Life Cycle Analysis of Residential Heating Alternatives for PM 2.5 Reduction in Central and Southern Cities in Chile

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EXECUTIVE SUMMARY

The goal of this study was to compare the environmental impact of the current residential heating systems in Central and Southern cities in Chile, with alternative energy sources such as electricity, as well as the impact of a higher contribution of solar energy in the Central Interconnected System (SIC). A Life Cycle Analysis (LCA) was conducted in order to compare its environmental impact.

The study is divided into 4 parts: Chapter 1 describes the goal and scope of the LCA, Chapters 2 and 3 provides information of the current electricity matrix in the locations where the study is developed, as well as the most common heating technologies. Chapters 4 and 5 describes the proposed scenarios and environmental impact results.

The results of this study prove that the main pollutant from these heating systems are fine particles, which represent a high risk to human health. However, if electricity replaces 30% of the current heating systems, the emissions of PM 2.5 would be reduced in 9.5%, moreover, if 30% of that electricity comes from solar energy, the reduction of fines particles would be 17.2%. In an optimistic scenario, when 80% of heating systems are based on electricity, the reduction of this pollutant would be 30%, in addition, if this electricity is 30% solar, the reduction of PM 2.5 would be 63.9%.

In addition, the use of firewood in all the scenarios proposed, contribute the most in the GHG emissions related with carbon dioxide biogenic and methane biogenic, nevertheless, the high dependency on fossil fuels for electricity production generates a high impact in the $CO_{2\text{-eq}}$ emissions from carbon dioxide and methane fossil, as well as nitrogen oxides.

To reduce the GWP in the scenarios where electricity is used for residential heating, the grid will have to become cleaner, reducing the amount of coal and petroleum as well as conventional hydro. Despite being renewable, conventional hydro presented a high number of GHG emissions, this could be attributable to the environmental impact of the downstream water that flows from the dam and inundates green fields that will decompose and generate GHG, mainly methane.

In an ideal scenario, where solar energy replaces 100% the electricity generation from coal, natural gas and petroleum diesel, and hydro run-of-river replaces 100% conventional hydro, the use of 30% of electricity with these characteristics would reduce in 27.8% the emissions of $CO_{2\text{-eq}}$ from carbon dioxide fossil compared with heating systems, and 76.6% from the current electricity matrix. In total, the reduction of $CO_{2\text{-eq}}$ under this ideal scenario would be 0.35 tons per MWh of heat produced, compared with heating systems and 0.4 tons MWh compared with the current electricity mix in Chile.

In conclusion, the replacement of heating systems for electricity would be a solution to reduce the emissions of PM, especially fine particles. However, this would have an impact in the GHG emissions that comes from fossil fuels in the electricity production, such as carbon dioxide fossil, nitrogen oxides and methane fossil.

It is suggested from the results of this project, to stimulate the use of electricity for residential heating but, first of all, improve the quality of the energy produced in Chile by introducing less contaminant technologies such as solar.

With a coast that extends for over 4,000 kilometers and it's home to the world's driest desert, the country has privileged conditions for the development of non-conventional energy. At this time, the energy sector is one of the most dynamic areas of the Chilean economy. It is expected that within the next few years, a cleaner energy matrix becomes a reality that can benefit the quality of life of all Chileans.

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Introduction

Projections of economic growth in Chile in the following years involve higher energy demand and therefore, the need of an efficient energy supply in order to ensure both sustainable and economic growth.

In that context, consumption of firewood represents an important role, considering the high availability of this energy source in Chile. In the entire country, the capacity of energy generation from biomass is estimated to be from 310 MW to 470 MW (Ministry of Energy, 2008).

The main use of firewood is for residential heating, however, firewood is associated not only with environmental issues, but also with public health problems. Fine particulate matter (PM 2.5) is an air pollutant that are two and one half microns or less in width, that is an issue when reaches high levels. These particles are able to travel deeply into the respiratory tract, reaching the lungs, exposure to fine particles can produce asthma and hearth disease. Long term exposure to fine particulate matter could be related with increased rates of chronic bronchitis, reduced lung function and increased mortality from lung cancer and heart disease (New York State Department of Health, 2011). Other alternatives commonly used are liquefied natural gas (LNG), electric heaters, refined oil, etc.

Data from the Ministry of the Environment (MMA) shows the low air quality of various cities in the Center and South of Chile (MMA, 2015). Figure 1 shows that, of the 49 stations monitoring contaminant PM 2.5 in the country, 29 are above the annual standard (20 µg/m3).

Several studies suggest the replacement of inefficient heating devices currently used in these cities. It is estimated that a non-certified firewood system may release 6,600 times more PM than a heating system based on clean fuels such as electricity, natural gas or paraffin (EPA, 2016). The graphical comparison is shown in Figure 2.

The Interconnected Central System (SIC) grid supplies 92.2% of the Chilean population (Generadoras de Chile, 2016). Currently, the Chilean Energy Matrix is highly dependent on mostly-imported fossil fuels, with only 3% of total capacity and generation coming from Non-Conventional Renewable Energies (Eurostat, 2015). The use of electricity for residential heating could be a good choice because this source would reduce the environmental impact produced by PM 2.5; however, the high prices of this commodity play against this alternative.

Therefore, in this study, it is analyzed the environmental impact of using electricity for residential heating, as well as the impact of a higher contribution of solar energy in the SIC. A Life Cycle Analysis is conducted in order to compare its environmental impact. A beneficial result could bring greater implementation of solar energy for electricity usage and residential heating. This analysis will also provide some basis for the development of future incentive programs, that encourage the use of cleaner energies.

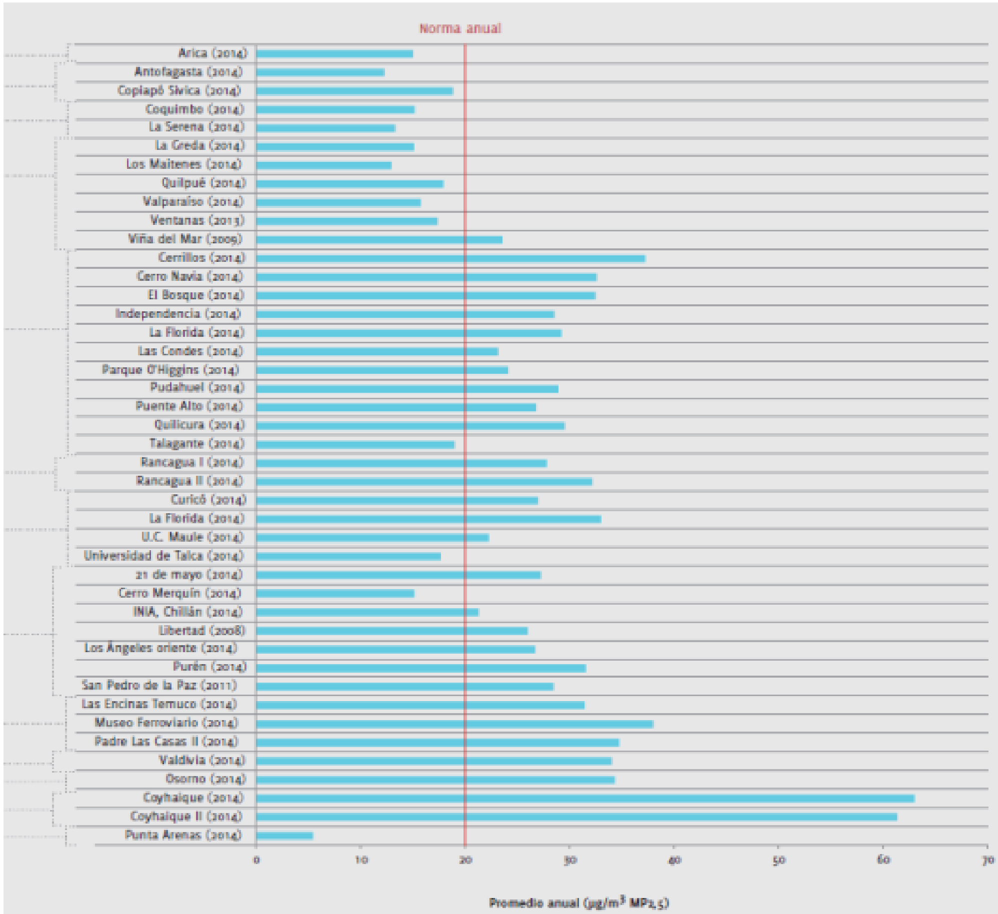


Figure 1. Average concentration of PM 2.5 (μg/m3) in 49 monitoring stations in Chile.

