District Heating in Temuco

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Abstract:

Burning firewood for heating purposes in South-West Chile results in serious air pollution issues. The biggest cities in the region are in the forefront of the list with worst air quality in the continent, which culminates during winter days. The biggest local issue is the concentration of PM2.5 in the air, which not just leads to unbearable air quality, but for severe health issues and premature deaths in the city of Temuco. Currently, around 90% of the households use inefficient, individual wood stoves for space heating, which results to high PM2.5 emission. The municipality would aims to mitigate the effects with banning the use of firewood at critical days, and with the help of stove replacement program.
In this study, District Heating solution is introduced to offer a possible alternative heating option for the city, which can solve the given air quality problem. The introduction of the technology and its consequences are assessed, elaborated on the following research question:
How can the introduction of a District Heating system in Temuco help to solve the city's air quality problem?
Based on the current and the projected future heat demand, the study identifies the areas of the city where district heating is suitable, and evaluates different supply solutions which are fulfilling the demand of the chosen areas. The result of the different technical assortment are compared with the respective consequences of the stove replacement program while assessing economic and pollutant emission perspectives. In the last part of the study, the possible barriers are identified, and new policies are advised to shape the framework more favorable for district heating solutions.

Preface

This report is composed by András Beda, as a part of the Master program in Sustainable Energy Planning and Management. The theme of the project is *Master's Thesis*, in the 4th semester of the program.

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Finally, I would most importantly like to thank my parents and my girlfriend, Camila for supporting me throughout these years. Without your encouragement, exhilaration and love I would not be the same person as I am today.

Reading guide

Through the report, source references are in the form of the Harvard method, and all are listed at the end of the report. References from books, articles or the like will appear with the last name of the author and the year of publication in the form of [Author, Year]. If there is no stated year on a source it will be referred as: [Author, n.d.]. If the author is a company, a homepage or for other reasons is not stated, the reference is referred to as: [Name, Year], e.g [Ministry of Energy, 2017].

Figures and tables in the report are numbered according to the respective chapter. In this way the first figure in chapter 2 has number 2.1, the second number 2.2 and so on. Explanatory text is found under the given figures and tables. Figures without references are composed by the author.

The calculations during the study were made be original values, but are displayed roundedly, thus slight differences can appear when comparing results in the report.

Monetary values are presented in Euros, but cited sources can present values in different currencies like U.S. Dollars or Chilean Peso. These currencies were exchanged with the rate of 1 EUR = 1.1569 USD = 725.9115 CLP, as it stood February 1, 2018.

András Beda

Abbreviations

AChEE	Chilean Energy Efficiency Agency
CHP	Combined Heat and Power
COP	Coefficient of Performance
DE	District Energy
DECI	District Energy in Cities Initiative
DH	District Heating
DHW	Domestic Hot Water
GHG	Greenhouse Gas
GOC	Government of Chile
HDD	Heating Degree Day
MINVU	Ministerio de Vivienda y Urbanismo de Chile
MMA	Ministry of Environment
MTOE	Million Tonnes of Oil Equivalent
NDC	National Determined Contribution
NHPC	Net Heat Production Cost
NPV	Net Present Value
O&M	Operation and Maintenance
OECD	Organization for Economic Co-operation and Development
PM	Particulate Matter
RQ	Research Question
TES	Thermal energy storage
TPES	Total Primary Energy Supply
UN	United Nations
USD	United States Dollars
WHO	World Health Organization

Table of contents

Chapter 1 Introduction **1**
1.1 Heating and air pollution . . . 1
1.1.1 Climate change . . . 1
1.1.2 Air quality . . . 2
1.2 Chile . . . 3
1.2.1 The energy situation in Chile . . . 4
1.2.2 Climate change and air quality . . . 5
1.3 Temuco . . . 6

Chapter 2 Problem analysis **8**
2.1 Air pollution in chile . . . 8
2.2 Air pollution in Temuco . . . 9
2.3 Current strategies to mitigate emissions . . . 12
2.4 District Heating . . . 13

Chapter 3 Problem statement **15**
3.1 Research question . . . 15
3.2 Delimitation . . . 16
3.3 Research design and research structure . . . 16

Chapter 4 Worldview and Theoretical approach **19**
4.1 Heat demand . . . 19
4.2 District Heating . . . 20
4.3 District Energy in Cities Initiative . . . 21
4.4 Choice Awareness Theory . . . 21
4.4.1 Applicability, limitations and significance of the theories . . . 24

Chapter 5 Methodology **26**
5.1 Research method . . . 26
5.2 Data collection methods . . . 27
5.2.1 Literature review . . . 27
5.2.2 Interviews . . . 28
5.3 Policy analysis . . . 28
5.4 Selection of modelling tools . . . 28
5.4.1 Heat demand . . . 28
5.4.2 Energy system modelling . . . 29
5.5 Energy System design . . . 30
5.5.1 Current heat demand . . . 31
5.5.2 Future demand . . . 33
5.5.3 Identification of suitable areas . . . 34
5.5.4 Sizing of the system . . . 35

5.5.5 Reference scenario . . . 36
5.5.6 DH scenarios . . . 37
5.5.7 Effective width . . . 37
5.5.8 Emissions - Impact Pathway Approach . . . 39

Chapter 6 Framework conditions in Chile 40
6.1 Governance framework in Chile . . . 40
6.2 Building energy standards . . . 41
6.3 Stove replacement program . . . 42
6.4 Framework for DH and CHP . . . 43
6.5 Electricity market . . . 43
6.6 Summary of most important influences . . . 44

Chapter 7 Heat Demand 45
7.1 Current Demand . . . 45
7.1.1 Hourly distribution . . . 46
7.2 Future Demand . . . 47
7.2.1 Demand of the Large saving alternative . . . 48
7.2.2 Demand of the Medium saving alternative . . . 49
7.2.3 Identification of suitable areas . . . 49
7.2.4 Sizing of the system . . . 50

Chapter 8 Reference supply system 54
8.1 Large saving alternative . . . 55
8.2 Medium saving alternative . . . 55

Chapter 9 Resources and included technologies 57
9.1 Available resources . . . 57
9.1.1 Biomass . . . 57
9.1.2 Geothermal energy . . . 58
9.1.3 Solar energy . . . 58
9.1.4 Electricity . . . 59
9.2 Included parts and used technologies . . . 59
9.2.1 Heat production units . . . 59
9.2.2 Heat storage . . . 62
9.2.3 Distribution network . . . 63
9.2.4 Substations and home connections . . . 63

Chapter 10 District Heating Scenarios and emissions 64
10.1 Scenarios for the Medium saving alternative . . . 65
10.1.1 Biomass Scenario . . . 65
10.1.2 Heat pump Scenario . . . 67
10.1.3 Mixed Scenario . . . 69
10.2 Scenarios for the Large saving alternative . . . 71
10.2.1 Biomass Scenario . . . 71
10.2.2 Heat pump Scenario . . . 72
10.2.3 Mixed Scenario . . . 72

10.2.4 Comparison of emissions . . . 72

Chapter 11 Economic analysis and comparison 74

11.1 NPV and payback for the Medium saving alternative . . . 74
11.2 NPV and payback for the Large saving alternative . . . 77
11.2.1 Effect of higher heat saving . . . 77
11.3 Sensitivity analysis . . . 78
11.3.1 Heat price . . . 78
11.3.2 Discount rate . . . 78
11.3.3 Biomass price . . . 79
11.4 Comparison to reference scenario . . . 80

Chapter 12 Policy recommendations 83

12.1 Barriers in the heating sector and policy recommendations . . . 83
12.1.1 Data availability . . . 83
12.1.2 Lack of support for investors . . . 83
12.1.3 Lack of support/not adequate support for energy efficiency . . . 84
12.1.4 Additional recommendations . . . 84
12.2 Recommendation for the broader institutional framework . . . 85

Chapter 13 Discussion 87

13.1 Difficulties and considerations . . . 87
13.2 Limitations of the project . . . 88
13.3 Future work . . . 89

Chapter 14 Conclusion 91

Bibliography 92

Appendix A 104

A.1 List of successful and declined interviews . . . 104
A.2 Requirements for the modelling tool . . . 104
A.3 Phases of connected districts - Large saving alternative . . . 105
A.4 Phases of connected districts - Medium saving alternative . . . 106
A.5 Cash flows - Medium saving, Biomass scenario . . . 107
A.6 Cash flows - Medium saving, Heat pump scenario . . . 108
A.7 Cash flows - Medium saving, Mix scenario . . . 109

1 Introduction

1.1 Heating and air pollution

Since the time, when humankind discovered and learned how to control fire, feeling warm and having sufficient heat is considered to be a basic human need at all part of the world. Over the years the technology to provide interior heating developed from the open fire method through fireplaces and cast-iron stoves to the nowadays used solutions. [of Encyclopaedia Britannica, 2008]

Due to the development of different heating solutions, the industrial revolution and the inventions of the last centuries, humankind can enjoy a higher standard of living, quality of life and increased life expectancy than ever before [Roser, 2017].

Despite of the development, today still 2.8 billion people rely on solid fuels (wood, crop wastes, charcoal, coal) and simple stoves for cooking and heating [International Energy Agency, 2014]. Burning different kind of raw materials and fossil fuels has serious negative effects on the environment and the climate of the planet, which can lead us to irreversible consequences.

1.1.1 Climate change

Nowadays, the widely discussed aspect of burning fossil fuels and emitting greenhouse gas (GHG) is climate change.

> *"Climate change refers to a change of climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and that is in addition to natural climate variability observed over comparable time periods."* [United Nations, 1992]

Climate change and the warming of our climate is evident, as the increases in global average air and ocean temperatures, melting of snow and ice at the polar region and rising global average sea level is observed worldwide [Reisinger R.K. Pachauri, 2007].

The historically high greenhouse gas emission from human activities is the biggest factor in climate change [European Commission, n.d.]. Without action, it is estimated that the average surface temperature will rise by more than 3 °C, at the end of the 21st century. [United Nations, n.d.]

1.1.2 Air quality

Another consequence of burning fuels is air quality, which is seemingly important, especially in cities where pollution levels are extremely high. According to [WHO, 2018], heat generation has one of the biggest affect - out of all human activities - on air quality as it emits a lot of different pollutants to the atmosphere.

Air pollution emerges as a big issue worldwide, which can be seen on Figure 1.1.

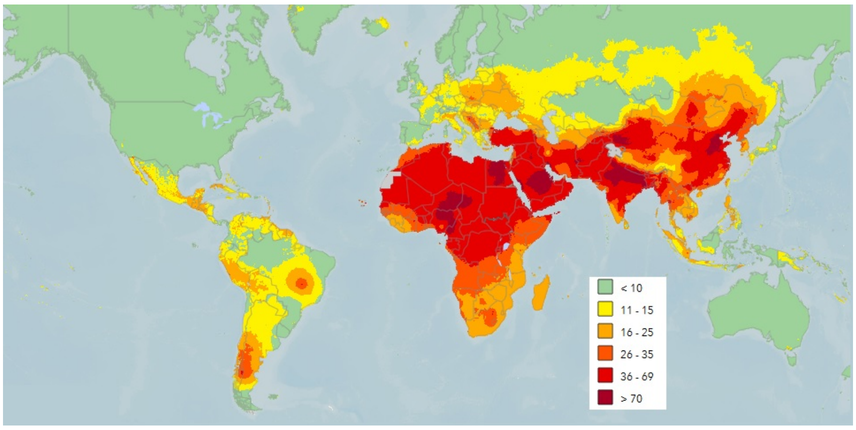

Figure 1.1. Global ambient air pollution (PM2.5: μg/m^3) [WHO, 2018].

> *"Air pollution is a complex mixture of particulate matter (PM), gases, and vapor-phase molecules continuously interacting with each other and the atmosphere."* [Brook and Rajagopalan, 2009]

Nowadays, the concentration of particulate matter is widely used indicator of air quality. PM is the general term used for a mixture of liquid droplets and solid particles in the air, and consists ash, pollen, aerosols, smoke, fumes and dust. Although, the makeup of PM varies with place, season and weather conditions [Ministry of the Environment and Climate Change Ontario, 2010].

Particle pollution can come from primary or secondary sources. Primary sources cause particle pollution by themselves, like wood stoves and open-air fires, while secondary sources emit gases that can form particles later. These sources are power plants and coal fires [United States Environmentla Protection Agency, n.d.].

We can distinguish 2 main types of particular pollution, PM 10 and PM2.5. PM10 means a particulate matter which is smaller than 10 micrometers in diameter, and PM2.5 includes particulate matters with 2.5 micrometers or less in diameter [WHO, 2018].

Until the last years, PM10 was the most used indicator to measure the amount of pollution in the air, but following WHO's recommendation, the use of PM2.5 is more widespread nowadays. [Patagon Journal, 2016]. The reason for the change is the smaller particles are more harmful to the human body than PM10, in this way they can be better indicators of air quality.

WHO also suggest long-term and short-term guideline values for acceptable air quality. Regarding PM2.5, 10 μg/m^3 as an annual mean is considered acceptable, while the daily mean shouldn't be higher than 25 μg/m^3. The related numbers for PM 10 are 20 and 50 μg/m^3 respectively [WHO, 2006].

In the modern and urban world, the burning of fossil fuels (coal, oil, and diesel) by industry, power generation, and automobile traffic is the major source of PM [Brook and Rajagopalan, 2009].

Air pollution is getting worse in urban areas all part of the globe, but poorer countries and cities are the most affected . According to [WHO, 2016] in 98% of the cities with more than 100.000 inhabitant in developing countries, the air quality is the worst than WHO's quality standards. According to WHO's database several cities in China, India and South America the average level of PM2.5 is well over 100 μg/m^3.

While in high-income countries the pollution levels are getting slowly better, in developing countries the pollution is already high, and it is just getting even worse [WHO, 2016]. One of these countries is Chile, which has severe air pollution issues.

1.2 Chile

Chile is a country in South America, bordered by Peru to the north, Bolivia to the northeast and Argentina to the east. The country's entire western border is the Pacific Ocean, with 6 435 kilometres coastline [Drake, 2018]. Chile's population in 2016 is estimated at 18 million. The country's gross domestic product (GDP) in 2016 was 247 billion USD [World Bank, n.d.]. Chile's GDP per capital is 23 478 USD, which is the highest in South America, ahead of Uruguay, Argentina and Brazil [International Energy Agency, 2018].

Chile is a democratic republic, governed by the president of Chile. The country is divided to 16 administrative regions - can be seen on Figure 1.2 -, and several different climate zones [Drake, 2018]. Because of its unique shape and topography, its climate has at least seven major climatic sub-types, diverse from the world's driest desert, through Mediterranean climate to Alpine tundra [Universidad de Chile, n.d.].

Around 85% of the country's population live in urban areas, with 40% in the Santiago Metropolitan Region [Drake, 2018]. The capital of the country is Santiago, which is located in the in the central area, dominates the country in terms of population and agricultural resources.

The Chilean economy is stable, which encourages trade and investment [Dirección General de Relaciones Económicas Internacionales, 2015]. During the last 40 years, Chile went to a rapid development, and has similar levels of income - 21.000 USD/year - [World Bank, 2016], and life expectancy like developed countries. Chile's economy has grown impressively in the past two decades. From 2003 to 2013, real growth averaged 4.65% per year, despite a 1.7% fall during the 2009 global financial crisis [OECD, 2017]. In 2010, Chile joined to the Organization for Economic Co-operation and Development (OECD) , and still the only South American member of the Organization.

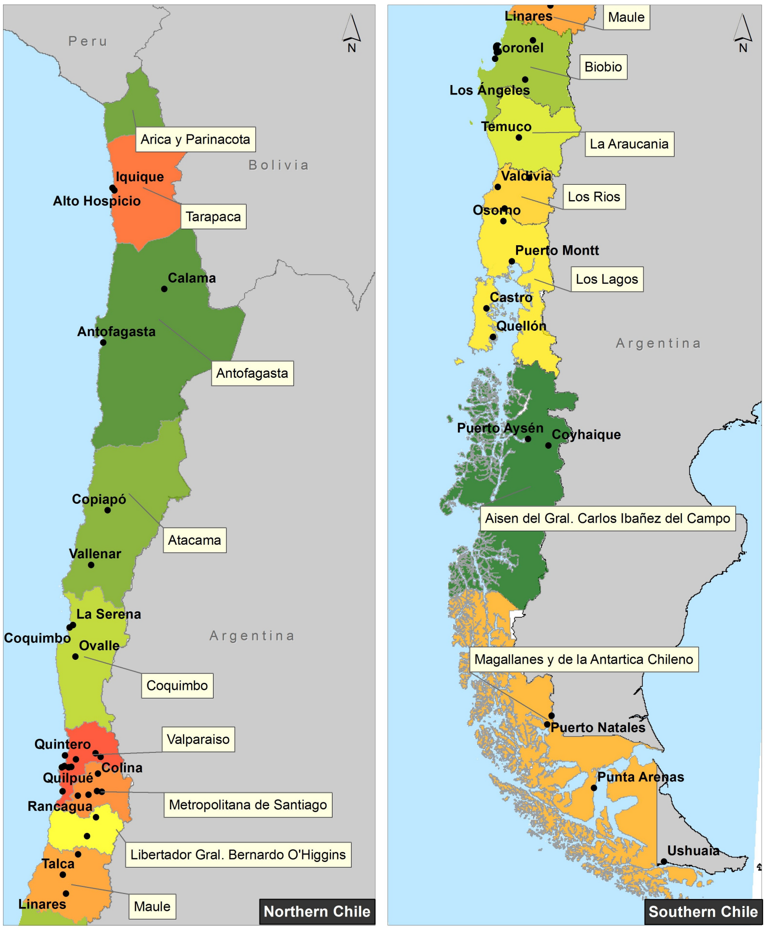

Figure 1.2. Regions of Chile [MapAction, 2017]

1.2.1 The energy situation in Chile

High share of Chile's total primary energy supply (TPES) depends on import, as its domestic energy production covers only 34.7% (2016) of its 37.5 million tonnes of oil equivalent (MTOE) TPES [International Energy Agency, 2018]. In the country, oil is the most important energy source, followed by biofuels (mostly firewood) and coal.

Fossil fuels are responsible for 73.2% of the TPES in 2016, in more detailed, 41.1% oil, 20.3% coal and 11.7% natural gas. Renewables are also important part of the energy generation, they were accounted for 26.8% in 2016, with 21.2% biofuels and waste, 4.5% hydropower, 0.5% wind and 0.7% solar energy [International Energy Agency, 2018]. While the almost 27% can be considered as a high share, it is important to point out, that the main share of renewables are coming from the burning of firewood for heating and cooking in residential houses.

The historical distribution of the resources can be seen on Figure 1.3.

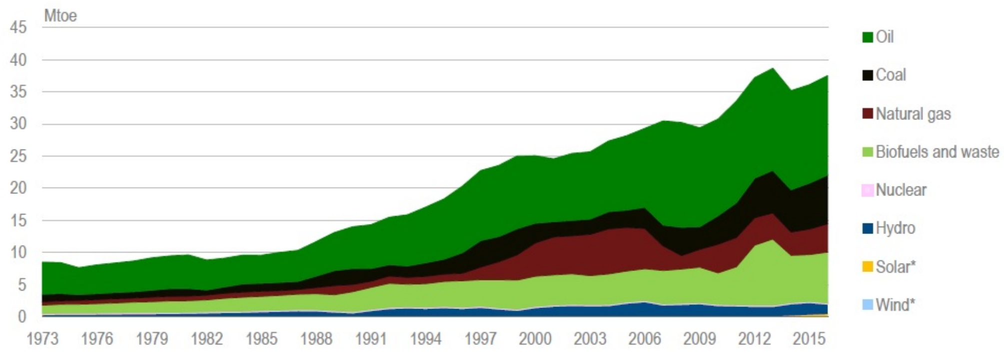

Figure 1.3. TPES by source, 1973-2016 [International Energy Agency, 2018]

1.2.2 Climate change and air quality

Chile is a country highly vulnerable to the impacts of Climate Change, the low level of the coasts throughout its territory, the snow and glacial regime of its rivers, its oceans which is source of the fishing that constitutes a key resource for Chile are all endangered by climate change [Ministerio del Medio Ambiente, 2011b].

In January 2017, the Chilean Congress ratified the Paris Agreement and defined Chile's related National Determined Contribution (NDC), which is to reduce the CO_2 intensity of GDP by 30% from the 2007 levels by 2030 [Government of Chile, 2015].

In 2013, Chile's GHG emission was 109.9 million tons of carbon dioxide equivalents (MtCO2-eq.) [Ministry of Environment, 2016]. GHG emissions grew by 113% from 1990 to 2013, and by 19% from 2010 to 2013. The GHG emissions by secrtor can be seen on Figure 1.4.

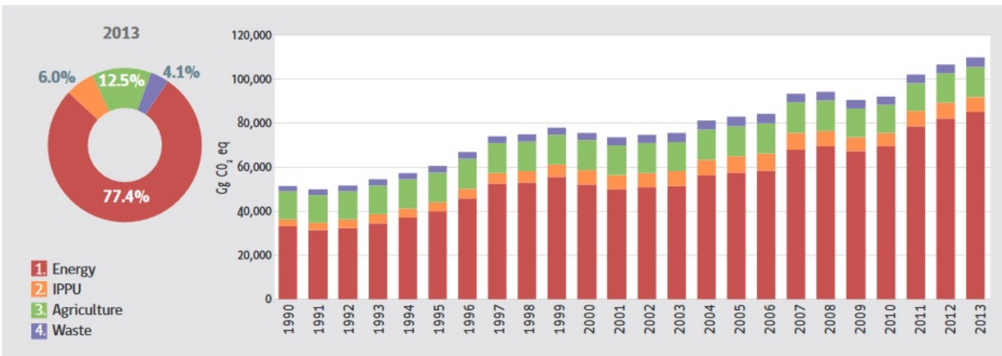

Figure 1.4. GHG emissions by sector, 1973-2016 [Ministry of Environment, 2016]

According to the International Energy Agency, in 2015 the global average of CO_2 emissions per person was 4.4 tons, which was equal with the Chilean emission per person, which is well below the average of 9.7 tons CO_2 per capita of the OECD countries. At a Latin American level, Chile contributed 4.7% of the region's emissions, being below Mexico, Brazil, Argentina and Venezuela. Worldwide, its contribution was about 0.25% of global emissions [International Energy Agency, 2017].

As it was presented before, Chile faces a complex energy problem, including vulnerability of own resources to climatic changes, additionally with health issues related to firewood-combustion [Schueftan and González, 2013].

According to [WHO, 2016], six Chilean cities are among the 20 most polluted ones in the American continent, considering annual mean PM2.5 concentration. Coyhaique has the highest pollution rates in the whole continent, and Padre Las Casas, Osorno, Temuco, Andacollo and Rancagua are the other 5 cities in the list of most polluted cities.

According to Ernesto Gramsch, the seasonal difference makes the problem even worse

"The WHO figure is an average throughout the year, in cities - especially in the south - at winter, where there is no wind, and the pollution is coming from the heating system, the situation can be way worse" [Garrido, 2018].

1.3 Temuco

One of the cities - which was already highlighted during the previous section - with the worst air quality is Temuco, where air pollution by respirable particulate maters (PM10 and PM2.5) is the biggest environmental and public health problems in the city of Temuco [Suiza, 2016].

The city of Temuco is to the capital of the Province of Cautín and the Region of Araucanía. It has an area of 464 km^2 and a population of around 285,000 inhabitants [Wikipedia, n.d.b]. The map of the region can be seen on Figure 1.5.

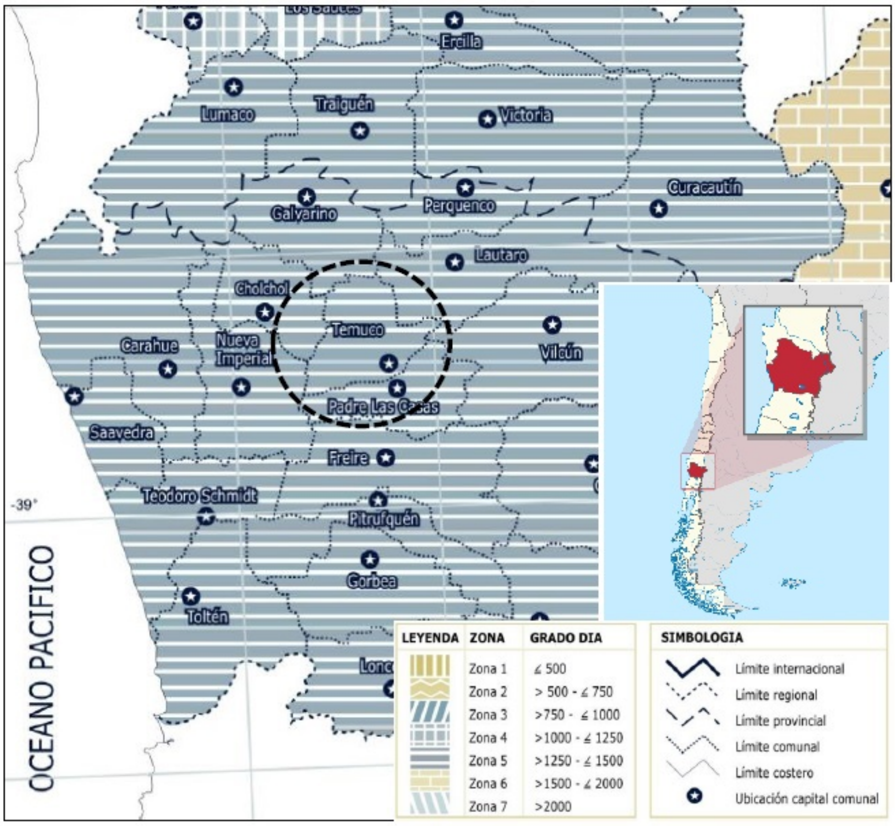

Figure 1.5. Map of the Araucania region, with the caracteristics of the thermal zone [Suiza, 2016]

Temuco is located in the thermal zone 5, according to the classification made by the Ministry of Housing and Urban Planning (Ministerio de Vivienda y Urbanismo de Chile (MINVU) , which is characterized as a cold and rainy area, with short summers and moderate solar radiation. The climate - which as it was stated before affects the air quality - can be seen on Figure 1.6.

According to MINVU's classification, the heating degree days per year is between 1,250 and 1,500 hours.

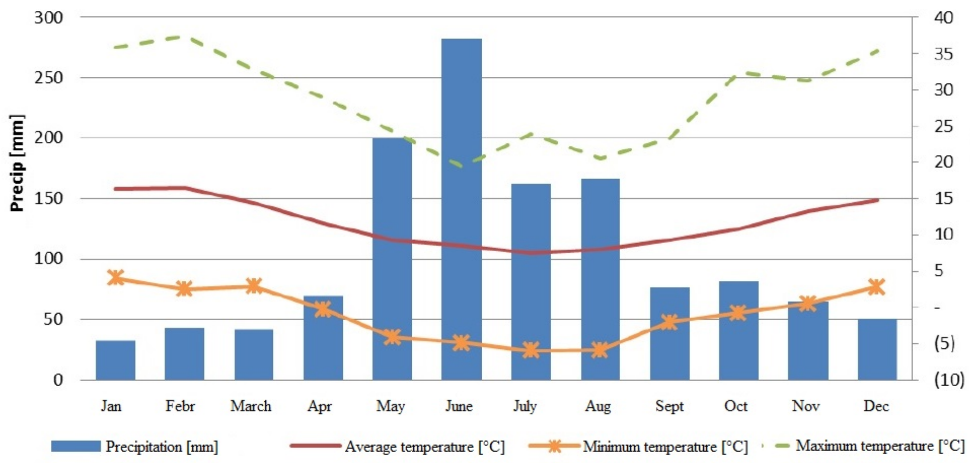

Figure 1.6. Climate of Temuco [Suiza, 2016]

According to [WHO, 2016], in Temuco the annual mean concentration of PM2.5 was 31 $\mu g/m^3$, while the annual mean of PM10 was 50 $\mu g/m^3$ in 2016, which are way over the WHO's recommendation. It is considered that the use of wood in homes is responsible for 82% and 94% of total annual emissions of PM10 and PM2.5 [Ministerio del Medio Ambiente, 2016]. The main causes of these emissions are found in the very low levels of thermal insulation of homes, the use of old heaters and firewood that does not meet minimum quality standards [Suiza, 2016].

During the last years, the Government of Chile (GOC) realized that air pollution is a growing and serious issue in the country, that is why it started to look for international help and cooperation to solve the issue. This study will focus on the city of Temuco, which is one of the cites effected the most by the air pollution.

Problem analysis 2

2.1 Air pollution in chile

> *"Air pollution is the most complex and visible environmental problem in urban areas in central-southern Chile ."* [Ministerio del Medio Ambiente, 2011a]

90% of the population of Chile lives in polluted urban areas, like Santiago, Temuco and Valdivia [Kavouras et al., 2001]. Today there are about 10 million Chileans exposed to high concentrations of particulate matter, much of it from the combustion of wood for heating[Ministerio del Medio Ambiente, 2014]. [International Energy Agency, 2018] estimates, that air pollution is responsible for 8 billion USD in medical expenses and 4000 premature deaths.

The national energy production in Chile highly depends on biomass, as it represents 72% of the nationally produced energy [International Energy Agency, 2018].

