermal consumption (Sources: [35],[36])

Using data of tab.60, it is possible to calculate the specific thermal consumption value (tab.61), which can be used later for the calculation of the thermal energy consumption of the individual paper production plants.

	2019	2018
Specific thermal consumption $\boldsymbol{\delta_{paper}}$ $(\boldsymbol{TJ/tn})$	0.004819737	0.004740953

Table 61: Paper production - Specific thermal consumption

Thermal energy analysis for paper production plants

This chapter analyzes the energy consumption associated with the individual paper production plants. This allows both to have more precise data and to be able to locate the energy demand from a geographical point of view. For this purpose, a search was carried out to identify the plants (and related company) present in Italy, and subsequently a search was carried out for each plant, in order to obtain information on production, production capacity and energy consumption.

As of 2019, there are 153 paper production plants in Italy (both paper mills and processing plants)[35]; however, there is no information regarding the number of paper mills, where the processes with the greatest heat consumption are present, such as the paper drying process. In the following analysis, only paper mills will be considered, which, as mentioned, have the highest thermal consumption.

The data collected by the companies allowed the evaluation of thermal energy consumption for 39 paper mills out of 153, that is 25.5% of the plants in Italy. The plants considered are shown in tab.62, with information on geographic location (latitude and longitude) and thermal energy consumption calculated. Below will be indicated the various paper manufacturing companies with their relative plants, and the information made available by the companies themselves.

Plant	Company	Region	Latitude	Longitude	Thermal consumption (TJ)			
					2020	2019	2018	2017
Verzuolo	Burgo Group	Piemonte	44.59687817	7.485999429		1,651.369		
Avezzano	Burgo Group	Abruzzo	41.99495894	13.43877132		825.685		
Sora	Burgo Group	Lazio	41.69846199	13.58502276		1,308.710		
Duino	Burgo Group	Friuli-Venezia Giulia	45.79501113	13.59072939		825.685		
Villorba	Burgo Group	Veneto	45.74897356	12.25077566		842.198		
Sarego	Burgo Group	Veneto	45.42176891	11.39588125		627.520		
Lugo	Burgo Group	Veneto	45.74336766	11.52067965		218.806		
Toscolano	Burgo Group	Lombardia	45.64303381	10.61833819		511.924		
Tolmezzo	Burgo Group	Friuli-Venezia Giulia	46.39524643	13.01540064		710.089		
Treviso	Burgo Group	Veneto	45.6864298	12.3253403		255.962		
Chiampo	Burgo Group	Veneto	45.53556293	11.29869225		231.192		
Ovaro	Reno De Medici	Friuli-Venezia Giulia	46.48178298	12.86304773	772.896	787.035	733.514	740.532
Santa Giustina	Reno De Medici	Veneto	46.07127217	12.03749393	1,952.579	1,988.299	1,853.088	1,870.819
Villa Santa Lucia	Reno De Medici	Lazio	41.48491078	13.7870971	1,789.864	1,822.608	1,698.664	1,714.917
Arco	Fedrigoni - Cordenons	Trentino-Alto Adige	45.90254409	10.87875518		442.729	474.711	462.234
Varone	Fedrigoni - Cordenons	Trentino-Alto Adige	45.91034151	10.83798747		307.130	329.316	320.660
Verona	Fedrigoni - Cordenons	Veneto	45.33022248	10.99083959		459.506	492.699	479.749
Fabriano	Fedrigoni - Cordenons	Marche	43.32410544	12.8920589		801.272	859.153	836.572
Pioraco	Fedrigoni - Cordenons	Marche	43.17953092	12.98825182		157.727	169.121	164.675
Cordenons	Fedrigoni - Cordenons	Friuli-Venezia Giulia	45.96836331	12.7124004		207.938	222.958	217.098
Scurelle	Fedrigoni - Cordenons	Trentino-Alto Adige	46.06718953	11.50108284		64.528	69.189	67.371
Porcari	Lucart	Toscana	43.8492333	10.60678659	1,094.580	1,189.145	1,128.199	1,062.031
Borgo a Mozzano - Diecimo	Lucart	Toscana	43.95112883	10.50348864	1,094.580	1,189.145	1,128.199	1,062.031
Castelnuovo di Garfagnana	Lucart	Toscana	44.11879947	10.40529311	497.536	540.520	512.818	482.741
Avigliano	Lucart	Basilicata	40.72223301	15.7443169	149.261	162.156	153.845	144.822
Via Lazzareschi	Sofidel-Soffass	Toscana	43.82035983	10.60821329	924.100			
Via Leccio	Sofidel-Soffass	Toscana	43.81828247	10.61761957	469.900			