MMA (2015)

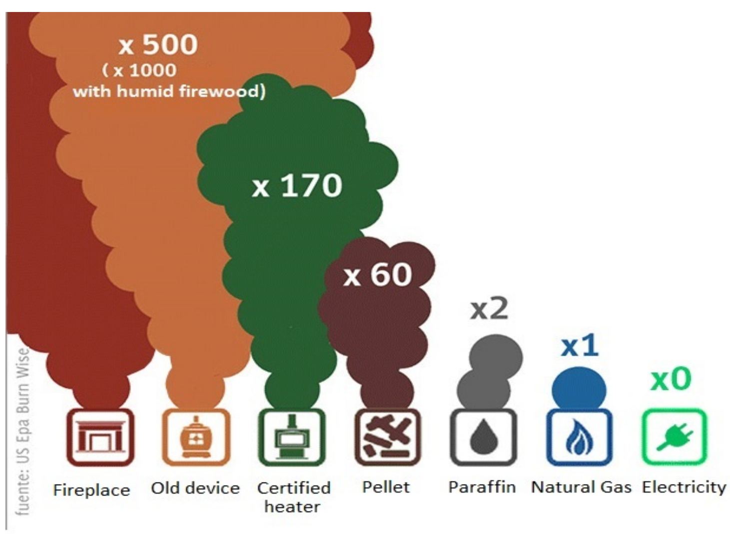


Figure 2. Comparison of PM 2.5 emissions from different heating devices

US EPA Burn Wise (2016)

1. Goal and Scope

Three different scenarios are analyzed in this study. "Scenario 1" (Figure 3) considers the heaters proposed by the "Sustainable Heating" program, shown in detail in Chapter 4, these 10 devices are based on firewood, pellets, paraffin and natural gas respectively.

Currently, there is no city in the Central-Southern Chile that uses electricity as its primary source of heat, even in small fractions. Therefore, "Scenario 2" proposes a higher percentage of electricity for residential heating.

Finally, "Scenario 3" represents the same participation of electricity for residential heating as Scenario 2, but a higher contribution of solar energy in the SIC grid is proposed.

The goal is to estimate the environmental impact of switching from firewood-based residential heating to electricity, on the one hand, considering the current SIC network energy matrix, on the other, with a higher contribution of solar energy.

For all the scenarios, this study considers the emissions from the production of high voltage electricity in power plants in Chile to the transmission/distribution at residential level. The streamlined life cycle of heating systems, consists in the production and transportation of the fuel required.

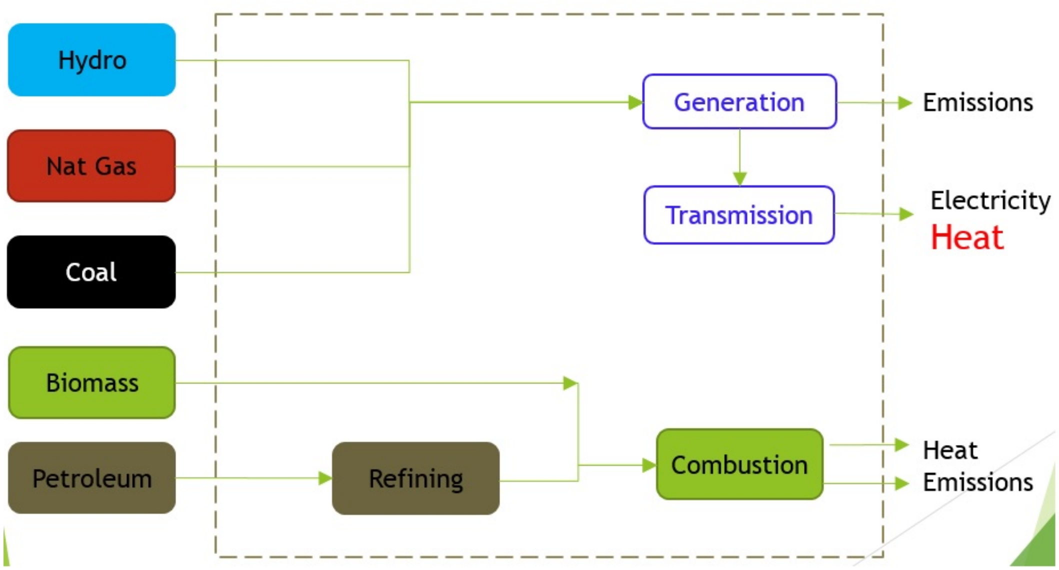


Figure 3. Scenarios 1 and 2

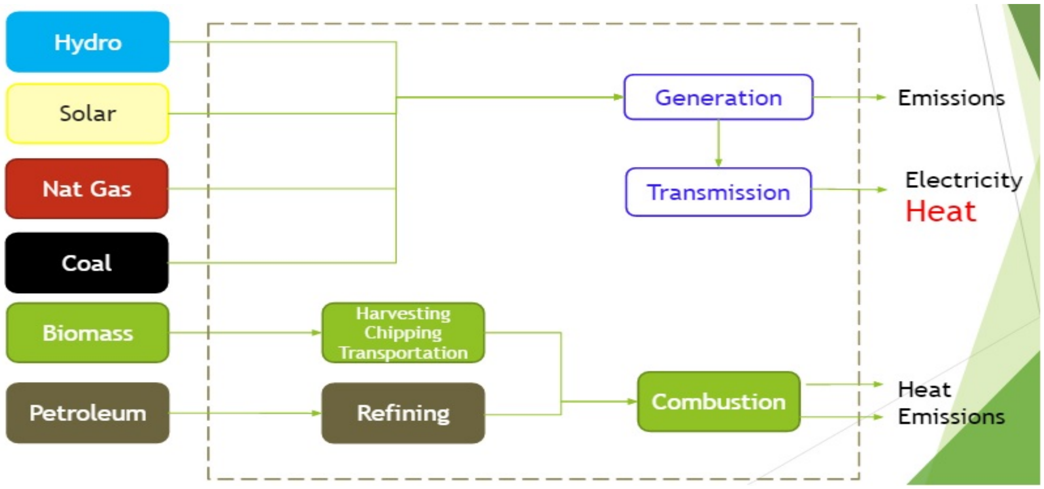


Figure 4. Scenario 3

Functional Unit

The functional unit (FU) will be the residential consumption of 1 MWh of heat. A combination of heating technologies per city will be assumed based on previous studies made in the country.

Boundaries

The dotted line in Figures 3 and 4 represents the system's boundary. On the one hand, this analysis starts from the production of electricity in the SIC grid to the distribution of this energy to the households, considering all the transmission losses. However, the raw materials required for this process are not part of the study, as well as the power plants construction and infrastructure.

On the other hand, this analysis starts from the harvesting/chipping and transportation of firewood to the households, and also the intermediate processes of different fuels for the most commonly used heating devices.

Because the greatest populations affected by air pollution in Chile are located in the Central-Southern cities, this study will focus on Rancagua, San Fernando, Rengo, Talca, Concepción, Los Angeles, Temuco, Valdivia and Puerto Montt, which are also connected to the SIC network. However, the results of this analysis are expected to be applicable to other areas with critical pollution levels. One such city is Coyhaique, in the Aysén region, where the interconnection of the SIC-Aysén systems may become a reality one day, or to enhance the development of micro grids.

2. Energy Matrix of Chile

2.1 SIC Grid

The main electrical systems in Chile are the Large Northern Interconnected System (SING-Sistema Interconectado del Norte Grande), and the Central Interconnected System (SIC- Sistema Interconectado Central), which represent 99% of the total installed capacity in the country. The Aysén and Magallanes electric systems in the south are much smaller and have several not interconnected subsystems, whose existence is because geographical isolation, making them very expensive to interconnect with the SIC (Central Energía, 2015).

The SIC grid supplies power to the central and most densely populated regions of Chile. This system has an installed capacity of 15.2 GW (20 GW is the installed capacity SIC-SING) and a total load of 52.9 TWh (72 TWh is the total load in both SIC-SING). Currently, 51% of the installed capacity corresponds to thermoelectric power plants (mainly coal, natural gas and oil), 40% hydro, 5% wind and 4% solar (CDEC SIC, 2016).

The location of the cities with similar air pollution issues, are shown in the red circles in Figure 7. All of them are connected to the SIC, and therefore, the environmental impact of electricity production/distribution from different sources will be measured.