According to measurements in different parts of the country, the residential combustion of firewood corresponds between 45% and 97% of the total emissions in the examined cities[Ministerio del Medio Ambiente, 2014]. Moreover, the often low-quality firewood is being burned inefficiently, consequently it is the largest cause of air pollution by particulate matter in the country [Schueftan et al., 2016].

According to [Bailis et al., 2015], Chile has one of the highest wood consumption per capita in the the world, although the use shows big variation between the regions, due to availability and climate. In Central Chile - where there are more economic activities-, industrial wood consumption is more common, while in southern Chile - due to colder climate-, the residential consumption is more significant [Reyes et al., 2015]. In South-central Chile, biomass is the cheapest energy resource, consequently nearly 80% of households use it for heating and cooking [International Energy Agency, 2018], [Instituto Forestal, 2012].

According to [Schueftan and González, 2013], firewood is 4-6 times cheaper than diesel, gas or electricity, thus not only residents, but also public buildings and schools use the resource to heat. The economic advantage is significant, especially with considering the low thermal efficiency of buildings in the country (which result to high energy consumption) [Schueftan and González, 2013].

Although burning firewood is not a new solution for heating purposes, in dense urban areas of Chile it leads to serious environmental issues, which also has economic and social consequences [Schueftan et al., 2016]. It has a direct impact on the population, since the particulate matter resulting from the combustion of wood is highly damaging to health. 96% of the pollution corresponds to PM10, from which 93% are fine particles (PM 2.5) [Ministerio del Medio Ambiente, 2014], which is responsible for more than 4 thousand premature deaths per year due to contamination. The Average monthly concentration of PM2.5 in different Chilean cities can be seen on Figure 2.1, where Temuco shows high concentration.

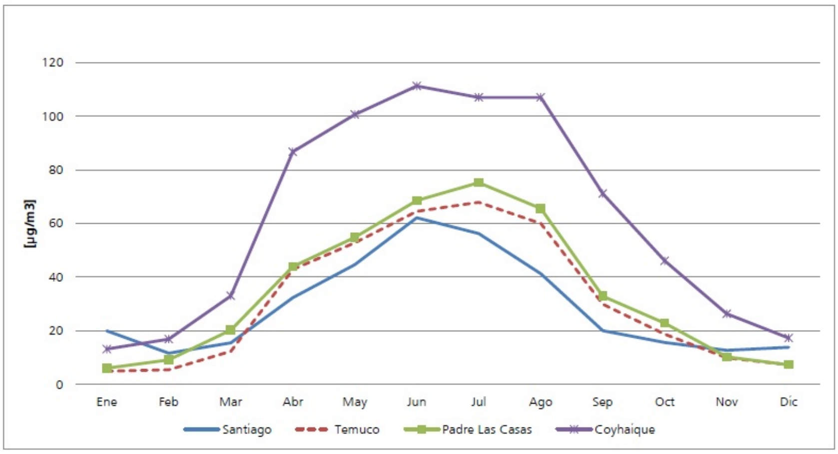

Figure 2.1. Average monthly concentration of PM2.5 (μg/m^3) [Suiza, 2016].

Firewood combustion for heating also has global consequences, during the process, high amount of GHG is emitted to the atmosphere. The extent of emission depends on the quality of biomass, which is often uncertain in Chile, as the purchase of wood often happens at informal markets or not from forests managed in a sustainable way [Reyes et al., 2015].

In spite of the high level of wood consumption, households in south-central regions of Chile do not have sufficient indoor temperature, as the study from [Waldo Bustamante, 2009] points it out, the indoor temperature in the region is between 14.3 °C to 16.5 °C during winter, and the reason is the inadequate insulation of the buildings. According to [Schueftan and González, 2013], when buildings have low thermal efficiency, to reach higher level of comfort, more energy is needed. In central-south regions this means the burning of more firewood for heating which also plays a big role in the high level of PM emission.

According to [Gómez et al., 2017], the major factors contributing to high emissions are: *"(1) poor wood combustion equipment quality, characterized by low energy efficiency and high emissions, (2) poor quality fuel with high moisture contents in wood, (3) inadequate insulation of houses, and (4) improper use of equipment."*

2.2 Air pollution in Temuco

The pollution from wood burning is a significant problem in Southern Chile (south of 35°S), the 2 million citizen of this region are exposed to higher than 30 μg/m^3 annual ambient PM2.5 concentration[Jorquera et al., 2018]. This part of the country has the highest rates of poverty, consequently a lot of citizens live in subsidized, low quality housing, of which 85% were built before 2007 [Jorquera et al., 2018].

According to [A Sanhueza et al., 2008], Temuco is one of the worst cities in the world regarding wood-smoke-pollution. Air pollution by particulate matter (MP10 and MP2.5) constitutes one of the biggest environmental and public health problems in the city of Temuco [Suiza, 2016]. In 2014, 24% of the annual death in the city were caused by cardiovascular and 11% to respiratory causes, connected to air pollution [A Sanhueza et al., 2008].

The results from [Cereceda-Balic et al., 2009] says, that PM10 sometimes surmounts the 900 or 1000 $\mu g/m^3$, from which 80-90% is PM2.5. In 2013, there were 33 days where the actual air pollution was over the MP10 norm and for 109 days it was above the norm for MP 2.5 [Suiza, 2016].

Timeline of monthly ambient PM2.5 concentrations ($\mu g/m^3$) measured at three urban monitoring sites at Temuco can be seen on Figure 2.2.

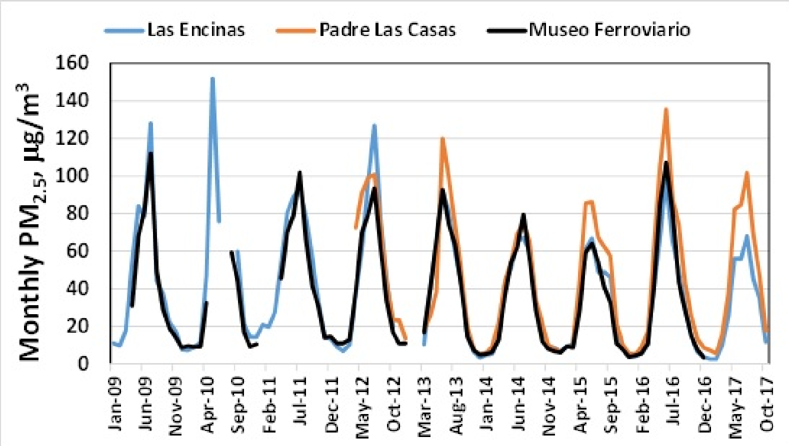

Figure 2.2. Monthly ambient PM2.5 concentration in Temuco in 2014 [Ministerio del Medio Ambiente, 2015b]

The total consumption of electric and thermal energy in the commune is 1784 [GWh/year], where 75% is correspond to the consumption of thermal energy. The largest consumer of energy corresponds to the residential sector, with 70% of total consumption, followed by the private sector with 27% and the public sector with 3% [Suiza, 2016]. The graph of the previously mentioned distribution can be seen on Figure 2.3.

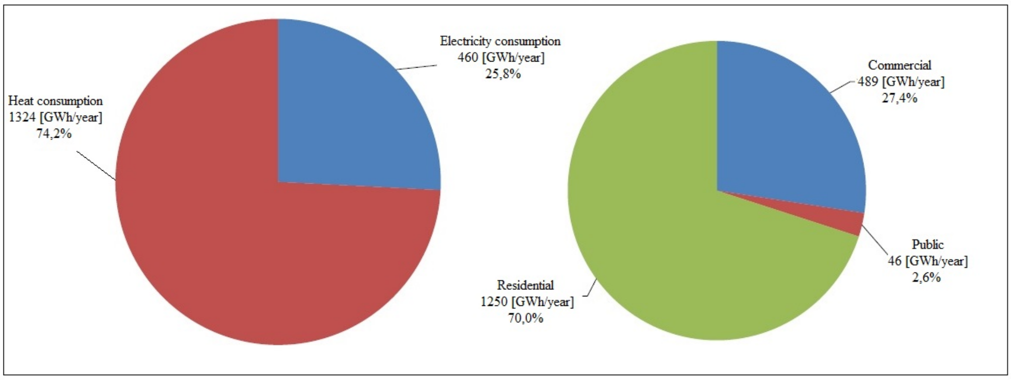

Figure 2.3. Distribution of energy use in Temuco by sector [Suiza, 2016]

It is considered that the use of wood in the community has the biggest responsibility in the emissions, where homes are responsible for 82% and 94% of total annual emissions of MP10 and MP2.5 [Ministerio del Medio Ambiente, 2016]. A study with detailed spectroscopy analysis, made by [Cereceda-Balic et al., 2009] showed, that the PM emission from wood burning in houses are way more significant than industry and traffic.

The biomass consumption for the year 2014 reaches a total of 957.8 GWh/year, and the distribution of consumption for this year is shown in Figure 2.4 [Suiza, 2016].

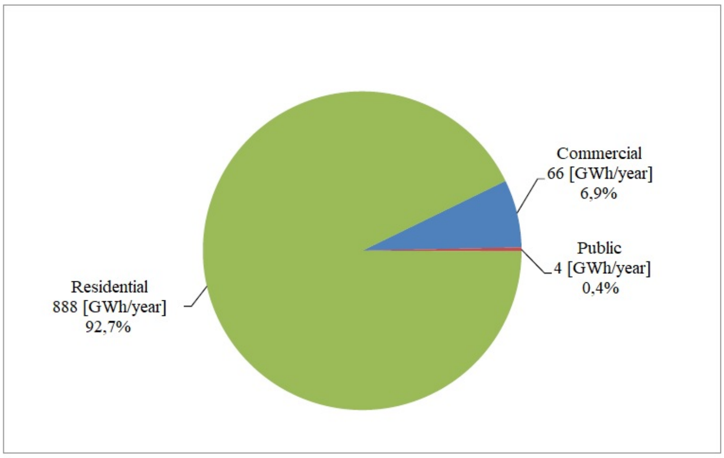

Figure 2.4. Biomass consumption by sector in 2014 [Suiza, 2016]

From the previous figure, it can be seen that the residential sector is responsible for 92.7% of the biomass consumption, the commercial sector for 6.9% and the public sector is responsible for only one 0.4% [Suiza, 2016].

According to the Residential Characterization Survey (Encuesta de Caracterización Residencial en Relación al Uso de Leña y sus Arte-factos de Combustión), 85% of households in Temuco use firewood as fuel. It is the main energy source for heating and cooking, reaching a consumption of around 660,000 m^3/year. The distribution of different fuels used for heating can be seen on Figure 2.5.

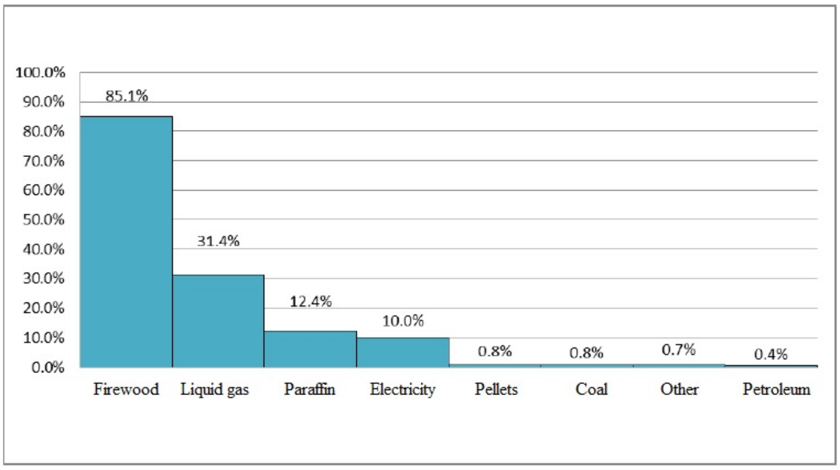

Figure 2.5. Fuel use for heating [Suiza, 2016].

According to [Suiza, 2016], the main causes of these emissions are found in the very low levels of thermal insulation of homes, the use of old heaters and firewood that does not meet minimum quality standards.

Additionally, in south-central cities, at the time of air pollution emergencies, partial or total ban of firewood combustion is enforced by the authorities, which has serious effect on low-income households [Schueftan and González, 2013]. While households with higher income turn to gas or electricity for heating, low-income households can not afford the higher cost of alternative fuels. Consequently, at the time of bans, they need to deal with even lower indoor temperature in their badly insulated houses [Schueftan and González, 2013].

2.3 Current strategies to mitigate emissions

As the households were identified as the main cause of pollution, controlling emissions from individual sources is required. This is -according to [Gómez et al., 2017] - challenging, as it involves large number of stakeholders, who responsible for a small share of the emissions individually. Consequently, regulations need to target household choices, involving utilized technology, quality and quantity of consumed wood and the insulation of the houses [Gómez et al., 2017].

To reach improvement in air quality, structural measures are required [Ministerio del Medio Ambiente, 2014]. During the last years, the GOC introduced new strategies and policies to cut back emissions in urban areas. Although, results from similar programs points out, that the most cost-efficient way to cut back emission is house insulation, according to [Schueftan et al., 2016], this solution is expensive, therefore its application is limited. Subsidies on fuel prices, or punitive tax system is also a limited option, as most of the transactions take place in informal markets, so as per [Gómez et al., 2017], the emphasis has been put on promoting alternative households choices.

The current policies to address the problem varies from utilizing subsidies to encourage more efficient and less polluting technologies for heating and cooking, introducing new standards for combustion equipment and firewood quality, to improve the insulation of the building stock [Gómez et al., 2017]. One of the most important part the strategy are the decontamination plans, which today are required for every bigger cities in the country by the Ministry of the Environment [Ministerio del Medio Ambiente, 2014].

The first step of the GOC was the introduction of emission norms for heaters. This regulation sets standards about emissions and energy efficiency for every heater entering the market, by obliging them for pre-sale certification [Ministerio del Medio Ambiente, 2014]. By restrictions of energy efficiency, the GOC aims to lower firewood use for heating, permitting certified heaters around 70% efficiency (improving from the nowadays used 15 to 25% efficiecy) [Ministerio del Medio Ambiente, 2014]. The combined effort means that the stoves produce more heat and less pollution at the same time.

An old stove can be seen on Figure 2.6, before replaced for a new one during the program.

Figure 2.6. Old woodstove in Temuco [Ariztia, 2016]

Despite of the previously mentioned approaches, ambient air pollution of PM2.5 is still high. According to [Jorquera et al., 2018], the slow process can be explained with 3 factors: (1) continuous migration from villages towards the city, during which low-income people move in and continue to use old technology, (2) people still use unregulated cooking stoves, and (3) the wealthier citizens increase their energy consumption per capita, which higher the emissions.

[Reyes et al., 2015] states that another drawback for the exchange program is the price of heating cost connected to the firewood substitutes. The significant increase of cost would lead to higher energy poverty - especially as the price of the substitutes are growing-, as it would have negative effects on indoor temperature and people's health. [Reyes et al., 2015] also argues, that the reduced demand for firewood would also have a negative effect on local economy - currently the firewood market gives important income for thousands of small and medium landowners-, as it would lead to less employment in the forestry, and lower prices for farmers.

Based on the previous arguments, a new solution should be found to to mitigate the negative impacts of burning firewood and bad air quality, while still keeping the positive aspects - like contribution in the local economy - of using biomass as a fuel. When considering this aspects, the consequence can be subtract that the improvement of the overall heating system is needed, considering system solutions like District Energy (DE) Systems.

2.4 District Heating

The DH system is a solution to provide heat for several users connected by pipes. The network moves heat from one or more heat producing units to buildings, supplying the space heating and DHW demands of households, shops and offices, and the need of the industry[Frederiksen and Werner, 2014].

The benefits of the solution include the higher efficiency of the system (compared to individual solutions), as the aggregated demand of the covered area can be satisfied with lower resource use; the wider use of renewable resources and flexibility between resources connected in the system; emission reduction; higher security of supply for costumers; and the possibility to use excess heat [Frederiksen and Werner, 2014].

The solution also consist some challenges, like the high up front investment; the risk that citizens does not want to participate in the system; the sizing of the system is a hard task and requires complex project development process; and in case of decreasing future demand, the currently needed capacities are unutilized [Frederiksen and Werner, 2014], [Rosada, 1988].

Problem statement 3

At the present time, humankind's most urgent issue to face is climate change, which is possibly the biggest challenge in its history. Additionally to the global effects, humanity's practice of burning fossil fuels for energy productions has serious local effects as well. One of the biggest problem in urban areas is the quality of air, which has serious health effects on the local population.

Air pollution is an emerging issue in Chile, where 6 of the most polluted cities of the American continent are located. The cause of the problem in the country is the overuse of wood as a heatsource, which emits significant amount of PM10 and PM2.5 pollutants to the atmosphere. The problem is more severe in the southern part of the country, where the colder climate demands more heating, and bigger amount of wood combustion.

One of the cities with the biggest challenge is Temuco, where households are responsible for around 93% of the PM emissions. Most of these households use firewood as source of heating, while the quality of their stoves and the insulation of the houses are far from adequate. The reason why people continue to burn biomass for heating is its price - it is 4-6 times cheaper than alternative solutions-, as high share of the people considered to be affected by energy poverty.

The current solution of stove replacement -provided by the GOC- is not fast enough, and the success of the problem is also uncertain. Consequently, the GOC started to examine the opportunity of other ways to cut back emissions, eliminate energy poverty, and help the country to fulfill its share in the Paris Agreement. Last year, the Government of Chile has announced a new district energy strategy, and cities of the country signed agreements to participate in United Nations' (UN) District Energy in Cities initiative.

All the reasons stated before led the research to investigate the possibility of implementing a District Heating (DH) in the city of Temuco, which leads to the following research question and sub-questions:

3.1 Research question

How can the introduction of a DH system in Temuco help to solve the city's air quality problem?

Sub-questions

- 1. What is the heat demand in the city (in different parts of the city) and which parts of the city has high enough heat density to implement District Heating system?
- 2. What is the result of the reference supply system - based on the current stove replacement program?
- 3. What is the best technical arrangement and operation of the District Heating system to reach higher emission reduction and lower cost?
- 4. Is the system economically viable - considering business economic perspective - and is it appealing for investors?
- 5. What are the policy barriers for implementing a DH system in Temuco, and what are the recommended framework changes?

3.2 Delimitation

and cause for non-inclusion

The delimitations of the project are the follows:

- The focus of the study is only the city of Temuco, although the city is merging with Padre Las Casas, the DH assessment only covers the territories of Temuco.
- The study only focuses on the residential sector, as it was identified as the biggest emitter during the Problem analysis. The inclusion of the commercial sector and industry should be part of the future works.
- During the design of the reference supply system, the gratification of individual household demands are not assessed. The assumption was made, that all households will receive a stove suitable for their demands.
- The network design does not reach the level of individual house appliances, only calculates the average distribution system length, substation numbers, and excludes the pumping facilities.
- Regarding air quality measures, and connected external costs, only the effects of PM2.5 is assessed.
- Because of the limited time, the analysis of the current political framework possibly does not reach the needed depth.

Additionally the following parts should be included to consider the study as a finalized study, not a preliminary one:

3.3 Research design and research structure

The structural approach of the project can be seen on Figure 3.1. The first part of the project - from the Introduction to the Problem Statement - followed a top-down approach to identify the air quality problem in Chile, the city of Temuco, define its causes and the current strategies to mitigate them.

As an alternative solution, the introduction of DH system was carried out, which is identified as a potential answer to the problem.

The Worldview and Theoretical framework introduces the technology of DH - included the 4th generetion DH-, UN's District Energy in Cities initiative and Chilean framework (reality) for DH. Later, the Methodology sector presents the the different methods used during the study, from the data collection, through the design and sizing of the system, until the economical calculations.

Thereafter, the analysis tries to answer the research question, and sub-questions, analyzing the technical and economic viability of a DH system, and analyzing the emission saving potential.

The discussion part raise awareness about the connected concerns, make suggestions about possible improvement in the governance framework (policies) and propose a tariff system for the DH system. The conclusion summarize the findings of the research, with the purpose of answering the research question (RQ), states the identified barriers, and give recommendation for the future work.

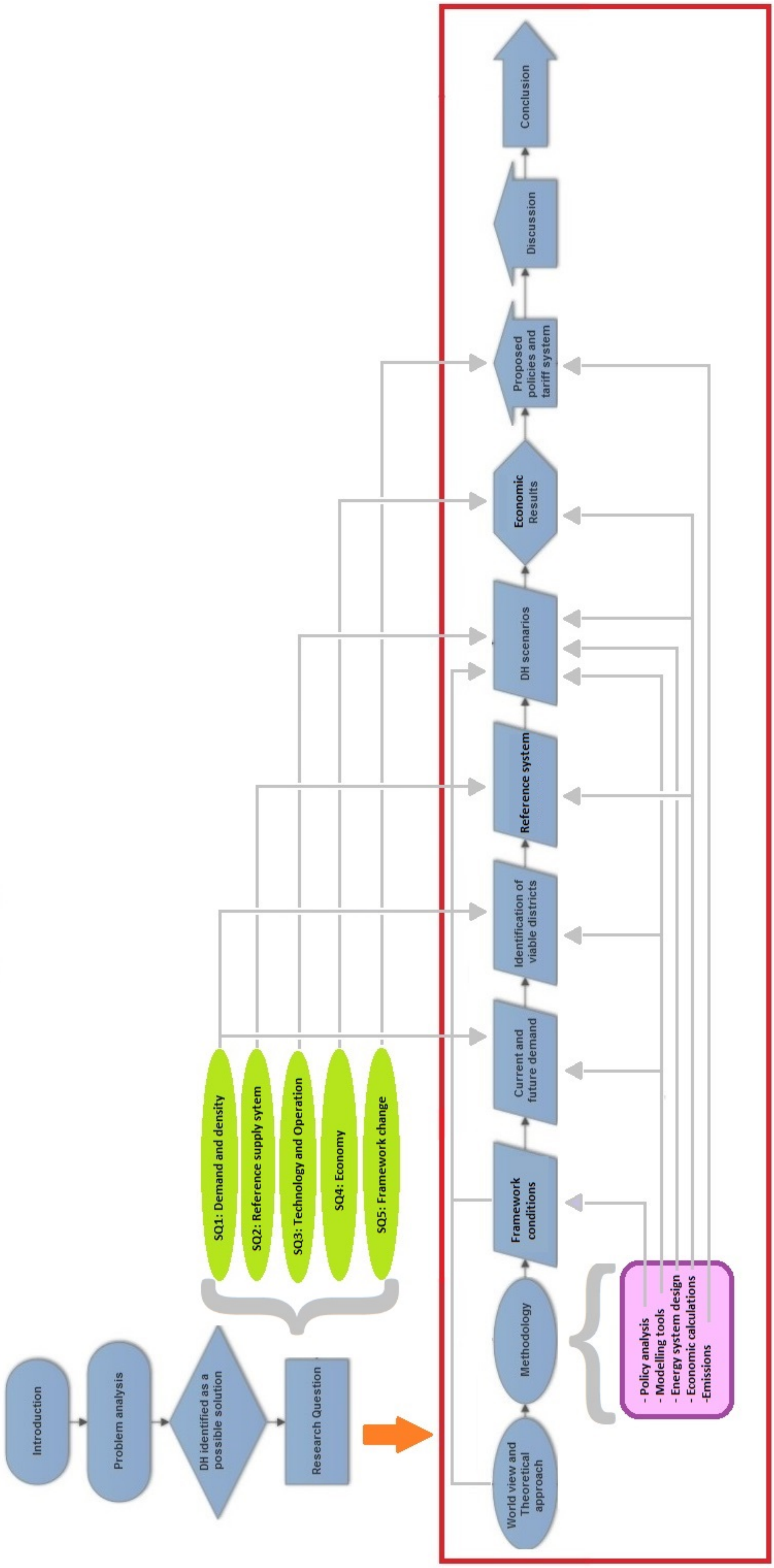

Figure 3.1. Project Outline

Worldview and Theoretical approach 4

Before starting to analyze the situation in Temuco, and answer the research question and sub-questions presented in Section 3.1, it is essential to present the worldview and theories upon the analysis is based, and will be followed while modelling and analyzing the effects of shifting from individual heating to DH in the city of Temuco. For this, firstly the concept of heating is presented, with the current district energy landscape and the UN Environment's District Energy in Cities initiative. Later, the overview of the current district heating technology will be opened up. Lastly, the theory of choice awareness and technological change are described to understand the shift from individual heating to DH system.

4.1 Heat demand

To be able to develop a solution to gratify heat needs, the definition of heat demand is needed. This section gives a brief introduction for heat demand, following [Frederiksen and Werner, 2014].

According to [Frederiksen and Werner, 2014], the heat energy demand is the energy needed for heating purposes over a specific time, consequently its unit is [kWh]. While designing and sizing a heating system, one of the most important parameter is the peak heat demand, which is the hour during the year with the highest heat consumption. Every heating system – including DH systems – must be able to satisfy the highest need, consequently need to be sized for this demand [Frederiksen and Werner, 2014].

[Frederiksen and Werner, 2014] categorized the heat demand for different groups, thus heat demand in residential and commercial sector consists of:

- Space heating: is the needed heat to fulfill a comfort temperature inside the building. It is highly dependable from the outside temperature, as in colder climate more heat is needed to reached the sufficient inside temperature, thus seasonal deviation is experienced in the need.
- Domestic Hot Water (DHW): heated water provided to citizens for different needs. DHW use is not connected to outside temperature, as e.g. people also take shower during summer and wintertime. The demand shows differences during the day - it is higher in the morning and evening, while almost zero overnight - as it follows the different human activities.

4.2 District Heating

The first commercial district heating system was developed at the end of the 19th century, and significant development can be observed during the centuries regarding efficiency, resource and technology. Nowadays, most of the operating systems are in Western Europe - especially in Scandinavia - where there is traditionally big need for space heating [Frederiksen and Werner, 2014].

The implementation of DH systems is driven by several factors, like reducing fire hazard, the change from coal to cheaper fuel, and to reduce fuel demand [Frederiksen and Werner, 2014], or because it can be a tool to decarbonize the energy system, and to promote energy efficiency, thus reducing cost of current systems [Connolly et al., 2014].

During its operation, the DH network moves heat from a centralized points of production or a number of distributed heat producing units to buildings, supplying the space heating and DHW demands of households, shops and offices, and the need of the industry. In this way, the aggregated demand of the covered area can be satisfied with lower resource use, as the efficiency of the system is better than the individual solutions - like the wood stoves in Temuco - [Frederiksen and Werner, 2014]. Another advantage of the solution is that it supports the idea to use combined heat and power (CHP), which also helps to connect the electricity and heating sector, thus provide more flexibility.

Water is used as a heat conductive medium, to transport the calorific energy from the production units to the enduse. The water is transported in a distribution network, containing isolated pipes and substations. Another important part of the system can be the heat storage, where the heated water can be stored for later use. Depending the size, the tanks can collect significant amount of energy, to supply at later time, when the demand is higher.

For the system to be competitive, the heat source should be obtained locally, from excess heat what would be wasted otherwise, or from renewables like geothermal, solar thermal, or local and sustainable biomass. According to [Frederiksen and Werner, 2014], the length of the distribution network should be minimized, to reduce investment costs, as well as the proper sizing of the system to avoid surplus capacity.

District heating is a proven energy solution, which is used in several cities in worldwide, and the number is growing continuously. Big variety of generation technologies can supply the system, while looking for synergies between, heating, cooling, hot water supply and electricity [UN Environment, 2018].

"Cities are adopting district energy systems to achieve important benefits including: affordable energy provision; reduced reliance on energy imports and fossil fuels; community economic development and community control of energy supply; local air quality improvements; CO2 emission reductions; and an increased share of renewables in the energy mix." [UN Environment, 2015]

The main benefits of DH are: (1) Improvements in energy efficiency, (2) lower cost to integrate renewables, (3) pollution reductions, and (4) resiliency and energy security [Frederiksen and Werner, 2014].

4.3 District Energy in Cities Initiative

Today, the use of DE and DH is promoted by EU strategies [European Parliament, 2018] and also initiatives from UN [UN Environment, 2018]. Consequently, the use of the technology is expected to spread outside Europe. According to [UN Environment, 2018], cities in North America, China and Latin America are expected to enhance their district energy potential.

United Nations' District Energy in Cities Initiative (DECI) "is working to raise awareness on the opportunities and multiple benefits of district energy" [UN Environment, 2018].

DECI is a multi-stakeholder partnership coordinated by UN Environment, with the aim of implementing new policies that will encourage investment in district energy system [UN Environment, 2018]. The goals of the Initiative include doubling the rate of building energy efficiency, and helping local and national governments to meet their climate targets.

According to [UN Environment, 2015], One of the cheapest and most efficient solutions to reduce primary energy demand (and decrease air pollution - is the development of modern, efficient, low-carbon district energy in cities.

Shifting to district energy systems is essential towards low-cost energy, and with the development of technologies the system can be connected to already existing municipal systems like, waste management, sewage system and transport [UN Environment, 2018].

4.4 Choice Awareness Theory

The description of the Choice Awareness Theory in this section is based on [Lund, 2014].

The Choice Awareness Theory focuses on the societal level. It addresses a decision making process involving different individuals and organizations, representing different level of power and interest [Lund, 2014]. The center of the theory is obviously the choice itself, and the consciousness that there are different true choices. At the societal level, the collective perspective needs to be open-up, and inform about that there are other choices to disperse the perception of no choice.

