Heat Roadmap Chile

Quantifying the potential of clean district heating and energy efficiency for a long-term energy vision for Chile

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Nomenclature

Country/Region Codes

CL	Chile
EU	European Union

Abbreviations

CCS	Carbon Capture Storage
CHP	Combined heat and power
CO_2	Carbon dioxide
COP	Coefficient of performance
DE	District energy
DH	District heating
EESM	Energy efficiency savings measures
GHG	Greenhouse gas
HP	Heat pump
HRCL	Heat Roadmap Chile
HRE	Heat Roadmap Europe (project series starting in 2012)
LSHP	Large scale heat pump
Mton	Million tons
MUSD	Million United States Dollars
OSM	©OpenStreetMap contributors
PELP	"Planificación Estratégica de Largo Plazo", Long-term strategic planning
PES	Primary energy supply: all energy that is used, before conversion, as input to supply the energy system
PM	Particulate matter
PV	Photovoltaic
RES	Renewable energy sources

Scenarios

A – E	Scenarios A, B, C, D, E; developed for the PELP [1]
Combo	Combined reference scenario using "

Executive Summary

The purpose of the Heat Roadmap Chile (HRCL) project is to create an evidence-based Roadmap to contribute to the discourse on the future of the heating sector and its role in Chile's energy system and air decontamination plans, as well as create the data, methods, and knowledge necessary to further develop the long-term planning for the future of the sector. This HRCL project is the first of its kind for Chile and builds on the Heat Roadmap Europe series of studies, which combine local (geographic) data with knowledge on energy savings and detailed all sector hour-by-hour energy system analysis. The project combines both the local potentials for the entire country – by creating the Chile Heat Demand Map – and assesses the country-wide potential for district heating. This is combined with modelling the country's energy systems as a whole, allowing for the development of a Heat Roadmap Chile scenario for 2050, and an insight towards the overall Chilean energy perspective.

Currently, the heating demand is mostly covered by individual heating technologies, which are commonly fueled using biomass. The existing technologies tend to be inefficient and highly polluting, which result in hazards to the health of the local population due to the poor air quality from high concentrations of particulate matter, and subsequently in high public spending on remedial measures [2]. In addition to ambitions regarding the particle emissions coming out of the heating sector, Chile is a signatory to the Paris Agreement, indicating the national commitment to contribute to the reduction of greenhouse gas (GHG) emissions. Moreover, energy planning is expected to need to continue supporting the overall objective of supplying (sustainable) energy to all nationwide and balance the environmental and economic needs of the forestry sectors with the biomass demands in the energy system.

In Heat Roadmap Chile, a redesign of the future heating and energy system for Chile is simulated using only proven and market available technologies. This shows that it is possible to combine the current decontamination and decarbonization approaches (typically regarding better thermal performance of buildings and more efficient individual supply systems) with wide-spread district heating using excess heat, efficiency and renewable sources.

Results

By providing the scientific evidence and tools that can support the decontamination and decarbonization of the heating and energy sector in Chile, an alternative vision for the future energy system of Chile is presented and new planning instruments and enabling frameworks can be developed and encouraged, enabling new policies and preparing the ground for a radical transformation of the heating market and the associated new investments. This is done based on a socio-economic approach towards energy system analysis.

The resulting Heat Roadmap Chile scenario for 2050 has a 40% district heating market share. This district heating has a highly diverse, efficient, and flexible supply system, which consists mostly of highly efficient cogeneration (60%), large scale heat pumps (20%), excess heat from industry (10%), and the remainder being supplied by a combination of direct renewables such as geothermal and solar thermal energy, with a small share of direct biomass boilers. This system both allows for a high level of efficiency by integrating excess heat from industry and power production that would otherwise be wasted and renewability, by unlocking the potential to use geo- and solar thermal. At the same time, the increased flexibility (driven by the interconnection between the thermal and electricity sectors, in the form of cogeneration and large-scale heat pumps) allows for a higher level of integration of (intermittent) renewable electricity sources.

