POLITECNICO DI TORINO

Master's Degree in Energy and Nuclear Engineering

Master's Degree Thesis

Heat pumps in the renovation of buildings: insights from a regional scale techno-economic and environmental assessment

Supervisors

Prof. Alessandro CASASSO

Prof. Rajandrea SETHI

Candidate

Edoardo RUFFINO

OCTOBER 2020

Abstract

A relevant share (30-40%) of the world energy demand is due to the heating and cooling of buildings and, hence, the reduction of greenhouse gas (GHG) and air pollutant emissions is the key to improve the environmental sustainability of this sector. A possible solution is the widespread adoption of heat pumps. They have become popular in new buildings, but, as the renewal rate of the building stock is slow, it is critical to also focus on existing buildings and to increase the number of installations.

This thesis presents an analysis of the technical, economic, and environmental issues concerning the introduction of heat pumps in existing buildings in the Piedmont region (NW Italy). The regional air quality situation highlights the need to prevent a substantial increment in wood biomass and in other fossil fuels usage and to avoid a further worsening. Therefore, the database of building energy certifications, covering about 17% of the building stock, was analyzed deriving geo-referenced datasets on the diffusion of the technologies powered by the aforementioned fuels.

Methane pipelines have not reached relatively large areas of this region yet, so oil and LPG systems cover a relevant share of their heating demand. Hence, the replacement of these expensive fuels represents a priority from the points of view of energy efficiency, air quality, climate, and economy. Instead, considering the entire region, methane covers the largest percentage of heating (78%) and domestic hot water (69%) production. Moreover, concerning DHW production, electric boilers also provide for a relevant share (24%). Nonetheless, heat pumps can conveniently replace these technologies. However, there are two major technical issues concerning the introduction of heat pumps in existing buildings: the matching with existing heating terminals and the climatic conditions. The existing building stock was mostly built around the '60s-'70s and employs high-temperature radiators, which are considered to be hardly suitable for heat pumps. Furthermore, heat pumps show a decrease in performance when working with low external temperatures, such as those typically occurring in the winter season. These two technological issues were addressed, and possible solutions were identified. Finally, an economic evaluation of the heat pumps was developed in the hypothesis of installing them in three different Piedmont locations (Turin, Cuneo, and Oulx), for three different types of building (a private house, a hotel, and a building used as offices) and with two different levels of insulation. Both air source and ground source typologies were considered. Results confirm the relevance of working hours (which depend on the climate and the building type) as the most influential parameter to determine the economic convenience independently of incentives.

Table of Contents

List of Tables V

List of Figures VII

Acronyms XI

1 Environmental and energy context analysis of Piedmont 1

1.1 Geographical information on Piedmont 1

1.2 PRQA and Piedmont legislation 5

1.2.1 What is the PRQA? 5

1.2.2 Overview of legislation on air quality 5

1.2.3 Acute contaminants 11

1.2.4 Fact-finding survey of PRQA 14

1.3 Analysis of energy sources for heating, cooling and DHW production 17

1.3.1 Share of domestic energy services 19

1.3.2 Geographical diffusion of domestic energy services 24

1.4 Municipalities not reached by natural gas pipelines 28

1.5 Air quality and regional monitoring system 31

2 Technical aspects of heat pump installations 37

2.1 Overview on heat pumps 37

2.2 Performance parameters 39

2.3 Matching with heating terminals 42

2.3.1 Conventional radiators 43

2.3.2 Novel radiators and other systems 47

2.4 Issues due to the installation in cold climates and possible solutions 50

2.4.1 Enhanced air-source heat pumps 53

2.4.2 Gas engine heat pumps 62

2.4.3 Solar-assisted air source heat pumps 64

2.4.4 Ground source heat pumps 71

2.5 Other issues 77

2.5.1 Maintenance 77
2.5.2 Auxiliaries 77
2.5.3 Users habits 77

3 Economic assessment 81
3.1 Introduction and data selection criteria 81
3.2 Methods 85
3.2.1 GSHP simulation with Earth Energy Designer 85
3.2.2 Evaluation of costs and performances of the ASHP 86
3.2.3 Existing system 88
3.2.4 Economical indicators 88
3.3 Results and discussion 92

4 Conclusions 99

A PRQA and legislation 103
A.1 Municipalities list and zoning 103
A.2 Statistics on pollutant concentrations and emissions 134

B Processing of SIPEE database 143

C Analyses on air quality and regional monitoring system 151

Bibliography 157

List of Tables

1.1 Piedmont districts extent and population 3
1.2 Main characteristics of the built up area and of the three other areas 9
1.3 Identification of municipalities belonging to Plan and Maintenance zones subdivided by districts 10
1.4 Main characteristics of the built up area and of the Piedmont area concerning the ozone 11
1.5 Minimum and maximum percentage contribution to annual average concentration of most impacting pollutants by heating systems subdivided by zones 16
1.6 Comparison of properties covered by the SIPEE database and properties counted by Istat 19
1.7 Energy services and number of buildings where they are installed . 19
1.8 Share of each fuel per energy service 20
1.9 Domestic hot water production systems subdivided by district . . . 25
1.10 Summer cooling production systems subdivided by district 26
1.11 Winter heating production systems subdivided by district 27
1.12 Municipalities not reached by natural gas pipelines in Piedmont . . 28
1.13 Number of monitoring stations of PM_{10} and NO_2 per zone and how many exceed the limits 32

2.1 Typical thermal emissions of cast iron radiators 45
2.2 Typical thermal emissions of aluminum radiators 45
2.3 Comparison of different heat pump cycles to a one stage cycle . . . 59
2.4 Decomposition of the predicted effect on electricity consumption of owning a heat pump for the mean household 79

3.1 Thermal transmittance value of the elements of the building envelope 82
3.2 Annual thermal loads and annual peak thermal loads of the eighteen case studies 83
3.3 Electricity prices for households and non-households users 84
3.4 Natural gas prices for households and non-households users 84

3.5 Ground properties values assumed in the EED simulation 85
3.6 Heat carrier properties values assumed in the EED simulation . . . 85
3.7 Values of indexes included in the cost of equity 90
3.8 Values of indexes included in the cost of debt 91
3.9 The profitability of the GSHP investment on the hypothesis of the natural gas-powered existing system 93
3.10 The profitability of the ASHP investment on the hypothesis of the natural gas-powered existing system 94
3.11 The profitability of the GSHP investment on the hypothesis of the diesel fuel-powered existing system 95
3.12 The profitability of the ASHP investment on the hypothesis of the diesel fuel-powered existing system 96
3.13 The profitability of the GSHP investment on the hypothesis of the LPG-powered existing system 97
3.14 The profitability of the ASHP investment on the hypothesis of the LPG-powered existing system 98

A.1 List of Piedmont municipalities in Plan and Maintenance zones . . 103
A.2 Percentage contribution to annual average concentration of PM_{10} by the sectors identified for the source apportionment 137
A.3 Percentage contribution to annual average concentration of $PM_{2.5}$ by the sectors identified for the source apportionment 138
A.4 Percentage contribution to annual average concentration of NO_2 by the sectors identified for the source apportionment 139
A.5 Percentage contribution to annual average concentration of nitrate ion by the sectors identified for the source apportionment 140
A.6 Percentage contribution to annual average concentration of sulphate ion by the sectors identified for the source apportionment 141
A.7 Percentage contribution to annual average concentration of ammonium ion by the sectors identified for the source apportionment . . 142

C.1 List of which monitoring stations whose pollutants surveys are in compliance with the hourly limits of PM_{10} and NO_2 and which not 151
C.2 List of which monitoring stations whose pollutants surveys are in compliance with the average annual limits of PM_{10} and NO_2 and which not 153

List of Figures

1.1 Physical map of Piedmont . . . 2
1.2 Population density map of Piedmont in 2018 . . . 4
1.3 Previous zoning map of Piedmont . . . 6
1.4 Zoning map of Piedmont . . . 8
1.5 Zoning map of Piedmont concerning the ozone . . . 12
1.6 Spatial distribution of percentage contribution to annual average concentration of PM_{10} and $PM_{2.5}$ due to residential heating . . . 15
1.7 Percent distribution of production systems of domestic hot water . . . 21
1.8 Percent distribution of production systems of summer cooling . . . 22
1.9 Percent distribution of production systems of winter heating . . . 23
1.10 Domestic hot water production systems map . . . 25
1.11 Summer cooling production systems map . . . 26
1.12 Winter heating production systems map . . . 27
1.13 Fraction of DHW plants supplied by natural gas and electric power in each municipality . . . 29
1.14 Fraction of heating plants supplied by LPG, diesel oil and solid biomass in each municipality . . . 30
1.15 Geographical distribution of pollutants monitoring stations . . . 31
1.16 Days exceeding the 24-hour limit for PM_{10} . . . 34
1.17 Value of the 36^{th} higher exceeding concentration of PM_{10} for each monitoring station . . . 34
1.18 Average yearly concentrations of PM_{10} . . . 35
1.19 Days exceeding the hourly limit for NO_2 . . . 35
1.20 Value of the 19^{th} higher exceeding concentration of NO_2 for each monitoring station . . . 36
1.21 Average yearly concentrations of NO_2 . . . 36

2.1 Conceptual diagram of an air-to-water heat pump . . . 38
2.2 Temperature differential and coefficient of performance . . . 40
2.3 Design of an aeraulic plant located in a passageway . . . 46
2.4 Sketch of a ventilation-radiator . . . 47

2.5 Schematic diagram of the RRH system 48
2.6 Horizontal temperature contours at 1.2 m height for the RRH and the ACH 49
2.7 Heating circuit flow temperature and efficiency 49
2.8 Annual temperature curve under ground 50
2.9 Average heating COP for air and ground source heat pumps (left and right, respectively) based on data taken from industrial surveys and field trials 51
2.10 Correlation between the heat delivered by an average heat pump, the temperature and the efficiency 52
2.11 Correlation between the heat delivered by an average heat pump, the temperature and the efficiency 53
2.12 Temperature distribution of Alessandria, Bardonecchia, Cuneo and Turin throughout 2019 54
2.13 Enhanced ASHP with scroll compressor and economizer 55
2.14 Test system and sensor locations for the ASHP prototype 57
2.15 Heating capacity, power input and EER depending on evaporating temperature of the improved ASHP 57
2.16 Simplified schematics of two-stage cycle with intercooler, two-stage cycle with closed economizer, and cascade cycle 60
2.17 Simulation results of COP and heating capacity at 50 °C supply temperature 61
2.18 Simulation results for the systems with the economizer at 50 °C supply temperature and considering auxiliary power 62
2.19 Losses of the conversion process of an electric heat pump 63
2.20 Reference SHP system proposed by the IEA SHC Task 44 65
2.21 Classification of solar thermal and heat pump systems in parallel, serial and regenerative system concepts 67
2.22 Design of the insulation of the highly compact solar heat pump system 69
2.23 System diagram of the highly compact solar heat pump 70
2.24 Effect of ground heat exchanger area on heating performance 72
2.25 Effect of ground heat exchanger area on cooling performance 72
2.26 Effect of ground heat exchanger pipe depth on COP 72
2.27 Effect of ground heat exchanger pipe depth on energy consumption 73
2.28 Effect of ground heat exchanger flow rate on energy consumption . 74
2.29 Effect of ground heat exchanger horizontal pipe spacing on COP . . 74
2.30 Effect of ground heat exchanger horizontal pipe spacing on energy consumption 74

3.1 The reconstructed sinusoidal trend of temperature 87
3.2 Specific or unsystematic risk and systemic risk 89

A.1 Source apportionment of yearly PM_{10} emissions 134
A.2 Source apportionment of yearly $PM_{2.5}$ emissions 134
A.3 Source apportionment of yearly NO_2 emissions 135
A.4 Source apportionment of yearly nitrate ion emissions 135
A.5 Source apportionment of yearly sulphate ion emissions 136
A.6 Source apportionment of yearly ammonium ion emissions 136

B.1 Production of sanitary water by means of electric power 143
B.2 Production of sanitary water by means of natural gas 144
B.3 Production of sanitary water by means of diesel fuel and/or fuel oil 144
B.4 Production of sanitary water by means of LPG 145
B.5 Production of sanitary water by means of district heating/cooling . 145
B.6 Production of summer cooling by means of electric power 146
B.7 Production of summer cooling by means of natural gas 146
B.8 Production of winter heating by means of electric power 147
B.9 Production of winter heating by means of natural gas 147
B.10 Production of winter heating by means of diesel fuel and/or fuel oil 148
B.11 Production of winter heating by means of LPG 148
B.12 Production of winter heating by means of district heating/cooling . 149
B.13 Production of winter heating by means of biomass 149

Acronyms

ACE
: Attestato di Certificazione Energetica (Energy Certification Certificate)

ACH
: Air Conditioner Heating

AHRI
: Air-conditioning, Heating & Refrigeration Institute

APE
: Attestato di Prestazione Energetica (Energy Performance Certificate)

ARERA
: Autorità di Regolazione per Energia Reti e Ambiente (Regulation Authority for Energy network and Environment)

ARPA
: Agenzia Regionale per la Protezione Ambientale (Regional Agency for the Environmental Protection)

ASHP
: Air Source Heat Pump

CDD
: Cooling Degree Days

CHP
: Combined Heat and Power

COP
: Coefficient Of Performance

D.C.R.
: Deliberazione del Consiglio Regionale (Regional Council Deliberation)

DCF
: Discounted Cash Flow

DHW
: Domestic Hot Water

D.G.R.
: Deliberazione della Giunta Regionale (Regional Board Deliberation)

D.LGS.
: Decreto Legislativo (Legislation)

D.P.R.
: Decreto del Presidente della Repubblica (Decree of the President of the Republic)

DX
: Direct expansion

EER
: Energy Efficiency Ratio

EHP
: Electric Heat Pump

EHPA
: European Heat Pump Association

EMRP
: Equity Market Risk Premium

EUROSTAT
: European Statistical Office

GDP
: Gross Domestic Product

GEHP

Gas Engine Heat Pump

GHE

Ground Heat Exchanger

GHG

Greenhouse Gases

GSHP

Ground Source Heat Pump

GWP

Global Warming Potential

HDD

Heating Degree Days

HHV

High Heating Value

ICE

Internal Combustion Engine

IDX

Indirect expansion

IEA

International Energy Agency

IRR

Internal Rate of Return

IRS

interest Rate Swap

ISTAT

Istituto Nazione di Statistica (Italian National Institute of Statistics)

LHV

Low Heating Value

LPG

Liquefied Petroleum Gas

MISE

Ministero dello Sviluppo Economico (Italian Ministry of Economic Development)

MTBF

Mean Time Between Failure

NPV

Net Present Value

NZEB

Nearly Zero-Energy Building

PBT

Payback time

PRQA

Piano Regionale di Qualità dell'Aria (Air Quality Regional Program)

PV

Photovoltaic

RRH

Refrigerant-heated Radiator Heating

SAGHP

Solar Assisted Ground Source Heat Pump

SAHP

Solar Assisted Heat Pump

SCF

Simple Cash Flow

SCOP

Seasonal Coefficient of Performance

SEER
Seasonal Energy Efficiency Ratio

SHC
Solar Heating & Cooling Programme by IEA

SHP
Solar Heat Pump

SICEE
Sistema Informativo per la Certificazione Energetica degli Edifici (Information Systems of Buildings Energy Certification)

SIPEE
Sistema Informativo per la Prestazione Energetica degli Edifici (Information Systems of Buildings Energy Performance)

SISTAN
Sistema Statistico Nazionale (National Statistical System)

SPF
Seasonal Performance Factor

SRRQA
Sistema Regionale di Rilevamento della Qualità dell'Aria (Air Quality Regional Survey System)

ST
Solar Thermal

WACC
Weighted Average Cost of Capital

Chapter 1

Environmental and energy context analysis of Piedmont

This chapter aims to present the territorial context for which the techno-economic feasibility of heat pumps will be assessed. Section 1.1 deals with the main morphological, socio-economical characteristics of the Region. Section 1.2 introduces the law in force with a focus on the "Piano Regionale di Qualità dell'Aria" (PRQA). Then, Section 1.3 analyzes the distribution of the sources used to provide the different energy services required by the users, especially domestic hot water and heating firstly, and cooling secondly. Section 1.4 is an overview of which municipalities have not been served by the national natural gas network yet. Finally, Section 1.5 concerns the examination of the main parameters concerning the air quality in order to determine the situation of each territory.

1.1 Geographical information on Piedmont

To review the technical solutions in detail and better comprehend some particular perspectives, a brief analysis of the morphology and the socio-economical structure of Piedmont is worth the candle.

Piedmont (Piemonte, in Italian) is a region in northwest Italy. The denomination derives from the medieval Latin "Pedemontium" or "Pedemontis" [2], which means "foothills of the mountains" and it is very illustrative of the morphology because the territory is mainly subdivided between an imposing mountain chain and a wide flood plain. They are the initial western part of the Alps and the Po valley, respectively. A morphological peculiarity of this area is the absence of a hilly

Figure 1.1: Physical map of Piedmont [1].

landscape adjacent to the mountains. The main hilly area is in the middle of the plain, namely the Monferrato. Nevertheless, almost half the region is mountainous (43.3%), whereas only 26.4% is plain [3]. The climate is mainly continental but varies according to the territory: in the lower areas, there may be an impressive annual thermal amplitude from less than 0 °C in winter to almost 30 °C in summer; instead, the mountain region reveals an alpine climate. In the end, the Piedmont region consists of nine districts: Alessandria, Asti, Biella, Cuneo, Novara, Turin, Vercelli, and Verbano-Cusio-Ossola. The largest territory is not the country seat but Cuneo, which covers almost 70 km^2 more than Turin. The other administrative centers are in charge of decisively smaller areas (see Table 1.1).

District	Population	Share (%)	Total area (km^2)	Population density (people/km^2)
Alessandria	421,284	9.67	3,559	118.38
Asti	214,638	4.93	1,510	142.13
Biella	175,585	4.03	913	192.26
Cuneo	587,098	13.48	6,895	85.15
Novara	369,018	8.47	1,340	275.33
Turin	2,259,523	51.87	6,827	330.97
Verbano C.O.	158,349	3.63	2,261	70.04
Vercelli	170,911	3.92	2,082	82.10
Piemonte	4,356,406	100.00	25,387	171.60

Table 1.1: Piedmont districts extent and population on January 1, 2020 [4, 5].

In the last decades of the XX century, the population kept decreasing, especially in the agricultural areas in the South of the region and where the old industrial plants were dismissed. Right now more than half of inhabitants dwell in Turin district (see Table 1.1). At the same time, the population has got older and older. In 2008 the 22% of the population was over 65 years old [1].

The industries raised in the XX century in Turin and its suburbs suddenly contributed to the largest part of the economic growth. That's why the crisis of the Seventies and the following decades that affected Turin, affected mostly the whole region. However, the morphology had always influenced the economy of Piedmont. Therefore, the agricultural economies that have been developed all things considered are livestock holdings near Cuneo, paddy fields near Vercelli, vineyards near Asti, and fruit orchards near Saluzzo.

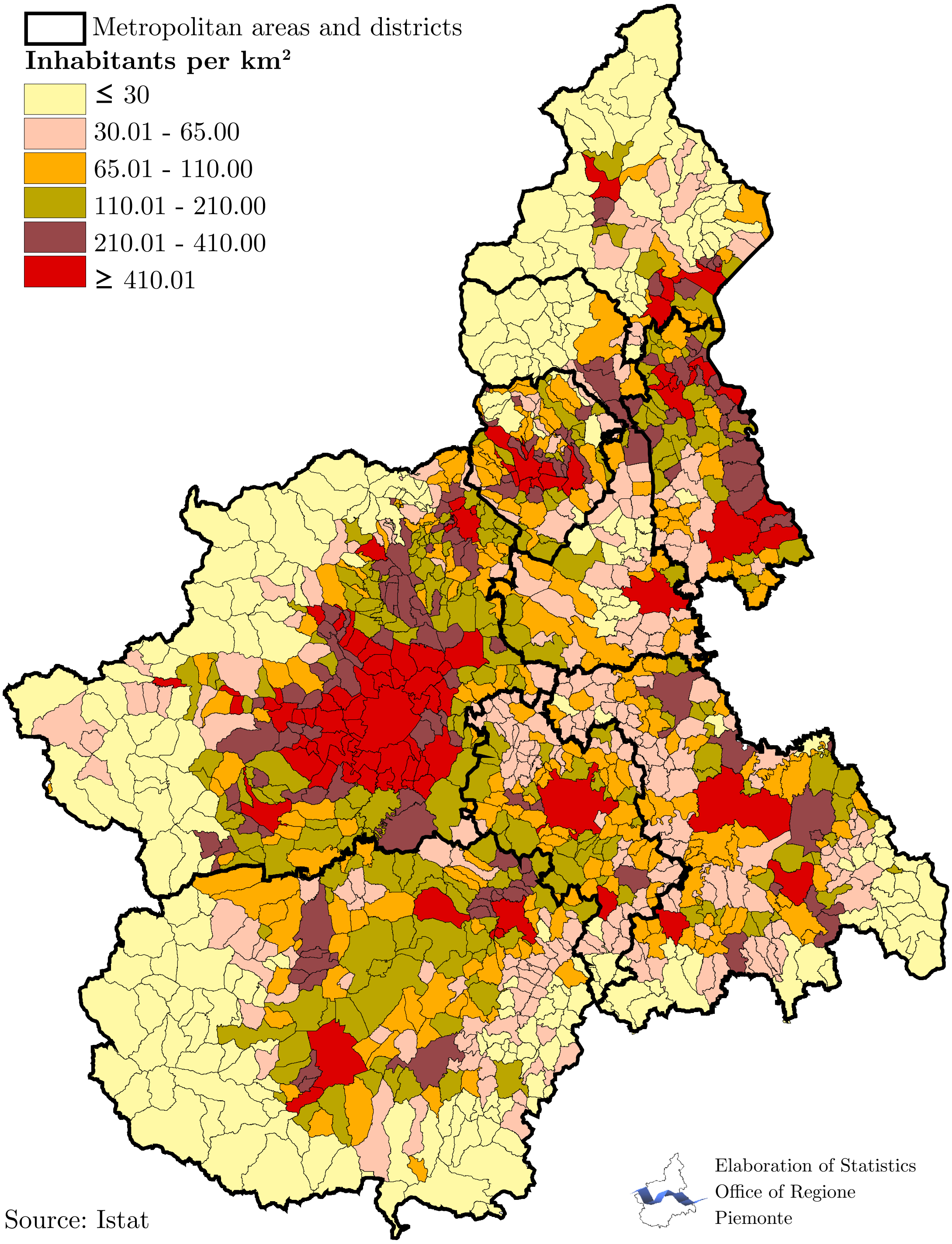


Figure 1.2: Population density map of Piedmont in 2018 [3].

1.2 PRQA and Piedmont legislation

1.2.1 What is the PRQA?

The “Piano Regionale di Qualità dell’Aria” (PRQA) is the regional program that reports the planning, the coordination, and the supervision about the atmospheric pollution in order to gradually improve the environmental conditions and to protect human and environmental health [6].

This plan was approved by the Regional Council with the D.C.R. 25 March 2019, n. 364-6854.

In more detail, the documentation of PRQA describes:

- Air quality and activities that mostly affect it (agriculture, energy, transports sector, industry);
- Detailed technical studies that validate the PRQA subject from a scientific point of view;
- Measurements of emissions and the relative way to reduce them;
- Results of modeling simulations for air quality control measures, which indicate that air quality pollution has to respect the legislative limits within 2030, such as European directive 2008/50/CE decree.

1.2.2 Overview of legislation on air quality

The air quality is analyzed employing contaminant monitoring systems, and the first public network in Piedmont was introduced in Turin by the municipality in 1971 as a result of the application of the law 13 July 1966, n. 615 [6]. This decision allowed measuring the excessive concentration of sulfur dioxide (SO_2), which led the Mayor to start the process to serve building with methane instead of more polluting heating systems.

Moreover, transposing European legislation, the D.P.R. 24 May 1988, n. 203 states that Regions are responsible for measuring and controlling pollutant concentrations and emissions and that they have to compile a government agenda to improve the air quality and environmental conditions of their territories. Then, the D.Lgs. n. 351/1999 adds modeling simulations to simple measurements.

The regional law n. 43 of 7 April 2000 establishes the zoning of the Piedmont territory based on the air quality evaluation carried on by ARPA during the previous five years. The two zones are the “Zona di Piano” (Plan zone) and the “Zona di Mantenimento” (Maintenance or Conservation zone). The former is a zone where the concentration of pollutants is too high. Therefore, intervention is needed to reduce emissions. Whereas the latter satisfies the limits already, it

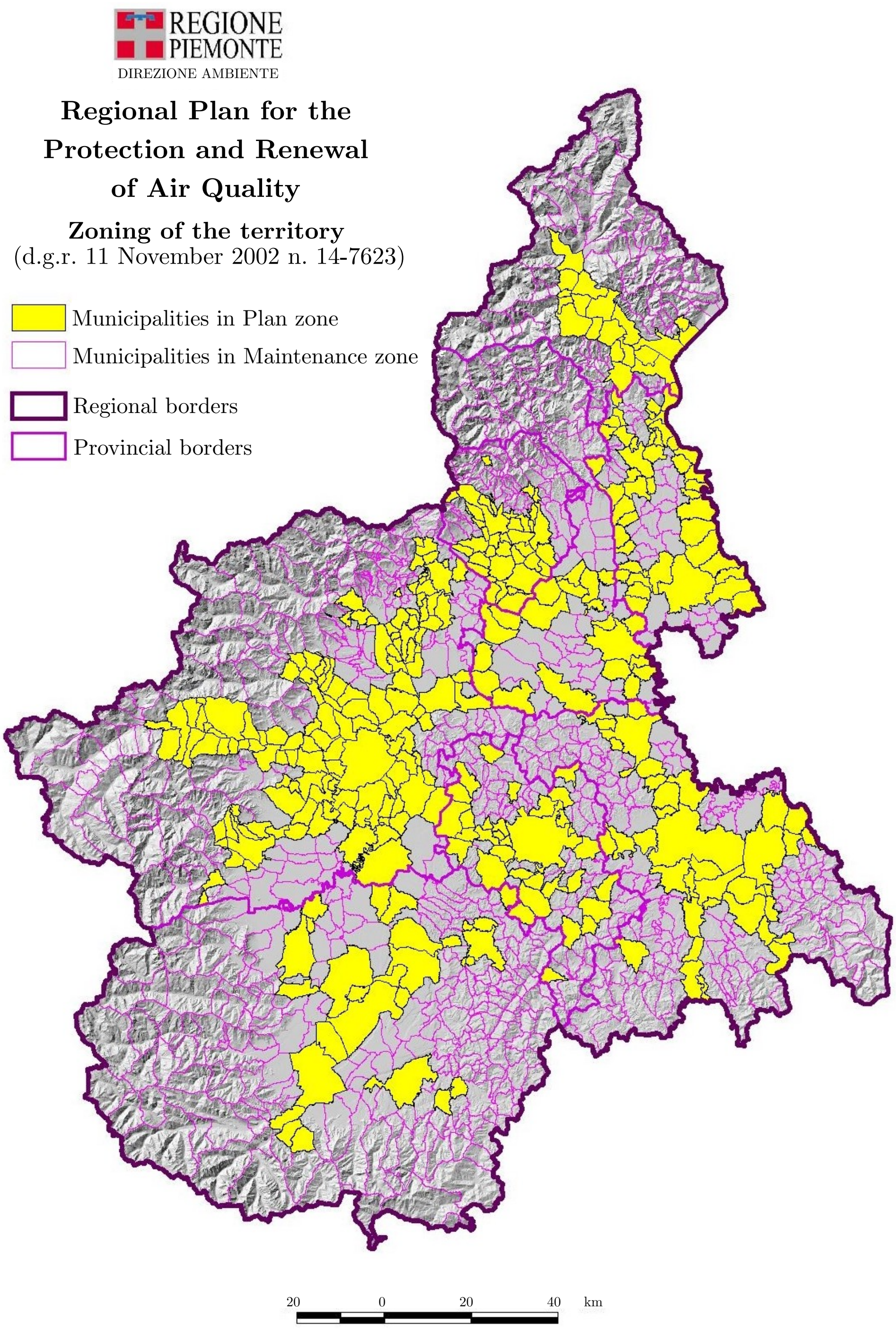


Figure 1.3: Previous zoning map of Piedmont, which distinguishes between Plan and Maintenance zones [7].

is sufficient to conserve the current state. Although the current legislation goes beyond this classification and prefers to reduce emissions uniformly all over the territory, the zoning is still critical for authorities to evaluate the condition of Piedmont and make decisions. The zoning has to be updated at least every five years in compliance with article 4 of the D.Lgs. n. 155/2010.

However, the regional law n. 43 of 7 April 2000 is still valid concerning the management and control of the air quality because it defines the use of the PRQA and other relating instruments, namely the "Sistema Regionale di Rilevamento della Qualità dell'Aria" (SRRQA) e the "Inventario delle Emissioni IREA" (IREA emissions inventory).

Since that regional law, several programs for specific sectors have been developed, such as the plan for incentivizing sustainable mobility or smarter heating systems. Then, the zoning was updated in compliance with the D.G.R. 11 November 2002, n. 14-7623 and with the D.Lgs. n. 155/2010 and D.G.R. 29 December 2014, n. 41-855, which produced the following zoning:

- "Agglomerato di Torino" (Turin built-up area) - zone code IT0118;
- "Zona denominata Pianura" (Plain denominated zone) - zone code IT0119;
- "Zona denominata Collina" (Hill denominated zone) - zone code IT0120;
- "Zona denominata di Montagna" (Mountain denominated zone) - zone code IT0121.

Demographic data, presence of services, and polluting emissions outline the delimitation of the Turin built-up area. As regards the pollutants, the territorial distribution of PM_{10}, NO_x, NH_3, and VOCs was examined by the first zoning proponents, as they are primary pollutants or precursors of PM_{10} and nitrogen dioxide, which exceed the upper assessment threshold over a large part of the Piedmont territory. This first zoning proposal finds out a subdivision very similar to the orographic map of the region since the mountainous areas are not so affected by polluting emissions. Then, ARPA and the University of Turin proposed to use a Functional Cluster Analysis. The examination adopted two different aggregation algorithms. The first is based on the 90 percentile of the spatial series of the grid points that fall within the municipal territory. The second depends on the weighted average of the concentrations of the grid points that fall within the municipality. The weights are represented by the portion of the municipal built-up area within a given cell. The authors conducted the analysis considering only PM_{10} and NO_2 particles, which were the most critical pollutants in 2014. The algorithm identifies as optimal a subdivision of the territory into three zones. Cluster 1 corresponds to the Alpine belt between the Ligurian Alps and the Lepontine Alps, Cluster 3 to

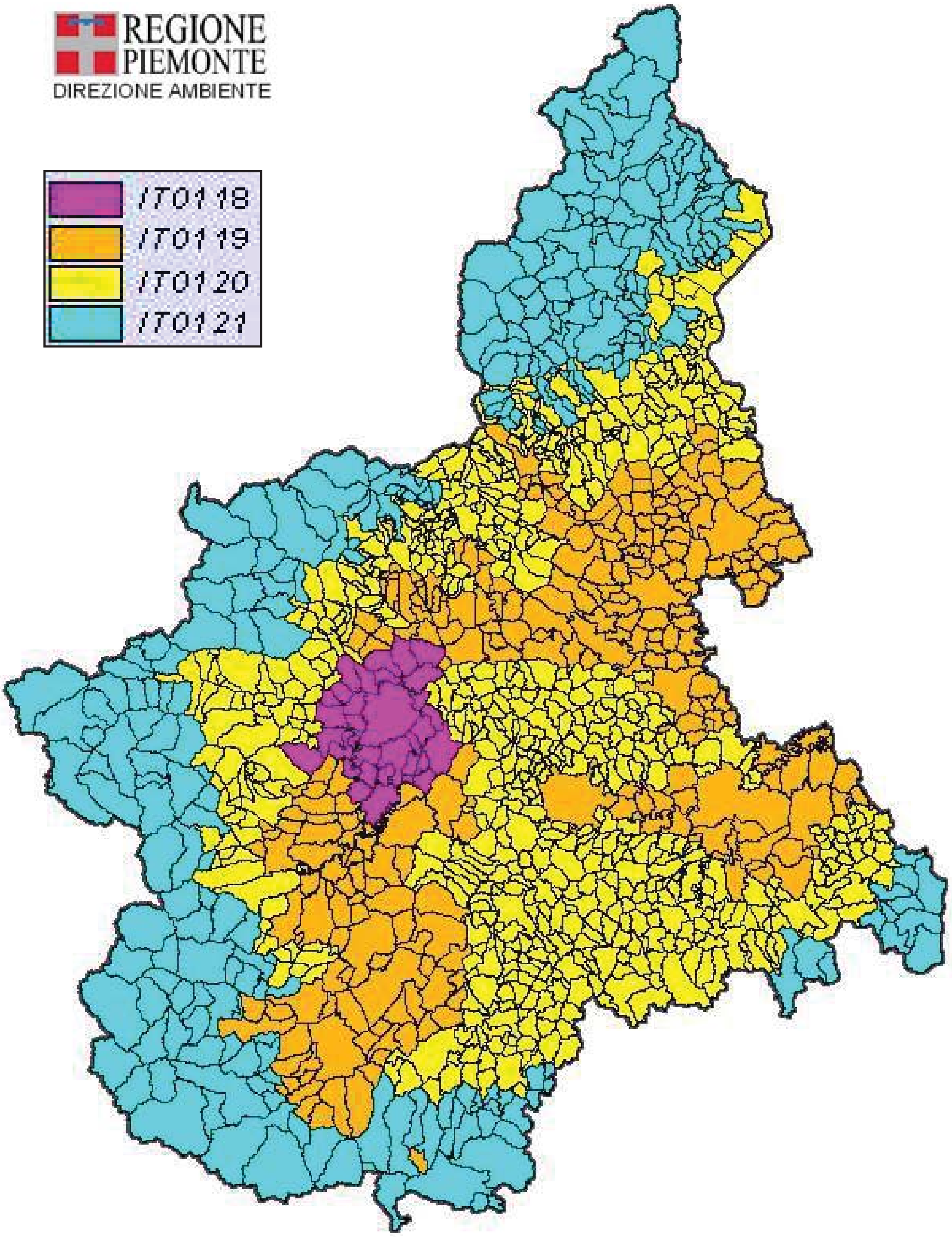


Figure 1.4: Zoning map of Piedmont, according to the D.G.R. 29 December 2014, n. 41-855.

Characteristics	Units	IT0118	IT0119	IT0120	IT0121	Total
Municipalities	-	32	269	660	245	1.206
Population	-	1555778	1326067	1368853	195532	4446230
Munic. areas	ppl/km^2	838	6595	8811	9144	25389
Pop. density	t/km^2	1856	201	155	21	175
PM_{10} em. density	t/km^2	3.57	0.78	0.55	0.13	0.56
NO_x em. density	t/km^2	16.68	3.70	2.36	0.34	2.45
VOC em. density	t/km^2	19.44	3.11	4.18	2.05	3.64
NH_3 em. density	t/km^2	2.76	4.02	1.03	0.19	1.56

Table 1.2: Main characteristics of the built up area and of the three other areas, according to the D.G.R. 29 December 2014, n. 41-855.

central Piedmont containing the built-up area of Turin, the remainder (cluster 2) to the hilly and lowland municipalities not included in the previous zones.

In the end, compiling the definite zoning, some mountainous municipalities found out to border plain or hilly zones. The criteria utilized for assigning them to a specific zone different than mountain were:

- Cluster value;
- Population density greater than 50 inhabitants/km^2;
- Emission density greater than 1 t/km^2 concerning at least two pollutants within PM_{10}, NO_x and NH_3.

In particular, all mountainous municipalities with clusters other than 1 have been allocated to the neighboring area (hills or plains). Besides, all the contiguous municipalities that satisfy the last two parameters of the previous list were assigned to the neighboring area (hill or plain). With this procedure, a mountainous area, which has concentrations of the pollutants examined below the upper assessment threshold, has been identified. Finally, the country seats of the provinces of Biella and Asti, which fall into the hills according to the ISTAT classification, have been attributed to the plain area for both their high population and emission density and their contiguity with the plain. Table 1.2 reports the characteristic of each zone. In more detail, the classification of each municipality is described in Annex A.1 and summed up in Table 1.3. The goal of this zoning is the protection of human health against NO_2, SO_2, C_6H_6, CO, PM_{10}, $PM_{2.5}$, Pb, As, Cd, Ni, B(a)P, and Ozone. In compliance with article 16 of implementing decision 850/2011/EU and article 19 of D.Lgs. 155/2010, the new zoning and classification of the regional territory has had to be applied since 2014 for reporting air quality information.

District	In Plan zone	In Maintenance zone	Total number of municipalities	Share of Plan zone municipalites
Alessandria	37	153	190	19.47%
Asti	32	86	118	27.12%
Biella	36	46	82	43.90%
Cuneo	27	223	250	10.80%
Novara	44	44	88	50.00%
Turin	126	189	315	40.00%
Verbano C.O.	21	56	77	27.27%
Vercelli	20	66	86	23.26%

Table 1.3: Identification of municipalities belonging to Plan and Maintenance zones subdivided by districts, according to the D.G.R. 29 December 2014, n. 41-855.

As shown in Table 1.3, the areas with more plan zones are the districts of Novara and Turin. In the case of Turin district, the reason may lie in the enormous width of a metropolis and its suburbs, although there are many mountainous municipalities. In the case of Novara, the motivations could be the proximity to Milan and the location in the middle of the Po Valley. However, there are no doubts that cities play an important role in the pollutant emissions since the areas near the administrative centers for the provinces are in the Plan zone.

The D.G.R. 18 May 2018, n. 36-6882 is the latest update concerning the zoning of the territory. It states, according to the D.G.R. 29 December 2014, n. 41-855, that every municipality which overcomes the limits reported in the D.Lgs. n. 155/2010 for three or more years has to be administered as the regional law n. 43/2000 treated the plan zones. Therefore, authorities must actuate environmental policies regarding the sectors of agriculture, energy, industry, and transport.

However, as mentioned above, the zoning is no longer relevant to state the emission limits, as the 2016 update of the D.G.R. n. 46-11968 of 4 August 2009 does not differentiate on this point. Nevertheless, there is still a limit that accounts for the zoning, and it is related to biomass fed heat generators from 35 kW_t to 3 MW_t of rated power. In more detail, the average hourly values of particulate matter in the Plan zone must be lower than 30 mg/Nm^3, considering an 11% oxygen concentration in dry smokes. On the other hand, the limit is 50 mg/Nm^3 in Maintenance zones. The efficiency of heat generators and NO_x emissions have the same maximums, instead. Concerning Maintenance zones, the law always requires an efficiency larger than 82% when the rated power is just between 500 and 3000 kW_t. Besides, if the public authority finances the installation at least partially, the limit of particulate matter emissions is 30 mg/Nm^3, like in the Plan zone. The regional decree considers also the interval of the rated power between 3 and 6 MW_t, and between 6 and 20 MW_t, but does not differentiate between zones.

Characteristics	Units	IT0118	IT0122	Total
Municipalities	-	32	1174	1.206
Population	-	1555778	2890452	4446230
Munic. areas	ppl/km^2	838	24551	25389
Pop. density	t/km^2	1856	118	175

Table 1.4: Main characteristics of the built up area and of the Piedmont area concerning the ozone, according to the D.G.R. 29 December 2014, n. 41-855.

In the end, the D.G.R. 29 December 2014, n. 41-855 presents distinct zoning for the ozone since it is not present in the emissions inventory. The reason is that it forms in the atmosphere through chemical-physical processes of other substances called precursors (VOC and NO_x). Besides, large-scale transport phenomena significantly affect the ground concentrations of this pollutant. In any case, this administrative order identifies only the Turin built-up area (IT0118) and the Piedmont area (IT0122). The main characteristics of these areas are shown in Table 1.4 and in Figure 1.5.

1.2.3 Acute contaminants

The previous zoning and analysis are based on three main pollutants: particulate matter (PM_{10} and $PM_{2.5}$), nitrogen dioxide (NO_2), and ozone (O_3). The reason is that they are the most acute contaminants in the Piedmont region. The D.G.R. 23 June 2015, n. 38-1624 explains in detail why these pollutants are worth being studied and which problems they may cause to humans.

Particulate matter (PM_{10} and $PM_{2.5}$)

The PM_{10} and $PM_{2.5}$ are fractions of powders with a diameter smaller than 10 and 2.5 μm, respectively. They consist mainly of solid inorganic and organic material. The origin of the airborne particulate is very varied. The most likely sources are:

- The lifting of natural dust;
- The emissions of unburnt substance from thermal plants (use of solid and liquid fuels, such as coal, wood, diesel, fuel oils) and diesel engines;
- The formation of aerosols of saline compounds.

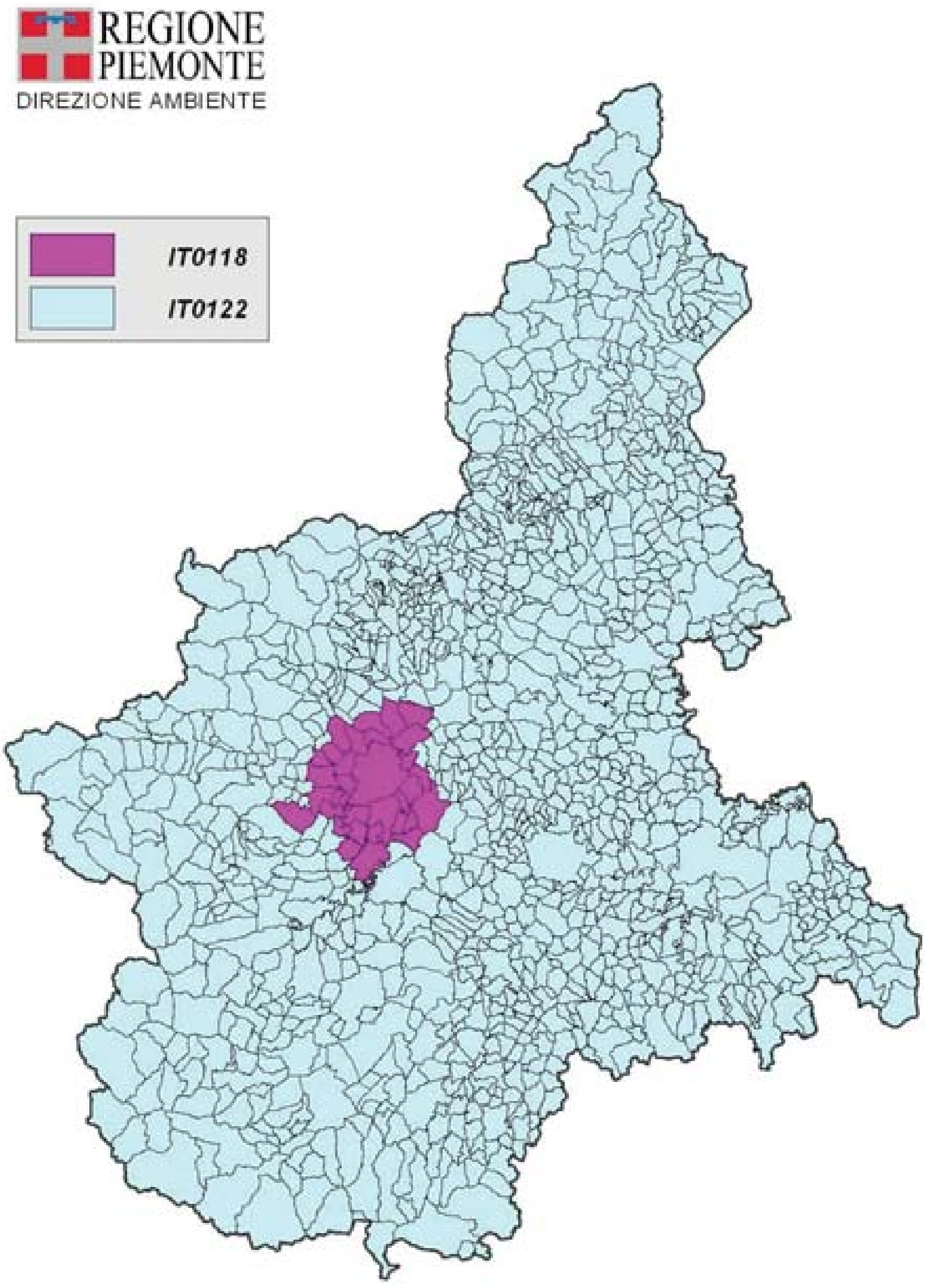


Figure 1.5: Zoning map of Piedmont concerning the ozone, according to the D.G.R. 29 December 2014, n. 41-855.

The second is the cause of the highest interest for the following analyses about regional heating systems, of course. The chemical quality and the ability to absorb toxic substances on its surface, such as heavy metals, polycyclic aromatic hydrocarbons, . . . , are the main reasons for the toxicity of particulate. In more detail, the absorption phenomenon mainly affects fine particles with a diameter of fewer than 10 μm (PM_{10}, $PM_{2.5}$, PM_1). Concerning the path they travel in the human body, PM_{10} stops in the upper respiratory tract, whereas $PM_{2.5}$ goes deeper, up to the bronchi. Smaller diameter particles can reach the pulmonary alveoli, too.

Nitrogen dioxide (NO_2)

Nitrogen dioxide is a reddish, pungent-smelling, highly toxic gas. It is mostly formed in the atmosphere by oxidation of monoxide (NO), which is the primary pollutant that forms in combustion processes. Emissions from anthropogenic sources derive both from combustion processes (thermoelectric power plants, heating, traffic) and non-combustion production processes (production of nitric acid, nitrogen fertilizers, . . .).

The first origin is the one that is more important for the following analyses on energy services. Regarding humans, it is an irritating gas for the respiratory system and eyes, causing bronchitis up to pulmonary edema and death. Concerning the environment, it is a reactive compound that has a fundamental role in the formation of ozone. Since it is partially soluble in water, it has an acidifying action on this and contributes to the formation of acid rains.

Ozone (O_3)

It is a highly poisonous toxic gas for all living things. Nevertheless, ozone is naturally present in the atmosphere between 10 and 40 km from the Earth's surface. There it is essential to life on Earth as it screens the ultraviolet radiation (UV rays) from the Sun. On the other hand, up to 10 km from the Earth's surface, ozone is an air pollutant and is produced mainly by photochemical reactions due to other polluting gases.

Humans contribute by emitting nitrogen oxides and volatile organic compounds through vehicle traffic, combustion processes, and the evaporation of fuels and solvents. Relatively low concentrations of ozone may cause effects such as irritation to the throat and respiratory tract and burning eyes; higher concentrations can lead to alterations in respiratory functions and an increase in the frequency of asthma attacks. Ozone is also responsible for damage to vegetation and crops, with the disappearance of some tree species from urban areas.

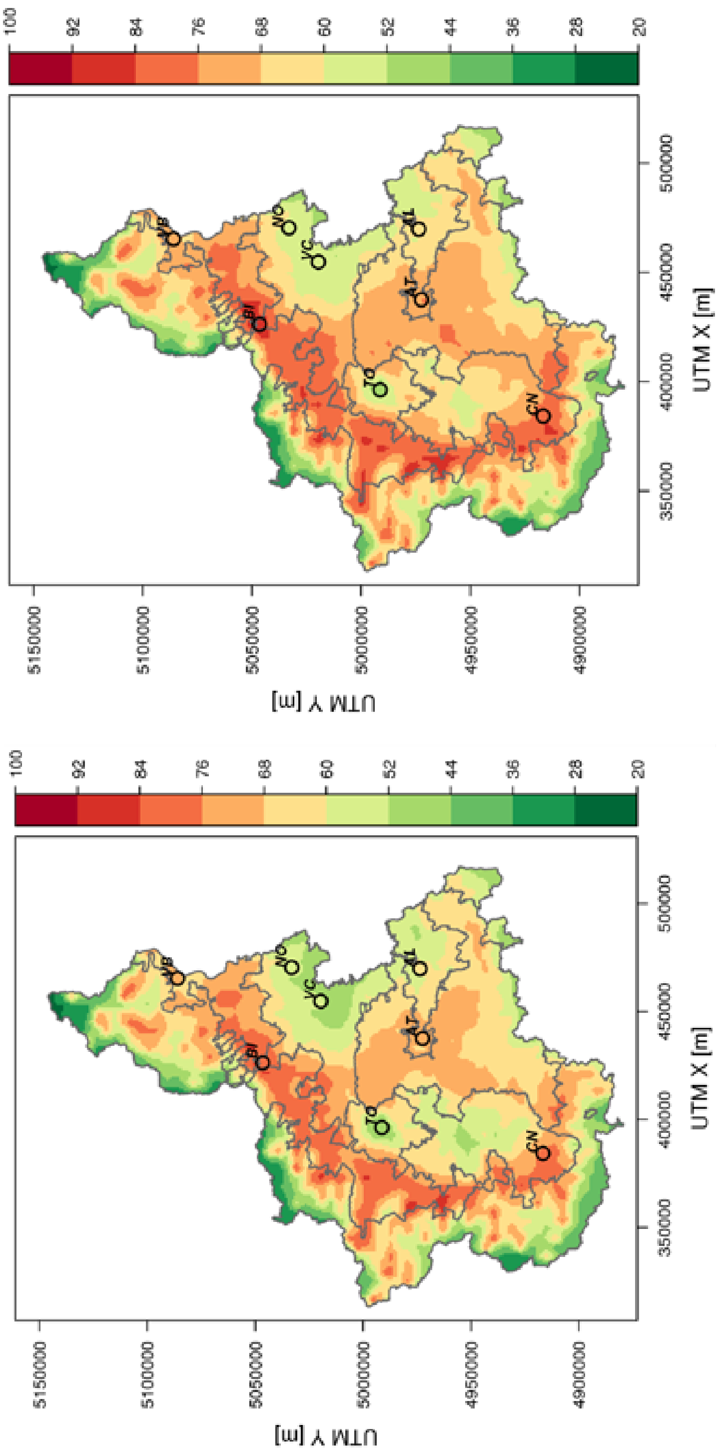
1.2.4 Fact-finding survey of PRQA

As mentioned in Subsection 1.2.1, the PRQA provides a detailed study of the current situation in Piedmont from the viewpoint of the excess of the limit values. This analysis is interesting because highlights the areas that may require mostly a change in residential heating and cooling solutions because of their high emitting values.

In order to isolate the areas that are mostly affected by residential heating related issues, it is necessary to identify the parameters strictly linked with them. As shown in Figures A.1-A.6, PM_{10} and $PM_{2.5}$ emissions are mostly due to the residential sector with a very little contribution by others. Also, sulfate may be a good indicator because the sector analyzed affects its emissions by 40-50%. Nevertheless, the industrial sector impacts it almost the same way, so it is hard to identify sulfate only with the residential sector, whereas for $PM_{2.5}$ and, especially, PM_{10} it is not. Therefore this equivalence is even more valid for the measuring stations out of the town, where the contribution of the transport sector is slighter. Besides, the PRQA unveils that residential heating impacts in relative terms more in hilly and mountainous zones compared to Turin or plain areas. This particular behavior is well shown in Figure 1.6.

In addition, Table 1.5 shows that the largest contribution to PM_{10} emissions is connected to wood heating. Instead, non-wood heating affects mostly sulfate emissions, but with significant differences from zone to zone. For instance, the analysis of stations in the Turin residential area reveals that non-wood heating impacts by 55-65%, whereas its contribution plunges to 20-30% in the suburbs, considering the more detailed data reported in Tables A.2-A.7. Due to this nosedive, the contribution in sulfate emissions and concentration of wood and non-wood heating systems is almost the same in these areas. Then, the industry sector starts counting more compared to downtown areas with percentages similar to the above-mentioned items. Instead, wood and non-wood heating affect similarly (15-20%) in Zone IT0119, although the contribution of industries is 40-80%.

In the end, the industry sector throws its weight about also in zones IT0120 and IT0121. However, in this case, the contribution of wood heating is almost double or even more than non-wood heating. These particular relations may be correlated to the fact that the zones analyzed are usually less and less polluted in absolute terms distancing from Turin or other towns, so the industry sector impacts more in relative terms, while the transport sector becomes irrelevant. The rising of the percentage contribution of wood heating in zones IT120 and IT0121 may be also linked to the fact that this technology is not so widespread in Turin anymore, whereas it is elsewhere. In any case, Section 1.3 will delve into the distribution of the actual heating technologies used in Piedmont.



(a) PM_{10}

(b) $PM_{2.5}$

Figure 1.6: Spatial distribution of percentage contribution to annual average concentration of PM_{10} and $PM_{2.5}$ due to residential heating obtained by means of the source apportionment method and relative Plan zones [6].

Pollutants	Zones	Wood heating		Non-wood heating		Other sources	
		Min	Max	Min	Max	Min	Max
PM_{10}	IT0118	39.2%	67.9%	0.9%	5.6%	26.5%	59.9%
	IT0119	48.0%	81.2%	0.7%	2.4%	16.4%	51.3%
	IT0120	56.6%	81.5%	0.8%	1.8%	16.7%	42.6%
	IT0121	76.7%	79.4%	0.7%	1.1%	19.5%	22.6%
$PM_{2.5}$	IT0118	45.9%	69.3%	1.4%	5.4%	25.3%	52.7%
	IT0119	56.3%	83.6%	1.0%	2.5%	13.9%	42.7%
	IT0120	64.9%	80.1%	0.8%	1.8%	18.1%	34.3%
	IT0121	78.9%	80.7%	0.7%	1.0%	18.3%	20.4%
NO_2	IT0118	0.5%	5.3%	6.5%	10.7%	84.0%	93.0%
	IT0119	1.5%	10.6%	7.6%	12.2%	77.2%	90.9%
	IT0120	4.8%	14.9%	7.9%	16.0%	69.1%	87.3%
	IT0121	5.4%	14.4%	7.9%	12.9%	72.7%	86.7%
NO_3^-	IT0118	12.9%	16.8%	1.9%	2.6%	80.6%	85.2%
	IT0119	12.3%	16.8%	0.0%	3.0%	80.2%	87.7%
	IT0120	9.5%	19.5%	2.5%	3.5%	77.0%	88.0%
	IT0121	12.5%	15.2%	2.8%	4.0%	80.8%	84.7%
SO_4^{2-}	IT0118	9.4%	35.7%	17.5%	58.4%	5.9%	73.1%
	IT0119	6.6%	34.2%	5.6%	26.4%	39.4%	87.8%
	IT0120	10.0%	53.6%	3.2%	23.9%	22.5%	86.8%
	IT0121	13.4%	45.2%	7.7%	27.1%	27.7%	78.9%
NH_4^+	IT0118	11.0%	21.0%	5.8%	25.0%	54.0%	83.2%
	IT0119	10.2%	23.4%	1.9%	9.8%	66.8%	87.9%
	IT0120	9.6%	25.0%	3.4%	9.3%	65.7%	87.0%
	IT0121	20.7%	21.1%	5.3%	8.1%	70.8%	74.0%

Table 1.5: Minimum and maximum percentage contribution to annual average concentration of most impacting pollutants by heating systems subdivided by zones. The whole set of data is reported in Tables A.2-A.7.

1.3 Analysis of energy sources adopted for heating, cooling and DHW production

SICEE (Sistema Informativo per la Certificazione Energetica degli Edifici - Information Systems of Buildings Energy Certification) was the denomination of the regional database of the energy certifications of buildings until 2014, but the word "performance" has been preferred to "certification" since then. Therefore, the name changed to SIPEE, in compliance with the D.G.R. 4 February 2014, n. 17-7073. The SICEE was born in compliance with clause 2 of article 9 of the D.lgs. 192/2005, by which the Government gave the responsibility to check and record the performance of the buildings to each Region. That's why the SIPEE is available officially on the Sistemapiemonte website [8] for a wide range of users:

- Certifying agencies;
- Citizens;
- Notaries;
- Institutions and educational subjects;

According to the above-mentioned D.lgs. 192/2005 and subsequent amendments and additions, the energy performance, energy efficiency or building efficiency is the annual amount of energy consumed or expected to be consumed by a standard building to satisfy its needs, i.e. summer and winter conditioning, sanity water, ventilation, and lighting. This quantity is computed by evaluating several parameters that consider insulation, technical characteristics and installation, design and location concerning the weather, sun exposition, adjacent structures influence, and other factors that contribute to the energy requirements. Then the certificate of energy certification (Attestato di Certificazione Energetica, ACE) is defined as the document prepared in compliance with the rules contained in this decree, certifying the energy performance and possibly some energy parameters characteristic of the building. Also, in this case, the ACE became the APE, since the word "performance" substituted "certification", as mentioned above.

The SIPEE database includes information about eight different types of domestic energy service:

- Domestic hot water;
- Summer cooling;
- Winter heating;
- Lighting;

- Combi-systems;
- Renewable energy production;
- Transport;
- Mechanical ventilation.

For each of this entry, the SIPEE sample gives great information, but the pieces of information that are interesting for the analysis to perform are:

- District;
- Latitude;
- Longitude;
- Cadastre information;
- APE subject (single housing unit or whole building and relative number of housing units);
- Fuel;
- Type of installation and plant.

Cadastre information is truly important because it leads to identifying a housing unit uniquely since potential different housing services of the same house are not reported together.