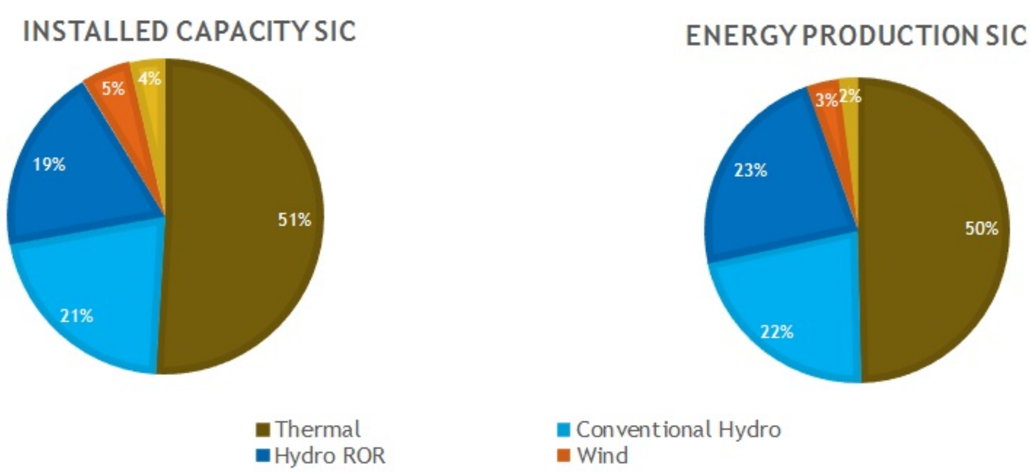


Figure 5. Installed Capacity and Energy Production SIC by technology

CDEC (2016)

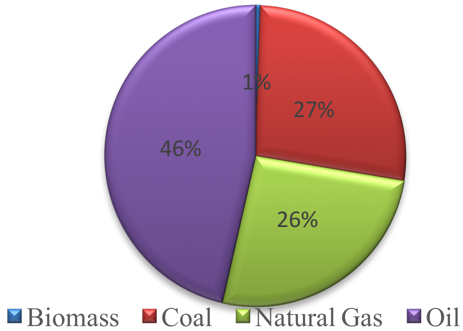


Figure 6. Thermal electricity by type of fuel

CDEC (2016)

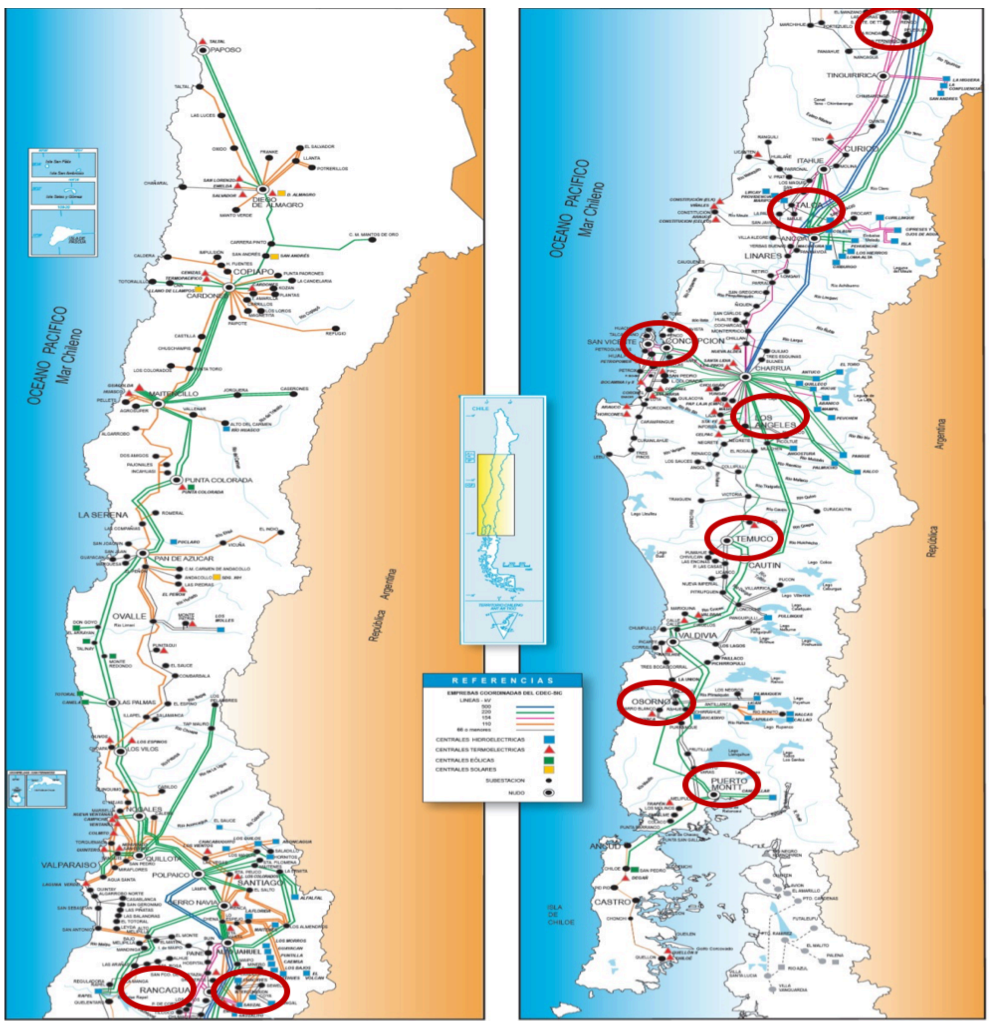


Figure 7. Map of SIC grid

CDEC (2016)

As mentioned before, the study aims to analyze the environmental impact that could bring the implementation of electricity and particularly solar energy in residential heating. It is proposed the north of the SIC grid as a location for a solar plant as is shown in Figure 8, due to the northern area of the central region covered by the SIC receives similar levels of global horizontal irradiance (GHI) as the north (Chilesol, 2014). This may be very beneficial given that the SIC has had several power cuts in the last decade, the most notable being in 2008 due to the severe drought that substantially affected the hydro-dominated SIC distribution.

Figure 8. Northern area of SIC grid

CDEC (2016)

2.2 Transmission losses

In order to calculate the energy required to distribute the electricity to the customers in every city, it is important to consider the transmission losses in the system.

Data from the World Bank shows a 5% of electric power transmission and distribution losses in 2012 as is shown in Figure 9, this include losses in transmission between sources of supply and points of distribution and in the distribution to consumers, including pilferage. However, for this analysis, 8% of losses will be assumed considering the trend of the past 10 years. A sensitivity analysis on this value could be made in order to assess the variability of the results.

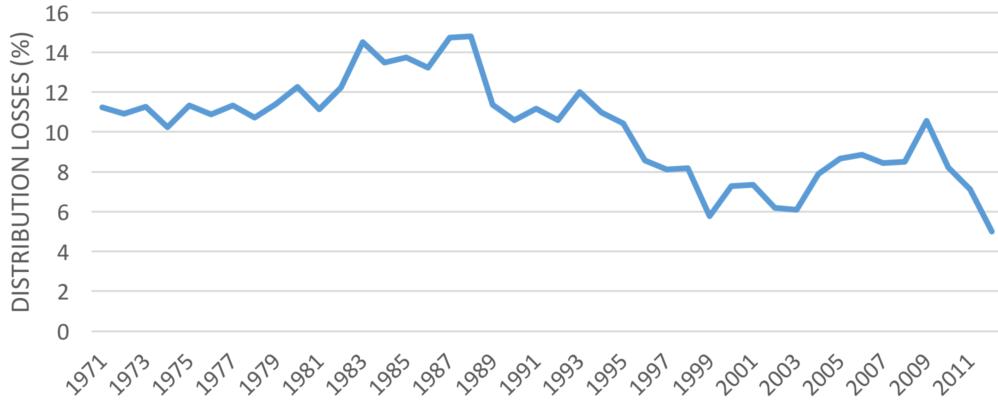


Figure 9. Electric power transmission and distribution losses in Chile

World Bank (2014)

2.3 Energy required per functional unit

The main technologies for electricity production in the SIC grid are detailed below. As explained before, at the moment no city uses electricity for residential heating, or very low fractions which is insignificant compared with firewood usage, however, this situation will be compared with energy supply from the SIC grid in the Scenario 2, considering the current contribution of those power plants. In addition, Scenario 3 proposes a 30% contribution of solar energy to the grid, reducing the current dependency on fossil fuels.

Table 1. Contribution to electricity production in Scenario 2 and 3

Technology	Installed Capacity (MW)	Scenario 2 (%)	Scenario 3 (%)
Conventional Hydro	3,402	22.26%	16.05%
Petroleum Diesel	3,340	21.86%	15.76%
Hydro Run-of-River (ROR)	3,068	20.08%	14.48%
Coal	2,302	15.06%	10.86%
Natural Gas	1,774	11.61%	8.37%
Wind	820	5.37%	3.87%
Solar	446	2.92%	30.00%
Biomass	115	0.75%	0.54%
Propane	14.3	0.09%	0.07%

3. Heating systems in Chile

3.1 Air Pollution from wood burning

According to the Ministry of the Environment (MMA), in Chile 68% of the household energy consumption per month is for heating (MMA, 2016). Most of the current heating technologies are responsible for reaching harmful emissions levels, which affects not only the environment but also the human health; only in the Metropolitan Region of Santiago, it accounts for 30% of the pollutants (MMA, 2016).

Electric heating is one of the cleanest systems but the high cost of electricity discourages families to prefer this technology, while wood has been broadly used in Chile.

The government has implemented some initiatives to mitigate this situation:

- Restriction in the use of firewood systems when the pollutants concentration exceeds the permitted levels. This temporary solution affects the life quality of people because the indoor temperature does not reach the minimum standard of comfort.
- Prohibition of physical activity in open spaces.
- Children, pregnant women, older adults and chronically ill people must use masks when walking outside.
- General recommendations for the correct use of heating devices based on firewood: buying from certified sellers, ensure a correct combustion, etc.
- Subsidies in the replacement of heating systems under the program "Sustainable Heating", and improvement in the façade of homes in order to reduce heat losses.