Valdottavo	Sofidel-Soffass	Toscana	43.94317587	10.49391597	184.100			
Monfalcone	Sofidel-Soffass	Friuli-Venezia Giulia	45.7880897	13.57472926	292.100			
Val Fegana	Sofidel-Soffass	Toscana	43.94298174	10.49388808	161.000			
Pietrabuona	Cartiere Carrara	Toscana	43.87147718	10.68673842		375.902	380.085	338.001
Tassignano	Cartiere Carrara	Toscana	43.82458076	10.56584185		1,258.713	1,272.718	1,131.799
Pratovecchio	Cartiere Carrara	Toscana	43.78378286	11.72461655		87.606	88-581	78.773
Ferrania	Cartiere Carrara	Liguria	44.36141995	8.316099015		312.161	315.634	280.686
Porcari	Essity	Toscana	43.82712008	10.63731331	630.163	663.933	665.561	1,003.795
Altopascio	Essity	Toscana	43.82712008	10.63731331	157.541	165.983	166.390	179.249
Collodi	Essity	Toscana	43.89630542	10.65651548	264.668	278.852	279.535	301.139
Calziocorte	Cartiera dell'Adda	Lombardia	45.80205572	9.418694485				484.211
Lucca	DS Smith	Toscana	43.82576625	10.60424387		1,992.503	2,039.5332	2,103.455
Total						25,779.945		

Table 62: Paper production - Thermal energy consumption calculated for each plant

The sum of the thermal energy calculated for each plant is equal to 25.78 PJ, even if the values found refer to different years for the different years based on the data found for processing; to partially overcome the problem, the year 2019 is taken as a reference (more information is available), adding the thermal consumption for 2020 of the Sofidel-Soffass company plants (5 plants) and 2017 for the company plant Cartiere Dell'Adda.

Even if the plants analyzed represent 25.5% of the total, the total thermal energy calculated per plant represents 59.8% of the total thermal energy of the paper sector supplied by Assocarta (43.1 PJ), and 29.9% of the total energy for the paper sector (86.27 PJ). Comparing with the Paper & wood sector considered for the 1 & 2 approach, the total thermal energy calculated per plant represents 35.4% and 24.1% respectively of the total thermal energy and total energy consumption of the sector. Here too the different classification of the industrial sectors does not allow a direct comparison but only a qualitative one.

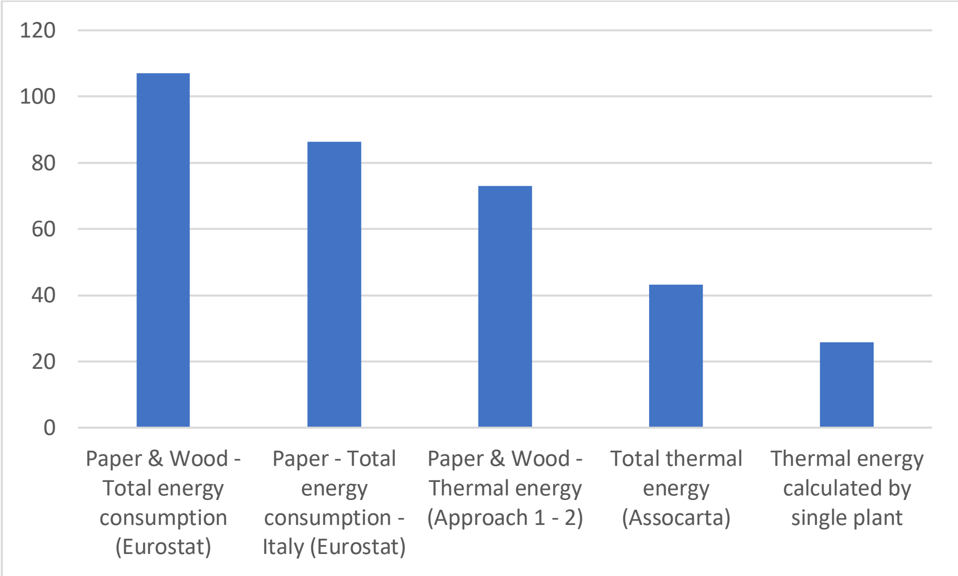

Figure 43: Paper production - energy consumption and thermal energy consumption for Paper and Paper & Wood sectors