As the above-mentioned law is not so old, the archive of certifications can not cover the whole buildings of Piedmont. The reason is that APEs are produced only in case of new installation or refurbishment. Therefore, to check how much the SIPEE database [9] is thorough, a comparison with data given by Istat [3] will be carried on. However, the SICEE sample does not account only for housing units such as Istat but considers both housing units and entire buildings. Nevertheless, the number of elements for every single edifice is usually specified, luckily. Therefore it is possible to obtain the total number of housing units reported in the SIPEE considering that, when the caption "entire building" appears, it means that all the housing units of that edifice can boast the same technical solution for energy production. That's why it is possible to make a comparison between the available data without a remarkable error. As shown in Table 1.6, the percent coverage of the SIPEE sample compared to the Istat survey is almost 17%. It may seem a low value, but it is not, considering the short period since which the law has entered into force.

District	SIPEE (properties)	Istat (properties)	Percentage covered (%)
Alessandria	50,985	289,315	17.62
Asti	20,813	137,357	15.15
Biella	15,763	121,505	12.97
Cuneo	61,140	425,856	14.36
Novara	32,485	213,891	15.19
Turin	244,786	1,342,741	18.23
Verbano C.O.	19,201	135,810	14.14
Vercelli	18,147	119,989	15.12
Totale	463,320	2,786,464	16.63

Table 1.6: Comparison of properties covered by the SIPEE database and properties counted by Istat, elaboration of data obtained from [3, 9].

1.3.1 Share of domestic energy services

Summer cooling, winter heating, and domestic hot water are the most significant energy services to analyze in order to evaluate the Piedmont zone that is not served by the national gas network.

Energy service	Installations	Percentage of buildings with the system installed (%)
Domestic hot water	370,992	95.49
Summer cooling	25,384	6.53
Winter heating	387,678	99.78
Lighting	30,239	7.78
Combi-systems	3,114	0.80
Renewable energy production	31,641	8.14
Transport	2,226	0.57
Mechanical ventilation	8,888	2.29

Table 1.7: Energy services and number of buildings where they are installed, elaboration of data obtained from [9].

The reason is that domestic hot water and winter heating are installed in almost every edifice, as shown in Table 1.7. Instead, summer cooling is less common, with a percentage of about 7%, which is comparable to lighting or renewable energy production. However, they are not as interesting as cooling because of the low

Fuel	Sanitary water (%)	Summer cooling (%)	Winter heating (%)	Lighting (%)	Renewable energy production (%)
Gaseous biomass	0.03	0.02	0.04	0.00	0.02
Liquid biomass	0.02	0.00	0.04	0.00	0.27
Solid biomass	1.03	0.02	2.75	0.00	8.63
Coal	0.00	0.00	0.00	0.00	0.00
Electric power	23.82	96.04	3.78	98.92	7.82
Wind power	0.00	0.00	0.00	0.00	0.01
Natural gas	69.13	3.53	77.61	0.05	0.32
Diesel oil	0.75	0.00	1.43	0.00	0.23
Fuel oil	0.01	0.00	0.02	0.00	0.00
LPG	2.20	0.06	2.07	0.00	0.03
Solar photovoltaic sys.	0.00	0.01	0.00	0.02	22.15
Thermal solar energy	0.31	0.01	0.04	0.00	41.68
District cooling	0.01	0.02	0.07	0.00	0.00
District heating	2.17	0.06	11.05	0.00	1.41
Others	0.16	0.21	0.18	1.01	17.45

Table 1.8: Share of each fuel per energy service (not considering buildings where the systems analyzed is not installed), elaboration of data obtained from [9].

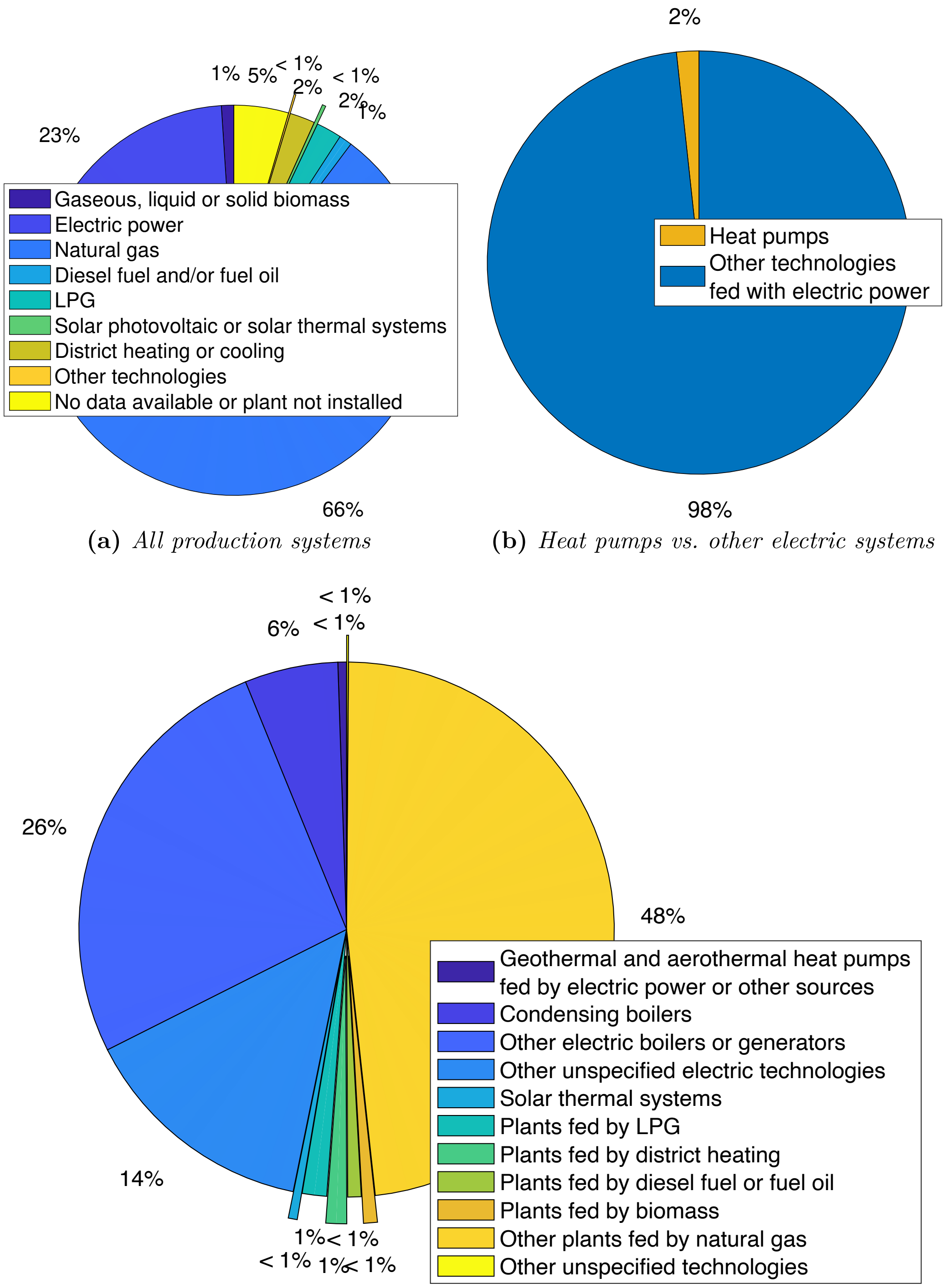
share (< 1%) of natural gas in their feeding basket (see Table 1.8).

In particular, these data help to understand what are the most widespread technological solutions chosen to supply each energy service. This aspect is significant because it is a basis that can be useful to decide which service is more feasible to be updated in order to make it more sustainable and cheaper to run, hopefully. However, the greatest obstacle to a green transition is usually the investment cost, whereas the operative cost is not. That's why it may be interesting to consider also the distribution of heat pumps, since they may be a valid trade-off between the two aspects.

Domestic hot water

Domestic hot water is produced mostly by electric power or natural gas, and the share of other technical solutions is low compared to the former couple, as shown in Figure 1.7a. Instead, Figure 1.7b highlights that heat pumps are not so widespread for this kind of energy service.

Although the market of new installations is shifted almost totally to condensing



(a) *All production systems* **(b)** *Heat pumps vs. other electric systems*

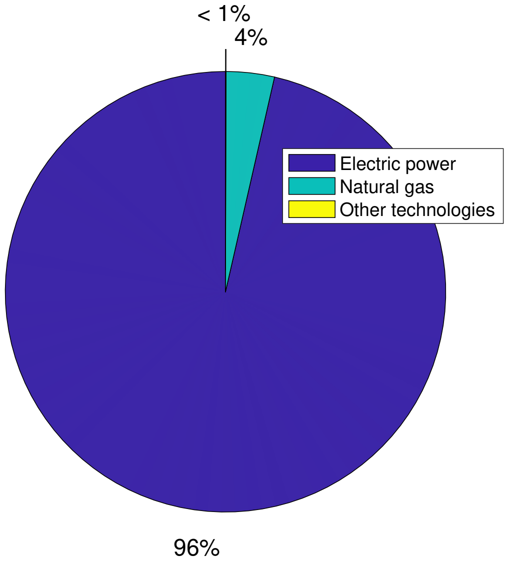
(c) *All typologies of chosen systems*

Figure 1.7: Pie charts of percent distribution of production systems of domestic hot water, elaboration of data obtained from [9].

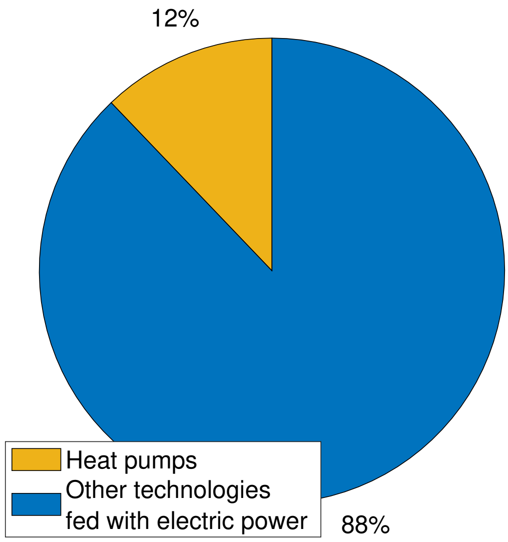
boilers, a substantial share of existing installments is still covered by natural gas and traditional electric boilers (see Figure 1.7c). It would better to substitute both technologies because they are not so energy efficient compared to others, such as condensing boilers. Condensing boilers are fed by electric power as well, but their efficiency is higher. In any case, a heat pump can guarantee a primary energy reduction by 15-50% compared to them [10], therefore they should be changed as well, if possible. Also, heat pumps' lifetime is longer, they are reliable, and they require minimal maintenance.

Regardless, such a large share of natural gas proves the presence of gas at an affordable price in at least half the region. On the other hand, natural gas is hard to substitute with greener technologies because it is a more widespread technology, so it is always cheaper to install and sometimes to maintain. However, a gas solution entails possible leakage or explosion that an electrical installation should prevent more easily.

Summer cooling



(a) *All production systems*

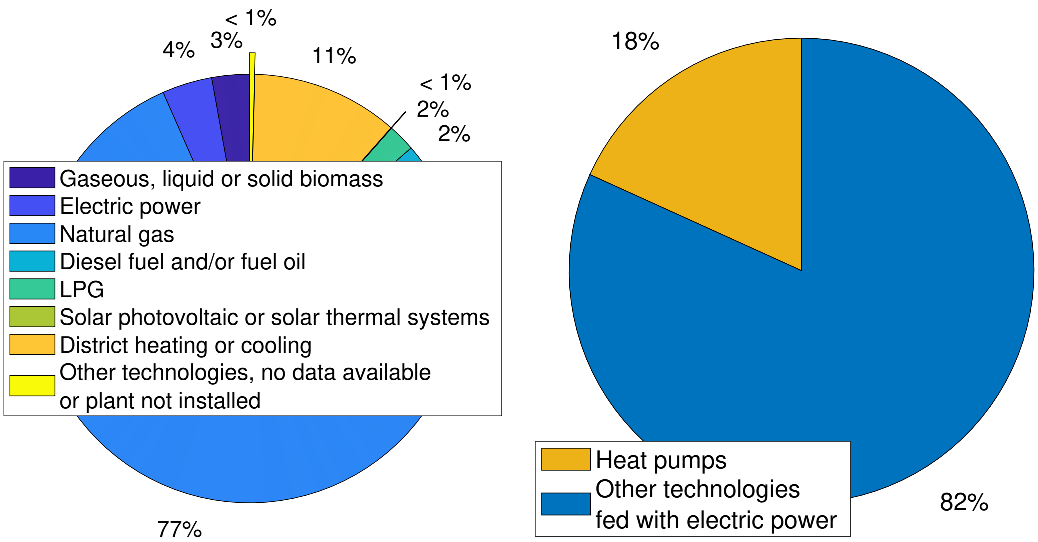


(b) *Heat pumps vs. other electric systems*

Figure 1.8: Pie charts of percent distribution of production systems of summer cooling (not considering buildings where the systems analyzed is not installed), elaboration of data obtained from [9].

In the case of summer cooling, the electric power carries on almost entirely the production (96%). The natural gas covers a share of 4%, and all other technologies are under 1% (see Figure 1.8a). From the viewpoint of heat pumps, the situation is no more so unbalanced since the heat pumps are used in 12% of circumstances when an electricity-driven technology is installed, as shown in Figure 1.8b.

Winter heating



(a) *All production systems* **(b)** *Heat pumps vs. other electric systems*

Figure 1.9: Pie charts of percent distribution of production systems of winter heating, elaboration of data obtained from [9].

As shown in Figure 1.9a, winter heating systems are powered mainly by natural gas (77%, which is the biggest share among the three services analyzed). The second most utilized source is the district heating, which is fringe in the other cases. Figure 1.9b reveals that also the share of heat pumps is the highest among the three considering the electricity-driven systems, but not in general. For instance, heat pumps cover a lower portion than those for summer cooling with respect to all technologies available.

1.3.2 Geographical diffusion of domestic energy services

As mentioned above, the SIPEE sample gives the latitude and longitude of each building, as well. Therefore, it is possible to identify the geographical diffusion of fuels or energy sources per type of energy service.

Domestic hot water

As shown in Figure 1.10 and Table 1.9, domestic hot water production is mainly based on natural gas. This type of fuel is spread mostly in the areas of Alessandria, Novara, and Verbano-Cusio-Ossola, which are the most eastern districts of Piedmont. The electric power covers a share of 15-30%, depending on how big is the incidence of natural gas since the other sources are very rare. Concerning that, only in Cuneo province, the sum of other fossil fuels (LPG, diesel fuel, and fuel oil) overcomes 7%, whereas, in the other cases, it is always under 5% or lower. In the end, Cuneo and Turin districts are the only two areas where the district heating reaches almost 3%, quite much compared to the others that have a share (significantly, sometimes) lower than 1%.

Regarding the geographical diffusion of each supply, it is possible to notice that all the maps are very similar to the one in Figure 1.2 about population density. Anyhow, this is not unexpected, since it is logical that the two variables are correlated. District heating/cooling map (see Figure B.5 for more details) is extremely curious because it highlights well that this technical solution is widespread only in big towns or cities.

Summer cooling

Tables 1.10 shows that summer cooling is not so widespread. However, most systems are powered by electricity. In this case, the geographical distribution is strictly correlated to population density, as well.

Winter heating

Whereas the geographical distribution (see Figure 1.12) is quite similar to the previous cases, Table 1.11 shows a different situation. Although natural gas is always the most widespread solution, electric power is not the runner-up anymore: district heating covers the 18.22% of the installations in Turin, and it is important in Cuneo as well with almost 8%. Its contribution is not so negligible also in Alessandria and Biella provinces, whereas it is in the others. All the other sources cover a good share in any province.

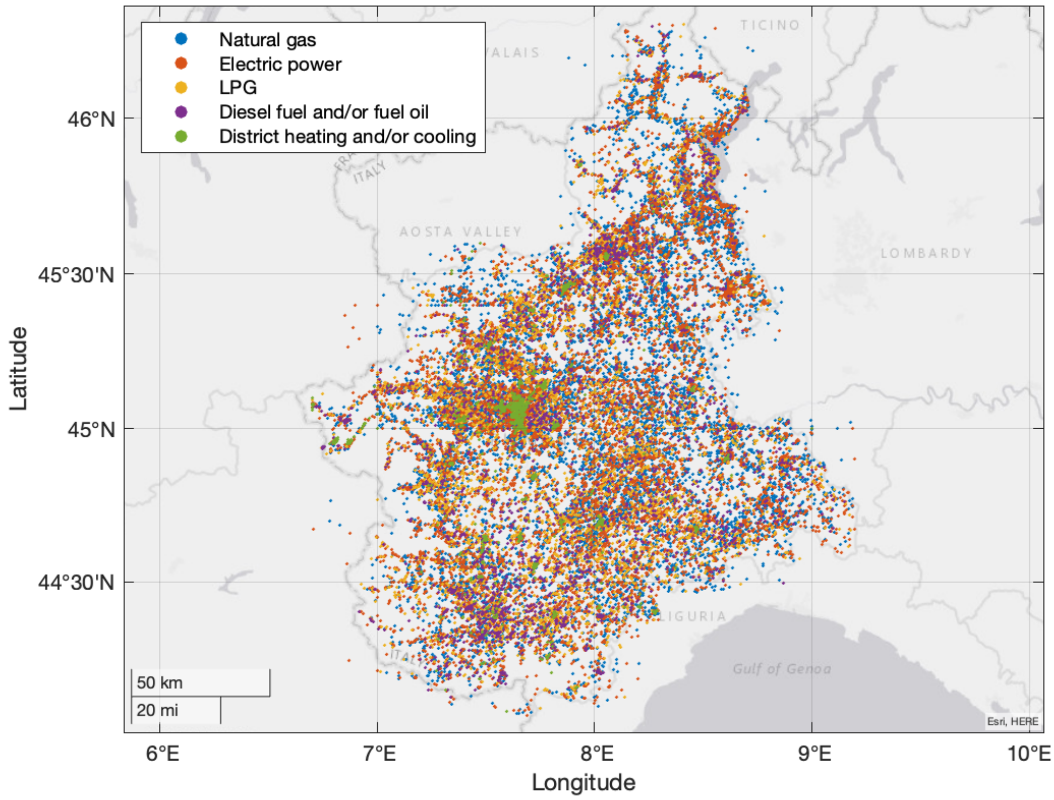


Figure 1.10: Domestic hot water production systems map, elaboration of data obtained from [9].

District	Natural gas (%)	Electric power (%)	LPG (%)	Diesel fuel and/or fuel oil (%)	District heating and/or cooling (%)	Others (%)	No data available or system not installed (%)
Aless.	73.23	15.85	2.11	1.16	1.17	1.35	5.13
Asti	61.02	27.75	3.88	1.02	0.17	2.19	3.97
Biella	58.23	28.16	2.73	1.93	0.94	2.05	5.95
Cuneo	59.11	24.48	4.35	2.66	2.74	2.92	3.74
Novara	75.97	16.51	1.00	0.53	0.01	1.40	4.58
Turin	64.88	24.46	1.46	0.67	2.92	1.02	4.58
V.C.O.	79.34	12.71	1.65	0.93	0.00	1.63	3.73
Vercelli	66.04	22.65	3.02	1.42	0.19	1.75	4.93

Table 1.9: Domestic hot water production systems subdivided by district, elaboration of data obtained from [9].

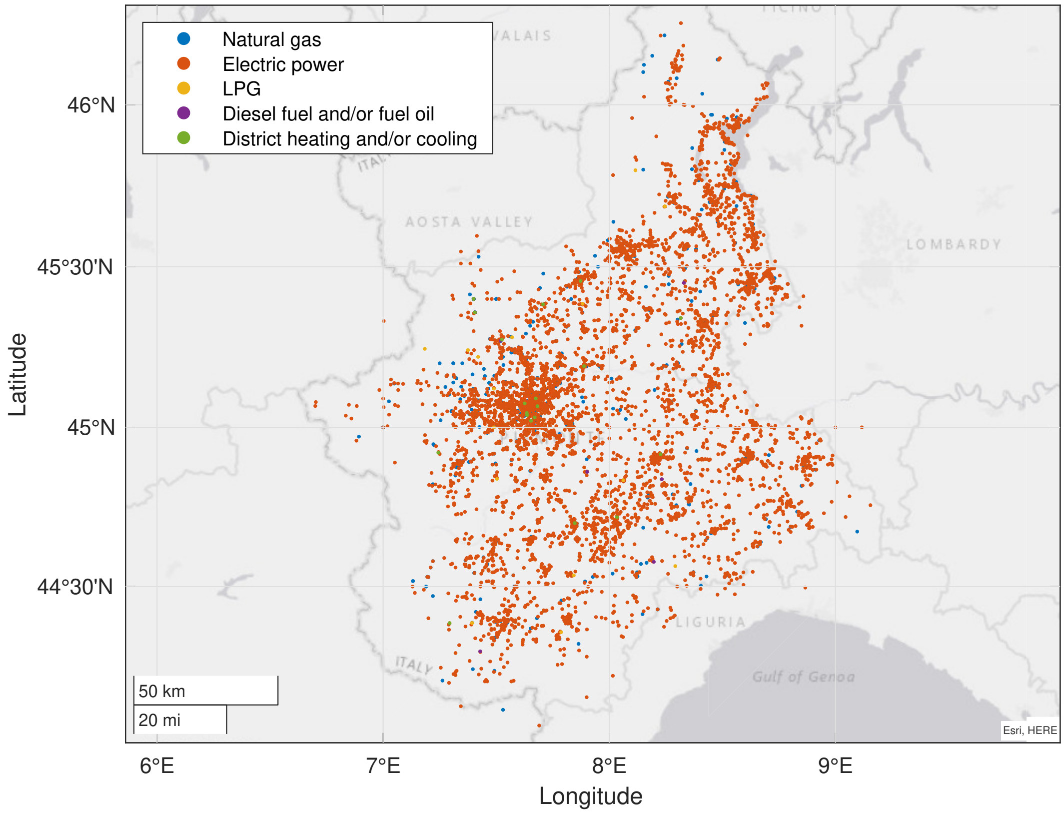


Figure 1.11: Summer cooling production systems map, elaboration of data obtained from [9].

District	Natural gas (%)	Electric power (%)	LPG (%)	Diesel fuel and/or fuel oil (%)	District heating and/or cooling (%)	Others (%)	No data available or system not installed (%)
Aless.	0.25	7.23	0.00	0.00	0.00	3.52	89.00
Asti	0.20	5.93	0.01	0.01	0.01	3.17	90.69
Biella	0.15	4.45	0.01	0.00	0.01	4.81	90.57
Cuneo	0.13	4.98	0.01	0.00	0.01	7.95	86.92
Novara	0.33	10.92	0.00	0.00	0.00	1.74	87.00
Turin	0.25	6.05	0.00	0.00	0.01	4.31	89.38
V.C.O.	0.24	3.79	0.00	0.00	0.00	2.48	93.49
Vercelli	0.18	7.17	0.01	0.00	0.00	3.23	89.41

Table 1.10: Summer cooling production systems subdivided by district, elaboration of data obtained from [9].

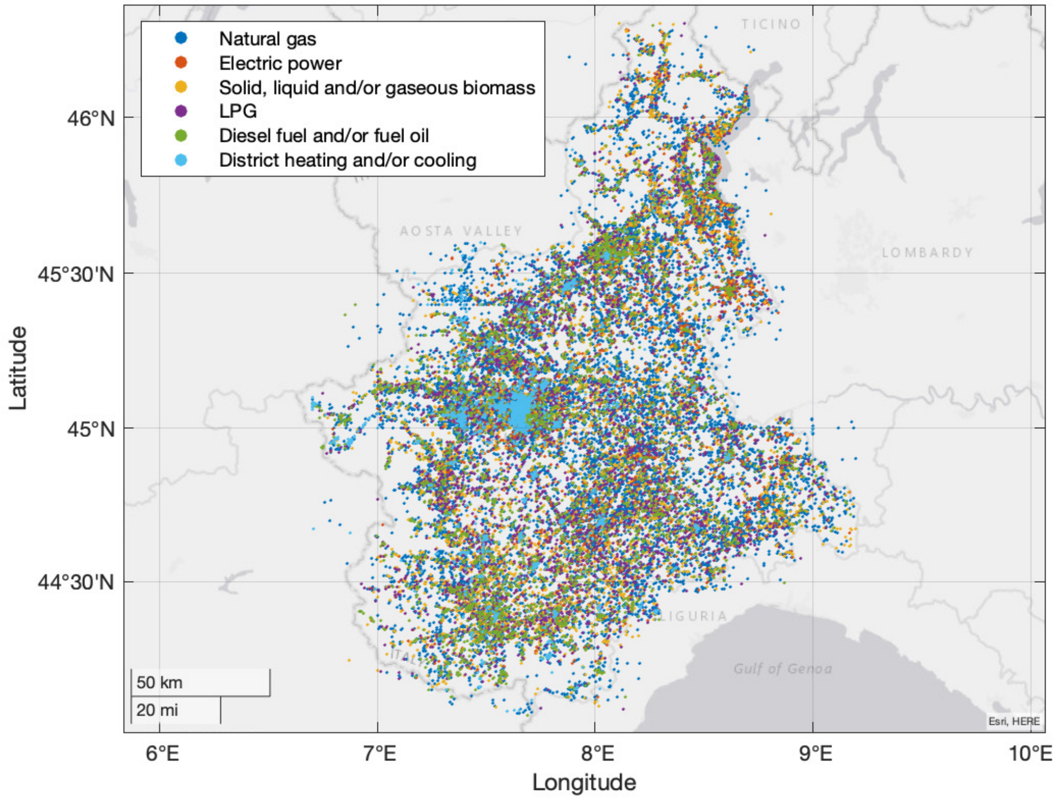


Figure 1.12: Winter heating production systems map, elaboration of data obtained from [9].

District	Natural gas (%)	Electric power (%)	LPG (%)	Diesel fuel and/or fuel oil (%)	District heating and/or cooling (%)	Bio-mass (%)	Others, no data available or system not installed (%)
Aless.	87.46	3.54	2.07	1.62	1.99	2.78	0.53
Asti	84.59	3.34	3.85	2.27	0.53	4.76	0.67
Biella	81.43	2.91	2.50	4.70	3.88	4.12	0.46
Cuneo	71.17	4.87	4.22	5.69	7.79	5.84	0.41
Novara	89.15	6.16	1.06	1.06	0.01	2.10	0.46
Turin	73.16	3.26	1.48	1.69	18.22	1.76	0.44
V.C.O.	89.67	4.09	1.42	1.19	0.01	3.23	0.38
Vercelli	84.68	3.68	2.80	3.51	0.27	4.69	0.36

Table 1.11: Winter heating production systems subdivided by district, elaboration of data obtained from [9].

1.4 Municipalities not reached by natural gas pipelines

In the previous sections, natural gas technologies have turned out to be extremely widespread and used solutions. However, the data by the Italian Ministry of Economic Development concerning the situation of the national gas network in 2014 (latest data available) reveal that some municipalities have not been reached by the pipelines yet [11]. In Piedmont, they are 175 (see Table 1.12), and they are distributed mainly in mountainous areas.

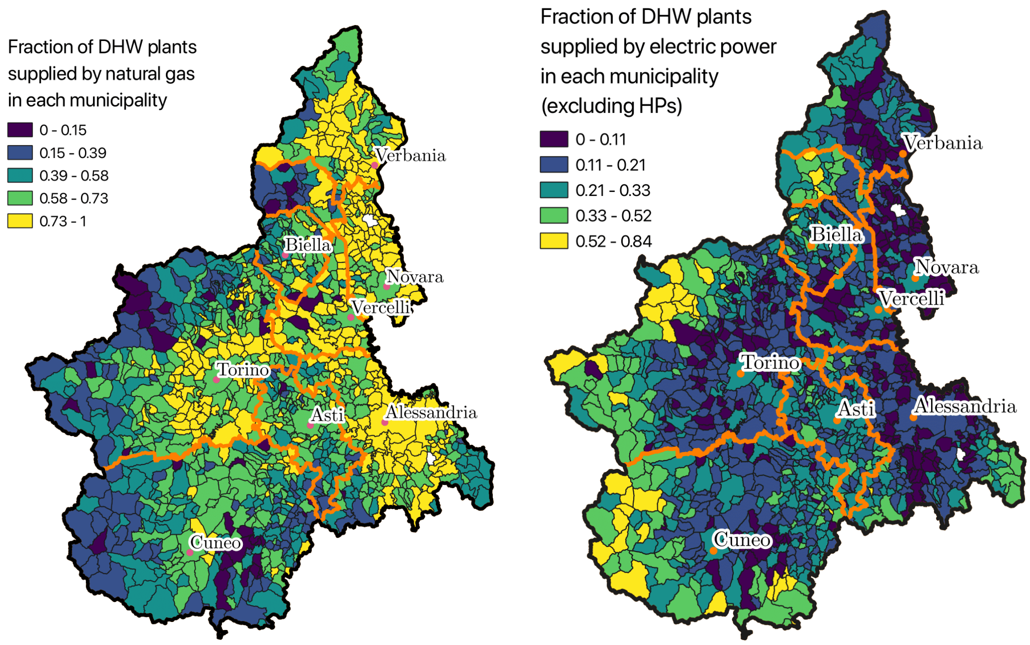
Elevation	Number of municipalities
Under 300 m	11
Between 300 and 600 m	33
Between 600 and 1000 m	91
Over 1000 m	40

Table 1.12: Number of municipalities not reached by natural gas pipelines in Piedmont, elaboration of data obtained from [11].

Figure 1.13a shows the aforementioned distribution. Many mountainous areas have a share of natural gas fed technology for the DHW production lower than 40%. It is extremely appealing to notice that the distribution of electric power technologies is almost specular to that of natural gas. This aspect may prove that electric boilers are the most spread solutions in all those towns where the natural gas network is lacking or meager, but, above all, that natural gas is usually the favorite fuel when available.

Considering now the production for heating purposes, maps in Figure 1.14 reveals that the most polluting technologies, such as LPG or diesel fuel, are mostly diffused in mountainous zones, where natural gas is lacking. The same is valid for the usage of solid biomasses. Biomasses are at least less impacting from the sulfate emissions viewpoint, but more concerning the particulate matter, as reported in Table 1.5. However, this table does not differentiate the fact that biomass fed plants are more spread than non-wood technologies, so it is consequential that they impact more in the emissions mix of any area.

These more impacting technologies spread out further in areas that are less severe concerning the emissions of particulate and other pollutants, such as IT119 or IT120. In any case, the substitution with greener installments, such as heat pumps, should be a feasible investment to reduce the human impact on the local environment. As heat pumps are powered by electricity, the national electric power

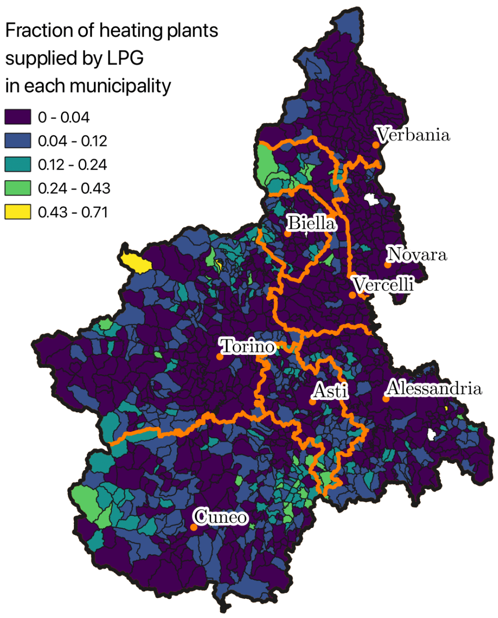


(a) *Natural gas* **(b)** *Electric power (excluding HPs)*

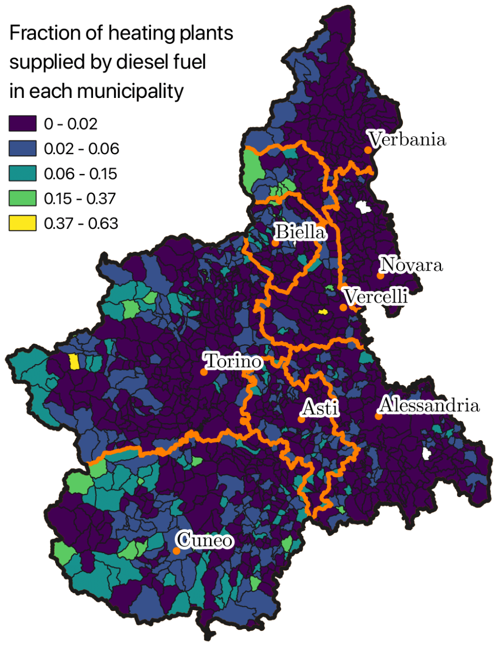
Figure 1.13: Fraction of DHW plants supplied by natural gas and electric power in each municipality, elaboration of data obtained from [9, 12].

mix is a fundamental factor to evaluate if the entire energy generation process is less polluting than with the usage of more traditional technologies. However, the impact on the local environment by a heat pump will always be smaller compared to an LPG or diesel fuel plant, because the electricity generation plants are placed rarely in these zones.

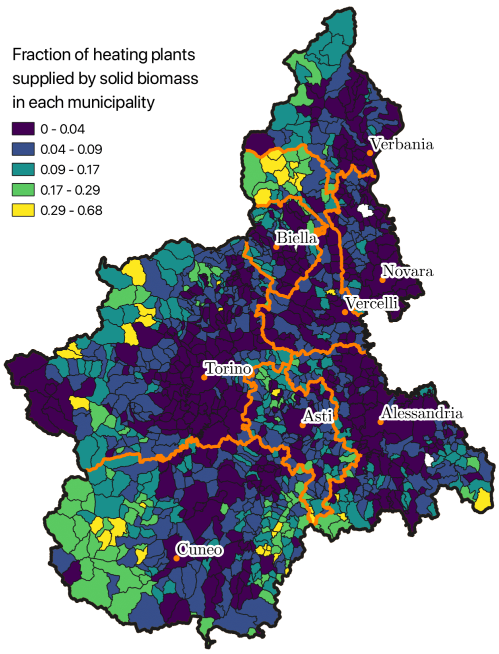
In urbanized territories, natural gas is far more common. Nevertheless, at the same time, the situation concerning polluting emissions is generally more severe. Therefore, if economically feasible, the switch with heat pumps is recommended.



(a) *LPG*



(b) *Diesel fuel*



(c) *Solid biomass*

Figure 1.14: Fraction of heating plants supplied by LPG, diesel oil and solid biomass in each municipality, elaboration of data obtained from [9, 12].

1.5 Air quality and regional monitoring system

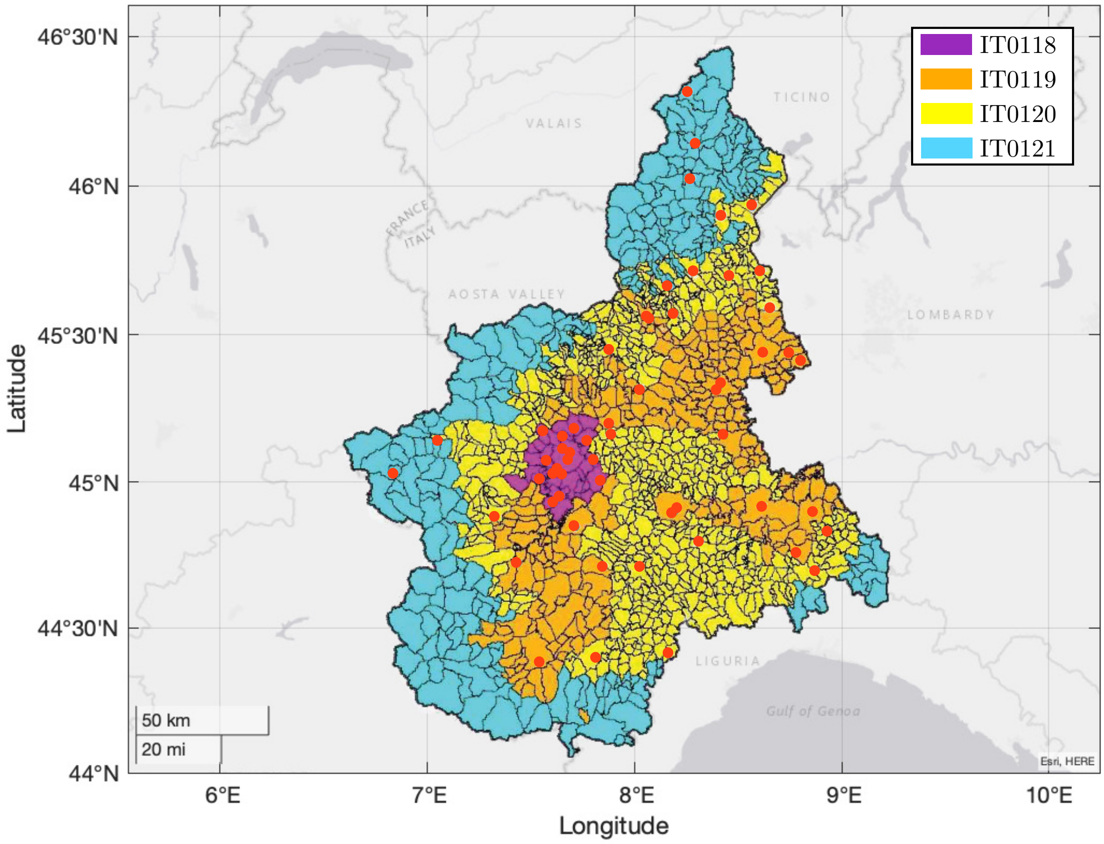


Figure 1.15: Geographical distribution of pollutants monitoring stations (red dots), elaboration of data obtained from [13] and the D.G.R. 29 December 2014, n. 41-855.

The air quality analysis is based fundamentally on two pollutants: particulate matter smaller than 10 μm (PM_{10}) and nitrogen dioxide (NO_2). The reason is that they are the most impacting substances in Piedmont, according to [6]. As a matter of fact, also the study about the zoning of the Piedmont territory was based on these two pollutants, as reported in Subsection 1.2.2.

The data of pollutant concentrations are available on the Sistemapiemonte platform [13], and the regional monitoring system supplies them. It consists of about 81 monitoring stations [6]. In more detail, 54 public and 5 private stations provide data about NO_2 and PM_{10} [13]. The geographical position of every station is shown in Figure 1.15. The mountainous zone is the one with fewer stations by far, whereas the others are quite comparable. The largest density stays in the Turin built-up area, of course, since its width is significantly smaller compared to the

Zone	Total monitoring stations	Stations exceeding			
		Average hourly PM_{10} limit	Average hourly NO_2 limit	Average yearly PM_{10} limit	Average yearly NO_2 limit
IT0118	15	9	0	0	10
IT0119	20	7	0	0	16
IT0120	18	1	0	0	7
IT0121	6	0	0	0	2

Table 1.13: Number of monitoring stations of PM_{10} and NO_2 per zone and how many exceed the limits, elaboration of data obtained from [13] and the D.G.R. 29 December 2014, n. 41-855.

others. However, monitoring stations are widespread all over the region.

The measurement of the particulate matter happens through a 24-hours collection on a filter in standardized conditions. Then, the analysts perform a gravimetric determination of filtered powders. Besides, some "beta" analyzers of PM_{10} have been bought during the years. The mass of the particulate is determined by measuring the attenuation of low β radiations produced by a radioactive source inside the instrument. In more detail, the rays cross a filter. After 24 hours, the difference in the absorption of beta rays by the filter is proportional to the concentration of PM_{10} in the sample [14].

Instead, nitrogen oxides are analyzed through a chemiluminescence method. If the nitrogen monoxide reacts with ozone, the reaction produces a peculiar luminescence whose intensity is proportional to the NO concentration. This test is specific for the nitrogen monoxide, so a molybdenum converter has to transform nitrogen dioxide into nitrogen monoxide. Then, the measure of NO is carried to the original NO_2 quantity [15].

The D.Lgs. 155 of 13/08/2010 is the regulatory reference on this topic. It establishes some limit values:

- For PM_{10} concentrations:
  - The 24-hour limit value for the protection of human health. The daily average of PM_{10} concentrations must not exceed the value of 50 μg/m^3 more than 35 times per calendar year;
  - The annual limit value for the protection of human health. The annual average of PM_{10} concentrations must not exceed 40 μg/m^3;
- For NO_2 concentrations:

- The hourly limit value for the protection of human health. The hourly average of NO_2 concentrations must not exceed the value of 200 $\mu g/m^3$ more than 18 times per calendar year;
- The annual limit value for the protection of human health. The annual average of NO_2 concentrations must not exceed the value of 40 $\mu g/m^3$.

Figure 1.16 and Table C.1 shows that the highest concentration, and therefore emissions, of PM_{10} happens in the cities. All Turin monitoring stations are out of limits. Also, two stations over fives in the suburbs do not respect the values. Then, in other county seats, the limits are generally not respected, such as in Alessandria, Asti, and Vercelli. Table 1.13 highlights that the Turin built-up zone and the Plain zone are the most polluted areas where the limits are mostly exceeded, as expected. On the other hand, areas in the Mountain zone do not have polluting issues at all concerning this aspect. Concerning the annual limit, any measurement never overcomes it (see Figure 1.18 and Table C.2).

Regarding nitrogen dioxide, the situation is quite different. Figure 1.19 and Table C.1 shows that the hourly values are exceeded only in three stations. And only Torino - Rebaudengo more than one. However, the exceeding days are far under the law limits of 18 days per year. On the other hand, the annual limits are overcome by a vast majority of areas (see Figure 1.21 and Table C.2).

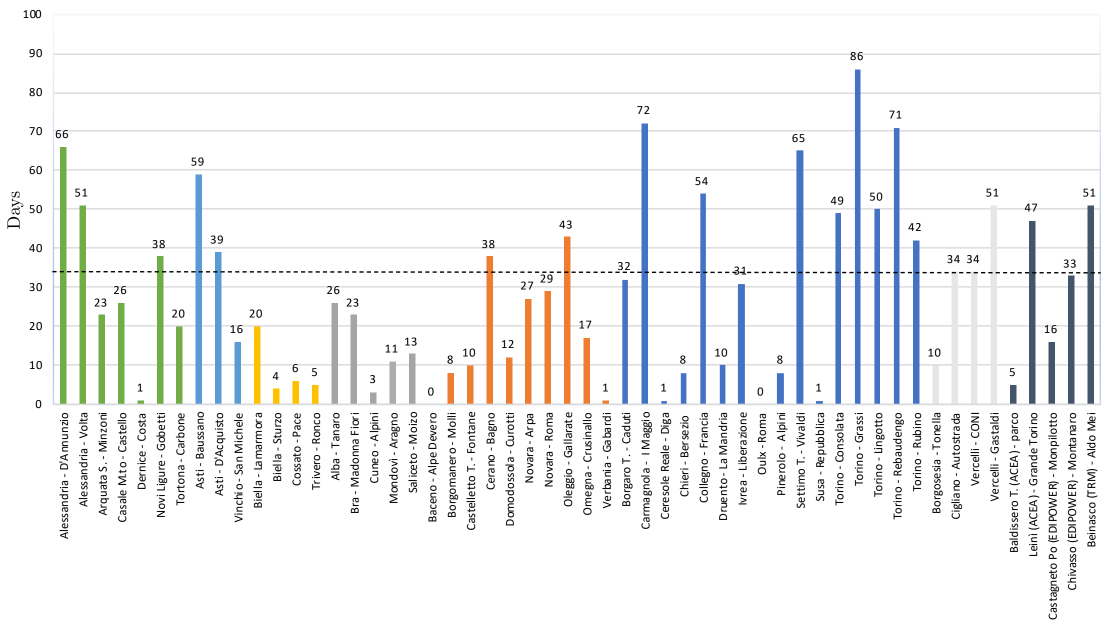


Figure 1.16: Days exceeding the 24-hour limit for PM_{10}, elaboration of data obtained from [13].

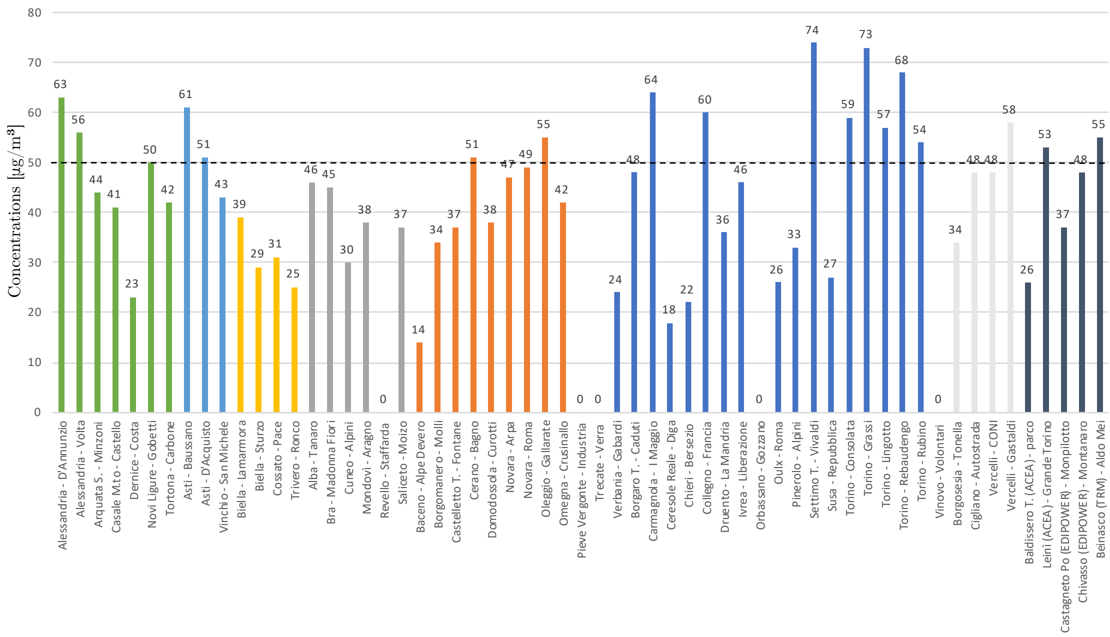


Figure 1.17: Value of the 36th higher exceeding concentration of PM_{10} for each monitoring station, elaboration of data obtained from [13].

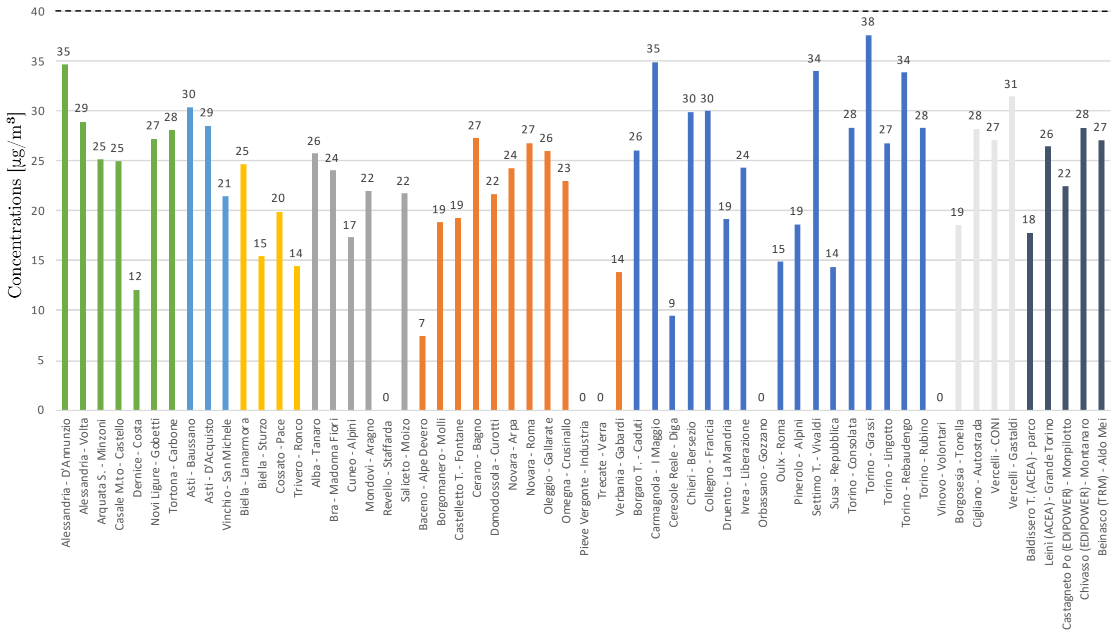


Figure 1.18: Average yearly concentrations of PM_{10}, elaboration of data obtained from [13].

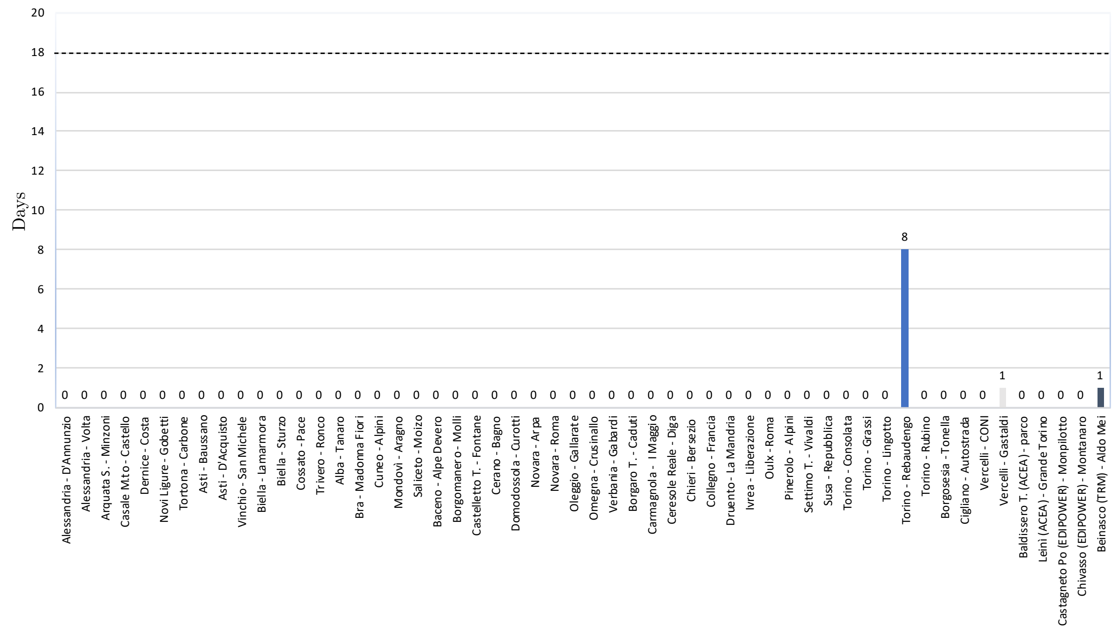


Figure 1.19: Days exceeding the hourly limit for NO_2, elaboration of data obtained from [13].

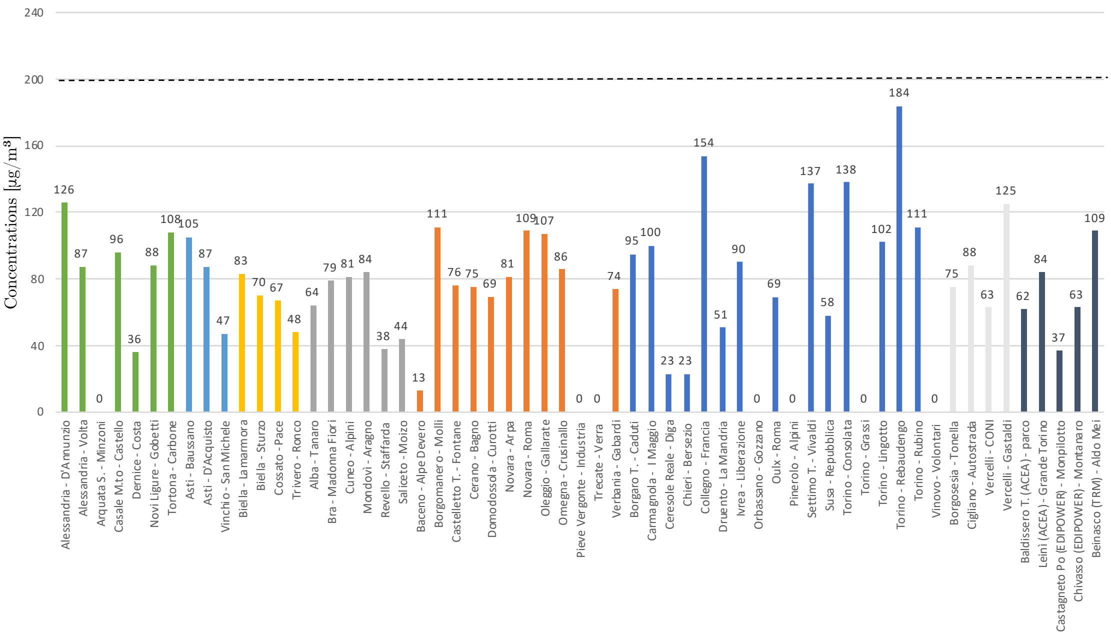


Figure 1.20: Value of the 19th higher exceeding concentration of NO_2 for each monitoring station, elaboration of data obtained from [13].

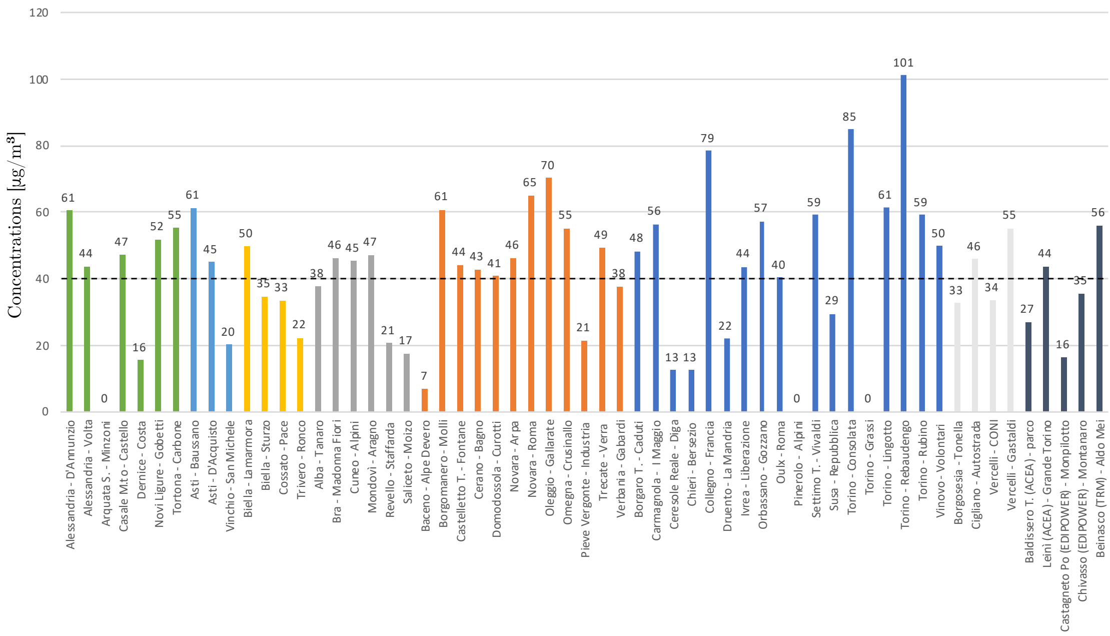


Figure 1.21: Average yearly concentrations of NO_2, elaboration of data obtained from [13].

Chapter 2

Technical aspects of heat pump installations

This chapter aims to present the heat pumps as an alternative to traditional systems for supplying the requested energy services to the zones not reached by methane pipelines. Section 2.1 introduces the operating functioning of heat pumps, whereas Section 2.2 concerns the main performance parameters in more detail. Section 2.3 and Section 2.4 analyze the two main problems related to heat pump applications: the matching with existing terminals and the issues due to the cold climates or low outdoor temperatures, respectively. Then, Section 2.5 is an overview of the other possible issues that a heat pump installation may entail.

2.1 Overview on heat pumps

There are many advantages to consider heat pumps as the technical solution for heating in residential buildings. Above all, the electric power used to run them is often cheap and greener than other fuels, such as natural gas. Besides, heat pumps can supply heating, cooling, and domestic hot water (DHW). Figure 2.1 is a representation of a very simply air-to-water plant. There are three different circuits in this system: in the first, outdoor air heats the refrigerant in the heat pump, the second increases the temperature of the water that circulates in the heating medium circuit, namely the third, which supply heating and DHW. Although there are lots of different installations typologies that vary depending on the number of circuits, the type of source (air or ground), the energy services supplied (heating, cooling, and DHW), etcetera, the idea behind is fairly the same of this diagram.

The revenue of the heat pump vending sector was about 1.5 billion euros in 2018, with an increase of 11% compared with the previous year. The number of heat pumps sold is usually one million, but the last record was 1.4 million in 2018 [17].