3.2 Types of heating systems and emissions

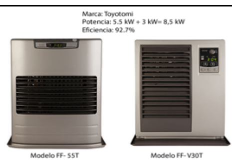
The *Sustainable Heating* program suggests the best alternatives of heating technologies that complies with the legislation. This initiative encourages people to change their current heating device for a less contaminant and efficient stove. The MMA also provides a guide to decide which is the most suitable heating system for each type of home (MMA, 2016).

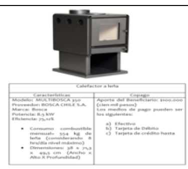
It is always recommended to have an A/C system but since this alternative is not affordable for the majority of the population, some suggestions are: central heating and high efficiency boilers for people living in apartments, in small homes the recommendation is using liquefied natural gas (LNG) or refined oil, only if the place has a good ventilation. In larger households, it is suggested using high power heaters (more than 5 kW) such as split heaters or natural gas stoves, LNG or paraffin stoves are also recommended, however, this alternative is more expensive.

Crude oil is mainly imported from Ecuador, Brazil, Colombia and Argentina, and the United States is Chile's leading source of refined petroleum products. Most of the natural gas comes as LNG from Trinidad and Tobago, Qatar and Yemen. Chile has two terminals of regasification: Mejillones, in the north, and Quintero, near the large urban areas of Valparaíso and Santiago (EIA, 2016).

The following table summarizes the heating systems that the MMA has accepted and are included in the Sustainable Heating program:

Table 2. Heating systems recommended by the MMA

Technology	Fuel	Base quantity	Efficiency (%)
 1	Refined oil	Power: 8.5 kW Model: Toyotomi	92.7
 2	Pellet	Power 7 kW Brand: Cadel	88.5
 3	LNG	Power 7.7kW Brand: Ursus Trotter	81
 4	Pellet	Power: 8.5kW Brand: Cadel	88
 5	Pellet	Power: 6.2kW Brand: Amesti	87.5

 6	Refined oil	Power: 10.3 Brand:Toyotomi	92
 7	Wood	Power:8.5 kW Brand:Bosca	75.1
 8	Wood	Power: 8.5 kW Brand: Bosca	75.12
 9	Wood	Power: 10.4kW Brand: Amesti	79
 10	Pellet	Power: 7.3 kW Brand: Toyotomi	92

MMA (2016)

The emissions from each heating system will depend on: fuel, efficiency, use of the heater, etc. In the biomass-based heating system, the crucial factor is the fuel quality. The United States Environmental Protection Agency (EPA) recommends a maximum moisture level of 20%, since using wet biomass may increase the PM emissions significantly (EPA, 2016).

Despite the government efforts, a large number of households still own old inefficient stoves. The replacement of these systems become crucial to reduce respiratory diseases in winter season and ensure a good life quality. The current systems and emission factors are summarized in Table 3.

Table 3. PM 2.5 emissions produced by different heating systems

Technology	Fuel	Emissions g PM 2.5/kg of wood
Franklin Stove	Wood	23.28
Fireplace	Wood	23.39
Simple stove	Wood	56.21
Double combustion stove	Wood	33.38

MMA (2016)

The heating systems described in Table 2 will be considered in this study in order to assess their environmental impact, however, the wood stoves efficiency will be assumed 70% according to the EPA minimal requirements for Certified Wood Heaters (EPA, 2015). Table 4 summarize the amount of heat in kWh produced by 1 kg of fuel burned, based on the systems efficiency and fuel heating value (HV).

Table 4. Heating System proposed by the Ministry of the Environment

System	Fuel	Efficiency (%)	Fuel HV	Unit	HV kWh/kg
1	Paraffin	92.7	9156	kcal/kg	10.65
2	Pellet	76.5	8500	BTU/lb.	5.49
3	LNG	81	12100	kcal/kg	14.07
4	Pellet	88	8500	BTU/lb.	5.49
5	Pellet	87.5	8500	BTU/lb.	5.49
6	Paraffin	92	9156	kcal/kg	10.65
7	Wood	70	2700	kcal/kg	3.14
8	Wood	70	2700	kcal/kg	3.14
9	Wood	70	2700	kcal/kg	3.14
10	Pellet	92	8500	BTU/lb.	5.49

Engineering Tool Box & Southern Maine Renewable Sources

4. Scenarios and Inventory Analysis

4.1 Residential heating

A previous study developed in 2013, revealed the high dependence of firewood in the energy supply for residential heating as shown in Figure 10. The city of Concepción, however, shows a slight variation, where 82.6% of households used firewood, 10.4% LNG, 6% paraffin, 1% natural gas, and 0% electricity. This city will be the baseline for the analysis in this study, being able to extrapolate the results to the other cities.

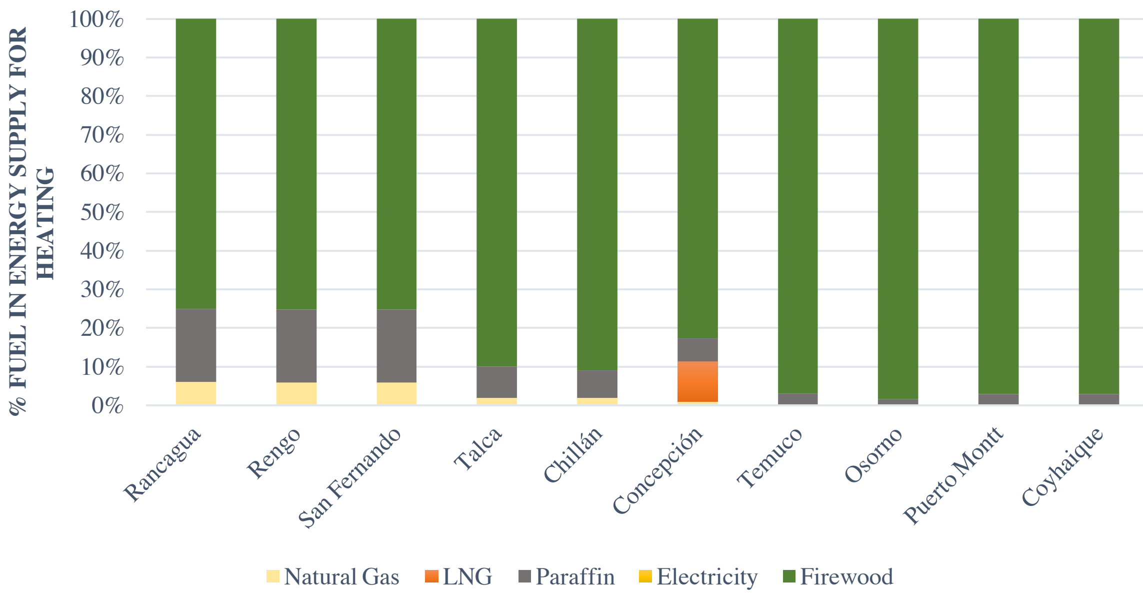


Figure 10. Contribution of each fuel in the energy supply for heating in 2013

UNTEC (2014)

Scenario 1 will be defined as the mix of fuels needed to produce a FU (1 MWh of heat), considering the current situation of the city of Concepción described in Figure 10. On the other hand, scenario 2 and 3 will propose an increase from 0 to 30% in electricity for residential heating, this means, 300 kWh would be supplied by the SIC grid.

The energy required in kWh from different heating sources for all the scenarios is summarized in Table 5. It was assumed that 3% of firewood corresponds to pellets.

Table 5. Energy required in the production of 1 MWh from different heating sources

	Scenario 1		Scenario 2 & 3	
	% of FU	Total kWh	% of FU	Total kWh
Electricity	0%	0	30%	300
Pellet	2.5%	25	1.7%	17
Wood	80.1%	801	56.1%	561
Paraffin	6.0%	60	4.2%	42
LNG	11.4%	114	8.0%	80
Total	100%	1,000	100%	1,000

The total amount of energy in kWh required to produce a FU from different heating systems is presented in Table 6, which combines information from Tables 4 and 5. This estimation is based on the number of systems that provide that source of energy, for example, in order to produce 25 kWh of heat from Pellet, it is required that each of the 4 pellet stoves provide 6.2 kWh. Considering the stoves efficiencies, it can be calculated the total fuel mass in kg required to produce a FU.