The 40% district heating market share roughly corresponds to the areas indicated as 'dense' and 'very dense' in the Chile Heat Demand map, with the largest relative market share potentials being in the Región Metropolitana de Santiago, Región de Magallanes y Antártica Chilena, Región del Bío-Bío, and Región de Valparaíso. These findings mean that the large market share for district heating nationally, mean that for many cities, a substantial coverage and city-wide network is socially cost-optimal.

To decontaminate, decarbonize, and reduce energy system costs simultaneously, inefficient (fossil) fuel consumption is replaced with energy efficiency and renewable energy in the heating and electricity systems. This has the potential to significantly reduce imports of fossil fuels and improve the balance of payments, while also increasing investment in the development of local energy efficiency and use of local resources. It also creates an energy system which is more resilient to fuel price fluctuations, as more expenses are tied to investments. The scenario development in Heat Roadmap Chile 2050 allows for the decontamination of the heating sector through cleaner heating; faster decarbonization; affordable comfort and health, increased security of supply, and presents an enabling pathway to a 100% renewable energy system.

Based on the data, knowledge, methodologies, and scenarios developed and made available by the Heat Roadmap project, it is clear that Chile should also focus on implementing district heating projects and city-wide networks at the local level, and develop enabling frameworks and markets to support the widespread implementation of district heating technologies and infrastructures.

Decontamination through cleaner heating

- By reducing PM emissions from heating to only 1,600 tonnes per year. This represents a 99% reduction compared to today and a 40% reduction compared to only considering more efficient boilers, electrification, and increased thermal performance of buildings.

Faster decarbonization

- CO_2 emissions reductions, with the total energy system (including heating, electricity, and transport) emitting 82.2 Mton energy relayed CO_2 emissions per year. This is the lowest level of CO_2 emissions compared to all the scenarios, and on average having a 20% lower contribution to energy-related CO_2 emissions than the alternatives.

Affordable comfort and health

- There are no additional total socio-economic energy system costs compared to conventional approaches, and a slight decrease in the costs if considering only the heating and electricity sector. On top of this, there are likely to be benefits that arise from cleaner indoor and outdoor environments; increased indoor climate and prevention of under-heating related illnesses.

Increased security of supply

- The use of fossil fuel in the Heat Roadmap for Chile can be reduced by over 130 TWh/year, by halving the use of natural gas and eliminating the use of coal. This significantly reduces the need for natural gas imports.

Cost-efficient transition to 100% renewable energy

- The scenario for Heat Roadmap Chile here aligns, in its approach, with the potential further development of a Smart Energy System, which in the long run supports and enables a full transition to 100% renewable energy.

In order to realize this transition, an integrated planning approach is recommended. Concretely, this involves recommendations at the national level to create clear, long-term visions that consider the whole energy system, and which take into consideration the synergies that exist between the different sectors of the energy system. For district heating specifically, an enabling framework is required that recognizes the natural monopolistic nature of district heating and allows for regulation and policy to safeguard against on the one hand under-provision of district heating; and on the other hand, protects consumers. In addition, district heating should be integrated into existing policy instruments, such as the development of decontamination plans and the framework surrounding the development of (decentralized) electricity production.

Al a local level, the development of integrated energy planning is recommended to both take place through the support of pilot projects, but develop longer term plans to ensure ongoing expansion, so that in the long run the full market potentials can be capitalized upon to provide their environmental and socio-economic benefits. In particular, the development of several innovation regions is recommended, to be able to showcase the impact of district heating at a city-wide level and function as a frontrunner and test case in Chile.

Methodology and approach

The overall objective in the Heat Roadmap Chile project is to provide new capacity and skills for lead-users in the heating energy sector, including policymakers, planners, civil society, researchers and private partners at local and national level. These data, freeware tools, methodologies, analyses, results, and training materials are made available online.