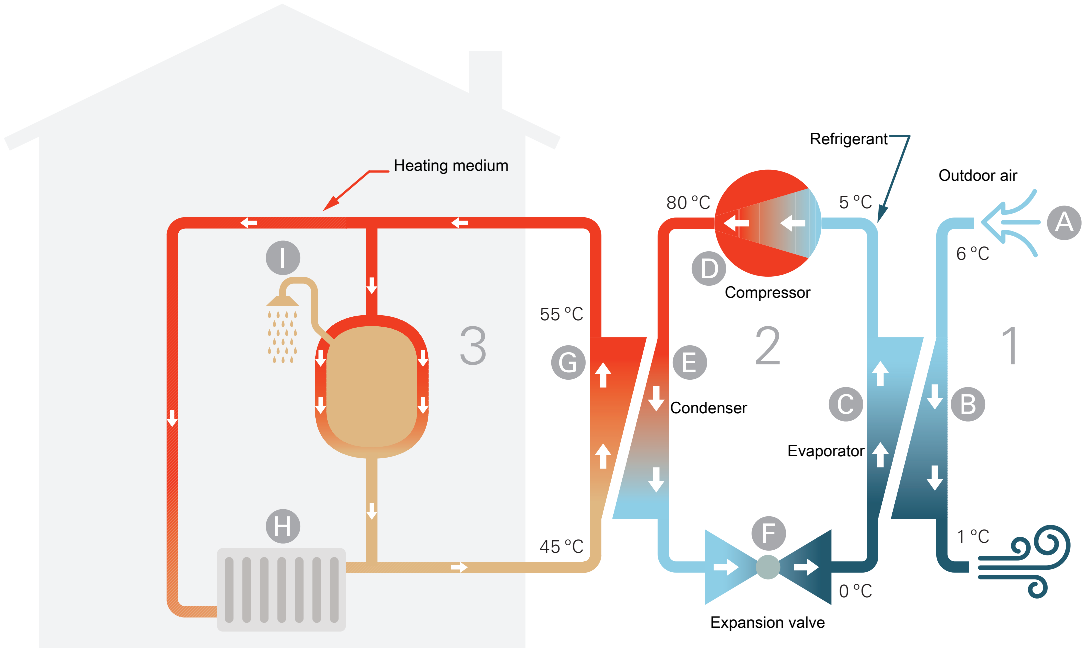


Figure 2.1: Conceptual diagram of an air-to-water heat pump. The temperatures are only examples and may vary between different installations and time of year [16].

However, although the choice of heat pumps in new houses is rising, it is not the same for renovating. In this case, the number of consumers choosing heat pumps is still low [18]. The reasons are two essentially:

- External issues related to the context of installation;
- Intrinsic issues related to the heat pump technology itself.

For instance, the previous plant to substitute, the existing pipe dimensions, the heating terminals types, the poor insulation, etcetera, represent some likely external issues. They can be defined as external in the sense that they do not depend on the heat pump itself, but on previous installations. In any case, the new installer has to face them to reduce their impact on the heat pump performances. On the other hand, an example of an intrinsic issue is the difference in performance between an aerothermal heat pump and a geothermal one. The latter usually has a higher coefficient of performance (COP) because the temperature of the ground or the groundwater (the heat source) is more constant throughout the year compared to air. Anyhow, external and intrinsic problems are strictly correlated. For instance, the temperature may also be considered as an exterior issue. The reason is that it mainly depends on the site where the heat pump is located, although the selection of a specific heat pump typology may change the source, then the temperature of interest. That's why sometimes the solution to one kind of issue solves another, as well.

According to [19], the most effective retrofit options are the insulating improvements, the installation of high-efficiency heating systems, and the usage of renewable energy sources. In this context, a heat pump may be a suitable option. However, as mentioned above, some obstacles make the heat pumps quite hard to place, at least at first instance.

In any case, according to [10], the installation of a heat pump connected system has generally to consider the following aspects to be as much effective as possible:

- High building quality and improved insulation to reduce energy demand;
- The capacity of the heated pump well matched to the heating demand of the house to prevent overuse of the immersion heaters and excessive on-off cycles;
- Correct sizing of boreholes and trenches in order to avoid ground freezing in case of GSHPs;
- Pumps must be charged with the exact necessary amount of refrigerant (or brine), and possible leakages must be entirely avoided;
- The temperature of heating circuits must be set to the minimum comfortable value, and the occupants should be aware of what happens if it is increased;
- Optimization of algorithms and operating modes in order to attenuate parasitic losses as possible and to control the defrost of ASHPs.

2.2 Performance parameters

To make any quantitative consideration about these issues, it is important to define a parameter that takes into account the units of heat that a heat pump produces starting from a unit of electric power. This index is the above-mentioned coefficient of performance (COP), which is defined as:

$$\mathrm{COP} = \frac{Q_{\mathrm{HP,heating}}}{E_{\mathrm{HP}}} \tag{2.1}$$

where $Q_{\mathrm{HP,heating}}$ stands for the heat produced and E_{HP} for the energy consumption, according to EN 14511:1-2018. It is dimensionless (kW/kW), and it is a steady-state measurement. It is tested at 7 °C dry bulb external temperature and at 20 °C indoor temperature, whereas the output of the pump is 35 °C for air-to-air units, according to EN 14511:2-2018, which also deals with other typologies and operating conditions. While the heat pump works in cooling mode the coefficient is called energy efficiency ratio (EER) and is defined as:

$$\mathrm{EER} = \frac{Q_{\mathrm{HP,cooling}}}{E_{\mathrm{HP}}} \tag{2.2}$$

where $Q_{\mathrm{HP,cooling}}$ stands for the cooling capacity provided and E_{HP} for the electricity consumed [20, 21]. It is measured in kW/kW.

Those definitions are typical of Europe whereas testing conditions are slightly different in the US, and the last indicator itself assumes another meaning, according to [10, 22, 23]. The American AHRI (Air-conditioning, Heating & Refrigeration Institute) defines the EER as the system output in Btu/h per watt of electrical energy, and it is the equivalent of COP nothing but in imperial measures. The correlation with the European COP is:

$$\mathrm{EER} = 3.41213 \cdot \mathrm{COP} \tag{2.3}$$

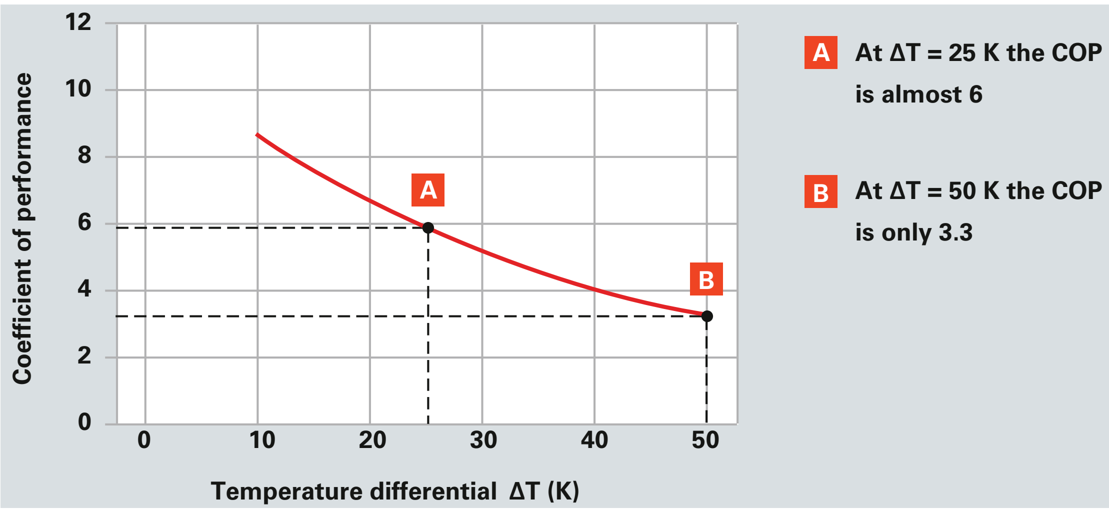


Figure 2.2: Temperature differential and coefficient of performance [24].

The performance of a heat pump depends extremely on what Staffell et al. [10] calls the "lift", namely the difference in temperature (ΔT_{lift}) between the water outlet from the HP to the heating or cooling system and the outdoor air or the ground source. In other words, the lower the temperature differential between the heating circuit flow temperature and the heat source inlet temperature, the higher the coefficient of performance. The following rule of thumb applies [24]:

- Flow temperature 1 K lower, COP 2.5% higher;
- Source temperature 1 K higher, COP 2.7% higher.

In practice, the COP loss varies from 0.6 to 1.0 per 10 °C interval. For instance, operation point A in Figure 2.2 shows a COP of 6 with a $\Delta T_{\text{lift}} = 25\,°\text{C}$ and point B only 3.3 with $\Delta T_{\text{lift}} = 50\,°\text{C}$. Then it is easy to understand why the goal is to reduce the discrepancy between the two values as much as possible. Since manufacturers are obligated to communicate a single value of COP for each model, it is not always easy to deduce the real performance of a machine from its technical sheets. However, several companies are used to publish more than one value of COP and, considering field researches as well, Staffell et al. [10] have been able to obtain the following relations for COPs depending on the "lift":

$$\text{COP}_{\text{ASHP}} = 6.81 - 0.121 \cdot \Delta T_{\text{lift}} + 0.000630 \cdot \Delta T_{\text{lift}}^2 \quad \text{for } 15 \leq \Delta T_{\text{lift}} \leq 60 \tag{2.4a}$$

$$\text{COP}_{\text{GSHP}} = 8.77 - 0.150 \cdot \Delta T_{\text{lift}} + 0.000734 \cdot \Delta T_{\text{lift}}^2 \quad \text{for } 20 \leq \Delta T_{\text{lift}} \leq 60 \tag{2.4b}$$

Instead, Mouzeviris and Papakostas [25] propose:

$$\text{COP}_{\text{ASHP}} = 7.378 - 0.1534 \cdot \Delta T_{\text{lift}} + 0.001 \cdot \Delta T_{\text{lift}}^2 \quad \text{for } 15 \leq \Delta T_{\text{lift}} \leq 65 \tag{2.5a}$$

$$\text{COP}_{\text{GSHP}} = 9.908 - 0.2172 \cdot \Delta T_{\text{lift}} + 0.0015 \cdot \Delta T_{\text{lift}}^2 \quad \text{for } 15 \leq \Delta T_{\text{lift}} \leq 65 \tag{2.5b}$$

Furthermore, they also suggest some relations for the EER:

$$\text{EER}_{\text{ASHP}} = 5.8115 - 0.154 \cdot \Delta T_{\text{lift}} + 0.0014 \cdot \Delta T_{\text{lift}}^2 \quad \text{for } 5 \leq \Delta T_{\text{lift}} \leq 40 \tag{2.6a}$$

$$\text{EER}_{\text{GSHP}} = 7.4433 - 0.199 \cdot \Delta T_{\text{lift}} + 0.0015 \cdot \Delta T_{\text{lift}}^2 \quad \text{for } 5 \leq \Delta T_{\text{lift}} \leq 40 \tag{2.6b}$$

For a particular installation, the Seasonal Performance Factor (SPF or SCOP, Seasonal Coefficient of Performance) is more representative of the effective functioning of the equipment. The reason lies in the fact that SPF takes into account not only steady-state conditions of operation but also the outdoor temperature. That's why it can not be easily compared among different heat pumps by different companies. Anyhow, it is truly illustrative of the annual performance of a heat pump. It is defined as:

$$\text{SPF} = \frac{Q_{\text{HP,heating}} + Q_{\text{aux}}}{E_{\text{HP}} + E_{\text{aux}} + E_{\text{fan}} + E_{\text{defrost}}} \tag{2.7}$$

where the further terms with respect to COP are the production and consumption by auxiliary heaters (Q_{aux} and E_{aux}), the electricity used to circulate the coolant loop or outdoor air (E_{fan}) and to defrost ASHP systems (E_{defrost}). As well as for COP, there is a seasonal relative parameter also for EER, i.e. the Seasonal Energy Efficiency Ratio (SEER), which Americans consider an alternative of SPF instead of a cooling mode parameter.

According to [10], the average annual SPF of a heat pump (SPF) can be actually calculated by weighting the COP for each period by the electricity consumed in that period (E_i):

$$\text{SPF}_{\text{HP}} = \frac{\sum_i \text{COP}(\Delta T_{\text{lift},i}) \cdot E_i}{\sum_i E_i} \tag{2.8}$$

Since $E = Q/\mathrm{COP}$, the previous relation can be expressed by means of the heat demand of the property (Q_i), which is easier to evaluate directly:

$$\mathrm{SPF_{HP}} = \frac{\sum_i Q_i}{\sum_i Q_i/\mathrm{COP}(\Delta T_{\mathrm{lift},i})} \tag{2.9}$$

Then the SPF of the overall system is defined as:

$$\mathrm{SPF_{sys}} = \frac{\mathrm{SPF_{HP}}}{1 + e_{\mathrm{aux}} + e_{\mathrm{frost}}} \tag{2.10}$$

where e_{aux} stands for the fraction of electricity required by the auxiliary heaters and e_{frost} by the defrosting. Alternatively, it can also be computed as:

$$\mathrm{SPF_{sys}} = \frac{\mathrm{SPF_{HP}}}{1 + (\mathrm{SPF_{HP}} - 1) \cdot q_{\mathrm{aux}} + e_{\mathrm{frost}}} \tag{2.11}$$

considering the heat delivered by the back-up heater (q_{aux}) multiplied by a suitable coefficient to take into account the smaller efficiency of this kind of systems compared to heat pumps.

Then it is possible to evaluate when the heat pump is more convenient with respect to a condensing boiler. The comparison can be made computing the minimum SPF that the heat pump must satisfy. This index is defined as:

$$\mathrm{SPF_{min}} = \frac{\eta_{\mathrm{heater}}}{\eta_{\mathrm{grid}} \cdot \eta_{\mathrm{trans}}} \tag{2.12}$$

where η_{heater} stands for the efficiency of the condensing boiler, η_{grid} for the efficiency of central electricity-producing plants, η_{heater} is complementary to the unit of the transmission and distribution losses. It is important to notice that the efficiency of condensing boilers is often computed with respect to the LHV obtaining values bigger than 100%. This is convenient for the manufacturers since their products seem very efficient, but it is not strictly correct thermodynamically speaking. However, the efficiency of these machines is very high also with respect to HHV, up to 95.4% [26]. Then the efficiency of central electricity-producing plants is 38.9% on average [10], whereas the transmission and distribution losses are about 7.4% in Italy [27] so the efficiency is 92.6%. Therefore the minimum SPF must be higher than about 2.6 in Italy.

2.3 Matching with heating terminals

Since the SIPEE database does not include a specific classification of terminals, it is worth considering all main types of them that may be present in a residential building and their relative operative temperatures [10]:

- Direct air heating (25-35 °C);

- Underfloor heating (30-45 °C);
- Large-area radiators (45-60 °C);
- Conventional radiators (60-75 °C).

The last item is probably the mainly widespread technology considering the existing building stock, but it is not always perfectly suitable with heat pumps. That's why some expedients are necessary, as explain below. The other solutions have advantages and drawbacks, too.

2.3.1 Conventional radiators

An installer can often come across into old heating terminals, such as hot temperature radiators, which require a very high inlet temperature (65-70 °C, or even more). Heat pumps can reach a maximum of 60 °C, especially old models [10], but the newest can achieve flow temperatures up to 70 °C [24]. If anything, these should only be utilized for DHW heating because, although they can work without an auxiliary heater or something equivalent, this is possible only with a reduction of efficiency and a rise in running costs. Therefore, for heat pumps operating in mono mode, system temperatures in excess of 55 °C should be avoided [24, 28].

The traditional simplest solution is to add a back-up heater that increases the water temperature to the desired value. Nevertheless, these kinds of systems are not efficient enough. Therefore, if they have to be run frequently, they would increase the operational cost of the systems [10]. That being so, the heat pump is not convenient anymore.

The best way to operate is to consider the inlet and outlet temperature of both the heat pump and the radiator and the ambient temperature. According to Myhren and Holmberg [29], the two main parameters related to this topic are:

- The difference between the inlet and the outlet temperature of the radiator:

$$\Delta T = T_{\text{water,in}} - T_{\text{water,out}} \tag{2.13}$$

- The mean temperature difference between the radiator surface and the room ambient air:

$$\Delta T_{\text{m}} = \frac{T_{\text{water,in}} - T_{\text{water,out}}}{\ln\left(\frac{T_{\text{water,in}} - T_{\text{air}}}{T_{\text{water,out}} - T_{\text{air}}}\right)} \tag{2.14}$$

Concerning the first item, it is necessary to highlight that the majority of heat pumps are designed to work with a 5 °C temperature difference between inlet and outlet. On the other hand, the common ΔT that hot temperature radiators are used to exploit is up to four times higher, usually 20 °C. In order to provide a certain amount of heat, bigger is the ΔT lower is the necessary flow rate, since the thermal power balance is:

$$\dot{m} \cdot c_p \cdot \Delta T = k \cdot A \cdot \Delta T_{\mathrm{m}} \tag{2.15}$$

where $\dot{m}$ stands for the mass flow of water inside the radiator, c_p for the specific heat capacity of water, k for the total heat transfer coefficient, and A for the area of the radiator surface. For instance, if 16 kW are required, a usual boiler and a heat pump employ very different quantities of water:

$$\dot{m}_{\mathrm{rad}} = \frac{\Phi_{\mathrm{requested}}}{c_p \cdot \Delta T} = \frac{16000\,(\mathrm{W})}{4186\left(\frac{\mathrm{J}}{\mathrm{kg \cdot K}}\right) \cdot 20\,(\mathrm{K})} = 0.1911\,(\mathrm{kg/s}) = 688\,(\mathrm{l/h}) \tag{2.16}$$

$$\dot{m}_{\mathrm{HP,5}} = \frac{\Phi_{\mathrm{requested}}}{c_p \cdot \Delta T} = \frac{16000\,(\mathrm{W})}{4186\left(\frac{\mathrm{J}}{\mathrm{kg \cdot K}}\right) \cdot 5\,(\mathrm{K})} = 0.7645\,(\mathrm{kg/s}) = 2752\,(\mathrm{l/h}) \tag{2.17}$$

A partial solution is not to directly connect the heat pump and the radiator. An inertial storage tank is usually installed in order to separate the primary circuit, which serves the heat pump, and the secondary circuit, which serves the radiators. This alternative allows a higher ΔT in the secondary circuit, which halves the flow rate required:

$$\dot{m}_{\mathrm{HP,10}} = \frac{\Phi_{\mathrm{requested}}}{c_p \cdot \Delta T} = \frac{16000\,(\mathrm{W})}{4186\left(\frac{\mathrm{J}}{\mathrm{kg \cdot K}}\right) \cdot 10\,(\mathrm{K})} = 0.3822\,(\mathrm{kg/s}) = 1376\,(\mathrm{l/h}) \tag{2.18}$$

However, this solving is not always efficient because the diameter of the existing water pipes could not be large enough. The issue is rare on the connection between the heat pump and the manifold because the pipes used in this case are usually between 20 and 30 mm, if copper-made, or until 32 mm, if multilayered [30]. These diameters, coupled with flow rate like the result of Equation 2.18, usually allow reaching the energy demand of the building. The problem usually lies in the connection between the manifold and every radiator. The pipes devoted to this purpose have a smaller diameter, and sometimes they are not large enough to supply the needed quantity of water.

Another issue is the performance of the radiators itself. According to the EN 442-2:2014, the heat power output of a radiator is calculated as follows:

$$\Phi = K_{\mathrm{m}} \cdot \Delta T_{\mathrm{m}}{}^{n} \tag{2.19}$$

where K_{m} is the constant of the model, and n is the exponent of the characteristic equation (obtained from experimental results applying the method explained in Annex C of EN 442-2:2014). The coefficient K_{m} is determined as:

$$K_{\mathrm{m}} = \frac{\Phi_{50}}{50^{n}} \tag{2.20}$$

where Φ_{50} is the reference heat power output usually given by the manufactures and computed with $\Delta T_\mathrm{m} = 50\,°\mathrm{C}$. The logical consequence is that the higher is the ΔT_m, the larger is the amount of heat transferred. Nevertheless, the reason for the choice of a reference ΔT_m equal to 50 °C is the fact that radiators have been conventionally coupled with boilers, which work with higher temperatures than heat pumps. A large ΔT_m is difficult to reach with the ΔT typical of heat pumps, also considering that the mean ambient room temperature is usually assumed equal to 20 °C. This aspect entails a decrease in the intrinsic performance of the radiator.

Depth (mm)	Height (mm)	Thermal emission per element with the following ΔT_m (W)				
		30 °C	35 °C	40 °C	50 °C	60 °C
95	558	40	48	57	76	97
	680	46	56	67	90	114
	870	56	68	81	109	138
130	558	48	59	70	93	118
	680	57	70	83	112	143
	870	70	86	102	138	175
160	558	58	71	85	114	144
	680	69	85	101	136	173
	870	84	103	123	166	211

Table 2.1: Typical thermal emissions of cast iron radiators [31].

Depth (mm)	Height (mm)	Thermal emission per element with the following ΔT_m (W)				
		30 °C	35 °C	40 °C	50 °C	60 °C
95	580	65	81	96	130	164
	680	74	92	110	147	188
	870	92	133	135	183	234

Table 2.2: Typical thermal emissions of aluminum radiators [31].

It is critical to quantify the worsening a heat pump can cause from this point of view. To make a quick comparison, Tables 2.1 and 2.2 report the performance of the most widespread types of radiators, i.e. cast iron and aluminum radiators. As mentioned above, a high ΔT_m guarantees a large amount of heat transferred. For instance, $\Delta T_\mathrm{m} = 50\,°\mathrm{C}$, which is typical of radiators coupled with traditional boilers (about 75 °C inlet and 65 °C outlet temperature), supplies approximately twice the heat of $\Delta T_\mathrm{m} = 30\,°\mathrm{C}$. $\Delta T_\mathrm{m} = 30\,°\mathrm{C}$ implies a mean radiator temperature of 50 °C, which can be obtained through an inlet temperature of 52.5 °C and an outlet of 47.5 °C, or through 55 °C and 45 °C, depending on the ΔT chosen between inlet and outlet (usually 5 or 10 °C, as previously discussed). This is the highest value that a heat pump-coupled solution can achieve. As a rule of thumb, the emission of a radiator may be corrected by a factor equal to 0.507 if $\Delta T_\mathrm{m} = 30\,°\mathrm{C}$, 0.398 if 25 °C, and 0.296 if 20 °C, where the coefficient is unitary if $\Delta T_\mathrm{m} = 50\,°\mathrm{C}$ [30]. However, this reduction of the heat transferred per element may be compensated by the improvement of the COP of the heat pump (compared to the efficiency of a boiler) and by the addition of more components in each radiator.

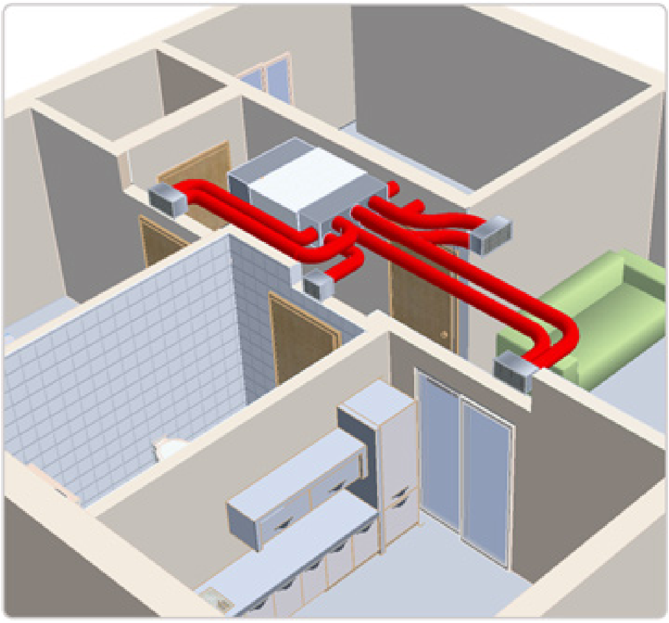


Figure 2.3: Design of an aeraulic plant located in a passageway [32].

Anyway, this addition is rarely sufficient or even possible and the house owner has to carry out other operations, such as improving the thermal insulation of the house and reducing the energy demand or substituting old pipes. Nevertheless, they are obviously extremely intrusive actions and should be avoided. That's why the smarter and easiest alternative is probably an aeraulic plant. It is able to integrate the heating demand and, if necessary, to supply summer cooling. This improvement requires only a false ceiling that is not as invasive as other masonry operations. The main part is usually located in the housing passageway, then several ducts supply the conditioned air in every room, as shown in Figure 2.3. Although sometimes these systems can supply all the heating load and substitute totally the old radiators, it is always preferable not to do it. The reasons are essentially two:

- The radiators are usually installed on the perimetrical walls and the occupants feel a better resulting thermal comfort since the temperature gradient is more uniform in the room compared to an only-ventilation system;
- The temperature of air exiting from the mechanical ventilation system has not to be very high, so as not to invalidate the thermal comfort of the occupants by enhancing the temperature gradient.

In addition, the air jet exiting from an aeraulic plant may have not only thermal problems but also speed-related ones. If the velocity is too high, some dust and particles present in the room are recirculated and it is not pleasant for sure.

2.3.2 Novel radiators and other systems

Figure 2.4: Sketch of a ventilation-radiator [29].

A solution to the aforementioned issues may be the ventilation-radiator proposed by Myhren and Holmberg [29]. In this installment, the airflow enters the lower part of the radiator from outside. Then, the rising through the component warms the flow, as shown in Figure 2.4. The fluid is driven partly by the pressure drop between inside and outside, partly flowed by buoyancy forces. The advantage of the ventilation is that it lets the system have lower temperatures to reach the same result in heating the room. The consequence is the rise in COP. For instance, a reduction of the supplied water temperature from 50 to 45 °C increases the COP of the heat pump by about 7-8% (with a specular reduction of electricity consumption). Finally, the most effective ventilation-radiators have a narrow air channel because the higher is the velocity of the fluid, the more efficient is the heat transfer. Nevertheless, too high speed may cause drafts close to the radiator, which may be unpleasant. However, the fresh air supply directly from outdoor reduces Sick Building Syndrome (SBS) symptoms and increases work productivity.

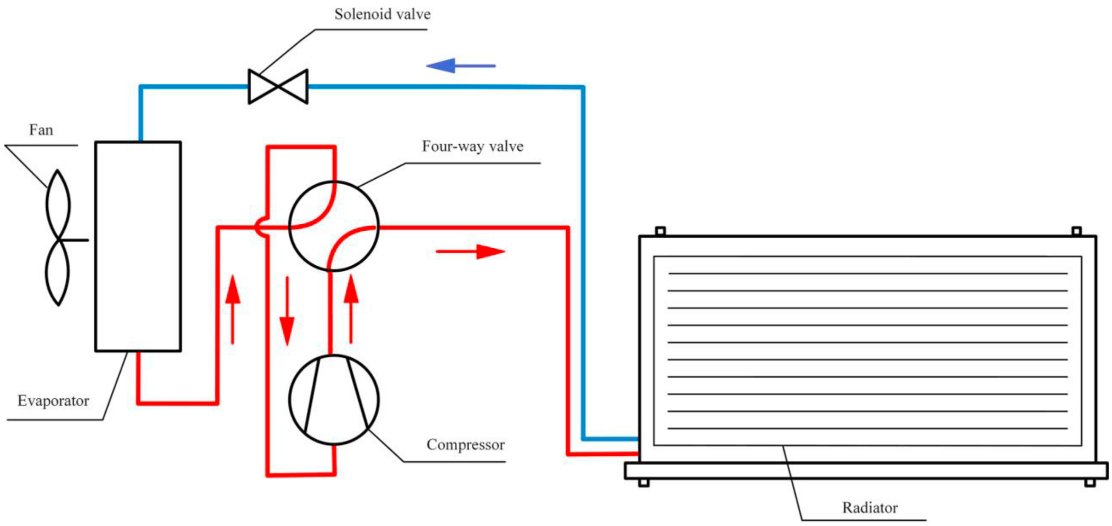
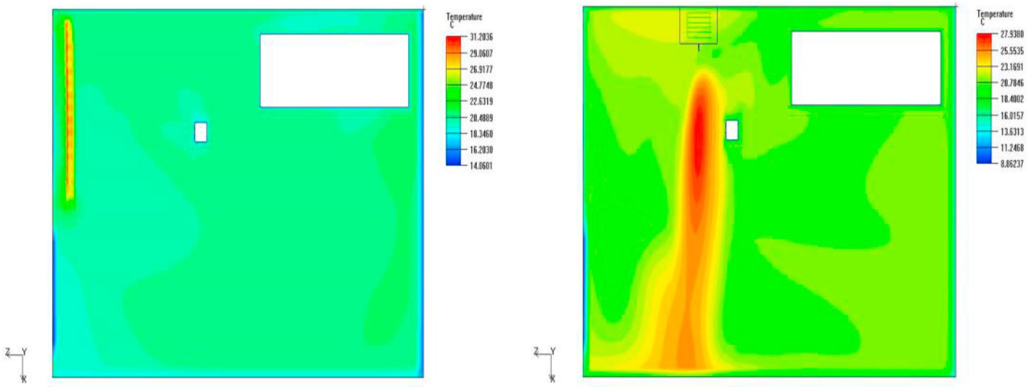


Figure 2.5: Schematic diagram of the RRH system [33].

Shao et al. [33] proposed another innovative heating system that they called "refrigerant-heated radiator heating" (RRH). It works with an air source heat pump. As shown in Figure 2.5, the radiator acts directly as the condenser of the heat pump, and the working fluid is the R410A. They highlighted that this installment has good efficiency and is relatively cheap. Nevertheless, the most interesting analysis of the authors is about thermal comfort. They compared the novel system to a traditional air conditioner heating (ACH) installed on the ceiling. They found that the new solution can guarantee a far more uniform temperature in the room. In this case, the temperature is always between 19.5 °C and 21.5 °C (see Figure 2.6a). Instead, the ACH causes a large temperature gradient, since the temperature can reach 27 °C near the air vent (see Figure 2.6b). This gradient is perceived by any occupant, of course. Therefore, the radiator, if well dimensioned, is better at least from the thermal comfort point of view.

In general, fan-assisted radiators, underfloor heating, ceiling heating with continuous mandatory ventilation, and similar installations are in principle more suitable



(a) *Refrigerant-heated radiator heating* (b) *Air conditioner heating*

Figure 2.6: Horizontal temperature contours at 1.2 m height [33].

to work with heat pumps compared to high-temperature radiators. For instance, fan-assisted radiators can work with 45-60 °C, whereas underfloor heating with 30-45 °C, and fan-coil units with 40-50 °C [25]. In more detail, the reason why the underfloor heating is usually the most indicated technology is very vividly shown in Figure 2.7: an operation temperature of 35 °C guarantees a COP twice higher than 55-60 °C and also with 45 °C the heat pump has an efficiency 1 unit higher with respect to the temperature required by radiators.

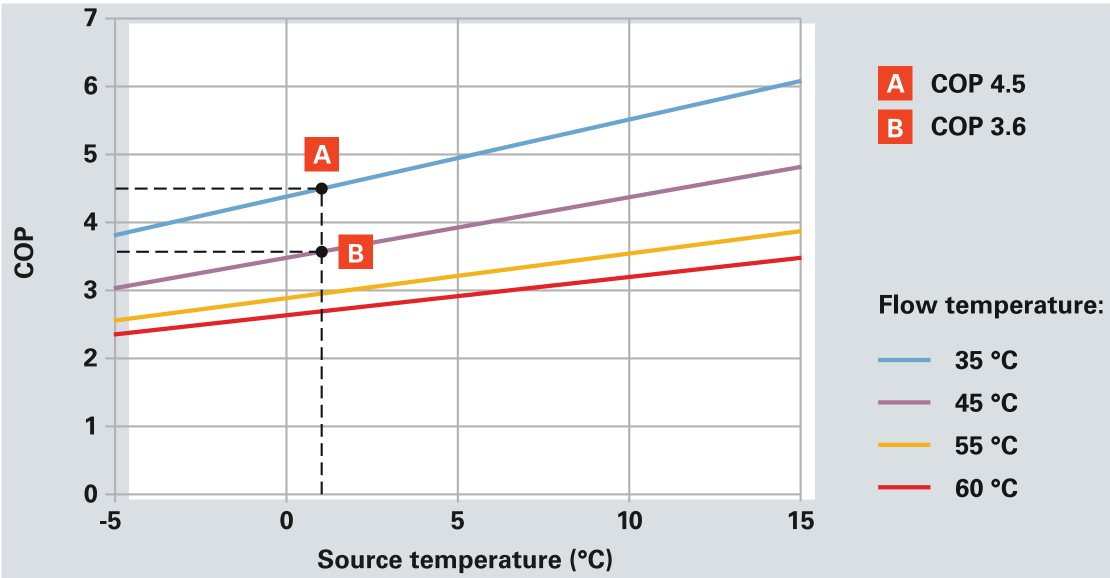


Figure 2.7: Heating circuit flow temperature and efficiency [24].

2.4 Issues due to the installation in cold climates and possible solutions

Heat pumps are not usually able to work with an outdoor temperature that is lower than -15/-25 °C without a deep decrease in performance [10]. This issue affects especially ASHP because the temperature of the source of GSHP is more constant throughout the day or the year. Figure 2.8 reveals that below 7-10 meters underground the temperature varies just by some degrees and beneath 15 meters is almost constant throughout the year. Besides, GSHPs take advantage of the specific heat capacity of the soil or of the water, which is larger (on a volumetric basis) than that of air.

Figure 2.9 is a plot of the average COP of one hundred commercial models and shows that the performance of the GSHP is normally higher than the respective of ASHP, as analytically shown by (2.4a) and (2.4b), which are the polynomial fittings of the curves in the above-mentioned chart. However, this is only a theoretical result since the manufacturers also declare COP equal to 7, which is quite impossible to reach in real applications. Besides, it is difficult to obtain temperature differences so small they can be comparable with the one used in the technical sheets. Field tests prove that the usual efficiencies are 3.0-3.5 for ASHP and 3.3-4.2 for GSHP when operated in real houses [10].

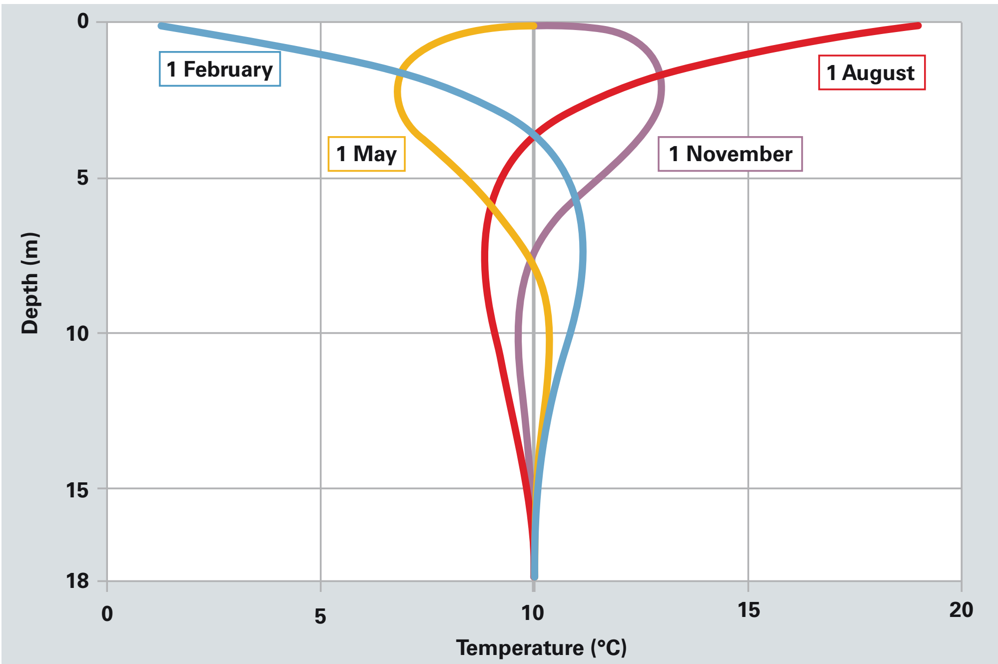


Figure 2.8: Annual temperature curve under ground [24].

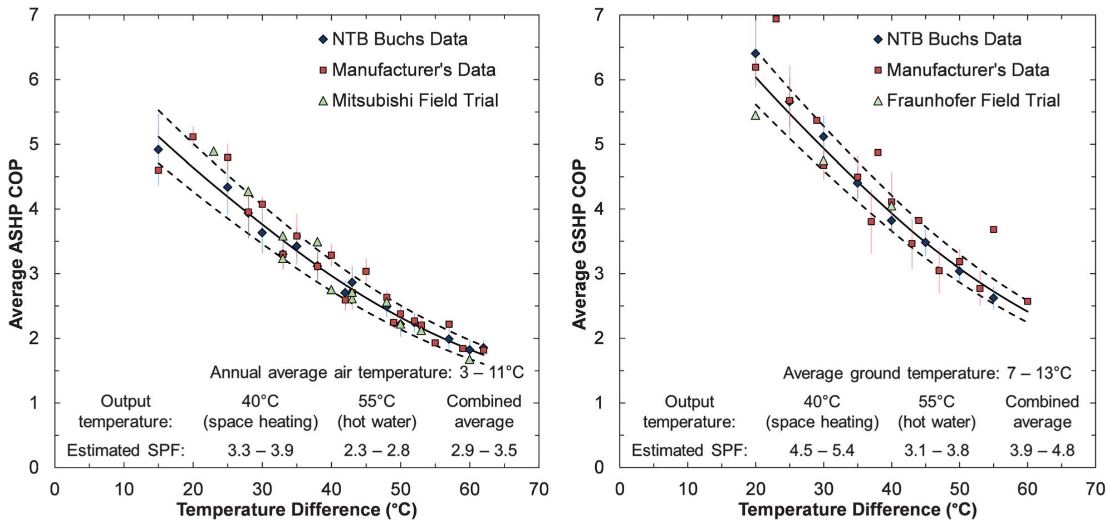


Figure 2.9: Average heating COP for air and ground source heat pumps (left and right, respectively) based on data taken from industrial surveys and field trials [10].

Concerning ASHPs, cold temperatures can cause a heating capacity and COP nosedive because of the freezing effect. This phenomenon consists of the creation of frost on the heat pump evaporator surface. In more detail, it happens when the surface temperature of the evaporator is below the freezing point and the dew point of the moist air, namely the ambient air humidity is higher than the saturation humidity at the surface temperature of the evaporator. Guo et al. [34] subdivided the frost formation process into three distinctive phases:

- In the first phase, water freezes and forms a thin layer on the evaporator surface, then granular ices appears. During this phase, the ice growth rate, the heating capacity, and the COP increases. The reason is that the frost deposition makes the surface rough, then the heat transfer coefficient increments, whereas the air flow rate does not change;
- In the second stage ice grows in radius. During this phase, the ice growth rate, the heating capacity, and the COP slightly decreases or remain constant;
- In the third point, the ice crystals grow in their length and create a fluffy frost layer. Then, the evaporating pressure and wall temperature keep decreasing and the frost layer gets bigger and bigger. Unfortunately, an event provokes the other and vice versa, creating a mutual relationship. This circumstance is an issue since it enhances the thermal resistance between air and fluid, and the heat exchanger does not work well anymore.

These three phases showed up during both simulations and field tests. As shown in

Figure 2.10, the difference between the two is around 8%.

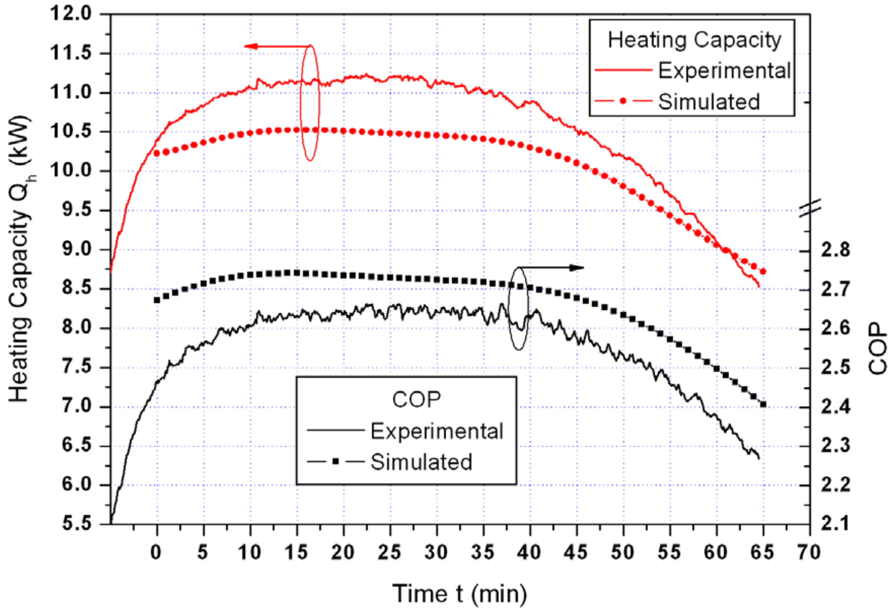


Figure 2.10: Comparison of experimental heating capacity and COP with simulated results under condition of $T_{\mathrm{a,i}} = 0\,°\mathrm{C}$, RH = 75% [34].

Therefore, a system able to thaw it becomes necessary. The most conventional solutions are two:

- Defrost cycle;
- Electric resistance heater.

The first essentially consists of running the machine reversely. Therefore, it has the disadvantage that the occupants feel a lower indoor temperature for some time, and it may be uncomfortable, especially if they are not aware of the exact reason for that. Instead, the drawback of the second solution is the increasing electrical consumption and the related cost, which is not pleasant as well. In any case, the defrosting affects the overall efficiency, but its contribution is extremely hard to quantify. Each manufacturer behaves in different ways: for instance, someone declares COP including these losses, others consider a reduction of performances by 10% or suggest to apply specific coefficients.

Besides, the heating system temperature and, consequently, the heating demand are maximum when the efficiency is minimum, as shown in Figure 2.11. When the outside temperature is low the building requires a great amount of heat to guarantee the comfort of occupants. At the same time, the efficiency of the heat

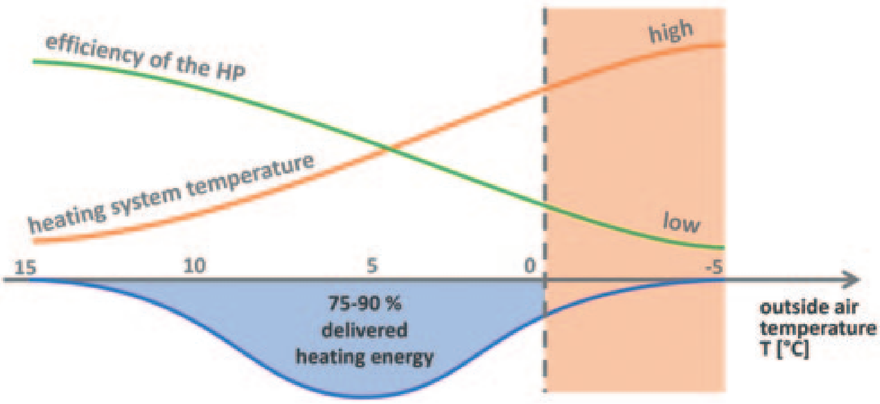


Figure 2.11: Correlation between the heat delivered by an average heat pump, the temperature and the efficiency [18].

pump drops down due to the intrinsic characteristics of the machine. This lacking synchrony is another main issue of a heat pump running in cold climates.

Although the issues concerning cold climate are severe, it is also curious to point out that these phenomena are concentrated in a very short lapse of the heat pump operation time. According to [18], an average heat pump delivers 75-90% of heating energy with an outside air temperature higher than 0 °C. For instance, let us evaluate some sample cities in Piedmont, such as Alessandria, Bardonecchia, Cuneo, and Turin. The choice has been made considering that they may be quite representative of the different climates of the Region. The processing of data by ARPA [35] reveals that the percentage of the year whose minimum daily temperature was below zero in 2019 is 21.37%, 37.26%, 13.97%, and 13.42%, respectively. The mountainous town has the largest share, as expected. In any case, it is necessary to bear in mind that the highest energy demand is in the winter season in a place like Bardonecchia, so this aspect can not be neglected during the heat pump design.

2.4.1 Enhanced air-source heat pumps

The main issues for ASHPs at remarkably low ambient temperature are essentially four [36]:

- Insufficient heat output, since the demand increases while the heat pump capacity decreases. The lower refrigerant mass flow rate exiting the compressor at high-pressure ratios is the main reason for that;
- High discharge temperature from the compressor due to the low suction pressure and the high-pressure ratio across the compressor. Without improvements,

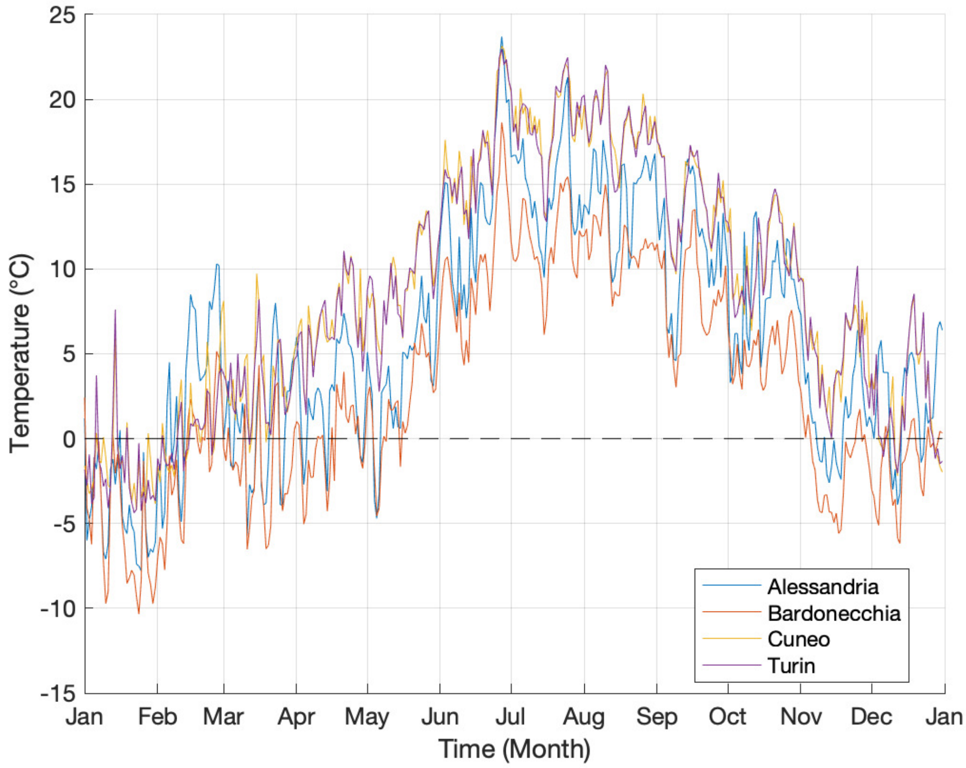


Figure 2.12: Temperature distribution of Alessandria, Bardonecchia, Cuneo and Turin throughout 2019, elaboration of data obtained from [35].

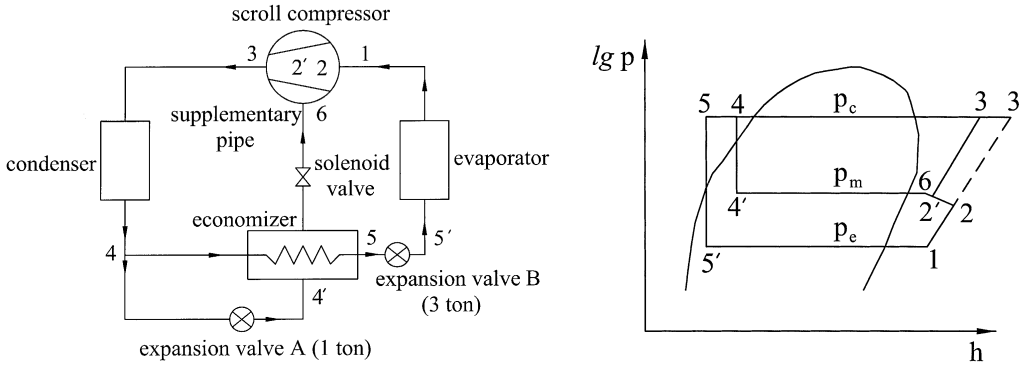
the only solution is to shut down the heat pump for low ambient temperature;

- COP decreasing due to the high-pressure ratio;
- Conventional heat pumps designed for low ambient temperatures usually have a too large capacity at ordinary ambient temperatures.

Scroll compressor and economizer

The innovation proposed by M. Guoyuan et al. [37] is the introduction of a scroll compressor and an economizer, as shown in Figure 2.13. The use of a scroll compressor, which varies the rotary speed depending on the heating load and has liquid-injected inlets, allows the heat pump to perform well even under low ambient temperatures (-10 to -20 °C).

The superheated fluid exiting the compressor is a hot dense vapor at high pressure (state 3). It supplies heat to the water in the condenser and becomes a



(a) *Principle of the ASHP cycle* **(b)** *The cycle in* ln(p)-h *diagram*

Figure 2.13: Enhanced ASHP with scroll compressor and economizer [37].

saturated or sub-cooling liquid (state 4). Then the high pressure cooled refrigerant in the circuit splits in half: one part goes to the expansion valve A, the other directly in the economizer. The former partially vaporizes crossing the valve and becomes chilled (state 4'). Entering the economizer, it absorbs the heat from the fluid that does not overpass the expansion valve. The second fluid is now sub-cooled (state 5), whereas the first flows back into the scroll compressor through the supplementary connection (state 6). Then, the second fluid expands in valve B and enters the third heat exchanger, namely the evaporator. Here, the air heats the refrigerant, which evaporates (state 1). At this point, it comes into the scroll compressor that increases the pressure of the fluid. The compressor mixes the two parts of the refrigerant until the medium pressure is lower than the one in the compression chamber or when the solenoid valve closes the additional circuit. Finally, the scroll compressor compresses the mixed refrigerant to the condensing pressure, starting the cycle again.

When the ambient temperature is relatively high, the prototype works as a conventional heat pump by cutting the solenoid valve off. Instead, when it is under a set point, the valve is open. This possibility expands the operating range improving efficiency. For instance, it can work at -5 °C without severe issues.

The supplementary fluid enters the scroll compressor so quickly that the process can be considered adiabatic. Then, assuming ideal gas, the combination of the first law of thermodynamics and the state equation of ideal gas provides the mass into the compressor. In more detail, the empiric formula of the dimensionless flow rate (α) which travels along the supplementary circuit is:

$$\alpha = \frac{\dot{m}_\mathrm{s}}{\dot{m}_\mathrm{c}} = \frac{\dot{m}_\mathrm{c} - \dot{m}_\mathrm{e}}{\dot{m}_\mathrm{c}} = \frac{\xi \cdot v_2 \cdot (p_\mathrm{m} - p_2)}{R \cdot k \cdot T_6} \tag{2.21}$$

where $\dot{m}_\mathrm{s}$ stands for the mass flow rate of refrigerant in the supplementary circuit (kg/s), $\dot{m}_\mathrm{c}$ for the mass flow rate of refrigerant in the condenser (kg/s) and $\dot{m}_\mathrm{e}$ for the mass flow rate of the evaporator in the evaporator (kg/s), ξ for the resistance factor of refrigerant flowing in the supplementary circuit (it can be determined by the experiment and reflects the error between practical process and ideal process), v_2 for the specific volume of refrigerant in state point 2 (m^3/kg), p_m for the medium pressure or economizer pressure (kPa), p_2 for the pressure of refrigerant in state point 2 (kPa), R for the gas constant for refrigerant (kJ/kg/K), k for the adiabatic index of refrigerant, and T_6 for the refrigerant temperature in state point 6 (K).

Assuming that the process 1-2 is isentropic, the fluid enthalpy in state 2 is:

$$h_2 = h_1 + w_\mathrm{id} \tag{2.22}$$

where w_id stands for the 1-2 isentropic compressing work (kJ/kg). As mentioned before, the supplementary suction is supposed adiabatic, therefore:

$$h_{2'} = \alpha \cdot h_6 + (1-\alpha) \cdot h_2 \tag{2.23}$$

Inferring that also 2'-3 is isentropic:

$$h_3 = h_{2'} + w_\mathrm{ih} \tag{2.24}$$

where w_id stands for the 2'-3 isentropic compressing work (kJ/kg). Therefore, the heating capacity, the cooling capacity and the compressing work capacity are, respectively:

$$\Phi_\mathrm{heating} = \dot{m}_\mathrm{c} \cdot (h_3 - h_4) \tag{2.25a}$$
$$\Phi_\mathrm{cooling} = \dot{m}_\mathrm{e} \cdot (h_1 - h_5) \tag{2.25b}$$
$$P_\mathrm{i} = \dot{m}_\mathrm{c} \cdot h_3 - \dot{m}_\mathrm{s} \cdot h_6 - \dot{m}_\mathrm{e} \cdot h_1 \tag{2.25c}$$

Finally, the heating and cooling efficiencies are, respectively:

$$\mathrm{COP} = \frac{\eta_\mathrm{m} \cdot \eta_\mathrm{mo} \cdot \Phi_\mathrm{heating}}{P_\mathrm{i}} \qquad \mathrm{EER} = \frac{\eta_\mathrm{m} \cdot \eta_\mathrm{mo} \cdot \Phi_\mathrm{cooling}}{P_\mathrm{i}} \tag{2.26}$$

where η_m stands for the mechanical efficiency and η_mo for the motor efficiency.

The authors performed the experimental tests with the prototype in Figure 2.14. They used a glycol solution for the evaporator and water for the condenser. An electric heater regulated the temperature of the solution, while an air flow rate cooled the water through a fan coil unit. The related flow meter and liquid level indicator allow an uncertainty on the quantities of interest of about 2.6%.

Assuming two condensing temperatures (45 and 48 °C), the heating capacity decreases with the reduction of the evaporating temperature. The relation is almost linear, as shown in Figure 2.15a. However, the heat pump at -25 °C still supplies

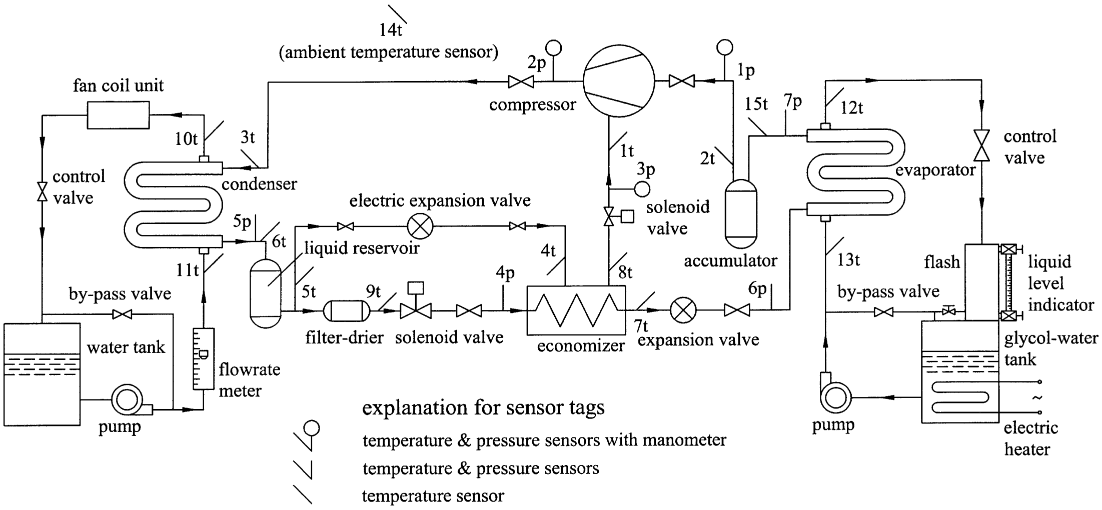
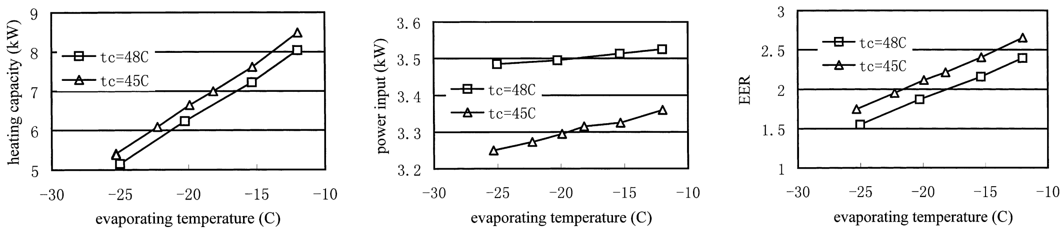


Figure 2.14: Test system and sensor locations for the ASHP prototype [37].



(a) *Heating capacity* **(b)** *Power input* **(c)** *EER*

Figure 2.15: Heating capacity, power input and EER depending on evaporating temperature of the improved ASHP [37].

5.5 kW, which is the typical energy demand in North China, where the minimum ambient temperature is -15 °C. Therefore, the heat pump should work quite well in those conditions. Besides, the graph shows that the heat delivered raises if the water temperature falls. Hence, the reduction of condensing temperature is another possible improvement.