Table 6. Mass of fuel required in the production of 1 FU from different heating sources

	Scenario 1			Scenario 2 & 3		
Fuel	Energy (kWh)	Energy input (kWh)	Mass (kg)	Energy (kWh)	Energy input (kWh)	Mass (kg)
1. Paraffin	30	32.36	3.04	21	22.65	2.13
2. Pellet	6.196	8.10	1.47	4.3	5.67	1.03
3. LNG	114	140.49	9.98	79.7	98.35	6.99
4. Pellet	6.196	8.10	1.47	4.3	5.67	1.03
5. Pellet	6.196	8.10	1.47	4.3	5.67	1.03
6. Paraffin	30	32.61	3.06	21	22.83	2.14
7.Wood	267.1	381.63	121.53	187	267.14	85.07
8. Wood	267.1	381.63	121.53	187	267.14	85.07
9. Wood	267.1	381.63	121.53	187	267.14	85.07
10. Pellet	6.196	8.10	1.47	4.3	5.67	1.03
11. Electric	0	0	-	300	324	-
Total	1,000	1,382.74	386.58	1,000	1,291.92	270.61

A higher electricity participation as proposed in Scenario 2 and 3 for residential heating would reduce 109.4 kg of wood in order to produce a MWh of heat.

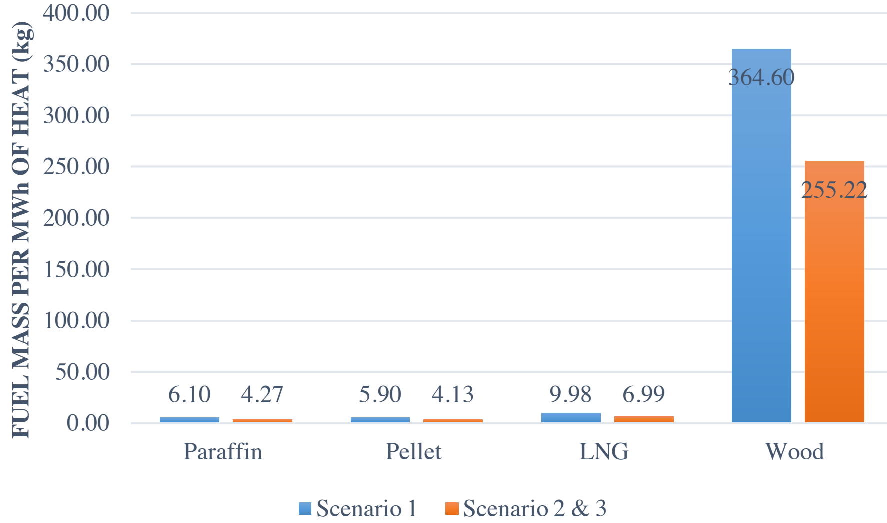


Figure 11. Fuel mass required to produce a MWh of heat

4.2 Electricity

In order to assess the environmental impact of increasing the electric supply for residential heating by 30%, it is necessary to consider the current energy matrix of the SIC grid (Scenario 2). Subsequently, the benefit of increasing the participation of solar energy by 30%, represented by Scenario 3, will be analyzed in the next section.

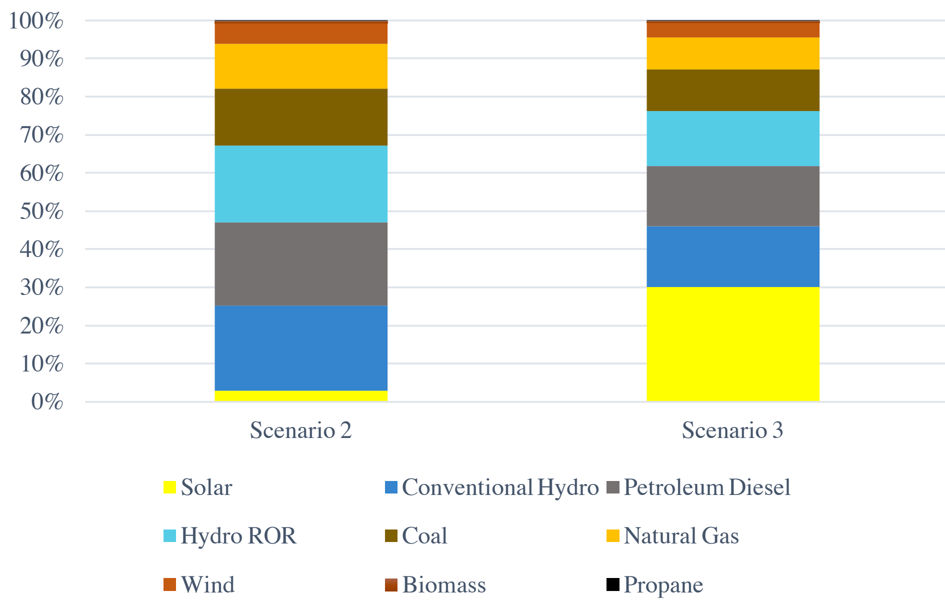


Figure 12. Energy required in the production of 300 kWh from different technologies under Scenarios 2 and 3

5. Environmental Impact Results

5.1 Greenhouse Gas Emissions

Global Warming Potential (GWP) factors express how much heat a greenhouse gas traps compared to an equivalent amount of CO_2 within a certain period of time (IPCC, 2014). The following table shows the GWP factors for the accumulated impact over 100 years of the most prominent greenhouse gases in each of the five assessment reports (AR5).

Table 7. GWP factors (AR5)

Substance	Cumulative forcing over 100 years
Carbon dioxide, fossil (CO_2)	1
Methane, fossil (CH4)	28
Methane, biogenic (CH4)	25.25
Dinitrogen monoxide (N2O)	265
Chlorofluorocarbons (CFC-12)	10200
Sulfur hexafluoride (SF6)	23500

IPCC (2014)

The SimaPro database was used to get the GHG emissions of fuels used in residential heating stoves. The units are grams of substance per kg of fuel, with exception of wood emissions in grams per kWh of heat produced, as it is shown in the following table:

Table 8. GWP emission data heating systems (g/kg)

Heating System	Carbon dioxide,biogenic	Carbon dioxide, fossil	Methane, biogenic	Methane, fossil	Nitrous Oxide	CFC-12	Sulfur hexafluoride
Pellet	49.336	125.757	0.014	0.358	0.496	1.55E-07	2.14E-05
Wood (g/kWh)	706.217	61.367	1.299	0.072	0.925	5.58E-08	1.50E-06
Paraffin	43.035	683.824	0.114	1.263	2.540	1.56E-06	1.48E-05
LNG	0.007	1.885	0.000	0.018	0.005	5.34E-10	4.77E-08

The emissions of $CO_{2\text{-eq}}$ per kg of fuel burned (and per kWh of heat from wood) are calculated with the GWP factors, as detailed in the table below:

Table 9. CO2-eq emission data heating systems (g CO2-eq/kg of fuel)

Heating System	Carbon dioxide,biogenic	Carbon dioxide, fossil	Methane, biogenic	Methane, fossil	Nitrous Oxide (N2O)	CFC-12	Sulfur hexafluoride
Pellet	49.336	125.757	0.359	10.029	131.423	0.002	0.502
Wood	706.217	61.367	32.790	2.012	245.032	0.001	0.035
Paraffin	43.035	683.824	2.871	35.361	673.034	0.016	0.348
LNG	0.007	1.885	0.001	0.507	1.309	0.000	0.001

Data from SimaPro was also used in order to quantify the impact of the production of 1 kWh of electricity from different sources. For this study, the emissions from solar electricity production is assumed zero:

Table 10. GWP emission data electricity production technologies (g/kWh)

Technology	Carbon dioxide,biogenic	Carbon dioxide, fossil	Methane, biogenic	Methane, fossil	Nitrous Oxide (N2O)	CFC-12	Sulfur hexafluoride
Conventional Hydro	25.526	1002.388	0.174	3.853	2.922	2.67E-07	5.82E-06
Petroleum Diesel	0.481	308.608	0.001	0.192	5.133	5.23E-08	1.85E-06
Hydro ROR	0.093	4.267	0.000	0.007	0.016	5.36E-09	2.04E-07
Coal	1.316	1095.022	0.006	1.534	3.174	6.72E-08	1.25E-06
Natural Gas	2.679	725.210	0.010	2.452	1.548	2.31E-07	1.75E-05
Wind	0.689	26.303	0.003	0.069	0.083	1.04E-06	1.04E-06
Solar	0.000	0.000	0.000	0.000	0.000	0.00E+00	0.00E+00
Biomass	1536.654	119.232	0.009	0.206	0.710	1.74E-07	4.83E-06
Propane	1.104	308.117	0.002	0.222	0.301	3.26E+00	2.89E-06
Total	1568.542	3589.147	0.206	8.535	13.887	3.26E+00	3.54E-05

Table 11 summarizes the emissions that comes from the SIC grid electricity production in g of $CO_{2\text{-eq}}$ /kWh, for Scenario 2 and 3:

Table 11. CO2-eq emission data electricity production SIC grid (g CO2-eq/kWh)

	Carbon dioxide, biogenic	Carbon dioxide, fossil	Methane, biogenic	Methane, fossil	Nitrous Oxide (N2O)	CFC-12	Sulfur hexafluoride
Scenario 2	17.917	543.221	1.047	39.829	647.527	31.080	0.051
Scenario 3	12.919	391.686	0.755	28.719	466.895	22.410	0.037

Finally, the chart below shows the GHG emissions for each Scenario in the production of 1 MWh of heat. The emissions of carbon dioxide biogenic from heating systems are larger than electricity, the same situation for methane biogenic but in lower amounts of $CO_{2\text{-eq}}$. However, the emissions of carbon dioxide fossil, nitrous oxide and methane fossil are higher in Scenarios 2 and 3 mainly because the use of fossil fuels for electricity production.