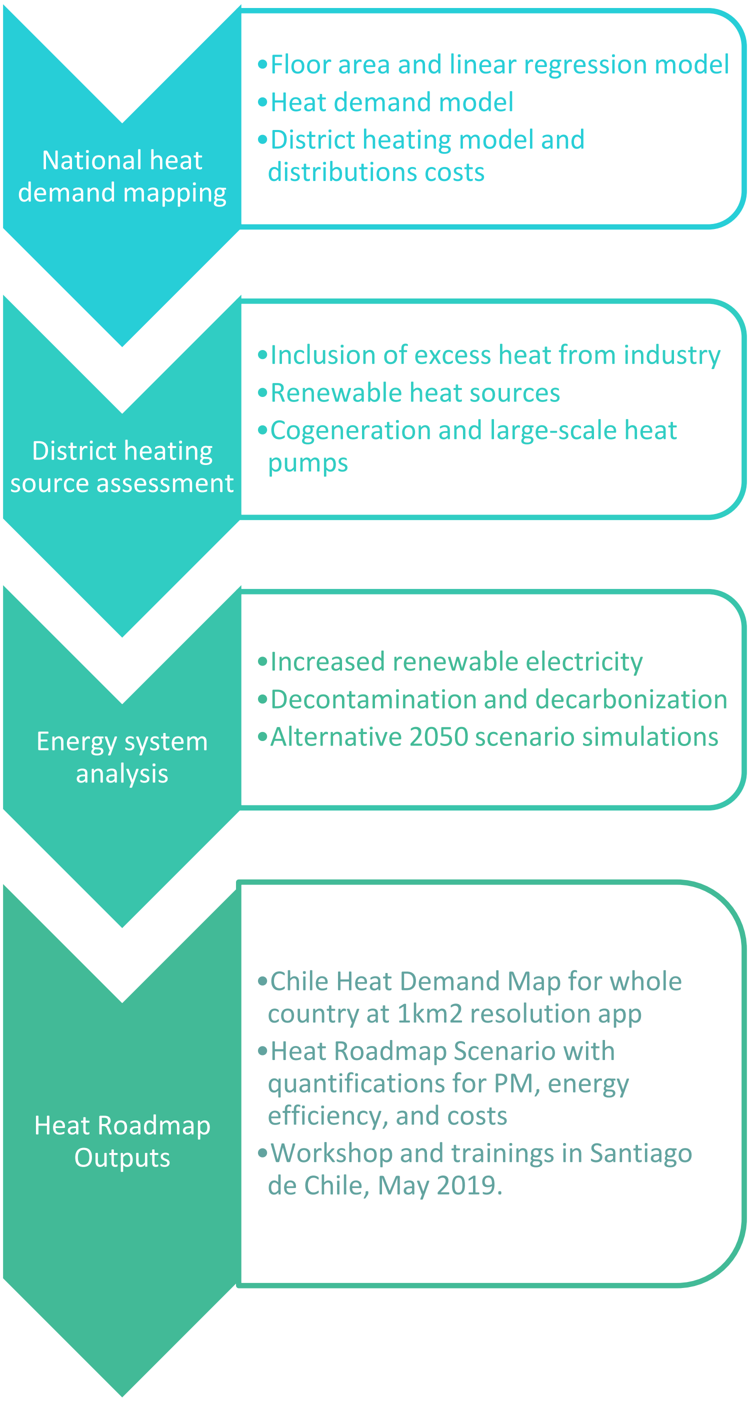
To develop the Chile Heat Demand Map and Heat Roadmap for Chile scenarios, several unique methods for energy planning, modelling and simulating have been combined based on the Heat Roadmap methodology, which has been in development since 2012 and has been applied to almost 30 countries. The Heat Roadmap methodology aims to both recognize the inherently local nature of heating (and particularly district heating), but with the understanding that the design and development of the heating system should be aligned with and in support of reaching the strategic objectives of the wider energy system. Underpinning the Heat Roadmap methodology is the combination of energy mapping and systems modelling of all sectors of the energy systems modelling, in order to be able to understand not just the national system effects of district heating but also the local dimension.