"Choice involves the act of thinking and the process of judging the pros and cons of multiple options and selecting one of the options for action." [Lund, 2014]

This theory deals with how to implement radical technological changes at the societal level.

Technological change

Technology is the application of scientific knowledge by which humankind sustain and magnifies its living conditions [Lund, 2014]. When a new technology develops as a niche innovation, it challenges the existing regime (or political decision-making processes).

According to [Müller, 2003], there are 4 aspects of technology: Technique, Knowledge, Organization, and Product. Later [Hvelplund, 2005] added Profit as the fifth part of the technology, which is especially important when analyzing the energy system [Lund, 2014]. The different parts of technology can be seen on Figure 4.1.

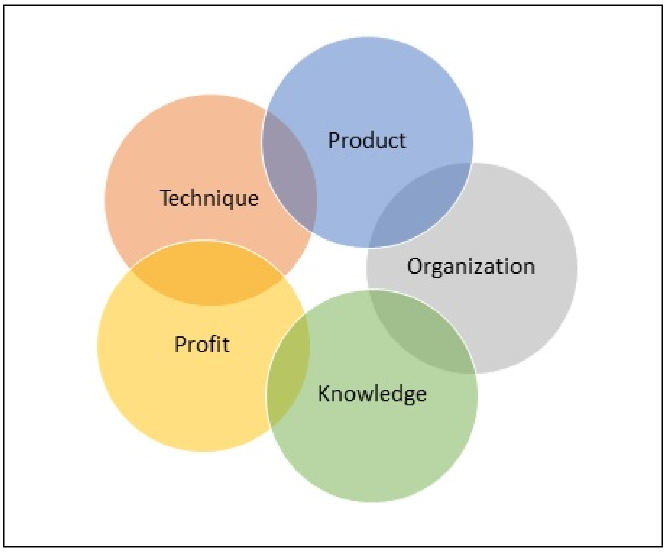

Figure 4.1. Definition of technology. Based on [Lund, 2017].

If one dimension is changed, at least one of the others will follow, otherwise the initial change will be discarded. According to [Lund, 2014], the level of change is increasing with the number of elements that changed, when two or more elements are changed, than the change is considered as a radical technological change.

The change will challenge the current institutions and organizations and most probably it will raise opposition. Because of that, the existing institutions will not create and promote new alternatives, sometimes they even try to eliminate new solutions/technologies, or at the end showing that there is no other choice just to stay with the current way [Lund, 2014].

The reason for the society having the perception of no choice, can be the elimination of technical alternatives (supported by old actors who can lose from the implementation of the new technology), as well as the institutional barriers to the implementation of the new technology.

According to [Lund, 2014], the solution is to raise awareness that there are other solutions. He argues, that

"the rise of choice awareness involves the design and promotion of technical alternatives and the use of evaluation methods, as well as the design of institutional alternatives."

When applying the theory, the research method consist the following steps:

- Step 1: Identification and design of technical alternative strategies to fulfill the given political (in the case of this thesis is to decrease PM emissions to the atmosphere of urban areas) or economical objectives. The description and design of alternatives is the core of the Choice Awareness Strategy.

  "Alternatives must be designed in such a way that they are equally comparable in term of the central parameters. . . , and in a way that the direct costs correspond to those of the main proposal." [Lund, 2014]

- Step 2: Conduct feasibility studies to measure how the alternatives are compared to each other, and for what extend they fulfill the political goal. It should include the evaluation of environmental, social and economic costs. Consequently, these studies can use socioeconomic or business economic evaluations.
- Step 3: Identification of institutional barriers of the implementation of the technological change. As the existing framework favors the old technological shames.

  When a different alternative is presented, there is still a chance that even though it is a better solution than the original one, but for different institutional reasons it cannot be implemented. That is the reason why it is necessary to identify barriers and propose solutions to the problems.
- Step 4: Identification of further – more general barriers - in the institutional framework, like lack of knowledge, lack of institutions providing relevant information.

The step by step research method can be seen on Figure 4.2.

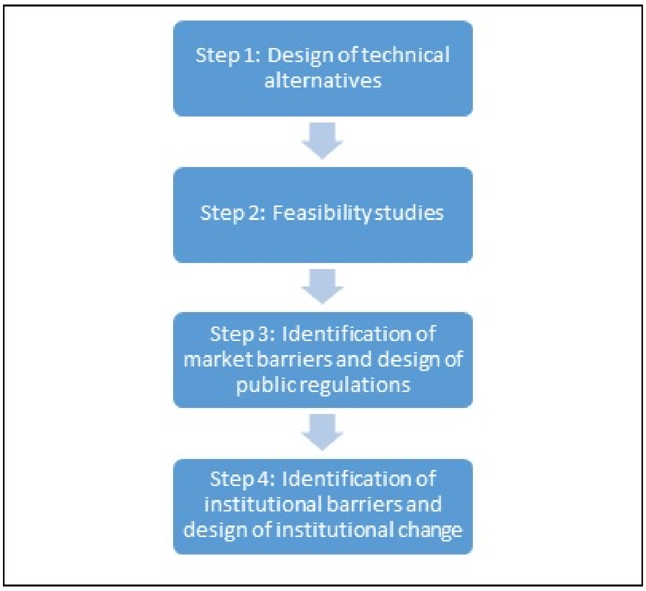

Figure 4.2. Step by step research method, figure recreated from [Lund, 2014].

Scenario Planning

While designing technical alternatives, future scenarios are made which are compared to each other, based on feasibility, social or environmental benefits. For this it is necessary to introduce Scenario planning.

According to [Benedict, 2017], the aim of scenario planning is to identify trends, projections or alternative strategies to project several possible futures (or alternatives), which make it possible to assess the design of energy systems, the needed policies and processes.

This tool is widely used in business planning, it should be applied more often in policy formulation and the field of sustainable development.

Application of theories

Relating the theory of Choice Awareness and Technological Change to the focus of this master thesis: the shift from individual firewood heating to DH represents a technological change. The district heating sector is basically non-existing in Chile, so the shift is assumed to cause a change in different elements of technology defined before.

The shift to DH leads to changes in the profit aspect, as new actors may appear in the energy market, and the profit potentially will shift from the traditional market players to the new DH ones. With the use of the CHP plants, it is foreseen that multipurpose organizations are developed, in this way to fit in the future smart energy systems.

Organizational changes are also expected in the legislative system of Chile, because new policies and support schemes are necessary to set the legislative framework for DH. The knowledge element is also changing, as there is need to educate customers how to distribute heat in their houses, how they need to use the new technology, which is a big change (and possibly challenge) considering the currently used technology of burning firewood in individual stoves. There is also need for new knowledge in the market of suppliers on how to deliver heating efficiently and how to maintain the system.

So it is easy to see, that the proposed solution is a radical technological change, thus according to [Lund, 2014], it is essential to promote the new choice towards the public, and make them aware of the new technology. For this, the thesis will follow the next steps:

- 1. Designing (several) alternative district heating solutions to the given political objective to decrease air pollution in the city of Temuco.
- 2. Conducting a feasibility study to compare the different district heating solutions with the current solution (the wood stove replacement program) and with each other.
- 3. Defining barriers in the current framework of the heating sector which are unfavorable for the district heating solution, and making policy recommendations.
- 4. Identifying wider barriers in the County's institutional structure.

4.4.1 Applicability, limitations and significance of the theories

Choice awareness theory states that radical technological change challenges the existing organizations, and poses threat to them, thus this organizations will not promote real alternatives, moreover are interested in choice elimination.

This thesis element does not correspond completely for the case of DH in Temuco, as the municipality already made steps towards the development of DH system in the city, as during the last year the city signed agreement with UNEP, and started the preparation for the implementation of the technology. The relevance and applicability of the theory lies in the fact, that institutional changes have not take place yet, thus the regime still favors the current solution and does not give space to the new technology, and also the general public lacks knowledge about the technology and its implication.

In this sense, with the help of the choice awareness theory the current institutional barriers can be identified and recommendation can be made to make the regime encouraging for DH solutions.

The limitation of the theory lies in the fact that awareness itself will not change the regime of policies. Every individual is self interested thus they need to have strong reason to push towards change, which is also true for the governmental body who makes the policies in the country. Showing a true choice is a good first step, but does not necessary result in actual actions.

Methodology 5

The purpose of the chapter is to introduce the methods used during this thesis to answer the research question presented in Chapter 3.1. Firstly, the overall research method is presented through the introduction of qualitative and quantitative methods. Later the ways of data collection is presented, followed with the modelling tool used during the analysis. The different methods and steps used in the technical analysis is also presented in the chapter.

5.1 Research method

During the thesis both quantitative and qualitative research methods were used, thus the research follows the mixed research method. In principal, qualitative research is used to gain understanding about the topic, to reveal the background, the reasons, motivations and the whole framework (regime) in which the problem exists. The qualitative method usually function as a base for the quantitative method. Quantitative research is used to quantify the problem, and to find objective, measurable results, which can be the base for comparison. During the research method, measured, or previously calculated data is used as a starting point of the analysis to quantify the the result [DeFranzo, 2011].

In the thesis, qualitative methods were used to understand the Chilean heating system, and the one in Temuco. It is also used to understand the legislations in the country, and identify the barriers for district heating system, consequently the main qualitative method is the literature review.

Quantitative method were used to quantify the problem of heating in Temuco, thus the modelling and simulation of the system is an example of using a quantitative method. For this, excel and EnergyPRO were, used, which will be introduced later in this chapter. The collection of numeric inputs for the model is also a quantitative approach, thus the review of official documents and the conducted interview is also classified to this category.

The research which uses both qualitative and quantitative methods, called mixed research method. In this method, the 2 parts are complementing each other, thus the integration provides a better understanding for the problem [Charles Teddlie, 2009]. When using the mixed methods, the researcher achieves a deeper understanding of the problem, and also offsets the weaknesses of the separate approaches.

5.2 Data collection methods

The most important base of any research is the properly collected data, which enables the researcher to find the best answer to the research question, and to reach a reliable solution.

This section introduces the techniques used during the research to collect the needed qualitative and quantitative information. In the sense, primary and secondary data can be distinguished from each other, consequently primary and secondary data collection methods are differ from each other. As the name describes, primary data is the data which is collected by the researcher for the first time - through interviews, surveys, experiments-, and secondary data is the one which was already gathered or produced by somebody else [Geoffrey R. Marczyk, 2005].

When using a secondary source, it is not known how the data was collected and analyzed, thus the reliability, suitability and adequacy of the data is needed to be analyzed, and the use of several resources are recommended[Geoffrey R. Marczyk, 2005]. In this research, secondary data is used, as the researcher did not have the chance to travel and examine the situation in Chile by himself.

During the investigation, two methods have been used to assist and ensure a valid and in-depth analysis, semi-structured individual interviews (and e-mails), and written (archival) literature study.

Generally, the availability of data is the biggest limitation during the research, which will be addressed later in the report.

5.2.1 Literature review

The literature review is a method, used to understand the topic of a research. The literature can be previously done research in the same, or similar topic, technology descriptions, statistics about the examined field, documents which has the same focus at other geographical places, and so on. The traditional literature review (or archival literature study), is used to gather more knowledge regarding the analyzed topic, to define the problem which can lead to the research question [Geoffrey R. Marczyk, 2005]. As the method of inclusion and/or exclusion is not used, the literature review can not be considered as systematic literature review.

The document analysis during the thesis is used to provide background information about the current energy system and legislation in Chile, to gather heat consumption data and about the available renewable resources. While collecting data, and analyzing the content, critical approach is necessary, as the interest of the authors and actuality can affect the reliability.

During the research, several governmental, municipal and research reports were investigated and used, and some of them proved to be more valid and comprehensive than the others. The most important documents are the *Estrategia Energética Local de Temuco*, conducted by the commission of the municipality, the *Estudio de usos finales y curva de oferta de conservación de la energía en el sector residencial de Chile* by the GOC, and Ministry of Energy's *Energy 2050: Chile's Energy Policy.*

5.2.2 Interviews

Interviews are primary data sources which are used - and wanted to be used - for collecting the best information about demographic, current heating consumptions, conditions of houses in Temuco, the currently running woodstove replacement program, previous district heating pilot-project in the city, and available renewable resources in the region.

Unfortunately, only two interview were conducted during the data collection, as the other contacted persons/utilities did not answer to the requests. The aim of the interviews is/would have been to have more punctual data about the city of Temuco, and to validate the information collected from the literature review, but because of the limited number, the aim was not completely reached. The successful interviews were carried out through Skype. The interviews were recorded, and were relistened to make sure the best understanding.

The interviews are a semi-structured expert interview, which gives the interviewer the opportunity to change pathways during the interview [Kvale, 2007]. Open-ended questions were asked to give space to the interviewee to answer in a way which he finds most valuable and to get precise understanding of his standpoint. This strategy also helps the interviewer to ask follow-up questions, which further deepens the understanding [Galletta, 2013].

Interviews were made with Eduardo Araneda Schüler, the Coordinator of Local Energy Strategy in Temuco, and with Felipe Ignacio Loyola Torres, member of the International Renewable Energy Academy and citizen of Temuco. The list of the attempted interviews can be found in the Appendix.

5.3 Policy analysis

During the literature review, several documents about the governmental and legislative framework are processed to have a wider understanding about the energy landscape in Chile. The thematic analysis of this documents help to identify the concerning governmental bodies and policies, the possible barriers and opportunities regarding the implementation of DH system in the country. An overview of the relevant policies is presented in Chapter 6, while the identified barriers (connected with the results of the analysis) will presented in the Discussion.

5.4 Selection of modelling tools

5.4.1 Heat demand

In a heating system - like DH-, an hourly demand-supply balance is needed, or in other words, the hourly energy production should be able to satisfy the hourly heat demand, to be able to secure the comfortable inside temperature throughout the year. Eventhough the current solution - individual heating with mainly wood stoves- is not a system solution, thus one can not speak about energy balances, the determination of hourly demand is necessary to be able to design the DH system.

As hourly data is not available for the city of Temuco, the distribution is made from the yearly data with the us of the Heating Degree Day (HDD) method - introduced later in

Chapter 5 - in Microsoft Excel. [1]

5.4.2 Energy system modelling

When designing an energy system, the first step should be the choice of suitable energy modelling tool.

In case of modelling the reference scenario, one can not talk about a system solution, as currently - and in current future strategies- individual solutions are presented. This scenario is only made to be a base for comparing the investment costs and emissions of the proposed systems with the current (planned) one. For this aim, Microsoft Excel is a suitable tool, thus it is used to calculate the investment cost and emissions for the reference scenario.

The selection of energy modelling software for the proposed DH solutions is made by following the a review of different modelling tools which deal with the integration of renewable energy [Connolly et al., 2010], and a lecture from the *Technical energy system analysis and policy design* [Nielsen, 2017] course.

In the research paper, 37 modelling tools were analyzed to provide a detailed comparison between the tools. 7 different types of software were distinguished, simulation tools, scenario tools, equilibrium tools, top-down tools, bottom-up tools, operation optimization tools and investment optimization tools [Connolly et al., 2010]. These categories can describe the tools exclusively or collectively.

The handout from [Nielsen, 2017] is used to identify the requirements towards the modelling tool - see it in Appendix. For modelling the district heating system of Temuco, a software is needed to be able to model the system of a city. For this it needs to be a simulation tool, able to compare different scenarios, able to make operation and investment optimization, to analyze different energy technologies to identify the best investment options and alternatives. It is also important to model hourly changes in the heating sector, the integration of a CHP plant and thermal storage, and the interaction with the electricity spot market. Additionally, the tool has to be freely accessible with available information and handbooks for the use.

For all these reasons, EnergyPRO is used to model the District Heating system of Temuco, while - as it was mentioned above - the reference scenario (which consists individual heating solutions in every households) is modelled in Microsoft Excel.

Microsoft Excel

Microsoft Excel is a software from the company, called Microsoft, which *"allows users to organize, format and calculate data with formulas using a spreadsheet system"* [Techopedia, n.d.]. Excel uses a collection of cells arranged into rows and columns to organize and manipulate data, which include basic mathematical calculations, using graphing tools, creating pivot tables and macros. [Wikipedia, n.d.a].

In the thesis Excel is used for basic mathematical calculations during the determination

[1] Data availability generally is the biggest challenge during the thesis, even to identify the yearly demands was a big task.

of current demand and the future demand forecast, during the design of the reference scenario and to calculate economic and emission results, furthermore to present the results in graphical charts.

EnergyPRO

EnergyPRO is developed by EMD International A/S from more than 20 years, the current version is EnergyPRO 4.5, which is used for the thesis.

EnergyPRO is a deterministic input/output model for energy system modelling. It is one of the most flexible modelling tool for techno-economic optimization and analysis, including CHP plants [EMD International A/S, n.d.], boilers, wind and solar power, and various complex energy systems.

The tool optimizes the operation of the given system, defined by available technologies, weather conditions , investment and maintenance costs of the elements, fuel prices, the defined electricity spot market, taxes, etc. [EMD International A/S, n.d.].

During the project, two different modules of the tool is used, the Design and Accounts modules. The first one is used to optimize the technical and economical operation of the system for one year, while the Accounts module used to make detailed economic analysis during the whole lifetime of the project.

The calculations in the Design module are based on the different pre-set conditions like, weather data, electricity price, heat demands, Operation and Maintenance (O&M) costs, fuels, energy conversion units and storage, while the Accounts setting needs additional information about investment, financing and taxation, to calculate payback time and Net Present Value (NPV) .

The tool works with hourly data, so the distribution files present hourly values, thus each of them contains 8784 data. Distribution files for common years (not leap year) are made to repeating the 24 data from 28th of February to prepare the date for the 29th of February.

5.5 Energy System design

The aim of the study is to satisfy Temuco's (the parts of the city where the heat demand density is high enough) current and future heat demand with a District Heating system, and determine the feasibility of the solution, additionally compare it to the current/currently planned solution.

When designing the energy system, the process follows the following steps:

- 1. Defining the current energy demand,
- 2. Forecasting the future demand,
- 3. Identification of suitable areas for DH,
- 4. Sizing of the DH system,
- 5. Modelling the reference system,
- 6. Modelling of the DH system using renewable resources and fulfilling the future demands.

The order of the steps can be unusual at the first glance, as the sizing of the DH system is before the reference system. The decision of this order is made to allow the researcher to design the reference system in a way which corresponds the best with the size of the district heating system - as it will be discussed later, the reference scenario in this study is not the current situation, but a one which the municipality would like to achieve with the stove replacement program. Correspondingly, the economic and environmental effects of the stove replacement program is only comparable with the DH solution, if it reaches to as many households as the proposed DH solution.

5.5.1 Current heat demand

MS Excel 2016 is used to calculate the heat demand in Temuco, where the outcome is an hourly model with an estimated heat demand for every hour.

As it was addressed before, the availability of data is considered as week point of the research, as not even the local expert was able to give more punctual data, than the estimate found in the Energy Strategy of the city. After the evaluation of the accessible consumption data, the decision was made that because of the lack of sufficient industrial and commercial demand, only residential loads will be included in the study [2].

According to [Suiza, 2016], the average household heat demand for space heating is 13.46 [MWh/year] in Temuco, but more punctual statistics does not exist considering the size and age of buildings, and does not differentiate between the newer and older neighborhoods. Regarding the DHW demand [Corporación de Desarroll o Tecnológico, 2010] states that the average household demand is 1.816 [MWh/year] in Chile.

From [Besser and Vogdt, 2017], data is retrieved regarding average heat demand per square meter in houses built before 2000, between 2000 and 2007, and after 2007 - according to the actual building code, which will be introduced in Chapter 6. This country general data was applied to the city of Temuco, to be able to distinguish between houses built in different years. An assumption was made, that the average size of houses are the same in every constriction year category.

From [Corporación de Desarroll o Tecnológico, 2010], the dispersion of houses is known according to their construction age in the whole country, and can be seen on Figure 5.1.

[2] Even though during the Problem Analysis the individual households were identified as the biggest emitters, the inclusion of industry and commercial sector would give opportunity to achieve even bigger emission cutback, and would also raise the heat demand density of districts, make more of them suitable for DH

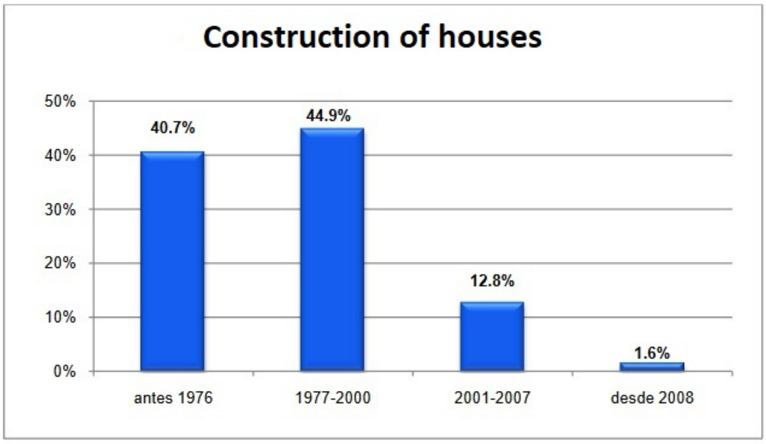

Figure 5.1. Distribution of houses by year of construction [Corporación de Desarroll o Tecnológico, 2010]

The assumption is made that this distribution is also appropriate for the city of Temuco, and steady in all the districts of the city. With the help of these data the annual heat demand of the city is calculated.

Hourly distribution

As it was explained above, yearly consumption data is not adequate enough in the case of modelling a heating system. The determination of an hourly distribution is necessary to model the energy scenarios.

The heat demand in residential households consists of two parts, the space heating and domestic hot water use. The hourly space heating demand is calculated from the yearly demand with the use of the Heating Degree Day (HDD) model. Space heating needs are governed by the outside temperature, as when it is colder outside, more energy is needed to heat up the rooms to a comfortable temperature.

Using the HDD model, the number of hours is determined where the outside temperature is lower than the temperature needed inside the houses to provide a comfortable temperature. The base temperature for heating degree days is set to 18 °C [Schueftan and González, 2013], while the heating period starts on 1st April and ends on 30st November [Torres, 2018]. Between these two dates, the hours must be determined and counted when the outside temperature is lower than the base temperature and when heat has to be supplied. One heating degree hour means one hour when the outside temperature is 1 °C lower than the base temperature [Bromley].

$$HDD = \sum T_{base} - T_o$$

Where Tbase means the base temperature and To indicates the outside temperature.

In EnergyPRO, local weather data is available from Temuco during the last 6 years, so the heating degree hours were possible to calculate for these year. The coldest year - the one which has more degree hours- is selected as the base year of the calculations. Distribution of the yearly demand is made with the use of the HDD method to have the hourly space heating demand.

The domestic hot water use is the other part of the heating demand, which varies in every hour of the year. The monthly/seasonal consumption is considered constant, while alteration during the day follows a pattern connected to the citizens activity. Consumption profile for Chile was not available, so a measurement made by [Department for Environment, Food and Rural Affairs, 2008] was used to determine the hourly consumption, and the pattern during the day can be seen in the following Figure 5.2.

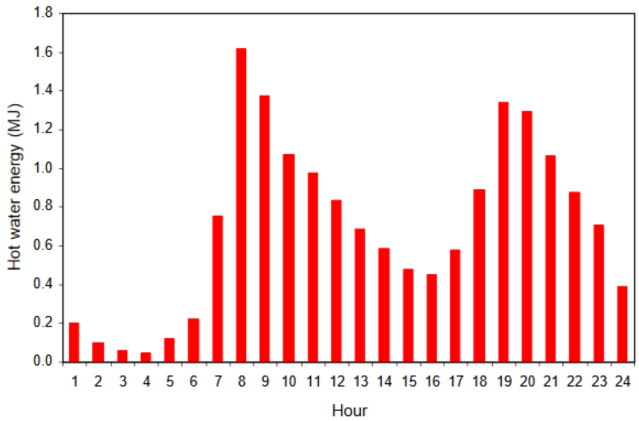

Figure 5.2. Hot water pattern [Department for Environment, Food and Rural Affairs, 2008]

The heat demand is the sum of the space heating and domestic hot water demands in every hours of the year.

5.5.2 Future demand

Planning for future needs in any sector of society is a challenging exercise. It is especially true for energy demand, because it depends on many factors, like weather, technology, policies and regulations, income, consumer behaviour and energy price.

Two contradictory trends can be identified in the city of Temuco, as the population is growing - between the last 2 certified census, the yearly population growth was 1.58% [3] [Instituto Nacional de Estadísticas de Chile, 2002] and [Instituto Nacional de Estadísticas de Chile, 2017] - which increases the demand, while because the better building envelopes for new houses and the refurbishment of old buildings the consumption is decreasing.

Considering the uncertainty in how the building stock will look like in 30 years - which is the expected lifetime of the project-, 2 different alternatives will be carried out and analyzed during the research. In both occasions the assumptions are made that the new buildings will be constructed by following the the current building code - even though it is expected that in the future, the building code will be more strict-, the average building size will stay the same as today, and - as [Cárdenas et al., 2011] states - after the refurbishment,

[3] The population growth is not equal in all of the districts of the city, in the already dense areas 0.5% annual population growth is assumed.

buildings will require 30% less energy to reach the same comfort temperature. In both eventualities certain number of houses, being built before 2000, will be refurbished or demolished and replaced, but the percentage is different.

In the first alternative - call it Large saving - the assumed housing mix will change in the next 30 years as follows:

2028	2038	2048
16.6% of "Before 2000" houses are replaced	33.3% of "Before 2000" houses are replaced	50% of "Before 2000" houses are replaced
8.3% of "Before 2000" houses are refurbished	16.6% of "Before 2000" houses are refurbished	25% of "Before 2000" houses are refurbished

Table 5.1. Ratio of replaced and refurbished houses in the Large saving supposition

In the second alternative - the Medium saving - the assumed housing mix will change in the next 30 years as follows:

2028	2038	2048
10.0% of "Before 2000" houses are replaced	20.0% of "Before 2000" houses are replaced	30.0% of "Before 2000" houses are replaced
10.0% of "Before 2000" houses are refurbished	20.0% of "Before 2000" houses are refurbished	30.0% of "Before 2000" houses are refurbished

Table 5.2. Ratio of replaced and refurbished houses in the Medium saving supposition

It is to be noted, that because of the higher ratios, the Large saving way - as the name implies - will result in lower demand, and intends to show the consequence of money spend (possibly from government or municipal subsidy or grant) on insulating and replacing old houses.

For both alternatives, the heat demand is calculated for 2018, 2028, 2038 and 2048, to identify the trend of consumption, and the districts with the suitable heat demand density for DH in all 4 phases.

5.5.3 Identification of suitable areas

The implementation of DH is only viable at areas where the heat density is high enough [Connolly, 2015]. According to [Heat Roadmap Europe, 2016], current district heating technology requires heat demand densities above 100 TJ/km^2, so it is necessary to define the sufficient parts of the city, where the heat density is high enough to make it suitable for DH.

Based on [Municipalidad Temuco, 2015b], the city of Temuco is divided to 91 micro-zones, which subdivisions are used for the study and can be seen on Figure 5.3.

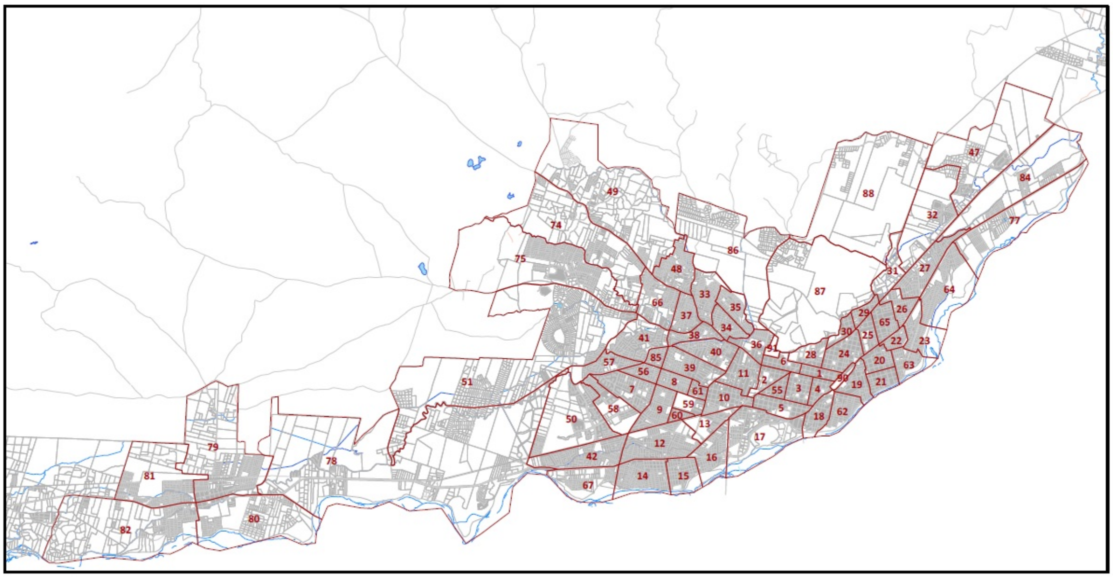

Figure 5.3. Micro-zones in Temuco [Municipalidad Temuco, 2015b]

The size and population of every micro-zones are known, so the calculation of density is possible. As it was stated above the housing mix is assumed to be even . With the use of the 2 assumptions regarding the building stock, the future demand and correspondingly the heat densities are calculated for every zones, which is the determining factor for connecting to the DH system.