The power input does not vary consistently depending on the evaporating temperature, as shown in Figure 2.15b. The decrease has not a pronounced slope, so the behavior is extremely different from a conventional ASHP. In the last case, the reduction is linear. If the evaporating temperature decreases, the suction pressure in the main circuit drops according to it. Keeping the condensing temperature constant, the pressure ratio borne by the compressor increases correspondingly. Then, the mass flow rate and the power consumption of the compressor decreases with the increase of the pressure ratio. Nevertheless, the flow rate from the supplementary circuit keeps the total mass flow rate exiting the compressor almost the same. Consequently, power input does not vary a lot. Finally, the power input variation is more pronounced if the condensing temperature is lower.

Since the power input varies a little, the EER and the COP have almost the same behavior as the heating capacity, as shown in Figure 2.15c.

However, the improved ASHP is worth the candle unless the evaporating temperature is extremely low. At -15 °C, the heating capacity, the power input, and the efficiency increase by 8.6%, 2.5%, and 6.0%, respectively, compared to the conventional ASHP. At -12 °C, the rise is restricted to 5.5%, 1.6%, and 3.7%, respectively. In conclusion, the solenoid valve should be open only when the evaporating temperature is below -10 °C.

Besides, another advantage of this system is that the supplementary inlet can reduce the discharge temperature of the compressor by 5-6 °C. The reason for the importance is that low discharge temperature is vital to the reliability of the machine.

Two-stage air-source heat pump

Stefan S. Bertsch [38] studied different types of heat pumps and, in the first instance, found out that the cascade cycle, the two-stage cycle with intercooling, and the two-stage cycle with economizing have the best performances at low temperatures (see Table 2.3). Then he tried to figure out which is the best among them with Eckhard A. Groll [36].

Every system analyzed uses R410A as the refrigerant. The condenser works with water, whereas the evaporator with air. The operating temperatures are -20 °C (environment), and 50 °C (hot water supply). The heating capacity is 17 kW. The water flow rate through the condenser is 1500 l/h, which entails a water temperature difference of 16 °C between supply and return. The choice is based not on heat pump optimization criteria, but the demand of inhabitants. A first trial run allows the researchers to find the right design according to heating capacity and efficiency. Then they tested a range of operating conditions to ascertain the different performances of the machine.

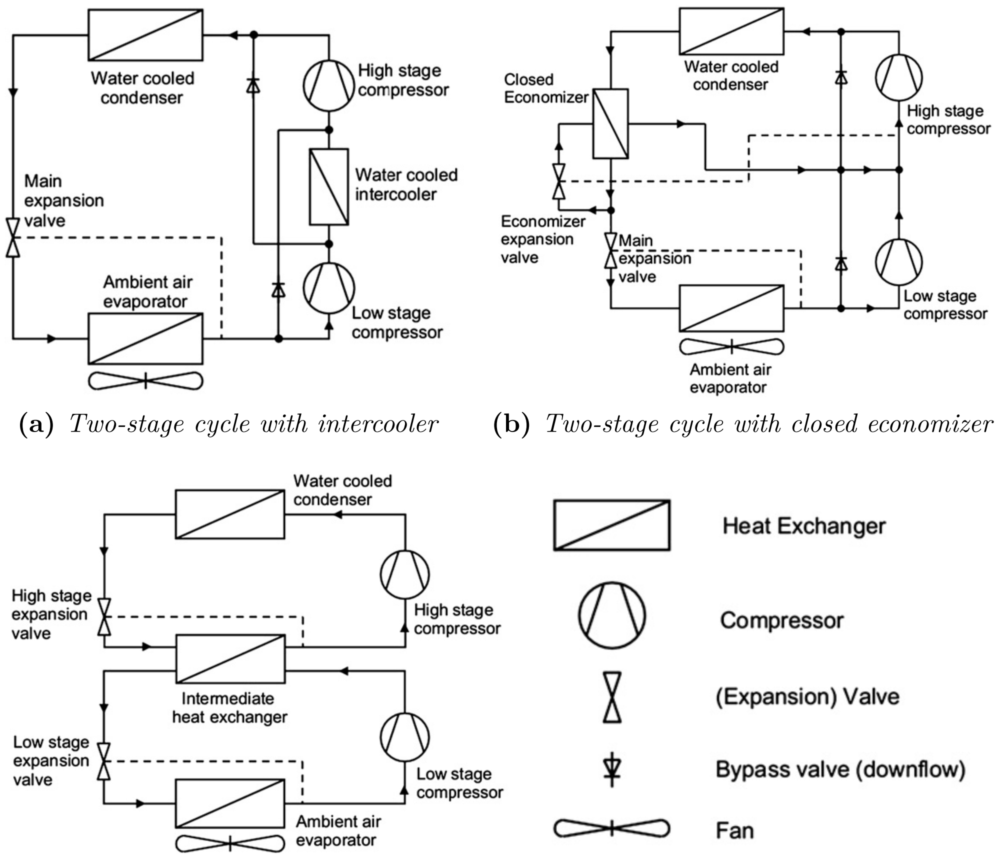
The first solution analyzed is the insertion of an intercooler, as shown in Figure 2.16a. This component is located in the discharge line of the first single-stage compressor, which is the suction line of the second one. Alternatively, a single two-stage compressor can be used with the intercooler. This system allows controlling the discharge temperature of the first compressor before entering the second. This opportunity is not possible without it and allows us to increase the performances at low temperatures. The main drawback is the oil migration. That's why the authors recommend an oil separator or a piece of similar equipment to guarantee the distribution between both compressors.

Concept	Preferred compressor	Heat output steps	Relative efficiency (%)	Relative heat capacity (%)	Discharge temperature
Single-stage cycle	Recip	1	100	100	Too high
Two-stage cycle with intercooler	Two-stage	1	130	100	Acceptable
	Sc, Recip, Rot	3	130	140	Acceptable
Two-stage cycle with economizer	Two-stage	1	130	100	Low
	Sc, Recip, Rot	3	130	150	Low
Cascade cycle	Sc, Recip, Rot	1	140	140	Low
Refrigerant injection	Sc, Screw	2	100	115	High
Oil cooling	Recip, Rot	1	100	100	Acceptable
Mechanical subcooling	Recip, Sc	2	100	120	Too high

Table 2.3: Comparison of different heat pump cycles to a one stage cycle, where "Sc" stands for scroll, "Recip" for reciprocating, "Rot" for rotary, "Two-stage" for two-stage compression in one shell [38].

The second solution is the closed economizer (see Figure 2.16b), which is also proposed by M. Guoyuan et al. [37] and discussed above. This equipment allows controlling the second compressor suction pressure more precisely than the intercooler. At the same time, it can reduce the temperature of the refrigerant before entering the expansion valve, enhancing the system COP. The theoretical intermediate pressure is calculated as the square root of the first compressor discharge pressure and the suction pressure of the latter. This value determines the size of each compressor. Then a testing phase figures out the simulated intermediate pressure by adjusting the refrigerant injection. The goal is to reach a desired superheat value entering the high-pressure compressor.

The greatest benefit of the third solution, which is a cascade cycle (see Figure 2.16c), is the opportunity to use different refrigerants. The point is that performances of low-temperature high-pressure refrigerants, such as R140A, R404A, R507, and CO_2, decline at high temperatures, whereas high-temperature low and intermediate-pressure refrigerants, such as R123 and R134a, fall at low temperatures. Therefore, each of them can work in the optimal range of operating conditions.

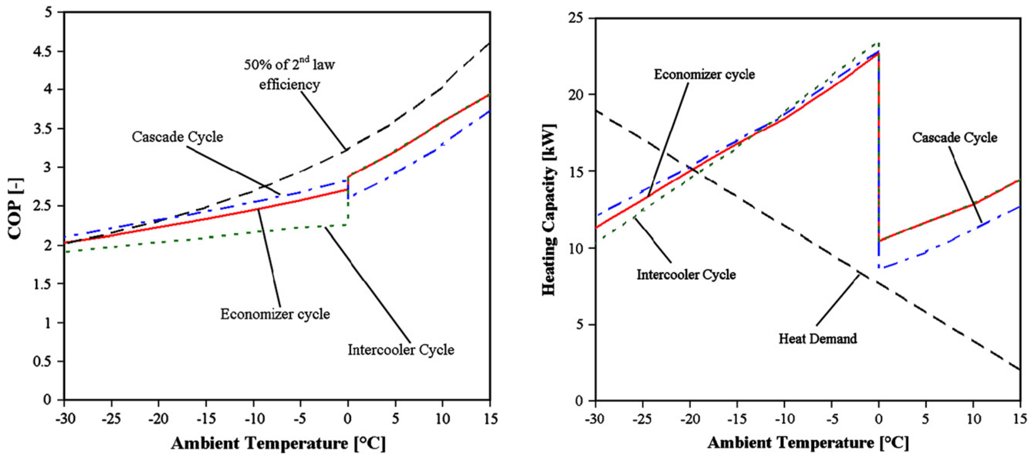


(a) *Two-stage cycle with intercooler* **(b)** *Two-stage cycle with closed economizer*

(c) *Cascade cycle* **(d)** *List of symbols*

Figure 2.16: Simplified schematics of two-stage cycle with intercooler, two-stage cycle with closed economizer, and cascade cycle [36].

Besides, some refrigerants have a saturation pressure below one atmosphere at -30 °C evaporating temperature, and these characteristics entail small volumetric capacities and large compressors. Hence, another advantage is the chance to be able to avoid this fact with good plant design. The choice of the refrigerant takes R404A and R134a due to reliable performances. The evaporating temperature of the R134a cycle is 0 °C, whereas the condensation temperature of the R404A cycle is 8 °C. However, the cascade cycle is extremely performing at high overall pressure ratios (low ambient temperature and high supply one), but not when losses, due to low-pressure ratios across compressors, dominate. This aspect also forbids reversing the operation mode or running in part load. Authors suggest adding an outdoor-evaporator to the high-temperature stage cycle to use it in single-stage mode. Therefore, installation and maintenance costs are more expensive than previous solutions, but greater efficiencies at high-temperature lifts and not requested oil management may validate the choice.

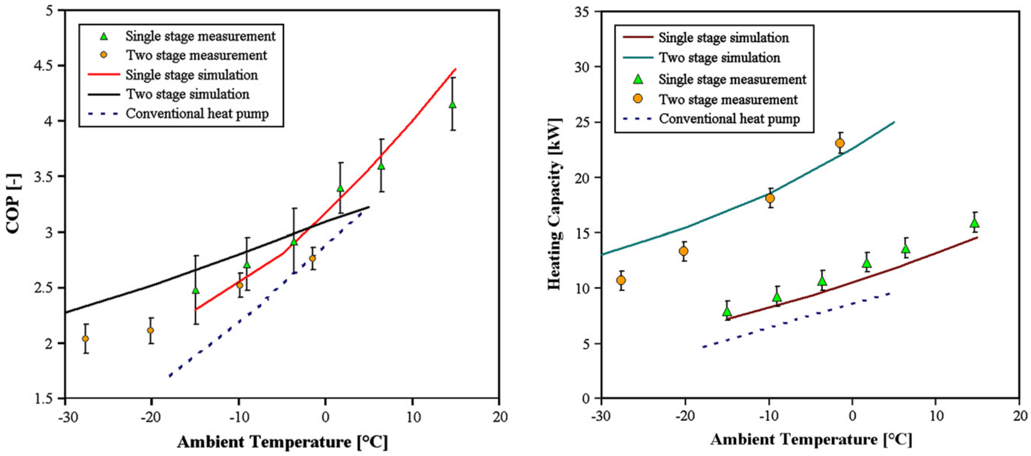


(a) *COP* (b) *Heating capacity*

Figure 2.17: Simulation results of COP and heating capacity at 50 °C supply temperature [36].

A steady-state simulation was performed in order to evaluate the performances of the three different solutions. The ambient temperature varied from -30 to 10 °C, whereas the heat supply temperature from 40 to 60 °C. The authors did not consider frost formation, so defrost necessity. Besides, the systems work in a two-stage configuration only below an ambient temperature of 0 °C. At higher ambient temperatures, the heat pump prefers running in single-stage mode to reduce its capacity and prevent the compressors from running at low-pressure ratios. Figure 2.17a attests to the lowest COP of the intercooler cycle. The reason is the relatively high temperature of the return water flowing through the intercooler (about 35 °C). On the contrary, the cascade cycle shows the best performances. Concerning the heat capacity, Figure 2.17b does not point out any remarkable differences among the three solutions. Therefore, the evaluation should be made on the COP analysis. That's why the intercooler seems to be the weakest technology. However, also the cascade cycle is to avoid due to the difficulties in operating in the reserve mode. In conclusion, the authors suggest the close economizer as the best solution, like also M. Guoyuan et al. recommend [37].

Hence, the close economizer cycle is the object of the final analysis by Stefan S. Bertsch and Eckhard A. Groll. This simulation was performed with the same previous hypotheses, nothing but considering also the auxiliary power consumption of the supplementary systems and quasi-steady-state conditions. The uncertainty



(a) *COP* **(b)** *Heating capacity*

Figure 2.18: Simulation results for the systems with the economizer at 50 °C supply temperature and considering auxiliary power [36].

on the results is between 3% and 6% for the heating and cooling capacities, whereas between 3% and 9% for the heating and cooling COPs. The results are reported in Figure 2.18, where there are the field test measurements, as well. Figure 2.18a shows that measurements for the single-stage fit well the curve obtained by the model. On the other hand, the curve of the two-stage configuration is less precise at low temperatures because there are not so many compressor performance maps at those temperatures. However, both operation modes are more performing than a conventional heat pump. Besides, they do not fall with a linear slope, especially the two-stage. The two-stage operation mode can also guarantee a larger heating capacity compared to the other solutions.

Therefore, the two-stage system with an economizer can face all the problems which heat pumps have in cold climates. Its cost is quite more expensive than a traditional heat pump, but always cheaper than a GSHP, which may be another solution to the above-mentioned issues. According to the authors, the main challenge of the two-stage system with an economizer is the implementation of a good control system, which they were not able to find available on the market.

2.4.2 Gas engine heat pumps

A possible solution to the problems related to cold climates is the gas engine heat pump (GHEPs or GHPs), which uses an internal combustion engine (ICE) to drive the compressor. It is based on the principle of combined heat and power (CHP), so it can use the heat produced and the one captured from the exhaust gasses to warm up the system directly. These installations can also work below -20 °C, making unnecessary auxiliary heaters or other kinds of solutions.

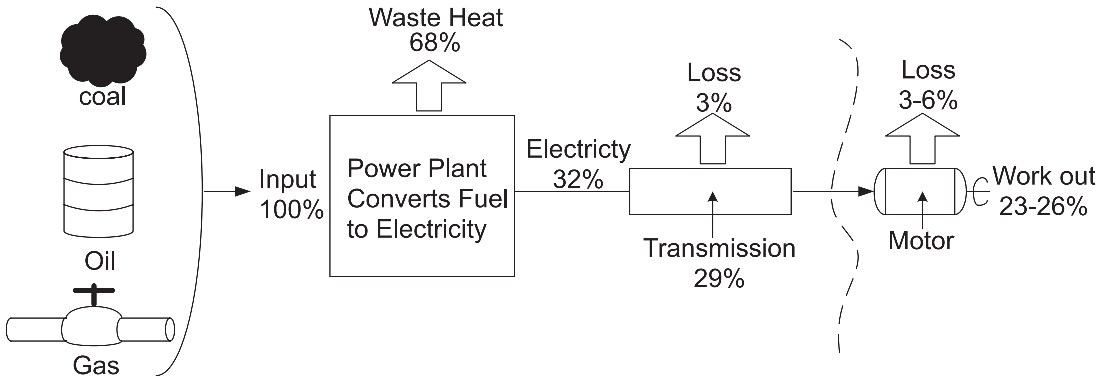


Figure 2.19: Losses of the conversion process of an electric heat pump [39].

A reversible vapor open compressor HP is generally the main component of a GEHP. The main difference is that an ICE, and not an electric motor, runs the compressor. The system consists of two parts:

- The HP, which includes the open compressor, the heat exchangers, and the expansion valve;
- The ICE system.

The efficiency of the ICE is around 25-40%, which seems smaller than conventional electric heat pump (EHP) efficiency. Nevertheless, fuel combustion produces waste heat that can be recovered by about 80% [40]. This heat can be:

- Transferred to air, which is used in heating processes;
- Transferred to water, which is heated this way.

Considering that, the total efficiency is comparable to the traditional EHP. Thermodynamically speaking, the efficiency of power stations is about 40%, as well. Therefore, the result is that the final efficiency of an EHP is not truly higher considering all the processes starting from primary fuel, as shown in Figure 2.19. GEHPs can also be more economical convenient with respect to electric heat pumps in countries where the gas costs less compared to electricity, such as Japan and the US in 2012, according to [10]. It is quite the same if the fuel is propane or LPG. Besides, Zhang et al. [41] found that the ambient temperature does not affect GEHPs in constant speed mode so much, compared to EHPs. In any case, the engine speed impacts the performances of both systems quite a lot, and GEHPs work more reliably at low speed. In more detail, experimental results by Jia et al. [42] show that, when the engine velocity increases from 1400 rpm to 2600 rpm, the natural gas consumption rises by 89%, and the total heat production by 30%. At the same time, the COP decreases by 44%. The reason is that a reduction in suction pressure and an increment of discharge pressure follow a rise in speed. The consequent compressor ratio is bigger than before, so the COP and the efficiency of the compressor shaft lower. However, the authors recommend setting the minimum engine speed at around 1400 rpm.

From the environmental point of view, the situation is a bit different, instead. Big power stations usually can afford the economical and technical expense of more refined emissions cleaner or similar devices, so the equivalent CO_2 per kWh should be fewer. Nevertheless, the oxidizing catalytic converter can increase the CO and hydrocarbon conversion, respectively until 90% and between 68.6% and 89.8%, according to Cramer and Saunders [43]. Ganji [44] even found that, in some circumstances, gas engine heat pumps produce about half CO_2 compared to electric heat pumps. The clear separation is the national electricity mix: if less than 50% of electricity production derives from natural gas, electric heat pumps still produce less CO, CO_2, and NO_x. However, the high efficiency of GEHPs allows small fuel consumption, and the emissions are still lower than conventional boilers. In addition, they are usually 70% more efficient than natural gas heaters.

On the other hand, running and maintenance spending is still too high to allow ample distribution, especially among small residential consumers. Buildings with a 25-1000 kW demand are the only possible applications until now, although smaller engines evolve swiftly. In any case, the main problem is that the components require maintenance every 10 thousand hours, i.e. just over a year, according to [10].

In the end, there are all the safety-related issues to consider, as mentioned in Subsection 1.3.1. A device fed by fossil fuels may lead to leakages or explosions, which should be less likely with an electric one.

2.4.3 Solar-assisted air source heat pumps

The transfer of solar energy to the ASHP system happens by using direct solar irradiation and latent heat from the air. Therefore, solar energy has two main roles:

- To supply electric power to the system through photovoltaic (PV) panels;
- To supply heat to the systems through solar thermal systems.

In the second case, it can supply heat directly only to the DHW or to the whole heating system. There are also hybrid PV-thermal air source heat pumps. Therefore, solar energy can improve the operation of an ASHP, meet a higher ratio of energy demand, and produce additional electricity. In more detail, solar-assisted solutions can increase the COP by 30-60% compared to conventional ASHP [45]. Nevertheless, solar-assisted air source heat pumps require higher investments and maintenance costs. Moreover, the management of daily tasks is more complicated.

Since there are three different configurations, it is necessary to define the system boundaries properly. The scheme proposed by the IEA in the SHC context is one of the most employed in the literature about SAHPs [45, 46, 47, 48]. In more detail, the diagram is explained in the IEA SHC Task 44 / HPP Annex 38 [49].

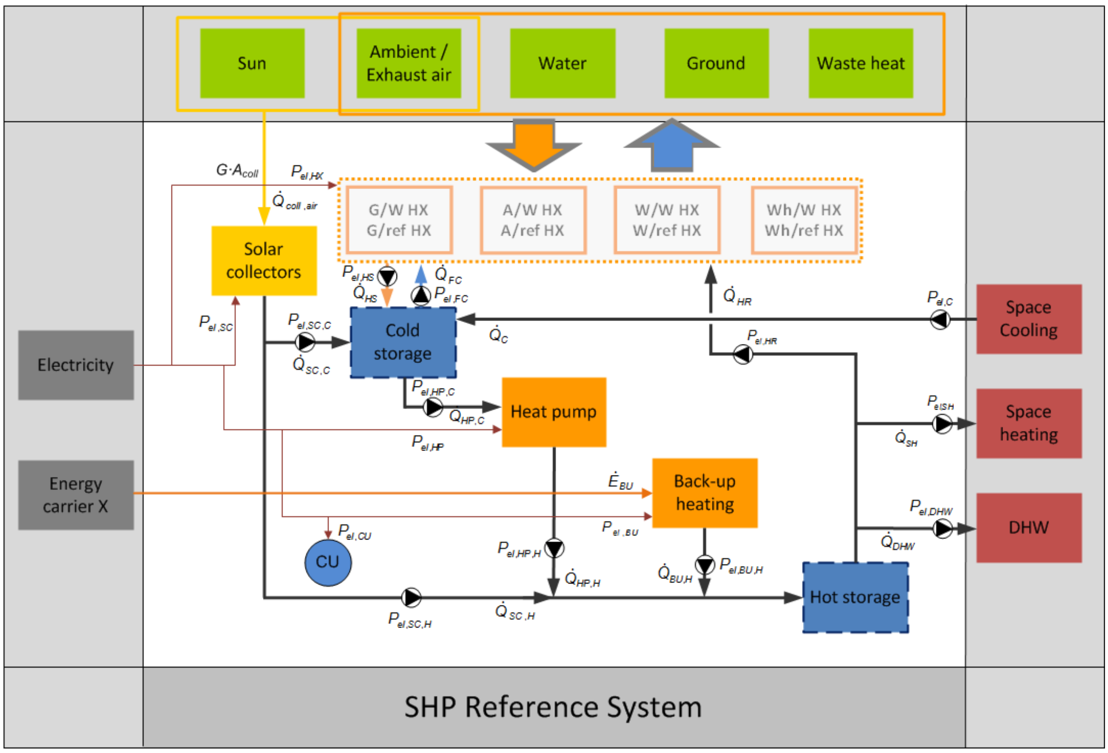


Figure 2.20: Reference SHP system proposed by the IEA SHC Task 44 [49].

The main areas are essentially four: the central white rectangle contains the functioning system, the upper the primary energy sources, the one on the left electricity and other energy carriers, and the one on the right the three energy services provided (space cooling, space heating, and DHW). Ambient and exhaust air, water, ground, and waste heat can be considered as heat sources ($\dot{Q}_{\mathrm{HS}}$), heat sinks for free cooling ($\dot{Q}_{\mathrm{FC}}$), or energy dissipation for active cooling ($\dot{Q}_{\mathrm{HR}}$).

Since solar collectors can transform solar irradiation and heat from the ambient air (including latent heat) into useful heat, the relative energy source boxes have been included in the same yellow frame. The energy input to the collectors splits into $G \cdot A_{\mathrm{coll}}$, which stands for the total irradiation, and $\dot{Q}_{\mathrm{coll,air}}$, linked to the ambient air. The blue circle denominated “CU” represents the energy consumption of the control units. It comprehends all the systems not included in the component-specific controls, such as for the heat pump or the back-up heating unit. However, the estimation of the energy consumption of the control units is not always trivial. Similarly, the electricity consumption of the pumps is represented with the pump symbol, and other components are not included. In real applications, they must be acknowledged, of course. Finally, both heat and cold storages are represented through dashed frames. This graphical choice is because they are rarely present in every installment. Therefore, the dashed box can be neglected and reduced to a nodal point. For instance, if the solar collector and a borehole supply directly the evaporator of the heat pump, the cold storage is reduced to a nodal point for the quantity $\dot{Q}_{HS}$, $\dot{Q}_{SC,C}$, and $\dot{Q}_{HP,C}$.

It is significant to notice that the arrows represent the flows in their physical direction (from higher to lower temperatures) and not necessarily the hydraulic configuration of the system. However, they provide valid information about the interactions among different components.

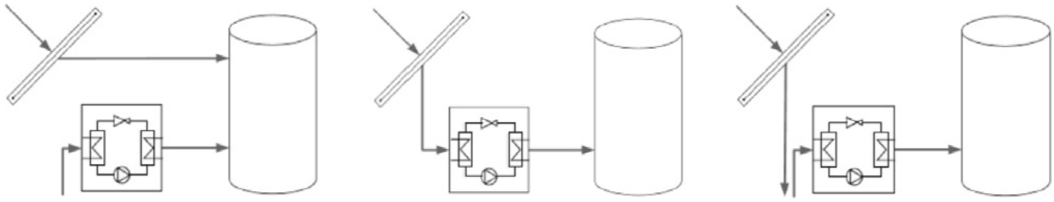
Basing on the scheme proposed by IEA, Wang et al. [45] highlights some different subsystems:

- Heat pump only (HP), which is the orange box with the heat pump lettering;
- Solar assisted air source heat pump system (SHP), considering the heat pump (HP) with the solar collectors;
- Solar thermal air source heat pump system (ST-ASHP), which is the SHP plus the circulation water pumps;
- Solar assisted air source heat pump system with PV arrays (PV-ASHP), which is the SHP plus the PV arrays but without the battery storage;
- Hybrid solar thermal air source heat pump system with PV arrays (PV/T-ASHP), which is a hybrid system that can provide both electric power and heat from the solar source.

ST-ASHP system

This kind of plant transforms the irradiation of the Sun into thermal energy that can be used directly by the users or supplied to the ASHP. However, concerning the generation method, the ST-ASHPs can be classified into two different systems:

- Direct expansion solar assisted system (DX-SA);
- Indirect expansion solar assisted system (IDX-SA).



(a) *Parellel* **(b)** *Serial* **(c)** *Regenerative*

Figure 2.21: Classification of solar thermal and heat pump systems in parallel, serial and regenerative system concepts [45, 46].

In the first case, the solar collectors work together with the heat pump and serve as its evaporator. Frank et al. [46] further subdivide the second typology according to the interaction with the heat pump. As shown in Figure 2.21, it can be:

- Parallel, whose solar collectors can supply heat for heating and/or DHW, or cooling directly or via storage to the users, without using the heat pump that can do the same;
- Serial, whose solar collectors act as a heat source for the heat pump, directly or via storage;
- Regenerative, whose solar collectors are used to regenerate another source (usually ground in GSHP).

According to a market survey by Ruschenburg et al. [47], the most widespread technology in 2013 was the parallel with a share equal to 61%. Serial systems covered 6% and regenerative only 1%. Any combination of the three systems counts for at least 33%. ST-ASHP can be categorized also depending on the fluid and its temperature. The media is air or another fluid (usually liquid), whereas the temperature is low-medium (under 100 °C) or high (up to 2500 °C). However, only low or medium temperatures installations actually work in real applications.

Wang et al. [45] found that several studies highlight that solar efficiency decreases with the growth of solar irradiation and the decrease of ambient temperature. The reason is that, in these circumstances, solar heat can increase the evaporating temperature more notably. On the other hand, there are fewer studies concerning how extreme outdoor conditions impact performance. However, Huang et al. [50] analyzed DX-SAHP systems and discovered that irradiation and humidity act a fundamental part. Without irradiation, the frost formation begins when the temperature is around 6-7 °C, and the humidity 50-70%. Instead, if the solar irradiation is 100 W/m^2, any frosting occurs unless the outdoor temperature is smaller than -3 °C and the humidity above 90%. Anyway, the frosting impact on heating performance is almost negligible after 360 min of operation. Besides, Qiu et al. [51] found out through modeling simulations that medium temperature systems work better in these circumstances since their COP is up to 55% higher at -25 °C compared to low or high-temperature installations. Experimental surveys by Liu et al. [52] verify Qiu's results since they highlighted that when the ambient temperature is -15 °C performance of SAHPs increases by 62% in heat capacity and 59% in COP compared to simple HPs.

PV-ASHP system

In these installments, the PV arrays produce electricity, which feeds the heat pump. When the electric power produced is not enough, the heat pump is also able to integrate with the one provided by the grid. On the other hand, the electricity produced by the PV-ASHP can also be inserted into the grid if the generation is abundant. This circumstance occurs particularly throughout the central hours of the day when the heating load of the building is restrained, and the solar irradiation is maximum.

PV-ASHP systems are categorized according to direct or indirect expansion types or depending on the array configurations. Nevertheless, the most important classification is based on the lighting absorbing material of the PV modules. Silicon, amorphous silicon, and crystalline silicon technologies are the most widespread, but also other materials are used, such as cadmium telluride, cadmium sulfide, or organic and polymer cells.

According to the research by Wang et al. [53], PV-ASHP systems could save 41.16% of exergy consumption per unit investment for cooling and 35.02% for heating compared to the ASHP powered by electricity from the national grid. Throughout the lifetime of about 26 years, this kind of system can also reduce the emissions of CO_2 by 11.10 tons. Besides, it can diminish operation costs. It is essential to notice that all these results are based on the Chinese energy mix, which is still strongly fulfilled by carbon. As usual, the national energy mix influences deeply the results of every analysis. However, a nosedive in energy consumption and greenhouse gas emissions is conceivable for almost every location, considering how significant the results of this study are.

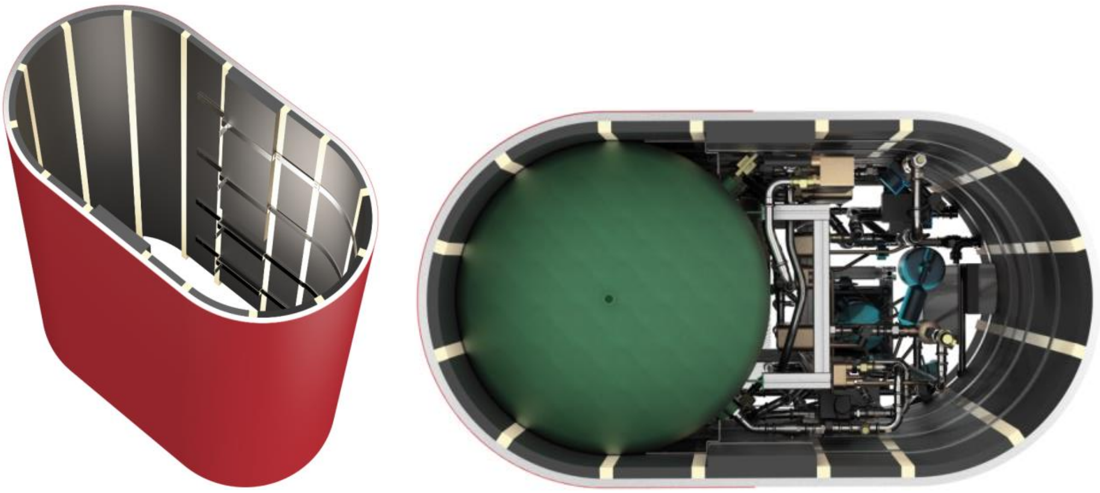
PV/T-ASHP system

PV panels usually convert from 4% to 17% of the solar irradiation into electricity [45]. The leftover transforms into heat. This heat may ruin the PV modules since their degradation increases at high temperatures. Therefore, further heat has to be subtracted by the system. This circumstance is achievable by making PV arrays work indeed as solar collectors. That's why the more spread configuration is serial since the PV/T collectors are employed to regenerate the heat exchanger. Besides, these modules can save space compared to the usage of detached PV panels and solar collectors.

Concerning performances, Kamel et al. [54] discovered that the heat pump electricity consumption is reduced by 20% in winter by using PV/T solar-assisted installments, especially for nearly zero-energy buildings (NZEBs). Moreover, PV/T-ASHPs (and PV-ASHPs) are less depending on ambient temperature than ST-ASHPs, since they rely mostly on solar irradiation. However, the longest payback time and a complex control system are the reasons that curb the spread of this technology right now.

Highly compact solar heat pump system

An unusual solution is the highly compact solar heat pump system proposed by Mojic et al. [48]. The development was carried on together with Energie Solaire SA (industrial partner), the Institute of Thermal Engineering IWT (research partner), and the Institute for Solar Technology SPF (research partner).



(a) *Without hydraulic components* **(b)** *With hydraulic components*

Figure 2.22: Design of the insulation of the highly compact SHP system [48].

The system is a novel brine-to-water heat pump prototype with the following components:

- A variable speed heat pump with an economizer refrigerant cycle and a desuperheater, developed by IWT;
- Unglazed selective collectors, by Energie Solaire S.A.;
- Thermal combi-storage optimized for heat pump use, featuring improved stratification even with high inlet mass flows, by SPF;

- Vacuum insulation panels to guarantee high insulation, by SPF;
- Hydraulics and control systems, which can supply space heating directly without using the storage, if necessary, developed jointly by SPF and IWT.

Besides, all these elements stay in a compact design. The unglazed selective collectors may also directly provide heat to the combi-tank if the temperature is high enough, as shown in the system diagram in Figure 2.23.

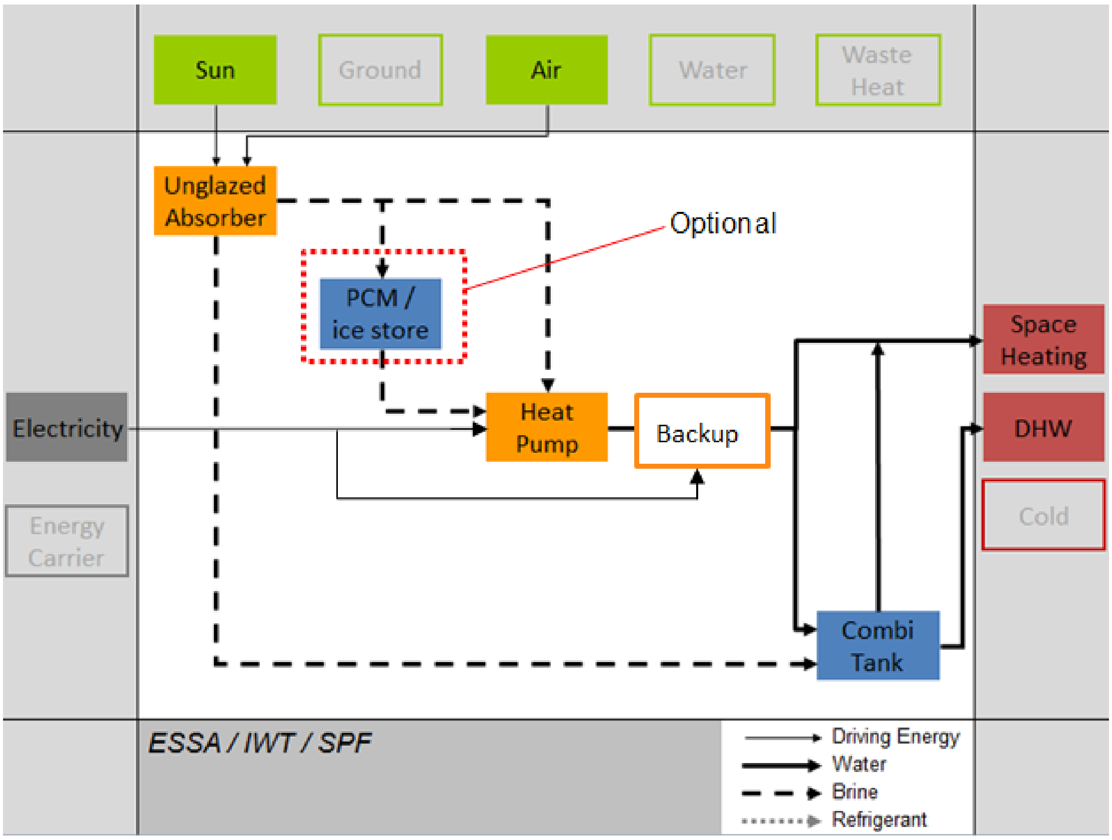


Figure 2.23: System diagram of the highly compact solar heat pump [48].

Several simulations and field tests have proved that the COP is still significant (equal to 2.8) even though the source temperature is remarkably low (-15 °C), and the condenser water outlet temperature is 34 °C. Moreover, increasing the last one up to 48 °C for DHW, the COP decreases only to 2.3. The main reason for these results is the economizer. Nevertheless, normal operations usually entail higher brine temperatures, so the COP results often between 4.4 and 5.9. Finally, the electric savings of this machine are around 28% compared to a conventional one, such as the SPF, which is 40% higher.

2.4.4 Ground source heat pumps

A low-enthalpy ground source heat pump uses the energy stored in the ground as a heat source in a very efficient way. As it does not require extremely hot rocks, it can be installed in most of the world [55]: boreholes, shallow trenches, and, rarely, ponds and lakes are the means to extract that heat. The ground, the groundwater, or both represent the heat source in winter, and a sink for the heat transferred from the building in summer. Therefore, the main distinction is between closed loops and open loops. The formers employ the ground with extracting nothing but heat, whereas the others materially extract the water. The water always operates as the process fluid in open loops. Closed loops are subdivided into direct circulation systems (DX-GSHPs) and indirect circulation (or secondary loops) systems (IDX-GSHPs). In both cases, there is a heat exchanger placed in a borehole. In the first case, the refrigerant that flows in the borehole is the same that crosses the heat pump condenser. In the second case, a refrigerant flows in the borehole heat exchanger and transfers heat to the fluid of the heat pump circuit, which in turn exchanges heat with the room. The ground heat exchanger can be placed vertically or trenched horizontally. In the end, regarding the open systems, water disposal can happen in the same borehole (standing column), in another borehole (well doublet system), or in a lake, pond, or river (single well). Closed-loops ground source heat pumps are pollution-free, obviously [56]. Even concerning the interaction with the ground, the only impact is related to the heat transfer. In open loops, the water occurs a change only in temperature and usually not in composition. In any case, the disposal should be careful not to increase the temperature in the lake, the pond, the river, or the aquifer. Nevertheless, the interaction with the aquifer or, in general, the ground can cause a deterioration of the heat source (water or ground) and its performance. The more likely reason is the over-exploitation if the system is not designed well from the extracting and disposing viewpoint.

Healy and Ugursal [56] performed an analysis of residential closed loops systems in cold climates. According to them, the main parameters that affect the performance and the cost of a GSHP are:

- GHE size and depth of GHE below grade;
- GSHP capacity;
- Heat transfer fluid type and flow rate;
- GHE pipe size and horizontal pipe spacing;
- Soil type.

Their study is a modeling simulation based on the most diffuse commercial heat pumps. Figure 2.24 shows that the GHE area decrease causes the reduction

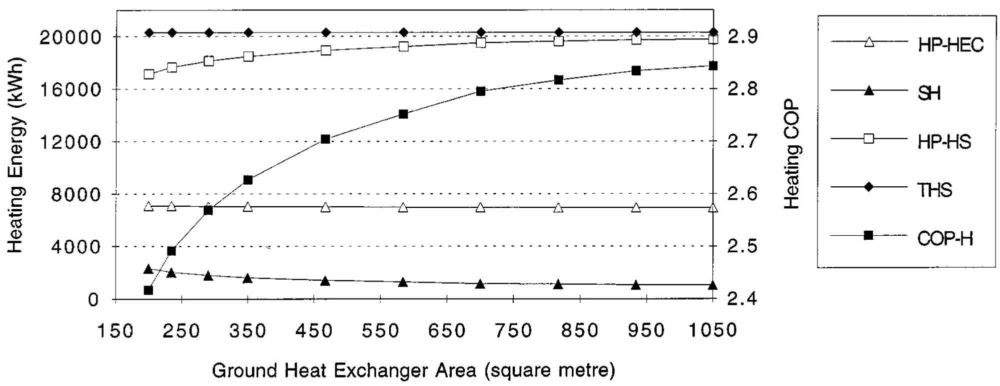


Figure 2.24: Effect of ground heat exchanger area on heating performance [56].

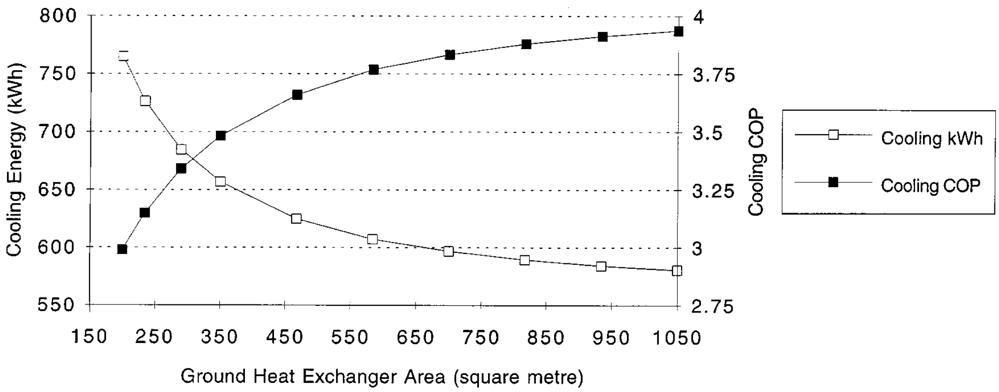


Figure 2.25: Effect of ground heat exchanger area on cooling performance [56].

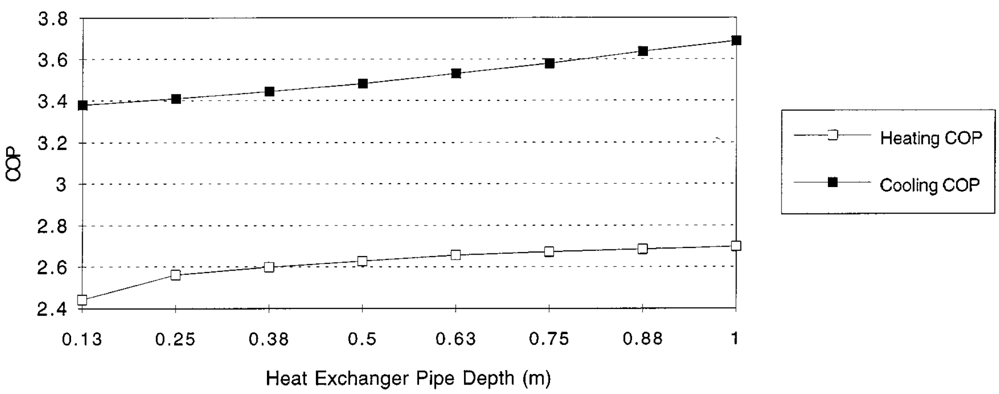


Figure 2.26: Effect of ground heat exchanger pipe depth on COP [56].

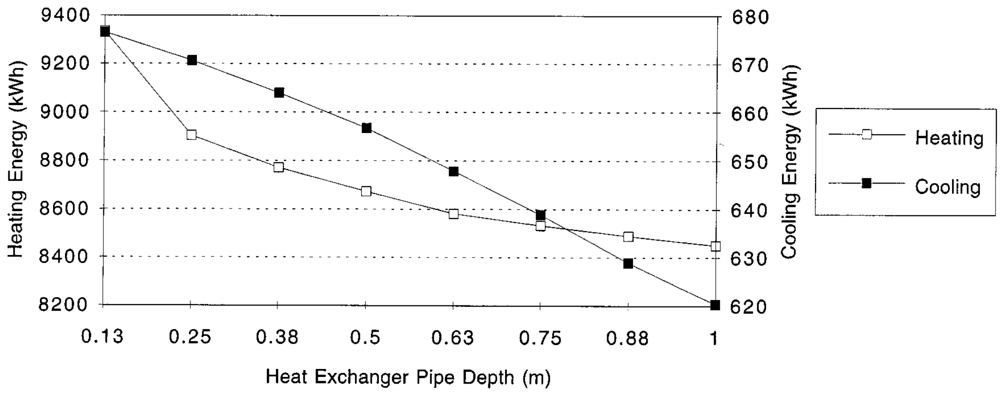


Figure 2.27: Effect of ground heat exchanger pipe depth on energy consumption [56].

of the heat supplied by the heat pump (HP-HS) and the COP. Considering a constant total heat supplied (THS), the supplemental heating energy consumption (SH) increases to guarantee it. At the same time, electricity consumption does not change. The reason is the simultaneous drop of the COP. Almost the same happens concerning cooling (see Figure 2.25). However, energy consumption is approximately 1/14 compared to heating, so the heat pumps should be dimensioned depending on the heating load. Anyhow, areas extended less than 350 m^2 generate an abrupt decline in performance. For wider GHEs, the slope is less noticeable. That's why the optimum surface should be roughly 350 m^2. Besides, a horizontal GHE of these measures fit an average backyard, whereas a bigger one may not.

An aspect that influences very much on the total installation cost is the excavation. Figure 2.26 shows how the COP increases with the depth, whereas Figure 2.27 how the energy consumption decreases. It interesting to notice that, in also this case, there is a point where the slope changes suddenly. It is around 0.30 meters, which could be chosen as the optimum. Nevertheless, it is more appropriate 0.5 m because it has to consider that the laid-down pipes must not interfere with roots, digging, or any activity carried on the installation area.

Concerning the heat pump size, two aspects are in opposition:

- The more the heat capacity increases, the more the installation costs and the more the cooling performances decrease since the machine is over-dimensioned for that task;

- The more the heat capacity decreases, the less the installation costs, but the higher the supplemental heat and the total energy consumptions are.

A trade-off for each specific installment is necessary.

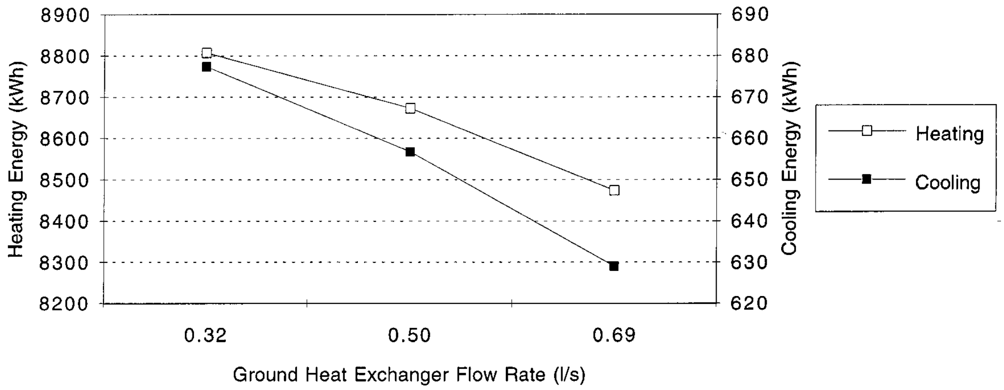


Figure 2.28: Effect of ground heat exchanger flow rate on energy consumption [56].

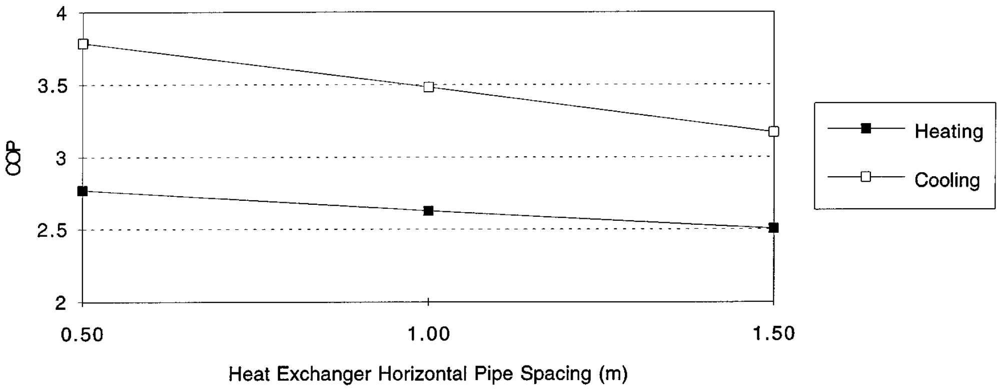


Figure 2.29: Effect of ground heat exchanger horizontal pipe spacing on COP [56].

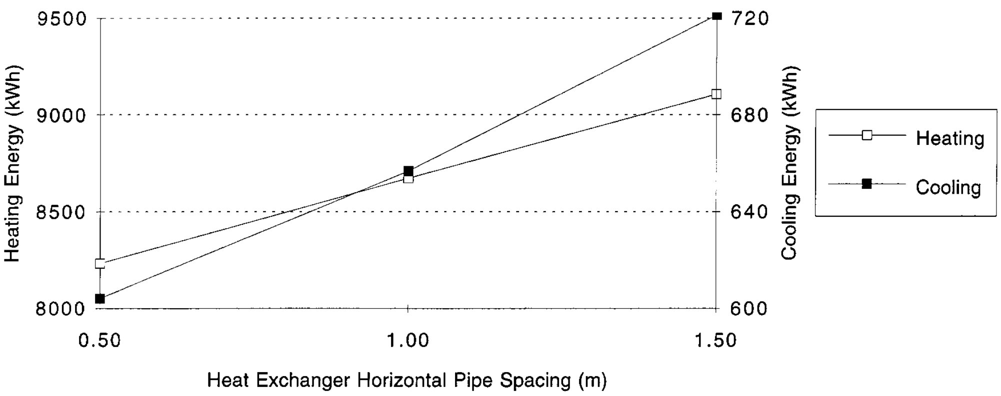


Figure 2.30: Effect of ground heat exchanger horizontal pipe spacing on energy consumption [56].

Another noteworthy point in cold climates is the anti-freeze solution that flows in the GHEs. Several materials are suitable for this task. For instance, 20% by mass of sodium chloride in water can guarantee the lowest freezing point, equal to -17 °C. Nevertheless, the best compromise between performance and price is usually ethylene or propylene glycol. Besides, it is also non-corrosive, so it should not ruin the pipes of the GHE. This aspect is critical because closed loops pipes are almost impossible to repair, and any loss is a possible danger for the ground or the aquifer (if present).

If the flow rate of the fluid in the GHE accelerates, the heat transfer coefficient increases as the Reynolds number rises. Therefore, the energy consumption for heating and cooling decreases (by approximately 4-5%, as shown in Figure 2.28). Nevertheless, the requirement for pumping is too much for the little advantage, so high-speed flow is not recommended. Likewise, the reduction of energy consumption due to the increase in the radius of the pipe is not sufficient to justify the resulting larger drilling costs.

On the contrary, the pipe spacing is quite important. The reason is that the closer the pipes are, the less wide has to be the excavation with a consequent money saving. Healy and Ugursal [56] have considered the optimal area of 350 m^2 and a spacing varying from 0.5 to 1.5 meters. The results highlight that the increase in pipe spacing reduces the COP and enlarges the energy consumption (see Figure 2.29 and 2.30). That's why it is better to reduce the pipe spacing as much as possible. Instead, the type of soil does not notably affect the performance of a GSHP.

Solar-assisted GSHPs

Ground source heat pumps work well if the heat obtained from the ground perfectly matches the heat transferred to it. That's why it is crucial to balance the heating and cooling demand adequately. If this circumstance does not occur, the system is heating or cooling dominated originating a phenomenon called "thermal drift" [57]. If the plant is heating dominated, the temperature of the source decreases more and more, reducing the performance of the heat pump. If it is cooling dominated, the temperature increases, but it is less likely, especially in cold climates. Therefore, the aim is to maintain the temperature almost constant.

A solar-assisted GSHP can balance the thermal drift by introducing the heat coming from the collectors into the ground. Furthermore, the introduction of solar collectors allows reducing the total length of the boreholes with consequent lower drilling costs. As the drilling is one of the most expensive operations in GSHP installations, this saving is usually more substantial than the expenditure for the solar collectors. Besides, Emmi et al. [57] performed several computer simulations of solar-assisted GSHPs installed in a multi-story residential building and founded that solar collectors can prevent a decrease in performance by 10% in 10 years regardless the location. Fabrizio et al. [58] obtained similar results, although they highlight a slight increase in electric power consumption due to the auxiliaries.

Comparison with ASHPs

ASHPs can guarantee an easier installation compared to GSHPs, especially in renovating. Besides, their design is simple, and they are available on the market with competitive costs and many applications. On the other hand, GSHPs have lower energy consumptions and better performances. The reason is that the COP depends on the temperature lift, as shown in Equation 2.4a et seq. The temperature of the ground or the groundwater is usually higher than the air temperature during the winter season or, at least, less fluctuating throughout the day or the year. Therefore, GSHPs are more expensive to install, but less to operate [25].

Considering more specific analyses, Hakkaki-Fard et al. [59] compared an ASHP and a direct expansion ground source heat pump (DX-GSHP) applied in a residential building in the cold climate of Montreal (Canada). The choice of a DX-GSHP instead of an IDX-GSHP (indirect expansion or secondary loop ground-source heat pump) is explained by the fact that it is the most efficient solution between the two for space conditioning and domestic hot water production. Besides, it is cheaper to install and operate. On the other hand, the design issues are more severe since the disposal of water is always delicate because of the requirement to secure mandatory environmental protection.

The results show that the energy consumption with the DX-GSHP will be reduced by 50%, but the relative payback time is more than 15 years. Nevertheless, if the cost of the borehole diminished by 50%, the period would reduce to a few years. Moreover, the authors highlight that the number of boreholes should be determined by a cost-effective design because their increase to more than 3 or 4 units (considering the same HP capacity) may not justify the higher expenditure. Another already mentioned problem concerning the boreholes is that the average temperature throughout the years decreases if the system is not designed well and the summer sink mode does not balance the winter usage. Finally, if the borehole wall temperature is lower compared to the outside air for a relevant part of winter, the increase of the heat pump capacity and the number of boreholes is often necessary to maintain good efficiency. For these reasons, if the difference between the peak loads and the nominal capacity of the heat pump is wide, it is better to install an ASHP. Therefore, any GSHP must be designed carefully and savings in installation costs usually cause higher expenditures in operations.

In the end, also Urchueguía et al. [60] founded that oversizing causes a fall in performance for both systems. In any case, they highlight that a rationally dimensioned GSHP can guarantee a saving by about 40% of power consumption compared to ASHPs.

2.5 Other issues

2.5.1 Maintenance

The compressor is the most expensive and complicated component of a heat pump. It usually lasts 15-25 years, and the percentage of compressors that need an annual replacement is 1.7%. In any case, the mean time between failure (MTBF) is between 20 and 40 years in small scale GSHPs [10].

Another tricky part of a GSHP is the plastic underground tube. This component is seldom replaceable, especially in the case of vertical loops. In any case, the expected lifetime is up to 50 years [10].

A further maintenance-related problem is the usage of fluorocarbon refrigerants. They have an extremely high global warming potential. During operations, they gradually leak from the pipes of the heat pumps and spread into the environment. Some sources evaluate this discharge as 1% of the whole refrigerant used in a year [10], others as 2%-5% of the nominal charge per year [61]. According to the first esteem, a typical 10 kW system leaks 25 g of R410-A, which is equivalent to 50 kg of CO_2. However, the heat pump is a viable energy service to reduce local GHG emissions. Abdeen Mustafa Omer evaluated the reduction from 15% to 77% [55]. In 2009 the IEA already foresaw an annual global cut by 8%, estimating a likely 30% growth of market share.

2.5.2 Auxiliaries

The auxiliary heater has to be well-sized because COP has been found to decrease by 30% when the heater works only 5 hours a day and even by 40% in inverter-driven models. However, a good design can minimize the usage of these kinds of systems to only 3-6% in terms of heat supplied in domestic installations [10].

Also, water pumps require a certain amount of energy to distribute the water all over the system. The consumption is around 150 kW of electricity per year, which means adding a further 3-5% to the overall electric power demand [10]. However, any hydronic heating system needs water pumps, and, for instance, condensing boilers usually consume almost the same amount of energy of heat pumps from this point of view.

2.5.3 Users habits

Efficiency improvement is usually seen as the most effective way to reduce the environmental impact of human activities. Nevertheless, this way of thinking depends on the assumption that the consumption of energy remains the same after the enhancement. Based on economic theory, the expectation is that the higher fabricating efficiency would reduce the unit cost of a product or a service. If the price decreases, the demand will partially rise. This outcome also happens in the energy market field.

Bente Halvorsen and Bodil Merethe Larsen tried to demonstrate it with their research work [62]. Their study was performed in Norway, where the heat pump diffusion raises extraordinarily in the first decade of the XXI century. In 2000 less than 1% of houses owned a heat pump, whereas up to 25% did in 2012. However, the majority of them bought a heat pump as an integration to existing heating services since, at that time, most heat pumps used to stop working at -15 °C.

The result is that people usually change their habits once the heat pump has been installed. In this case, although the consumption of fossil fuels falls, users often have less environmentally friendly behaviors. For instance, office occupants raise the average temperature of 1 °C thinking that the heat pump is not as polluting as the previous traditional heating system. Nevertheless, electricity consumption rises more than a thousand kWh per additional degree Celsius. The situation is slightly different in the case of house owners who have to pay for the electricity by themselves. However, they set the temperature almost 0.4 °C higher, because it is still cheaper than before. This behavior can be luckily reduced by good insulation that helps to enhance the thermal comfort of occupants, especially during nights.

Besides, for each kWh of firewood or fossil fuel demand is reduced by, about 0.2-0.3 kWh of supplemental electricity is requested. This exchange entails the rising of the overall efficiency of household energy consumption when using electricity for heating. Nevertheless, this does not mean that the performance becomes five times better, because the usage of the systems may alter as already discussed. For instance, the temperature can increase or decrease.

The study also includes a survey among users and finds out that the opportunity to heat the entire residence with a heat pump employs more than 1600 kWh compared to other cases where this is not possible. Furthermore, who declare to have purchased fewer fossil fuels since the installation of the heat pumps found out that has increased the annual electricity use by 3500 kWh. Finally, users are used to switching heating services from electric power to fossil fuels during the coldest periods of the year. The reasons are that the heat pump is not sufficient and that sometimes it does not work at all under a definite outdoor temperature, especially ASHP.