Burgo group

Burgo group is an Italian company that mainly deals with the production of various types of paper (eg papers for publishing and fine papers). It owns 12 paper production plants, of which 11 in Italy and 1 in Belgium [37][38].

Plants	Company	Region	Latitude	Longitude
Verzuolo	Burgo Group	Piemonte	44.59687817	7.485999429
Avezzano	Burgo Group	Abruzzo	41.99495894	13.43877132
Sora	Burgo Group	Lazio	41.69846199	13.58502276
Duino	Burgo Group	Friuli-Venezia Giulia	45.79501113	13.59072939
Villorba	Burgo Group	Veneto	45.74897356	12.25077566
Sarego	Burgo Group	Veneto	45.42176891	11.39588125
Lugo	Burgo Group	Veneto	45.74336766	11.52067965
Toscolano	Burgo Group	Lombardia	45.64303381	10.61833819
Tolmezzo	Burgo Group	Friuli-Venezia Giulia	46.39524643	13.01540064
Treviso	Burgo Group	Veneto	45.6864298	12.3253403
Chiampo	Burgo Group	Veneto	45.53556293	11.29869225

Table 63: Burgo group - plants location

The company provides the production capacity values of the individual plants (tab.64).

Plants	Production capacity ($^{tn}/_{y}$)
Verzuolo	400,000
Avezzano	200,000
Sora	317,000
Duino	200,000
Villorba	204,000
Sarego	152,000
Lugo	53,000
Toscolano	124,000
Tolmezzo	172,000
Treviso	62,000
Chiampo	56,000
Total	1,940,000

Table 64: Burgo group - production capacity for each plant

Data are also provided on production, divided by Italy (11 plants) and Belgium (1 plant) for 2019.

	2019	
Total production	1,994,000	t
Belgium	332,262	t
Italy ($\boldsymbol{p_{Italy}}$)	1,661,738	t

Table 65: Burgo group - total paper production

To estimate the actual production of each plant, it is assumed that it is proportional to the production capacity of the plant itself.

$$n_i = \frac{c_i}{c_{tot}}$$

n_i: production factor of plant i;

c_i: paper production capacity of plant i;

c_{tot}: total production capacity;

Plants	Production factor n_i
Verzuolo	0.206185567
Avezzano	0.103092784
Sora	0.163402062
Duino	0.103092784
Villorba	0.105154639
Sarego	0.078350515
Lugo	0.027319588
Toscolano	0.063917526
Tolmezzo	0.088659794
Treviso	0.031958763
Chiampo	0.028865979

Table 66: Burgo group - Production factor n_i

Now is possible to calculate the paper production for each plant.

$$p_i = p_{Italy} * n_i$$

p_i: paper production of plant i;

p_{Italy}: total italian paper production;

Paper production p_i (t)	2019
Verzuolo	342,626.3918
Avezzano	171,313.1959
Sora	271,531.4155
Duino	171,313.1959
Villorba	174,739.4598
Sarego	130,198.0289
Lugo	45,397.99691
Toscolano	106,214.1814
Tolmezzo	147,329.3485
Treviso	53,107.09072
Chiampo	47,967.69485

Table 67: Burgo group - paper production for each plant

For the calculation of the thermal energy the production values p_i (tab.67) and the specific consumption δ_{paper} of tab.61 calculated starting from the Assocarta data are used.

$$q_i = p_i * \delta_{paper}$$

q_i: thermal energy consumption of plant i;

p_i: paper production of plant i;

δ_{paper}: specific thermal consumption ($^{TJ}/_{tn}$);

	Thermal energy consumption (TJ)
Verzuolo	1651.369211
Avezzano	825.6846053
Sora	1308.710099
Duino	825.6846053
Villorba	842.1982974
Sarego	627.5203
Lugo	218.8064204
Toscolano	511.9244553
Tolmezzo	710.0887605
Treviso	255.9622276
Chiampo	231.1916895
Total	8009.140671

Table 68: Burgo group - thermal energy consumption calculated for each plant

Reno De Medici RDM Group

RDM group owns 3 paper production plants in Italy, plus other plants in other European countries [39].