5.5.4 Sizing of the system

As the demand is decreasing in the dense areas in both suppositions, the districts which are passing the heat density criteria today, may not be suitable for the technology in the future, in this way the whole system will become more and more oversized during the upcoming years if the system is sized for the current demand.

To address that issue, the design strategy was made that the DH system should be sized for the future demand of 2048 (only consisting the districts with higher than 100 TJ/km^2 heat density). In 2018 -as the 1st phase-, only districts with the highest heat demand densities will be connected to the DH system, until the limit of the preset total heat demand is reached. Until 2048, new districts will be added to the system in 3 more phases - 10 years apart from each other - until the sum of their demand reaches the available power. The visualization of sizing can be seen on Figure 5.4.

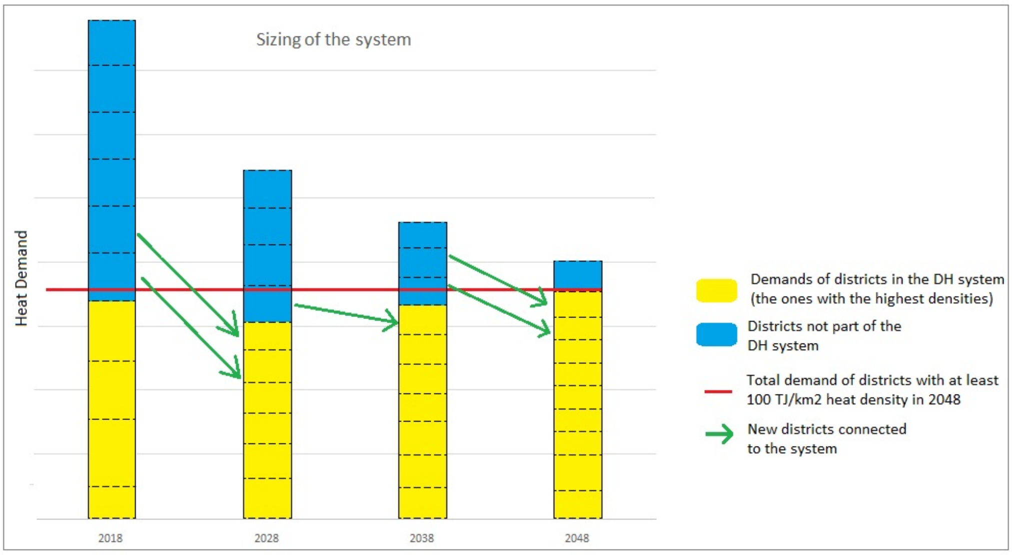

Figure 5.4. Visualization to determine the connected micro-zones

Explanation: Let's say that there will be 8 districts with more than 100 TJ/km^2 density in 2048, consequently their total heat demand will determine the size of the system. Because their demand is decreasing during the years, their demand is higher than the limit - set based on their 2048 demand - at the start of the project (and also in 10 and 20 years from today). Thus not all of them can be connected to the system now, just the ones with the highest densities (on the illustration 4 districts can be connected to the system, as their summarized demand fits under the limitation). As the demands of districts decrease during the years, more and more zones can be added to the system, until in 2048 all the sufficiently dense ones will be connected.

5.5.5 Reference scenario

As it was stated before, the reference scenario of the study is not the current situation in Temuco, but the one which the municipality would like to reach with its stove replacement program.

The current program aims to replace 27000 stoves during the next years, and keep continues it further in the future, while securing the finances.

The scenario is defined to reach as many households as the proposed DH solution to be able to make a valid comparison between them. The study, [Gómez et al., 2017] summarize the stage and results of the current program, and introduces different types of stoves which are used during the exchange program.

Based on the statistics from the [Dittborn, 2017], the share of installed firewood, pellet and kerosene stoves are known, which distribution will be used to calculate the needed investment and the emissions during the next 30 years.

5.5.6 DH scenarios

As it was introduced before, 2 alternatives are analyzed during the research differentiated by the future building mix, thus future heat demand. For both cases, 3 technologically different setups (scenarios) are designed to fulfill the heat demand. The first scenario primarily using biomass CHP to heat generation, the second one is primarily using electric heat pumps, and the third one is a mixed system, including geothermal energy.

The biomass, heat pump and mixed scenarios are similar among the two alternatives, with the aim to identify the effect of the higher level of refurbishment.

The different DH scenarios are modelled and analyzed with EnergyPRO, while following the pre-set operation strategy of Minimizing Net Heat Production costs. The tool calculates the generation cost of the different included technologies, and prioritize them starting with the cheapest one, based on fuel cost, and variable O&M costs. Then the model starts to satisfy the hourly demands with the cheapest one, until the needed demand is reached.

With the tool, the annual fuel use, production share, and total utilization is calculated, with the connected cost which will be important for the economic comparison.

5.5.7 Effective width

As the detailed - house by house- planning of the DH system is not the scope of the study, the size of the distribution system, the substations and house appliances are included as high-level estimates.

For determining the length of the distribution system the effective width method was used. With the effective width calculation, the connection between the a given land area and the length of the district heating pipe network within [Urban Persson, 2010].

$$w = A_L / L$$

where w represents the effective width, Al is the total land area and L is the length of the pipes.

Based on existing DH systems, [Urban Persson, 2010] established a power function for effective width, which follows:

$$w = 61.8 \cdot e^{-0.15}$$

In the formula e stands for the so called plot ratio, which is the proportion of the total building space and the total land area of the examined area.

As the previously mentioned values are available for the 91 micro-zones, first the plot ratio was calculated, which helped to determine the effective width of the districts. Knowing the value of effective width and the total land area, from the first equation the length of the distribution system is calculated for each micro-zones.

Economic calculations

In the research different scenarios are made to supply heat demand for the city of Temuco. In each scenario, the aim is to find a proper technical compilation, with an operation strategy, while minimizing the cost the system. Additionally, an economic comparison is made between the scenarios, considering investment costs and Net Present Value (NPV). It is important to emphasize that the calculations are made from a business perspective, to evaluate the feasibility of the scenarios, and compare them to the running stove replacement program.

The cost of the different technologies are mainly obtained from the official document from the Chilean Ministry of Energy [Ministerio de Energia, 2018], while the connected technical parameters are from the Danish Energy Agency's different technology catalogues [Danish Energy Agency, 2017], [Danish Energy Agency, 2018a], [Danish Energy Agency, 2018b], [Danish Energy Agency, 2016]. Prices from the Danish catalogues were used, when Chilean data was not available, and will be stated everytime it happened. Both the Chilean and Danish documents give information about capital investment costs and also Operation and Maintenance (O&M) costs.

The revenues in the project are earned from the sale of heat for the end users and - in the scenarios where CHP plant is included- from the sale of electricity to the national grid. While the electricity price is driven by the Chilean spot market, the price of the sold heat is set by the 'owner' of the project. In the study market-based pricing principle - also known as a competition-based strategy-, is used. In this strategy, a company is evaluating the prices of similar products in the market and set its price accordingly [Morris and Morris, 1990].

When following this strategy, according to [Anthony, 2018] it is important to evaluate the price sensitivity of the costumers, and in case of price sensitive buyers, it is recommended to match the competitors price, or go below that.

[Torres, 2018] confirmed the information of the several studies - examined through the literature research -, that "most people in Chile will always choose the cheapest option". For that case it was chosen to match the price of the commonly used market alternative, which is the use of firewood for heating, and electricity or natural gas for DHW. An average cost for the used energy in calculated and will be used for heat price in the DH system. During the sensitivity analysis, the effect of lowering the heat price will be assessed.

The DH scenarios will be compared by NPV and payback times will be also calculated. NPV is method to analyze the profitability of investment projects, by showing the present value of future cash inflows and outflows with the help of a pre-set discount rate during a given time period [Hopkinson, 2017].

To determine the NPV of the scenarios, the following formula is used:

$$\text{NPV} = \sum_{t=0}^{n} \frac{NP_t}{(1+i)^t}$$

where NPt means the Net payment (cash inflow or outflow) at time t, i is the discount rate, and n represents the lifetime of the project.

The discount rate used in the project is 6.0% as it is set by the GOC [Ministerio de Desarrollo Social, 2016], and uses 1,9% yearly inflation during the 30 years of lifetime.

As it was stated before, the study is made from a business perspective, so the applying corporate tax and carbon tax will be included in the calculations, accordingly both NPV and payback time is calculated by EnergyPRO's Account mode.

As the calculation of NPV relies on multiple assumptions and estimates, sensitivity analysis will be made with different discount rates, heat prices, and fuel prices.

5.5.8 Emissions - Impact Pathway Approach

With the introduction of new technology, the environmental impacts of heat generation is changing. To evaluate the different scenarios, and compare them to the reference, their pollutant emissions are calculated with the connected social costs.

For this evaluation, the impact pathway approach is followed, in which environmental costs and benefits are estimated from the quantified impacts [Friedrich R., 2001], in this case the PM2.5 emissions from the investigated technologies. As first step, the quantified emissions are calculated with EnergyPRO, and then the related economic costs are assessed.

It is important to note, that emissions does not only cause local damages, but with GHG emissions the environmental effects can occur hundreds of kilometers away, or globally. Nonetheless, these global effects - and their costs- do not form part of the focus of this study.

The economic consequences of the different scenarios are compared and evaluated as the last step of the assessment.

Framework conditions in Chile 6

To be able to design and analyze the current heating system of Temuco, and be able to develop other solutions, it is necessary to get to know the framework conditions in the country. It is gives base to identify barriers and give folicy recommendation to support the implementation of DH in Chile. In this section, the most important institutions and legislations are presented, which has influence on the system

6.1 Governance framework in Chile

The most important energy policy institution is the Ministry of Energy (Ministerio de Energia), which was created in 2010. The responsibilities of the Ministry includes the elaboration, coordination and implementation of national energy policies, the development of strategies and action plans [Ministerio de Energia, n.d.b].

Another relevant entitiy is the Chilean Energy Efficiency Agency (Agencia Chilena de Eficiencia Energética or AChEE), was also created recently, in 2012 [Nasirov and Silva, 2014]. AChEE is public-private foundation, created to promote and support efficient energy use in the residential, commercial, transport and mining sectors [International Energy Agency, 2018].

The Ministry of Environment (Ministerio de Medio Ambiente or MMA) is the leading governing body corresponding to the design of environmental policies and programs to protect the nature, natural resources and biodiversity [Ministerio de Medio Ambiente, n.d.]. One of the departments is the Council of Ministers for Sustainability (Consejo de Ministros para la Sostenibilidad) which is responsible for climate change policy.

One of the biggest success of the Ministry of energy was the development and introduction of the country's long-term energy vision and policy (national energy policy), the Energy 2050: Chile's Energy Policy (Energía 2050: Política Energética de Chile), which was carried out after public consultation [Ministerio de Energía, 2016]. The Energy Policy is sustained by 4 pillars: Quality and Security of Supply, Energy as a Driver of Development, Environmentally-friendly Energy, and Energy Efficiency and Energy Education [Ministerio de Energía, 2015], and has middle-range targets to 2035 and long-range targets to 2050.

The aim of the strategy is to incite the transition from import dependent (mostly oil and coal) energy regime towards a self-supplying and modern sector, where energy is affordable for the entire population [Ministerio de Energía, 2015].

The most important goals of the policy are to reach 70% renewable share in the electricity generation by 2050 (60% by 2035); to focus on cost-effective thermal technologies with low emissions - such as biomass[1]-; to meet OECD standards for efficient buildings and to lower GHG emissions with at least 30% by 2030[Ministerio de Energía, 2015].

Chile has also become a pioneer in the use of instruments for the mitigation of greenhouse gases, by introducing tax on CO_2 emissions from fixed sources -power generation units (e.g boilers) with capacity bigger than 50 MW are the subjects of the tax-, to counteract environmental externalities. The tax need the be paid on both the emission of global pollutants (CO_2) and the emission of local pollutants, like SOx, NOx, and PM. Additionally, a tax is created for cars, calculated based on their urban performance and NOx emissions. The law was implemented in 2014[Ministerio de Hacienda, 2014], but was only implied from 2017 and paid from this year [International Energy Agency, 2018]. The tax is set at 5 USD per tonne of CO2 [Ministerio de Hacienda, 2014].

Other legislations which are relevant to the topic of the thesis is the "Política de Uso de la Leña y sus Derivados para Calefacción" (translated to Policy for the Use of Firewood and its Derivatives for Heating) and the Local Atmospheric Decontamination Plans. The aim of the first policy is to limit pollutant emission from burning firewood, to promote the sustainable production and use of firewood [de Chile, 2015]. The policy consist 6 focus areas: (1) building efficiency, (2) support the change for sustainable and quality firewood, (3) support of biomass use for heating, (4) improve energy efficiency for heating, (5) institutional framework and (6) education.

The Atmospheric Decontamination Plans (Plan de Descontaminación Atmosférica) are made locally, with the aim of decreasing the air pollution of the given cities. Most of these plans - including the plan in Temuco- aim to solve the pollution coming from residential houses, by offering stove replacement programs to promote efficient stoves using firewood, pellets or kerosene [Ministerio del Medio Ambiente, 2015a]. Additionally, the GOC introduced a new labeling scheme for stove energy efficiency, in which all firewood stoves (from 2015) and all pellet heaters (from 2017) are needed to be labeled [International Energy Agency, 2018].

6.2 Building energy standards

In 1977, a climate-housing zoning system was introduced, with design recommendations to improve energy efficiency [Alvarado, 2013]. In 2000, Compulsory standards were introduced in 2010 and 2007, regarding vertical elements (wall structures) of houses and roof structures respectively.

The requirements are different at locations with different heating needs. According to [Besser and Vogdt, 2017], based on the heating degree-days, the country is divided to 7 thermal zones, and the city of Temuco is located in zone 5 [Suiza, 2016]. The maximum thermal transmittance level in the centre-south regions of Chile was set from 2.5 $W/m^2/K$ to 1.7 $W/m^2/K$ concerning walls, and from 1.0 $W/m^2/K$ to 0.4 $W/m^2/K$ for roofs [Alvarado, 2013]. In this region it requires 2 cm insulation for walls, 14 cm for roofs,

[1]Biomass is considered renewable and sustainable resource in the country: "biomass is an abundant source of energy, it is local, renewable, clean and fairly accessible as long as the correct decisions are made in order to encourage adequate use of the resource" [Ministerio de Energía, 2015]

and 5 cm for ventilated floors [Schueftan and González, 2013]. However, the 2007 Norm requires much less insulation than used in other OECD countries with similar climate.

Based on a study from [Corporación de Desarroll o Tecnológico, 2010], the average heating demand of dwellings are reduced with more than 50%, which can be seen on Figure 6.1.

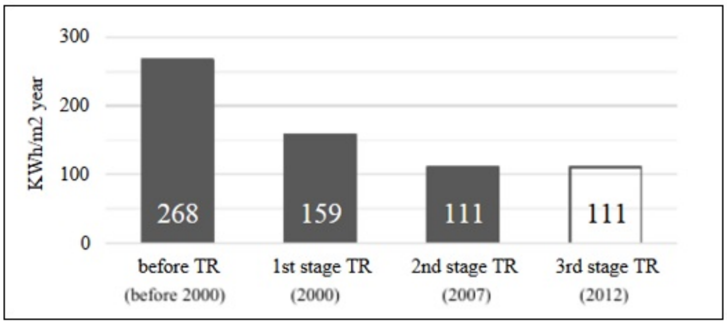

Figure 6.1. Average heating energy demand of Chilean dwellings before and after the Thermal Regulation [Besser and Vogdt, 2017].

This study correlates with the data retrieved from the interview with Eduardo Alvarez, who stated that since 2015 - since the new Atmospheric Decontamination Plan for Temuco and Padre Las Casas-, the requirements for energy demand were established at 110 kWh m2/year in houses of Temuco [Araneda, 2018].

However, according to [Alvarado, 2013], it is important to mention that 80% of the housing stock in the central-south region does not meet the these standards, and will be in use for several decades, which shows the need for retrofit programs.

Consequently, Chile started a thermal refurbishment program in 2008, and reached to 0.6% of the existing dwellings [Schueftan and González, 2013]. The aim of the subsidy is to bring thermal efficiency of houses to the 2007 Norm.

In 2011, a system for energy labeling was established. This is a voluntary comparative system for residential buildings, with different energy efficiency categories between high and low efficiency [International Energy Agency, 2018].[2]

6.3 Stove replacement program

As it was already mentioned in the Problem Analysis, wood-stove replacement programs became the key emission control ordination in several cities - including Temuco -, announced and supported by the decontamination plans [Ministerio del Medio Ambiente, 2016]. Several versions of the program existed from the early 2000's, with the aim to replace firewood stoves to new kerosene and pellet ones. In the new programs, the GOC, or local municipalities pay for the stove, the beneficiaries can chose from different type of stoves: wood, gas, kerosene or pellet [Ariztia, 2016].

[2] Even though, 32000 residential buildings were labeled, the inventory is considered not accurate enough to use it as a base for this study.

As part of its decontamination plan, the city of Temuco aims to complete 27,000 woodstove changes by 2022 - which is 35% of the total woodstoves[Araneda, 2018], [Ministerio del Medio Ambiente, 2016]. According to [Jorquera et al., 2018], 7700 stoves were replaced between 2011 and 2017, and the rest is coming during the upcoming years.

6.4 Framework for DH and CHP

In 2015, CHP plants generated 5.6 TWh of electricity, which correspondes 7.4% of the total generation, and according to AChEE there is potential for an additional of 875 and 1 500 megawatt electrical (MWe) in the industrial and other sectors respectively. To build further capacity, in 2012 the Ministry of Energy launched its Fostering CHP Program to support feasibility studies and help the possible projects with funding [International Energy Agency, 2018].

Regarding the framework of district heating, there are only a couple of case studies and pilot projects about the technology in Chile, and there are also no regulations. Even though, there are goals associated with DH in the Chile's 2050 energy policy and the Local Atmospheric Decontamination Plans support pilot projects and provide co-financing, regulations and action plans haven't been conducted until the time of this master thesis.

In 2017, the GOC announced that it is cooperating with the UNEP to develop its strategy for district energy in cities [UN Environment, 2017]. The technical solutions - suggested by UNEP - could include biomass CHP and heat pumps.

Together with UNEP and its partners - including Aalborg University -, the country is developing the Heat Roadmap for Chile, which can gain from the findings of this thesis.

6.5 Electricity market

Although the focus of the study is heating, today we can not address the topic without the connection to the electricity situation in the country, as today and in the future the 2 sectors are more and more interacting with each other. During the study CHP plant and heat pumps will also connect the 2 sectors, thus the basic understanding of the electricity market is necessary.

In Chile, the electricity market is open, thus private companies can build and operate generation units, and connect them to the national transmission and electricity lines [International Energy Agency, 2018]. Until last year, there were 2 separate electricity system (and market) in the country, the SIC southern and central part of the country - covering over 90 % of the country -, and SING covering the northern part [Javier Bustos-Salvagno, 2017].

The 2 systems were interconnected in December, 2017, and now covers the whole country [Townley, 2018]. In the country, the national spot market is supervised by the an Independent System Operator called Load Economic Dispatch Center (CDEC) operates the system and let the generating plants to deliver electricity by following the order set by their bidding price. [Javier Bustos-Salvagno, 2017].

The price setting in the system follows the peak-load pricing scheme, thus the spot price is equal to the marginal cost of electricity generation, plus the "opportunity cost of installing peak capacity" [Javier Bustos-Salvagno, 2017]. As the country is aiming to reach 60% renewable share in electricity in electricity generation by 2035, and 70% by 2050 [Ministerio de Energía, 2015], the marginal cost of electricity is expected to decrease in the future.

6.6 Summary of most important influences

The currently valid building regulation was identified - with the its effect on the heating demand compared to older buildings-, which gives the base for the future demand projections.

Currently, there is an ongoing wood stove replacement program in the city of Temuco, consequently the program gives the base for the reference scenario.

The Fostering CHP program and the Local Decontamination Plan are identified as a possible opportunities for future funding, but the framework conditions for DH are not developed at the moment.

As during the scenarios, the different heat production units emit CO_2, they are obliged to pay the carbon tax of 5 USD/ton.

Heat Demand 7

When starting to design th DH system, the first steps are the calculations of the heat demands needed to be supplied in the city Temuco. As it was introduced in Chapter 5, data to for the calculation was limited, consequently only the residential sector is included in the DH system. DH systems are designed for long lifetime - in this case 30 years -, so the definition of the current, and future demand is also needed.

7.1 Current Demand

According to [Frederiksen and Werner, 2014], the heat demand in residentials consists of 2 elements,space heating and DHW, consequently separate calculations are needed during the identification of heat demand.

In Chile, there is no database with punctual consumption data for households, which can be explained by the fact, that most of them use firewood for heating purposes, what they most of the time purchase at informal markets [Gómez et al., 2017]. Consequently, the demands of households in Temuco need to be calculated with the help of local and national estimates abut average household demands.

According to the Census, made in 2017, there are 94,533 houses in Temuco [Instituto Nacional de Estadísticas de Chile, 2017]. These houses were build with compliance of the actual house code, in force at the time of their constructions, so the identification of construction year is necessary.

A study, carried out by the GOC, identifies the proportion of houses built in different years, with the result of 40.7% being built before 1976, 44.9% between 1977 and 2000, 12.8% between 2000 and 2007, and 1.6% after the new building code was introduced in 2007 [Corporación de Desarroll o Tecnológico, 2010]. This distribution was applied for the city of Temuco during the heat demand calculation.

As these buildings were build with different standards, their space heat consumptions differ. A study from [Besser and Vogdt, 2017], define the differences regarding the building codes, and states that the annual average consumption per square meter in houses built before 2000 is 268 kWh, in houses between 2000 and 2007 is 159 kWh, and in houses built after 2007 is 111 kWh. From Temuco's Energy Strategy, the average yearly household space heat demand is known, it is 13.46 MWh [Suiza, 2016], so the calculation of the different heat needs can be calculated in the city, and can be seen in Table 7.1.

Construction of houses	Consumption [kWh/m2/year]	Percentage in house stock	Consumption per house [kWh/year]	Number of houses
before 1976	268	40.70%	14341	38475
1977-2000	268	44.90%	14341	42445
2000-2007	159	12.80%	8508	12100
after 2007	111	1.60%	5939	1513
			Avg.: 13460	Total: 94533

Table 7.1. Household heat demand by construction of year in Temuco

With the help of the previously calculated demands, the current space heat demand of the city is 1,272,414 MWh/ year.

From [Corporación de Desarroll o Tecnológico, 2010], the yearly average DHW consumption is known, and it is 1816 kWh/year. Multiplying this with the number of houses, the yearly DHW demand for Temuco is 171,700 MWh/year.

As the total heat demand is the sum of the space heating demand and the DHW demand, the total Heat demand of Temuco is 1,444,114 MWh/year, from which 88% is the space heating and 12% is DHW use. The yearly demand means 18.41 GJ/habitant, which is in the middle range of the EU average of 10-50 GJ/hab [Urban Persson, 2015][1], which validates the correctness of the calculation.

7.1.1 Hourly distribution

As it was explained in Chapter 5, hourly values are needed for the proper sizing of the system, so the yearly consumption needs to be distributed in all 8784 hours of the year.

The space heating demand depends on the outside temperature, consequently the HDD method was used for the distribution - as it was explained in the Methodology. The HDD were calculated for the last 6 years, with the condition of the heating season - between 1st April and 30th November, and the results can be seen in Table

	2012	2013	2014	2015	2016	2017
SUM HDD [day]	2180	2188	2146	2118	2099	2309

Table 7.2. Sum of HDD during the last 6 years in Temuco

To fulfill the demand in the city, the coldest year is selected for the sizing, which is the year with the most HDD. Thus the year of 2017 is selected to the further calculations.

The yearly heat demand is distributed to every hour of the day based on the amount of HDD in the given hour, as HDD shows with how many °C the temperature was above the base temperature in the given hour, consequently determine the needed heat. The hourly space heating demand can be seen on Figure 7.1.

[1] The average of 10-50 GJ/hab in the documents stands for the space heating demand, which is 16.22 GJ/hab in Temuco

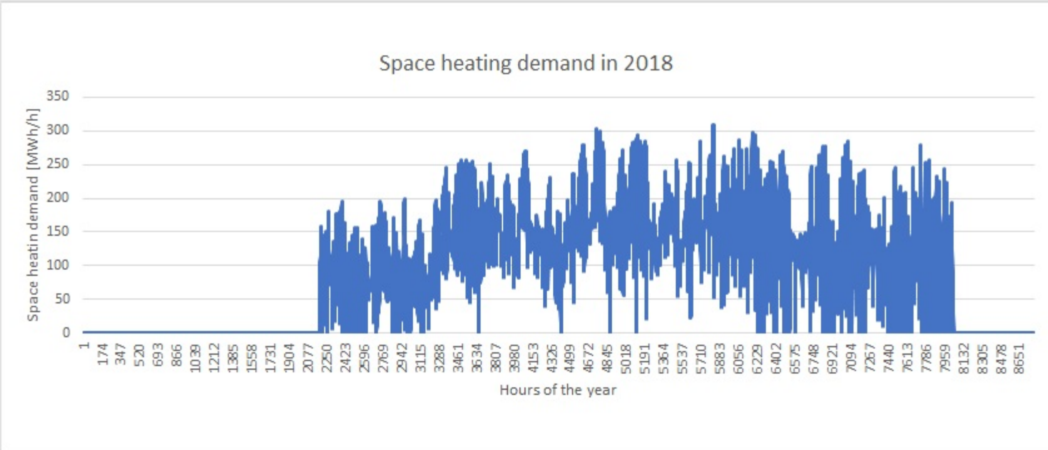

Figure 7.1. Space heating demand in 2018

The DHW demand does not depend on the outside temperature, but follows the habit of people. While using the consumption pattern - introduced in Chapter 5 -, the demand for every hour of the year is calculated.

The total hourly demand is the sum of the space heating and DHW demands, and the distribution can be seen on Figure 7.2.

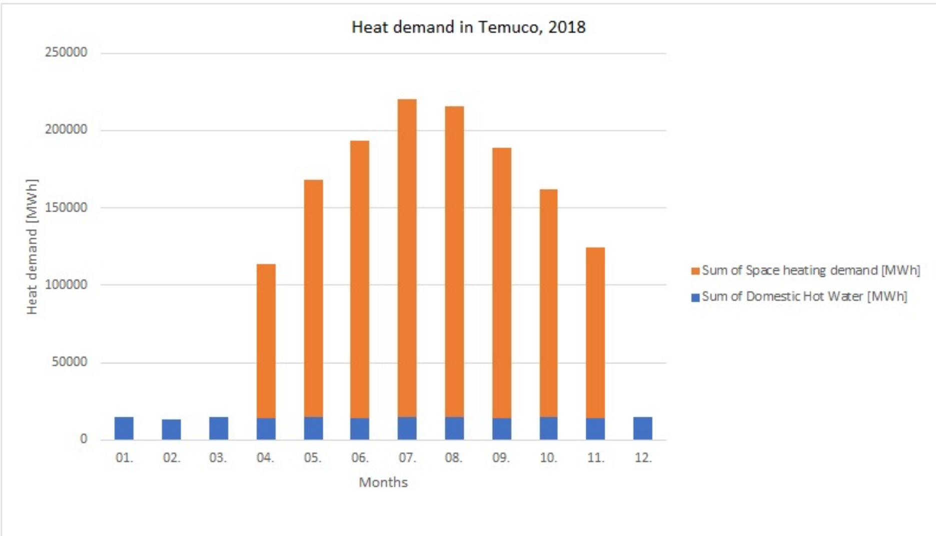

Figure 7.2. Heat demand in 2018

For the sizing an important value is the maximum heat demand, which is 530.91 MWh.

7.2 Future Demand

Forecasting the future demand is a hard task, as it depends from several factors like, growth of population, future building mix, economic situation of the habitants, etc.

The assumptions were made that the new houses will be built with the current housing standards, and the average house size will stay the same as today. According to [Cárdenas et al., 2011], with the refurbishment of old houses, an average of 30% heat saving can be achieved. The annual population growth is 1.58%. With the previous conditions, the heat demands of the different categories was calculated, which can be seen on Table 7.3.

Construction of houses	State	Consumption/per house [kWh/year]
before 1976	Not-refurbished	14341.01
	Refurbished	10038.71
1977-2000	Not-refurbished	14341.01
	Refurbished	10038.71
2001-2007	Not-refurbished	8508.29
	Refurbished	
after 2007	Not-refurbished	5939.75
	Refurbished	

Figure 7.3. Heat consumption of the different type of houses

As it was stated in the Methodology, 2 eventualities are carried out to make the study more valuable by making technical solution for different future alternatives. Additionally the difference between the 2 alternatives is aiming to show the importance of retrofitting.