Considering all the statistics, the surveys, and the predictive models developed, the researchers found out the results reported in Table 2.4. Households who have the opportunity to differentiate their heating systems save the largest energy amount. The reason is that users can make a choice depending on climate variations. Therefore the resulting efficiency of each equipment is higher. The term “constant”

	Effect on electricity consumption (kWh)
A. Direct effects of heat pump ownership	−763
Constant	2,546
Use the pump for cooling during summer	72
Use the heat pump to heat the entire residence	274
Use less fuel oil after installing a heat pump	59
Number of substitution possibilities	−3,714
B. Indirect effects of heat pump ownership	1,058
Indoor temperature	484
Fuel oil consumption	204
Firewood consumption	370
C. Total effect on electricity consumption of owning a heat pump	295

Table 2.4: Decomposition of the predicted effect on electricity consumption of owning a heat pump for the mean household [62].

includes the above-mentioned changes in behavior or other variables due to the heat pump installation, as well. Summing up all the effects, we can highlight a small boost in electricity consumption. However, the increase is particularly restrained compared to the uncertainty of the analysis. It is intrinsically quite high because researchers addressed the technical surveys to common users. That's why we can not state that the increase in consumption can be taken for granted. Nevertheless, it is fundamental because it points out this aspect.

In conclusion, the analysis highlights that an increase in efficiency not always entails a benefit for the environment. Therefore some corrective measures should accompany efficiency improvements. In more detail, the authors suggest a rise in energy costs or an awareness-raising project.

However, the spread of heat pumps requires an expansion of the electricity network. The increase in the size of power generation plants or the simultaneous diffusion of electricity-producing microgeneration systems may help to achieve this goal. For instance, solar PV and micro-CHP are the most common solutions. A 10% penetration of heat pumps in the UK require 12-17 TWh of electric power per year [10]. This size is typical of a large nuclear or coal plant.

Chapter 3

Economic assessment

This chapter aims to present an economic assessment of the installation of an air-source heat pump (ASHP) and a ground-source heat pump (GSHP). Section 3.1 introduces the data chosen for this analysis and the motivations of their selection. Section 3.2 deals with the methods used to simulate the various systems. Finally, Section 3.3 reports the results and the relative discussion.

3.1 Introduction and data selection criteria

The economic assessment accomplished consists of a comparative analysis between two different heat pump-based systems (a GSHP and an ASHP) and a hypothetic conventional existing system.

The study deals with three locations that exemplify the three different climate conditions existing in the Piedmont region: Turin, which represents the administrative center and the flood plain, Cuneo, the hill, and Oulx, the mountain. Then, the analysis considers three different building types per each area with their characteristic energy demand. The last changing parameter is the grade of insulation, which can be low or high. Therefore, eighteen cases are performed.

The heating, cooling, and DHW demands, the thermal insulation levels, and the different building typologies are based on the study published by Rivoire et al. [63]. In more detail, they considered a single-family detached house (called "house"), a small two-story office building ("office"), and a multi-story hotel ("hotel"). The thermal transmittance value of the elements of the building are reported in Table 3.2. The authors computed the energy demand depending on six different locations. The differences between each city are based on a different number of degree days that identifies six climate conditions. They are Seville (Spain), Bologna (Italy), Lisbon (Portugal), Belgrade (Serbia), Berlin (Germany), and Stockholm (Sweden).

Hence, the heating, cooling, and DHW demand of the Piedmont cities are

Element	High insulation thermal transmittance	Low insulation thermal transmittance	Unit
External wall	0.28	1.60	$W/(m^2{\cdot}K)$
Under-roof slab	0.51	1.76	$W/(m^2{\cdot}K)$
Roof	0.24	2.38	$W/(m^2{\cdot}K)$
Floor	0.15	0.75	$W/(m^2{\cdot}K)$
Window	1.43	5.68	$W/(m^2{\cdot}K)$

Table 3.1: Thermal transmittance value of the elements of the building envelope in “high insulation” and “low insulation” cases [63].

computed considering a linear correlation between them and the heating degree days (HDD) or the cooling degree days (CDD). Each Piedmont city is compared to the city of the work of Rivoire et al. that has the number of HDD as similar as possible. Therefore, Turin (2617 HDD) is based on Belgrade (2743 HDD), Cuneo (3012 HDD) on Berlin (3172 HDD), and Oulx (4100 HDD) on Stockholm (4632 HDD). For instance:

$$Q_{\text{heating,Turin}} = \frac{\text{HDD}_{\text{Turin}}}{\text{HDD}_{\text{Belgrade}}} \cdot Q_{\text{heating,Belgrade}} \tag{3.1}$$

The database by Rivoire et al. contains monthly thermal loads (kWh) and monthly peak thermal loads (kW), and the relative annual values for the Piedmont case studies are reported in Table 3.2.

As mentioned above, a GSHP and an ASHP were considered for the analysis. They both are compared to a hypothetic system already installed in the sample buildings. The system consists of a conventional boiler to provide heating and DHW, and an electric air conditioning unit for the cooling, which guarantees the same performance of the new ASHP. The simulation of the existing systems is performed considering three different fuels for the boiler: natural gas, diesel fuel, and LPG.

The electricity and natural gas costs per kWh vary depending on the quantity of energy consumed in a year and the type of user. The user can be a “household”, suitable for the “house” case, or a “non-household”, for the “hotel” and “office” cases. Eurostat provides the costs of the electricity for households and non-households [64], and the natural gas for households [65], whereas ARERA that of the natural gas for non-households [66]. The prices are reported in Table 3.3 and 3.4. Since ARERA supplies the prices in €/Sm^3, the low heating value (LHV) of natural gas has been considered equal to 9.59 kWh/Sm^3. The diesel oil price is 1084.18 €/m^3, according to the MISE [67]. Considering an LHV equal to 10083 kWh/m^3, the diesel fuel results to cost 0.1075 €/kWh. Instead, Casasso et al. [68] suggest an LPG price

City, insulation (high or low) and building			Annual thermal load Heating (MWh)	Cooling (MWh)	DHW (MWh)	Annual peak thermal load Heating (kW)	Cooling (kW)	DHW (kW)
Turin	H	Hotel	276.8	30.6	6.8	153.6	86.2	4.8
		House	8.4	1.6	2.8	7.4	4.8	0.9
		Office	14.0	10.4	0.7	22.9	24.4	0.3
	L	Hotel	946.7	33.0	6.8	400.0	104.8	4.8
		House	43.7	0.3	2.8	25.4	4.8	0.9
		Office	92.1	3.7	0.7	62.3	23.5	0.3
Cuneo	H	Hotel	332.2	13.3	7.3	167.5	41.1	5.3
		House	10.4	0.4	2.9	7.4	1.9	1.0
		Office	20.2	5.5	0.8	28.0	17.0	0.3
	L	Hotel	1131.9	14.3	7.3	406.5	35.9	5.3
		House	52.5	0.0	2.9	25.8	0.0	1.0
		Office	115.3	0.0	0.8	60.8	0.0	0.3
Oulx	H	Hotel	414.1	6.7	7.7	167.6	23.7	5.6
		House	14.9	0.0	3.0	8.5	0.0	1.0
		Office	29.2	1.9	0.8	27.2	8.9	0.3
	L	Hotel	1376.9	6.5	7.7	436.8	25.8	5.6
		House	68.6	0.0	3.0	28.2	0.0	1.0
		Office	153.5	0.0	0.8	70.7	0.0	0.3

Table 3.2: Annual thermal loads and annual peak thermal loads of the eighteen case studies.

Users	Prices	Units	Applicability range (consumption)
Households	0.4676	€/kWh	Under 1000 kWh
	0.2521	€/kWh	Between 1000 and 2500 kWh
	0.2341	€/kWh	Between 2500 and 5000 kWh
	0.2324	€/kWh	Between 5000 and 15000 kWh
	0.2252	€/kWh	Over 15000 kWh
Non-households	0.3713	€/kWh	Under 20 MWh
	0.2213	€/kWh	Between 20 and 500 MWh
	0.1870	€/kWh	Between 500 and 2000 MWh
	0.1575	€/kWh	Between 2000 and 20000 MWh
	0.1285	€/kWh	Between 20000 and 70000 MWh
	0.1063	€/kWh	Between 70000 and 150000 MWh
	0.0910	€/kWh	Over 150000 MWh

Table 3.3: Electricity prices for households and non-households users in the second semester of 2019 including all taxes and levies, according to Eurostat [64].

Users	Prices	Units	Applicability range (consumption)
Households	0.1477	€/kWh	Under 280 MWh
	0.0934	€/kWh	Between 280 and 2800 MWh
	0.0742	€/kWh	Over 2800 MWh
Non-households	0.0794	€/kWh	Under 250 MWh
	0.0595	€/kWh	Between 250 and 2500 MWh
	0.0398	€/kWh	Between 2500 and 25000 MWh
	0.0318	€/kWh	Between 25000 and 250000 MWh
	0.0794	€/kWh	Over 250000 MWh

Table 3.4: Natural gas prices for households and non-households users in the second semester of 2019 including all taxes and levies, according to Eurostat [65] and ARERA [66].

equal to 1350 €/m^3 and an LHV of 7300 kWh/m^3, therefore the cost obtained is 0.1849 €/kWh.

The choice of three different fuels is because the profitability of the investment is supposed to be undoubtedly different depending on them. As reported, the fuel prices per kWh of diesel and, especially, LPG are higher than that of natural gas. In some cases, LPG cost is even double compared to natural gas. Therefore, the new installment may be feasible in the areas not reached by the natural gas pipelines, and not where the network arrives.

3.2 Methods

3.2.1 GSHP simulation with Earth Energy Designer

Concerning the GSHP, the computation of the borehole length and its cost was performed by the Earth Energy Designer (EED) software [69]. Saturated sand was chosen as the reference ground. The values of its properties are the ones the software recommends for this type of soil (see Table 3.5).

Properties	Values			Units
	Turin	Cuneo	Oulx	
Sediment	Saturated sand	Saturated sand	Gneiss	-
Thermal conductivity	2.400	2.400	2.900	W/(m·K)
Volumetric heat capacity	2.500	2.500	2.100	MJ/(m^3·K)
Ground surface temperature	12.6	11.3	7.1	°C
Geothermal heat flux	0.06	0.06	0.06	W/m^2

Table 3.5: Ground properties values assumed in the EED simulation.

The borehole heat exchanger is a double-U type. The flow rate is equal to 1 l/s. The properties of the U-pipe are the default ones: the outer diameter of 32 mm, the wall thickness of 3 mm, the thermal conductivity of 0.420 W/(m·K), and the shank spacing of 70 mm. The borehole thermal resistance is automatically computed by the software. The heat carrier fluid is a solution by 25% of mono propylene glycol, whose properties are reported in Table 3.6.

Properties	Values	Units
Thermal conductivity	0.475	W/(m·K)
Specific heat capacity	3,930.000	J/(kg·K)
Density	1,033.000	kg/m^3
Viscosity	0.008	kg/(m·s)
Freezing point	−10.00	°C

Table 3.6: Heat carrier properties values assumed in the EED simulation.

The simulation period virtually lasts 25 years of operation. The heating seasonal performance factor (SPF_heat) is assumed equal to 4, the cooling seasonal performance factor (SPF_cool) to 5, and the domestic hot water seasonal performance factor (SPF_DHW) to 3. The drilling expenses are assumed equal to 1 thousand euros (€) per borehole as fixed cost plus 50 €/m. Besides, the ditch requires 10 €/m.

The simulation is performed to find the optimum depth of the boreholes with some constraints. The fluid temperature has to be between -3 °C and 30 °C in order to be sure to avoid the freezing point. The available area for the drilling is 19 m × 19 m for the house (as suggested by Healy and Ugursal [56]), 150 m × 150 m for the hotel, and 30 m × 20 m for the office (default value by EED).

Since the costs of the heat pump and the buffer tank have to be added to the price of the GHE previously computed, the following relations [70] help to estimate this cost:

$$y_\text{heat pump} = 297.8 \cdot x_\text{heat pump} + 5313.4 \tag{3.2a}$$

$$y_\text{buffer} = 0.7 \cdot x_\text{buffer} + 770.5 \tag{3.2b}$$

where y is the cost (in €) and x the specific capacity (measured in kW for the heat pump and in liters for the buffer tank). To compute the latter a ratio equal to 25 l/kW has been hypothesized. The sum of these three amounts represents the total investment cost.

Furthermore, it is necessary to evaluate also the cost of energy consumption. Therefore, the performance factors of the heat pump are calculated using the technical data sheets of the "ELFOEnergy Ground Medium[2]" heat pump produced by Clivet [71]. The reference heat pump outlet temperatures are equal to 45 °C for heating mode and 7 °C for cooling. On the other hand, the mean fluid temperature at the end of each month computed by EED is the requested reference fluid temperature, of course. At this point, it is possible to compute the energy consumption of each of the eighteen cases starting from the correspondent by Rivoire et al. Then, the energy demand is multiplied by the electricity cost to obtain the annual charge for electricity consumption.

3.2.2 Evaluation of costs and performances of the ASHP

The evaluation of the SCOP and the SEER is based on the hourly maximum (T_max) e minimum (T_min) temperature. Since the values measured by ARPA Piemonte [72] are daily, an algorithm is necessary to simulate the hourly progression. A proposal by Chow and Livermore [73] has been chosen. The hourly temperature is defined as:

$$T(t) = f_1 \cdot T_\text{min} + f_2 \cdot T_\text{max} \tag{3.3}$$

with:

$$f_1 = \frac{\cos\left(\pi \cdot \frac{t_{\min}-t}{24+t_{\min}-t_{\max}}\right)+1}{2} \qquad \text{if } t < t_{\min} \tag{3.4a}$$

$$f_1 = \frac{\cos\left(\pi \cdot \frac{t-t_{\min}}{t_{\max}-t_{\min}}\right)+1}{2} \qquad \text{if } t_{\min} < t < t_{\max} \tag{3.4b}$$

$$f_1 = \frac{\cos\left(\pi \cdot \frac{24+t_{\min}-t}{24+t_{\min}-t_{\max}}\right)+1}{2} \qquad \text{if } t > t_{\max} \tag{3.4c}$$

and:

$$f_2 = 1 - f_1 \tag{3.5}$$

where t stands for the time of interest (expressed in hours), $t_{\max}$ the time when the temperature is maximum (at 2 p.m.), and $t_{\min}$ when the temperature is minimum (usually at dawn). The trends for the first week of January and July in Turin are shown in Figure 3.1 as an example.

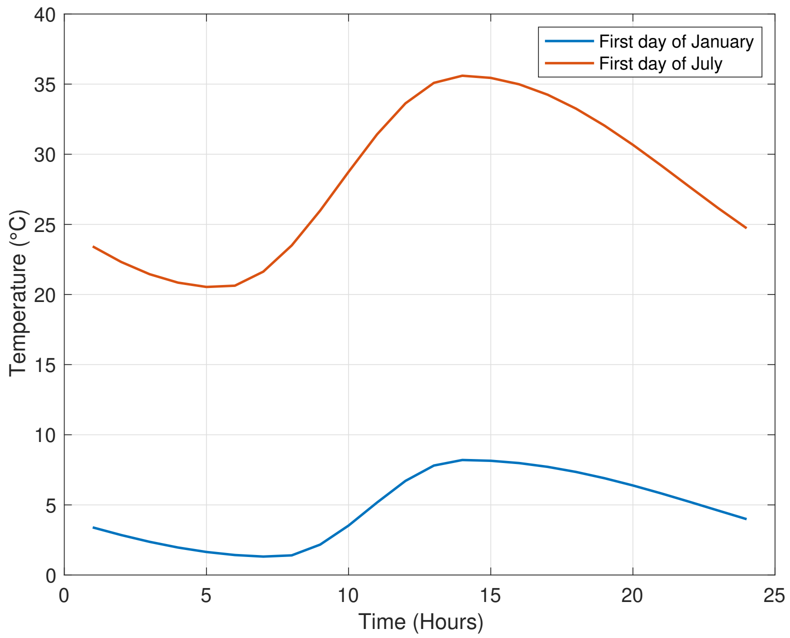


Figure 3.1: The reconstructed sinusoidal trend of temperature, shown for the first day of January and July.

At this point, 18.3 °C (65 °F) has been chosen as the reference temperature, according to the suggestion by the ASHRAE [74]. The temperatures are collected in different temperature bins (from -11 to 17 °C for the heating season and from 19 to 40 °C for the cooling one) and their frequencies per every bin are reported. Also, the heating degree days (HDD) and the cooling degree days (CDD) are calculated as suggested by the ASHRAE:

$$\mathrm{HDD} = 18.3 - T_{\mathrm{bin}} \tag{3.6a}$$

$$\mathrm{CDD} = T_{\mathrm{bin}} - 18.3 \tag{3.6b}$$

Then, it is possible to compute the relative COP and EER to every bin with the Equation 2.5a and 2.6b, respectively. Similarly to the GSHP case, the outlet temperatures are supposed to be equal to 45 and 7 °C. The weighted average of the performance factors with respect to the temperature bins allows calculating the SCOP and the SEER. Finally, the energy consumption is computed similarly to the GSHP case. In this case, the total investment cost is equivalent to only the sum of the heat pump and the buffer tank expenditures (no GHEs required, of course).

3.2.3 Existing system

The hypothesized existing system consists of a boiler and an air conditioning unit.

The former supplies heating and DHW. Its efficiency is evaluated according to the D.G.R. n. 46-11968 of 4 August 2009 (updated to 9 June 2016). The law requires the calculation of combustion efficiency, and this aspect fits the present analysis because the distribution and transmission losses are supposed to be the same for this old system, the GSHP, and the ASHP. As already mentioned, three different simulations are performed to compare the profitability of the investment with respect to the existing system. The reason is that the fuels chosen (natural gas, diesel fuel, and LPG) for the three simulations have a truly different cost per kWh. Furthermore, the analysis of Chapter 1 reveals that the distribution of natural gas is not uniform all over the region, and diesel fuel and LPG are the more polluting alternatives among the most frequent ones.

Instead, the air conditioning unit has the same SEER of the ASHP computed in the previous subsection.

3.2.4 Economical indicators

Some indicators are necessary to perform the economic assessment. They are the net present value (NPV), the payback time (PBT), and the interest rate of return (IRR). The analysis can consider a discount rate (i) or not. In this study, both approaches are applied. In simple cash flow (SCF) methods, the calculation of the profitability of the investing occurs summing the annual cash flow (the difference between the incomes or savings and the expenditures) to the investment cost (or the remaining of the previous year). In discounted cash flow (DCF) methods, it is fundamental to choose a correct discount rate to compare cash flows that derive from an investment over the whole lifetime. The reason for this approach is that a certain amount of money invested today is more worth than the same sum in the future, which will lose purchasing power due to inflation and other economic conjunctures.

Discount rate and weighted average cost of capital

The discount rate is usually chosen equal to the weighted average cost of capital (WACC), which is calculated basing on the financial structure of the investment:

$$\mathrm{WACC} = K_{\mathrm{e}} \cdot \frac{E}{D+E} + K_{\mathrm{d}} \cdot \frac{D}{D+E} \tag{3.7}$$

where K_{e} stands for the cost of equity and K_{c} for the cost of debt. In this analysis the proportion has been chosen equal to 50%-50%.

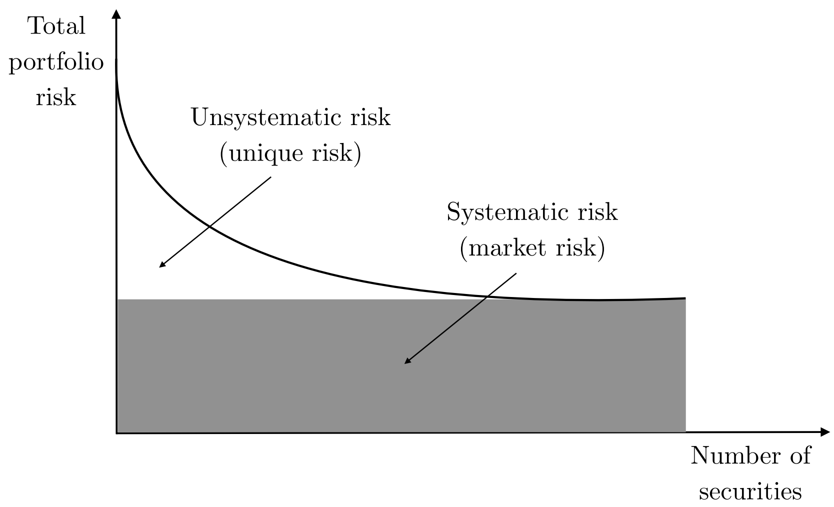


Figure 3.2: Specific or unsystematic risk and systemic risk.

The cost of equity is the minimum interest rate that an investor has to guarantee to his its equity investors for the funds received. It accounts for two components: the "specific or unsystematic risk" of certain investment, and a "systemic risk" (R_{f}) that is depending on the evolution of the economy as a whole. Figure 3.2 shows the correlation between the two and their dependence on the number of securities, namely the ability to face some inauspicious (from the investors' viewpoint) microeconomic factors, such as labor strikes. It should be, at least, equal to the systemic risk ("risk-free"):

$$K_{\mathrm{e}} \geq R_{\mathrm{f}} \tag{3.8}$$

In most of cases, R_f is assumed equal to the government bond at short term since it is the less risky investment. However, the investors expect to have:

$$K_\text{e} = R_\text{f} + \text{premium} \tag{3.9}$$

where the premium is defined as:

$$\text{premium} = R_\text{s} + \beta \cdot (R_\text{m} - R_\text{f}) \tag{3.10}$$

considering that:

- R_s is the small stock premium due to reduced liquidity (only for small investors);
- β is the sensitivity of a specific investment rate of return to the market modification;
- R_m is the market return;
- $R_\text{m} - R_\text{f}$ is the equity market risk premium (EMRP).

The values of these parameters are reported in Table 3.7.

Indexes	Values	References
R_f	0.97%	BTP 10Y [75]
R_s	0.0%	Assumed
$R_\text{m} - R_\text{f}$	6.5%	KMPG's report [76]
β	1	Assumed
K_e	7.47%	-

Table 3.7: Values of indexes included in the cost of equity.

On the other hand, the cost of debt is the interest an investor pays on his debt. It is defined as:

$$K_\text{d} = \text{IRS} + \text{spread} \tag{3.11}$$

where the interest rate swap (IRS) is a fixed interest rate stock that is exchanged with a variable interest rate stock, and the spread is the increase of the interest rate depending on the capability of the investor to return the capital. The relative values are reported in Table 3.8.

In the end, the WACC, which is equivalent to the discount rate, results equal to 4.14%.

Indexes	Values	References
IRS	0.97%	IRS 10Y [77]
Spread	1.0%	Assumed
K_{d}	0.80%	-

Table 3.8: Values of indexes included in the cost of debt.

Net present value

The net present value (NPV) of cash flow is given by the algebraic sum of the investment cost (I) and the net cash flows (B_{t}) over the whole lifetime of the project that are discounted at a certain nominal rate (i):

$$\mathrm{NPV} = -I + \frac{B_1}{1+i} + \frac{B_2}{(1+i)^2} + \cdots + \frac{B_n}{(1+i)^n} = -I + \sum_{t=1}^{n} \frac{B_t}{(1+i)^t} \tag{3.12}$$

where t stands for the numer of year considered and n for the total number of years. An investment project is accepted once the NPV ≥ 0. The basic rule suggests to choose the project with the higher NPV, among others that have a comparable initial investment.

Internal rate of return

The internal rate of return (IRR) is the value of i that makes the discounted cash flow equal to the investment cost in n years:

$$-I + \sum_{t=1}^{n} \frac{B_t}{(1+i)^t} = 0 \tag{3.13}$$

Therefore, the internal rate of return is the discount rate that makes NPV = 0. The higher it is, the more the investment is profitable. In more detail, if it is larger than the discount rate assumed, it means that the investment keeps being lucrative in n years even though more unfavorable economic contingencies happen. On the other hand, a lower value indicates that the investment will not be paid back in n years with the discount rate supposed.

Payback time

The payback time (PBT) measures the time (τ) in which negative cash flows become equal to positive cash flows (NPV = 0):

$$-I + \sum_{t=1}^{\tau} \frac{B_t}{(1+i)^t} = 0 \tag{3.14}$$

It describes the opportunity to choose the investment with the shortest period of return of the invested capital.

3.3 Results and discussion

The entire economic assessment is performed considering 25 years as the maximum period to return the investment. Tables 3.9 et seq. highlight that the profitability of the heat pump systems depends essentially on the initial investment cost, the working hours (or the thermal loads), and the fuel price per kWh. The cross-shaped symbols show the unavailability of the indicator and whether the investment is not profitable at all in 25 years.

Concerning natural gas, the economic convenience is less likely since its unit cost of heat is slightly higher than that of heat pumps. Therefore, Tables 3.9 and 3.10 demonstrate that, when the investment is too high (hotel and often office), the cost savings due to the introduction of the electrical power in place of natural gas do not compensate for the initial expenditure. Hence, the heat pump is rarely cost-effective without an economic incentive. In this case, the Italian law 27 December 2019, n. 160 (extension of the law 3 August 2013, n. 90), established the “ecobonus” incentive, which is equivalent to the 65% of the investment, up to 30000 € per apartment or 96000 € per building unit. It helps to reach a positive NPV and remunerative PBT and IRR for “house” and “office” cases. On the contrary, it is rarely useful for the “hotel” since the total refund is not substantial compared to the initial expenditure in this situation.

Tables 3.11 and 3.12 prove that the diesel-powered system is worth being replaced in the majority of cases. In practice, without incentives, the new installment is not lucrative only when the previous plant does not consume so much fuel. The reason is that high working hours and, consequently, severe thermal loads requested implies a great expenditure in terms of diesel fuel. Therefore, the annual saving of this amount pays the investment back in a few years. On the other hand, the introduction of incentives makes every new installment profitable.

Finally, Tables 3.13 and 3.14 indicate that the substitution of the LPG-powered plant is always feasible. The main reason is the very high price of LPG per kWh compared to electricity cost (sometimes even double). Therefore, the working hours, the thermal loads, and the investment costs hold a secondary role from this viewpoint. However, the “hotel” case study is far more profitable because of its thermal load and the relative annual saving, as happens to the diesel fuel specimen.

In the end, it important to notice that, with the law 17 July 2020, n. 77, the Italian government introduces the “superbonus”, namely the refund of a 110% of building refurbishment investments. With this temporary incentive scheme, which should end in 2021 and is meant as a post-COVID-19 pandemic economic stimulus for residential users and commercial activities located in residential buildings. It is obvious that every new installment is profitable under these circumstances since the annual running costs of an electric-driven heat pump are lower than almost every other solution.

City, insulation (high or low) and building			Ecobonus applied NPV (€)	PBT (years)	IRR (-)	Ecobonus not applied NPV (€)	PBT (years)	IRR (-)
Turin	H	Hotel	-24002	×	2.29%	-101346	×	-2.80%
		House	4920	11.04	8.28%	-2140	×	2.56%
		Office	5011	15.87	6.13%	-11067	×	0.29%
	L	Hotel	-357119	×	-5.18%	-434463	×	-6.73%
		House	15440	9.85	9.21%	-2178	×	3.51%
		Office	11192	16.34	5.98%	-27794	×	0.13%
Cuneo	H	Hotel	-43491	×	0.76%	-120835	×	-4.24%
		House	3188	13.91	6.85%	-4138	×	1.06%
		Office	1927	20.44	4.93%	-14229	×	-1.01%
	L	Hotel	-322194	×	-4.73%	-399538	×	-6.39%
		House	442	23.98	4.29%	-19310	×	-1.72%
		Office	12413	16.27	6.00%	-30293	×	0.15%
Oulx	H	Hotel	-108617	×	-3.17%	-185961	×	-7.30%
		House	16856	5.75	16.30%	-7314	×	-0.06%
		Office	55026	3.96	25.21%	-22318	×	-2.84%
	L	Hotel	-672040	×	-10.08%	-749384	×	-11.29%
		House	-7276	×	2.32%	-31446	×	-2.83%
		Office	-8569	×	3.33%	-85913	×	-2.89%

Table 3.9: The profitability of the GSHP investment on the hypothesis of the natural gas-powered existing system.

City, insulation (high or low) and building			Ecobonus applied NPV (€)	Ecobonus applied PBT (years)	Ecobonus applied IRR (-)	Ecobonus not applied NPV (€)	Ecobonus not applied PBT (years)	Ecobonus not applied IRR (-)
Turin	H	Hotel	-27974	×	×	-105318	×	×
		House	4087	8.22	10.36%	-2973	×	0.38%
		Office	5086	7.32	10.51%	-10991	×	-8.01%
	L	Hotel	-233192	×	×	-310536	×	×
		House	20720	4.79	21.08%	3102	18.22	6.13%
		Office	26832	5.08	18.84%	-12154	×	-1.16%
Cuneo	H	Hotel	-53802	×	×	-131146	×	×
		House	3290	8.51	9.45%	-4035	×	-1.25%
		Office	3811	8.24	8.43%	-12345	×	-8.10%
	L	Hotel	-307630	×	×	-384974	×	×
		House	6576	6.57	12.26%	-13176	×	-12.29%
		Office	30627	4.59	21.32%	-12079	×	-1.24%
Oulx	H	Hotel	-104751	×	×	-182095	×	×
		House	19383	2.91	35.54%	-4787	×	-2.23%
		Office	63980	1.60	65.60%	-13364	×	-11.43%
	L	Hotel	-480792	×	×	-558136	×	×
		House	4728	6.41	11.46%	-19442	×	×
		Office	53973	3.11	33.02%	-23371	×	-7.95%

Table 3.10: The profitability of the ASHP investment on the hypothesis of the natural gas-powered existing system.

City, insulation (high or low) and building			Ecobonus applied NPV (€)	PBT (years)	IRR (-)	Ecobonus not applied NPV (€)	PBT (years)	IRR (-)
Turin	H	Hotel	191449	7.24	14.48%	114105	11.98	9.69%
		House	7485	9.28	10.12%	424	23.72	4.43%
		Office	11685	10.79	8.44%	-4392	×	2.72%
	L	Hotel	361021	11.15	9.94%	283677	13.53	8.53%
		House	25996	8.22	12.06%	8377	17.61	6.38%
		Office	52817	8.50	11.51%	13831	19.01	5.83%
Cuneo	H	Hotel	214204	7.03	15.03%	136860	11.14	10.44%
		House	6258	9.92	9.09%	-1068	×	3.39%
		Office	11389	10.97	8.32%	-4767	×	2.60%
	L	Hotel	535804	8.61	12.91%	458460	10.22	11.38%
		House	30124	8.10	12.28%	10372	17.08	6.61%
		Office	64463	8.14	12.21%	21757	17.25	6.54%
Oulx	H	Hotel	211520	8.37	12.59%	134176	12.76	9.08%
		House	20958	5.32	18.27%	-3212	×	2.43%
		Office	68583	3.64	28.05%	-8761	×	1.80%
	L	Hotel	370739	13.69	8.21%	293395	15.66	7.28%
		House	31047	9.54	10.11%	6877	20.53	5.32%
		Office	60528	10.20	8.79%	-16816	×	3.00%

Table 3.11: The profitability of the GSHP investment on the hypothesis of the diesel fuel-powered existing system.

City, insulation (high or low) and building			Ecobonus applied NPV (€)	PBT (years)	IRR (-)	Ecobonus not applied NPV (€)	PBT (years)	IRR (-)
Turin	H	Hotel	187477	2.91	36.42%	110133	5.85	19.37%
		House	6652	7.09	13.33%	-409	×	3.67%
		Office	11760	5.93	15.81%	-4317	×	0.73%
	L	Hotel	484948	3.23	33.35%	407604	4.19	26.44%
		House	31276	3.90	26.82%	13657	9.65	12.04%
		Office	68457	3.34	31.51%	29471	8.70	13.32%
Cuneo	H	Hotel	203894	2.95	35.99%	126550	5.58	20.24%
		House	6360	7.10	13.14%	-966	×	3.01%
		Office	13272	6.18	15.30%	-2883	×	2.19%
	L	Hotel	550368	2.97	36.18%	473024	3.75	29.32%
		House	36258	3.51	29.98%	16506	8.63	13.42%
		Office	82677	2.86	36.85%	39971	6.99	16.40%
Oulx	H	Hotel	215385	2.85	37.30%	138041	5.22	21.54%
		House	23484	2.68	38.94%	-686	×	3.37%
		Office	77537	1.46	71.73%	193	24.45	4.26%
	L	Hotel	561986	3.10	34.70%	484642	3.89	28.32%
		House	43051	3.13	33.61%	18881	8.17	14.15%
		Office	123071	2.10	50.19%	45727	6.90	16.59%

Table 3.12: The profitability of the ASHP investment on the hypothesis of the diesel fuel-powered existing system.

City, insulation (high or low) and building			Ecobonus applied NPV (€)	PBT (years)	IRR (-)	Ecobonus not applied NPV (€)	PBT (years)	IRR (-)
Turin	H	Hotel	538744	3.77	28.77%	461400	4.73	23.61%
		House	21541	5.73	18.60%	14481	9.05	12.80%
		Office	30068	7.41	13.79%	13990	14.20	8.10%
	L	Hotel	1518622	4.46	24.73%	1441278	4.83	23.17%
		House	83855	4.32	25.01%	66237	5.96	19.03%
		Office	167461	4.63	23.30%	128475	6.57	17.38%
Cuneo	H	Hotel	629594	3.47	31.16%	552251	4.23	26.17%
		House	23085	5.62	18.99%	15760	8.79	13.18%
		Office	37449	6.67	15.67%	21293	11.68	9.95%
	L	Hotel	1918847	3.51	31.11%	1841503	3.74	29.38%
		House	99076	4.16	25.94%	79324	5.67	19.93%
		Office	207820	4.25	25.39%	165114	5.84	19.41%
Oulx	H	Hotel	727561	3.83	28.42%	650217	4.53	24.57%
		House	43440	3.79	27.67%	19270	9.33	12.44%
		Office	105921	2.96	35.32%	28577	11.17	10.40%
	L	Hotel	2051638	4.85	22.92%	1974294	5.13	21.88%
		House	120073	4.75	22.83%	95903	6.42	17.77%
		Office	250837	5.48	19.51%	173493	8.49	13.62%

Table 3.13: The profitability of the GSHP investment on the hypothesis of the LPG-powered existing system.

City, insulation (high or low) and building			Ecobonus applied NPV (€)	PBT (years)	IRR (-)	Ecobonus not applied NPV (€)	PBT (years)	IRR (-)
Turin	H	Hotel	534773	1.34	78.52%	457429	1.74	60.96%
		House	20708	4.04	26.35%	13648	6.88	16.64%
		Office	30143	3.90	26.92%	14065	9.15	12.67%
	L	Hotel	1642550	1.16	90.62%	1565206	1.26	83.37%
		House	89136	1.93	54.74%	71517	2.74	39.42%
		Office	183101	1.72	61.51%	144114	2.51	42.86%
Cuneo	H	Hotel	619284	1.27	82.51%	541940	1.60	66.25%
		House	23188	3.73	28.62%	15862	6.16	18.45%
		Office	39333	3.66	28.95%	23177	7.08	16.20%
	L	Hotel	1933411	1.01	103.40%	1856067	1.09	96.25%
		House	105210	1.69	62.57%	85458	2.36	45.48%
		Office	226034	1.41	74.56%	183328	1.98	53.64%
Oulx	H	Hotel	731427	1.10	94.84%	654083	1.34	78.57%
		House	45966	1.87	56.49%	21796	4.98	22.50%
		Office	114875	1.18	88.44%	37531	4.87	22.97%
	L	Hotel	2242886	0.94	110.95%	2165542	1.00	104.27%
		House	132078	1.44	73.26%	107908	1.99	53.30%
		Office	313379	1.11	94.26%	236036	1.75	60.48%

Table 3.14: The profitability of the ASHP investment on the hypothesis of the LPG-powered existing system.

Chapter 4

Conclusions

A relevant share (30-40%) of the world energy demand is due to the heating and cooling of buildings and, hence, the reduction of greenhouse gas and air pollutant emissions is the key to improve the sustainability of this sector. In this view, this thesis addressed the techno-economic feasibility of a massive introduction of heat pumps in the Piedmont region (NW Italy).

Piedmont is a region of about 4.5 million inhabitants characterized by a high gross domestic product (GDP) per capita and, in some areas, severe air quality issues, which have been highlighted by monitoring data and are addressed by the Regional Plan for Air Quality (PRQA, in Italian). It emerged that the most critical pollutants are particulate matter (PM_{10} and $PM_{2.5}$), nitrogen dioxide (NO_2), and tropospheric ozone during summer. Heating affects mostly PM and NO_2 since health concern due to tropospheric ozone is reached only during summer. In more detail, the particulate emissions are closely linked to the wood heating sector. This correlation is highlighted, above all, by the fact that, in the areas where the "transport" component and the "industry" components are less important, the heating sector impacts on particulate emissions by more than 75%. Concerning the non-wood heating, similar reasoning can be carried out with the emissions of the sulfate ion. Then, certain pollutants can be considered good "tracers" to identify the areas where obsolete energy technologies are existent and should be replaced.

In this regard, the data of the SIPEE database were processed. The SIPEE is the regional database of building energetic certifications, and it covers 463,320 building units over the 2.79 million properties counted by Istat. Therefore, right now, the database covers around 17% of the Istat sample, but, as the energy certification of buildings is compulsory since 2009 for building construction, sale, rental, and refurbishment, the expectation is that the coverage of SIPEE will increase in the future. According to this database, the production of water domestic hot water found out to be performed mainly employing natural gas (70%) and electricity (25%), whereas for the heating the share of natural gas rises to 77%, and district heating provides a significant contribution (11%). Instead, cooling is almost entirely guaranteed by electricity. In more detail, with respect to the total electricity-driven systems, heat pumps are scarcely diffused for domestic hot water production, whereas they cover a modest share of the space heating demand. However, the effective share of heat pumps with respect to all available technologies is really low for every energy service analyzed.

Geo-referenced datasets were developed based on the SIPEE database to show where different heating and DHW technologies are diffused. For instance, the distributions of natural gas and electricity systems (excluding heat pumps) for the production of domestic hot water show how natural gas is always the preferred solution for producing DHW. Natural gas is generally used when available, both for DHW and for heating, except for large urban centers where district heating plays a leading role, too. Diesel and LPG are diffused only in the areas not reached by gas pipelines, whereas wood biomass is used in rural and mountainous areas. In any case, it is necessary to replace these technologies with less polluting alternatives, such as heat pumps.

From a technical viewpoint, the installation of heat pumps in Piedmont has to face two main issues. The former is the fact that the regional building stock was fabricated mainly in the '60s or '70s. Hence, the energy performances of the building itself are mediocre, and the typical heating terminals installed are not generally suitable to work with the heat pumps. As discussed in Chapter 2, there are several solutions to overcome these problems. The best-case scenario is when radiators are over-sized to work with an inlet of 65-70 °C, so they also work well with the lower temperatures achievable through a heat pump. In other cases, the solutions are different and can be split into traditional ones, such as a back-up heater (to be switched on to cover the demand peaks), or innovative ones, such as novel ventilation radiator systems, which reduce the required inlet temperature. Another subdivision is into more impacting alternatives, such as a substantial masonry renovation of the building envelope, or less impacting ones, such as an auxiliary aeraulic plant.

The second issue is related to the cold climate of Piedmont. This aspect is a problem because it causes a decrease in air-source heat pump performance, which occurs when the heating demand is higher. Ground-source heat pumps are less dependent on climatic conditions since they exploit the thermal inertia of the subsurface.

Since the economic viability of heat pumps affects the possibility of their massive penetration into the brand-new and existing building stock, an analysis was conducted on 18 different case studies and related thermal loads that vary depending on the type of building ("hotel", "house" and "office"), the insulation level (high or low) of the building itself, and the location (Turin, Cuneo, and Oulx). Each case takes into account three solutions for the production of heating, cooling, and DHW:

- A ground-source heat pump (GSHP);
- An air-source heat pump (ASHP);
- A conventional system, consisting of a boiler and an air conditioning plant.

The simulation of the boiler examines three different fuels (natural gas, diesel, and LPG) because their price affects the feasibility of the investment. Furthermore, the application, or not, of the incentive provided for by the law influences the results, as well.

For the evaluation of the investment, various parameters were calculated, namely the weighted average cost of capital (WACC), the net present value (NPV), the payback time (PBT), and the internal rate of return (IRR). The replacement of diesel technologies is convenient in the case of intense heating demand, e.g. in the "hotel" case. On the other hand, the replacement of LPG systems is practically always convenient due to its high price per kWh. The fuel price is a limiting factor for replacing gas boilers since the saving margin of heat pumps is very narrow and hardly justifies the large initial investment required by a heat pump. In this case, the incentive regime is the key to determine the economic convenience of heat pumps. Finally, ASHPs are usually more lucrative than GSHPs because of their lower investment cost. For instance, a new installment, which is feasible for both ASHPs and GSHPs, instead of a diesel fuel-powered existing system, necessitates a PBT included from 2 to 7 years in the first case and from 4 to 14 in the second one. A similar time is required in the case of natural gas (from 1 to 9, and from 4 to 21 years), whereas the difference is less pronounced for LPG (from 1 to 4, and from 3.5 to 7.5 years).

In any case, the energy cost of heat pumps (i.e., the unit cost per thermal kWh delivered to the building) is the lowest among the technologies analyzed and, hence, incentives on the capital costs can make this investment economically convenient. From this point of view, the recently approved incentive scheme called "Superbonus", which covers 110% of the investment for relevant building energy refurbishment, will boost the expansion of heat pumps. This incentive scheme, however, should be temporary[1]. That's why the analysis did not take it into account.

This work provided a knowledge basis for planning the regional policies of Piedmont that aim to increase the share of heat demand covered with heat pumps. However, further developments are necessary: among them, an analysis of how such expansion could affect the electrical grid.

[1]Current deadline on December 2021.

Appendix A

PRQA and legislation

A.1 Municipalities list and zoning

The following tables show the zoning of Piedmont municipalities in compliance with the D.G.R. 29 December 2014 n. 41-855 [7]. In more detail, items are, respectively:

- "Codice ISTAT", which is the six-digit numerical code that ISTAT assigns to every municipalities;
- Toponym;
- Area (m^2);
- Population in 2004;
- Plan zone or Maintenance zone;
- District.

Table A.1: List of Piedmont municipalities in Plan (P) and Maintenance (M) zones [7].

ISTAT code	Municipality	Area (m^2)	2004 population	Zone	District
006001	Acqui Terme	34,016,810	20,142	P	AL
006002	Albera Ligure	21,935,032	349	M	AL
006003	ALESSANDRIA	203,486,613	90,532	P	AL
006004	Alfiano Natta	13,098,545	779	M	AL
006005	Alice Bel Colle	12,360,687	780	M	AL
006006	Alluvioni Cambiò	9,665,294	1,013	M	AL

006007	Altavilla Monferrato	11,366,897	505	M	AL
006008	Alzano Scrivia	2,168,204	409	M	AL
006009	Arquata Scrivia	22,866,514	5,848	P	AL
006010	Avolasca	12,182,192	292	M	AL
006011	Balzola	18,272,455	1,440	M	AL
006012	Basaluzzo	15,262,499	1,935	M	AL
006013	Bassignana	28,256,583	1,799	M	AL
006014	Belforte Monferrato	7,859,876	432	P	AL
006015	Bergamasco	13,218,785	747	M	AL
006016	Berzano di Tortona	2,826,866	153	M	AL
006017	Bistagno	17,148,559	1,805	M	AL
006018	Borghetto di Borbera	39,401,735	1,993	M	AL
006020	Borgo San Martino	9,763,057	1,379	M	AL
006019	Borgoratto Alessandrino	6,737,858	598	M	AL
006021	Bosco Marengo	44,559,062	2,497	P	AL
006022	Bosio	67,185,045	1,183	M	AL
006023	Bozzole	9,045,931	311	M	AL
006024	Brignano Frascata	17,396,667	482	M	AL
006025	Cabella Ligure	42,683,960	603	M	AL
006026	Camagna Monferrato	9,289,308	546	M	AL
006027	Camino	18,445,921	763	M	AL
006028	Cantalupo Ligure	22,634,745	552	M	AL
006029	Capriata d'Orba	27,804,061	1,862	M	AL
006030	Carbonara Scrivia	5,003,609	1,014	P	AL
006031	Carentino	9,965,757	311	M	AL
006032	Carezzano	10,488,187	429	M	AL
006033	Carpeneto	13,433,382	923	M	AL
006034	Carrega Ligure	55,469,911	113	M	AL
006035	Carrosio	6,949,803	468	M	AL
006036	Cartosio	16,712,541	782	M	AL
006037	Casal Cermelli	11,870,992	1,208	P	AL
006039	Casale Monferrato	86,359,437	35,328	P	AL
006038	Casaleggio Boiro	12,348,685	379	M	AL
006040	Casalnoceto	12,961,351	907	P	AL
006041	Casasco	9,087,648	141	M	AL
006042	Cassano Spinola	13,771,502	1,863	P	AL
006043	Cassine	33,070,726	3,015	M	AL
006044	Cassinelle	24,565,947	883	M	AL
006045	Castellania	7,426,623	99	M	AL
006046	Castellar Guidobono	2,664,893	404	M	AL
006047	Castellazzo Bormida	45,057,905	4,428	P	AL

006048	Castelletto d'Erro	5,891,777	144	M	AL
006049	Castelletto d'Orba	13,813,828	1,979	M	AL
006050	Castelletto Merli	11,638,282	499	M	AL
006051	Castelletto Monferrato	9,628,377	1,511	P	AL
006052	Castelnuovo Bormida	12,971,695	666	M	AL
006053	Castelnuovo Scrivia	45,300,676	5,617	P	AL
006054	Castelspina	5,521,784	403	M	AL
006055	Cavatore	8,621,467	295	M	AL
006056	Cella Monte	5,552,692	541	M	AL
006057	Cereseto	10,351,628	471	M	AL
006058	Cerreto Grue	5,078,733	346	M	AL
006059	Cerrina Monferrato	17,270,898	1,598	M	AL
006060	Coniolo	10,410,491	440	P	AL
006061	Conzano	11,617,499	1,001	M	AL
006062	Costa Vescovato	7,715,326	346	M	AL
006063	Cremolino	14,042,488	1,066	M	AL
006064	Cuccaro Monferrato	5,191,967	358	M	AL
006065	Denice	7,197,807	206	M	AL
006066	Dernice	18,266,929	235	M	AL
006067	Fabbrica Curone	53,908,422	808	M	AL
006068	Felizzano	25,088,893	2,405	P	AL
006069	Fraconalto	17,791,383	332	M	AL
006070	Francavilla Bisio	7,364,904	466	M	AL
006071	Frascaro	5,176,385	457	M	AL
006072	Frassinello Monferrato	8,414,965	542	M	AL
006073	Frassineto Po	29,672,362	1,462	M	AL
006074	Fresonara	6,866,355	703	P	AL
006075	Frugarolo	27,000,995	1,913	P	AL
006076	Fubine	25,495,208	1,689	M	AL
006077	Gabiano	18,026,602	1,245	M	AL
006078	Gamalero	12,123,251	787	M	AL
006079	Garbagna	20,596,228	719	M	AL
006080	Gavazzana	3,247,596	129	M	AL
006081	Gavi	51,557,024	4,557	M	AL
006082	Giarole	5,387,336	693	M	AL
006083	Gremiasco	17,581,335	370	M	AL
006084	Grognardo	9,106,861	315	M	AL
006085	Grondona	26,134,183	548	M	AL
006086	Guazzora	2,960,694	311	M	AL
006087	Isola Sant'Antonio	23,345,794	754	M	AL
006088	Lerma	13,336,101	816	M	AL

006089	Lu	21,852,648	1,207	M	AL
006090	Malvicino	8,429,427	124	M	AL
006091	Masio	22,250,325	1,488	M	AL
006092	Melazzo	20,105,572	1,241	M	AL
006093	Merana	9,489,358	181	M	AL
006094	Mirabello Monferrato	13,207,585	1,381	P	AL
006095	Molare	32,829,676	2,101	M	AL
006096	Molino dei Torti	2,801,931	685	M	AL
006097	Mombello Monferrato	19,636,257	1,105	M	AL
006098	Momperone	8,530,721	225	M	AL
006099	Moncestino	6,754,207	238	M	AL
006100	Mongiardino Ligure	33,045,055	193	M	AL
006101	Monleale	9,714,583	624	M	AL
006102	Montacuto	23,759,907	335	M	AL
006103	Montaldeo	5,630,820	311	M	AL
006104	Montaldo Bormida	5,849,817	676	M	AL
006105	Montecastello	6,611,928	352	M	AL
006106	Montechiaro d'Acqui	17,809,660	556	M	AL
006107	Montegioco	5,134,630	315	M	AL
006108	Montemarzino	9,877,854	361	M	AL
006109	Morano sul Po	15,954,912	1,580	P	AL
006110	Morbello	23,028,957	456	M	AL
006111	Mornese	13,057,998	703	M	AL
006112	Morsasco	10,765,375	683	M	AL
006113	Murisengo	15,193,390	1,525	M	AL
006114	Novi Ligure	56,421,613	28,204	P	AL
006115	Occimiano	22,499,452	1,409	P	AL
006116	Odalengo Grande	15,378,708	537	M	AL
006117	Odalengo Piccolo	7,528,490	268	M	AL
006118	Olivola	2,695,590	142	M	AL
006119	Orsara Bormida	4,959,205	428	M	AL
006120	Ottiglio	14,439,664	702	M	AL
006121	Ovada	35,750,944	11,673	P	AL
006122	Oviglio	27,288,488	1,248	M	AL
006123	Ozzano Monferrato	15,214,787	1,558	M	AL
006124	Paderna	4,516,050	242	M	AL
006125	Pareto	41,487,751	643	M	AL
006126	Parodi Ligure	12,378,782	751	M	AL
006127	Pasturana	5,240,525	1,086	M	AL
006128	Pecetto di Valenza	11,445,749	1,322	M	AL
006129	Pietra Marazzi	8,080,325	949	M	AL

006130	Piovera	15,799,966	791	M	AL
006131	Pomaro Monferrato	13,476,069	398	M	AL
006132	Pontecurone	29,526,764	3,820	P	AL
006133	Pontestura	18,926,019	1,539	M	AL
006134	Ponti	11,715,733	679	M	AL
006135	Ponzano Monferrato	11,546,843	405	M	AL
006136	Ponzone	69,036,221	1,217	M	AL
006137	Pozzol Groppo	14,086,414	394	M	AL
006138	Pozzolo Formigaro	36,278,533	4,793	P	AL
006139	Prasco	6,035,466	535	M	AL
006140	Predosa	33,073,981	2,068	P	AL
006141	Quargnento	36,143,839	1,346	M	AL
006142	Quattordio	17,837,702	1,722	P	AL
006143	Ricaldone	10,622,211	650	M	AL
006144	Rivalta Bormida	10,295,155	1,452	M	AL
006145	Rivarone	6,937,574	383	M	AL
006147	Rocca Grimalda	15,829,635	1,400	P	AL
006146	Roccaforte Ligure	20,526,060	172	M	AL
006148	Rocchetta Ligure	10,929,735	208	M	AL
006149	Rosignano Monferrato	20,012,155	1,659	M	AL
006150	Sala Monferrato	7,633,438	446	M	AL
006151	Sale	45,063,246	4,253	M	AL
006152	San Cristoforo	3,560,288	595	M	AL
006153	San Giorgio Monferrato	7,133,519	1,294	P	AL
006154	San Salvatore Monferrato	31,732,879	4,629	P	AL
006155	San Sebastiano Curone	3,858,346	589	M	AL
006156	Sant'Agata Fossili	7,786,662	425	M	AL
006157	Sardigliano	13,327,306	438	M	AL
006158	Sarezzano	13,933,446	1,171	M	AL
006159	Serralunga di Crea	8,991,514	627	M	AL
006160	Serravalle Scrivia	14,753,687	6,073	P	AL
006161	Sezzadio	34,331,568	1,276	M	AL
006162	Silvano d'Orba	12,682,541	1,856	M	AL
006163	Solero	22,553,744	1,661	P	AL
006164	Solonghello	4,904,470	234	M	AL
006165	Spigno Monferrato	54,699,981	1,188	M	AL
006166	Spineto Scrivia	3,864,638	340	M	AL
006167	Stazzano	17,720,233	2,168	M	AL
006168	Strevi	15,401,836	2,055	M	AL
006169	Tagliolo Monferrato	26,966,650	1,499	M	AL
006170	Tassarolo	7,332,838	598	M	AL

006171	Terruggia	6,442,660	825	M	AL
006172	Terzo	8,941,274	862	M	AL
006173	Ticineto	8,086,969	1,381	M	AL
006174	Tortona	98,188,863	26,623	P	AL
006175	Treville	4,643,903	267	M	AL
006176	Trisobbio	8,503,963	681	M	AL
006177	Valenza	51,139,919	20,489	P	AL
006178	Valmacca	12,382,413	1,089	M	AL
006179	Vignale Monferrato	18,828,741	1,114	M	AL
006180	Vignole Borbera	8,537,462	2,154	P	AL
006181	Viguzzolo	18,281,462	2,964	P	AL
006182	Villadeati	14,564,611	513	M	AL
006183	Villalvernia	4,570,001	932	P	AL
006184	Villamiroglio	9,526,564	336	M	AL
006185	Villanova Monferrato	16,703,908	1,769	P	AL
006186	Villaromagnano	6,122,242	754	M	AL
006187	Visone	12,268,720	1,178	M	AL
006188	Volpedo	10,511,071	1,197	M	AL
006189	Volpeglino	3,223,835	162	M	AL
006190	Voltaggio	52,313,665	769	M	AL
005001	Agliano Terme	15,458,509	1,658	M	AT
005002	Albugnano	9,590,245	486	M	AT
005003	Antignano	11,044,608	1,002	P	AT
005004	Aramengo	11,361,852	639	M	AT
005005	ASTI	151,377,885	73,434	P	AT
005006	Azzano d'Asti	6,507,804	390	M	AT
005007	Baldichieri d'Asti	5,207,234	1,000	P	AT
005008	Belveglio	5,320,511	330	M	AT
005009	Berzano di San Pietro	7,307,626	440	M	AT
005010	Bruno	8,999,586	379	M	AT
005011	Bubbio	16,055,908	917	M	AT
005012	Buttigliera d'Asti	19,087,756	2,164	P	AT
005013	Calamandrana	12,711,875	1,639	P	AT
005014	Calliano	17,420,252	1,443	P	AT
005015	Calosso	15,758,179	1,298	M	AT
005016	Camerano Casasco	6,712,064	502	M	AT
005017	Canelli	23,439,622	10,297	P	AT
005018	Cantarana	9,725,977	863	M	AT
005019	Capriglio	5,153,825	308	M	AT
005020	Casorzo	12,717,474	658	M	AT
005021	Cassinasco	11,715,353	639	M	AT

005022	Castagnole delle Lanze	21,596,743	3,711	P	AT
005023	Castagnole Monferrato	17,144,632	1,238	M	AT
005024	Castel Boglione	11,871,552	645	M	AT
005032	Castel Rocchero	5,628,083	385	M	AT
005025	Castell'AIfero	20,028,310	2,736	P	AT
005026	Castellero	4,191,315	297	P	AT
005027	Castelletto Molina	3,043,189	184	M	AT
005028	Castello di Annone	23,185,568	1,868	P	AT
005029	Castelnuovo Belbo	9,649,072	931	M	AT
005030	Castelnuovo Calcea	8,107,421	794	M	AT
005031	Castelnuovo Don Bosco	21,687,630	3,101	P	AT
005033	Cellarengo	10,580,113	651	M	AT
005034	Celle Enomondo	5,466,979	461	M	AT
005035	Cerreto d'Asti	3,862,113	253	M	AT
005036	Cerro Tanaro	4,858,139	615	M	AT
005037	Cessole	11,993,933	429	M	AT
005038	Chiusano d'Asti	2,528,024	236	M	AT
005039	Cinaglio	5,409,230	470	M	AT
005040	Cisterna d'Asti	10,864,504	1,257	M	AT
005041	Coazzolo	4,091,362	301	M	AT
005042	Cocconato	16,440,394	1,629	P	AT
005044	Corsione	5,151,604	183	M	AT
005045	Cortandone	5,005,411	288	M	AT
005046	Cortanze	4,342,519	266	M	AT
005047	Cortazzone	10,449,105	637	M	AT
005048	Cortiglione	8,574,643	565	M	AT
005049	Cossombrato	5,116,606	493	M	AT
005050	Costigliole d'Asti	36,815,980	5,963	P	AT
005051	Cunico	6,655,595	496	M	AT
005052	Dusino San Michele	11,924,589	951	P	AT
005053	Ferrere	14,027,759	1,542	M	AT
005054	Fontanile	8,155,711	572	M	AT
005055	Frinco	7,158,667	752	M	AT
005056	Grana	5,956,762	628	M	AT
005057	Grazzano Badoglio	10,605,924	655	M	AT
005058	Incisa Scapaccino	20,609,516	2,112	P	AT
005059	Isola d'Asti	13,413,346	2,078	P	AT
005060	Loazzolo	14,756,483	356	M	AT
005061	Maranzana	4,509,814	317	M	AT
005062	Maretto	4,849,315	370	P	AT
005063	Moasca	4,113,824	422	M	AT