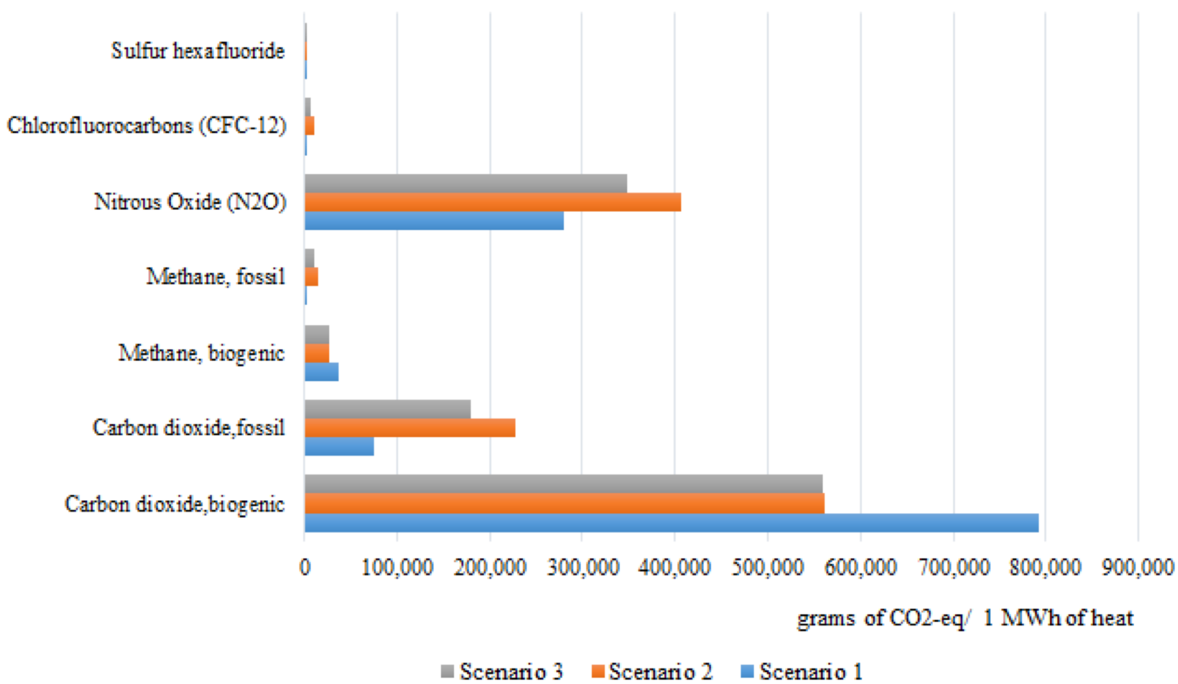


Figure 13. GHG emissions under 3 different scenarios (g CO2-eq/ functional unit)

5.2 Particulate Matter

According to the International Reference Life Cycle Data System handbook published by the European Commission, particulate matter is measured in a variety of ways: total suspended particulates (TSP), particulate matter less than 10 microns in diameter (PM10), particulate matter less than 2.5 microns in diameter (PM2.5) or particulate matter less than 0.1 microns in diameter (PM0.1) (European Commission, 2010). Tables 12 and 13 show the PM emissions from fuels, in grams per kg of fuel (wood in grams per kWh of heat), and technologies for electricity production, in grams per kWh:

Table 12. PM emissions of different fuels (g/kg)

Heating System	Particulates, > 10 µm	Particulates, > 2.5 µm, and < 10µm	Particulates, < 2.5 µm
Pellet	0.097	0.026	0.115
Wood	0.030	0.050	0.675
Paraffin	0.313	0.166	0.208
LNG	3.47E-04	1.46E-04	4.08E-04

Table 13. PM emissions of different technologies for electricity production (g/kWh)

Technology for Electricity Production	Particulates, > 10 µm	Particulates, > 2.5 µm, and < 10µm	Particulates, < 2.5 µm
Conventional Hydro	0.795	0.180	1.224
Petroleum Diesel	0.016	0.005	0.631
Hydro ROR	0.031	0.013	0.005
Coal	1.153	0.067	0.503
Natural Gas	0.082	0.024	0.089
Wind	0.084	0.026	0.022
Solar	0.000	0.000	0.000
Biomass	0.068	0.028	0.084
Propane	0.023	0.007	0.025
Total	2.252	0.350	2.584

Figure 14 shows the PM emissions for each Scenario in the production of 1 MWh of heat. The greatest emissions of PM 10 are in Scenario 1, mainly due to the use of firewood. However, the main air pollutant is PM 2.5, which is also the most dangerous for human health. There is a slight decrease in emissions by incorporating a higher proportion of electricity as an alternative technology (Scenario 2), and a 15% reduction of this pollutant when considering a more diversified electricity supply (Scenario 3).

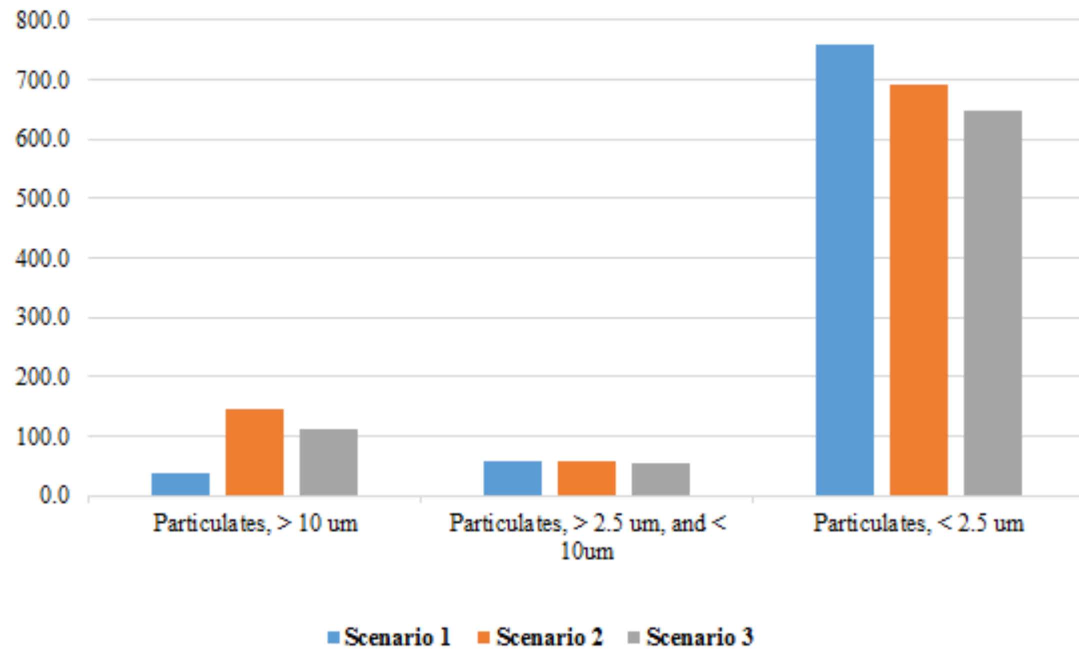


Figure 14. PM emissions under 3 different scenarios (g PM/ FU)

5.3 Sensitivity Analysis GWP

The results of the study prove that encouraging homeowners to use electricity for residential heating might be an effective solution in decreasing the concentrations of particulate matter in the air, especially PM 2.5. However, there is a negative impact in the GHG emissions from the electricity production, due to the high dependency on coal-based thermal power plants in Chile.

If the goal is to reduce this impact, the contribution of solar energy should be at least 90% in the case of $CO_{2\text{-eq}}$ emissions from carbon dioxide fossil, and 60% in emissions from nitrogen oxides. This situation is for all scenarios where electricity is introduced for residential heating in 20%, 40%, 60% and 80%, as is shown in Figures 15 and 16.