7.2.1 Demand of the Large saving alternative

In the first alternative, higher share of houses - introduced in Chapter 5.5.2 - are assumed to be replaced and refurbished by 2028, 2038 and 2048. If the refurbishments and replacements follow the prediction of the alternative, the building stock will look like as it stands in Table 7.3:

		2018		2028		2038		2048	
Construction of houses	State	Number of houses	Percentage in house stock	Number of houses	Percentage in house	Number of houses	Percentage in house stock	Number of houses	Percentage in house stock
before 1976	Not-refurbished	38,475	40.7%	28,856	26.1%	19,237	14.9%	9,619	6.4%
	Refurbished	-	0.0%	3,206	2.9%	6,412	5.0%	9,619	6.4%
1977-2000	Not-refurbished	42,445	44.9%	31,834	28.8%	21,223	16.4%	10,611	7.0%
	Refurbished	-	0.0%	3,537	3.2%	7,074	5.5%	10,611	7.0%
2001-2007	Not-refurbished	12,100	12.8%	12,100	10.9%	12,100	9.4%	12,100	8.0%
	Refurbished	-	0.0%	-	0.0%	-	0.0%	-	0.0%
after 2007	Not-refurbished	1,513	1.6%	31,043	28.1%	63,297	48.9%	98,736	65.3%
	Refurbished	-	0.0%		0.0%	-	0.0%	-	0.0%
Total		94,533		110,577		129,344		151,297	

Table 7.3. House stock in the future - Large saving alternative

Applying the previously calculated average demands for the house stock, the projected future demands for Temuco can be seen in Table 7.4.

	2018	2028	2038	2048
Space heating [MWh/year]	1,272,414	1,225,395	1,194,550	1,182,625
DHW [MWh/year]	171,700	200,841	234,928	274,800
Total demand [MWh/year]	1,444,114	1,426,237	1,429,479	1,457,425

Table 7.4. Future demands - Large saving alternative

7.2.2 Demand of the Medium saving alternative

In the second alternative, a yearly 1% of replace and refurbishment is projected, consequently the building mix will develop as follows in Table 7.5.

		2018		2028		2038		2048	
Construction of houses	State	Number of houses	Percentage in house stock	Number of houses	Percentage in house stock	Number of houses	Percentage in house stock	Number of houses	Percentage in house stock
before 1976	Not-refurbished	38,475	40.7%	30,780	27.8%	23,085	17.8%	15,390	10.2%
	Refurbished	-	0.0%	3,847	3.5%	7,695	5.9%	11,542	7.6%
1977-2000	Not-refurbished	42,445	44.9%	33,956	30.7%	25,467	19.7%	16,978	11.2%
	Refurbished	-	0.0%	4,245	3.8%	8,489	6.6%	12,734	8.4%
2001-2007	Not-refurbished	12,100	12.8%	12,100	10.9%	12,100	9.4%	12,100	8.0%
	Refurbished	-	0.0%	-	0.0%	-	0.0%	-	0.0%
after 2007	Not-refurbished	1,513	1.6%	25,649	23.2%	52,508	40.6%	82,552	54.6%
	Refurbished	-	0.0%		0.0%	-	0.0%	-	0.0%
Total		94,533		110,577		129,344		151,297	

Table 7.5. House stock in the future - Medium saving alternative

When applying the previously calculated average demands for the house stock, the projected future demands for Temuco can be seen in Table 7.6.

	2018	2028	2038	2048
Space heating [MWh/year]	1,272,414	1,264,915	1,273,590	1,301,184
DHW [MWh/year]	171,700	200,841	234,928	274,800
Total demand [MWh/year]	1,444,114	1,465,756	1,508,518	1,575,984

Table 7.6. Future demands - Medium saving alternative

7.2.3 Identification of suitable areas

As it was introduced in Chapter 5.5.3, a minimum heat density is needed to for the implementation of DH system. According to [Heat Roadmap Europe, 2016], current district heating technology requires heat demand densities above 100 TJ/km^2, so the identification of suitable areas are needed.

For the density calculation, the city of Temuco was divided to 91 micro-zones, following the city plan provided by the Municipality of Temuco.

From the size of the micro-zones and the current population, the density of each sector was calculated, and with the help of the previously calculated building heat demands, the heat densities of each zones are defined. According to the calculation, currently 49 micro-zones have suitable density for the district heating system, with the heat demand of 1,266,496 MWh/year, representing 88% of the households.

When calculating the future population density another factor has been taking into account, which is the uneven population growth. Although the total population of Temuco is growing with 1.58%, but according to [Municipalidad Temuco, 2015a], the arriving new population tends to settle down in the outer parts of the city - in the currently less dense areas-, which is also supported by the city planners, who aims for decentralization [Municipalidad Temuco, 2015a]. This means that the population growth is not steady in every district of the city, thus the estimation was made, that in the already dense areas, only 0.5% annual population growth will be realized. The peripheral densification can be seen on Figure 7.4.

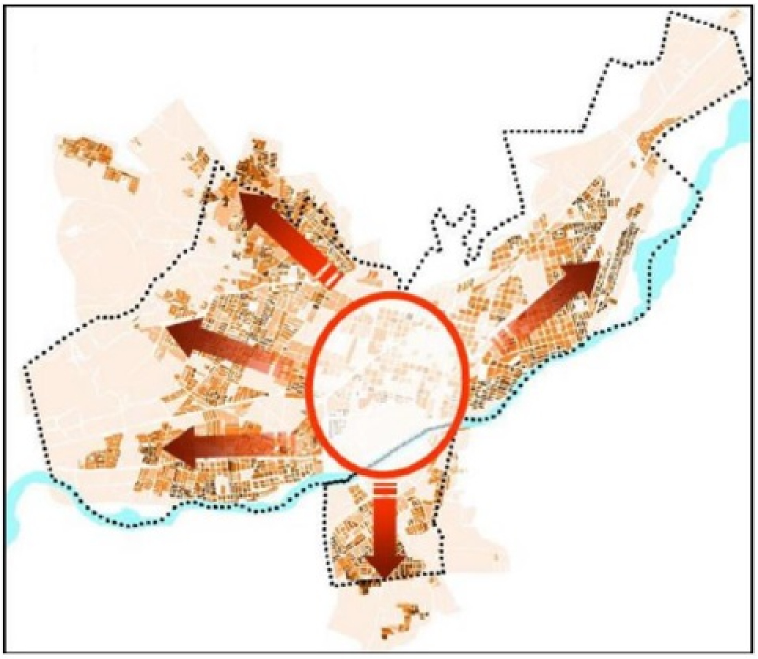

Figure 7.4. Peripheral densification [Municipalidad Temuco, 2015a]

Taking this criteria into consideration, the heat demand shows decrease during the next 30 years in the micro-zones which have high density today. Consequently, in the Large saving alternative, 43 districts - with the heat demand of 955,442 MWh/year-, and in Medium saving alternative, 46 districts - with the heat demand of 1,073,161 MWh/year - have the sufficient heat density for DH.

7.2.4 Sizing of the system

To avoid the over-sizing of the system - due to the decreasing demand -, the system is sized for the future demand of 2048. As it was explained in Chapter 5.5.4, this means that in 2048 all the districts with sufficient demand will be part of the system, but - because their demand is bigger today than it will be in the future-, not all of them can be added to the system immediately, at the start of the project.

As it was explained in Chapter 5.5.4, the zones will added to the system in 4 phases - 10 years apart from each other -, starting in 2018 and finishing in 2048.

Large saving alternative

In the first alternative 43 districts pass the criteria of density, and their total demand is 955,442 MWh/year, thus this is will be the demand for which the system will be sized. If we examine how many districts can 'fit under' the limit in 2018 (as it was explained, the districts with the highest densities are connected), the result is 31, with the total demand of 945,857 MWh. These districts has the minimum of 182 TJ/km^2 density, and will be added to the system in Phase 1.

In 2028, 3 more districts are connected in Phase 2., resulting the heat demand of 938,025 in the system. (The demands of the individual districts are decreasing, that is the reason why new districts can be added to the system.) The density of these districts are higher than 162 TJ/km^2.

In 2038 at Phase 3, 2 more districts can be connected with the system, raising the total demand (compared to the demand without the 2 districts) to 927,513 MWh. The density of these districts are higher than 143 TJ/km^2.

At last, in 2048 the last 7 districts are connected to the system, which will reach its total demand of 955,442 MWh in that year. The phases of connections can be seen on Figure 7.5 and in bigger size in the Appendix A.3.

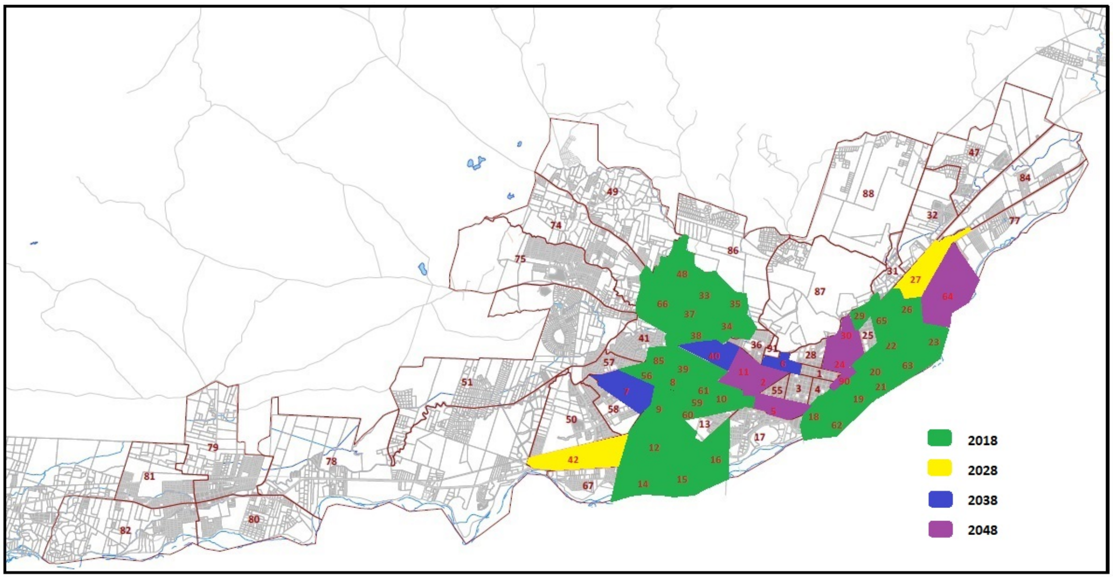

Figure 7.5. Zones connected to the DH system during the 4 phases - Large saving alternative

Medium saving alternative

In the second alternative, the demand decreases with lower pace - due to the smaller saving from replacement and refurbishment. The sizing is the alternative follows the same analogy as the first one, and 46 districts pass the criteria of density in 2048, with the total demand of 1,073,161 MWh/year.

In 2018, the most dense 35 districts can 'fit under' this limit with the total demand of 1,042,929 MWh. These districts has the minimum of 169 TJ/km^2 density, and will be added to the system in Phase 1.

In 2028 at Phase 2, 1 more districts can be connected to the DH, while raising the total demand to 1,034,356 MWh. The density of these districts are higher than 159 TJ/km^2.

At Phase 3, in 2038 , 4 more districts can be connected with raising the total demand to 1,068,395 MWh. The density of these districts are higher than 135 TJ/km^2.

At last, in 2048 the last 6 districts are connected to the system, which will reach its total demand of 1,073,161 MWh in that year. The phases of connections can be seen on Figure 7.6 and in bigger size in the Appendix A.4.

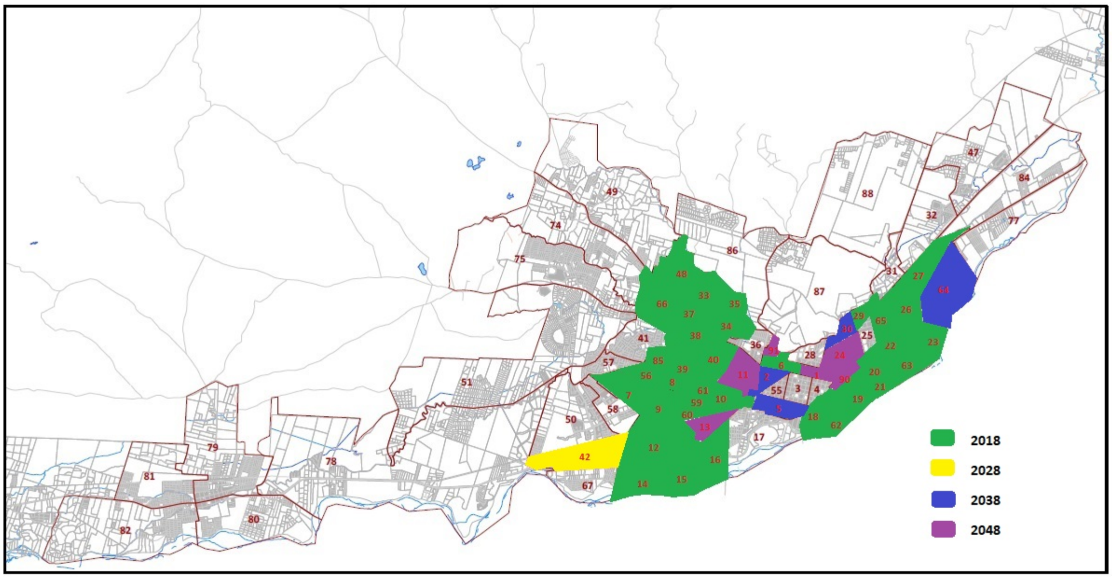

Figure 7.6. Zones connected to the DH system during the 4 phases - Medium saving alternative

The number of connected houses for both alternatives can be seen in Table 7.7.

	2018	2028	2038	2048
Alternative 1	61,917	69,596	78,356	92,381
Alternative 2	68,271	74,543	84,834	93,953

Table 7.7. Number of connected houses

It is to be noted, that the 'shape' of the DH systems is analogous with Figure 7.4 from [Municipalidad Temuco, 2015a], about peripheral densification.

After identifying the districts which will be connected during the 4 phases of implementation, the yearly heat demands of the system is known for both alternatives. Following the same analogy as used for calculating the current hourly distribution for Temuco, the hourly heat demands - sum of the space heating and DHW demand - are calculated, and used as input for the modelling of different DH scenarios.

Summary and result of the section

In this chapter, the current and future heat demands were calculated to identify the suitable districts for the DH system and the distribution of hourly demands, which gives answer to Sub-question 1.

Conclusion can be drawn that there are zones in the city with high enough heat density, with decreasing heat demand during the next 30 years. In the Large saving alternative, 31 districts are connected to the system in 2018 -with the demand of 955,442 MWh/year-, followed by 3, 2 and 7 additional ones during the next phases. In the Medium saving alternative, after the initial 35 districts, 1, 4 and 6 more districts are connected.

Reference supply system 8

As it was introduced before, the reference scenario is not the current system in Temuco, but the one which the municipality would like to achieve with its stove replace programs.

In the program, the participants can choose between wood stoves - with high efficiency-, kerosene, or pellet stoves. Currently, the beneficiary pays around 100 USD of the cost, the rest is payed by the budget of the program [Dittborn, 2017]. In the current program different stoves are available within the 3 main types, but one from each fuel type is used to calculate the needed investment costs, and emissions.

From a report made by the Ministry of the Environment of Chile, the share of the different technology is known, resulting to the 16224 replaced stoves countrywide [Dittborn, 2017]. The shares of the 3 technology can be seen on Figure 8.1.

	Stove exchange so far [nbr]	Percentage
Wood stove	10090	62%
Pellet Stove	3977	25%
Kerosene Stove	2157	13%
Total	16224	

Figure 8.1. Number of already replaced stoves in Chile [Dittborn, 2017]

From [Gómez et al., 2017], the stoves used in the current program are known, thus one from each category is chosen to calculate the investment cost and the emissions connected to the new stoves. The chosen models are summarized in Figure 8.2.

Fuel type	Model	Heating capacity [kW]	Efficiency	Emission factor [g/MWh]	Full Price [EUR]
Wood	Estufa a Leña Amesti Nordic	8.2 kW	76%	82.8	719
Pellet	ESTUFA AMESTI A PELLET	6.3 kW	89%	32.4	1439
Kerosene	Toyotomi MODELO: FF-55	5.5 kW	93%	75.6	1167

Figure 8.2. Efficiency and price of included stoves [Gómez et al., 2017]

In the reference supply scenario(s), the 'extended version' of the current exchange program is modelled, where the replacement reaches the same amount of households as the DH supplies in the 2 alternatives. In the scenario, the government's one time investment - payed as subsidy - is calculated to compare it to the investment cost of the DH scenarios.

The calculations of O&M and fuel costs are not part of the reference supply system, as those associated costs are payed by the consumers.

As the reference scenario is used to compare the investment cost and emissions, thus the assumption is made that all the replacement will be done in 2018.

From [Universidad de Chile, 2014], the associated social cost for 1 tonnes of PM2.5 emission is 31,477 EUR, which is reasonable if we compare it to the data from EU countries [AEA Technology Environment , 2005].

8.1 Large saving alternative

In this alternative, the district heating system reaches 61,917; 69,596; 78,356 and 92381 households in 2018, 2028, 2038 and in 2048.

Investment cost

If the stove replacement affect the same amount of households and the share of the 3 replacement technology will be as from until today, the total investment cost for replacing the households' wood-stoves is 88,234,754 EUR.

This cost is valid, if all the stoves are replaced in 2018. The price could show big differences if the introduction of stoves last for long years.

Emissions and connected external cost

The calculation of emissions happened in 4 stages, as the different districts are connected to the DH system. In the first 10 years, the yearly emission from the new stoves are account for 65.72 tonnes of PM2.5, which is 657.26 tonnes during the first 10 years. In the second period, yearly 65.18 tonnes of PM2.5 will be emitted, while in the third, yearly 64.45 tonnes. This means, 1,953.59 tonnes all together in the next 30 years.

When calculating the external environmental costs of the emission with the data given for Temuco, it means yearly average of 2.05 million EUR in every year, and total 61,494,507 EUR during the next 30 years.

8.2 Medium saving alternative

When applying the projected energy savings and population growth of the Medium Saving alternative, the district heating system reaches 68,271; 74,543; 84,834 and 93,953 households during the 4 phases of implementation

Investment cost

Similarly to the first alternative, the stove replacement affect the same amount of households and the share of the 3 replacement technology is the same, the total investment cost for replacing the households' wood-stoves is 89,736,490 EUR.

Emissions and connected external cost

Following the same 4 phases as previously, the yearly emission from the new stoves are account for 72.47 tonnes of PM2.5 during the first 10 years. In the second period, yearly 71.87 tonnes of PM2.5 will be emitted, while in the third, yearly 74.24 tonnes. This means, 2,185.88 tonnes all together in the next 30 years.

When calculating the external environmental costs of the emission with the data given for Temuco, it means yearly average of 2.30 million EUR in every year, and total 68,806,437 EUR during the next 30 years.

As one of the aims to calculate 2 different alternatives is to show the effect of refurbishment and replacement of houses, it can already be seen that the first alternative results to 11% less total PM2.5 emissions as the second one.

It is important to note, that if not all the replacements are done in 2018, the emissions would be even higher in both alternatives, considering the currently used inefficient stoves.

The summary of investments, emissions, and external costs can be seen in Table 8.1.

	Investment for stove replacement [EUR]	Total PM 2.5 emission [ton]	Total External cost of PM [EUR]
Alternative I.	88,234,754	1,953.59	61,494,507
Alternative II.	89,736,490	2,185.88	68,806,437

Table 8.1. Investments, emissions and external costs of alternatives

Summary and result of the section

In this chapter, the investment cost and emissions of the reference scenarios was introduced, which gives answer to Sub-question 2.

The conclusion is that the Government needs to invest around 90 million EUR to reach 92-94,000 households in the city during the extension of the stove replacement program, as a one time investment or subsidy.

During this extension, significant amount of PM2.5 emission cut back could be reached, but the yearly emission would still be around 65 tonnes, responsible for 61 and 68 million EUR external cost.

Resources and included technologies 9

This chapter gives a brief introduction of the DH components been used during the modelling, with the cost of the different technologies and fuel resource potentials.

In a DH system the heat is transported from the production unit - through the distribution system - to the end users, consequently these 3 parts are the most important components of the system.

The heat production units extract energy from the resources to supply energy for the city. The resources can be fossil fuel based - coal, or natural gas- or local renewable sources like biomass, solar or geothermal, which can contribute to cut back emissions.

The calorific energy is transported by water through the transmission line and distribution system, consists of isolated pipelines. During the system, different substations are used to lower temperature and pressure until the water arrives to the house appliances, where it is used for space heating or DHW production. In the system, the heated water can also be stored in hot water tanks, to cover future demands.

9.1 Available resources

As the used technology depends on the available resources, the evaluation of local resources is the first step in the process. The Municipality of Temuco made its Energy Strategy [Suiza, 2016] in 2016, in which the researchers collected the locally available resources, which are biomass, solar and geothermal energy. Following this document, these 3 resources were examined further.

9.1.1 Biomass

In the region, several sources of potentially usable biomass were identified by a study made by the Ministry of Environment, and provided by Eduardo Araneda, the Coordinator of Local Energy Strategy in Temuco. The study identified post-harvest residue of pine and eucalyptus plantations, the native forest and the sawmill industry as the main sources of biomass in the region [Schüler, 2014].

The total available biomass within 90 km of Temuco is 1,075,657 tonnes per year, and the share can be seen on Figure 9.1.

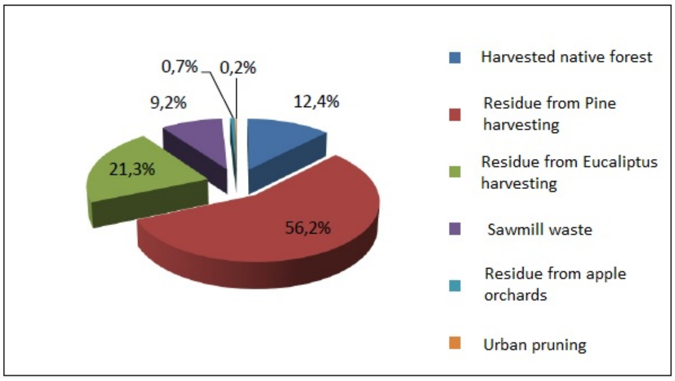

Figure 9.1. Dispersion of available biomass in the region [Schüler, 2014]

The biggest potential is in pine residues, 604,275 tonnes per year, which is the byproduct of the paper and saw industries. According to [Schüler, 2014], most of the residue is left in situ, as currently does not worth to collect it, although, this residues could be the fuel of the future heat production units. According to the study, this residue has the calorific value of 3.4 MWh/ton and would have the price of 58.77 EUR/ton.

9.1.2 Geothermal energy

Chile has high geothermal potential, with an estimated capacity between 3000 and 16,000 Mwe [Payera, 2018]. The region of Araucanía is one of the six areas for high enthalpy geothermal, with a great potential for production [Aravena et al., 2016].

Even though the solution is not widely used today, the Government of Chile - as part of the Clean Technology Fund (CTF) - supports a risk mitigation program in the geothermal exploration stage. These funds are aiming to encourage developers to make the necessary investments to carry out drilling and construction of plants. The support can include priority loans and long-term subordinated loans, short-term bridge loans, and guarantees in case of exploration failure [Ministerio de Energia, n.d.a].

According to [Universidad de Chile, 2014], Temuco has favorable condition for the use of geothermal energy, with the potential of 1,534,270 MWh/year.

9.1.3 Solar energy

In Temuco, the yearly average of horizontal global solar radiation is 1,405 kWh/m^2, which is considered as good potential [Suiza, 2016]. The comparison of the radiation in Temuco with other cities can be seen on Figure 9.5.

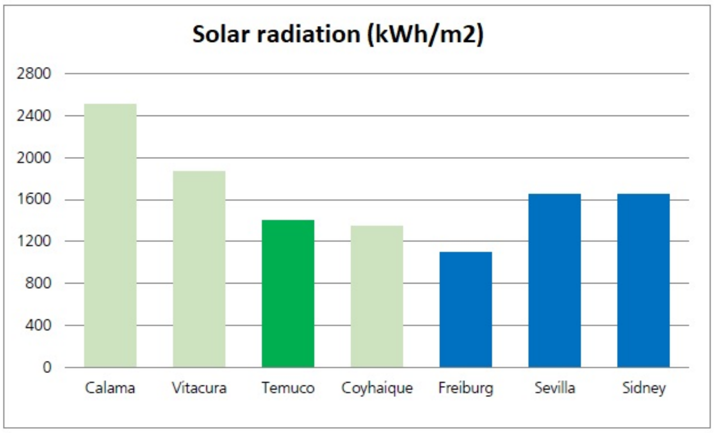

Figure 9.2. Horizontal radiation in different cities in Chile and the world [Suiza, 2016]

All the tree renewable sources have good potential for heat generation, consequently all of them will be used in the proposed scenarios.

9.1.4 Electricity

Nowadays, the heating and electricity sectors are not separate entities from each other, but have several interconnections between them. Technologies like CHP and heat pumps are the links between the systems, thus electrically driven technologies can supply heat, and cogeneration plans can sell their produced electricity to the spot market.

Since the price of electricity is not constant during the year, the knowledge of the hourly electricity price is necessary. The used data is accessed from [National Energy Commission, 2018b], but only the locational marginal prices were available in hourly distribution - otherwise monthly average price is accessible from [National Energy Commission, 2018a]-, which increase inaccuracy in the calculations, as the offer prices and the spot market price are higher than the marginal price.

9.2 Included parts and used technologies

As it was introduced, the most important parts of the DH system are the heat generation unit(s), the distribution system, heat storage, substations and house appliances. During the study, the heat generation units and heat storage are properly sized and modelled with EnergyPRO, the distribution system with substations and home appliances are not sized as the detailed design of the system is not the within the scope of the research, and could be a topic for a whole study by itself. About these parts, high level estimates are made to get an estimate about their investment and O&M costs.

9.2.1 Heat production units

CHP plant

CHP plants are suitable and widely used in DH systems, as the cogeneration of electricity and heat makes it more favorable than single purpose units. This advantage can be originated in the higher efficiency, which has it economic and environmental consequences/benefits [Frederiksen and Werner, 2014]. According to [European Comission, 2016], modern CHP plants can have 30% primary energy saving, compared to the separate generation of heat and electricity.

In most CHPs, the electricity generation is considered the primary process, while the delivered heat is categorized as secondary/added value. Another advantage of the technology is the flexibility, as the plant does not need to run on full capacity all the time - although that is the economically most beneficial operation-, and the regulation time is usually low [Danish Energy Agency, 2012].

As the CHP needs to supply a big heat load, back-pressure steam turbine CHP plant is used, which is suitable for the large load, and gives flexibility on fuel. For the DH in Temuco a biomass boiler with flue gas heat recovery - which increases the efficiency of the boiler - is chosen [Frederiksen and Werner, 2014]. The chosen technology is large CHP, running on wood chips, the installed capacity will be determined in the scenarios, based on the load share and operation strategies.

The summary of technical data and costs can be seen in Table 9.1. It has to be noted, that most of the connected costs were obtained from the official documents from the Ministry of Energy [Ministerio de Energia, 2018] in Chile (not just the CHP but all other technologies), the Danish Technical Catalogues is used when data from Chile is not available, which will be stated all time when it occur. The cost of wood chips is from [Schüler, 2014].

Technical data	
Electrical efficieny [%]	27.9%
Heat efficiency [%]	83.5%
Lifetime [years]	30
Minimum load [%]	40.0%
Warm start-up time (hours)	2
Cold start-up time (hours)	12
Particles (g per GJ fuel)	0.3

Financial data	
Capital investment [M€/MWe]	2.679
Fixed O&M [€/MWe/year]	80381
Variable O&M [€/MWh_e]	4.3
Woodchips cost [€/ton]	58.773

Table 9.1. Technical and Financial data for CHP [Danish Energy Agency, 2018a], [Ministerio de Energia, 2018], [Schüler, 2014]

Boiler

A heat-only boiler, running on biomass is also an often used technology in DH systems. Modern boilers are flexible and can run on partial load [Frederiksen and Werner, 2014]. The boiler in the system is only used for supplying the peak demand, and to be the back-up in case of emergency situations with the other generation units. Consequently, a boiler with low investment cost would have been chosen - in case of available data -, which means lower efficiency, and higher O&M costs. As only data from the Danish Energy Catalogue were accessible, the costs of the boiler does not comply to this chosen type of boiler, as it is an efficient one, with low O&M cost.

The technical and financial data about the boiler can be seen in Table 9.2.

Technical data	
Efficieny [%]	114.9%
Lifetime [years]	20
Minimum load [%]	20.0%
Particles (g per GJ fuel)	0.3

Financial data	
Capital investment [M€/MW]	0.7
Fixed O&M [€/MW/year]	32774
Variable O&M [€/MWh]	1
Woodchips cost [€/ton]	58.773

Table 9.2. Technical and Financial data for the Wood Chips Boiler [Danish Energy Agency, 2018a], [Schüler, 2014]

Electric heat pump

During its operation, heat pumps move heat from a lower temperature heat source to a higher temperature heat sink, while using electricity as source of energy [Danish Energy Agency, 2016]. Large scale heat pumps can be utilized in industrial processes and can fit good into DH systems. The Coefficient of Performance (COP) - the ratio between the energy transferred for heating and the electric input used during the process [Frederiksen and Werner, 2014] - is usually between 3 and 5 for compression heat pumps, but depends on the efficiency of the used heat pump and temperature difference between heat source and heat sink [Danish Energy Agency, 2016].

The technology has several advantages, like the incorporation of the electricity and heating systems - which can be an important element in the future smart energy system -, and the lack of emission from fuel burning, which makes it appealing in the city if Temuco. [1] Chile's aim for high share of renewable electricity production played role in the inclusion of the solution.