005064	Mombaldone	12,209,801	257	M	AT
005065	Mombaruzzo	22,168,588	1,178	M	AT
005066	Mombercelli	14,283,435	2,274	P	AT
005067	Monale	9,165,231	948	P	AT
005068	Monastero Bormida	13,711,594	978	M	AT
005069	Moncalvo	17,437,825	3,319	P	AT
005070	Moncucco Torinese	14,302,507	816	M	AT
005071	Mongardino	6,580,662	989	M	AT
005072	Montabone	8,613,293	357	M	AT
005073	Montafia	14,532,374	986	M	AT
005074	Montaldo Scarampi	6,631,183	704	M	AT
005075	Montechiaro d'Asti	10,308,966	1,412	P	AT
005076	Montegrosso d'Asti	15,592,122	2,141	P	AT
005077	Montemagno	15,932,775	1,214	M	AT
005121	Montiglio Monferrato	26,941,189	1,693	M	AT
005079	Moransengo	5,377,959	227	M	AT
005080	Nizza Monferrato	30,409,663	10,027	P	AT
005081	Olmo Gentile	6,149,597	100	M	AT
005082	Passerano Marmorito	12,032,977	454	M	AT
005083	Penango	9,555,817	566	M	AT
005084	Piea	9,154,433	592	M	AT
005085	Pino d'Asti	4,139,932	225	M	AT
005086	Piovà Massaia	11,146,438	676	M	AT
005087	Portacomaro	11,197,028	1,976	P	AT
005088	Quaranti	2,633,356	203	M	AT
005089	Refrancore	13,135,657	1,624	M	AT
005090	Revigliasco d'Asti	8,870,325	865	M	AT
005091	Roatto	6,363,071	385	M	AT
005092	Robella	12,407,850	545	M	AT
005093	Rocca d'Arazzo	12,520,301	942	M	AT
005094	Roccaverano	28,923,017	473	M	AT
005095	Rocchetta Palafea	7,834,579	401	M	AT
005096	Rocchetta Tanaro	15,594,232	1,454	M	AT
005097	San Damiano d'Asti	47,911,647	8,024	P	AT
005098	San Giorgio Scarampi	6,737,769	122	M	AT
005099	San Martino Alfieri	7,299,224	717	M	AT
005100	San Marzano Oliveto	9,731,019	1,061	M	AT
005101	San Paolo Solbrito	11,817,553	1,127	P	AT
005103	Scurzolengo	5,396,660	617	M	AT
005104	Serole	12,113,573	166	M	AT
005105	Sessame	8,966,010	281	M	AT

005106	Settime	6,577,902	561	M	AT
005107	Soglio	3,233,928	164	M	AT
005108	Tigliole	16,056,355	1,676	P	AT
005109	Tonco	11,749,100	895	M	AT
005110	Tonengo	5,611,545	196	M	AT
005111	Vaglio Serra	4,695,933	293	M	AT
005112	Valfenera	22,479,585	2,265	P	AT
005113	Vesime	12,318,491	683	P	AT
005114	Viale	4,033,161	269	M	AT
005115	Viarigi	13,710,564	986	M	AT
005116	Vigliano d'Asti	6,628,135	823	M	AT
005119	Villa San Secondo	6,231,360	385	M	AT
005117	Villafranca d'Asti	13,074,492	3,041	P	AT
005118	Villanova d'Asti	41,803,294	5,027	P	AT
005120	Vinchio	9,331,166	665	M	AT
096001	Ailoche	10,892,255	321	M	BI
096002	Andorno Micca	11,748,281	3,595	M	BI
096003	Benna	9,418,758	1,168	P	BI
096004	BIELLA	46,575,690	46,350	P	BI
096005	Bioglio	18,803,828	1,049	M	BI
096006	Borriana	5,323,634	904	P	BI
096007	Brusnengo	10,654,389	2,127	M	BI
096008	Callabiana	7,122,304	139	M	BI
096009	Camandona	9,076,183	425	M	BI
096010	Camburzano	3,865,350	1,194	M	BI
096011	Campiglia Cervo	11,597,420	176	M	BI
096012	Candelo	15,119,899	7,989	P	BI
096013	Caprile	7,987,619	221	M	BI
096014	Casapinta	2,934,480	480	M	BI
096015	Castelletto Cervo	14,755,835	862	M	BI
096016	Cavaglià	25,867,479	3,644	P	BI
096017	Cerreto Castello	2,448,565	662	P	BI
096018	Cerrione	27,904,283	2,818	P	BI
096019	Coggiola	23,696,073	2,285	M	BI
096020	Cossato	27,658,262	15,078	P	BI
096021	Crevacuore	11,736,895	1,813	M	BI
096022	Crosa	992,056	332	M	BI
096023	Curino	21,654,345	480	M	BI
096024	Donato	12,064,206	750	M	BI
096025	Dorzano	4,718,024	493	P	BI
096026	Gaglianico	4,614,537	3,871	P	BI

096027	Gifflenga	2,350,624	122	M	BI
096028	Graglia	20,097,952	1,620	M	BI
096029	Lessona	11,870,236	2,487	M	BI
096030	Magnano	10,374,298	384	P	BI
096031	Massazza	11,723,160	534	P	BI
096032	Masserano	27,159,308	2,315	M	BI
096033	Mezzana Mortigliengo	4,465,969	618	M	BI
096034	Miagliano	674,528	631	P	BI
096035	Mongrando	16,510,682	4,040	P	BI
096084	Mosso	17,194,077	1,760	M	BI
096037	Mottalciata	18,163,426	1,445	P	BI
096038	Muzzano	6,057,257	673	M	BI
096039	Netro	12,484,777	1,010	M	BI
096040	Occhieppo Inferiore	4,056,792	3,943	P	BI
096041	Occhieppo Superiore	5,181,491	2,956	P	BI
096042	Pettinengo	13,145,439	1,567	M	BI
096043	Piatto	3,610,798	527	M	BI
096044	Piedicavallo	17,668,436	189	M	BI
096046	Pollone	16,367,585	2,208	P	BI
096047	Ponderano	7,056,209	3,896	P	BI
096048	Portula	11,659,588	1,505	M	BI
096049	Pralungo	7,151,697	2,734	P	BI
096050	Pray	9,132,301	2,434	M	BI
096051	Quaregna	5,894,853	1,325	P	BI
096052	Quittengo	8,024,425	221	M	BI
096053	Ronco Biellese	3,813,292	1,496	P	BI
096054	Roppolo	8,745,779	907	P	BI
096055	Rosazza	8,851,935	89	M	BI
096056	Sagliano Micca	15,030,198	1,731	M	BI
096057	Sala Biellese	8,093,280	622	P	BI
096058	Salussola	38,621,460	2,043	P	BI
096060	San Paolo Cervo	8,688,235	139	M	BI
096059	Sandigliano	10,027,146	2,834	P	BI
096061	Selve Marcone	2,204,509	100	M	BI
096062	Soprana	5,195,061	822	M	BI
096063	Sordevolo	13,761,948	1,346	M	BI
096064	Sostegno	19,449,641	764	M	BI
096065	Strona	3,730,146	1,217	P	BI
096066	Tavigliano	11,267,721	953	M	BI
096067	Ternengo	1,973,068	310	M	BI
096068	Tollegno	3,379,712	2,678	P	BI

096069	Torrazzo	5,836,289	204	M	BI
096070	Trivero	29,140,885	6,663	M	BI
096071	Valdengo	7,893,676	2,556	P	BI
096072	Vallanzengo	4,099,081	236	M	BI
096073	Valle Mosso	9,078,984	3,965	P	BI
096074	Valle San Nicolao	13,461,478	1,136	M	BI
096075	Veglio	6,404,593	643	M	BI
096076	Verrone	8,630,775	1,155	P	BI
096077	Vigliano Biellese	8,227,450	8,406	P	BI
096078	Villa del Bosco	2,559,860	380	M	BI
096079	Villanova Biellese	7,950,525	185	P	BI
096080	Viverone	12,558,284	1,434	P	BI
096081	Zimone	2,899,100	413	P	BI
096082	Zubiena	12,502,264	1,286	P	BI
096083	Zumaglia	2,442,993	1,114	M	BI
004001	Acceglio	151,369,721	167	M	CN
004002	Aisone	36,891,631	269	M	CN
004003	Alba	54,137,717	30,083	P	CN
004004	Albaretto della Torre	4,784,905	249	M	CN
004005	Alto	7,763,159	113	M	CN
004006	Argentera	76,306,002	105	M	CN
004007	Arguello	4,988,555	184	M	CN
004008	Bagnasco	30,922,735	1,043	M	CN
004009	Bagnolo Piemonte	63,225,693	5,704	M	CN
004010	Baldissero d'AIba	15,286,944	1,083	M	CN
004011	Barbaresco	7,653,336	656	M	CN
004012	Barge	82,054,614	7,571	M	CN
004013	Barolo	5,627,118	697	M	CN
004014	Bastia Mondovì	12,010,877	660	M	CN
004015	Battifollo	11,205,468	252	M	CN
004016	Beinette	17,656,297	2,898	M	CN
004017	Bellino	62,330,923	165	M	CN
004018	Belvedere Langhe	5,049,575	384	M	CN
004019	Bene Vagienna	49,252,510	3,420	M	CN
004020	Benevello	5,421,145	451	M	CN
004021	Bergolo	3,244,542	80	M	CN
004022	Bernezzo	25,810,917	3,195	M	CN
004023	Bonvicino	7,263,935	122	M	CN
004025	Borgo San Dalmazzo	22,389,856	11,742	P	CN
004024	Borgomale	8,386,157	399	M	CN
004026	Bosia	5,651,009	208	M	CN

004027	Bossolasco	14,657,455	686	M	CN
004028	Boves	51,758,293	9,507	M	CN
004029	Bra	59,467,331	28,819	P	CN
004030	Briaglia	6,193,973	314	M	CN
004031	Briga Alta	52,486,384	56	M	CN
004032	Brondello	10,147,432	349	M	CN
004033	Brossasco	28,033,778	1,123	M	CN
004034	Busca	65,923,091	9,671	M	CN
004035	Camerana	22,241,373	709	M	CN
004036	Camo	3,654,681	215	M	CN
004037	Canale	17,616,784	5,544	M	CN
004038	Canosio	48,513,403	92	M	CN
004039	Caprauna	11,508,078	128	M	CN
004040	Caraglio	41,633,909	6,476	M	CN
004041	Caramagna Piemonte	26,785,538	2,853	P	CN
004042	Cardè	19,318,927	1,077	M	CN
004043	Carrù	25,809,000	4,161	M	CN
004044	Cartignano	6,474,105	172	M	CN
004045	Casalgrasso	17,630,520	1,353	M	CN
004046	Castagnito	7,047,192	1,875	M	CN
004047	Casteldelfino	32,874,326	208	M	CN
004048	Castellar	3,397,983	253	M	CN
004049	Castelletto Stura	17,104,657	1,179	M	CN
004050	Castelletto Uzzone	14,860,165	364	M	CN
004051	Castellinaldo	7,793,603	881	M	CN
004052	Castellino Tanaro	12,452,413	335	M	CN
004053	Castelmagno	48,501,201	104	M	CN
004054	Castelnuovo di Ceva	6,211,933	127	M	CN
004055	Castiglione Falletto	4,638,733	643	M	CN
004056	Castiglione Tinella	11,507,954	866	M	CN
004057	Castino	15,606,807	525	M	CN
004058	Cavallerleone	16,389,865	578	M	CN
004059	Cavallermaggiore	51,527,450	5,160	M	CN
004060	Celle di Macra	31,578,476	114	M	CN
004061	Centallo	42,668,907	6,368	P	CN
004062	Ceresole Alba	37,145,653	2,092	M	CN
004063	Cerreto Langhe	9,788,147	463	M	CN
004064	Cervasca	18,274,888	4,360	M	CN
004065	Cervere	18,624,020	1,932	P	CN
004066	Ceva	42,660,166	5,795	M	CN
004067	Cherasco	81,589,415	7,624	P	CN

004068	Chiusa di Pesio	94,940,407	3,709	M	CN
004069	Cigliè	5,969,702	185	M	CN
004070	Cissone	5,934,468	82	M	CN
004071	Clavesana	17,287,783	845	M	CN
004072	Corneliano d'AIba	10,092,703	1,979	M	CN
004073	Cortemilia	24,852,155	2,511	M	CN
004074	Cossano Belbo	20,650,792	1,068	M	CN
004075	Costigliole Saluzzo	15,195,409	3,212	M	CN
004076	Cravanzana	7,801,846	394	M	CN
004077	Crissolo	49,196,643	204	M	CN
004078	CUNEO	119,618,225	54,914	P	CN
004079	Demonte	127,270,575	2,019	M	CN
004080	Diano d'AIba	17,529,333	3,112	M	CN
004081	Dogliani	35,523,647	4,636	M	CN
004082	Dronero	59,354,589	7,142	M	CN
004083	Elva	25,846,935	114	M	CN
004084	Entracque	160,998,211	836	M	CN
004085	Envie	25,003,355	1,971	M	CN
004086	Farigliano	16,534,540	1,766	M	CN
004087	Faule	7,063,271	425	M	CN
004088	Feisoglio	7,603,902	383	M	CN
004089	Fossano	130,044,493	24,198	P	CN
004090	Frabosa soprana	47,509,928	835	M	CN
004091	Frabosa sottana	37,631,502	1,462	M	CN
004092	Frassino	16,992,181	301	M	CN
004093	Gaiola	4,979,616	477	M	CN
004094	Gambasca	5,590,311	382	M	CN
004095	Garessio	129,614,595	3,505	M	CN
004096	Genola	13,712,522	2,380	P	CN
004097	Gorzegno	14,040,860	362	M	CN
004098	Gottasecca	13,002,597	191	M	CN
004099	Govone	18,915,413	1,991	P	CN
004100	Grinzane Cavour	3,821,721	1,863	P	CN
004101	Guarene	13,232,147	3,191	P	CN
004102	Igliano	3,380,085	80	M	CN
004103	Isasca	4,984,440	97	M	CN
004105	La Morra	24,226,167	2,668	M	CN
004104	Lagnasco	17,645,451	1,308	M	CN
004106	Lequio Berria	11,827,497	542	M	CN
004107	Lequio Tanaro	12,055,999	731	M	CN
004108	Lesegno	14,196,169	868	P	CN

004109	Levice	16,673,786	242	M	CN
004110	Limone Piemonte	70,960,223	1,572	M	CN
004111	Lisio	8,236,903	237	M	CN
004112	Macra	24,667,848	63	M	CN
004113	Magliano Alfieri	9,581,319	1,726	M	CN
004114	Magliano Alpi	32,826,641	2,145	M	CN
004115	Mango	20,134,302	1,359	M	CN
004116	Manta	11,699,370	3,392	M	CN
004117	Marene	29,021,676	2,803	M	CN
004118	Margarita	11,264,743	1,342	M	CN
004119	Marmora	41,132,040	97	M	CN
004120	Marsaglia	12,932,851	299	M	CN
004121	Martiniana Po	13,167,461	693	M	CN
004122	Melle	27,956,078	340	M	CN
004123	Moiola	15,049,856	282	M	CN
004124	Mombarcaro	14,556,510	319	M	CN
004125	Mombasiglio	17,702,076	636	M	CN
004126	Monastero di Vasco	17,516,299	1,214	M	CN
004127	Monasterolo Casotto	7,632,220	120	M	CN
004128	Monasterolo di Savigliano	15,018,280	1,200	M	CN
004129	Monchiero	4,941,157	560	M	CN
004130	Mondovì	87,371,230	22,068	P	CN
004131	Monesiglio	13,007,997	744	M	CN
004132	Monforte d'AIba	25,426,130	1,976	M	CN
004133	Montà	26,805,690	4,445	M	CN
004134	Montaldo di Mondovì	23,543,521	599	M	CN
004135	Montaldo Roero	11,698,328	889	M	CN
004136	Montanera	11,637,669	727	M	CN
004137	Montelupo Albese	6,624,069	494	M	CN
004138	Montemale di Cuneo	10,811,522	233	M	CN
004139	Monterosso Grana	42,256,283	597	M	CN
004140	Monteu Roero	24,475,894	1,627	M	CN
004141	Montezemolo	5,127,585	276	M	CN
004142	Monticello d'AIba	10,190,483	2,003	M	CN
004143	Moretta	24,036,321	4,226	P	CN
004144	Morozzo	22,270,390	1,985	M	CN
004145	Murazzano	27,571,474	836	M	CN
004146	Murello	17,366,013	904	M	CN
004147	Narzole	26,255,436	3,341	M	CN
004148	Neive	20,782,645	3,042	M	CN
004149	Neviglie	8,147,088	419	M	CN

004150	Niella Belbo	17,683,898	424	M	CN
004151	Niella Tanaro	15,724,606	1,021	M	CN
004152	Novello	11,746,436	968	M	CN
004153	Nucetto	7,630,844	451	M	CN
004154	Oncino	47,356,954	93	M	CN
004155	Ormea	124,931,564	1,904	M	CN
004156	Ostana	16,930,010	68	M	CN
004157	Paesana	58,194,746	3,027	M	CN
004158	Pagno	8,662,552	564	M	CN
004159	Pamparato	34,710,607	398	M	CN
004160	Paroldo	12,505,170	239	M	CN
004161	Perletto	10,051,570	321	M	CN
004162	Perlo	10,339,673	121	M	CN
004163	Peveragno	67,883,513	5,276	M	CN
004164	Pezzolo valle Uzzone	26,759,605	358	M	CN
004165	Pianfei	15,217,427	1,980	M	CN
004166	Piasco	10,589,866	2,827	M	CN
004167	Pietraporzio	55,418,560	99	M	CN
004168	Piobesi d'AIba	4,017,793	1,170	P	CN
004169	Piozzo	14,125,235	984	M	CN
004170	Pocapaglia	17,432,032	2,880	M	CN
004171	Polonghera	10,188,340	1,134	M	CN
004172	Pontechianale	96,159,512	202	M	CN
004173	Pradleves	19,256,831	306	M	CN
004174	Prazzo	52,342,623	205	M	CN
004175	Priero	21,777,339	477	M	CN
004176	Priocca	8,861,043	1,979	M	CN
004177	Priola	27,945,823	765	M	CN
004178	Prunetto	13,525,055	492	M	CN
004179	Racconigi	47,986,071	9,886	M	CN
004180	Revello	52,319,023	4,236	M	CN
004181	Rifreddo	6,892,237	1,071	M	CN
004182	Rittana	11,307,952	140	M	CN
004183	Roaschia	23,644,226	167	M	CN
004184	Roascio	6,054,909	80	M	CN
004185	Robilante	25,056,834	2,362	P	CN
004186	Roburent	30,137,565	559	M	CN
004188	Rocca Cigliè	7,070,824	149	M	CN
004189	Rocca de' Baldi	26,264,204	1,656	M	CN
004187	Roccabruna	24,214,794	1,482	M	CN
004190	Roccaforte Mondovì	84,701,116	2,054	M	CN

004191	Roccasparvera	11,272,269	700	M	CN
004192	Roccavione	19,326,281	2,848	P	CN
004193	Rocchetta Belbo	4,596,059	192	M	CN
004194	Roddi	9,284,888	1,426	M	CN
004195	Roddino	10,130,720	386	M	CN
004196	Rodello	8,839,410	970	M	CN
004197	Rossana	19,953,709	950	M	CN
004198	Ruffia	7,570,833	337	M	CN
004199	Sale delle Langhe	11,739,244	509	M	CN
004200	Sale San Giovanni	7,576,553	181	M	CN
004201	Saliceto	25,178,532	1,440	M	CN
004202	Salmour	12,735,070	716	P	CN
004203	Saluzzo	76,661,660	16,153	P	CN
004204	Sambuco	46,063,667	92	M	CN
004205	Sampeyre	98,885,501	1,129	M	CN
004206	San Benedetto Belbo	4,940,432	190	M	CN
004207	San Damiano Macra	54,476,801	451	M	CN
004210	San Michele Mondovì	18,154,763	2,064	P	CN
004208	Sanfrè	15,436,434	2,602	M	CN
004209	Sanfront	39,906,626	2,642	M	CN
004212	Santa Vittoria d'AIba	10,024,825	2,591	P	CN
004211	Sant'AIbano Stura	27,468,101	2,185	M	CN
004213	Santo Stefano Belbo	23,553,305	4,021	M	CN
004214	Santo Stefano Roero	13,393,989	1,314	M	CN
004215	Savigliano	110,744,481	20,456	P	CN
004216	Scagnello	8,927,050	209	M	CN
004217	Scarnafigi	30,362,139	1,936	M	CN
004218	Serralunga d'AIba	8,580,795	507	M	CN
004219	Serravalle Langhe	8,787,520	340	M	CN
004220	Sinio	8,606,901	471	M	CN
004221	Somano	11,796,133	399	M	CN
004222	Sommariva del Bosco	34,982,277	5,923	P	CN
004223	Sommativa Perno	17,225,759	2,800	M	CN
004224	Stroppo	28,100,398	98	M	CN
004225	Tarantasca	12,238,719	2,002	M	CN
004226	Torre Bormida	7,478,929	216	M	CN
004227	Torre Mondovì	18,586,941	521	M	CN
004228	Torre San Giorgio	5,366,492	696	P	CN
004229	Torresina	3,748,400	64	M	CN
004230	Treiso	9,485,972	764	M	CN
004231	Trezzo Tinella	10,438,839	350	M	CN

004232	Trinita’	28,057,974	2,005	M	CN
004233	Valdieri	153,175,495	950	M	CN
004234	Valgrana	23,090,340	815	M	CN
004235	Valloriate	16,937,795	158	M	CN
004236	Valmala	11,025,088	61	M	CN
004237	Venasca	20,424,434	1,563	M	CN
004238	Verduno	7,327,636	523	M	CN
004239	Vernante	61,223,712	1,307	M	CN
004240	Verzuolo	26,288,028	6,379	P	CN
004241	Vezza d’AIba	14,287,260	2,130	M	CN
004242	Vicoforte	25,684,680	3,103	M	CN
004243	Vignolo	7,946,418	2,112	M	CN
004244	Villafalletto	29,849,444	2,900	M	CN
004245	Villanova Mondovì	28,547,099	5,506	M	CN
004246	Villanova Solaro	14,838,304	788	M	CN
004247	Villar San Costanzo	19,508,869	1,446	M	CN
004248	Vinadio	184,192,756	718	M	CN
004249	Viola	20,951,592	470	M	CN
004250	Vottignasco	8,089,968	575	M	CN
003001	Agrate Conturbia	14,492,734	1,351	M	NO
003002	Ameno	10,357,023	906	M	NO
003006	Armeno	31,334,808	2,229	M	NO
003008	Arona	15,242,963	14,413	P	NO
003012	Barengo	19,527,369	916	M	NO
003016	Bellinzago Novarese	39,005,835	8,718	P	NO
003018	Biandrate	12,502,023	1,124	P	NO
003019	Boca	9,622,863	1,195	M	NO
003021	Bogogno	8,870,250	1,221	M	NO
003022	Bolzano Novarese	3,143,740	1,046	M	NO
003025	Borgo Ticino	13,661,737	4,229	P	NO
003023	Borgolavezzaro	21,083,424	1,909	M	NO
003024	Borgomanero	32,581,485	20,253	P	NO
003026	Briga Novarese	4,698,116	2,759	P	NO
003027	Briona	24,738,082	1,196	M	NO
003030	Caltignaga	22,365,746	2,447	M	NO
003032	Cameri	40,261,042	10,103	P	NO
003036	Carpignano Sesia	14,633,490	2,572	P	NO
003037	Casalbeltrame	16,079,543	883	P	NO
003039	Casaleggio Novara	10,576,195	869	M	NO
003040	Casalino	39,397,853	1,469	M	NO
003041	Casalvolone	17,455,974	831	P	NO

003042	Castellazzo Novarese	10,822,185	288	M	NO
003043	Castelletto sopra Ticino	14,662,960	9,323	P	NO
003044	Cavaglietto	6,444,232	417	M	NO
003045	Cavaglio d'Agogna	9,858,345	1,337	M	NO
003047	Cavallirio	8,318,991	1,254	M	NO
003049	Cerano	32,052,038	6,792	P	NO
003051	Colazza	3,280,679	443	M	NO
003052	Comignago	4,327,583	1,051	M	NO
003055	Cressa	7,103,562	1,480	P	NO
003058	Cureggio	8,274,317	2,303	P	NO
003060	Divignano	5,113,743	1,317	M	NO
003062	Dormelletto	7,404,783	2,546	P	NO
003065	Fara Novarese	9,206,637	2,085	M	NO
003066	Fontaneto d'Agogna	21,116,075	2,651	P	NO
003068	Galliate	29,479,318	14,423	P	NO
003069	Garbagna Novarese	11,206,551	1,023	M	NO
003070	Gargallo	3,788,526	1,730	M	NO
003071	Gattico	16,099,192	3,267	P	NO
003073	Ghemme	20,531,810	3,687	P	NO
003076	Gozzano	12,866,636	5,949	P	NO
003077	Granozzo con Monticello	19,464,653	1,274	M	NO
003079	Grignasco	14,344,691	4,803	P	NO
003082	Invorio	17,366,282	3,958	M	NO
003083	Landiona	7,263,514	600	M	NO
003084	Lesa	13,473,846	2,470	P	NO
003088	Maggiora	10,615,500	1,763	M	NO
003090	Mandello Vitta	6,258,590	272	M	NO
003091	Marano Ticino	7,871,342	1,524	P	NO
003093	Massino Visconti	7,180,753	1,106	M	NO
003095	Meina	7,226,450	2,407	P	NO
003097	Mezzomerico	7,726,792	1,005	M	NO
003098	Miasino	5,184,709	950	M	NO
003100	Momo	23,485,423	2,713	M	NO
003103	Nebbiuno	7,909,220	1,709	P	NO
003104	Nibbiola	11,378,616	762	M	NO
003106	NOVARA	103,089,949	102,746	P	NO
003108	Oleggio	38,018,932	12,490	P	NO
003109	Oleggio Castello	6,186,387	1,900	P	NO
003112	Orta San Giulio	7,073,876	1,170	P	NO
003114	Paruzzaro	4,829,403	1,710	P	NO
003115	Pella	7,783,626	1,159	M	NO

003116	Pettenasco	6,934,092	1,318	P	NO
003119	Pisano	2,913,516	816	P	NO
003120	Pogno	9,970,396	1,556	P	NO
003121	Pombia	12,296,310	1,834	P	NO
003122	Prato Sesia	12,104,230	1,961	M	NO
003129	Recetto	8,870,928	865	P	NO
003130	Romagnano Sesia	17,928,476	4,162	P	NO
003131	Romentino	17,613,069	4,436	P	NO
003133	San Maurizio d'OpagIio	8,311,507	3,064	P	NO
003134	San Nazzaro Sesia	11,249,972	728	M	NO
003135	San Pietro Mosezzo	34,893,969	1,789	P	NO
003138	Sillavengo	9,596,172	579	P	NO
003139	Sizzano	10,909,017	1,452	P	NO
003140	Soriso	6,269,427	746	M	NO
003141	Sozzago	12,886,453	953	M	NO
003143	Suno	21,304,342	2,802	M	NO
003144	Terdobbiate	7,349,983	465	M	NO
003146	Tornaco	13,326,140	870	M	NO
003149	Trecate	38,400,393	18,028	P	NO
003153	Vaprio d'Agogna	10,043,262	980	M	NO
003154	Varallo Pombia	13,599,159	4,598	P	NO
003157	Veruno	9,599,351	1,722	M	NO
003158	Vespolate	17,914,401	2,054	M	NO
003159	Vicolungo	12,841,606	857	P	NO
003164	Vinzaglio	15,568,004	612	M	NO
001001	Agliè	13,046,736	2,645	P	TO
001002	Airasca	15,714,412	3,652	P	TO
001003	Ala di Stura	46,573,821	469	M	TO
001004	Albiano d'Ivrea	11,617,698	1,707	M	TO
001005	Alice superiore	7,324,839	646	M	TO
001006	Almese	17,880,478	5,932	P	TO
001007	Alpette	5,744,432	278	M	TO
001008	Alpignano	11,883,767	17,036	P	TO
001009	Andezeno	7,500,806	1,829	P	TO
001010	Andrate	9,391,361	487	M	TO
001011	Angrogna	38,714,960	813	M	TO
001012	Arignano	8,177,422	943	M	TO
001013	Avigliana	23,207,813	11,791	P	TO
001014	Azeglio	10,008,792	1,303	M	TO
001015	Bairo	7,221,489	839	M	TO
001016	Balangero	12,913,628	3,055	P	TO

001017	Baldissero Canavese	4,451,296	510	M	TO
001018	Baldissero Torinese	15,412,099	3,488	P	TO
001019	Balme	62,961,507	98	M	TO
001020	Banchette	2,026,447	3,440	P	TO
001021	Barbania	12,807,932	1,538	M	TO
001022	Bardonecchia	132,105,833	3,015	M	TO
001023	Barone Canavese	4,022,561	588	M	TO
001024	Beinasco	6,757,473	18,393	P	TO
001025	Bibiana	18,691,683	2,998	M	TO
001026	Bobbio Pellice	94,320,420	603	M	TO
001027	Bollengo	14,131,425	2,026	P	TO
001028	Borgaro Torinese	14,321,909	13,317	P	TO
001029	Borgiallo	7,004,442	501	M	TO
001030	Borgofranco d'Ivrea	13,325,548	3,665	P	TO
001031	Borgomasino	12,392,003	819	M	TO
001032	Borgone Susa	4,922,826	2,310	P	TO
001033	Bosconero	11,003,252	2,998	P	TO
001034	Brandizzo	6,274,965	7,820	P	TO
001035	Bricherasio	22,751,474	4,101	M	TO
001036	Brosso	11,128,913	462	M	TO
001037	Brozolo	9,077,484	478	M	TO
001038	Bruino	5,576,878	7,928	P	TO
001039	Brusasco	14,356,702	1,679	M	TO
001040	Bruzolo	12,594,227	1,397	P	TO
001041	Buriasco	14,725,695	1,353	M	TO
001042	Burolo	5,404,421	1,338	M	TO
001043	Busano	5,128,691	1,442	M	TO
001044	Bussoleno	37,069,260	6,560	P	TO
001045	Buttigliera Alta	8,114,998	6,575	P	TO
001046	Cafasse	10,159,563	3,636	P	TO
001047	Caluso	39,508,738	7,387	M	TO
001048	Cambiano	14,220,487	6,008	P	TO
001049	Campiglione-Fenile	10,999,883	1,334	M	TO
001050	Candia Canavese	9,128,874	1,322	M	TO
001051	Candiolo	11,832,595	5,385	P	TO
001052	Canischio	11,952,347	289	M	TO
001053	Cantalupa	11,169,411	2,231	M	TO
001054	Cantoira	23,033,851	552	M	TO
001055	Caprie	16,229,305	1,958	P	TO
001056	Caravino	11,617,890	1,031	M	TO
001057	Carema	10,161,763	754	M	TO

001058	Carignano	50,737,763	8,777	P	TO
001059	Carmagnola	95,819,085	25,718	P	TO
001060	Casalborgone	20,087,912	1,798	M	TO
001061	Cascinette d'Ivrea	2,180,544	1,459	P	TO
001062	Caselette	14,331,977	2,698	P	TO
001063	Caselle Torinese	28,679,133	16,783	P	TO
001064	Castagneto Po	11,492,335	1,571	M	TO
001065	Castagnole Piemonte	17,234,404	1,944	M	TO
001066	Castellamonte	38,856,110	9,298	M	TO
001067	Castelnuovo Nigra	28,001,295	424	M	TO
001068	Castiglione Torinese	14,152,901	5,783	P	TO
001069	Cavagnolo	12,220,705	2,334	M	TO
001070	Cavour	48,998,646	5,481	M	TO
001071	Cercenasco	13,102,636	1,821	M	TO
001072	Ceres	28,023,494	1,068	M	TO
001073	Ceresole Reale	99,864,134	161	M	TO
001074	Cesana Torinese	121,597,646	1,043	M	TO
001075	Chialamberto	35,425,413	357	M	TO
001076	Chianocco	18,598,733	1,705	P	TO
001077	Chiaverano	12,000,016	2,226	M	TO
001078	Chieri	54,168,613	34,312	P	TO
001079	Chiesanuova	4,059,125	231	M	TO
001080	Chiomonte	26,637,140	992	M	TO
001081	Chiusa di San Michele	5,912,348	1,598	P	TO
001082	Chivasso	51,254,916	23,675	P	TO
001083	Ciconio	3,151,534	353	P	TO
001084	Cintano	5,309,935	262	M	TO
001085	Cinzano	6,179,680	389	M	TO
001086	Ciriè	17,762,444	18,609	P	TO
001087	Claviere	2,629,514	176	M	TO
001088	Coassolo Torinese	27,609,895	1,521	M	TO
001089	Coazze	56,676,498	3,039	M	TO
001090	Collegno	18,148,473	49,634	P	TO
001091	Colleretto Castelnuovo	6,209,674	331	M	TO
001092	Colleretto Giacosa	4,742,821	624	P	TO
001093	Condove	71,053,053	4,500	P	TO
001094	Corio	41,739,577	3,257	M	TO
001095	Cossano Canavese	3,295,271	552	M	TO
001096	Cuceglio	6,563,764	948	P	TO
001097	Cumiana	60,720,324	7,327	M	TO
001098	Cuorgnè	19,620,218	10,084	P	TO

001099	Druento	27,801,323	8,262	P	TO
001100	Exilles	46,623,341	285	M	TO
001101	Favria	14,834,202	4,584	M	TO
001102	Feletto	7,881,243	2,451	P	TO
001103	Fenestrelle	49,264,252	603	M	TO
001104	Fiano	12,119,627	2,648	P	TO
001105	Fiorano Canavese	4,520,241	878	M	TO
001106	Foglizzo	15,630,388	2,188	P	TO
001107	Forno Canavese	16,460,707	3,743	M	TO
001108	Frassinetto	24,808,540	287	M	TO
001109	Front	10,977,324	1,661	M	TO
001110	Frossasco	19,952,633	2,818	P	TO
001111	Garzigliana	7,403,767	521	M	TO
001112	Gassino Torinese	20,673,398	9,373	M	TO
001113	Germagnano	14,126,287	1,300	P	TO
001114	Giaglione	33,272,765	681	M	TO
001115	Giaveno	71,751,393	15,191	M	TO
001116	Givoletto	12,867,074	2,443	M	TO
001117	Gravere	18,722,803	736	M	TO
001118	Groscavallo	92,765,032	220	M	TO
001119	Grosso	4,331,968	1,002	P	TO
001120	Grugliasco	13,056,364	38,327	P	TO
001121	Ingria	14,603,696	50	M	TO
001122	Inverso Pinasca	7,976,222	678	M	TO
001123	Isolabella	4,747,814	414	M	TO
001124	Issiglio	5,679,514	414	M	TO
001125	Ivrea	29,987,003	24,016	P	TO
001126	La Cassa	12,093,039	1,475	M	TO
001127	La Loggia	12,853,991	6,838	P	TO
001128	Lanzo Torinese	10,344,028	5,296	P	TO
001129	Lauriano	14,247,450	1,443	M	TO
001130	Leinì	32,506,953	12,439	P	TO
001131	Lemie	45,298,242	209	M	TO
001132	Lessolo	7,769,064	1,990	P	TO
001133	Levone	5,419,300	475	M	TO
001134	Locana	132,264,148	1,720	M	TO
001135	Lombardore	12,695,244	1,555	M	TO
001136	Lombriasco	7,370,296	1,059	M	TO
001137	Loranzè	4,263,054	1,057	M	TO
001138	Lugnacco	4,887,181	378	M	TO
001139	Luserna San Giovanni	17,848,550	7,820	P	TO

001140	Lusernetta	7,097,144	508	M	TO
001141	Lusigliè	5,241,433	549	P	TO
001142	Macello	14,058,198	1,150	M	TO
001143	Maglione	6,334,860	497	M	TO
001144	Marentino	11,257,962	1,323	M	TO
001145	Massello	38,399,415	66	M	TO
001146	Mathi	7,073,130	4,004	P	TO
001147	Mattie	27,850,206	710	P	TO
001148	Mazzè	27,045,686	4,058	M	TO
001149	Meana di Susa	17,569,160	950	M	TO
001150	Mercenasco	12,740,179	1,205	P	TO
001151	Meugliano	4,553,172	96	M	TO
001152	Mezzenile	29,101,643	897	M	TO
001153	Mombello di Torino	4,072,839	378	M	TO
001154	Mompantero	30,026,304	681	M	TO
001155	Monastero di Lanzo	17,889,482	396	M	TO
001156	Moncalieri	47,358,705	55,059	P	TO
001157	Moncenisio	4,602,549	48	M	TO
001158	Montaldo Torinese	4,658,690	642	M	TO
001159	Montalenghe	6,482,502	888	P	TO
001160	Montalto Dora	7,406,034	3,461	P	TO
001161	Montanaro	20,897,346	5,326	M	TO
001162	Monteu da Po	7,465,752	900	M	TO
001163	Moriondo Torinese	6,465,629	808	M	TO
001164	Nichelino	20,385,149	48,297	P	TO
001165	Noasca	77,816,992	197	M	TO
001166	Nole	11,365,917	6,447	P	TO
001167	Nomaglio	3,106,416	336	M	TO
001168	None	24,629,153	7,866	P	TO
001169	Novalesa	28,634,334	560	M	TO
001170	Oglianico	6,269,128	1,365	M	TO
001171	Orbassano	22,318,597	21,667	P	TO
001172	Orio Canavese	7,104,192	799	M	TO
001173	Osasco	5,568,694	1,037	P	TO
001174	Osasio	4,578,355	785	M	TO
001175	Oulx	99,087,057	2,810	M	TO
001176	Ozegna	5,348,610	1,192	P	TO
001177	Palazzo Canavese	5,140,512	826	M	TO
001178	Pancalieri	16,016,436	1,969	M	TO
001179	Parella	2,558,802	458	M	TO
001180	Pavarolo	4,380,961	932	P	TO

001181	Pavone Canavese	11,301,847	3,812	P	TO
001182	Pecco	1,513,907	222	M	TO
001183	Pecetto Torinese	9,175,725	3,751	P	TO
001184	Perosa Argentina	26,380,187	3,532	M	TO
001185	Perosa Canavese	4,554,931	590	P	TO
001186	Perrero	63,279,404	779	M	TO
001187	Pertusio	4,186,935	736	M	TO
001188	Pessinetto	5,317,771	625	M	TO
001189	Pianezza	16,301,011	11,727	P	TO
001190	Pinasca	34,547,450	2,980	M	TO
001191	Pinerolo	49,925,988	34,264	P	TO
001192	Pino Torinese	21,729,335	8,586	P	TO
001193	Piobesi Torinese	19,706,826	3,424	M	TO
001194	Piossasco	40,117,156	16,961	P	TO
001195	Piscina	9,988,712	3,197	P	TO
001196	Piverone	10,591,166	1,267	M	TO
001197	Poirino	75,498,890	9,366	M	TO
001198	Pomaretto	8,398,160	1,110	M	TO
001199	Pont Canavese	19,317,776	3,822	M	TO
001200	Porte	4,524,539	987	P	TO
001201	Pragelato	89,097,788	536	M	TO
001202	Prali	72,323,280	322	M	TO
001203	Pralormo	29,807,354	1,827	M	TO
001204	Pramollo	22,549,503	241	M	TO
001205	Prarostino	10,127,109	1,268	M	TO
001206	Prascorsano	6,100,626	801	M	TO
001207	Pratiglione	7,809,894	598	M	TO
001208	Quagliuzzo	2,029,314	333	M	TO
001209	Quassolo	4,177,497	372	P	TO
001210	Quincinetto	18,056,717	1,049	M	TO
001211	Reano	6,627,703	1,510	M	TO
001212	Ribordone	44,122,448	81	M	TO
001215	Riva presso Chieri	35,840,185	3,849	P	TO
001213	Rivalba	10,867,310	991	M	TO
001214	Rivalta di Torino	25,120,854	18,266	P	TO
001216	Rivara	12,548,043	2,597	M	TO
001217	Rivarolo Canavese	32,161,927	11,976	P	TO
001218	Rivarossa	10,824,998	1,503	M	TO
001219	Rivoli	29,434,486	50,694	P	TO
001220	Robassomero	8,562,563	3,061	P	TO
001221	Rocca Canavese	14,196,891	1,678	M	TO

001222	Roletto	9,996,113	2,019	P	TO
001223	Romano Canavese	11,252,410	2,953	P	TO
001224	Ronco Canavese	96,534,518	353	M	TO
001225	Rondissone	10,673,507	1,668	P	TO
001226	Rorà	12,510,954	266	M	TO
001228	Rosta	9,108,819	3,801	P	TO
001227	Roure	59,212,490	934	M	TO
001229	Rubiana	26,961,127	2,208	M	TO
001230	Rueglio	15,120,134	795	M	TO
001231	Salassa	5,063,882	1,681	P	TO
001232	Salbertrand	39,041,174	522	M	TO
001233	Salerano Canavese	2,074,989	545	P	TO
001234	Salza di Pinerolo	16,071,055	73	M	TO
001235	Samone	2,358,197	1,513	P	TO
001236	San Benigno Canavese	22,252,075	5,307	P	TO
001237	San Carlo Canavese	20,887,886	3,534	M	TO
001238	San Colombano Belmonte	3,241,396	370	M	TO
001239	San Didero	3,307,401	500	P	TO
001240	San Francesco al Campo	14,987,635	4,440	M	TO
001242	San Germano Chisone	15,788,672	1,824	M	TO
001243	San Gillio	8,918,788	2,627	P	TO
001244	San Giorgio Canavese	20,664,976	2,486	P	TO
001245	San Giorio di Susa	19,677,574	1,015	P	TO
001246	San Giusto Canavese	9,663,451	3,143	P	TO
001247	San Martino Canavese	9,583,267	811	M	TO
001248	San Maurizio Canavese	17,363,623	7,613	P	TO
001249	San Mauro Torinese	12,744,869	18,367	P	TO
001250	San Pietro Val Lemina	12,573,518	1,494	P	TO
001251	San Ponso	2,153,542	278	M	TO
001252	San Raffaele Cimena	11,175,170	2,939	P	TO
001253	San Sebastiano da Po	16,664,143	1,874	M	TO
001254	San Secondo di Pinerolo	12,911,032	3,407	P	TO
001241	Sangano	6,651,375	3,767	P	TO
001255	Sant'Ambrogio di Torino	8,581,420	4,411	P	TO
001256	Sant'Antonino di Susa	9,849,326	4,118	P	TO
001257	Santena	16,164,297	10,313	P	TO
001258	Sauze di Cesana	78,230,274	201	M	TO
001259	Sauze d'OuIx	17,314,519	1,145	M	TO
001260	Scalenghe	31,674,390	3,156	M	TO
001261	Scarmagno	7,959,990	774	P	TO
001262	Sciolze	11,323,260	1,515	M	TO

001263	Sestriere	25,918,745	877	M	TO
001264	Settimo Rottaro	5,971,220	506	M	TO
001265	Settimo Torinese	32,083,906	47,372	P	TO
001266	Settimo Vittone	23,227,793	1,579	M	TO
001267	Sparone	29,530,292	1,175	M	TO
001268	Strambinello	2,283,084	263	P	TO
001269	Strambino	22,553,457	6,132	P	TO
001270	Susa	11,221,215	6,638	P	TO
001271	Tavagnasco	8,463,681	832	M	TO
001272	TORINO	130,182,917	902,255	P	TO
001273	Torrazza Piemonte	9,886,753	2,475	M	TO
001274	Torre Canavese	5,371,867	617	M	TO
001275	Torre Pellice	21,011,439	4,636	M	TO
001276	Trana	16,545,364	3,559	M	TO
001277	Trausella	12,617,390	148	M	TO
001278	Traversella	39,431,015	372	M	TO
001279	Traves	10,561,562	539	M	TO
001280	Trofarello	12,318,728	11,090	P	TO
001281	Usseaux	38,360,666	190	M	TO
001282	Usseglio	98,731,153	242	M	TO
001283	Vaie	7,228,176	1,413	P	TO
001284	Val della Torre	36,615,519	3,659	M	TO
001285	Valgioie	9,103,642	811	M	TO
001286	Vallo Torinese	6,327,474	743	M	TO
001287	Valperga	11,845,442	3,111	P	TO
001288	Valprato Soana	72,982,680	126	M	TO
001289	Varisella	22,360,154	764	M	TO
001290	Vauda Canavese	7,064,939	1,505	M	TO
001292	Venaria Reale	20,359,715	35,128	P	TO
001291	Venaus	19,229,739	968	M	TO
001293	Verolengo	29,349,183	4,647	P	TO
001294	Verrua Savoia	31,841,938	1,463	M	TO
001295	Vestignè	11,935,338	865	M	TO
001296	Vialfrè	5,039,784	233	P	TO
001297	Vico Canavese	32,835,645	883	M	TO
001298	Vidracco	2,868,369	541	M	TO
001299	Vigone	41,207,480	5,157	M	TO
001300	Villafranca Piemonte	50,645,887	4,813	M	TO
001301	Villanova Canavese	4,030,633	1,028	P	TO
001303	Villar Dora	5,656,931	2,867	P	TO
001305	Villar Focchiardo	25,652,670	2,041	P	TO

001306	Villar Pellice	60,271,646	1,213	M	TO
001307	Villar Perosa	11,539,108	4,263	P	TO
001302	Villarbasse	10,423,901	2,894	M	TO
001304	Villareggia	11,568,699	981	M	TO
001308	Villastellone	19,861,534	4,826	P	TO
001309	Vinovo	17,731,316	13,563	P	TO
001310	Virle Piemonte	14,004,192	1,116	M	TO
001311	Vische	17,049,480	1,356	M	TO
001312	Vistrorio	4,886,668	511	M	TO
001313	Viù	84,373,713	1,198	M	TO
001314	Volpiano	32,417,172	13,638	P	TO
001315	Volvera	20,850,131	7,782	P	TO
103001	Antrona Schieranco	100,807,474	529	M	VB
103002	Anzola d'OssoIa	13,470,156	449	P	VB
103003	Arizzano	1,508,552	2,009	P	VB
103004	Arola	5,972,039	284	M	VB
103005	Aurano	21,114,834	110	M	VB
103006	Baceno	76,921,259	963	M	VB
103007	Bannio Anzino	39,498,352	570	M	VB
103008	Baveno	16,684,019	4,741	P	VB
103009	Bee	3,747,456	700	M	VB
103010	Belgirate	7,212,463	515	P	VB
103011	Beura-Cardezza	29,236,100	1,354	P	VB
103012	Bognanco	58,772,357	283	M	VB
103013	Brovello-Carpugnino	8,326,474	607	M	VB
103014	Calasca-Castiglione	57,054,233	741	M	VB
103015	Cambiasca	3,410,139	1,529	M	VB
103016	Cannero Riviera	15,481,853	1,077	M	VB
103017	Cannobio	49,597,888	5,114	M	VB
103018	Caprezzo	7,271,138	170	M	VB
103019	Casale Corte Cerro	13,114,837	3,403	P	VB
103020	Cavaglio-Spoccia	18,065,413	273	M	VB
103021	Ceppo Morelli	40,045,812	384	M	VB
103022	Cesara	11,851,134	617	M	VB
103023	Cossogno	40,388,898	562	M	VB
103024	Craveggia	36,193,393	756	M	VB
103025	Crevoladossola	39,950,405	4,765	M	VB
103026	Crodo	53,722,171	1,487	M	VB
103027	Cursolo-Orasso	20,860,075	115	M	VB
103028	Domodossola	36,863,810	18,434	P	VB
103029	Druogno	28,741,319	955	M	VB

103030	Falmenta	16,320,500	201	M	VB
103031	Formazza	133,115,010	443	M	VB
103032	Germagno	2,725,468	205	M	VB
103033	Ghiffa	15,737,171	2,382	P	VB
103034	Gignese	14,339,455	913	M	VB
103035	Gravellona Toce	13,938,733	7,595	P	VB
103036	Gurro	13,284,391	288	M	VB
103037	Intragna	10,033,740	119	M	VB
103038	Loreglia	9,228,687	279	M	VB
103039	Macugnaga	99,463,367	647	M	VB
103040	Madonna del Sasso	15,136,094	460	M	VB
103041	Malesco	43,327,529	1,478	M	VB
103042	Masera	20,285,870	1,483	M	VB
103043	Massiola	8,751,000	169	M	VB
103044	Mergozzo	27,161,806	2,097	P	VB
103045	Miazzina	21,473,408	415	M	VB
103046	Montecrestese	86,090,848	1,197	M	VB
103047	Montescheno	22,030,291	452	M	VB
103048	Nonio	10,041,088	897	M	VB
103049	Oggebbio	21,909,816	922	M	VB
103050	Omegna	30,525,442	15,910	P	VB
103051	Ornavasso	25,886,103	3,277	P	VB
103052	Pallanzeno	4,294,211	1,200	P	VB
103053	Piedimulera	7,572,634	1,661	P	VB
103054	Pieve Vergonte	42,212,014	2,680	P	VB
103055	Premeno	7,913,603	776	P	VB
103056	Premia	86,593,560	607	M	VB
103057	Premosello Chiovenda	34,164,188	2,042	P	VB
103058	Quarna sopra	9,348,256	302	M	VB
103059	Quarna sotto	17,045,080	432	M	VB
103060	Re	27,311,428	805	M	VB
103061	San Bernardino Verbano	26,910,089	1,205	M	VB
103062	Santa Maria Maggiore	53,627,829	1,236	M	VB
103063	Seppiana	5,342,241	176	M	VB
103064	Stresa	34,014,241	5,066	P	VB
103065	Toceno	15,764,744	750	M	VB
103066	Trarego Viggiona	18,941,161	375	M	VB
103067	Trasquera	39,705,155	247	M	VB
103068	Trontano	57,693,749	1,684	M	VB
103069	Valstrona	51,067,556	1,286	M	VB
103070	Vanzone con San Carlo	15,783,283	482	M	VB

103071	Varzo	93,704,241	2,209	M	VB
103072	VERBANIA	37,735,321	30,796	P	VB
103073	Viganella	13,695,343	185	M	VB
103074	Vignone	3,576,594	1,150	M	VB
103075	Villadossola	18,046,114	6,905	P	VB
103076	Villette	7,371,944	250	M	VB
103077	Vogogna	15,349,252	1,743	P	VB
002002	Alagna Valsesia	72,426,240	451	M	VC
002003	Albano Vercellese	13,789,394	330	M	VC
002004	Alice Castello	24,570,147	2,602	P	VC
002006	Arborio	23,366,683	1,035	M	VC
002007	Asigliano Vercellese	26,333,606	1,374	P	VC
002008	Balmuccia	10,820,811	94	M	VC
002009	Balocco	16,673,148	273	P	VC
002011	Bianzè	41,786,631	2,043	M	VC
002014	Boccioleto	32,984,270	258	M	VC
002015	Borgo d'Ale	39,647,129	2,629	P	VC
002017	Borgo Vercelli	19,160,460	2,173	P	VC
002016	Borgosesia	41,085,260	13,755	M	VC
002019	Breia	7,363,385	184	M	VC
002021	Buronzo	25,126,941	967	M	VC
002025	Campertogno	34,433,101	226	M	VC
002029	Carcoforo	22,793,091	78	M	VC
002030	Caresana	23,837,061	1,083	M	VC
002031	Caresanablot	11,030,675	1,057	P	VC
002032	Carisio	30,182,337	953	P	VC
002033	Casanova Elvo	16,825,879	268	M	VC
002038	Cellio	9,945,621	898	M	VC
002041	Cervatto	9,652,067	48	M	VC
002042	Cigliano	25,228,589	4,551	P	VC
002043	Civiasco	8,379,098	264	M	VC
002045	Collobiano	8,783,476	126	P	VC
002047	Costanzana	20,884,901	847	M	VC
002048	Cravagliana	35,482,073	273	M	VC
002049	Crescentino	48,167,742	7,843	P	VC
002052	Crova	13,858,112	431	M	VC
002054	Desana	16,886,644	1,085	M	VC
002057	Fobello	28,200,539	246	M	VC
002058	Fontanetto Po	23,114,197	1,264	M	VC
002059	Formigliana	16,789,019	548	P	VC
002061	Gattinara	33,812,478	8,506	M	VC

002062	Ghislarengo	12,481,372	870	M	VC
002065	Greggio	11,963,711	382	P	VC
002066	Guardabosone	6,182,195	344	M	VC
002067	Lamporo	9,695,919	515	M	VC
002068	Lenta	18,973,643	968	M	VC
002070	Lignana	22,607,995	539	M	VC
002071	Livorno Ferraris	58,062,697	4,427	M	VC
002072	Lozzolo	6,633,189	797	M	VC
002078	Mollia	13,750,425	98	M	VC
002079	Moncrivello	20,234,574	1,437	M	VC
002082	Motta de' Conti	11,875,782	851	M	VC
002088	Olcenengo	16,550,819	635	M	VC
002089	Oldenico	6,509,390	236	M	VC
002090	Palazzolo Vercellese	14,011,471	1,348	M	VC
002091	Pertengo	8,352,697	328	M	VC
002093	Pezzana	17,592,880	1,146	P	VC
002096	Pila	7,846,966	118	M	VC
002097	Piode	14,113,183	205	M	VC
002102	Postua	15,991,370	568	M	VC
002104	Prarolo	11,602,904	616	P	VC
002107	Quarona	16,230,280	4,297	M	VC
002108	Quinto Vercellese	10,640,260	438	M	VC
002110	Rassa	43,430,348	69	M	VC
002111	Rima San Giuseppe	36,103,553	71	M	VC
002112	Rimasco	24,402,114	150	M	VC
002113	Rimella	26,169,830	129	M	VC
002114	Riva Valdobbia	61,309,240	236	M	VC
002115	Rive	9,344,432	426	M	VC
002116	Roasio	27,698,044	2,517	M	VC
002118	Ronsecco	24,047,890	606	M	VC
002121	Rossa	11,038,278	183	M	VC
002122	Rovasenda	29,171,498	1,010	M	VC
002123	Sabbia	14,266,695	78	M	VC
002126	Salasco	12,075,597	240	M	VC
002127	Sali Vercellese	8,757,742	128	M	VC
002128	Saluggia	31,626,848	4,128	P	VC
002131	San Germano Vercellese	30,782,329	1,789	M	VC
002035	San Giacomo Vercellese	9,613,661	352	M	VC
002133	Santhià	53,266,752	9,283	P	VC
002134	Scopa	19,227,000	376	M	VC
002135	Scopello	22,013,719	425	M	VC

002137	Serravalle Sesia	20,947,327	5,031	M	VC
002142	Stroppiana	18,278,601	1,201	P	VC
002147	Tricerro	12,338,231	627	M	VC
002148	Trino	70,585,171	7,788	P	VC
002150	Tronzano Vercellese	44,719,069	3,519	M	VC
002152	Valduggia	28,435,589	2,305	M	VC
002156	Varallo	85,724,095	7,452	M	VC
002158	VERCELLI	80,182,367	44,967	P	VC
002163	Villarboit	25,565,772	495	P	VC
002164	Villata	14,539,838	1,615	M	VC
002166	Vocca	22,061,833	158	M	VC

A.2 Statistics on pollutant concentrations and emissions

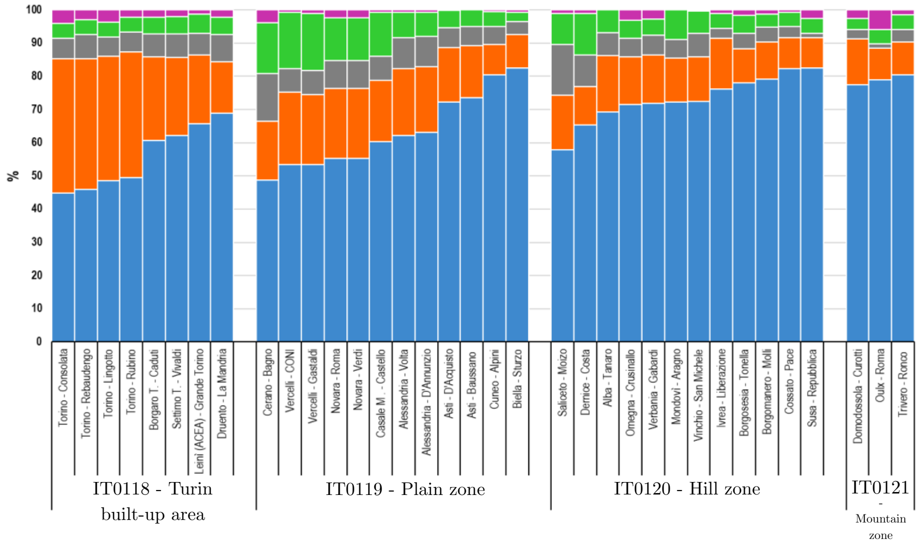


Figure A.1: Source apportionment of yearly PM_{10} emissions for each measuring station of Piedmont [6].