This includes a detailed spatial analysis in order to be able to understand the local nature of heating demands and in order to more accurately appreciate infrastructure costs. The Chile Heat Demand Map was developed using a floor area and a regression model, in order to establish a heat demand map with km^2 level mapping of thermal energy demands. In addition, cost curves for the investment in district heating transmission and distribution infrastructure, as well as energy losses in district heating, have been made for Chile in the HRCL project and used as inputs for the energy system simulation.

These district heating specific inputs have then been combined in the development of the energy system analysis. This hour-by-hour energy system analysis allows for an understanding of the impact of district energy, while including all other energy sectors. This approach ensures lower overall costs for the wider energy system, and avoids a suboptimal design based on only the heating system. Together, this results in a quantification of the effect of district energy on the decontamination and decarbonization of an integrated energy system.

Outputs

In addition to this report, the direct outputs of the Heat Roadmap Chile project have been the development of the Chile Heat Demand Map and its associated floor area and regression models; cost curves for the investment costs for district heating infrastructure in all Chilean regions; the design of almost 50 simulation models of the Chilean energy system (including the final Heat Roadmap Chile scenario for 2050) in the EnergyPLAN tool, and a variety of datasets to support the development of these models. These, and several training materials for their use, are all freely available.



The results of this work were presented and discussed during 2 days of workshops and 2 days of bilateral meetings in Santiago de Chile in May of 2019. Participants included planners and policy makers from local, regional and national government level; academics from engineering and regional development fields; civil society groups; and representatives from the private sector.

During these events, preliminary results were presented and discussed for feedback. In addition, the models and data that have been developed for this project were presented at the energy mapping and energy modelling workshops, with the dual focus of allowing for targeted feedback, and providing a training activity before the resources were made publicly available.

Key messages from Heat Roadmap Chile

1	**A 40% market uptake of district heating can aid to reduce total particulate matter pollution from the heating sector by approximately 99% compared to today, which could potentially result in almost 2,500 MUSD of savings for public health measures and approximately 2800 lives saved annually.**

- In the proposed Heat Roadmap for Chile scenario, PM emissions from heating are almost completely eliminated from urban areas. This could potentially result in almost 2,500 MUSD of savings for public health measures currently allocated for remedial measures, and approximately 2800 lives saved annually [2].
- This reduction is not due to a decreased overall biomass consumption, but rather due to its shift towards centralized combustion, where emissions are more easily reduced. For example, even though a highly efficient individual (pellet) biomass boiler only has a PM emission of approximately 10 mg/MJ, a centralized unit (in the form of a cogeneration plant or district heating boiler) is typically expected to be approximately 0,3 mg/MJ.
- This technology shift is the main driver behind the decrease in PM emissions in the Heat Roadmap for Chile, since the use of district heating also allows for the use of these much cleaner centralized combustion units.
- Total $PM_{2.5}$ and PM_{10} emissions for heating and electricity amount to only 1600 tons per year in the Heat Roadmap Scenario for 2050.

2	**The heating sector can be efficiently covered by district heating, which can cost-optimally supply around 40% of the heating market without representing additional costs in 2050.**

- In the proposed Heat Roadmap for Chile scenario for 2050, a 40% market share for district heating can be considered cost-optimal, in that it presents a balance of lower socio-economic cost to the energy system and allows for the fulfillment of decontamination and decarbonization objectives.
- Up to around 50% of the heating share could be supplied by district heating, without the costs exceeding the reference scenario, indicating that the 40% chosen in the Heat Roadmap Chile scenario is a conservative measure and district heating has the potential to play an extremely important role in the heating and energy system in Chile.
- While there are large variations between the different regions, based on this result, it is clear that Chile should focus on implementing district heating projects and city-wide networks at the local level and develop enabling frameworks and markets to support the widespread implementation of district heating technologies and infrastructures.