In the study, the technical parameters and costs were used from the Danish Technology Catalogue, with the COP of 3.5. The technical and financial data about the heat pump technology can be seen in Table 9.3.

Technical data	
Total net efficiency [%]	350.0%
Minimim load [%]	10.0%
Lifetime [years]	30
Particles (g per GJ fuel)	0

Financial data	
Capital investment [M€/MW]	0.7
Fixed O&M [€/MW/year]	2000
Variable O&M [€/MWh]	8.4
Fuel price [€/ton]	spot market price

Table 9.3. Technical and Financial data for Electric heatpumps [Danish Energy Agency, 2016]

Geothermal energy

The heat of the Earth from reservoirs can be directly utilized in a DH system through a ground source heat pumps [Danish Energy Agency, 2018b]. In the operation geothermal energy is utilized as a base load, for example covering around 30% of the DH demand. The heat pumps in the system can be heat or electricity driven, for this study an electric heat pump was chosen, as it provides more efficiency [Danish Energy Agency, 2018b].

The technical and financial data can seen in Table 9.4.

[1] It has to be noted, that in case of high fossil fuel share in the electricity generation mix, the use of electric heat pumps can lead to emissions at the place of the 'dirty' generation.

Technical data	
Heat generation capacity (% of heat input]	117.0%
Electrical demand[% of heat input]	17.0%
Lifetime [years]	30
Particles (g per GJ fuel)	0

Financial data	
Capital investment [M€/MW]	5.5099
Fixed O&M [€/MW/year]	37000
Variable O&M [€/MWh]	1.73
Fuel price [€/ton]	0

Table 9.4. Technical and Financial data for Geothermal energy [Danish Energy Agency, 2018b], [Ministerio de Energia, 2018]

Solar thermal production

The core of the technology is to collect solar radiation, and transfer it to thermal energy. The solar collectors heat up a special fluid - combination of water and antifreeze liquid - and the system delivers the heat directly to space heating and/or DHW, or to a thermal storage [Solar district heating, 2012].

During the calculations, stationary, flat plate collectors were used, as they considered cheap and they have high efficiency in DH systems [Frederiksen and Werner, 2014]. The choosen collector is made by Wagner Solar GmbH., and is called EURO L42 TS HTF [Institute for Solar Energy Research GmbH].

The technical and financial data can seen in Table 9.5.

Technical data	
Heat efficiency [%]	78.0%
Panel size [m2/panel]	2
Loss coefficient (a1) [W/ (m2 °C)]	3.86
Loss coefficient (a2) [W/ (m2 °C)2]	0.015
Lifetime [years]	30
Particles (g per GJ fuel)	0

Financial data	
Capital investment [M€/MW]	6.85
Fixed O&M [€/MW/year]	68539
Variable O&M [€/MWh]	0
Fuel price [€/ton]	0

Table 9.5. Technical and Financial data for Solar thermal [Institute for Solar Energy Research GmbH], [Ministerio de Energia, 2018]

9.2.2 Heat storage

When solar collectors are used in a DH system, the integration of a Thermal energy storage (TES) is necessary, and can increase the solar generation share in the system. The stored energy - from the solar collectors or from other generation units - can be used at later time, to fulfill the demand when the the production is not possible (the sun is not shining) - or more expansive [Frederiksen and Werner, 2014]. Additionally, in a DH system, CHP plants should have heat storage capacity to store the heat which can satisfy the weekly demand [Danish Energy Agency, 2018b].

According to [Danish Energy Agency, 2018b], storing heat in water tanks is the most cost-effective way of heat storage, although the challenges include the difficulty of insulation and required big size. Based on the size -and the connected capacity - one can distinguish between seasonal storage, large-scale and small-scale hot water tanks. In the study, sensible heat storage is used - stores thermal energy in liquid form without phase change -, as a short-term storage, to help the operation of solar thermal generation, to supply peak demands, to provide heat back-up and rapid heat access when it is needed.

The financial data can be seen in Table 9.6.

Financial data	
Capital investment [€/m3]	160
Fixed O&M [€/MW/year]	0
Variable O&M [€/MWh]	0

Table 9.6. Financial data for the Thermal storage [Danish Energy Agency, 2018b]

Prices from Chile were not available during the study, thus the Danish database was used for the calculations.

9.2.3 Distribution network

The distribution system transfers the heated water from the place of production to the end users. In the study 3rd generation DH is modelled, where the supply and return pipes are inside a common plastic jacket pipe.

The estimated size of the distribution network is made by the use of effective width method, introduced in Chapter 5.5.7. The length of the needed distribution system depends on the total land area and the total building space of micro-zones.

The accurate sizing of every pipes were not part of the study, as it exceeds the limitation of the project, and would require more technical calculations. Consequently, the price of the distribution pipes are an average price, based on the Danish Technology catalogue, and can be seen in Table 9.7.

Financial data	
Cap investment network [€/m]	548
Fixed O&M [€/MW/year]	0
Variable O&M [€/MWh]	1.5

Table 9.7. Financial data for the distribution system [Danish Energy Agency, 2017]

9.2.4 Substations and home connections

The design and sizing of these parts exceed the limits of the study. The number of substations were assumed to be the same, as the number of connected houses, an average cost of branch pipes per households are also included [Nielsen, 2014], while the price of home appliances are not included in the study.

The financial data for substations and branch pipes can be seen in Table 9.8.

	Financial data	
Substations	Cap investment substations [€/unit]	1900
	Fixed O&M [€/unit/year]	50
	Variable O&M [€/MWh]	0
Branch pipes	Cap investment branch pipes [€/house]	2280
	Fixed O&M [€/unit/year]	0
	Variable O&M [€/MWh]	0

Table 9.8. Financial data for Substations [Danish Energy Agency, 2012], [Nielsen, 2014]

District Heating Scenarios and emissions 10

For both alternatives - the 'Medium saving' and the 'Large saving'-, 3 different technological scenarios are made to supply the demand, which are:

- Scenario 1: Biomass scenario,
- Scenario 2: Heat pump scenario,
- Scenario 3: Mixed scenario, with the geothermal energy.

For the 2 alternatives the given scenarios are parallel with each other, they use the same technologies, follow the same criteria and operation strategy. Consequently the detailed description of the scenarios will be introduced with the 'Medium saving' alternative, and for the 'Large saving' alternative only the most important data and results are presented.

For all 6 scenarios, the following criterias are common:

- The aim in all scenario is to find the best assortment of the given technologies, while minimizing the investment and running cost of the system,
- The operation strategy aims to minimize the Net Heat Production Cost (NHPC),
- The solar thermal collectors are sized to cover most of the heat demand during the summer,
- The use of biomass boiler, which functions as a backup and peak load unit, should not exceed 5% regarding running time and total share of production,
- When included, CHP is only used during the heating season,
- When included, the number of turn-ons for the CHP plant should be optimized.

Even though, during the operation of CHP, heat production is a secondary process, but as the aim of the study is to secure the heat demand of the city, the operation of the unit is driven by the heat production in the models, and electricity is produced accordingly.

The calculation of heat price for all scenarios follows the market-based pricing principle, where the competitor - and currently used - technology is fire wood for space heating and natural gas for DHW [1]. For the calculations the average associated costs of fuel are included, 0.029 EUR/kWh for firewood and 0.165 EUR/kWh for natural gas. The

[1] Currently the households either use natural gas or electricity for DHW use, but there is no available data about the dispersion [Araneda, 2018], thus for simplicity, natural gas was used as the market competitor for DHW.

associated costs are multiplied by the average household consumptions, and adjusted with the average efficiency - assumed to be 40% [2]. Based on the calculation, the current effective heat price is 85.10 EUR/MWh. As the consumers are price sensitive, this price is set as the maximum heat price for the DH system. In the sensitivity analysis, the effects of lower and higher heat prices are assessed, as it is the main defining factor in revenues.

To calculate the NHPC, cost of the fuels, O&M costs and efficiencies of the different technologies are necessary inputs for the model, while for the economic calculations - introduced in Chapter 11 -, investment costs are also needed. The summary of technical details and needed costs were already introduced previously.

10.1 Scenarios for the Medium saving alternative

In the Medium saving alternative, the pace of the refurbishment and replacement is set to 1% per year respectively. Considering the changing demand of households and population growth, decreasing tendency is identified in the demand of the urban districts, thus the DH is sized to the future demand of 2048, and districts are connected in 4 phases to the system. From the projection, the yearly demand is known, which was distributed to hourly data with the help of the HDD method and DHW load pattern.

The most important hour during the year is the peak load hour, which means the hour with the biggest load during the year. In this alternative the peak demand is 445.33 MWh, which is the determining factor during the sizing of the system. As the biomass boiler is used in every scenario as the back-up capacity, the capacity of the boiler in every scenario is 455.33 MW, to be able to supply the heat demand in case of emergency.

10.1.1 Biomass Scenario

The Biomass scenario consist of a biomass CHP plant, biomass boiler, solar thermal production - as all the scenarios - and a thermal storage. The capacities of the elements can be seen in Table 10.1

System component	Characteristic
CHP heat capacity [MW]	265
CHP electric capacity [MW]	88.5
Boiler capacity [MW]	445.3
Size of thermal storage [m3]	40000
Solar thermal area [m2]	100000

Table 10.1. Elements of the system

In the scenario the CHP is the main heat producer, the boiler is used to cover peak demands and give backup to the system, and the solar thermal aims to cover the hot water demand during the hot months. The CHP also generates electricity, which is sold at the wholesale market. The unit also able to deliver heat to the heat storage, as well as the solar thermal generation.

[2]As the age and condition of the stoves vary in the city, and no statistical data is available, the 40% efficiency was chosen after discussion with the supervisor of the thesis. As it will be pointed out later, this assumption considered crucial regarding the result of the model.

The operation strategy aims to prioritize the available generation by the NHPC, and satisfy the needed demand starting with the cheapest technology. The production cost of the solar thermal and the boiler is constant - effectively 0 EUR/MWh [3] and 16 EUR/MWh respectively, as they use the same resources all the time when they produce. In case of the CHP the cost changes over time, based on the price of the sold electricity. The NHPC for the different technologies can be seen on Figure 10.1.

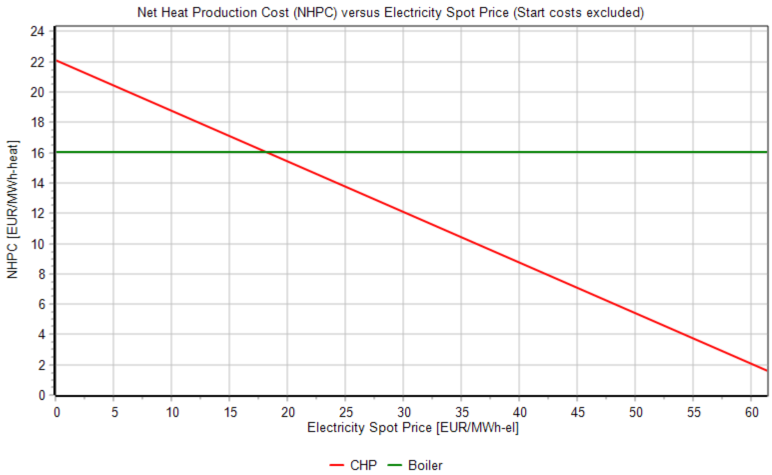

Figure 10.1. Net Heat Production Cost of the used technologies

The sizing of the different technologies follows the main criterias of maximum utilization for the boiler, and the summer DHW coverage from the solar generation. Consequently, the CHP has 265 MW of installed heat capacity, which covers 91.2% of the demand, while the boiler and solar thermal corresponds to 4.9 and 3.9%. The overview of the yearly production can be seen in Table 10.2.

Generation unit	Heat production [MWh/year]	Production share [%]
CHP	1,124,424	91.2%
Boiler	60,998	4.9%
Solar thermal	47,996	3.9%
Total	1,233,417	

Table 10.2. Annual heat production

The duration curve of the scenario shows the effect of the thermal store, as the production does not match the demand in every hour of the year, it is occasionally bigger, or lower. In this sense, the storage allows peak shifting to periods when the solar technology can produce, or to hours when the generation from CHP is more viable. The duration curve can be seen on Figure 10.2, and the effect of the storage in a typical winter week on Figure 10.3.

[3] There is no associated fuel cost for solar generation, the production cost only consist the variable O&M cost.

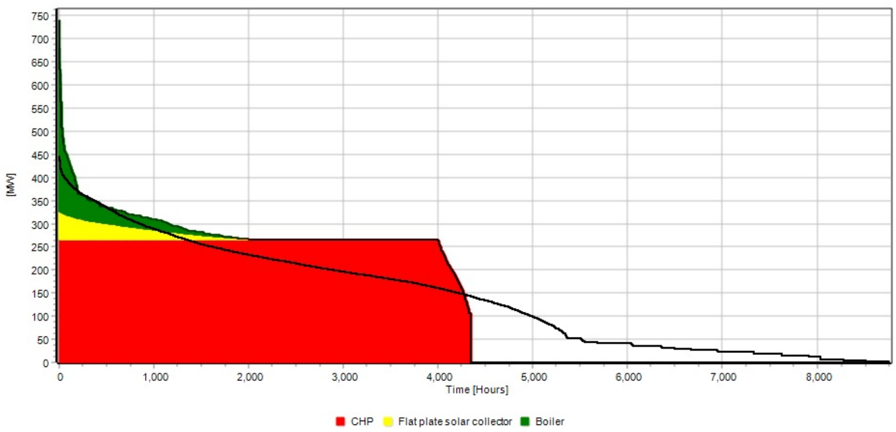

Figure 10.2. Duration curve during the first year of the project (2018)

During the operation, the CHP and boiler uses 396,103 tonnes of biomass as fuel, which is below the availability of pine residue nearby Temuco. While burning biomass, the units emit 1.65 tonnes of PM2.5, and 2333 tonnes of CO_2.

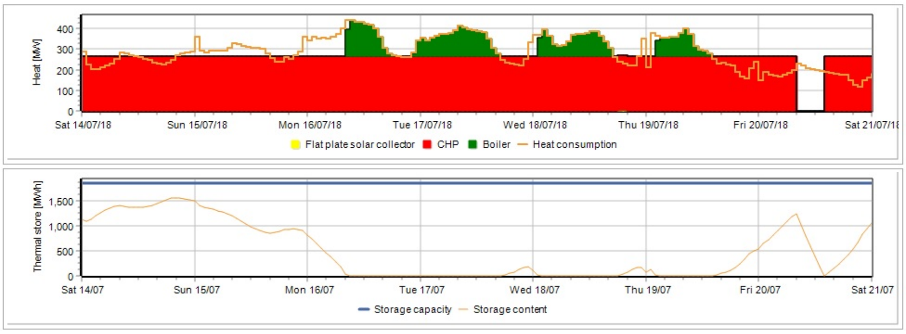

Figure 10.3. Heat production of different units and storage use during a winter week

It has to be noted, that the electricity production of CHP means additional emission cut back, as it can replace the generation of more polluting fossil fuel generation. The gain depends on the all-time actual emission factor of the total electricity generation in the region, which calculation exceeds the limit of the study, but can be a step during the future work.

10.1.2 Heat pump Scenario

In this scenario, industrial electric heat pumps cover the base load of the system - with COP of 3.5 -, while the capacity of the boiler and solar thermal are the same as in the previous scenario. Consequently the size of the heat pump station is determined by the limitation of the peak boiler, and occurs to be 225 MW. The capaticies of the included elements can be seen in Table 10.3.

System component	Characteristic
Electric heat pump capacity [MW]	225
Boiler capacity [MW]	445.3
Size of thermal storage [m3]	40000
Solar thermal area [m2]	100000

Table 10.3. Elements of the system

Difference from the previous scenario is that the heat pump runs on electricity, and does not generate electricity as the CHP before. Thus, the NHPC of the technology follows the increase of the electricity spot market price, which can be seen on Figure 10.4.

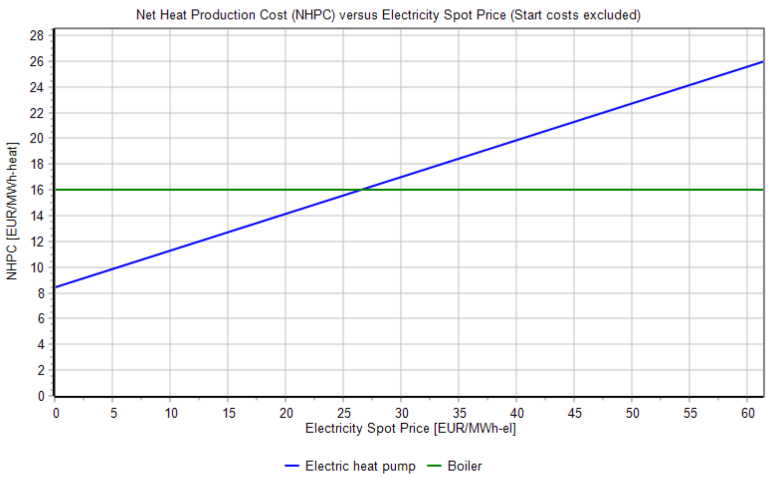

Figure 10.4. Net Heat Production Cost of the used technologies

As it can be seen from the Figure, there are hours when production from the boiler would be favorable, but because of the pre-set conditions, the priority of the utilization was set to be low, thus production from the unit occur only at times, when the heat pump can not cover the demand.

The overview of the yearly production can be seen in Table 10.4.

Generation unit	Heat production [MWh/year]	Production share [%]
Electric heat pump	1,125,672	91.3%
Boiler	59,750	4.8%
Solar thermal	47,996	3.9%
Total	1,233,417	

Table 10.4. Annual heat production

As the biomass use is significantly lower than in the previous scenario, the availability does not set a limit to the use neither in this situation, the connected PM and CO_2 emissions are also significantly lower, 0.43 tonne and 87 tonnes per year.

It has to be noted that the use of electricity as a resource does not mean 0 emission, just the 'move' of emission (or hiding of emission), as it occurs at the place of the production.

The energy mix of the electricity production defines the actual rate of emission, which - as it was also stated in the previous scenario - exceeds the limit of the study.

10.1.3 Mixed Scenario

In this scenario, several generation units are working together to satisfy the hourly demands. A geothermal heat plant is included and aims to cover base demand during the year. Other included technologies are biomass CHP, biomass boiler and solar thermal, the configuration of the scenario can be seen on Figure 10.5, and the capacities in Table 10.5.

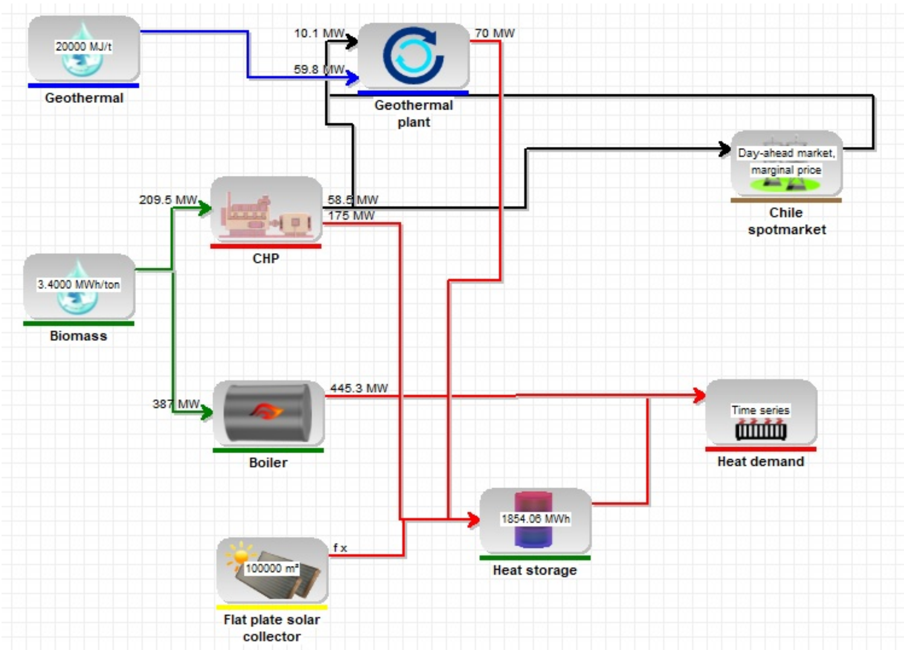

Figure 10.5. Configuration of the scenario

As it can be seen on the Figure, the CHP, the geothermal plant and the solar thermal generation are allowed to produce for storage. The geothermal plant uses electric driven technology to utilize the high geothermal potential of the region. The used electricity can directly come from the CHP, or from the electricity market. The characteristics of the units can be seen in Table 10.5.

System component	Characteristic
CHP heat capacity [MW]	175
CHP electric capacity [MW]	58.5
Boiler capacity [MW]	445.3
Geothermal capacity [MW]	70
Size of thermal storage [m3]	40000
Solar thermal area [m2]	100000

Table 10.5. Elements of the system

Similarly to the previous scenarios, the NHPC determines the priority of the utilization, and the summary for the used technologies can be seen on Figure 10.6.

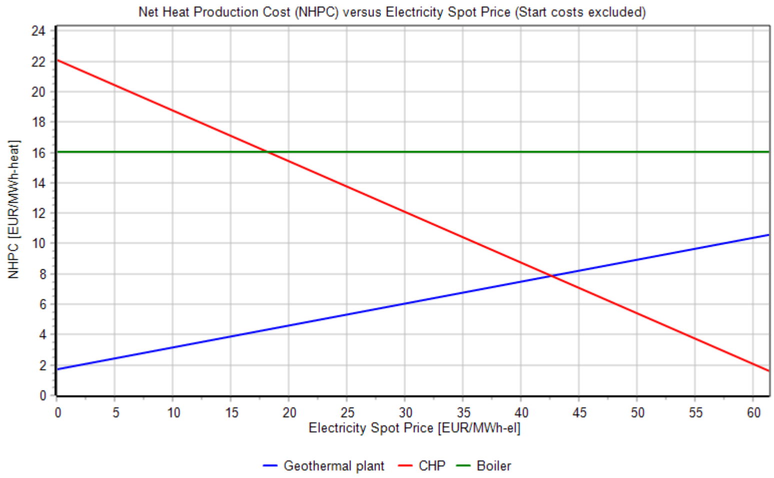

Figure 10.6. Net Heat Production Cost of the used technologies

From the Figure, it can be seen that the production cost of the boiler is constant - like in all scenarios -, the production cost of the geothermal is connected to the increase of the electricity price, while the CHP is getting more beneficial with the incremented electricity price. This means, that in most hours, the geothermal production has the highest priority, which changes in the hours when the spot market price is higher than 43 EUR.

During the sizing, the balance between the CHP and geothermal generation was aimed, with the later technology covering around 30% of the total yearly demand, as recommend in [Danish Energy Agency, 2018b]. The overview of the yearly production can be seen in Table 10.6.

Generation unit	Heat production [MWh/year]	Production share [%]
CHP	785,013	63.6%
Boiler	51,305	4.2%
Geothermal	349,104	28.3%
Solar thermal	47,996	3.9%
Total	1,233,417	

Table 10.6. Annual heat production

The importance of the storage can be seen from Figure 10.7, where a typical winter week is presented. The sizing of the generation unit is essential, as it can be seen that the CHP and geothermal plant is running on full capacity, and the boiler is only turning on when the thermal store is empty. In the hours of lower demand, the CHP can generate to the storage, to avoid the use of the boiler the next days.

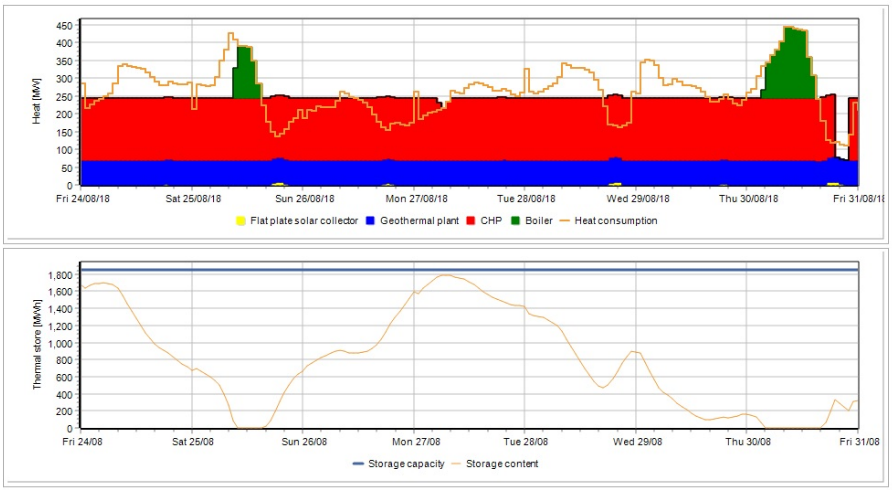

Figure 10.7. A typical week in winter, with production units and storage content

Emission occur from the CHP and the boiler, while burning biomass, and adds up to 1.22 tonnes of PM2.5, and 1640 tonnes of CO_2 during the year.

10.2 Scenarios for the Large saving alternative

As it was introduced, the scenarios are made in analogy with the respective scenarios for the Medium saving alternative, as the aim of this alternative is to analyze the effect of higher heat saving, so consentaneity is the driving aim.

In this alternative higher heat savings are reached with more refurbishment and replacement in the housing stock, consequently the total yearly and the peak demand are lower. The peak during the year is 393.52 MWh, thus this is the determining factor in the sizing. Consequently, the back-up boiler has the capacity of 393.52 MW in all scenarios.

10.2.1 Biomass Scenario

In the second biomass scenario, all the production units are smaller than in the previous one, as they need to fulfill smaller demand. The efficiencies and marginal costs are the same as in the first alternative, thus the NHPC order is also the same. The summary of capacities and share in the yearly production can be seen in Table 10.7.

System component	Capacity [MW]/ Size [m2]	Heat production	Production share [%]
CHP heat	235	997,735	90.9%
CHP electric	78.5	-	-
Boiler	393.5	52,344	4.8%
Thermal storage [m3]	40000	-	-
Solar thermal [m2]	100000	47,996	4.4%
	Total	1,098,075	

Table 10.7. Capacities and annual heat production

The smaller biomass use - 364,793 tonnes - results in smaller emissions, which are 1.45 tonnes of PM2.5 and 2067 tonnes of CO_2.

10.2.2 Heat pump Scenario

This heat pump scenario also follows the same analogy as the heat pump scenario in the Medium saving alternative. The criteria and operation strategy are the same, and the capacities and characteristics can be seen in Table 10.8.

System component	Capacity [MW]/ Size [m2]	production [MWh/year]	Production share [%]
Electric heat pump	200	1,002,134	91.3%
Boiler	393.5	47,945	4.4%
Thermal storage [m3]	40000	-	-
Solar thermal [m2]	100000	47,996	4.4%
	Total	1,098,075	

Table 10.8. Capacities and annual heat production

The connected emissions are 0.34 tonnes of PM2.5, and 70 tonnes of CO_2 (plus the hidden emissions from electricity production at a 'distant' power plant).

10.2.3 Mixed Scenario

This scenario includes the integration of geothermal production once again. The operation strategy also matches the one during the first alternative, following the NHPC. The characteristics and production share can be seen in Table 10.9.

System component	Capacity [MW]/ Size [m2]	Heat production	Production share [%]
CHP heat	150	688,822	62.7%
CHP electric	50.1	-	-
Boiler	393.5	53,543	4.9%
Geothermal capacity [MW]	60	307,715	28.0%
Thermal storage [m3]	40000	-	-
Solar thermal [m2]	100000	47,996	4.4%
	Total	1,098,075	

Table 10.9. Capacities and annual heat production

Once again, the emissions are coming form the burning of wood chips in the boiler and CHP, resulting 1.12 tonnes of PM2.5 and 1462 tonnes of CO_2.

10.2.4 Comparison of emissions

As the aim of the project is to decrease (PM2.5) pollution during the heat production, Table 10.10 shows the associated emissions from all 6 scenarios.

Emissions	Large saving alternative			Medium saving alternative		
	Biomass scenario	Heat pump scenario	Mix scenario	Biomass scenario	Heat pump scenario	Mix scenario
Total PM2.5 [ton]	1.45	0.35	1.13	1.65	0.43	1.22
CO2 [ton]	2067	70	1462	2333	87	1640

Table 10.10. Emissions from the different scenarios

As it is expected, the scenarios from the Large saving alternative has lower emissions as the respective ones in the Medium saving alternative. Within the alternatives, the Heat pump scenario pollutes the air in the smallest way, and the use of geothermal energy makes the Mixed scenario more favorable than the Biomass scenario.

Summary and result of the section

In this chapter, different technological arrangements were made to supply the needed heat demand during the 2 alternatives. In all scenarios, the operation strategy follows the NHPC, giving priority for the cheapest technology. Additionally, the connected emissions are also calculated, with which the chapter answers to Sub-question 3.

11 Economic analysis and comparison

In this chapter, the connected economic aspects are presented and analyzed. The assessment is made from a business perspective point of view, thus the profitability and payback of the investment are calculated.

As the aim of the study is connected to a social benefit -better air quality -, the discount rate is set to 6% during the calculation, which is the given social discount rate - the discount rate for social projects - in Chile. Social discount rates are usually lower than regular discount rates, as they give more weight for the well being of future generations.

Similarly to the DH scenarios, the detailed description is given to the Medium saving alternative - as the other alternative is done likewise-, and only the most important characteristics are introduced for the Large saving alternative.