Plants	**Company**	**Region**	**Latitude**	**Longitude**
Ovaro	Reno De Medici	Friuli-Venezia Giulia	46.48178298	12.86304773
Santa Giustina	Reno De Medici	Veneto	46.07127217	12.03749393
Villa Santa Lucia	Reno De Medici	Lazio	41.48491078	13.7870971

Table 69: RDM group - plants location

The company provides the production capacity values of the individual plants [40], also considering the plants not in Italy (tab.70).

	Production capacity (tn/y)
Ovaro	95,000
Santa Giustina	240,000
Villa Santa Lucia	220,000
Arnsberg (GERMANY)	220,000
Barcellona (SPAIN)	190,000
Blendecques (FRANCE)	110,000
Total	1,075,000

Table 70: RDM group - Production capacity for each plant

The company provides total energy consumption, biomass and fossil fuel consumption, as well as the total production of the group. It is assumed that the energy supplied by fossils and biomass is used for the production of thermal energy, which is therefore given by the sum of the two values; in fact, the sustainability report provided by the company speaks of over 2.4 million thermal MWh for 2020, equal to the sum of energy from fossil fuels and biomass. The specific thermal energy consumption indicated in the table is given by the ratio of the thermal energy value obtained and the total production.

	2020	**2019**	**2018**	**2017**
Production $\boldsymbol{p_{tot}}$ (t)	1,348,311	1,383,213	1,191,366	1,156,262
Total energy consumption (MWh)	2,772,083	2,757,575	2,553,091	2,559,187
Fossil fuels (MWh)	2,133,084	2,157,062	1,979,613	2,034,723
Biomass (MWh)	296,340	316,806	326,023	292,974
Thermal consumption (MWh)	2,429,424	2,473,868	2,305,636	2,327,697
Specific thermal consumption $\boldsymbol{\alpha_{th}}$ ($\boldsymbol{MWh/t}$)	1.801828	1.788494	1.935288	2.013122

Table 71: RDM group - aggregated data on production and energy consumption

To estimate the actual production of each plant, it is assumed that it is proportional to the production capacity of the plant itself.

$$n_i = \frac{c_i}{c_{tot}}$$

n_i: production factor of plant i;

c_i: paper production capacity of plant i;

c_{tot}: total production capacity;

	Production factor n_i
Ovaro	0.088372093
Santa Giustina	0.223255814
Villa Santa Lucia	0.204651163

Table 72: RDM group - Production factor n_i

Now is possible to calculate the paper production for each plant.

$$p_i = p_{tot} * n_i$$

p_i: paper production of plant i;

p_{tot}: total paper production;

Paper production (t)	**2020**	**2019**	**2018**	**2017**
Ovaro	119,153.0651	122,237.4279	105,283.507	102,181.293
Santa Giustina	301,018.2698	308,810.3442	265,979.386	258,142.214
Villa Santa Lucia	275,933.414	283,076.1488	243,814.4372	236,630.3628

Table 73: RDM group - Paper production calculated for each plant

Now it is possible to calculate the thermal energy value per plant, using the just calculated production values (tab.73) and the specific thermal energy consumption α_{th} indicated in tab.71. The results are shown in the following tab.74.

$$q_i = p_i * \alpha_{th}$$

q_i: thermal energy consumption of plant i;

p_i: paper production of plant i;

α_{th}: specific thermal consumption ($^{TJ}/_{tn}$);

Thermal energy consumption (TJ)	2020	2019	2018	2017
Ovaro	772.8958214	787.0352149	733.5139647	740.5324409
Santa Giustina	1,952.578917	1,988.29949	1,853.087911	1,870.818798
Villa Santa Lucia	1,789.864007	1,822.607866	1,698.663918	1,714.917232

Table 74: RDM group - Thermal energy consumption calculated for each plant

Lucart

Lucart is an Italian paper manufacturing company that owns 4 plants in Italy, as well as several other plants in Europe.