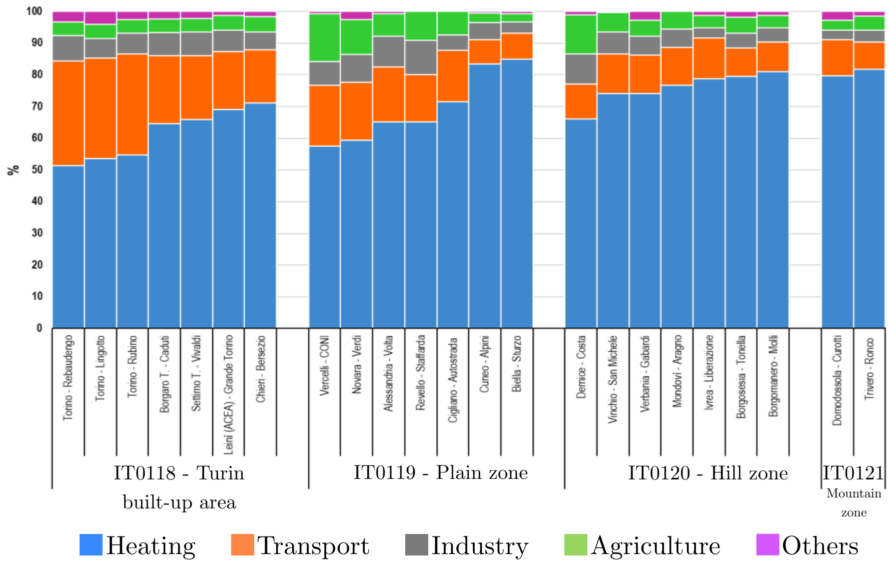


Figure A.2: Source apportionment of yearly $PM_{2.5}$ emissions for each measuring station of Piedmont [6].

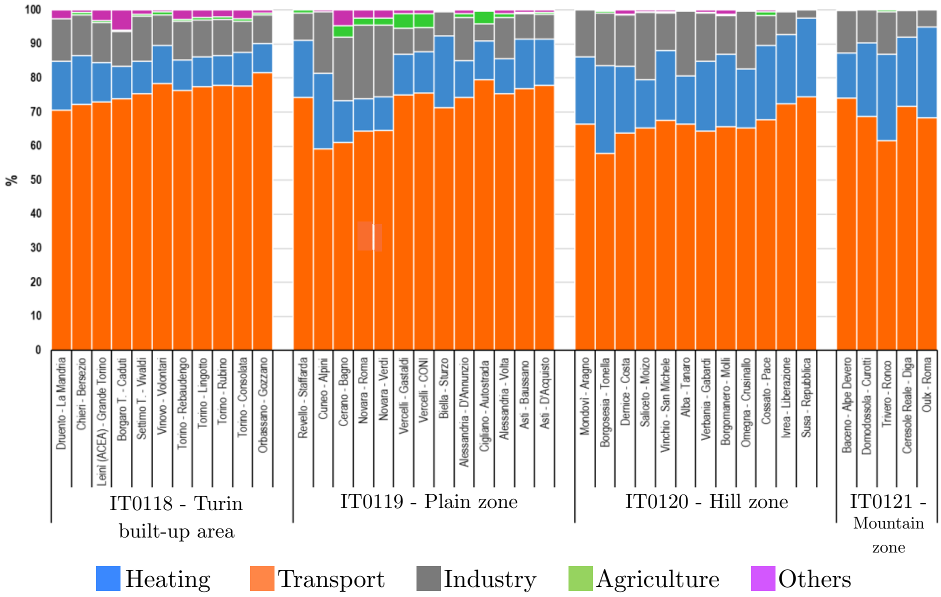


Figure A.3: Source apportionment of yearly NO_2 emissions for each measuring station of Piedmont [6].

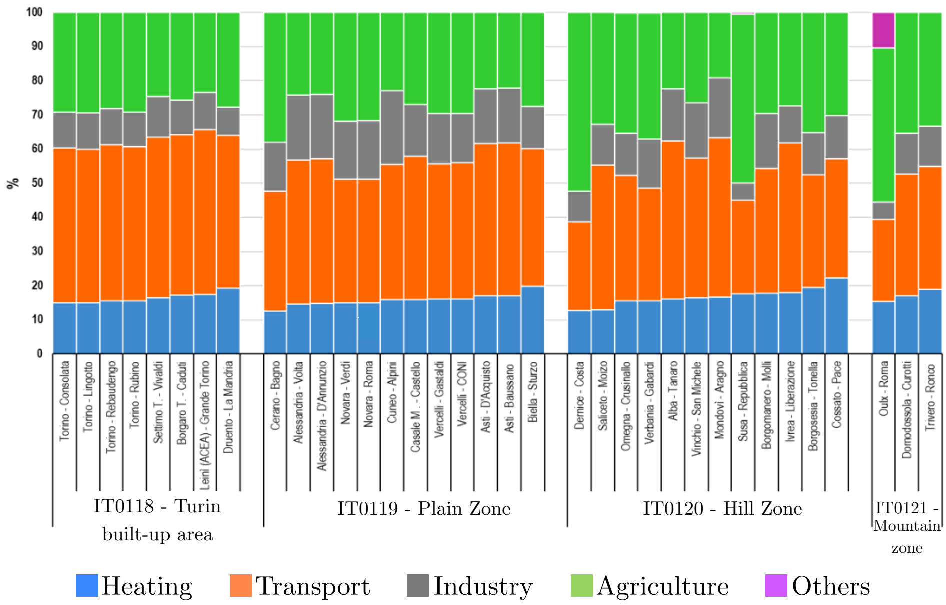


Figure A.4: Source apportionment of yearly nitrate ion (NO_4^-) emissions for each measuring station of Piedmont [6].

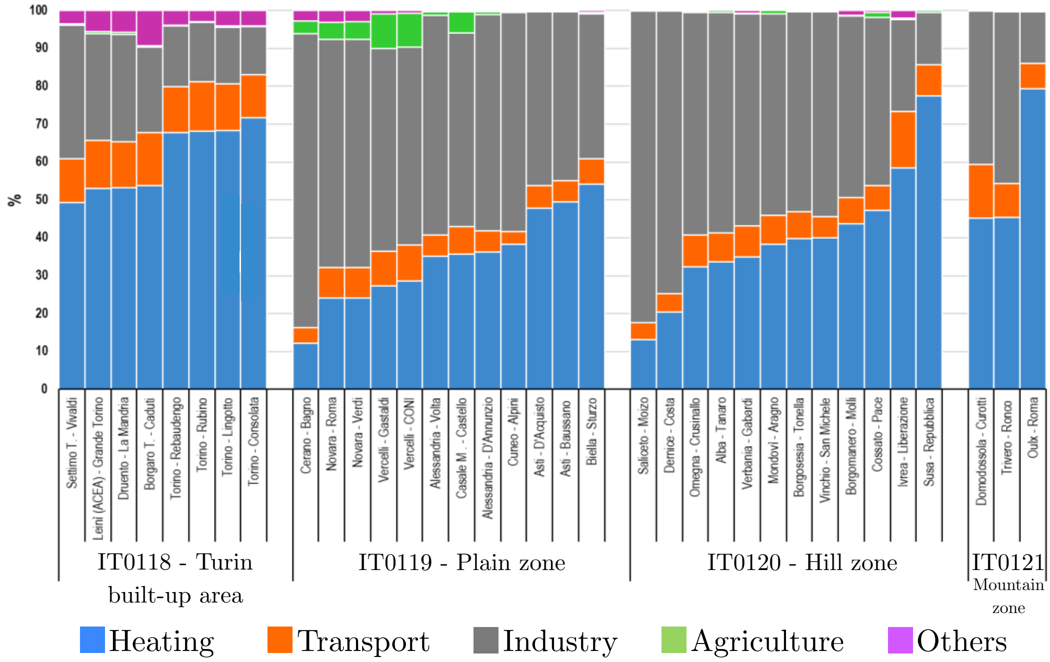


Figure A.5: Source apportionment of yearly sulphate ion (SO_4^{2-}) emissions for each measuring station of Piedmont [6].

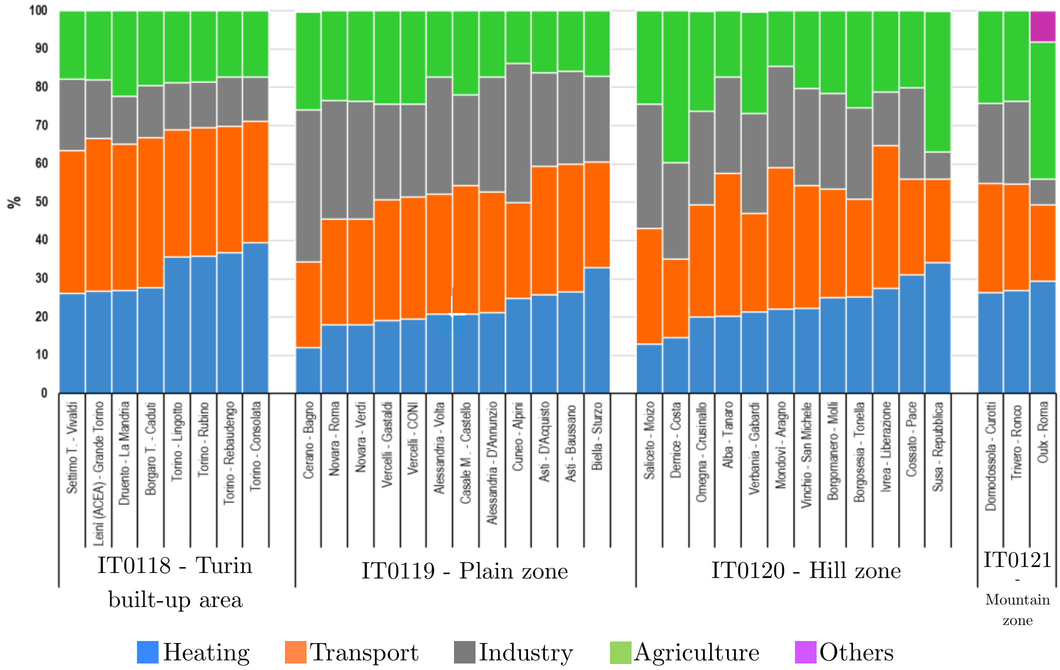


Figure A.6: Source apportionment of yearly ammonium ion (NH_4^+) emissions for each measuring station of Piedmont [6].

PARTICOLATO PM10 - Contributo percentuale alla media annuale - ZONA IT0118

	Industria	Riscaldamento a legna	Riscaldamento NON a legna	Automobili diesel	Automobili NON diesel	Veicoli leggeri	Veicoli pesanti	Motocicli e ciclomotori	Risospensione e usura	Ferrovie e off-road	Colture agricole	Zootecnia	Resto
	%	%	%	%	%	%	%	%	%	%	%	%	%
Torino - Consolata (TO)	6,1	39,2	5,6	6,7	0,9	7,1	5,5	3,4	14,9	1,9	0,9	3,5	4,2
Torino - Lingotto (TO)	5,7	44,2	4,4	6,3	0,9	6,5	5,3	3,1	13,6	1,8	0,9	3,5	3,7
Torino - Rebaudengo (TO)	7,3	41,2	4,9	6,5	0,8	6,7	5,5	3,2	14,4	2,1	0,9	3,6	3,0
Torino - Rubino (TO)	5,9	45,0	4,4	6,3	0,9	6,4	5,4	3,1	13,9	1,9	0,9	3,6	2,3
Borgaro T. - Caduti (TO)	6,8	58,9	1,7	4,1	0,6	3,6	4,3	1,6	8,2	2,7	0,8	4,4	2,2
Druento - La Mandria (TO)	8,3	67,9	0,9	2,7	0,5	2,3	2,9	1,1	3,9	2,1	0,7	4,5	2,3
Leini (ACEA) - Grande Torino (TO)	6,5	64,2	1,5	3,5	0,6	3,0	3,7	1,4	5,9	2,7	0,8	5,0	1,3
Settimo T. - Vivaldi (TO)	7,0	60,3	1,8	3,9	0,6	3,4	4,3	1,5	7,5	2,4	1,0	4,4	2,0

PARTICOLATO PM10 - Contributo percentuale alla media annuale - ZONA IT0119

	Industria	Riscaldamento a legna	Riscaldamento NON a legna	Automobili diesel	Automobili NON diesel	Veicoli leggeri	Veicoli pesanti	Motocicli e ciclomotori	Risospensione e usura	Ferrovie e off-road	Colture agricole	Zootecnia	Resto
	%	%	%	%	%	%	%	%	%	%	%	%	%
Alessandria - D'Annunzio (AL)	9,2	60,7	2,4	3,5	0,6	2,5	4,3	1,0	5,8	2,0	2,9	4,4	0,7
Alessandria - Volta (AL)	9,4	59,8	2,4	3,5	0,6	2,5	4,4	1,0	5,9	2,1	3,1	4,5	0,7
Casale M . - Castello (AL)	7,4	58,6	1,7	3,3	0,7	2,3	3,7	1,2	4,6	2,5	9,2	4,0	0,7
Asti - Baussano (AT)	5,6	71,3	2,3	2,7	0,5	2,1	3,4	0,9	4,5	1,6	1,1	4,0	0,0
Asti - D'Acquisto (AT)	5,9	70,0	2,2	2,8	0,5	2,2	3,6	0,9	4,7	1,6	1,2	4,1	0,2
Biella - Sturzo (BI)	3,9	81,2	1,3	1,8	0,4	1,5	1,8	0,6	3,2	0,7	0,9	1,9	0,7
Cuneo - Alpini (CN)	5,4	79,5	1,0	1,6	0,2	1,3	1,7	0,5	2,7	1,1	0,1	4,3	0,5
Novara - Roma (NO)	8,4	54,2	1,0	3,8	0,7	2,7	3,5	1,4	6,7	2,4	8,0	4,8	2,4
Novara - Verdi (NO)	8,3	54,3	1,0	3,8	0,7	2,7	3,4	1,4	6,7	2,4	8,1	4,8	2,3
Cerano - Bagno (NO)	14,5	48,0	0,7	4,1	0,8	2,2	3,1	1,2	4,3	2,0	10,3	5,0	3,9
Vercelli - CONI (VC)	7,0	52,3	1,1	3,7	0,8	2,8	3,7	1,5	6,8	2,6	13,0	4,0	0,8
Vercelli - Gastaldi (VC)	7,2	52,4	1,0	3,6	0,8	2,6	3,6	1,5	6,4	2,6	13,2	4,1	1,1

(a) *Zones IT0118 and IT0119*

PARTICOLATO PM10 - Contributo percentuale alla media annuale - ZONA IT0120

	Industria	Riscaldamento a legna	Riscaldamento NON a legna	Automobili diesel	Automobili NON diesel	Veicoli leggeri	Veicoli pesanti	Motocicli e ciclomotori	Risospensione e usura	Ferrovie e off-road	Colture agricole	Zootecnia	Resto
	%	%	%	%	%	%	%	%	%	%	%	%	%
Dernice - Costa (AL)	9,6	64,1	1,2	2,5	0,9	1,4	2,6	0,7	1,9	1,5	2,4	10,1	1,1
Vinchio - San Michele (AT)	7,0	70,6	1,8	2,5	0,6	1,7	3,2	0,6	2,9	2,0	1,5	5,3	0,4
Cossato - Pace (BI)	3,4	81,5	0,8	1,5	0,4	1,2	1,5	0,6	3,1	0,8	2,0	2,1	0,8
Alba - Tanaro (CN)	6,9	68,3	1,0	3,1	0,6	2,3	3,7	0,8	4,4	2,1	0,6	6,2	0,0
Mondovi - Aragno (CN)	5,6	71,4	0,8	2,1	0,4	1,7	2,7	0,5	3,2	2,6	0,1	8,8	0,0
Saliceto - Moizo (CN)	15,3	56,6	1,2	3,4	1,2	2,3	4,3	0,7	2,4	2,2	1,4	8,0	1,1
Borgomanero - Molli (NO)	4,4	78,3	0,8	2,2	0,5	1,5	2,1	0,6	3,5	0,8	1,3	2,7	1,3
Ivrea - Liberazione (TO)	2,9	74,8	1,4	2,5	0,8	2,1	3,0	0,8	4,6	1,4	1,2	3,2	1,2
Susa - Repubblica (TO)	1,2	81,5	1,0	1,3	0,3	1,0	1,7	0,3	4,2	0,4	0,9	3,6	2,7
Borgosesia - Tonella (VC)	4,7	76,9	1,0	1,9	0,6	1,5	1,9	0,6	2,8	0,8	1,6	3,7	1,7
Verbania - Gabardi (VB)	6,0	70,9	1,1	2,8	1,1	1,9	2,5	0,8	4,8	0,7	0,7	4,1	2,8
Omegna - Crusinallo (VB)	5,7	70,6	0,9	2,8	1,2	1,9	2,8	0,7	4,1	0,9	0,9	4,4	3,2

PARTICOLATO PM10 - Contributo percentuale alla media annuale - ZONA IT0121

	Industria	Riscaldamento a legna	Riscaldamento NON a legna	Automobili diesel	Automobili NON diesel	Veicoli leggeri	Veicoli pesanti	Motocicli e ciclomotori	Risospensione e usura	Ferrovie e off-road	Colture agricole	Zootecnia	Resto
	%	%	%	%	%	%	%	%	%	%	%	%	%
Trivero - Ronco (BI)	3,8	79,4	1,0	1,7	0,7	1,4	2,0	0,5	2,6	0,9	1,5	3,1	1,4
Oulx - Roma (TO)	1,3	77,8	1,1	1,2	0,4	0,9	1,9	0,3	4,5	0,3	1,7	2,6	6,1
Domodossola - Curotti (VB)	2,9	76,7	0,7	1,9	0,4	1,6	1,8	0,6	4,0	3,3	0,4	2,9	2,7

(b) *Zones IT0120 and IT0121*

Table A.2: Percentage contribution to annual average concentration of PM_{10} by the sectors identified for the source apportionment [6].

PARTICOLATO PM2.5 - Contributo percentuale alla media annuale - ZONA IT0118

	Industria	Riscaldamento a legna	Riscaldamento NON a legna	Automobili diesel	Automobili NON diesel	Veicoli leggeri	Veicoli pesanti	Motocicli e ciclomotori	Risospensione e usura	Ferrovie e off-road	Colture agricole	Zootecnia	Resto
	%	%	%	%	%	%	%	%	%	%	%	%	%
Torino - Lingotto (TO)	6,2	48,7	4,9	6,8	1,0	6,9	5,7	3,4	5,9	2,0	1,0	3,4	4,1
Torino - Rebaudengo (TO)	7,9	45,9	5,4	7,0	0,9	7,2	6,0	3,5	6,1	2,3	1,0	3,4	3,3
Torino - Rubino (TO)	6,4	49,7	4,9	6,8	1,0	6,9	5,9	3,4	6,0	2,1	1,0	3,5	2,6
Borgaro T. - Caduti (TO)	7,2	62,7	1,9	4,3	0,7	3,7	4,5	1,7	3,6	2,9	0,8	3,7	2,4
Chieri - Bersezio (TO)	5,6	69,3	1,8	3,5	0,6	2,8	4,2	1,1	2,1	2,5	0,8	4,1	1,7
Leini (ACEA) - Grande Torino (TO)	6,8	67,5	1,5	3,6	0,6	3,1	3,9	1,4	2,8	2,8	0,8	3,8	1,3
Settimo T. - Vivaldi (TO)	7,3	64,0	1,9	4,1	0,6	3,5	4,5	1,6	3,4	2,5	1,0	3,5	2,2
Vinovo - Volontari (TO)	5,6	68,1	1,4	3,9	0,6	3,2	4,2	1,4	2,7	2,5	0,9	4,0	1,6

PARTICOLATO PM2.5 - Contributo percentuale alla media annuale - ZONA IT0119

	Industria	Riscaldamento a legna	Riscaldamento NON a legna	Automobili diesel	Automobili NON diesel	Veicoli leggeri	Veicoli pesanti	Motocicli e ciclomotori	Risospensione e usura	Ferrovie e off-road	Colture agricole	Zootecnia	Resto
	%	%	%	%	%	%	%	%	%	%	%	%	%
Alessandria - Volta (AL)	9,7	62,7	2,5	3,7	0,7	2,5	4,6	1,1	2,6	2,2	3,0	4,0	0,8
Biella - Sturzo (BI)	3,5	83,6	1,3	1,8	0,5	1,5	1,8	0,7	1,3	0,7	0,9	1,8	0,7
Cuneo - Alpini (CN)	5,5	82,3	1,1	1,6	0,2	1,3	1,7	0,5	1,1	1,2	0,1	2,9	0,5
Revello - Staffarda (CN)	10,8	64,0	1,2	2,7	0,6	2,2	3,6	0,5	1,0	4,3	0,1	9,0	0,0
Novara - Verdi (NO)	8,6	58,3	1,1	4,0	0,7	2,9	3,6	1,5	3,1	2,5	7,0	4,1	2,5
Vercelli - CONI (VC)	7,4	56,3	1,2	3,9	0,9	2,9	3,9	1,6	3,1	2,8	11,5	3,6	0,8
Cigliano - Autostrada (VC)	4,9	70,5	1,0	3,0	0,7	2,1	4,3	1,0	2,2	2,8	4,6	2,8	0,0

(a) *Zones IT0118 and IT0119*

PARTICOLATO PM2.5 - Contributo percentuale alla media annuale - ZONA IT0120

	Industria	Riscaldamento a legna	Riscaldamento NON a legna	Automobili diesel	Automobili NON diesel	Veicoli leggeri	Veicoli pesanti	Motocicli e ciclomotori	Risospensione e usura	Ferrovie e off-road	Colture agricole	Zootecnia	Resto
	%	%	%	%	%	%	%	%	%	%	%	%	%
Dernice - Costa (AL)	9,5	64,9	1,2	2,6	1,0	1,4	2,6	0,7	1,1	1,5	2,4	10,0	1,1
Vinchio - San Michele (AT)	7,0	72,3	1,8	2,5	0,6	1,7	3,3	0,6	1,4	2,0	1,5	4,6	0,4
Mondovì - Aragno (CN)	5,8	75,8	0,9	2,3	0,4	1,8	2,8	0,5	1,3	2,7	0,1	5,4	0,0
Borgomanero - Molli (NO)	4,5	80,1	0,8	2,2	0,5	1,5	2,2	0,6	1,6	0,8	1,2	2,7	1,3
Ivrea - Liberazione (TO)	3,0	77,4	1,4	2,6	0,8	2,1	3,1	0,8	1,9	1,5	1,2	2,8	1,3
Borgosesia - Tonella (VC)	4,7	78,4	1,1	2,0	0,7	1,5	2,0	0,6	1,4	0,9	1,5	3,6	1,8
Verbania - Gabardi (VB)	6,0	73,1	1,1	2,9	1,1	2,0	2,5	0,8	2,1	0,7	0,7	4,2	2,9

PARTICOLATO PM2.5 - Contributo percentuale alla media annuale - ZONA IT0121

	Industria	Riscaldamento a legna	Riscaldamento NON a legna	Automobili diesel	Automobili NON diesel	Veicoli leggeri	Veicoli pesanti	Motocicli e ciclomotori	Risospensione e usura	Ferrovie e off-road	Colture agricole	Zootecnia	Resto
	%	%	%	%	%	%	%	%	%	%	%	%	%
Trivero - Ronco (BI)	3,8	80,7	1,0	1,7	0,7	1,4	2,0	0,5	1,2	0,9	1,4	3,1	1,5
Domodossola - Curotti (VB)	3,0	78,9	0,7	2,0	0,4	1,6	1,8	0,6	1,6	3,3	0,4	2,9	2,8

(b) *Zones IT0120 and IT0121*

Table A.3: Percentage contribution to annual average concentration of $PM_{2.5}$ by the sectors identified for the source apportionment [6].

BIOSSIDO DI AZOTO - Contributo percentuale alla media annuale - ZONA IT0118

	Industria	Riscaldamento a legna	Riscaldamento NON a legna	Automobili diesel	Automobili NON diesel	Veicoli leggeri	Veicoli pesanti	Motocicli e ciclomotori	Risospensione e usura	Ferrovie e off-road	Colture agricole	Zootecnia	Resto
	%	%	%	%	%	%	%	%	%	%	%	%	%
Torino - Consolata (TO)	9,1	0,5	9,4	15,8	5,1	19,5	34,1	2,0	0,0	1,2	0,6	0,0	2,7
Torino - Lingotto (TO)	10,8	0,6	8,2	15,9	5,0	18,8	34,4	1,9	0,0	1,2	0,7	0,0	2,3
Torino - Rebaudengo (TO)	11,2	0,6	8,4	15,6	4,9	18,3	34,2	1,8	0,0	1,5	0,6	0,0	2,8
Torino - Rubino (TO)	10,7	0,6	8,0	16,1	5,0	18,5	34,9	1,9	0,0	1,4	0,7	0,0	2,1
Borgaro T. - Caduti (TO)	10,3	2,2	7,2	16,7	4,4	14,2	32,9	1,2	0,0	4,5	0,4	0,0	5,9
Chieri - Bersezio (TO)	12,0	3,8	10,7	17,2	4,6	15,4	28,9	1,0	0,0	5,1	0,6	0,0	0,8
Druento - La Mandria (TO)	12,4	5,3	9,2	17,4	4,6	14,8	27,7	0,8	0,0	5,2	0,1	0,0	2,6
Leini (ACEA) - Grande Torino (TO)	11,9	3,1	8,3	17,5	4,6	14,2	30,0	1,1	0,0	5,7	0,5	0,0	3,2
Orbassano - Gozzano (TO)	8,5	2,0	6,5	19,3	4,8	14,8	39,2	1,1	0,0	2,5	0,5	0,0	0,9
Settimo T. - Vivaldi (TO)	13,2	2,1	7,4	17,0	4,4	13,9	35,4	1,2	0,0	3,7	0,5	0,0	1,4
Vinovo - Volontari (TO)	9,1	2,8	8,3	19,0	5,0	16,4	32,7	1,1	0,0	4,0	0,8	0,0	0,6

BIOSSIDO DI AZOTO - Contributo percentuale alla media annuale - ZONA IT0119

	Industria	Riscaldamento a legna	Riscaldamento NON a legna	Automobili diesel	Automobili NON diesel	Veicoli leggeri	Veicoli pesanti	Motocicli e ciclomotori	Risospensione e usura	Ferrovie e off-road	Colture agricole	Zootecnia	Resto
	%	%	%	%	%	%	%	%	%	%	%	%	%
Alessandria - D'Annunzio (AL)	12,7	2,4	8,4	16,2	3,9	11,9	37,1	1,0	0,0	4,3	1,1	0,0	1,1
Alessandria - Volta (AL)	12,1	2,2	8,0	16,1	3,8	11,2	39,1	0,9	0,0	4,3	1,2	0,0	1,0
Asti - Baussano (AT)	7,5	4,3	10,3	16,6	4,3	13,9	37,9	1,1	0,0	3,1	0,4	0,0	0,7
Asti - D'Acquisto (AT)	7,4	3,9	9,7	16,2	4,1	13,2	40,1	1,0	0,0	3,1	0,5	0,0	0,7
Biella - Sturzo (BI)	7,0	8,8	12,2	18,3	5,2	17,6	27,1	1,2	0,0	1,9	0,3	0,1	0,2
Cuneo - Alpini (CN)	18,0	10,6	11,7	14,7	3,9	13,4	22,2	0,8	0,0	4,2	0,0	0,0	0,5
Revello - Staffarda (CN)	7,9	9,2	7,6	13,4	3,5	11,2	19,3	0,2	0,0	26,6	1,0	0,0	0,0
Novara - Roma (NO)	21,5	1,5	8,0	15,0	3,8	11,8	28,0	1,2	0,0	4,7	2,1	0,1	2,4
Novara - Verdi (NO)	21,1	1,5	8,2	15,1	3,8	11,9	27,9	1,2	0,0	4,8	2,1	0,1	2,4
Cerano - Bagno (NO)	18,8	1,8	10,4	18,0	3,8	10,1	22,6	0,9	0,0	5,5	3,3	0,1	4,6
Vercelli - CONI (VC)	7,1	1,9	10,1	17,3	4,4	13,7	31,9	1,3	0,0	7,2	4,0	0,0	1,1
Vercelli - Gastaldi (VC)	7,6	2,1	9,7	17,2	4,3	13,0	31,6	1,2	0,0	7,8	4,3	0,0	1,2
Cigliano - Autostrada (VC)	5,1	4,6	6,9	16,1	3,5	9,9	40,8	0,6	0,0	8,5	3,6	0,0	0,4

(a) *Zones IT0118 and IT0119*

BIOSSIDO DI AZOTO - Contributo percentuale alla media annuale - ZONA IT0120

	Industria	Riscaldamento a legna	Riscaldamento NON a legna	Automobili diesel	Automobili NON diesel	Veicoli leggeri	Veicoli pesanti	Motocicli e ciclomotori	Risospensione e usura	Ferrovie e off-road	Colture agricole	Zootecnia	Resto
	%	%	%	%	%	%	%	%	%	%	%	%	%
Dernice - Costa (AL)	15,1	8,1	11,5	17,3	3,7	9,6	25,6	0,3	0,0	7,3	0,1	0,1	1,2
Vinchio - San Michele (AT)	11,1	8,5	12,0	15,9	3,9	11,7	27,0	0,5	0,0	8,6	0,3	0,0	0,6
Cossato - Pace (BI)	8,7	10,5	11,2	18,8	4,9	15,1	24,9	0,9	0,0	3,2	1,1	0,1	0,6
Alba - Tanaro (CN)	19,0	4,8	9,3	16,3	4,2	13,5	25,7	0,8	0,0	5,8	0,1	0,0	0,4
Mondovì - Aragno (CN)	13,7	10,1	9,8	14,9	3,9	12,7	22,8	0,6	0,0	11,6	0,0	0,0	0,0
Saliceto - Moizo (CN)	19,8	6,2	7,9	17,2	4,0	10,1	26,5	0,6	0,0	6,9	0,0	0,0	0,7
Borgomanero - Molli (NO)	11,3	8,0	13,3	17,9	4,3	13,3	27,3	0,8	0,0	2,1	0,4	0,1	1,3
Ivrea - Liberazione (TO)	6,7	6,8	13,5	18,8	5,1	15,4	28,9	0,9	0,0	3,3	0,4	0,0	0,2
Susa - Repubblica (TO)	2,3	14,9	8,2	18,0	4,1	11,5	39,3	0,5	0,0	1,1	0,0	0,0	0,0
Borgosesia - Tonella (VC)	15,4	9,8	16,0	16,2	4,3	14,2	20,2	0,7	0,0	2,2	0,5	0,1	0,4
Verbania - Gabardi (VB)	14,3	5,9	14,5	18,0	4,4	14,2	26,0	0,8	0,0	1,0	0,0	0,1	0,8
Omegna - Crusinallo (VB)	17,1	6,1	11,1	19,3	4,5	12,7	27,2	0,6	0,0	1,1	0,0	0,1	0,2

BIOSSIDO DI AZOTO - Contributo percentuale alla media annuale - ZONA IT0121

	Industria	Riscaldamento a legna	Riscaldamento NON a legna	Automobili diesel	Automobili NON diesel	Veicoli leggeri	Veicoli pesanti	Motocicli e ciclomotori	Risospensione e usura	Ferrovie e off-road	Colture agricole	Zootecnia	Resto
	%	%	%	%	%	%	%	%	%	%	%	%	%
Trivero - Ronco (BI)	12,5	13,6	11,8	17,1	4,8	14,8	21,8	0,7	0,0	2,4	0,4	0,1	0,0
Ceresole Reale - Diga (TO)	7,8	10,7	9,7	18,7	6,7	11,6	29,1	0,0	0,0	5,5	0,0	0,1	0,1
Oulx - Roma (TO)	5,1	14,4	12,2	14,9	3,3	9,7	39,4	0,4	0,0	0,5	0,0	0,0	0,0
Baceno - Alpe Devero (VB)	12,5	5,4	7,9	14,6	3,8	12,9	19,5	0,1	0,0	23,0	0,0	0,2	0,0
Domodossola - Curotti (VB)	9,7	8,7	12,9	14,8	4,2	14,9	21,9	0,9	0,0	11,9	0,0	0,0	0,0

(b) *Zones IT0120 and IT0121*

Table A.4: Percentage contribution to annual average concentration of NO_2 by the sectors identified for the source apportionment [6].

NITRATO - Contributo percentuale alla media annuale - ZONA IT0118

	Industria	Riscaldamento a legna	Riscaldamento NON a legna	Automobili diesel	Automobili NON diesel	Veicoli leggeri	Veicoli pesanti	Motocicli e ciclomotori	Risospensione e usura	Ferrovie e off-road	Colture agricole	Zootecnia	Resto
	%	%	%	%	%	%	%	%	%	%	%	%	%
Torino - Consolata (TO)	10,5	12,9	2,0	8,4	5,7	6,0	13,8	3,3	0,3	7,7	6,6	22,7	0,0
Torino - Lingotto (TO)	10,6	13,2	1,9	8,2	5,6	5,8	13,4	3,3	0,3	8,1	7,3	22,1	0,0
Torino - Rebaudengo (TO)	10,5	13,2	2,3	8,7	5,3	6,3	14,4	3,2	0,3	7,6	6,3	21,9	0,0
Torino - Rubino (TO)	10,0	13,5	2,1	8,4	5,7	6,1	13,6	3,4	0,3	7,7	6,8	22,4	0,0
Borgaro T. - Caduti (TO)	10,0	14,9	2,4	9,6	4,0	7,1	15,9	2,6	0,2	7,4	4,9	20,9	0,0
Druento - La Mandria (TO)	8,2	16,8	2,6	9,4	3,4	7,1	15,5	2,2	0,2	6,9	4,6	23,1	0,0
Leini (ACEA) - Grande Torino (TO)	10,8	15,1	2,3	10,1	3,5	7,3	16,9	2,4	0,3	7,7	4,5	19,0	0,0
Settimo T. - Vivaldi (TO)	11,9	14,3	2,2	9,7	3,7	6,8	16,2	2,3	0,3	7,9	5,7	18,9	0,0

NITRATO - Contributo percentuale alla media annuale - ZONA IT0119

	Industria	Riscaldamento a legna	Riscaldamento NON a legna	Automobili diesel	Automobili NON diesel	Veicoli leggeri	Veicoli pesanti	Motocicli e ciclomotori	Risospensione e usura	Ferrovie e off-road	Colture agricole	Zootecnia	Resto
	%	%	%	%	%	%	%	%	%	%	%	%	%
Alessandria - D'Annunzio (AL)	18,8	12,4	2,4	10,0	3,1	5,7	15,8	1,6	0,2	5,9	6,2	17,9	0,0
Alessandria - Volta (AL)	19,0	12,3	2,3	10,0	3,1	5,7	15,6	1,6	0,2	6,0	6,3	17,9	0,0
Casale M . - Castello (AL)	15,1	14,2	1,8	9,6	3,4	5,4	14,4	2,5	0,2	6,3	10,8	16,3	0,0
Asti - Baussano (AT)	16,0	14,2	2,8	9,8	3,3	6,5	16,1	1,4	0,2	7,3	3,9	18,3	0,0
Asti - D'Acquisto (AT)	16,1	14,3	2,8	9,8	3,3	6,4	16,0	1,5	0,2	7,3	4,0	18,3	0,0
Biella - Sturzo (BI)	12,4	16,8	3,0	8,6	4,2	5,9	14,4	1,4	0,2	5,7	5,7	21,8	0,0
Cuneo - Alpini (CN)	21,6	13,4	2,5	8,3	2,4	6,2	13,5	0,7	0,1	8,3	1,3	21,7	0,0
Novara - Roma (NO)	17,2	13,9	1,1	9,4	3,7	4,6	11,2	2,8	0,3	4,3	9,3	22,3	0,0
Novara - Verdi (NO)	17,1	13,8	1,1	9,4	3,7	4,6	11,2	2,8	0,3	4,3	9,4	22,4	0,0
Cerano - Bagno (NO)	14,4	12,6	0,0	9,9	3,5	4,3	10,5	2,6	0,4	3,9	13,2	24,7	0,0
Vercelli - CONI (VC)	14,4	15,2	0,8	9,3	4,1	5,1	12,7	3,3	0,3	5,1	12,7	16,9	0,0
Vercelli - Gastaldi (VC)	14,8	15,2	0,8	9,4	3,9	5,0	12,6	3,2	0,3	5,0	12,6	17,1	0,0

(a) *Zones IT0118 and IT0119*

NITRATO- Contributo percentuale alla media annuale - ZONA IT0120

	Industria	Riscaldamento a legna	Riscaldamento NON a legna	Automobili diesel	Automobili NON diesel	Veicoli leggeri	Veicoli pesanti	Motocicli e ciclomotori	Risospensione e usura	Ferrovie e off-road	Colture agricole	Zootecnia	Resto
	%	%	%	%	%	%	%	%	%	%	%	%	%
Dernice - Costa (AL)	9,0	10,2	2,5	6,3	3,5	3,2	8,6	0,8	0,1	3,4	9,2	43,3	0,0
Vinchio - San Michele (AT)	16,0	13,4	3,1	9,2	3,0	5,8	15,4	1,0	0,2	6,3	5,1	21,5	0,0
Cossato - Pace (BI)	12,6	19,5	2,8	7,3	4,1	4,7	11,9	1,7	0,2	5,0	6,7	23,5	0,0
Alba - Tanaro (CN)	15,3	13,3	2,9	10,6	3,2	7,1	17,5	0,7	0,2	7,0	2,7	19,6	0,0
Mondovi - Aragno (CN)	17,5	13,1	3,5	10,4	2,8	7,6	17,1	0,4	0,1	8,2	0,7	18,5	0,0
Saliceto - Moizo (CN)	11,9	9,5	3,5	9,6	4,5	6,2	15,4	0,3	0,1	6,0	4,8	28,0	0,0
Borgomanero - Molli (NO)	16,1	15,0	2,7	9,1	3,8	5,0	12,9	1,3	0,2	4,2	6,0	23,6	0,0
Ivrea - Liberazione (TO)	10,8	14,1	3,9	9,2	4,0	6,4	16,2	1,4	0,1	6,4	8,1	19,3	0,0
Susa - Repubblica (TO)	5,1	14,1	3,4	5,8	3,4	4,2	10,5	0,5	0,1	3,0	10,4	39,2	0,5
Borgosesia - Tonella (VC)	12,4	16,2	3,3	7,4	4,3	4,7	11,3	1,1	0,2	3,9	5,8	29,4	0,0
Verbania - Gabardi (VB)	14,4	13,0	2,6	7,7	7,3	4,3	10,2	0,6	0,1	2,7	4,9	32,0	0,2
Omegna - Crusinallo (VB)	12,2	12,6	2,9	8,4	7,3	4,9	12,0	0,5	0,1	3,4	5,2	30,1	0,2

NITRATO - Contributo percentuale alla media annuale - ZONA IT0121

	Industria	Riscaldamento a legna	Riscaldamento NON a legna	Automobili diesel	Automobili NON diesel	Veicoli leggeri	Veicoli pesanti	Motocicli e ciclomotori	Risospensione e usura	Ferrovie e off-road	Colture agricole	Zootecnia	Resto
	%	%	%	%	%	%	%	%	%	%	%	%	%
Trivero - Ronco (BI)	11,6	15,2	3,7	7,8	4,3	5,3	12,7	1,0	0,1	4,7	6,4	27,1	0,0
Oulx - Roma (TO)	5,1	12,5	2,8	4,8	3,2	3,5	9,8	0,4	0,1	2,2	18,2	26,9	10,5
Domodossola - Curotti (VB)	12,0	13,1	4,0	8,2	4,2	5,3	11,9	0,6	0,1	5,1	4,2	31,2	0,0

(b) *Zones IT0120 and IT0121*

Table A.5: Percentage contribution to annual average concentration of nitrate ion (NO_3^-) by the sectors identified for the source apportionment [6].

SOLFATO - Contributo percentuale alla media annuale - ZONA IT0118

	Industria	Riscaldamento a legna	Riscaldamento NON a legna	Automobili diesel	Automobili NON diesel	Veicoli leggeri	Veicoli pesanti	Motocicli e ciclomotori	Risospensione e usura	Ferrovie e off-road	Colture agricole	Zootecnia	Resto
	%	%	%	%	%	%	%	%	%	%	%	%	%
Torino - Consolata (TO)	12,7	7,9	63,8	2,8	1,6	3,1	0,6	1,7	0,0	1,5	0,0	0,2	4,1
Torino - Lingotto (TO)	15,0	11,3	57,0	3,1	1,8	3,4	0,7	1,9	0,0	1,5	0,0	0,2	4,2
Torino - Rebaudengo (TO)	16,0	9,4	58,4	2,9	1,7	3,2	0,7	1,8	0,0	1,8	0,0	0,2	3,9
Torino - Rubino (TO)	15,6	12,5	55,6	3,2	1,9	3,5	0,7	1,9	0,0	1,9	0,0	0,2	3,0
Borgaro T. - Caduti (TO)	22,5	23,6	30,1	2,9	1,9	2,7	1,0	1,3	0,0	4,2	0,0	0,4	9,3
Druento - La Mandria (TO)	28,3	35,7	17,5	2,3	1,8	2,1	1,1	0,9	0,0	3,9	0,0	0,6	5,8
Leini (ACEA) - Grande Torino (TO)	28,0	26,5	26,4	2,5	1,8	2,3	1,0	1,0	0,0	4,3	0,0	0,5	5,7
Settimo T. - Vivaldi (TO)	35,1	21,2	28,1	2,5	1,6	2,3	0,9	1,1	0,0	3,1	0,0	0,4	3,6

SOLFATO - Contributo percentuale alla media annuale - ZONA IT0119

	Industria	Riscaldamento a legna	Riscaldamento NON a legna	Automobili diesel	Automobili NON diesel	Veicoli leggeri	Veicoli pesanti	Motocicli e ciclomotori	Risospensione e usura	Ferrovie e off-road	Colture agricole	Zootecnia	Resto
	%	%	%	%	%	%	%	%	%	%	%	%	%
Alessandria - D'Annunzio (AL)	56,9	14,6	21,7	1,3	0,8	1,0	0,6	0,4	0,0	1,5	0,6	0,3	0,4
Alessandria - Volta (AL)	57,9	14,1	21,0	1,3	0,8	1,0	0,6	0,4	0,0	1,6	0,7	0,3	0,4
Casale M . - Castello (AL)	51,2	16,9	18,7	1,5	0,9	1,1	0,8	0,5	0,0	2,5	5,2	0,3	0,4
Asti - Baussano (AT)	44,6	23,1	26,4	1,3	0,7	1,1	0,7	0,5	0,0	1,3	0,0	0,3	0,0
Asti - D'Acquisto (AT)	46,0	22,4	25,5	1,3	0,8	1,1	0,8	0,5	0,0	1,3	0,0	0,3	0,0
Biella - Sturzo (BI)	38,2	34,2	19,9	1,3	1,9	1,4	0,7	0,5	0,0	1,0	0,1	0,2	0,6
Cuneo - Alpini (CN)	57,7	26,7	11,6	0,7	0,4	0,7	0,3	0,3	0,0	1,0	0,0	0,4	0,2
Novara - Roma (NO)	60,3	13,8	10,4	1,6	1,1	1,4	0,4	0,7	0,0	2,7	4,3	0,2	3,1
Novara - Verdi (NO)	60,2	13,7	10,5	1,6	1,1	1,3	0,4	0,7	0,0	2,8	4,3	0,2	3,1
Cerano - Bagno (NO)	77,5	6,6	5,6	1,0	0,7	0,6	0,2	0,3	0,0	1,3	3,2	0,2	2,9
Vercelli - CONI (VC)	52,2	15,6	13,0	1,8	1,4	1,6	0,8	0,7	0,0	3,2	8,7	0,3	0,7
Vercelli - Gastaldi (VC)	53,5	15,4	12,0	1,7	1,3	1,4	0,7	0,6	0,0	3,2	8,7	0,3	1,0

(a) *Zones IT0118 and IT0119*

SOLFATO - Contributo percentuale alla media annuale - ZONA IT0120

	Industria	Riscaldamento a legna	Riscaldamento NON a legna	Automobili diesel	Automobili NON diesel	Veicoli leggeri	Veicoli pesanti	Motocicli e ciclomotori	Risospensione e usura	Ferrovie e off-road	Colture agricole	Zootecnia	Resto
	%	%	%	%	%	%	%	%	%	%	%	%	%
Dernice - Costa (AL)	74,4	14,0	6,5	1,1	1,0	0,6	0,8	0,2	0,0	1,2	0,0	0,3	0,0
Vinchio - San Michele (AT)	54,1	22,4	17,6	1,1	0,7	0,8	0,8	0,3	0,0	1,9	0,0	0,4	0,0
Cossato - Pace (BI)	44,5	35,3	11,9	1,3	1,6	1,1	0,8	0,4	0,0	1,3	1,1	0,2	0,5
Alba - Tanaro (CN)	58,2	25,4	8,2	1,6	1,0	1,3	1,1	0,5	0,0	2,2	0,0	0,6	0,0
Mondovi - Aragno (CN)	53,1	30,7	7,6	1,1	0,7	0,9	0,7	0,3	0,0	3,8	0,0	0,9	0,0
Saliceto - Moizo (CN)	82,1	10,0	3,2	0,8	1,1	0,6	0,7	0,2	0,0	1,0	0,0	0,3	0,0
Borgomanero - Molli (NO)	47,9	33,6	10,2	1,6	1,3	1,3	0,9	0,4	0,0	1,3	0,0	0,2	1,3
Ivrea - Liberazione (TO)	24,4	37,2	21,1	2,1	5,6	2,6	1,3	0,7	0,0	2,5	0,0	0,4	2,0
Susa - Repubblica (TO)	13,7	53,6	23,9	1,9	1,7	1,5	1,7	0,3	0,1	1,2	0,0	0,6	0,0
Borgosesia - Tonella (VC)	52,7	28,6	11,1	1,4	1,6	1,2	1,1	0,4	0,0	1,4	0,1	0,3	0,1
Verbania - Gabardi (VB)	55,9	24,0	11,0	2,1	1,3	1,5	1,4	0,5	0,0	1,2	0,0	0,2	0,7
Omegna - Crusinallo (VB)	58,8	25,2	7,1	2,0	1,5	1,4	1,5	0,3	0,0	1,4	0,0	0,3	0,3

SOLFATO - Contributo percentuale alla media annuale - ZONA IT0121

	Industria	Riscaldamento a legna	Riscaldamento NON a legna	Automobili diesel	Automobili NON diesel	Veicoli leggeri	Veicoli pesanti	Motocicli e ciclomotori	Risospensione e usura	Ferrovie e off-road	Colture agricole	Zootecnia	Resto
	%	%	%	%	%	%	%	%	%	%	%	%	%
Trivero - Ronco (BI)	45,2	33,3	12,1	1,3	3,2	1,4	1,2	0,3	0,0	1,5	0,1	0,3	0,0
Oulx - Roma (TO)	13,4	52,2	27,1	1,6	1,2	1,3	1,4	0,3	0,1	0,8	0,0	0,5	0,0
Domodossola - Curotti (VB)	40,3	37,5	7,7	1,9	1,3	1,7	1,4	0,6	0,0	7,3	0,0	0,3	0,0

(b) *Zones IT0120 and IT0121*

Table A.6: Percentage contribution to annual average concentration of sulphate ion (SO_4^{2-}) by the sectors identified for the source apportionment [6].

AMMONIO - Contributo percentuale alla media annuale - ZONA IT0118

	Industria	Riscaldamento a legna	Riscaldamento NON a legna	Automobili diesel	Automobili NON diesel	Veicoli leggeri	Veicoli pesanti	Motocicli e ciclomotori	Risospensione e usura	Ferrovie e off-road	Colture agricole	Zootecnia	Resto
	%	%	%	%	%	%	%	%	%	%	%	%	%
Torino - Consolata (TO)	11,6	11,0	28,5	6,1	4,1	4,9	8,4	2,7	0,2	5,1	3,8	13,5	0,0
Torino - Lingotto (TO)	12,4	12,5	23,2	6,4	4,2	5,0	8,8	2,8	0,2	5,7	4,6	14,1	0,1
Torino - Rebaudengo (TO)	12,8	11,8	25,0	6,5	4,0	5,2	9,1	2,7	0,2	5,3	3,8	13,6	0,0
Torino - Rubino (TO)	12,0	12,9	22,9	6,5	4,3	5,2	9,0	2,9	0,2	5,5	4,3	14,4	0,0
Borgaro T. - Caduti (TO)	13,6	17,6	10,2	8,0	3,5	6,1	12,2	2,3	0,2	6,8	3,6	15,9	0,0
Druento - La Mandria (TO)	12,6	21,0	5,8	8,0	3,1	6,1	12,6	1,9	0,2	6,3	3,6	18,7	0,0
Leini (ACEA) - Grande Torino (TO)	15,3	18,3	8,5	8,3	3,1	6,2	13,1	2,1	0,2	7,0	3,4	14,6	0,0
Settimo T. - Vivaldi (TO)	18,7	16,4	9,7	7,7	3,1	5,6	12,0	2,0	0,2	6,6	4,1	13,8	0,0

AMMONIO - Contributo percentuale alla media annuale - ZONA IT0119

	Industria	Riscaldamento a legna	Riscaldamento NON a legna	Automobili diesel	Automobili NON diesel	Veicoli leggeri	Veicoli pesanti	Motocicli e ciclomotori	Risospensione e usura	Ferrovie e off-road	Colture agricole	Zootecnia	Resto
	%	%	%	%	%	%	%	%	%	%	%	%	%
Alessandria - D'Annunzio (AL)	30,2	13,0	8,1	7,4	2,4	4,3	11,3	1,2	0,2	4,6	4,5	12,7	0,0
Alessandria - Volta (AL)	30,6	12,9	7,9	7,4	2,4	4,3	11,1	1,3	0,2	4,7	4,6	12,7	0,0
Casale M . - Castello (AL)	23,7	14,9	5,9	7,6	2,8	4,3	11,2	2,0	0,2	5,4	9,5	12,5	0,0
Asti - Baussano (AT)	24,2	16,8	9,8	7,3	2,6	4,9	11,6	1,1	0,2	5,6	2,7	13,1	0,0
Asti - D'Acquisto (AT)	24,5	16,6	9,2	7,4	2,6	4,9	11,7	1,2	0,2	5,6	2,9	13,3	0,0
Biella - Sturzo (BI)	22,2	23,4	9,5	5,8	3,3	4,2	9,2	1,0	0,1	3,9	3,6	13,6	0,0
Cuneo - Alpini (CN)	36,2	18,7	6,1	5,3	1,6	4,0	8,2	0,6	0,1	5,4	0,7	13,2	0,0
Novara - Roma (NO)	30,9	14,0	4,1	7,0	2,9	3,6	7,9	2,1	0,2	3,8	7,8	15,7	0,0
Novara - Verdi (NO)	30,8	13,9	4,1	7,0	2,9	3,6	7,9	2,1	0,2	3,8	7,9	15,7	0,0
Cerano - Bagno (NO)	39,8	10,2	1,9	6,2	2,4	2,7	6,3	1,7	0,3	2,8	9,6	15,9	0,4
Vercelli - CONI (VC)	24,3	15,3	4,0	7,4	3,4	4,2	9,6	2,6	0,2	4,6	11,7	12,6	0,0
Vercelli - Gastaldi (VC)	25,0	15,3	3,7	7,4	3,3	4,1	9,5	2,6	0,2	4,6	11,6	12,7	0,0

(a) *Zones IT0118 and IT0119*

AMMONIO - Contributo percentuale alla media annuale - ZONA IT0120

	Industria	Riscaldamento a legna	Riscaldamento NON a legna	Automobili diesel	Automobili NON diesel	Veicoli leggeri	Veicoli pesanti	Motocicli e ciclomotori	Risospensione e usura	Ferrovie e off-road	Colture agricole	Zootecnia	Resto
	%	%	%	%	%	%	%	%	%	%	%	%	%
Dernice - Costa (AL)	25,1	11,1	3,6	4,9	3,0	2,5	6,5	0,7	0,1	2,8	7,2	32,6	0,0
Vinchio - San Michele (AT)	25,4	15,6	6,7	7,2	2,5	4,5	11,7	0,8	0,1	5,2	3,8	16,5	0,0
Cossato - Pace (BI)	23,7	25,0	6,0	5,2	3,3	3,5	8,1	1,2	0,1	3,7	4,7	15,5	0,0
Alba - Tanaro (CN)	25,1	16,1	4,1	8,5	2,7	5,8	13,7	0,6	0,2	5,9	2,0	15,5	0,0
Mondovi - Aragno (CN)	26,6	17,6	4,6	8,1	2,3	5,9	12,9	0,4	0,1	7,1	0,4	14,1	0,0
Saliceto - Moizo (CN)	32,4	9,6	3,4	6,7	3,9	4,4	10,6	0,2	0,1	4,4	3,7	20,7	0,1
Borgomanero - Molli (NO)	25,0	20,3	4,8	7,0	3,1	4,0	9,6	1,1	0,2	3,4	4,3	17,2	0,0
Ivrea - Liberazione (TO)	13,9	19,5	7,9	7,6	4,4	5,5	12,8	1,3	0,1	5,5	6,2	15,1	0,0
Susa - Repubblica (TO)	7,0	25,0	9,3	4,7	2,9	3,4	7,9	0,4	0,1	2,4	7,7	29,1	0,2
Borgosesia - Tonella (VC)	23,8	19,7	5,5	5,7	3,6	3,7	8,3	0,9	0,1	3,2	4,2	21,2	0,0
Verbania - Gabardi (VB)	26,2	16,2	5,1	6,1	5,6	3,5	7,7	0,6	0,1	2,3	3,3	23,1	0,4
Omegna - Crusinallo (VB)	24,4	16,0	4,0	6,7	5,8	4,0	9,2	0,5	0,1	2,9	3,6	22,5	0,2

AMMONIO - Contributo percentuale alla media annuale - ZONA IT0121

	Industria	Riscaldamento a legna	Riscaldamento NON a legna	Automobili diesel	Automobili NON diesel	Veicoli leggeri	Veicoli pesanti	Motocicli e ciclomotori	Risospensione e usura	Ferrovie e off-road	Colture agricole	Zootecnia	Resto
	%	%	%	%	%	%	%	%	%	%	%	%	%
Trivero - Ronco (BI)	21,5	20,7	6,2	5,9	4,0	4,1	9,3	0,8	0,1	3,7	4,5	19,2	0,0
Oulx - Roma (TO)	6,8	21,1	8,1	4,1	2,8	3,0	7,8	0,3	0,1	1,9	14,4	21,3	8,2
Domodossola - Curotti (VB)	20,9	21,1	5,3	6,2	3,3	4,1	8,5	0,6	0,1	5,7	2,6	21,6	0,0

(b) *Zones IT0120 and IT0121*

Table A.7: Percentage contribution to annual average concentration of ammonium ion (NH_4^+) by the sectors identified for the source apportionment [6].

Appendix B

Processing of SIPEE database

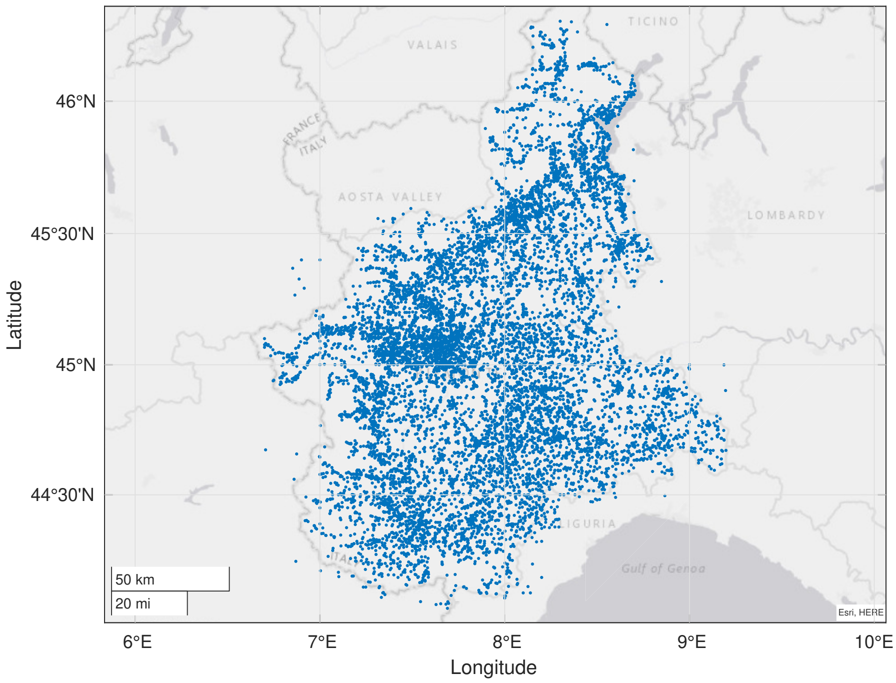


Figure B.1: Production of sanitary water by means of electric power, elaboration of data obtained from [9].