11.1 NPV and payback for the Medium saving alternative

In order to determine the economic feasibility of the scenarios, NPV calculations are used, with the additional calculations of payback times. As it was introduced before, the NPV of the investment is the sum of the positive and negative cash flows, actualized with the discount rate during the lifetime of the project. For the calculation, the investments costs, and the yearly expenditures - including fuel cost, O&M and taxes - and revenues are needed.

In this alternative, higher demand needs to be fulfilled, consequently the capacities of heat production units are higher, which brings higher investment costs at the first place.

The initial investment is paid at the first year, and for the 3 scenarios are 937 million, 867 million and 1,242 million Euros respectively. The share of different elements in the Mix scenario can be seen on Figure 11.1.

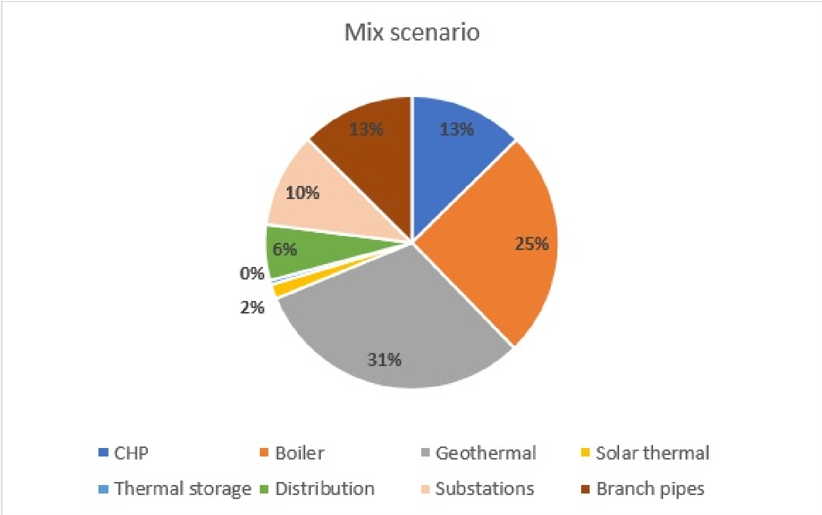

Figure 11.1. Parts of the initial investment for the Mix scenario

Aside from the investment costs of the additional districts during the next 3 phases, the yearly cash flows sum up from expenditures and revenues. The expenditures consist of the fuel cost,O&M cost and taxes, and the revenues are earned from the sale of heat, and - in the 2 scenarios which include CHP - from the sale of electricity. The expenditures in the third year (2020) can be seen on Figure 11.2.

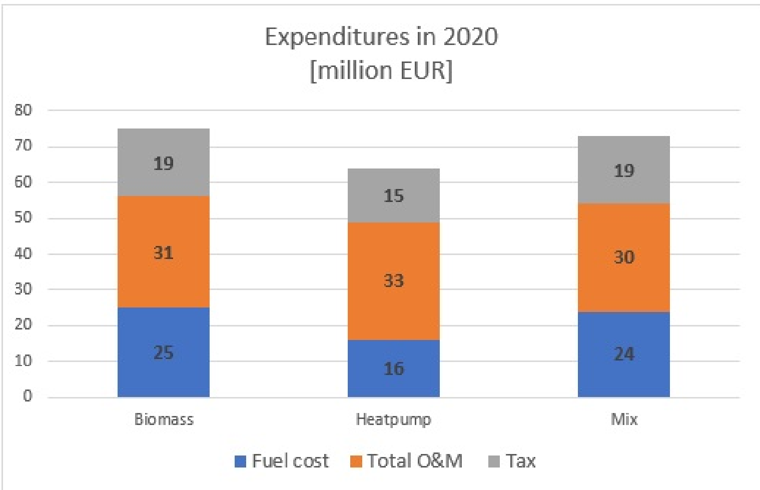

Figure 11.2. Expenditures of the different scenarios

The heat production is covering the heat demand, and the revenues are adding up from the sale of heat, and in the Biomass and Mix scenarios from the sale of electricity. The importance of the latter can be seen on Figure 11.3, where the summarized revenues are higher in the scenarios which sell electricity than in the Heat pump one.

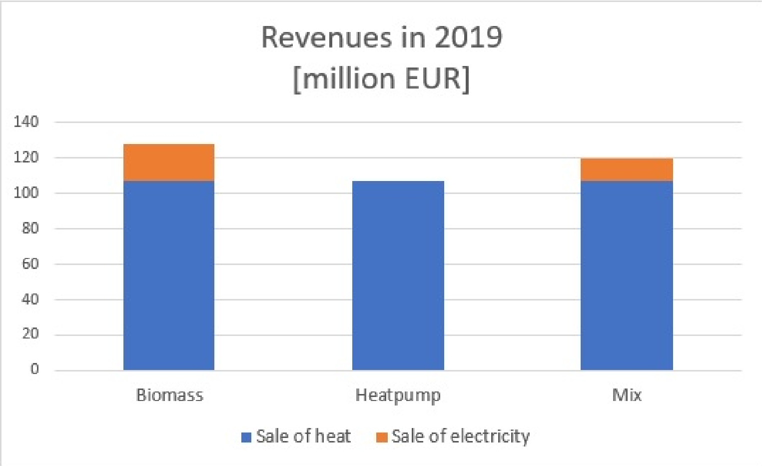

Figure 11.3. Revenues of the different scenarios

If the yearly balance of the positive and negative cash flows is positive, the then the year is profitable. After summing the positive and negative cash flows in every year during the lifetime, the NPV and payback can be calculated with the use of the discount rate. For the Heat pump scenario, the yearly cash flows can be seen in Figure 11.4 .

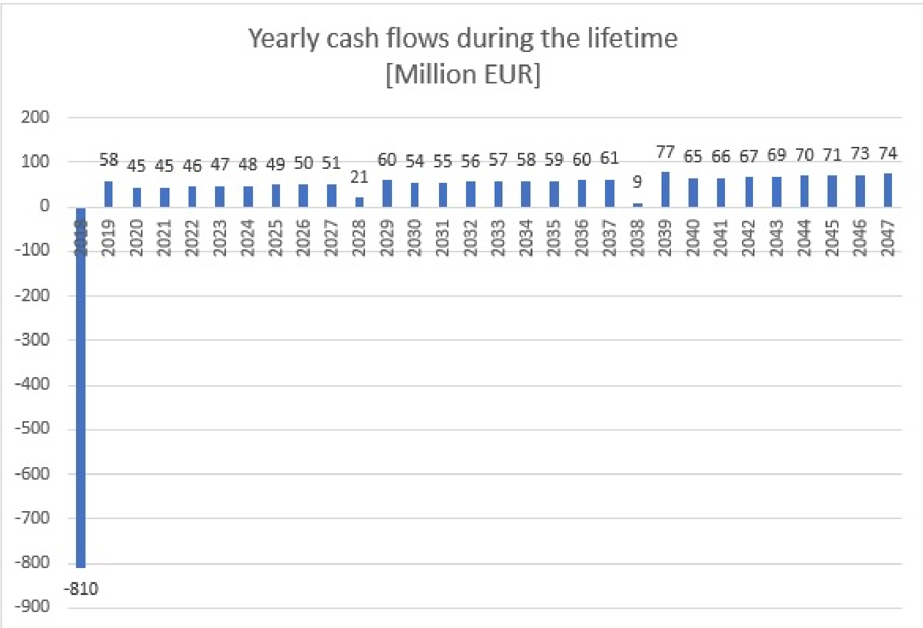

Figure 11.4. Yearly cash flows in the Heat pump scenario

In Table 11.1, the investment cost, NPV and payback time of the 3 scenarios can be found.

	Biomass	Heatpump	Mix
Investment cost [EUR]	937,071,217	867,360,217	1,242,202,217
Payback time [year]	14	17	19
NPV [EUR]	-12,378,955	-134,198,951	-341,178,863

Table 11.1. Economic features of the 3 scenarios - Medium saving

It can be seen that the NPVs for all scenarios are negative, thus none of the projects are feasible in a business economic perspective, even with the use of social discount rate. The payback of the investments only occur 14-19 years after the start of the project, which is also a long time.

It can be noticed, that even though in the Heat pump scenario the investment costs are lower than in the Biomass scenario, the NPV of the latter is still better, as the CHP sells the electricity to the wholesale market.

The negative values of NPV and the long payback time shows, that from a true business perspective the projects are not attractive, but considering other - social - benefits, probably the gains can counterbalance the negative results.

The summaries about the cash flows can be found in Appendix A.5, Appendix A.6, and in Appendix A.7.

11.2 NPV and payback for the Large saving alternative

Following the same path as in the Medium saving alternative, the summarized characteristics of the 3 scenarios can be seen in Table 11.2.

	Biomass	Heatpump	Mix
Investment cost [EUR]	872,101,124	801,744,126	1,162,864,126
Payback time [year]	15	16	20
NPV [EUR]	-23,565,408	-123,418,639	-336,187,822

Table 11.2. Economic features of the 3 scenarios - Large saving

The NPVs - similarly to the other alternative - are negative in all scenarios, and the payback time is also in the same range as in the previous alternative, thus the same conclusion can be drawn. Out of the scenarios, the Biomass scenario is the most profitable, as it pays back it's (high) investment cost in 15 years, and almost reaches 0 NPV.

11.2.1 Effect of higher heat saving

The respective scenarios in the 2 alternatives can show that the implied higher heat saving results in lower needed investment during the favorable alternative. The difference in the respective scenarios are 64,970,093 EUR; 65,616,091 EUR; and 79,338,091 EUR. Despite of the savings, the NPVs are still negative in the Large saving scenarios, and the payback times are just slightly shorter then previously.

11.3 Sensitivity analysis

During the economic assessment, several factors influences the result. Therefore, sensitivity analyses is done on different variables, which are - most importantly - the heat price, discount rate, and the price of biomass.

As the Biomass scenario is the closest for profitability, it will be the subject of the analysis, in the Medium saving alternative.

11.3.1 Heat price

As it was stated in Chapter 10, the calculated heat price depends highly on the assumed 40% average efficiency of the current stoves. With 30% of average efficiency, the heat price would have been 106.89 EUR (instead of 85.10 EUR/MWh), which is a significant difference, thus analyzing the effects of different heat prices is highly valuable.

During the analysis, the heat price is changed with 10% in every steps. The result of the analysis can be seen on Figure 11.5

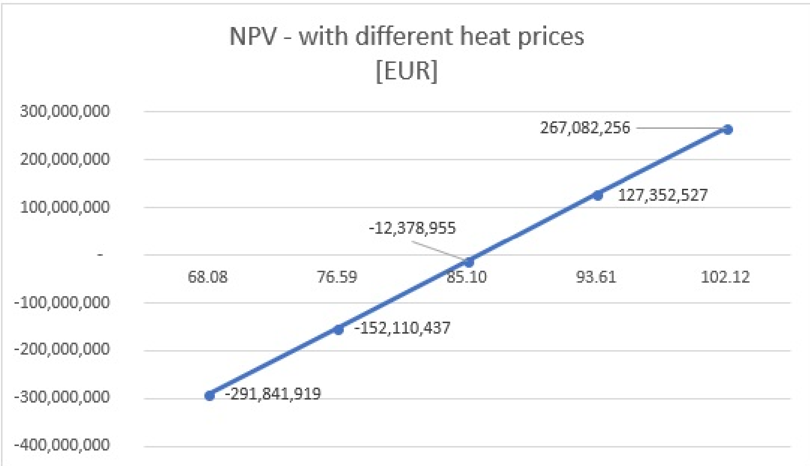

Figure 11.5. Sensitivity analysis, heat price

It can be seen from the Figure, that even the smallest, +10% change in the heat price results in positive NPV of 127,352,527 EUR - which is a huge difference-, meaning profitable investment considering business perspective. The significant change in the NPV means, that the model and the result is really sensitive to the heat price - and connectedly to the assumed current stove efficiency.

11.3.2 Discount rate

As the discount rate determine the present value of all cash flows, higher return can be achieved if the discount rate is lower than the currently used. On the other hand, actual discount rates are considered higher than the one set for social projects, thus it is relevant to analyze the effects of both lower and higher discount rates.

The results of the analysis can be seen on Figure 11.6.

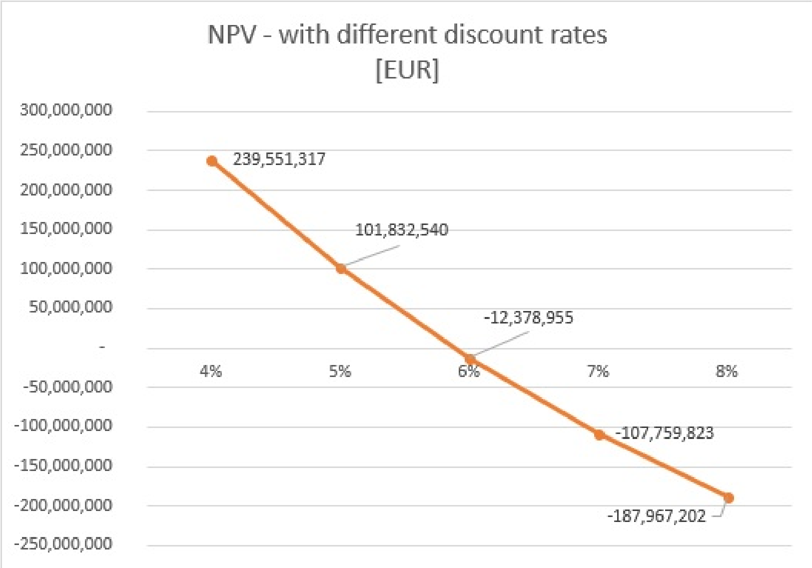

Figure 11.6. Sensitivity analysis, discount rate

As it was expected, with lower discount rate, the profitability increases, if the discount rate is set to 5% the NPV is 101,832,540 EUR, if it is 4%, the NPV is 239,551,317 EUR.

11.3.3 Biomass price

As in the analyzed scenario both the CHP and boiler is running on biomass, the price of the fuel defines the related cost of the expenditure. The effects of plus/minus 10% and 20% change in the biomass price can be seen on Figure 11.7.

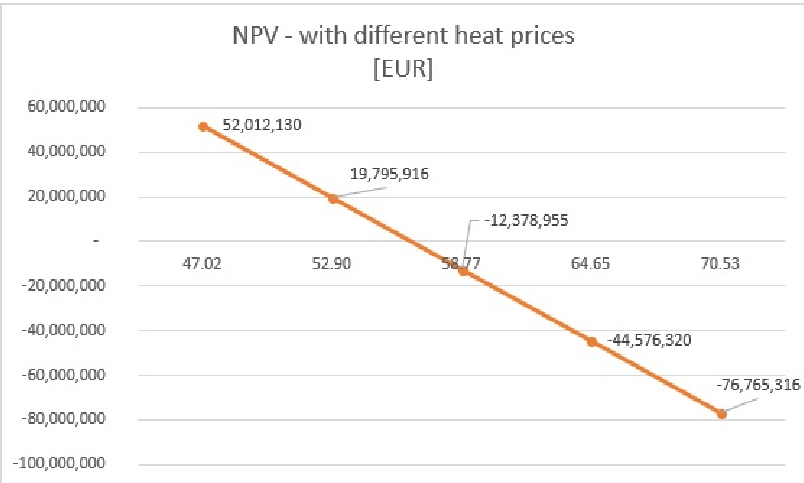

Figure 11.7. Sensitivity analysis, biomass price

The change is not so significant than in the first 2 analysis, but the expected tendency can be seen on the figure.

Summarized in a few words, if one of the key factors change by small percentage, the effects can be significant on the profitability of the project, thus careful and well planned planning is important in case of extended future work.

11.4 Comparison to reference scenario

Within the 2 different alternatives, the DH scenarios can be compared with their relating reference supply system in terms of economic and environmental matters.

As in the reference scenario, we can only speak about a one time investment - the government pays for the stove exchange-, and the future costs (O&M and fuel costs) are on the users, thus only the respective investment costs can be compared.

For the 2 alternatives, the different investment costs can be seen in Table 11.3.

Scenarios	Investment costs [EUR]	
	Medium saving	Large saving
Reference	88,234,754	89,736,490
Biomass	937,071,217	872,101,124
Heatpump	867,360,217	801,744,126
Mix	1,242,202,217	1,162,864,126

Table 11.3. Comparison of investment costs

As it can be seen from the Table, the order of magnitude is around 10 times bigger during the DH scenarios than in the reference supply systems. While in the reference system the investment cost means one time - not recovering - expenditure for the government, the DH scenarios have the potential to be remunerative in the future, either for private or public investors. In case of the municipality decides to involve private investors, the cost of the reference system can be used to mitigate the risk of the investment, or can be part of a possible funding scheme to attract investors.

Regarding environmental concerns, only PM2.5 was examined as a local air pollutant indicator. In the case of the reference system, significant cut back can be reached in PM2.5 emissions, if it is compared to the present situation. The current stove replacement program in the Decontamination plan is aiming to reduce the concentration level of PM2.5 with 67% in Temuco, by changing 27,000 stoves. In the reference supply system - which is effectively the extended version of the current program-, 92,381 and 93,953 stoves are replaced in the 2 alternatives, thus the cutback effect will be bigger[1].

Emissions from the DH scenarios are even lower, and the respective annual values can be seen in Table 11.4.

[1]Direct comparison to the current situation can not be done, as no PM2.5 emission data is available for the current situation. All the sources from the data collection states the concentration of PM2.5 in the air, but never the respective emissions.

Scenarios	PM2.5 Emissions [ton]	
	Medium saving	Large saving
Reference	2185.88	1953.59
Biomass	1.65	1.45
Heatpump	0.43	0.35
Mix	1.22	1.13

Table 11.4. Comparison of the related PM2.5 emissions

The differences are considerable, and shows the benefit of advanced renewable heat generation. Although, it should be noted, that in the Heat pump scenario, additional emissions occur at the site of electricity production. In the other 2 scenarios, emissions cutback are even bigger because of the electricity production, but these effects were not calculated during the study.

The difference between the scenarios can be quantified also with the comparison of external/societal costs. The external costs from PM emission for the DH scenarios vary between 10,866 EUR and 52,050 EUR annually, while in the reference system it is around 2-2,3 million EUR. The aggregated costs can be seen in Table 11.5.

Scenarios	Aggregated societal costs during the next 30 years [EUR]	
	Medium saving	Large saving
Reference	68,806,437	61,494,507
Biomass	1,561,506	1,373,464
Heatpump	406,063	325,987
Mix	1,152,085	1,066,556

Table 11.5. Comparison of the societal costs during the lifetime

Regarding the avoidable external cost, the DH scenarios shows high potential, even if the quantification is only done for PM2.5 emissions, thus assessment of other related GHG emissions should be included in the future.

In case of attracting possible investors for the DH solution, this avoided costs can be part of the formed supporting scheme.

In case of comparing the 2 alternatives, it can be seen that the Large saving alternative results in around 10-15% less emission, and in 7,311,930 EUR saving during the reference scenarios.

Summary and result of the section

In the first part of the chapter the profitability of the DH solutions were assessed, while aiming to answer Sub-question 4. The second part of chapter answers the core of the Research Question, while assessing the emitted PM2.5 in the reference and the DH scenarios.

The quantified analysis shows that the introduction of DH system significantly decreases the emission of PM2.5, thus increases the air quality of Temuco. When comparing the result to the - already advanced - results from the reference supply system, the cutback is more than thousandfold. Thus, the conclusion can be drawn, that DH is an effective way to solve the air quality problem of Temuco, although the associated costs are high.

As it can be seen from the business-economic analysis, the DH solutions probably won't be feasible with the current framework situation, but - as it was pointed out in the sensitivity analysis - the profitability highly depends on several factors, especially the assumed heat price.

For the reason to make the DH solution more viable, the government should shape the framework conditions, to support the realization of this highly effective emission decreasing solution.

Policy recommendations 12

Although decisions about implementation of DH may be made at local/municipality level, the driving national policies are the key in setting the framework and the possible supporting schemes.

12.1 Barriers in the heating sector and policy recommendations

12.1.1 Data availability

The biggest discovered barrier during the study was the lack of quality date, which should be the base for any type of heating system design, economic analysis and monitoring. Without, punctual measurement, processes can not be understood properly, which makes the policy making hard. Consequently, the GOC should define legal framework for energy data collection, where the first step is to make the - now voluntary- ratings of houses mandatory, and to make audits at the site of new constructions, to check if the new buildings match the given house code standards. Additionally, as currently the house code only sets values for residential buildings, standards should be also introduced for commercial buildings, followed by the inspection of the already constructed ones.

Another possibility to gain access to more accurate energy data can be from current market participants, like natural gas companies (where they operate). Thus, relevant local institutions should have legal authority to have access to the data of market participants.

12.1.2 Lack of support for investors

Another barrier which was identified is the lack of support for potential investors.

The ownership of such projects is an important aspect to consider when setting the framework. There are 3 main schemes how the DH system can be built and operated: by a private enterprise, with public-private partnership, or as a public utility [UN Environment, 2015]. The decision about the scheme needs to be made, and (probably) supported in the whole country.

As it can be seen from the previous business economic analysis, the feasibility of the implementation is questionable, thus changes in the framework and the introduction of new funding are necessary to attract private investors. (Another possibility if the municipality decides to invest to the new system - even if the business-economic calculations does not show positive result -, considering socio-economic advantages which counter-balance the stated disadvantage, in this way helping the societal well being of the community with the project.)

National support schemes for investors/developers should be made, to make the DH projects more attractive. As part of the the scheme, funding and incentives should be offered, in the form of grants, reduced interest loans, generation incentives, tax reduction, or risk mitigation funds for technologies like geothermal energy.

From the analysis, it is known that the biggest challenge for the DH system, and in this way for the investors, is the price sensitivity of the consumers, who are not able or willing to pay slightly higher price than they pay today. As it can be seen from the sensitivity analysis, even a small raise in heat price would result in profitable investment from business perspective. For this to be able to happen, for the costumers - to whom the raised heat price is too expensive - temporary subsidy mechanisms should be introduced. One possible way could be subsidy for insulation of their houses, which would lead to decreased consumption, and make the heat affordable. This also leads us for the next point.

12.1.3 Lack of support/not adequate support for energy efficiency

As today the burn of firewood is often banned in the winter period, citizens who heat with wood stoves experience cold in their unheated houses, due to its bad insulation. With the refurbishment of old houses not only this problem would be sold, but the average heat consumption could be deceased. Public benefit funds should be set up to for this purpose, as they are considered good way to shepherd investment to energy efficiency technologies like refurbishment of houses.

Additionally, from the comparison of the 2 alternatives during the analysis, it can be seen that a system for better housing stock requires smaller investment when setting up new generation technology. Although one should not forget that the connected cost of refurbishments is high, thus a balance between money spent on refurbishment and investment for better energy generation technology should be set by a detailed cost-benefit analysis.

To overcome the last 2 barriers (attracting investors and support energy efficiency), the money used in the stove replacement program, and the avoided social cost of PM2.5 emissions could be used for both purposes, in case of the implementation of the DH system. Additionally, the avoided social costs of CO_2 and NOX emissions (after assessment) should also be included to attract private investors and to support energy efficiency.

12.1.4 Additional recommendations

Carbon tax system

The monitor and adjustment of tax level is needed, as the current 5 USD/ton carbon tax is considered too low for power generation. The GOC should introduce higher tax rates for power generation, and also broaden the system for other sectors as well. From this extra income, a new fund can be set up to support the implementation of renewables. or energy efficiency programs.

Support and promotion of new renewable technologies

Support and promotion of DH, and connected generation technologies would help the recognition of the technologies. At first step, smaller demonstration DH projects should be carried out for awareness raising purposes, as the new technologies are not known in the country.

This is especially true for the geothermal technology, which has huge potential in the country and the region. Currently, the high development cost of the geothermal projects, connected to the risk throughout the exploration stage, constitute an important barrier for geothermal energy, so the introduction of risk mitigation measures should be an important step during the support of the technology. According to [Payera, 2018], the main barriers for the technology is the lack of knowledge, the not sufficient regulatory framework and the low social acceptance, based on lack of information, which all could be tackled with the support of demonstration projects.

Support the formal firewood market

Extra effort should be put on making the firewood market official. According to [Andrés Gómez-Lobo, 2006], the firewood market accounts for 1.2% of the total GDP in Araucanía, but only minimal share of the purchase happens at the formal firewood market, which results in major tax loss in the region. In case of the introduction of the DH system these loss could be recovered, as the operator of the new CHP plant would purchase the resource on the legal market. This additional tax income could be used developing renewable or energy efficiency projects.

12.2 Recommendation for the broader institutional framework

The development of the energy sector should be done in a more integrated way. The current strategies dedicate a lot of measures and attention to the electricity sector, while the heat and transportation sectors lack depth. Even though the 2050 Energy strategy mentions the development of DH in the country, but concrete goals and/or action plans were not find during the policy analysis. This measures should be done in the future.

Connecting the 3 sectors with smart energy system elements could be also beneficial for the power sector, and would also help the cooperation of different ministries.

When designing future strategies, the complete socio-economic costs of different technologies should be evaluated, which includes health, emission reduction, the higher innovation and development effect in connected sectors and employment considerations.

Higher emphasis should be put on attracting private funding in the energy development.

Support waste-to-energy projects. The treatment of waste is considered as an issue in Chile, and incineration of waste could help to solve the problem, while also could be an important resource in the future DH systems.

While making climate strategies, the collective effort between the government, the civil society and the private sector is needed (the making of the 2050 Energy Strategy was a good example for this effort). The evaluation of social consequences should be also considered during the process, as climate change effects the most vulnerable people.

Discussion 13

After the analysis of the technical simulations, economic calculations, and policy recommendations, in this chapter the difficulties, considerations and limitations of the master thesis is introduced, following by the recommended future work.

13.1 Difficulties and considerations

Lack of data

As it was stated throughout the whole report, the lack of punctual, measured data gave the biggest challenge during the master thesis. As the result of the inappropriate heating data, too much time was spent on making demand profiles, and to define the hourly distribution (which is obviously not as punctual as measured data would be), which time could have been used for a more detailed system design.

Moreover, according to [Lund, 2014], the decision about applied technologies (district heating or individual solutions), can only be made with "detailed data on the location of heat demands and knowledge on the future system of which district heating should be a part" [Lund, 2014]. Thus the outcome of the project can be influenced by the assumptions, and calculations made during the creation of data.

In this project, this statement is most true while calculating the current household expenditure for heating, as the assumed average 40% efficiency of current stoves determine the heat price for the DH solution, thus the whole profitability of the model. As the model highly depends on this specific data, it is considered to be the weak point of the thesis.

Structure of ownership

Decision about the owner of the project is an important aspect, as it defines the expectations towards it. In case of public ownership, the feasibility of the business perspective is not the main determining aim, because of socio-economic considerations. On the other hand, if the ownership involves private companies, the profitability get higher importance.

In this report, a business-economic analysis was made, and the additional benefits - avoidance of social costs - were assessed to make base for the policy recommendations - regarding possible funding.

Therefore the reference scenario is only used to (1) give base in the comparison of PM2.5 emissions - and connected social costs-, and to (2) quantify its associated investment costs, which can be avoided in the case of implementing the DH solution and can be used in funding schemes.

Challenges of the proposed DH solution

The DH solution faces considerable challenges during the implementation, when compared with the currently used individual solution.

In contrast with the individual solutions, the system needs to have back-up capacity which already makes the solution more expensive than the current one. The lack of infrastructure - distribution system, in-house applications and pipes - adds another element to the cost. The change in technology also raises cultural challenge. People are get use to cook on double purpose stoves (heating and cooking) and are not familiar with the operation of new heaters - what would come with the DH solution -, which aspects can add a factor in their resistance against change.

Another challenge is that the DH system is sized for the coldest winter, thus overcapacity can occur during the other years, plus uncertainty of future demand can also make the size of the system inadequate.

All of these challenges can offset the benefits of DH such as the longer lifetime, the capability to spread peak heat demand, higher efficiency, less emissions - just to name some-, thus an all-around assessment is needed for evaluation.

13.2 Limitations of the project

Even though the aim of the thesis was to do an all-around assessment of the DH solution in Temuco, the project has several limitations which are presented above:

From a technological point of view, the design of the DH system is not very detailed, as it lacks depth in control system, inclusion of pumping station and household applications, as it was not the main focus of the project. The COP of the included heat pumps in the respective scenario is considered to be constant during the year, even though it depends on temperature differences at the heat source side, and also from the delivery temperature, thus varies throughout the year. Consequently, detailed evaluation of heat sources for heat pumps should be made in the future, which would make the performance more punctual.

The geothermal generation is also simplified in the model, as it is not based on detailed seismic investigations, the temperate and depth is not known, which factors influence the potential and connected costs. Only the associated potential is known from the data source, which is utilized [1] in a heat generation unit, using nameplate efficiency, and average costs.

There are associated costs which are not included in the calculation, like price of land purchase and land use for the power generation units. Assessment has not been carried out regarding identification of suitable areas for the selected plants nearby the city.

During the economic calculations, different sources were used to identify the cost of different generation and distribution units. Most of the data is accessed from an official governmental document from Chile, where not all the used technologies were listed. The

[1] Not all the potential is used, it only sets limit to the usage.

costs of the biomass boiler, and all the parts of the distributing system was retrieved from the Danish technology catalogue, which mixture brings inaccuracy for the calculation.