Plant	Company	Region	Latitude	Longitude
Porcari	Lucart	Toscana	43.8492333	10.60678659
Borgo a Mozzano - Diecimo	Lucart	Toscana	43.95112883	10.50348864
Castelnuovo di Garfagnana	Lucart	Toscana	44.11879947	10.40529311
Avigliano	Lucart	Basilicata	40.72223301	15.7443169

Table 75: Lucart - plants location

The company provides production capacity of each plant [41] [42].

	Production capacity ($^{tn}/_{y}$)
Porcari	110,000
Borgo a Mozzano - Diecimo	110,000
Castelnuovo di Garfagnana	50,000
Avigliano	15,000
Total (including plant abroad)	396,000

Table 76: Lucart - Production capacity for each plant

In addition to the annual production, the company provides information regarding the consumption of natural gas and diesel: it is assumed that the use of these two fuels is destined to produce thermal energy. The specific heat consumption is calculated by dividing the value of the heat energy by the total annual production.

	2020	2019	2018	2017
Production $\boldsymbol{p_{tot}}$ (tn)	346,401	359,557	332,200	305,200
Diesel (GJ)	142,4	119,48	113,52	113.32
Natural gas (GJ)	3,940,346.51	4,280,802.02	4,061,401.74	3,823,197
Thermal energy (GJ)	3,940,488.91	4,280,921.5	4,061,515.26	3,823,310.76
Specific thermal consumption $\boldsymbol{\alpha_{th}}$ ($\boldsymbol{GJ/tn}$)	11.37551251	11.90609973	12.22611457	12.52723054

Table 77: Lucart - aggregated data on production and energy consumption

To estimate the actual production of each plant, it is assumed that it is proportional to the production capacity of the plant itself.

$$n_i = \frac{c_i}{c_{tot}}$$

n_i: production factor of plant i;

c_i: paper production capacity of plant i;

c_{tot}: total production capacity;

	Production factor $\boldsymbol{n_i}$
Porcari	0.277777
Borgo a Mozzano - Diecimo	0.277777
Castelnuovo di Garfagnana	0.126262
Avigliano	0.037878

Table 78: Lucart – Production factor $\boldsymbol{n_i}$

Now is possible to calculate the paper production for each plant.

$$p_i = p_{tot} * n_i$$

p_i: paper production of plant i;

p_{tot}: total paper production;

Paper production (tn)	*2020*	*2019*	*2018*	*2017*
Porcari	96,222.5	99,876.9	92,277.7	84,777.7
Borgo a Mozzano - Diecimo	96,222.5	99,876.9	92,277.7	84,777.7
Castelnuovo di Garfagnana	43,737.5	45,398.6	41,944.4	38,535.3
Avigliano	13,121.25	13,619.5	12,583.3	11,560.6

Table 79: Lucart - paper production calculated for each plant

Now it is possible to calculate the thermal energy value per plant, using the just calculated production values (tab.79) and the specific thermal energy consumption α_{th} indicated in tab.77. The results are shown in the following tab.80.

$$q_i = p_i * \alpha_{\mathrm{th}}$$

q_i: thermal energy consumption of plant i;

p_i: paper production of plant i;

α_{th}: specific thermal consumption ($^{\mathrm{GJ}}/_{\mathrm{tn}}$);

Thermal energy consumption (TJ)	2020	2019	2018	2017
Porcari	1,094.580	1,189.144	1,128.198	1,062.030
Borgo a Mozzano - Diecimo	1,094.580	1,189.144	1,128.198	1,062.030
Castelnuovo di Garfagnana	497.536	540.520	512.817	482.741
Avigliano	149.260	162.156	153.84	144.822

Table 80: Lucart - thermal energy consumption calculated for each plant

Sofidel – Soffass

Sofidel Italia and Soffass Italia belongs to the Sofidel Group, which is present in 14 states around the world. In Italy it manages 3 paper mills, 2 integrated plants (paper mill and converting) and 2 converting plants. In the following analysis, only paper mills and integrated plants will be considered, where there is the presence of highly energy-intensive thermal processes (paper drying).