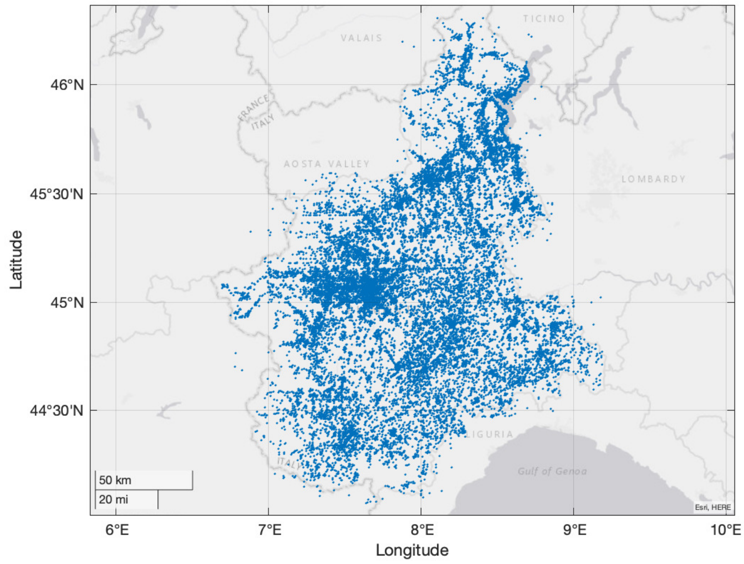


Figure B.2: Production of sanitary water by means of natural gas, elaboration of data obtained from [9].

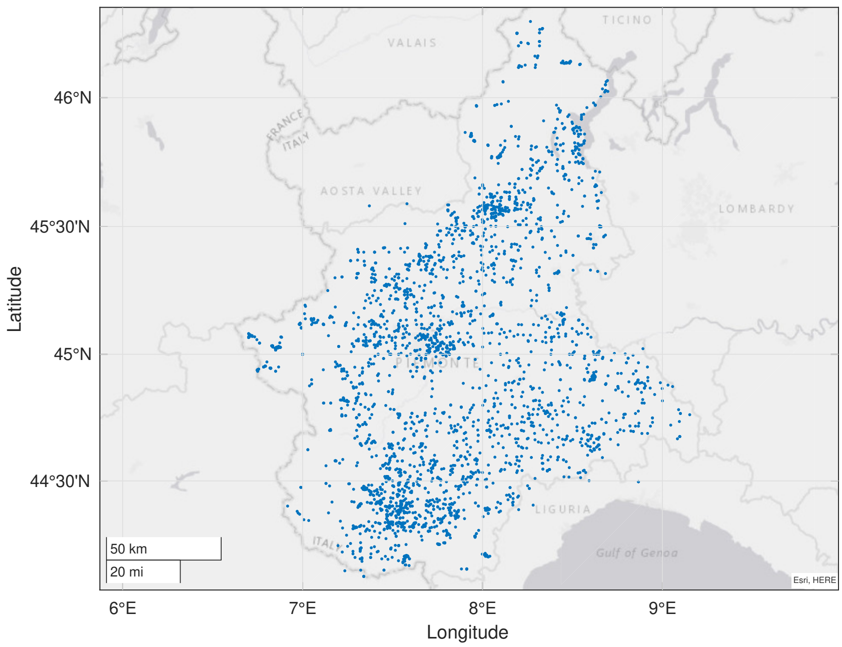


Figure B.3: Production of sanitary water by means of diesel fuel and/or fuel oil, elaboration of data obtained from [9].

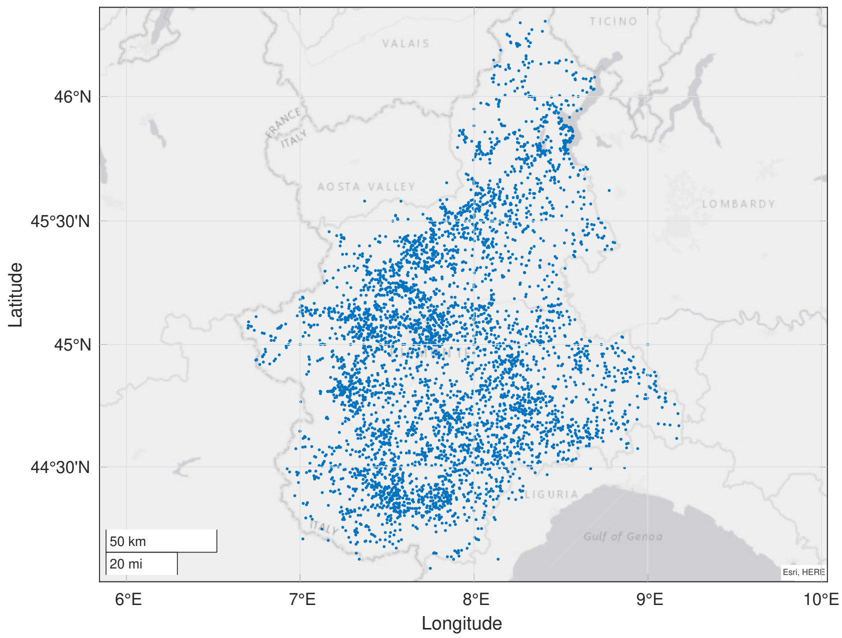


Figure B.4: Production of sanitary water by means of LPG, elaboration of data obtained from [9].

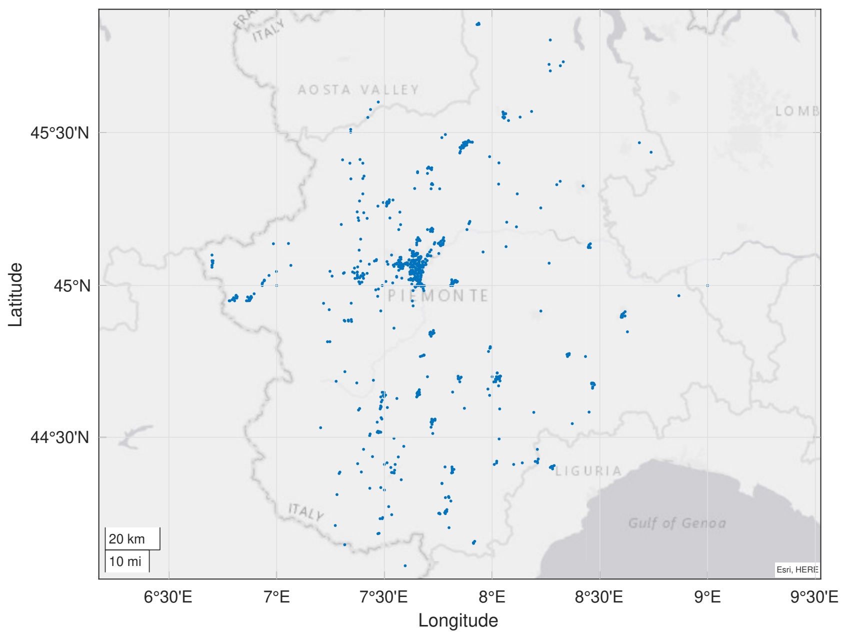


Figure B.5: Production of sanitary water by means of district heating/cooling, elaboration of data obtained from [9].

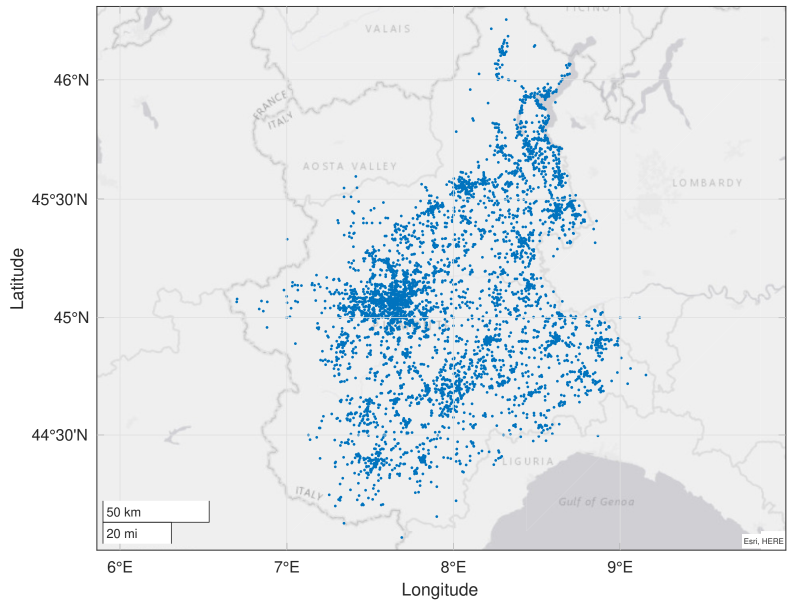


Figure B.6: Production of summer cooling by means of electric power, elaboration of data obtained from [9].

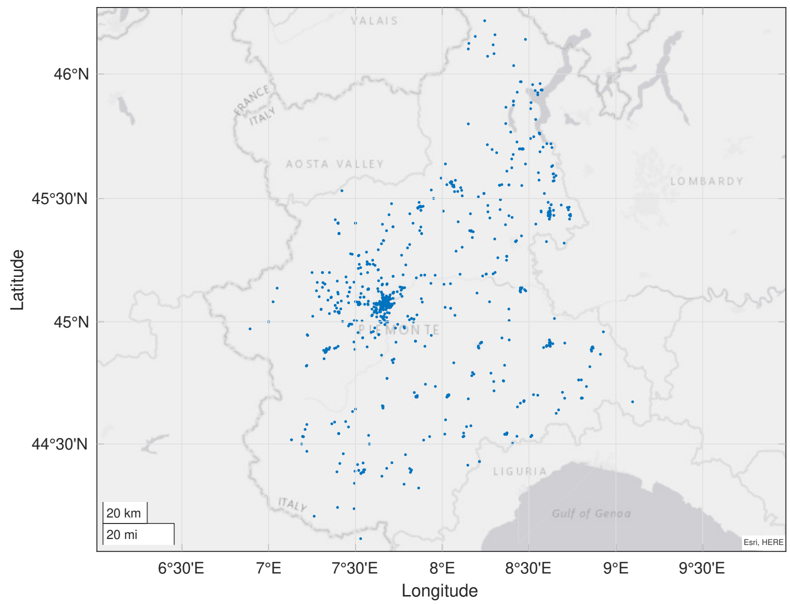


Figure B.7: Production of summer cooling by means of natural gas, elaboration of data obtained from [9].

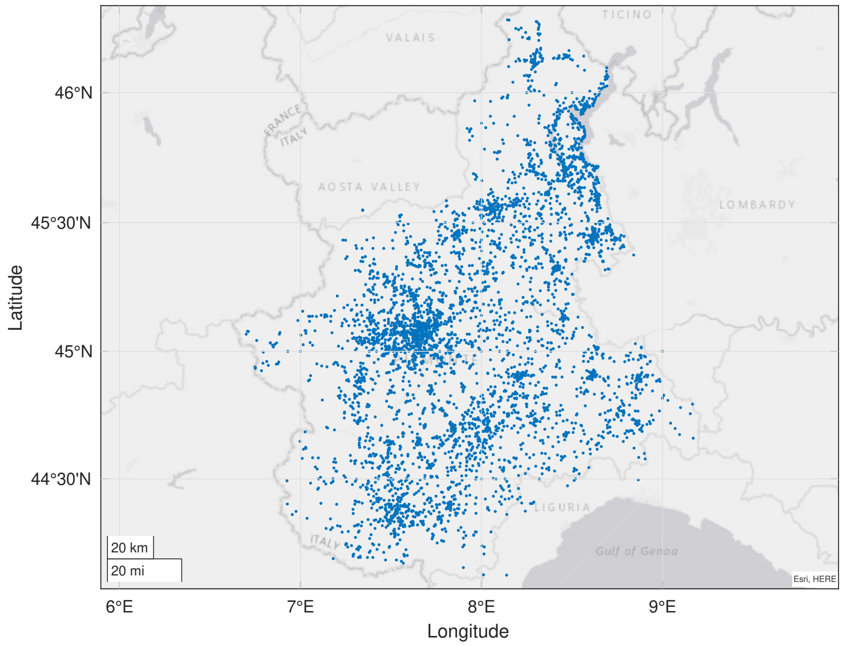


Figure B.8: Production of winter heating by means of electric power, elaboration of data obtained from [9].

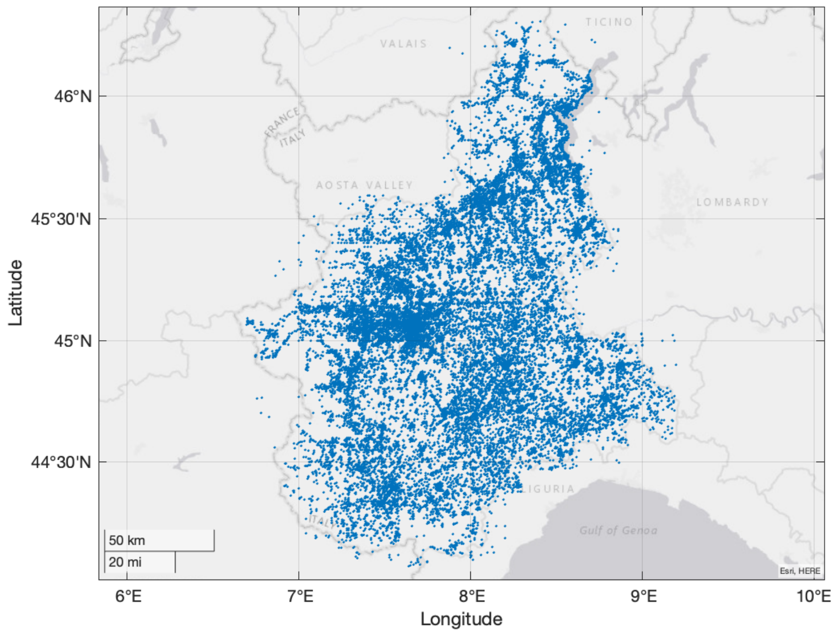


Figure B.9: Production of winter heating by means of natural gas, elaboration of data obtained from [9].

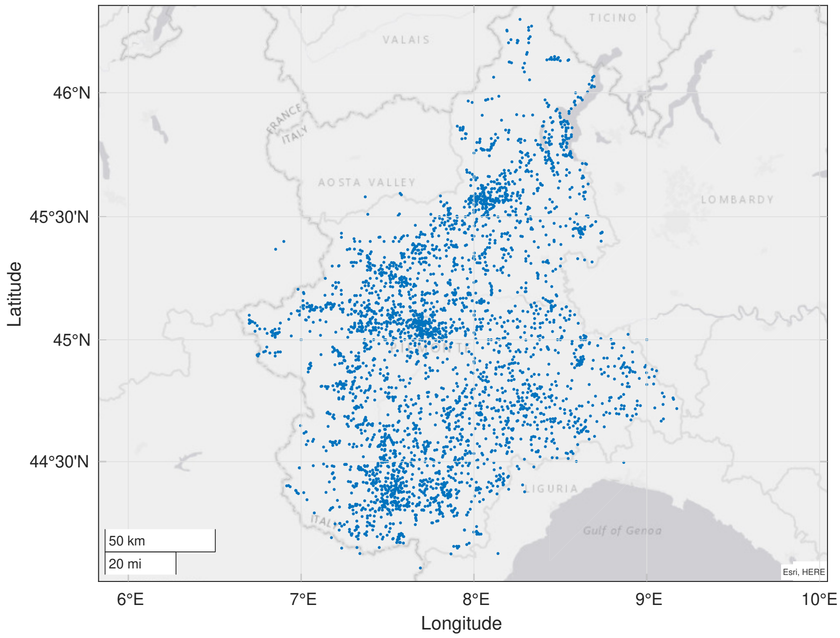


Figure B.10: Production of winter heating by means of diesel fuel and/or fuel oil, elaboration of data obtained from [9].

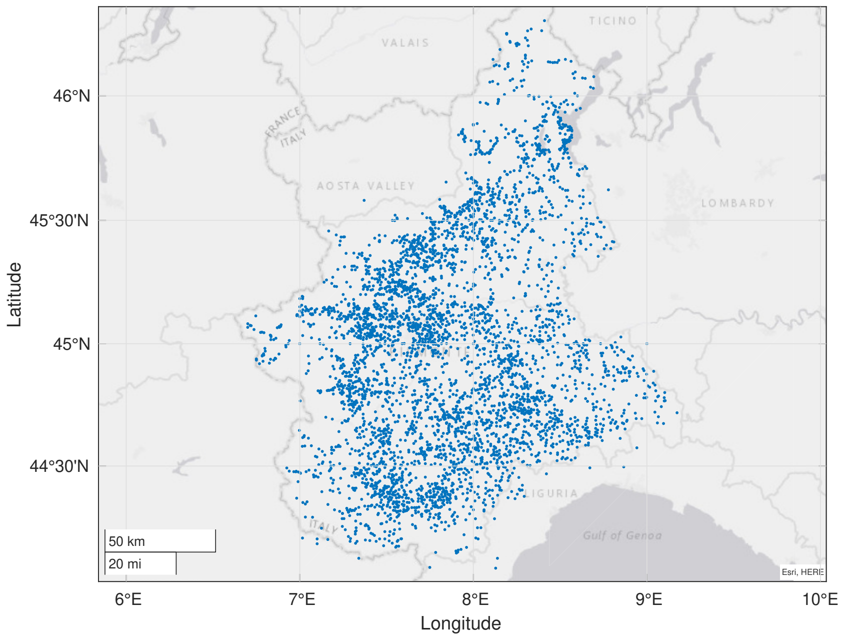


Figure B.11: Production of winter heating by means of LPG, elaboration of data obtained from [9].

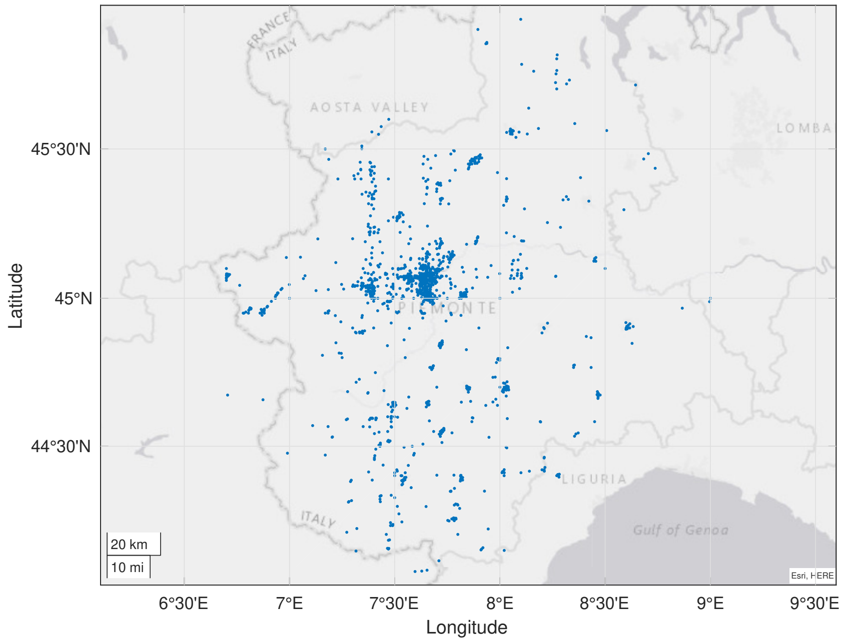


Figure B.12: Production of winter heating by means of district heating/cooling, elaboration of data obtained from [9].

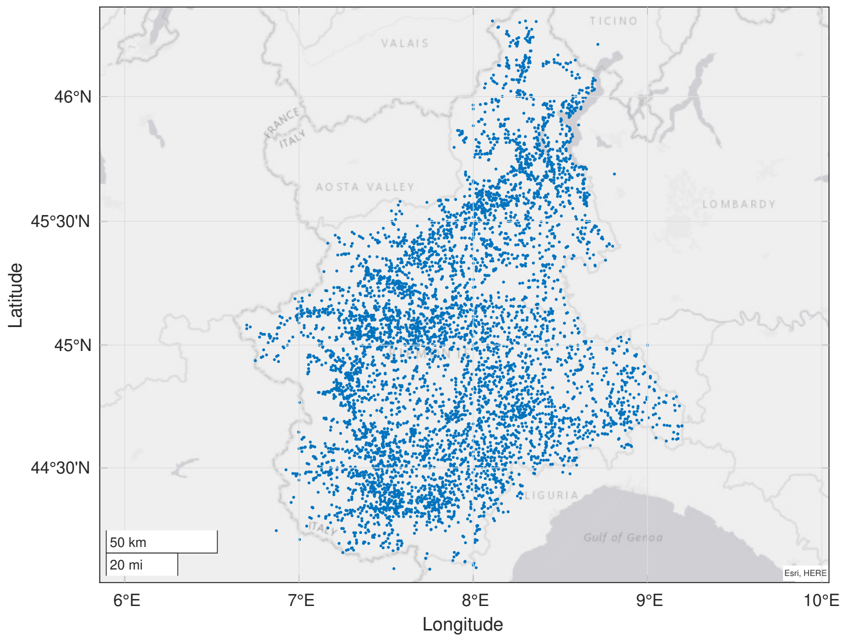


Figure B.13: Production of winter heating by means of biomass, elaboration of data obtained from [9].

Appendix C

Analyses on air quality and regional monitoring system

The following tables report a list of all the monitoring stations that measure PM_{10} and NO_2 concentrations and the relative zoning they belong to. It also point out if the law limits are respected or not in each area, according to the D.G.R. 29 December 2014, n. 41-855. The former is about the hourly values, while the latter about yearly ones.

Table C.1: List of which monitoring stations whose pollutants surveys are in compliance with the hourly limits of PM_{10} and NO_2 and which not (U stands for "unavailable data"), elaboration of data obtained from [13] and the D.G.R. 29 December 2014, n. 41-855.

#	District	Monitoring station	Zone	PM_{10}	NO_2
1	Alessandria	Alessandria - D'Annunzio	IT0119	No	Yes
2	Alessandria	Alessandria - Volta	IT0119	No	Yes
3	Alessandria	Arquata S. - Minzoni	IT0120	Yes	U
4	Alessandria	Casale M.to - Castello	IT0119	Yes	Yes
5	Alessandria	Dernice - Costa	IT0120	Yes	Yes
6	Alessandria	Novi Ligure - Gobetti	IT0119	No	Yes
7	Alessandria	Tortona - Carbone	IT0119	Yes	Yes
8	Asti	Asti - Baussano	IT0119	No	Yes
9	Asti	Asti - D'Acquisto	IT0119	No	Yes
10	Asti	Vinchio - San Michele	IT0120	Yes	Yes
11	Biella	Biella - Lamarmora	IT0119	Yes	Yes
12	Biella	Biella - Sturzo	IT0119	Yes	Yes
13	Biella	Cossato - Pace	IT0120	Yes	Yes

14	Biella	Trivero - Ronco	IT0121	Yes	Yes
15	Cuneo	Alba - Tanaro	IT0120	Yes	Yes
16	Cuneo	Bra - Madonna Fiori	IT0119	Yes	Yes
17	Cuneo	Cuneo - Alpini	IT0119	Yes	Yes
18	Cuneo	Mondovi - Aragno	IT0120	Yes	Yes
19	Cuneo	Revello - Staffarda	IT0119	U	Yes
20	Cuneo	Saliceto - Moizo	IT0120	Yes	Yes
21	Novara - VCO	Baceno - Alpe Devero	IT0121	Yes	Yes
22	Novara - VCO	Borgomanero - Molli	IT0120	Yes	Yes
23	Novara - VCO	Castelletto T. - Fontane	IT0120	Yes	Yes
24	Novara - VCO	Cerano - Bagno	IT0119	No	Yes
25	Novara - VCO	Domodossola - Curotti	IT0121	Yes	Yes
26	Novara - VCO	Novara - Arpa	IT0119	Yes	Yes
27	Novara - VCO	Novara - Roma	IT0119	Yes	Yes
28	Novara - VCO	Oleggio - Gallarate	IT0120	No	Yes
29	Novara - VCO	Omegna - Crusinallo	IT0120	Yes	Yes
30	Novara - VCO	Pieve Vergonte - Industria	IT0121	U	U
31	Novara - VCO	Trecate - Verra	IT0119	U	U
32	Novara - VCO	Verbania - Gabardi	IT0120	Yes	Yes
33	Torino	Borgaro T. - Caduti	IT0118	Yes	Yes
34	Torino	Carmagnola - I Maggio	IT0119	No	Yes
35	Torino	Ceresole Reale - Diga	IT0121	Yes	Yes
36	Torino	Chieri - Bersezio	IT0118	Yes	Yes
37	Torino	Collegno - Francia	IT0118	No	Yes
38	Torino	Druento - La Mandria	IT0118	Yes	Yes
39	Torino	Ivrea - Liberazione	IT0120	Yes	Yes
40	Torino	Orbassano - Gozzano	IT0118	U	U
41	Torino	Oulx - Roma	IT0121	Yes	Yes
42	Torino	Pinerolo - Alpini	IT0120	Yes	U
43	Torino	Settimo T. - Vivaldi	IT0118	No	Yes
44	Torino	Susa - Repubblica	IT0120	Yes	Yes
45	Torino	Torino - Consolata	IT0118	No	Yes
46	Torino	Torino - Grassi	IT0118	No	U
47	Torino	Torino - Lingotto	IT0118	No	Yes
48	Torino	Torino - Rebaudengo	IT0118	No	Yes
49	Torino	Torino - Rubino	IT0118	No	Yes
50	Torino	Vinovo - Volontari	IT0118	U	U
51	Vercelli	Borgosesia - Tonella	IT0120	Yes	Yes
52	Vercelli	Cigliano - Autostrada	IT0120	Yes	Yes
53	Vercelli	Vercelli - CONI	IT0119	Yes	Yes
54	Vercelli	Vercelli - Gastaldi	IT0119	No	Yes

55	AceaElectrabel Private Network	Baldissero T. - parco	IT0118	Yes	Yes
56	AceaElectrabel Private Network	Leinì - Grande Torino	IT0118	No	Yes
57	Edipower Private Network	Castagneto Po - Monpilotto	IT0120	Yes	Yes
58	Edipower Private Network	Chivasso - Montanaro	IT0119	Yes	Yes
59	TRM Private Network	Beinasco - Aldo Mei	IT0118	No	Yes

Table C.2: List of which monitoring stations whose pollutants surveys are in compliance with the average annual limits of PM_{10} and NO_2 and which not (U stands for "unavailable data"), elaboration of data obtained from [13] and the D.G.R. 29 December 2014, n. 41-855.

#	District	Monitoring station	Zone	PM_{10}	NO_2
1	Alessandria	Alessandria - D'Annunzio	IT0119	Yes	No
2	Alessandria	Alessandria - Volta	IT0119	Yes	No
3	Alessandria	Arquata S. - Minzoni	IT0120	Yes	U
4	Alessandria	Casale M.to - Castello	IT0119	Yes	No
5	Alessandria	Dernice - Costa	IT0120	Yes	Yes
6	Alessandria	Novi Ligure - Gobetti	IT0119	Yes	No
7	Alessandria	Tortona - Carbone	IT0119	Yes	No
8	Asti	Asti - Baussano	IT0119	Yes	No
9	Asti	Asti - D'Acquisto	IT0119	Yes	No
10	Asti	Vinchio - San Michele	IT0120	Yes	Yes
11	Biella	Biella - Lamarmora	IT0119	Yes	No
12	Biella	Biella - Sturzo	IT0119	Yes	Yes
13	Biella	Cossato - Pace	IT0120	Yes	Yes
14	Biella	Trivero - Ronco	IT0121	Yes	Yes
15	Cuneo	Alba - Tanaro	IT0120	Yes	Yes
16	Cuneo	Bra - Madonna Fiori	IT0119	Yes	No
17	Cuneo	Cuneo - Alpini	IT0119	Yes	No
18	Cuneo	Mondovi - Aragno	IT0120	Yes	No
19	Cuneo	Revello - Staffarda	IT0119	U	Yes
20	Cuneo	Saliceto - Moizo	IT0120	Yes	Yes
21	Novara - VCO	Baceno - Alpe Devero	IT0121	Yes	Yes
22	Novara - VCO	Borgomanero - Molli	IT0120	Yes	No

23	Novara - VCO	Castelletto T. - Fontane	IT0120	Yes	No
24	Novara - VCO	Cerano - Bagno	IT0119	Yes	No
25	Novara - VCO	Domodossola - Curotti	IT0121	Yes	No
26	Novara - VCO	Novara - Arpa	IT0119	Yes	No
27	Novara - VCO	Novara - Roma	IT0119	Yes	No
28	Novara - VCO	Oleggio - Gallarate	IT0120	Yes	Yes
29	Novara - VCO	Omegna - Crusinallo	IT0120	Yes	No
30	Novara - VCO	Pieve Vergonte - Industria	IT0121	U	Yes
31	Novara - VCO	Trecate - Verra	IT0119	U	No
32	Novara - VCO	Verbania - Gabardi	IT0120	Yes	Yes
33	Torino	Borgaro T. - Caduti	IT0118	Yes	No
34	Torino	Carmagnola - I Maggio	IT0119	Yes	No
35	Torino	Ceresole Reale - Diga	IT0121	Yes	Yes
36	Torino	Chieri - Bersezio	IT0118	Yes	Yes
37	Torino	Collegno - Francia	IT0118	Yes	No
38	Torino	Druento - La Mandria	IT0118	Yes	Yes
39	Torino	Ivrea - Liberazione	IT0120	Yes	No
40	Torino	Orbassano - Gozzano	IT0118	U	No
41	Torino	Oulx - Roma	IT0121	Yes	No
42	Torino	Pinerolo - Alpini	IT0120	Yes	U
43	Torino	Settimo T. - Vivaldi	IT0118	Yes	Yes
44	Torino	Susa - Repubblica	IT0120	Yes	No
45	Torino	Torino - Consolata	IT0118	Yes	No
46	Torino	Torino - Grassi	IT0118	Yes	U
47	Torino	Torino - Lingotto	IT0118	Yes	No
48	Torino	Torino - Rebaudengo	IT0118	Yes	No
49	Torino	Torino - Rubino	IT0118	Yes	No
50	Torino	Vinovo - Volontari	IT0118	U	No
51	Vercelli	Borgosesia - Tonella	IT0120	Yes	Yes
52	Vercelli	Cigliano - Autostrada	IT0120	Yes	No
53	Vercelli	Vercelli - CONI	IT0119	Yes	Yes
54	Vercelli	Vercelli - Gastaldi	IT0119	Yes	No
55	AceaElectrabel Private Network	Baldissero T. - parco	IT0118	Yes	Yes
56	AceaElectrabel Private Network	Leinì - Grande Torino	IT0118	Yes	No
57	Edipower Private Network	Castagneto Po - Monpilotto	IT0120	Yes	Yes
58	Edipower Private Network	Chivasso - Montanaro	IT0119	Yes	Yes

59	TRM Private Network	Beinasco - Aldo Mei	IT0118	Yes	No

Bibliography

[1] Treccani. *Piemonte*. URL: http://www.treccani.it/enciclopedia/piemonte/ (cit. on pp. 2, 3).

[2] Touring Club Italiano. *Guida d'Italia - Piemonte*. Ed. by Touring Editore S.r.l. - Milano. 8th Edition. Guida d'Italia del Touring Club Italiano. Touring Club Italiano, 1976 (cit. on p. 1).

[3] Regione Piemonte, Istat, and SISTAN. *I numeri del Piemonte - Annuario Statistico Regionale*. June 2019. URL: https://www.regione.piemonte.it/web/amministrazione/finanza-programmazione-statistica/statistica/numeri-piemonte-annuario-statistico-regionale (cit. on pp. 3, 4, 18, 19).

[4] Istat. *Superfici delle unità amministrative a fini statistici*. Feb. 2013. URL: https://www.istat.it/it/archivio/82599 (cit. on p. 3).

[5] Istat. *Popolazione residente al 1° gennaio: Piemonte*. Mar. 2020. URL: http://dati.istat.it/Index.aspx?QueryId=18540# (cit. on p. 3).

[6] Regione Piemonte. *Piano Regionale di Qualità dell'Aria (PRQA)*. Mar. 2019. URL: https://www.regione.piemonte.it/web/temi/ambiente-territorio/ambiente/aria/piano-regionale-qualita-dellaria-prqa (cit. on pp. 5, 15, 31, 134–142).

[7] Sistemapiemonte. *Qualità dell'aria in Piemonte - Documentazione*. URL: http://www.sistemapiemonte.it/cms/privati/ambiente-e-energia/servizi/510-qualita-dell-aria-in-piemonte/3040-documentazione (cit. on pp. 6, 103).

[8] Sistemapiemonte. *Sistema Informativo per la Prestazione Energetica degli Edifici (SIPEE)*. URL: http://www.sistemapiemonte.it/cms/privati/ambiente-e-energia/servizi/856-sistema-informativo-per-le-prestazioni-energetiche-degli-edifici-sipee (cit. on p. 17).

[9] Regione Piemonte. *Dati Piemonte ha più energia!* Nov. 2019. URL: http://www.dati.piemonte.it/novita/1-ultime/1141-dati-piemonte-ha-piu-energia.html (cit. on pp. 18–23, 25–27, 29, 30, 143–149).

[10] Iain Staffell, Dan Brett, Nigel Brandon, and Adam Hawkes. «A review of domestic heat pumps». In: *Energy Environ. Sci.* 5 (11 2012), pp. 9291–9306. DOI: 10.1039/C2EE22653G. URL: http://dx.doi.org/10.1039/C2EE22653G (cit. on pp. 22, 39–43, 50, 51, 63, 64, 77, 79).

[11] Ministero dello sviluppo economico. *Ambiti territoriali del settore della distribuzione del gas naturale.* Dec. 2012. URL: https://www.mise.gov.it/index.php/it/energia/gas-naturale-e-petrolio/gas-naturale/distribuzione/elenco-ambiti-territoriali (cit. on p. 28).

[12] Istat. *Basi territoriali e variabili censuarie.* 2011. URL: https://www.istat.it/it/archivio/104317 (cit. on pp. 29, 30).

[13] Sistemapiemonte. *La qualità dell'aria in Piemonte - Ricerca avanzata per stazioni di rilevamento.* URL: http://www.sistemapiemonte.it/ambiente/srqa/consultadati.shtml (cit. on pp. 31, 32, 34–36, 151, 153).

[14] Città Metropolitana di Torino. *Qualità dell'aria - PM_{10}.* URL: http://www.cittametropolitana.torino.it/cms/ambiente/qualita-aria/rete-monitoraggio/stazioni-monitoraggio/pm10 (cit. on p. 32).

[15] Città Metropolitana di Torino. *Qualità dell'aria - Ossidi di azoto.* URL: http://www.cittametropolitana.torino.it/cms/ambiente/qualita-aria/rete-monitoraggio/stazioni-monitoraggio/ossidi-di-azoto (cit. on p. 32).

[16] NIBE Energy Systems. *Indoor module NIBE VVM S320.* Markaryd, 2019. URL: https://www.nibe.eu/assets/documents/27041/331870-2.pdf (cit. on p. 38).

[17] Assoclima and Amici della Terra. *La pompa di calore - Una tecnologia chiave per gli obiettivi 2030.* Online. May 2019. URL: https://www.assoclima.it/media/files/1686_rapporto_pompedicalore_2019.pdf (cit. on p. 37).

[18] EHPA. *Heat Pumps in Renovation, Vol. 1, The most flexible technology when renovating any kind of building.* Online. Feb. 2020. URL: https://www.ehpa.org/about/news/article/how-to-move-away-from-fossil-fuels-efficient-deployment-of-heat-pumps-in-multifamily-buildings-is-p/ (cit. on pp. 38, 53).

[19] S. Rasoul Asaee, V. Ismet Ugursal, and Ian Beausoleil-Morrison. «Techno-economic feasibility evaluation of air to water heat pump retrofit in the Canadian housing stock». In: *Applied Thermal Engineering* 111 (2017), pp. 936–949. ISSN: 1359-4311. DOI: http://dx.doi.org/10.1016/j.applthermaleng.2016.09.117. URL: https://www.sciencedirect.com/science/article/abs/pii/S1359431116318130 (cit. on p. 39).

[20] Science Direct. *Energy Efficiency Ratio*. URL: https://www.sciencedirect.com/topics/engineering/energy-efficiency-ratio (cit. on p. 40).

[21] Qiu Tu, Lina Zhang, Wei Cai, Xiujuan Guo, Xiaojun Yuan, Chenmian Deng, and Jie Zhang. «Control strategy of compressor and sub-cooler in variable refrigerant flow air conditioning system for high EER and comfortable indoor environment». In: *Applied Thermal Engineering* 141 (2018), pp. 215–225. ISSN: 1359-4311. DOI: https://doi.org/10.1016/j.applthermaleng.2018.05.118. URL: http://www.sciencedirect.com/science/article/pii/S1359431117349992 (cit. on p. 40).

[22] B. Purushothama. «15 - Definitions of terms used in humidification engineering». In: *Humidification and Ventilation Management in Textile Industry*. Ed. by B. Purushothama. Woodhead Publishing India, 2009, pp. 227–252. ISBN: 978-81-908001-2-9. DOI: https://doi.org/10.1533/9780857092847.227. URL: http://www.sciencedirect.com/science/article/pii/B9788190800129500150 (cit. on p. 40).

[23] B. Warwicker. «15 - Desiccant materials for moisture control in buildings». In: *Materials for Energy Efficiency and Thermal Comfort in Buildings*. Ed. by Matthew R. Hall. Woodhead Publishing Series in Energy. Woodhead Publishing, 2010, pp. 365–383. ISBN: 978-1-84569-526-2. DOI: https://doi.org/10.1533/9781845699277.2.365. URL: http://www.sciencedirect.com/science/article/pii/B9781845695262500153 (cit. on p. 40).

[24] The Viessmann Group. *Technical manual - Heat pumps*. Mar. 2012. URL: https://cdn0.scrvt.com/2828ebc457efab95be01dd36047e3b52/ceab8eb0c449dcd2/103428a45b62/Technical-Guide-Heat-Pumps_04-2012_GB.pdf (cit. on pp. 40, 43, 49, 50).

[25] Georgios A. Mouzeviris and Konstantinos T. Papakostas. «Comparative analysis of air-to-water and ground source heat pumps performances». In: *International Journal of Sustainable Energy* 0.0 (2020), pp. 1–16. DOI: 10.1080/14786451.2020.1794864. URL: https://doi.org/10.1080/14786451.2020.1794864 (cit. on pp. 41, 49, 76).

[26] Dan Teodor Bălănescu and Vlad Mario Homutescu. «Experimental investigation on performance of a condensing boiler and economic evaluation in real operating conditions». In: *Applied Thermal Engineering* 143 (2018), pp. 48–58. ISSN: 1359-4311. DOI: https://doi.org/10.1016/j.applthermaleng.2018.07.082. URL: http://www.sciencedirect.com/science/article/pii/S1359431118309098 (cit. on p. 42).

[27] Kristina Sadovskaia, Dmitrii Bogdanov, Samuli Honkapuro, and Christian Breyer. «Power transmission and distribution losses – A model based on available empirical data and future trends for all countries globally». In: *International Journal of Electrical Power & Energy Systems* 107 (2019), pp. 98–109. ISSN: 0142-0615. DOI: https://doi.org/10.1016/j.ijepes.2018.11.012. URL: http://www.sciencedirect.com/science/article/pii/S0142061518335075 (cit. on p. 42).

[28] Rossato Group S.r.l. *Si può collegare la pompa di calore ad un impianto a termosifoni?* URL: https://www.rossatogroup.com/guide/pompe-di-calore/progettazione/120-si-puo-collegare-la-pompa-di-calore-ad-un-impianto-a-termosifoni.html (cit. on p. 43).

[29] Jonn Are Myhren and Sture Holmberg. «Design considerations with ventilation-radiators: Comparisons to traditional two-panel radiators». In: *Energy and Buildings* 41.1 (2009), pp. 92–100. ISSN: 0378-7788. DOI: https://doi.org/10.1016/j.enbuild.2008.07.014. URL: http://www.sciencedirect.com/science/article/pii/S0378778808001746 (cit. on pp. 43, 47).

[30] Rossato Group S.r.l. *Corso Pompe di Calore*. Aug. 2020. URL: https://www.rossatogroup.com/corsi-di-formazione/corsi-pompe-di-calore.html (cit. on pp. 44, 46).

[31] Rossato Group S.r.l. *Guida alla progettazione delle pompe di calore per riscaldamento, raffrescamento e acqua calda sanitaria*. URL: https://www.rossatogroup.com/documenti/documenti-tecnici/pompe-di-calore/13-manuale-progettazione-e-dimensionamento-pompe-di-calore/file.html (cit. on p. 45).

[32] Rossato Group S.r.l. *Ventilconvettore canalizzabile*. URL: https://www.rossatogroup.com/prodotti/trattamento-aria/ventilconvettori/ventilconvettore-canalizzabile.html (cit. on p. 46).

[33] Suola Shao, Huan Zhang, Lingfei Jiang, Shijun You, and Wandong Zheng. «Numerical Investigation and Thermal Analysis of a Refrigerant-heated Radiator Heating System coupled with Air Source Heat Pump». In: *Energy Procedia* 158 (2019). Innovative Solutions for Energy Transitions, pp. 2158–2163. ISSN: 1876-6102. DOI: https://doi.org/10.1016/j.egypro.2019.01.614. URL: http://www.sciencedirect.com/science/article/pii/S187661021930640X (cit. on pp. 48, 49).

[34] Xian-Min Guo, Yi-Guang Chen, Wei-Hua Wang, and Chun-Zheng Chen. «Experimental study on frost growth and dynamic performance of air source heat pump system». In: *Applied Thermal Engineering* 28.17 (2008), pp. 2267–2278. ISSN: 1359-4311. DOI: https://doi.org/10.1016/j.applthermaleng.

2008.01.007. URL: http://www.sciencedirect.com/science/article/pii/S1359431108000203 (cit. on pp. 51, 52).

[35] ARPA Piemonte. *Dataset su griglia NWIOI*. July 2020. URL: https://www.arpa.piemonte.it/rischinaturali/tematismi/clima/confronti-storici/dati/dati.html (cit. on pp. 53, 54).

[36] Stefan S. Bertsch and Eckhard A. Groll. «Two-stage air-source heat pump for residential heating and cooling applications in northern U.S. climates». In: *International Journal of Refrigeration* 31.7 (2008), pp. 1282–1292. ISSN: 0140-7007. DOI: https://doi.org/10.1016/j.ijrefrig.2008.01.006. URL: http://www.sciencedirect.com/science/article/pii/S0140700708000273 (cit. on pp. 53, 58, 60–62).

[37] Ma Guoyuan, Chai Qinhu, and Jiang Yi. «Experimental investigation of air-source heat pump for cold regions». In: *International Journal of Refrigeration* 26.1 (2003), pp. 12–18. ISSN: 0140-7007. DOI: https://doi.org/10.1016/S0140-7007(02)00083-X. URL: http://www.sciencedirect.com/science/article/pii/S014070070200083X (cit. on pp. 54, 55, 57, 59, 61).

[38] Stefan S. Bertsch. «Theoretical and Experimental Investigation of a Two Stage Heat Pump Cycle for Nordic Climates». MA thesis. West Lafayette, Indiana: Purdue University, 2005 (cit. on pp. 58, 59).

[39] Zhiwei Lian, Seong-ryong Park, Wei Huang, Young-jin Baik, and Ye Yao. «Conception of combination of gas-engine-driven heat pump and water-loop heat pump system». In: *International Journal of Refrigeration* 28.6 (2005), pp. 810–819. ISSN: 0140-7007. DOI: https://doi.org/10.1016/j.ijrefrig.2005.02.004. URL: http://www.sciencedirect.com/science/article/pii/S0140700705000551 (cit. on p. 63).

[40] Arif Hepbasli, Zafer Erbay, Filiz Icier, Neslihan Colak, and Ebru Hancioglu. «A review of gas engine driven heat pumps (GEHPs) for residential and industrial applications». In: *Renewable and Sustainable Energy Reviews* 13.1 (2009), pp. 85–99. ISSN: 1364-0321. DOI: https://doi.org/10.1016/j.rser.2007.06.014. URL: http://www.sciencedirect.com/science/article/pii/S1364032107001268 (cit. on p. 63).

[41] R.R. Zhang, X.S. Lu, S.Z. Li, W.S. Lin, and A.Z. Gu. «Analysis on the heating performance of a gas engine driven air to water heat pump based on a steady-state model». In: *Energy Conversion and Management* 46.11 (2005), pp. 1714–1730. ISSN: 0196-8904. DOI: https://doi.org/10.1016/j.enconman.2004.10.009. URL: http://www.sciencedirect.com/science/article/pii/S0196890404002468 (cit. on p. 63).

[42] Lei-Lei Jia, Rui Zhang, Xin Zhang, Zhen-Xi Ma, and Feng-Guo Liu. «Experimental analysis of a novel gas-engine-driven heat pump (GEHP) system for combined cooling and hot-water supply». In: *International Journal of Refrigeration* 118 (2020), pp. 84–92. ISSN: 0140-7007. DOI: https://doi.org/10.1016/j.ijrefrig.2020.04.033. URL: http://www.sciencedirect.com/science/article/pii/S0140700720301894 (cit. on p. 64).

[43] Kurt S. Creamer and James H. Saunders. «Evaluation of a Catalytic Converter for a 3.73 kW Natural Gas Engine». In: *SAE Technical Paper Series*. SAE International, Mar. 1993. DOI: 10.4271/930221. URL: https://doi.org/10.4271%2F930221 (cit. on p. 64).

[44] A. R. Ganji. «Environmental and Energy Efficiency Evaluation of Residential Gas and Heat Pump Heating». In: *Journal of Energy Resources Technology* 115.4 (Dec. 1993), pp. 264–271. DOI: 10.1115/1.2906431. URL: https://doi.org/10.1115%2F1.2906431 (cit. on p. 64).

[45] Xinru Wang, Liang Xia, Chris Bales, Xingxing Zhang, Benedetta Copertaro, Song Pan, and Jinshun Wu. «A systematic review of recent air source heat pump (ASHP) systems assisted by solar thermal, photovoltaic and photovoltaic/thermal sources». In: *Renewable Energy* 146 (2020), pp. 2472–2487. ISSN: 0960-1481. DOI: https://doi.org/10.1016/j.renene.2019.08.096. URL: http://www.sciencedirect.com/science/article/pii/S0960148119312832 (cit. on pp. 64–68).

[46] Elimar Frank, Michel Haller, Sebastian Herkel, and Jörn Ruschenburg. «Systematic Classification of Combined Solar Thermal and Heat Pump Systems». In: *EuroSun 2010 Conference*. Graz, Austria, Sept. 2010. URL: http://www.task44.iea-shc.org/data/sites/1/publications/096-frank1.pdf (cit. on pp. 65, 67).

[47] Jörn Ruschenburg, Sebastian Herkel, and Hans-Martin Henning. «A statistical analysis on market-available solar thermal heat pump systems». In: *Solar Energy* 95 (2013), pp. 79–89. ISSN: 0038-092X. DOI: https://doi.org/10.1016/j.solener.2013.06.005. URL: http://www.sciencedirect.com/science/article/pii/S0038092X13002260 (cit. on pp. 65, 67).

[48] I. Mojic, M.Y. Haller, B. Thissen, F. Hengel, and A. Heinz. «New generation of a highly compact solar heat pump system with boosted energetic efficiency». In: *CISBAT 2015*. Lausanne, Switzerland, Sept. 2015. URL: https://infoscience.epfl.ch/record/213401/files/7_MOJIC.pdf (cit. on pp. 65, 69, 70).

[49] Ivan Malenković, Peter Pärisch, Sara Eicher, Jacques Bony, and Michael Hartl. «Definition of Main System Boundaries and Performance Figures for Reporting on SHP Systems - Subtask B Deliverable B1». In: *IEA SHC Task 44 / HPP Annex 38*. Vienna, Austria, Dec. 2013. URL: https://www.task48.iea-shc.org/data/sites/1/publications/T44A38_Rep_B1_SHP_Perf_definition%20approved.pdf (cit. on p. 65).

[50] Wenzhu Huang, Jie Ji, Ning Xu, and Guiqiang Li. «Frosting characteristics and heating performance of a direct-expansion solar-assisted heat pump for space heating under frosting conditions». In: *Applied Energy* 171 (2016), pp. 656–666. ISSN: 0306-2619. DOI: https://doi.org/10.1016/j.apenergy.2016.03.048. URL: http://www.sciencedirect.com/science/article/pii/S0306261916303695 (cit. on p. 67).

[51] Guodong Qiu, Xinghua Wei, Zhenfei Xu, and Weihua Cai. «A novel integrated heating system of solar energy and air source heat pumps and its optimal working condition range in cold regions». In: *Energy Conversion and Management* 174 (2018), pp. 922–931. ISSN: 0196-8904. DOI: https://doi.org/10.1016/j.enconman.2018.08.072. URL: http://www.sciencedirect.com/science/article/pii/S019689041830935X (cit. on p. 68).

[52] Yin Liu, Jing Ma, Guanghui Zhou, Chao Zhang, and Wenlei Wan. «Performance of a solar air composite heat source heat pump system». In: *Renewable Energy* 87 (2016). Sustainable energy utilization in cold climate zone (Part II), pp. 1053–1058. ISSN: 0960-1481. DOI: https://doi.org/10.1016/j.renene.2015.09.001. URL: http://www.sciencedirect.com/science/article/pii/S0960148115302810 (cit. on p. 68).

[53] Chenguang Wang, Guangcai Gong, Huan Su, and Chuck Wah Yu. «Efficacy of integrated photovoltaics-air source heat pump systems for application in Central-south China». In: *Renewable and Sustainable Energy Reviews* 49 (2015), pp. 1190–1197. ISSN: 1364-0321. DOI: https://doi.org/10.1016/j.rser.2015.04.172. URL: http://www.sciencedirect.com/science/article/pii/S1364032115004426 (cit. on p. 68).

[54] Raghad Kamel, Navid Ekrami, Peter Dash, Alan Fung, and Getu Hailu. «BIPV/T+ASHP: Technologies for NZEBs». In: *Energy Procedia* 78 (2015). 6th International Building Physics Conference, IBPC 2015, pp. 424–429. ISSN: 1876-6102. DOI: https://doi.org/10.1016/j.egypro.2015.11.687. URL: http://www.sciencedirect.com/science/article/pii/S1876610215024194 (cit. on p. 69).

[55] Abdeen Mustafa Omer. «Ground-source heat pumps systems and applications». In: *Renewable and Sustainable Energy Reviews* 12.2 (2008), pp. 344–371. ISSN: 1364-0321. DOI: https://doi.org/10.1016/j.rser.2006.10.003. URL: http://www.sciencedirect.com/science/article/pii/S1364032106001249 (cit. on pp. 71, 77).

[56] P. F. Healy and V. I. Ugursal. «Performance and economic feasibility of ground source heat pumps in cold climate». In: *International Journal of Energy Research* 21.10 (1997), pp. 857–870. DOI: 10.1002/(SICI)1099-114X(199708)21:10<857::AID-ER279>3.0.CO;2-1. URL: https://onlinelibrary.wiley.com/doi/abs/10.1002/%28SICI%291099-114X%28199708%2921%3A10%3C857%3A%3AAID-ER279%3E3.0.CO%3B2-1 (cit. on pp. 71–75, 86).

[57] Giuseppe Emmi, Angelo Zarrella, Michele De Carli, and Antonio Galgaro. «An analysis of solar assisted ground source heat pumps in cold climates». In: *Energy Conversion and Management* 106 (2015), pp. 660–675. ISSN: 0196-8904. DOI: https://doi.org/10.1016/j.enconman.2015.10.016. URL: http://www.sciencedirect.com/science/article/pii/S0196890415009371 (cit. on p. 75).

[58] Enrico Fabrizio, Maria Ferrara, Giampiero Urone, Stefano P. Corgnati, Simone Pronsati, and Marco Filippi. «Performance Assessment of a Solar Assisted Ground Source Heat Pump in a Mountain Site». In: *Energy Procedia* 78 (2015). 6th International Building Physics Conference, IBPC 2015, pp. 2286–2291. ISSN: 1876-6102. DOI: https://doi.org/10.1016/j.egypro.2015.11.366. URL: http://www.sciencedirect.com/science/article/pii/S1876610215020986 (cit. on p. 76).

[59] Ali Hakkaki-Fard, Parham Eslami-Nejad, Zine Aidoun, and Mohamed Ouzzane. «A techno-economic comparison of a direct expansion ground-source and an air-source heat pump system in Canadian cold climates». In: *Energy* 87 (2015), pp. 49–59. ISSN: 0360-5442. DOI: https://doi.org/10.1016/j.energy.2015.04.093. URL: http://www.sciencedirect.com/science/article/pii/S0360544215005605 (cit. on p. 76).

[60] J.F. Urchueguía, M. Zacarés, J.M. Corberán, Á. Montero, J. Martos, and H. Witte. «Comparison between the energy performance of a ground coupled water to water heat pump system and an air to water heat pump system for heating and cooling in typical conditions of the European Mediterranean coast». In: *Energy Conversion and Management* 49.10 (2008), pp. 2917–2923. ISSN: 0196-8904. DOI: https://doi.org/10.1016/j.enconman.2008.03.001. URL: http://www.sciencedirect.com/science/article/pii/S0196890408000939 (cit. on p. 76).

[61] Roberto de Aguiar Peixoto, Dariusz Butrymowicz, James Crawford, David Godwin, Kenneth Hickman, Fred Keller, and Haruo Onishi. *IPCC/TEAP Special Report: Safeguarding the Ozone Layer and the Global Climate System*. IPCC/TEAP. 2005. URL: https://archive.ipcc.ch/pdf/special-reports/sroc/sroc05.pdf (cit. on p. 77).

[62] Bente Halvorsen and Bodil Merethe Larsen. «How do investments in heat pumps affect household energy consumption?» In: *Discussion Papers* 737 (2013). Ed. by Statistics Norway - Research Department. URL: https://www.ssb.no/nasjonalregnskap-og-konjunkturer/artikler-og-publikasjoner/_attachment/109798?_ts=13e3ae9f3f8 (cit. on pp. 78, 79).

[63] Matteo Rivoire, Alessandro Casasso, Bruno Piga, and Rajandrea Sethi. «Assessment of Energetic, Economic and Environmental Performance of Ground-Coupled Heat Pumps». In: *Energies* 11.8 (July 2018), p. 1941. DOI: 10.3390/en11081941. URL: https://doi.org/10.3390%2Fen11081941 (cit. on pp. 81, 82).

[64] Eurostat. *Electricity price statistics*. May 2020. URL: https://ec.europa.eu/eurostat/statistics-explained/index.php/Electricity_price_statistics (cit. on pp. 82, 84).

[65] Eurostat. *Natural gas price statistics*. May 2020. URL: https://ec.europa.eu/eurostat/statistics-explained/index.php/Natural_gas_price_statistics (cit. on pp. 82, 84).

[66] ARERA. *Prezzi finali del gas naturale per i consumatori industriali - UE e area Euro*. 2020. URL: https://www.arera.it/it/dati/gpcfr2.htm (cit. on pp. 82, 84).

[67] Ministero dello sviluppo economico. *Prezzi medi settimanali dei carburanti e combustibili*. URL: https://dgsaie.mise.gov.it/prezzi_carburanti_settimanali.php (cit. on p. 82).

[68] Alessandro Casasso, Pietro Capodaglio, Fulvio Simonetto, and Rajandrea Sethi. «Environmental and Economic Benefits from the Phase-out of Residential Oil Heating: A Study from the Aosta Valley Region (Italy)». In: *Sustainability* 11.13 (July 2019), p. 3633. DOI: 10.3390/su11133633. URL: https://doi.org/10.3390%2Fsu11133633 (cit. on p. 82).

[69] Hellström Göran and Sanner Burkhard. *Earth energy designer (EED): software for dimensioning of deep boreholes for heat extraction*. 1994. URL: https://buildingphysics.com/eed-2/ (cit. on p. 85).

[70] Matteo Rivoire. «Dynamic simulation and economic analysis of geothermal HVAC systems in different climate zones». MA thesis. Torino, Italia: Politecnico di Torino, Mar. 2017 (cit. on p. 86).

[71] Clivet. *ELFOEnergy Ground Medium² - Multifunzione*. URL: http://riclima.ch/wp-content/uploads/2019/07/ground-multifunzione-1.pdf (cit. on p. 86).

[72] ARPA Piemonte. *Banca dati meteorologica*. URL: https://www.arpa.piemonte.it/rischinaturali/accesso-ai-dati/annali_meteoidrologici/annali-meteo-idro/banca-dati-meteorologica.html (cit. on p. 86).

[73] D.H.C. Chow and Geoff J. Levermore. «New algorithm for generating hourly temperature values using daily maximum, minimum and average values from climate models». In: *Building Services Engineering Research and Technology* 28.3 (2007), pp. 237–248. DOI: 10.1177/0143624407078642. URL: https://doi.org/10.1177/0143624407078642 (cit. on p. 86).

[74] Enel X. *What Are Heating and Cooling Degree Days?* URL: https://www.enelx.com/n-a/en/stories/energy-efficiency-management/what-are-heating-and-cooling-degree-days (cit. on p. 87).

[75] Il Sole 24 Ore. *Rendimento BTP Italia 10 anni*. Sept. 2020. URL: https://mercati.ilsole24ore.com/obbligazioni/spread/GBITL10J.MTS (cit. on p. 90).

[76] KPMG Corporate Finance NL. *Equity Market Risk Premium – Research Summary*. June 2020. URL: https://indialogue.io/clients/reports/public/5d9da61986db2894649a7ef2/5d9da63386db2894649a7ef5 (cit. on p. 90).

[77] Il Sole 24 Ore. *Eurirs*. Sept. 2020. URL: https://mutuionline.24oreborsaonline.ilsole24ore.com/guide-mutui/irs.asp#storico (cit. on p. 91).