3 **District heating infrastructures are a prerequisite to being able to use multiple types of local direct renewable and efficiency options, unlocking the potential for decontamination and efficiency.**

- The inclusion of diverse sources in the district heating supply mix, rather than heat-only boiler systems, results in a scenario where a more complex, diversified, and realistic future district heating system is simulated.
- The supply mix consists of highly efficient cogeneration based predominantly on biomass (60%), large scale heat pumps (20%), excess heat from industry (10%), and the remainder being supplied by a combination of direct thermal renewables such as geothermal and solar thermal energy, with a small share of direct biomass boilers.
- This system both allows for a high level of efficiency by integrating excess heat from industry and power production that would otherwise be wasted and renewability, by unlocking the potential to use geo-and solar thermal.

4 **A redesign of the heating system can bring about large reductions in the primary energy supply, thereby making a more secure and efficient system.**

- District heating in the Heat Roadmap for Chile facilitates the efficient use of energy through the integration of excess heat from industry, the use of excess heat from power production in cogeneration, and through the improved use of renewable energy resources.
- Overall, this leads to a 13% reduction in primary energy compared to the reference scenario, and a large reduction in the need for coal and natural gas. This contributes to the Heat Roadmap for Chile having the lowest level of CO_2 emissions for the entire energy system compared to all the scenarios, and on average having a 20% lower contribution to energy-related CO_2 emissions than the alternatives.
- This reduction in fossil fuels greatly reduces the need for natural gas imports, strengthening the Chilean position with respect to international fuel price fluctuations and geopolitical considerations.

5 **The socio-economic costs of the energy system will not increase, and can be reduced through the implementation of district heating.**

- The proposed Heat Roadmap Chile scenario does not differ radically in total socio-economic costs compared to the (combined) reference scenario used in the *Planificación Estratégica de Largo Plazo (Energía 2050: Política Energética de Chile, Ministerio de Energía)* [1]. Looking at only heating and electricity, a slight decrease in annualized socio-economic costs is possible.

- This potential advantage comes primarily from the shift away from (fossil) fuels towards investments into local resources and infrastructures, having the potential to further boost local skills and economies, and also representing the shift away from variable costs and towards long-term investment costs.
- In terms of increasing and reducing markets, the largest changes in necessary investments are mostly in district heating related technologies (notably; heat exchangers and district heating supply technologies) and onshore wind capacity, with a comparatively lower need for large power plant investments if the Heat Roadmap Chile scenario is implemented.
- However, even though the total costs are lower, the implementation of district heating represents a radical shift from the current organization of the heating (and electricity) sector, so it is likely to implicitly require an (internal) redistribution of costs and benefits to provide an equal or low-cost solution for all involved stakeholders.

6	**The heating sector can play an important role by integrating the increasing shares of variable renewable energy and enhance the grid flexibility.**

- The Heat Roadmap for Chile aims to utilize the synergies between the energy sectors using an integrated approach. This mostly takes shape in the form of heat pumps, cogeneration, industrial heat recovery, and thermal storages.
- The use of flexible, dispatchable cogeneration capacity and renewable electricity in the heating sector can help balance the electricity grid when high levels of variable renewable energy are introduced, and allows for almost three times as much wind power integration, and a radical decrease in the need for large power plants.
- The scenario for Heat Roadmap Chile here aligns, in its approach, with the potential further development of a Smart Energy System, which in the long run supports and enables a full transition to 100% renewable energy.

7	**The benefits of district heating with regard to decontamination, decarbonization, and flexibility are most obvious when the infrastructure is implemented at scale, and demonstration projects and planning processes should aim towards developing a warm and clean city.**

- The benefits of district heating in terms of substituting inefficient biomass combustion are clearest when a city-wide approach is taken; with smaller pilots, the impact of air quality does not become clear if it is implemented in a few buildings spread throughout the city.
- One method of moving from pilot projects to lighthouse cities can be through the development of a competitive exemplary ‘clean and warm city’ to use as a case for other cities; both as a testing ground for technological solutions within a Chilean context, but also to develop stakeholder involvement and planning process innovations.