Plants	Type	Company	Region	Latitude	Longitude
Via Lazzareschi	Integrated plant	Sofidel-Soffass	Toscana	43.82035983	10.60821329
Via Leccio	Paper mill	Sofidel-Soffass	Toscana	43.81828247	10.61761957
Valdottavo	Paper mill	Sofidel-Soffass	Toscana	43.94317587	10.49391597
Monfalcone	Integrated plant	Sofidel-Soffass	Friuli-Venezia Giulia	45.7880897	13.57472926
Val Fegana	Paper mill	Sofidel-Soffass	Toscana	43.94298174	10.49388808

Table 81: Sofidel-Soffass - plants location

The company states that the annual production capacity is 1,428,000 t and provides consumption data on fossil fuels used for the cogeneration of thermal and electrical energy, and electricity from the grid.

Plants	Fossil fuels (TJ)	Electrical energy (TJ)	Electrical energy from cogeneration (TJ)
Via Lazzareschi	1,153.5	388.9	229.4
Via Leccio	558.4	187.2	88.5
Valdottavo	194.7	114.2	10.6
Monfalcone	382.3	107.5	90.2
Val Fegana	202.3	50.9	41.3

Table 82: Sofidel-Soffass - data about energy consumption for each plant

The thermal energy value is obtained by subtracting the electricity value obtained through cogeneration from the energy from fossil fuels.

Thermal energy consumption (TJ)	2020
Via Lazzareschi	924.1
Via Leccio	469.9
Valdottavo	184.1
Monfalcone	292.1
Val Fegana	161

Table 83: Sofidel-Soffass - Thermal energy consumption calculated for each plant

Cartiere Carrara

Cartiere Carrara operates 7 plants in Italy, of which 4 are paper mills.

Plants	Company	Region	Latitude	Longitude
Pietrabuona	Cartiere Carrara	Toscana	43.87147718	10.68673842
Tassignano	Cartiere Carrara	Toscana	43.82458076	10.56584185
Pratovecchio	Cartiere Carrara	Toscana	43.78378286	11.72461655
Ferrania	Cartiere Carrara	Liguria	44.36141995	8.316099015

Table 84: Cartiere Carrara - plants location

The company provides the production capacity values of the 4 plants [43] (tab.85).

	Production capacity (t/y)
Pietrabuona	37,330
Tassignano	125,000
Pratovecchio	8,700
Ferrania	31,000
Total	202,030

Table 85: Cartiere Carrara - production capacity for each plant

Furthermore, data are provided on total annual production (from 2017 to 2019), on total consumption and on electricity consumption. Total thermal energy consumption is estimated by subtracting electricity consumption from total consumption (tab.86).

	2019	2018	2017	
Production	208,971	206,804	183,878	t
Total energy	729,935,703	737,049,456	654,237,924	kWh
Electrical energy	164,829,408	165,655,533	146,110,318	kWh
Thermal energy	2034.382662	2057.018123	1829.259382	TJ

Table 86: Cartiere Carrara - data about total production and energy consumption

To estimate the actual thermal consumption of each plant, it is assumed that it is proportional to the production capacity of the plant itself.

$$n_i = \frac{c_i}{c_{tot}}$$

n_i: production factor of plant i;

c_i: paper production capacity of plant i;

c_{tot}: total production capacity;

Production factor n_i	
Pietrabuona	0.1847
Tassignano	0.6187
Pratovecchio	0.0430
Ferrania	0.1534

Table 87: Cartiere Carrara - Production factor n_i

Now it is possible to calculate the thermal consumption for each plant, multiplying the total thermal energy value (tab.86) by the production factor of each plant (tab.87). Results are shown in tab.88.

$$q_i = Q_{tot} * n_i$$

q_i: thermal energy consumption of plant i;

Q_{tot}: total thermal energy consumption;

Thermal energy consumption (TJ)	**2019**	**2018**	**2017**
Pietrabuona	375.9021174	380.0845742	338.0005579
Tassignano	1,258.713225	1,272.718237	1,131.79935
Pratovecchio	87.60644043	88.58118927	78.77323477
Ferrania	312.1608797	315.6341227	280.6862388

Table 88: Cartiere Carrara - thermal energy calculated for each plant

Essity

Essity is a multinational present in Italy since 1983 and operates throughout the national territory in the production of "tissue" paper materials (handkerchiefs, toilet paper, napkins, etc.) and in the marketing of personal hygiene products. To date, the company owns 3 paper mills in Italy (tab.(X)).