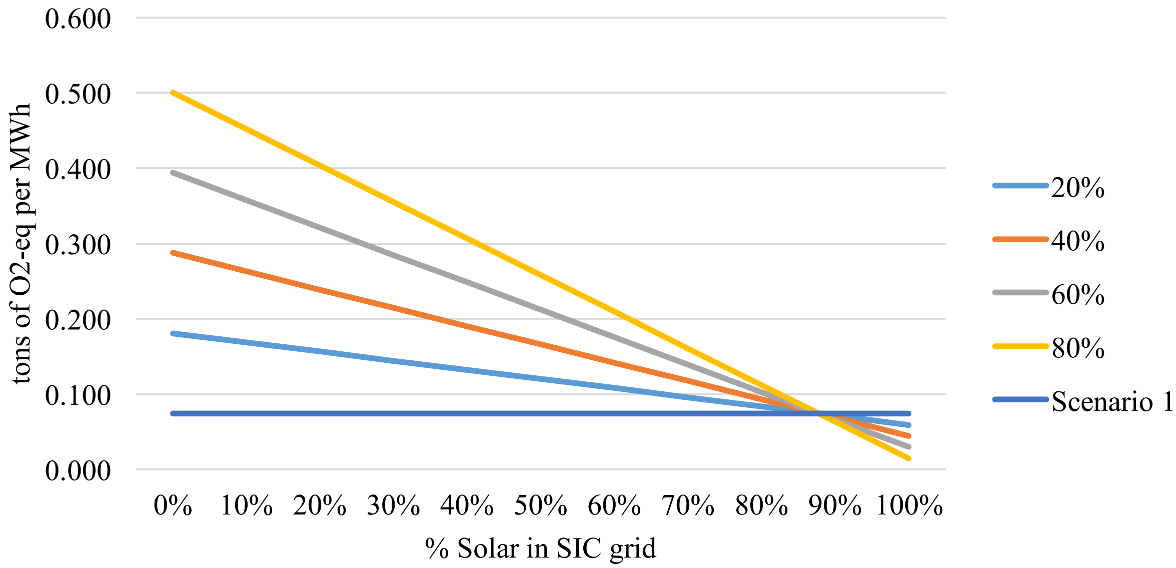


Figure 15. CO2-eq from carbon dioxide fossil in electricity for heating vs % Solar in SIC grid

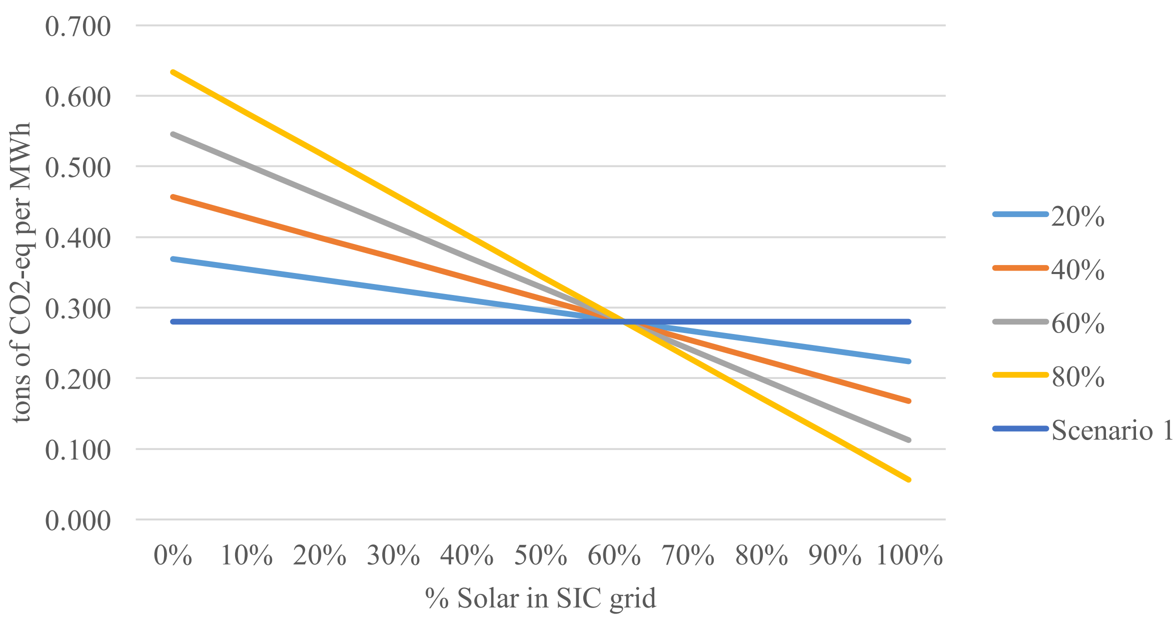


Figure 16. CO2-eq from nitrogen oxides in electricity for heating vs % Solar in SIC grid

In an ideal scenario, where solar energy replaces 100% the electricity generation from coal, natural gas and petroleum diesel, and hydro run of river replaces 100% conventional hydro, the use of 30% of electricity with these characteristics would reduce in 27.8% the emissions of $CO_{2\text{-}eq}$ from carbon dioxide fossil compared with heating systems, and 76.6% from the current electricity matrix.

In addition, 30% of electricity for residential heating would reduce in 29.5% the emissions of CO_{2eq} from nitrogen oxides compared with heating systems and 51.4% compared with the current electricity mix.

Finally, the total reduction of $CO_{2\text{-}eq}$ under this ideal scenario would be 0.35 tons per functional unit compared with heating systems and 0.4 tons per functional unit compared with the current electricity mix in Chile.

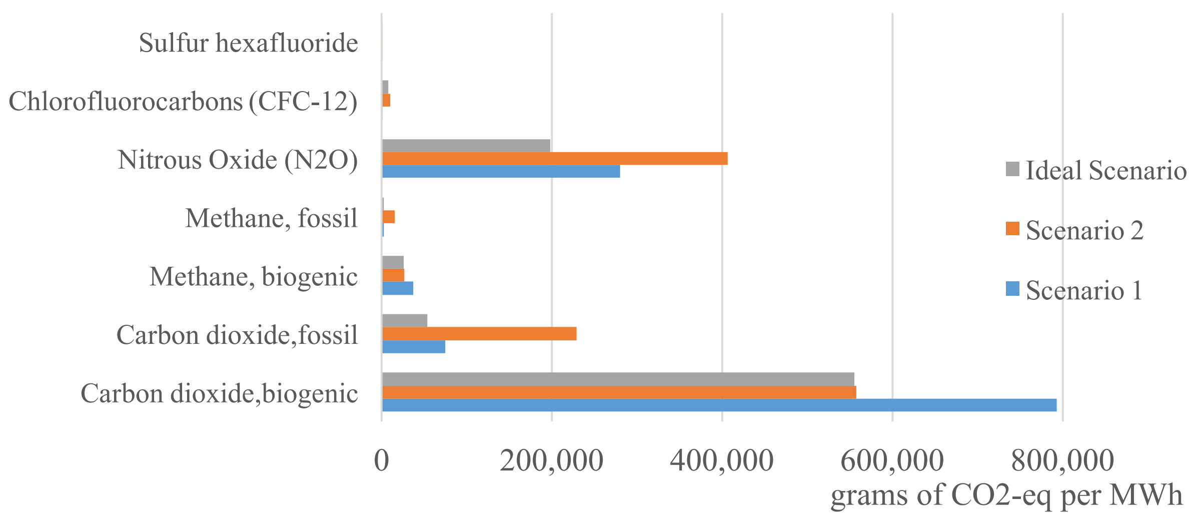


Figure 17. GWP emissions per functional unit

5.4 Sensitivity Analysis PM

In all the scenarios, a higher contribution of electricity for residential heating reduce the emissions of fine particles, and this reduction is higher when solar energy is introduced into the grid. For higher percentages, the gap between Scenario 1 and Scenario 3 is larger. This situation can be seen for particles smaller than 10 microns in diameter in Figures 18 and 19:

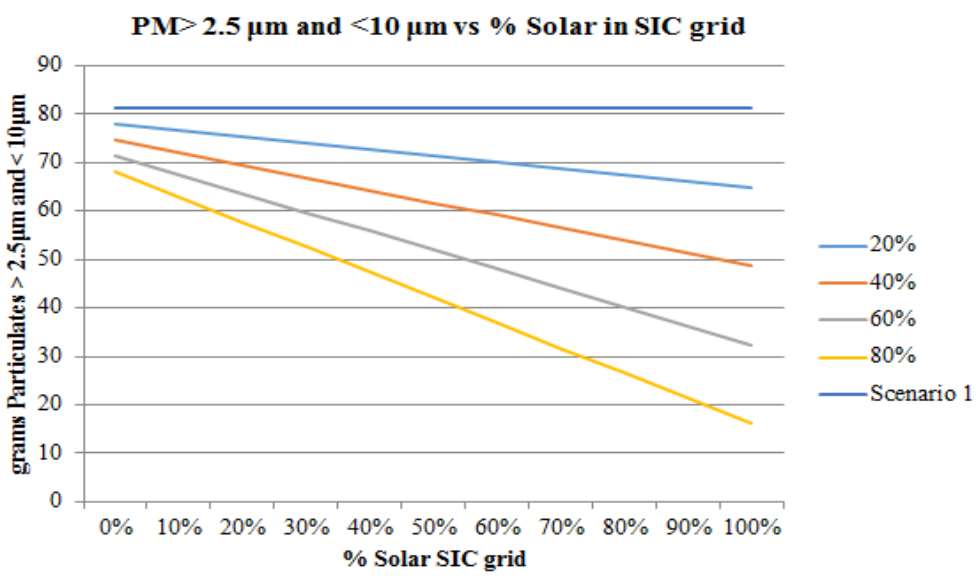


Figure 18. Comparison of 2.5µm <PM< 10µm emissions for Scenario 1 and electricity with different contributions of solar