Hourly spot market price was not available from Chile, just the marginal cost of production for the region, which gives inaccuracy for the model. Additionally the magnitude of spot market price can change significantly during the next 30 years, which factor was not considered in the model. As the NHPC of different technologies - which use and produce electricity - depends on the price, the assumed unchanged price during the next 30 years affects the accuracy, especially in the heat pumps scenarios.

One of the advantage of the DH systems is that the peak demand of the system is lower than the sum of individual demands, as not all the individual peaks happen in the same hour of the day/year. This important advantage can not be utilized when using the HDD model, which is the limitation of the method and thus limitation for the model.

In the future, it is expected that more strict regulation will be introduced in the building code, but this phenomena was not considered when calculating the future heat demand of the connected districts.

During the heat demand calculation the assumption was made that all citizens in the connected districts will opt for joining to the system which is probably not the reality (unless regulations will make it obligatory). Thus heat densities and heat demands could differ from the calculated one, resulting in an oversized system.

Commercial and industrial loads are not included in the analysis, as (1) households were identified as the main polluters, and more importantly (2) data was not available about them. These loads could change heat demand of districts, which would have effect on the DH system.

13.3 Future work

As it can be seen from the limitations, the study lacks depth in a few areas, thus further investigation would be needed before implementation, which could be done during the future work. Additionally to these aspects, there are different technologies which were not assessed in the study, and could be worthy to consider in the future. These solutions are presented below.

Based on different trends, projections and visions, the currently (mostly) separate electricity, heating, and transport systems will be interconnected in a common smart energy system in the future. Thus, future system design should consider all the synergies, and should not focus only on fulfilling the separate demands.

An important element in this system is the low temperature (or 4th generation) DH, which technology would worth to examine in the future. In the low temperature system more emphasis is put on low energy buildings, while bigger variety of generation technology can be included than today, as there are several solutions that only can supply on lower temperature than needed in the current DH systems, but would be suitable for the low temperature one.

One of the possible included technologies could be waste incineration, which can supply heat all year around. It should be noted, that because of environmental considerations, recycling always should be the priority in waste treatment, but other parts of the waste could be used in the incineration system.

In 4th generation, there is higher potential for using waste heat from the industry. As it was pointed out by [Araneda, 2018], a company, called MALTEXCO (a raw material factory for the brewing industry) is situated in Temuco, whose excess heat could be used in the DH system. The use of this resource was also considered during this study, but connection was not be able to established with the company, thus the extent of excess heat is not known at the moment.

During future works, other strategies should be assessed regarding the possible development phases and the network structure of the DH system in Temuco.

A possible option could be the development of several (smaller) separate DH systems with their own smaller generation unit(s), which systems could merge in the future. Another possibility to examine is when the DH starts in a smaller area, supplied by the accordingly sized generation unit(s), and expands over the years. Extra capacity is added to the system every time when new districts are connected during the expansion, in accordance with the demand of the newly connected districts.

14 Conclusion

The aim of this master thesis was to investigate the implementation of DH system in the city of Temuco, Chile.

As the city faces severe air quality issues, the replacement of old, polluting firewood stoves is necessary to decrease the emission of PM2.5. Contrary to the current governmental approach of replacing inefficient wood stoves with newer ones, the thesis offers and assess another solution, namely the shift from individual heating practice to District Heating.

During the thesis, the heat demand of the city was calculated together with the identification of suitable areas for DH. For these districts, different supply systems were designed to find the best technical arrangement regarding economic consideration, and potential emission reduction, with the aim of answering the following research question:

How can the introduction of a DH system in Temuco help to solve the city's air quality problem?

The key finding of the project is, that the introduction of the DH system can lead to significant emission decrease in all 3 examined scenarios (Biomass, Heat pump, Mixed), but it is not a cheap solution. More importantly, based on the economic calculation, not necessary feasible regarding business-economic perspective, as the NPV of all investments was negative. Additionally, sensitivity analysis on the most important factors were carried out to identify their influence on the feasibility. Lastly, several barriers were identified in the current framework which can weaken or hinder the implementation of the technology, and possible solutions were given to overcome this barriers.

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A

A.1 List of successful and declined interviews

	Interviewee	Occupation	Date
Succesfull interviews	Eduardo Araneda Schüler	Coordinator of Local Energy Strategy at the Municipality of Temuco	May 7, 2018
	Felipe Ignacio Loyola Torres	Member of IREA, Cizizen of Temuco	April 25, 2018
Declined interviews	Stephen Salter	President of Farallon Consultants Limited	
	Jose Torga	Regional Manager at Aguas Araucania	
	Ministry of Housing and Urbanism		
	Maltexco S.A. (factory in Temuco)		

A.2 Requirements for the modelling tool

How to choose the best energy system tool for your project

Choose the requirements for your tool (the more requirements the more complicated tool you need)

Energy sectors included in the model:
- [ ] Electricity
- [x] Heating
- [ ] Cooling
- [ ] Industry
- [ ] Transport

Energy networks:
- [x] Electricity
- [x] District Heating
- [ ] District Cooling
- [ ] Gas

Aggregation level:
- [ ] Aggregated group of technologies (e.g. PV is one input)
- [ ] Individual technologies (e.g. PV is each plant as an input)

Geographical area:
- [ ] Country
- [ ] Region/municipality
- [x] City
- [ ] Town
- [ ] Single energy system (building, district heating area etc.)

Connection to other areas:
- [ ] All areas are on same detail
- [x] Areas outside of model are simplified

Energy storages
- [x] Short term
- [x] Long-term (seasonal)

Acceptable Running time for the model itself:
- [ ] < 1 minute
- [x] < 15 minutes
- [ ] < 1 hour
- [ ] More than 1 hour

Scenario timeframe:
- [x] Multiple years
- [ ] Year
- [ ] Month
- [ ] Week
- [ ] Day

Temporal resolution of input:
- [ ] Annual
- [ ] Monthly
- [x] Hourly
- [ ] Minutes

Type:
- [x] Simulation model
- [x] Scenario
- [x] Optimisation model
  - [x] Operation
  - [x] Investments

Type of model:
- [x] Deterministic
- [ ] Stochastic
- [ ] Both

Operation Strategies:
- [x] Technical (e.g. reduce Fuel consumption)
- [x] Socio-economy
- [x] Business economy
- [ ] Consumer economy
- [ ] User defined operation

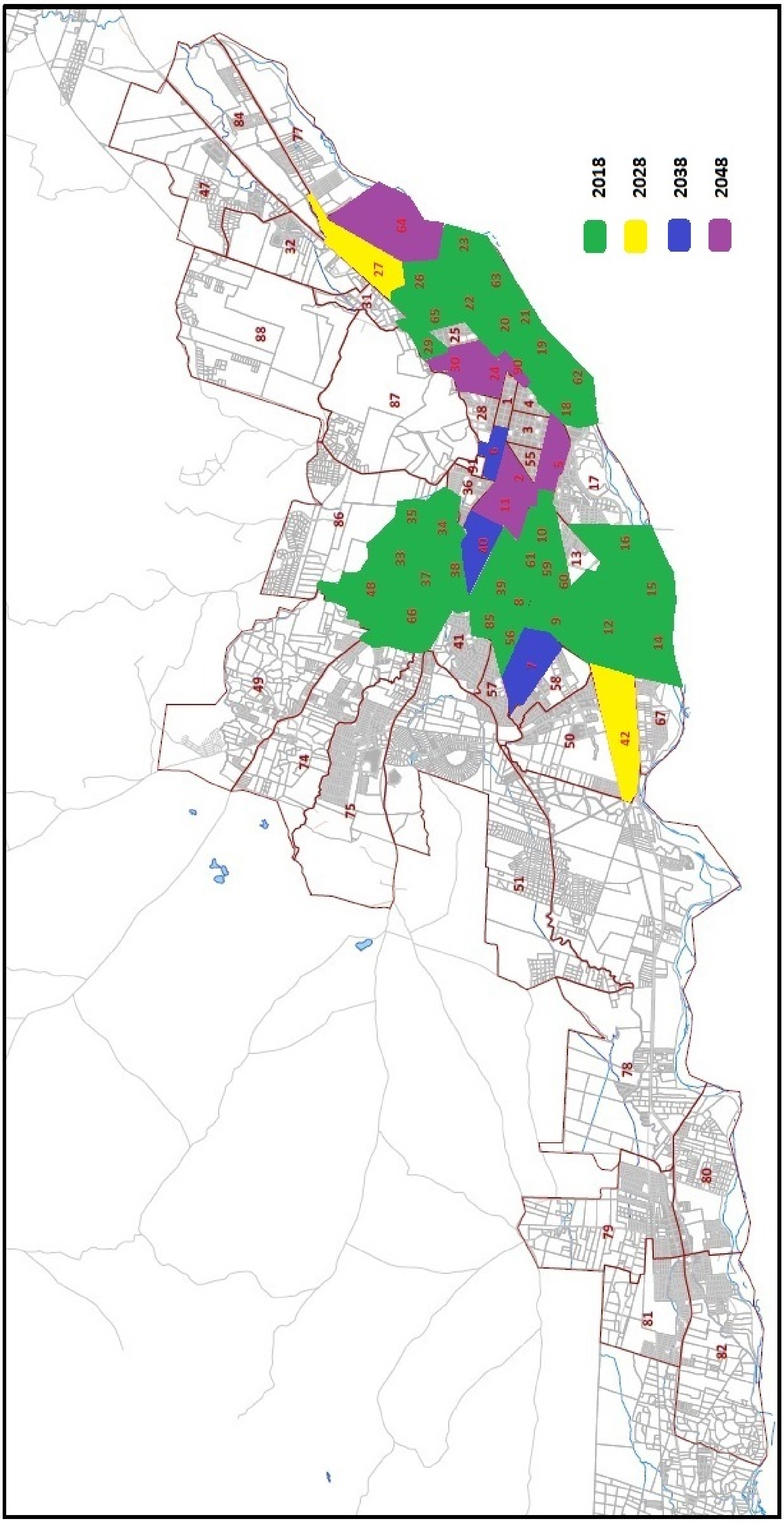
Energy output:
- [x] Fuel consumption
- [x] End-use energy demand
- [ ] Renewable energy share
- [ ] System efficiency

Environmental output:
- [x] Global effects (GHG/CO2)
- [x] Local effects
- [ ] Life Cycle Assessment

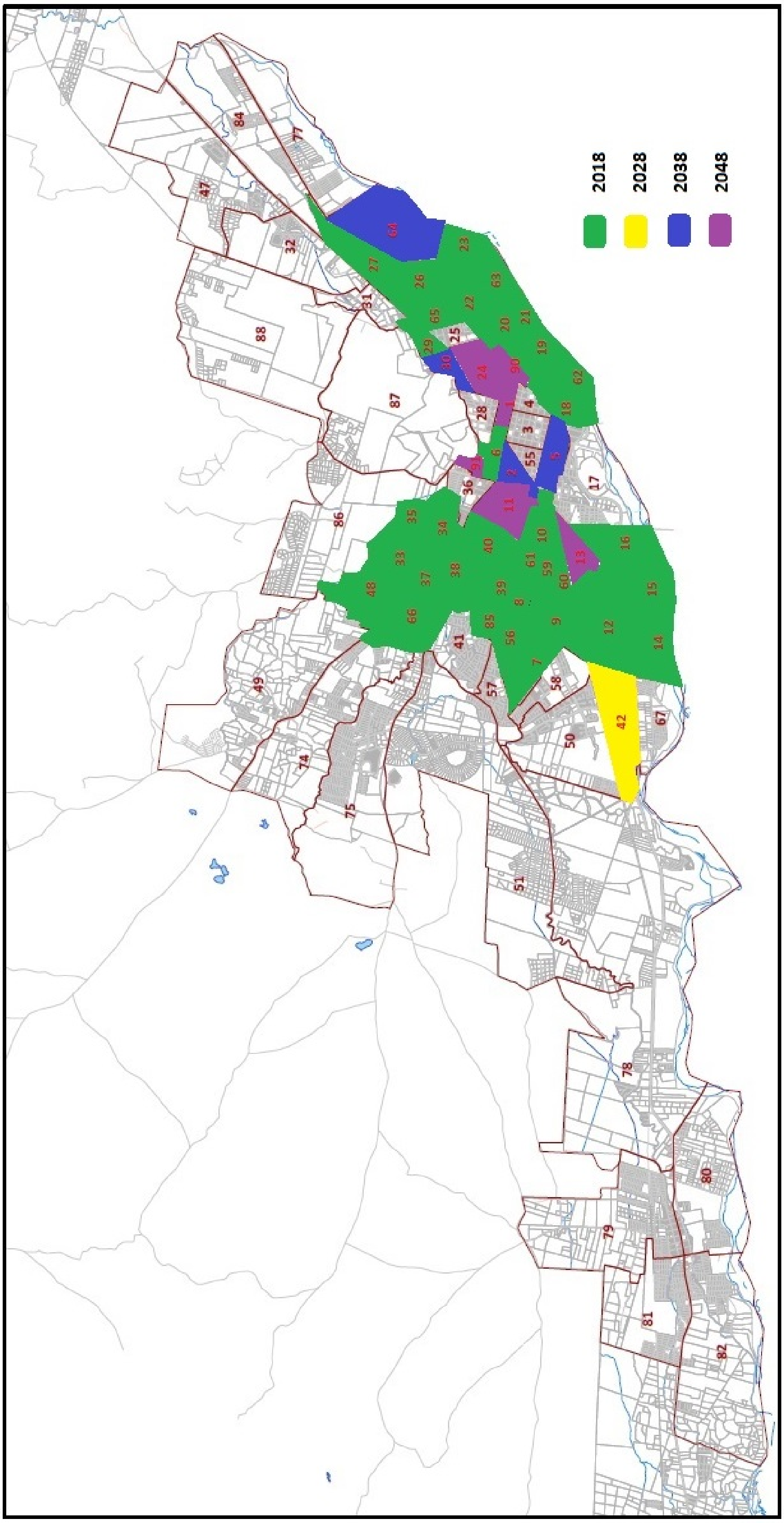
Economy output:
- [x] Investment costs
- [x] O&M costs
- [x] Fuel costs
- [x] Taxes & Subsidies
- [x] Emission costs
- [x] Total annual costs
- [x] NPV

It's up to you to find the specific tool. Read for inspiration: *"A review of computer tools for analysing the integration of renewable energy into various energy systems"* David Connolly et. al . http://dx.doi.org/10.1016/j.apenergy.2009.09.026

A.3 Phases of connected districts - Large saving alternative



A.4 Phases of connected districts - Medium saving alternative



A.5 Cash flows - Medium saving, Biomass scenario

Cash flow, summary

(All amounts in 1.000.000 EUR)

	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047
Revenues																														
Sale of heat	105	107	109	111	113	115	118	120	122	124	127	129	132	134	137	139	142	145	147	150	153	156	159	162	165	168	171	174	178	181
Sale of electricity	20	21	21	21	22	22	23	23	23	24	24	25	25	26	26	27	27	28	28	29	29	30	30	31	32	32	33	33	34	35
Total Revenues	**125**	**128**	**130**	**132**	**135**	**137**	**140**	**143**	**145**	**148**	**151**	**154**	**157**	**160**	**163**	**166**	**169**	**172**	**176**	**179**	**182**	**186**	**189**	**193**	**197**	**200**	**204**	**208**	**212**	**216**
Operating Expenditures																														
CHP_turnon	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fuel cost																														
Biomass	24	25	25	26	26	27	27	28	28	29	29	30	30	31	32	32	33	33	34	35	35	36	37	37	38	39	39	40	41	42
Electricity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fuel cost Total	**24**	**25**	**25**	**26**	**26**	**27**	**27**	**28**	**28**	**29**	**29**	**30**	**30**	**31**	**32**	**32**	**33**	**33**	**34**	**35**	**35**	**36**	**37**	**37**	**38**	**39**	**39**	**40**	**41**	**42**
O and M																														
CHP fixed	5	5	6	6	6	6	6	6	6	6	6	7	7	7	7	7	7	7	7	8	8	8	8	8	8	9	9	9	9	9
CHP variable	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	3	3	3	3	3	3
Boiler fixed	15	15	15	15	16	16	16	17	17	17	18	18	18	19	19	19	20	20	20	21	21	22	22	22	23	23	24	24	25	25
Boiler variable	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Flat plate solar fixed	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3	4	4	4	4	4	4	4	4	4	4	4	4	4
Distribution	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Substations	3	4	4	4	4	4	4	4	4	4	4	4	4	4	5	5	5	5	5	5	5	5	5	5	5	6	6	6	6	6
O and M Total	**30**	**30**	**31**	**31**	**32**	**32**	**33**	**34**	**34**	**35**	**36**	**36**	**37**	**38**	**38**	**39**	**40**	**41**	**41**	**42**	**43**	**44**	**45**	**45**	**46**	**47**	**48**	**49**	**50**	**51**
Payment group																														
Carbon tax	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Payment group Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Total Operating Expenditures	**54**	**55**	**56**	**57**	**58**	**59**	**60**	**61**	**62**	**64**	**65**	**66**	**67**	**69**	**70**	**71**	**73**	**74**	**75**	**77**	**78**	**80**	**81**	**83**	**84**	**86**	**88**	**89**	**91**	**93**
Net Cash from Operation	**71**	**73**	**74**	**76**	**77**	**78**	**80**	**82**	**83**	**85**	**86**	**88**	**90**	**91**	**93**	**95**	**96**	**98**	**100**	**102**	**104**	**106**	**108**	**110**	**112**	**114**	**117**	**119**	**121**	**123**
Investments																														
CHP	237	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Boiler	312	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Solar thermal	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Thermal Storage	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Distribution	76	0	0	0	0	0	0	0	0	0	4	0	0	0	0	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0
Substations	130	0	0	0	0	0	0	0	0	0	12	0	0	0	0	0	0	0	0	0	20	0	0	0	0	0	0	0	0	0
Branch pipes	156	0	0	0	0	0	0	0	0	0	14	0	0	0	0	0	0	0	0	0	23	0	0	0	0	0	0	0	0	0
Total Investments	**937**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**30**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**53**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Tax payments																														
Corporate tax	0	0	19	19	19	20	20	20	21	21	22	14	22	23	23	24	24	25	25	26	26	13	27	28	28	29	29	30	30	31
Total Tax payments	**0**	**0**	**19**	**19**	**19**	**20**	**20**	**20**	**21**	**21**	**22**	**14**	**22**	**23**	**23**	**24**	**24**	**25**	**25**	**26**	**26**	**13**	**27**	**28**	**28**	**29**	**29**	**30**	**30**	**31**
Cash Surplus	**-866**	**73**	**56**	**57**	**58**	**59**	**60**	**61**	**62**	**63**	**34**	**74**	**67**	**68**	**70**	**71**	**72**	**74**	**75**	**77**	**25**	**93**	**81**	**83**	**84**	**86**	**87**	**89**	**91**	**92**
Cash Account	**-866**	**-793**	**-737**	**-681**	**-623**	**-564**	**-504**	**-443**	**-381**	**-317**	**-283**	**-209**	**-142**	**-74**	**-4**	**67**	**139**	**213**	**288**	**365**	**390**	**483**	**564**	**646**	**730**	**816**	**904**	**992**	**1,083**	**1,176**

A.6 Cash flows - Medium saving, Heat pump scenario

Cash flow, summary

(All amounts in 1.000.000 EUR)

	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
Revenues															
Sale of heat	105	107	109	111	113	115	118	120	122	124	127	129	132	134	137
Sale of electricity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Revenues	**105**	**107**	**109**	**111**	**113**	**115**	**118**	**120**	**122**	**124**	**127**	**129**	**132**	**134**	**137**
Operating Expenditures															
Fuel cost															
Biomass	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Electricity	15	15	15	16	16	16	17	17	17	18	18	18	19	19	19
Fuel cost Total	**16**	**16**	**16**	**17**	**17**	**17**	**18**	**18**	**18**	**19**	**19**	**19**	**20**	**20**	**20**
O and M															
Heat pump fixed	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Heat Pump variable	9	10	10	10	10	10	11	11	11	11	11	12	12	12	12
Boiler fixed	15	15	15	15	16	16	16	17	17	17	18	18	18	19	19
Boiler variable	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Flat plate solar fixed	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Distribution	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Substations	3	4	4	4	4	4	4	4	4	4	4	4	4	4	5
O and M Total	**32**	**33**	**33**	**34**	**35**	**35**	**36**	**37**	**37**	**38**	**39**	**39**	**40**	**41**	**42**
Payment group															
Carbon tax	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Payment group Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Total Operating Expenditures	**48**	**49**	**50**	**51**	**52**	**53**	**54**	**54**	**56**	**57**	**58**	**59**	**60**	**61**	**62**
Net Cash from Operation	**57**	**58**	**59**	**60**	**62**	**63**	**64**	**65**	**67**	**68**	**69**	**70**	**72**	**73**	**75**
Investments															
Electric Heat Pump	157	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Boiler	312	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Solar thermal	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Thermal Storage	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Distribution	76	0	0	0	0	0	0	0	0	0	4	0	0	0	0
Substations	140	0	0	0	0	0	0	0	0	0	12	0	0	0	0
Branch pipes	156	0	0	0	0	0	0	0	0	0	14	0	0	0	0
Total Investments	**867**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**30**	**0**	**0**	**0**	**0**
Tax payments															
Corporate tax	0	0	15	15	15	16	16	16	17	17	17	10	18	18	19
Total Tax payments	**0**	**0**	**15**	**15**	**15**	**16**	**16**	**16**	**17**	**17**	**17**	**10**	**18**	**18**	**19**
Cash Surplus	**-810**	**58**	**45**	**45**	**46**	**47**	**48**	**49**	**50**	**51**	**21**	**60**	**54**	**55**	**56**
Cash Account	**-810**	**-752**	**-707**	**-662**	**-616**	**-569**	**-521**	**-472**	**-422**	**-372**	**-350**	**-290**	**-236**	**-181**	**-125**

	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047
Revenues															
Sale of heat	139	142	145	147	150	153	156	159	162	165	168	171	174	178	181
Sale of electricity	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Revenues	**139**	**142**	**145**	**147**	**150**	**153**	**156**	**159**	**162**	**165**	**168**	**171**	**174**	**178**	**181**
Operating Expenditures															
Fuel cost															
Biomass	1	1	1	1	1	1	1	1	1	1	1	1	1	2	2
Electricity	20	20	21	21	21	22	22	23	23	23	24	24	25	25	26
Fuel cost Total	**21**	**21**	**22**	**22**	**22**	**23**	**24**	**24**	**24**	**25**	**25**	**26**	**26**	**27**	**27**
O and M															
Heat pump fixed	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Heat Pump variable	13	13	13	13	14	14	14	14	15	15	15	15	16	16	16
Boiler fixed	19	20	20	20	21	21	22	22	23	23	23	24	24	25	25
Boiler variable	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Flat plate solar fixed	3	3	4	4	4	4	4	4	4	4	4	4	4	4	4
Distribution	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Substations	5	5	5	5	5	5	5	5	5	5	6	6	6	6	6
O and M Total	**42**	**43**	**44**	**45**	**46**	**47**	**48**	**48**	**49**	**50**	**51**	**52**	**53**	**54**	**55**
Payment group															
Carbon tax	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Payment group Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Total Operating Expenditures	**64**	**65**	**66**	**67**	**68**	**70**	**71**	**72**	**74**	**75**	**76**	**78**	**80**	**81**	**83**
Net Cash from Operation	**76**	**77**	**79**	**80**	**82**	**83**	**85**	**86**	**88**	**90**	**92**	**93**	**95**	**97**	**99**
Investments															
Electric Heat Pump	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Boiler	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Solar thermal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Thermal Storage	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Distribution	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0
Substations	0	0	0	0	0	20	0	0	0	0	0	0	0	0	0
Branch pipes	0	0	0	0	0	23	0	0	0	0	0	0	0	0	0
Total Investments	**0**	**0**	**0**	**0**	**0**	**53**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**
Tax payments															
Corporate tax	19	19	20	20	20	21	8	22	22	22	23	23	24	24	25
Total Tax payments	**19**	**19**	**20**	**20**	**20**	**21**	**8**	**22**	**22**	**22**	**23**	**23**	**24**	**24**	**25**
Cash Surplus	**57**	**58**	**59**	**60**	**61**	**9**	**77**	**65**	**66**	**67**	**69**	**70**	**71**	**73**	**74**
Cash Account	**-69**	**-11**	**48**	**108**	**170**	**179**	**256**	**321**	**387**	**454**	**523**	**593**	**664**	**736**	**810**

A.7 Cash flows - Medium saving, Mix scenario

Cash flow, summary

(All amounts in 1.000.000 EUR)

	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032
Revenues															
Sale of heat	105	107	109	111	113	115	118	120	122	124	127	129	132	134	137
Sale of electricity	13	13	13	13	14	14	14	14	15	15	15	16	16	16	16
Total Revenues	118	120	122	125	127	129	132	134	137	139	142	145	147	150	153
Operating Expenditures															
CHP_turnon	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fuel cost															
Biomass	17	17	18	18	18	19	19	19	20	20	21	21	21	22	22
Electricity	0	0	1	0	0	0	1	1	1	1	1	1	1	1	1
Fuel cost Total	17	18	18	19	19	19	20	20	20	21	21	22	22	22	23
O and M															
CHP fixed	4	4	4	4	4	4	4	4	4	4	4	4	4	5	5
CHP variable	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Boiler fixed	15	15	15	15	16	16	16	17	17	17	18	18	18	19	19
Boiler variable	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Geothermal fixed	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Geothermal variable	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Flat plate solar fixed	3	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Distribution	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Substations	3	4	4	4	4	4	4	4	4	4	4	4	4	4	5
O and M Total	30	31	32	32	33	33	34	35	35	36	37	37	38	39	40
Payment group															
Carbon tax	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Payment group Total	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Operating Expenditures	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62
Net Cash from Operation	70	71	72	74	75	77	78	79	81	83	84	86	87	89	91
Investments															
CHP	157	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Boiler	312	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Geothermal	386	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Solar thermal	20	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Thermal Storage	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Distribution	76	0	0	0	0	0	0	0	0	0	4	0	0	0	0
Substations	130	0	0	0	0	0	0	0	0	0	12	0	0	0	0
Branch pipes	156	0	0	0	0	0	0	0	0	0	14	0	0	0	0
Total Investments	1,242	0	0	0	0	0	0	0	0	0	30	0	0	0	0
Tax payments															
Corporate tax	0	0	18	18	19	19	20	20	20	21	21	14	22	22	23
Total Tax payments	0	0	18	18	19	19	20	20	20	21	21	14	22	22	23
Cash Surplus	-1,173	71	54	55	56	57	59	60	61	62	33	72	65	67	68
Cash Account	-1,173	-1,102	-1,047	-992	-936	-878	-820	-760	-699	-637	-605	-533	-467	-401	-333

	2033	2034	2035	2036	2037	2038	2039	2040	2041	2042	2043	2044	2045	2046	2047
Revenues															
Sale of heat	139	142	145	147	150	153	156	159	162	165	168	171	174	178	181
Sale of electricity	17	17	17	18	18	19	19	19	19	20	20	21	21	21	22
Total Revenues	156	159	162	165	168	171	175	178	181	185	188	192	196	199	203
Operating Expenditures															
CHP_turnon	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Fuel cost															
Biomass	23	23	23	24	24	25	25	26	26	27	27	28	28	29	29
Electricity	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Fuel cost Total	23	24	24	24	25	26	26	26	27	27	28	29	29	30	30
O and M															
CHP fixed	5	5	5	5	5	5	5	5	5	6	6	6	6	6	6
CHP variable	2	2	2	2	2	2	2	2	2	2	2	2	2	2	2
Boiler fixed	19	20	20	20	21	21	22	22	23	23	23	24	24	25	25
Boiler variable	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Geothermal fixed	3	4	4	4	4	4	4	4	4	4	4	4	4	4	4
Geothermal variable	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Flat plate solar fixed	3	3	4	4	4	4	4	4	4	4	4	4	4	4	4
Distribution	2	3	3	3	3	3	3	3	3	3	3	3	3	3	3
Substations	5	5	5	5	5	5	5	5	5	5	6	6	6	6	6
O and M Total	40	41	42	43	43	44	45	46	47	48	49	50	51	51	52
Payment group															
Carbon tax	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Payment group Total	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Total Operating Expenditures	64	65	66	67	68	70	71	72	74	75	77	78	80	81	83
Net Cash from Operation	92	94	96	98	100	102	103	105	107	109	112	114	116	118	120
Investments															
CHP	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Boiler	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Geothermal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Solar thermal	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Thermal Storage	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Distribution	0	0	0	0	0	10	0	0	0	0	0	0	0	0	0
Substations	0	0	0	0	0	20	0	0	0	0	0	0	0	0	0
Branch pipes	0	0	0	0	0	23	0	0	0	0	0	0	0	0	0
Total Investments	0	0	0	0	0	53	0	0	0	0	0	0	0	0	0
Tax payments															
Corporate tax	23	24	24	24	25	25	12	26	27	27	28	28	29	30	30
Total Tax payments	23	24	24	24	25	25	12	26	27	27	28	28	29	30	30
Cash Surplus	69	71	72	73	75	23	91	79	81	82	84	85	87	88	90
Cash Account	-263	-193	-121	-47	27	50	141	220	301	383	467	552	639	727	818