Plants	Company	Region	Latitude	Longitude
Porcari	Essity	Toscana	43.82712008	10.63731331
Altopascio	Essity	Toscana	43.82712008	10.63731331
Collodi	Essity	Toscana	43.89630542	10.65651548

Table 89: Essity - plants location

Figure 44: Essity - plant location

The company provides the production capacity of the individual plants for the year 2017 and 2020 [44][45] (tab.90).

Production capacity (tn/y)	**2020**	**2017**
Porcari	100,000	140,000
Altopascio	25,000	25,000
Collodi	42,000	42,000

Table 90: Essity - production capacity for each plant

The company also provides the production capacity of the entire company (including plants abroad) for the years 2017 and 2020, and the total production and thermal consumption of the company for the years from 2017 to 2020.

	2020	**2019**	**2018**	**2017**
Total capacity production (tn/y)	4,424,000	-	-	4,342,000
Total production (tn/y)	3,377,000	3,508,000	3,549,000	3,100,000
Total thermal energy (TJ)	27,878.4	29,372.4	29,444.4	31,132

Table 91: Essity - data about total production and total thermal energy consumption

For the calculation of thermal consumption it is considered that they are proportional to the production capacity of the individual plants; in this case 2 production factors will be calculated: the first relating to 2020 will also be applied to the 2018-2019 data, and the second relating only to 2017 (tab.92).

$$n_i = \frac{c_i}{c_{tot}}$$

n_i: production factor of plant i;

c_i: paper production capacity of plant i;

c_{tot}: total production capacity;

Production factor n_i	**2020**	**2017**
Porcari	0.022604	0.032243
Altopascio	0.005651	0.005758
Collodi	0.009494	0.009673

Table 92: Essity - production factor n_i

Thermal consumption for each plant can be calculated using the production factor n_i (tab.92) and the total thermal consumption indicated in tab.91. The results are shown in tab.93.

$$q_i = Q_{tot} * n_i$$

q_i: thermal energy consumption of plant i;

Q_{tot}: total thermal energy consumption;

Thermal consumption (TJ)	**2020**	**2019**	**2018**	**2017**
Porcari	630.1627	663.9330	665.5605	1,003.7954
Altopascio	157.5406	165.9832	166.3901	179.2491
Collodi	264.6683	278.8518	279.5354	301.1386

Table 93: Essity - thermal energy consumption calculated for each plant

Fedrigoni SpA – Cordenons Group

The Fedrigoni group together with the Cordenons Group manage 7 paper production plants in Italy, plus others around the world.

Plants	Company	Region	Latitude	Longitude
Arco	Fedrigoni - Cordenons	Trentino-Alto Adige	45.90254409	10.87875518
Varone	Fedrigoni - Cordenons	Trentino-Alto Adige	45.91034151	10.83798747
Verona	Fedrigoni - Cordenons	Veneto	45.33022248	10.99083959
Fabriano	Fedrigoni - Cordenons	Marche	43.32410544	12.8920589
Pioraco	Fedrigoni - Cordenons	Marche	43.17953092	12.98825182
Cordenons	Fedrigoni - Cordenons	Friuli-Venezia Giulia	45.96836331	12.7124004
Scurelle	Fedrigoni - Cordenons	Trentino-Alto Adige	46.06718953	11.50108284

Table 94: Fedrigoni - plants location

The company provides data on annual production and specific steam consumption, from which the total steam consumption can be derived [46] (tab.95).

	2019	2018	2017
Production (t)	521,745	542,817	536,518
Specific steam consumption $\left({}^{\boldsymbol{t_{steam}}}/_{\boldsymbol{t_{paper}}}\right)$	1.96	2.02	1.99
Steam consumption ($\boldsymbol{t_{steam}}$) $\boldsymbol{m_{Steam}}$	1,022,620.2	1,096,490.34	1,067,670.82

Table 95: Fedrigoni - data about total paper production and steam production

No information is provided either on production or on the production capacity for each plant. The only data available for the plants concern CO_2 emissions (tab.96).