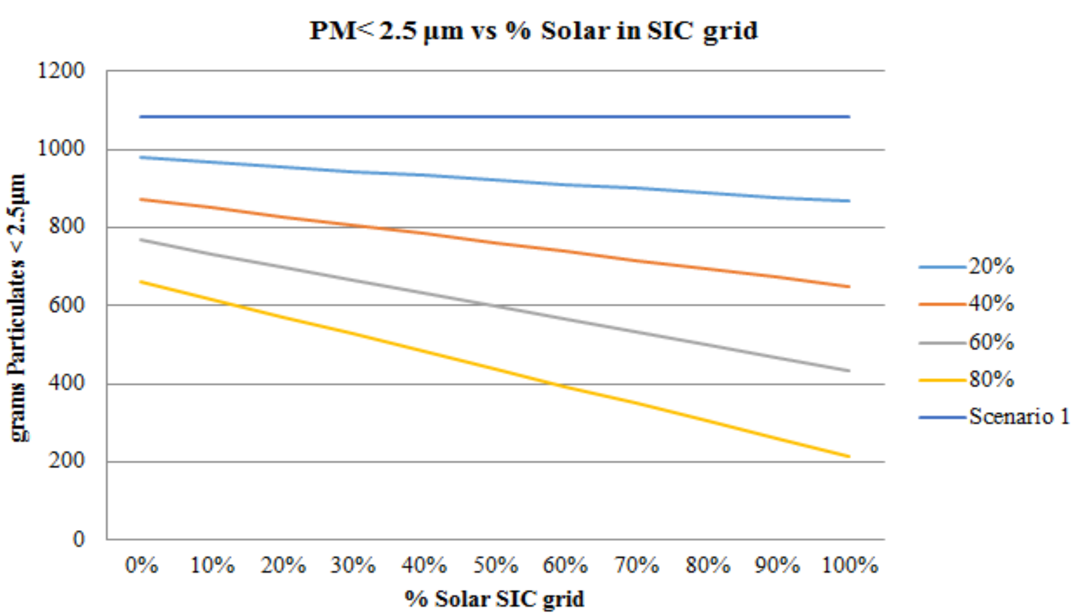


Figure 19. Comparison of PM<2.5µm emissions for Scenario 1 and electricity with different contributions of solar

Even though the impact of electricity in the reduction of particles bigger than 10µm is not significant compared as fine particles, the most important issue for human health corresponds to the last one. However, if the goal is to reduce those particles, the contribution of solar energy in the grid should be at least 90%, offsetting the impact of fossil fuels in this process.

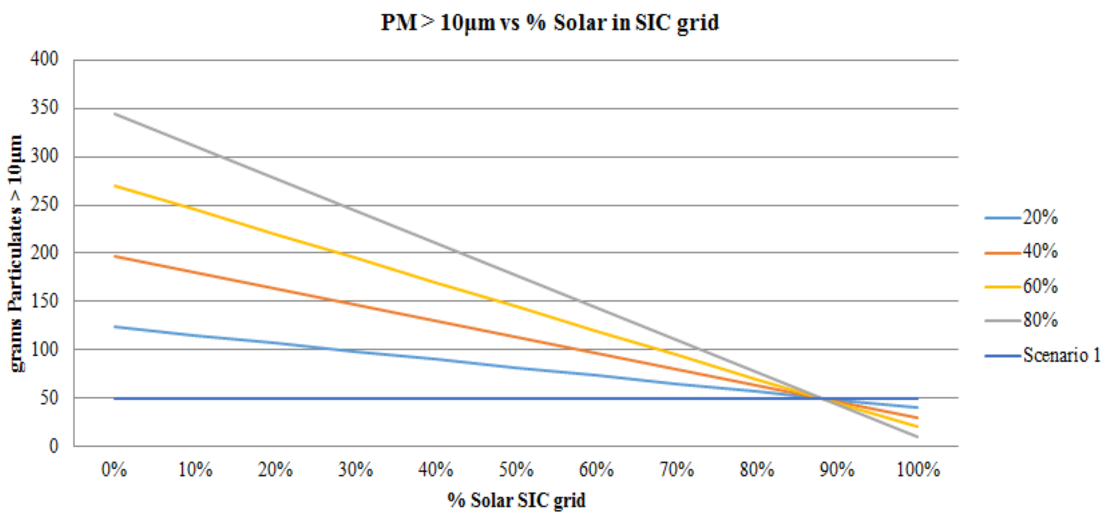


Figure 20. Comparison of PM> 10µm emissions for Scenario 1 and electricity with different contributions of solar

6. Conclusions and Recommendations

It is projected a total population of 18.8 million people in Chile by 2020, from which 34% is expected to live in Central-Southern cities (INE, 2014). On the other hand, recent studies demonstrate the growing energy demand for residential heating from 3.7 TWh to 5.42 TWh by 2020 and 7.9 TWh by 2040 (UNTEC, 2014).

Under this situation, it is projected a demand of 1.7 megatons of wood to satisfy the demand of residential heating by 2020, and 2.5 megatons by 2040, assuming that 90% of this fuel is required for that purpose. If this demand is translated into number of trees, more than 220,000 trees would be required to meet the demand by 2020, and more than 320,000 by 2040, assuming 7 tons of dry mass per tree.

Even though biomass is abundant in Chile, it is essential to consider the possible depletion of this resource, and therefore encourage the use of other energy alternatives that can meet the growing demand in the coming years.

In southern cities in Chile, air pollution is a permanent issue all the year because the most common residential heating technologies are based on firewood, fuel that burned in non-efficient stoves produce high amounts of particulate matter. Recently, one of this cities (Coyhaique) recorded the highest points of pollution per hour: the city had a peak of 882 micrograms per cubic meter of PM 2.5 in 2015 (CNN, 2016), i.e. almost five times more than what is considered an environmental emergency.

The results of this study prove that the main pollutant from these heating systems are fine particles, which represent a high risk to human health. However, if electricity replaces 30% of the current heating systems, the emissions of PM 2.5 would be reduced in 9.5%, moreover, if 30% of that electricity comes from solar energy, the reduction of fines particles would be 17.2%. In an optimistic scenario, when 80% of heating systems are based on electricity, the reduction of this pollutant would be 30%, in addition, if this electricity is 30% solar, the reduction of PM 2.5 would be 63.9%.

Also, the use of firewood in all the scenarios proposed, contribute the most in the GHG emissions related with carbon dioxide biogenic and methane biogenic, nevertheless, the high dependency on fossil fuels for electricity production generates a high impact in the $CO_{2\text{-eq}}$ emissions from carbon dioxide and methane fossil, as well as nitrogen oxides.

To reduce the GWP in the scenarios where electricity is used for residential heating, the grid will have to become cleaner, reducing the amount of coal and petroleum as well as conventional hydro. Despite being renewable, conventional hydro presented a high number of GHG emissions, this could be attributable to the environmental impact of the downstream water that flows from the dam and inundates green fields that will decompose and generate GHG, mainly methane.

In an ideal scenario, where solar energy replaces 100% the electricity generation from coal, natural gas and petroleum diesel, and hydro run of river replaces 100% conventional hydro, the use of 30% of electricity with these characteristics would reduce in 27.8% the emissions of $CO_{2\text{-eq}}$ from carbon dioxide fossil compared with heating systems, and 76.6% from the current electricity matrix. In total, the reduction of $CO_{2\text{-eq}}$ under this ideal scenario would be 0.35 tons per MWh of heat produced, compared with heating systems and 0.4 tons MWh compared with the current electricity mix in Chile.

In conclusion, the replacement of heating systems for electricity would be a solution to reduce the emissions of PM, especially fine particles. However, this would have an impact in the GHG emissions that comes from fossil fuels in the electricity production, such as carbon dioxide fossil, nitrogen oxides and methane fossil.

The reduction of the GWP is an important issue that each country of the world should introduce as part of the public policy. Developing nations tend to be less willing to participate on this type of policy since the problem was mainly triggered by developed nations, and this change on policy can play against their own development. However, Chile is a country committed to reduce its carbon footprint and participate on GWP policies.

Currently, there is a high dependence on biomass by heating systems in Chile, projecting a high intensity in the use of this resource, risking a possible depletion. It is essential to encourage the use of other energy alternatives that can meet the growing demand in the coming years. It is suggested from the results of this project, to stimulate the use of electricity for residential heating but, first of all, improve the quality of the energy produced in Chile by introducing less contaminant technologies such as solar.

With a coast that extends for over 4,000 kilometers and it's home to the world's driest desert, the country has privileged conditions for the development of non-conventional energy. At this time, the energy sector is one of the most dynamic areas of the Chilean economy. It is expected that within the next few years, a cleaner energy matrix becomes a reality that can benefit the quality of life of all Chileans.

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