Plants	CO_2 emissions $(^{tn}/_{y})$
Arco	48,240
Varone	33,465
Verona	50,068
Fabriano	87,307
Pioraco	17,186
Cordenons	22,657
Scurelle	7,031
Total	265,954

Table 96: Fedrigoni - CO_2 emissions for each plant

The information on the steam used is used to calculate the thermal energy. From [47] we obtain information about the temperature and pressure of the steam used in paper mills, from which we obtain the enthalpy values used for the calculation of thermal energy (tab.98).

Steam parameters		
Inlet temperature $\boldsymbol{T_{in}}$	293.15	K
Outlet temperature $\boldsymbol{T_{out}}$	507.05	K
Inlet pressure $\boldsymbol{p_{in}}$	1	bar
Outlet pressure $\boldsymbol{p_{out}}$	30	bar
Inlet entalphy $\boldsymbol{h_{in}}$	417.36	$^{kJ}/_{kg}$
Outlet entalphy $\boldsymbol{h_{out}}$	2,804.2	$^{kJ}/_{kg}$

Table 97: Fedrigoni - Steam parameters

Using steam consumption m_{Steam} of tab.95 thermal consumption can be calculated using the following formula.

$$Q_{tot} = m_{Steam} * (h_{out} - h_{in})$$

Q_{tot}: total thermal energy consumption

	2019	2018	2017	
Total thermal energy consumption	2,440.830798	2,617.147003	2,548.359	TJ

Table 98: Fedrigoni - total thermal energy consumption

In the absence of other data, to calculate the thermal energy consumption per plant, it is assumed that the production (and therefore the related energy consumption) of each plant is proportional to the CO_2 emissions.

$$w_i = \frac{CO_{2,i}}{CO_{2,tot}}$$

w_i: CO_2 factor of plant i;

$CO_{2,i}$: CO_2 emissions of plant i;

$CO_{2,tot}$: total CO_2 emissions;

The results are shown in tab.99.

CO_2 factor w_i	
Arco	0.181384751
Varone	0.125830031
Verona	0.18825812
Fabriano	0.328278574
Pioraco	0.064620197
Cordenons	0.085191424
Scurelle	0.026436903

Table 99: Fedrigoni - CO_2 factor

Using w_i (tab.99) and total thermal consumption of tab.98, the thermal consumption for each plant can be calculated. The results are shown in tab.100.

$$q_i = Q_{tot} * w_i$$

q_i: thermal energy consumption of plant i;

Q_{tot}: total thermal energy consumption;

Thermal energy consumption (TJ)	2019	2018	2017
Arco	442.7294859	474.7105568	462.2335382
Varone	307.1298144	329.3156879	320.6601442
Verona	459.5062169	492.6991741	479.749353
Fabriano	801.272455	859.1532874	836.5717977
Pioraco	157.7269682	169.1205562	164.675489
Cordenons	207.9378516	222.9584802	217.0983681
Scurelle	64.52800613	69.18926047	67.37072983

Table 100: Fedrigoni - thermal energy consumption calculated for each plant

DS Smith

DS Smith is an international company that in Italy (Lucca) owns the largest containerboard production plant in the country, with a production capacity of 410,000 $tn/_y$ [48].

Plant	Company	Region	Latitude	Longitude
Lucca	DS Smith	Toscana	43.82576625	10.60424387

Table 101: DS Smith - plant location

The company directly provides plant thermal consumption (tab.102).

Thermal energy consumption	2019	2018	2017	2016	
Lucca	1,992.503	2,039.533	2,103.455	2,100.564	TJ

Table 102: DS Smith - plant thermal energy consumption

Cartiera dell’Adda

This paper mill is situated in Calziocorte (Lombardia), with a capacity production of 220000 $tn/_y$.

Plant	Company	Region	Latitude	Longitude
Calziocorte	Cartiera dell'Adda	Lombardia	45.80205572	9.418694485

Table 103: Cartiera dell'Adda - plant location

The company provides plant thermal consumption referred to 2017 (tab.104).

Thermal consumption	2017	
Calziocorte	484.2108	TJ

Table 104: Cartiera dell'Adda - plant thermal energy consumption

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Tables

Figures