- For cities, a long-standing lighthouse function can be advantageous both in terms of collaboration with the private sector in order to test and showcase solutions, but also towards other regions and cities looking to learn from the capacities and experiences generated, and to generate and eventually export knowhow and expertise-based employment.

8	**Data, tools, models and methodologies specifically for heating and energy are an important part of planning and deployment for district heating and cleaner, decarbonized energy systems.**

- The Heat Roadmap methodology aims to both recognize the inherently local nature of heating (and particularly district heating), but with the understanding that the design and development of the heating system should be aligned with and in support of reaching the strategic objectives of the wider energy system. This requires both spatial and (hourly) energy system data, tools and models.
- Since heating is in some ways very local, data can be scarce, decentralized, or difficult to collect. In these cases, national datasets can be very useful to support the development of local solutions either by providing data and methodologies directly, or by allowing for benchmarks that can facilitate processes in earlier phases of energy planning and project development.
- In addition, the standardization of data and tools can allow for more widespread application and more secure and trusted decision results, and can help prevent the need for the repetitive development of new solutions, facilitating the more rapid deployment of district energy.

1 Introduction

In Chile, there are clear long-term goals to improve air quality and the living environment of the population. The purpose of these is to mitigate and reduce the effects of high levels of air pollution arising from inefficient wood burning for heating [2]. However, the pathways towards decontamination and the solutions to sustainably reach those goals are yet uncertain. The Heat Roadmap Chile (HRCL) project aids in the process of creating a new understanding of how a redesign of the heating sector can be beneficial for decontamination, while also contributing to the energy efficiency and decarbonization of the wider energy system. In doing so, this report sets out a long-term alternative that can help support the need for and prepare the ground for new initiatives and policies to support these processes.

The main purpose of the HRCL project is to create an evidence-based roadmap to present an alternative scenario about the future of the heating sector and its role in Chile's energy system and air decontamination plans. This work aims to support and broaden the discourse about the future of the sector and the overall energy system. Additionally, the project (and the data, models, methodologies, and additional materials made available with it in the project's website), serves as an input to the discussion and knowledge-building taking place among lead actors in the heating and energy sectors; policy makers, planners, industry and researchers at both the local and national level.

Currently, the heating demand is mostly covered by individual heating technologies, which are commonly fueled using biomass. The existing technologies tend to be inefficient and highly polluting, which result in hazards to the health of the local population due to the poor air quality from high concentrations of particulate matter, and subsequently in high public spending on remedial measures [2]. In addition to ambitions regarding the particle emissions coming out of the heating sector, Chile is a signatory to the Paris Agreement, indicating the national commitment to contribute to the reduction of greenhouse gas (GHG) emissions. In addition, energy planning is expected to need to continue supporting the overall objective of supplying (sustainable) energy to all nationwide and balance the environmental and economic needs of the forestry sectors with the biomass demands in the energy system.

Energy planning toward these long-term objectives, and long-term scenario development, is a process that is already taking place in Chile, and an ongoing development of further objectives and directions exists. This project builds heavily on the work done in 2017 under the umbrella of *Planificación Energética de Largo Plazo* (PELP), conducted by Chile's Ministry of Energy, using this as a reference for data and for long-term planning comparisons [1,3]. The scenarios that were developed during this time represent a point of comparison to the Heat Roadmap Chile scenarios in terms of presenting different pathways towards 2017 and 2050. At the same time, the developments of different pathways are expected to be updated, refined, and changed over time to reflect policy, knowledge, and innovation changes, and more appropriate reference scenarios may become available in the future. However, this project complements the PELP and other long-term planning scenarios by presenting a more specific focus on the role district heating can have in contributing to the decontamination of the heating sector and further efficiency and integration of renewables to the energy system. By aligning with these past initiatives and ongoing processes, the objective of Heat Roadmap Chile is also to provide an alternative and additional perspective on the potential pathways of the national heating and energy system, looking forward. This can then also feed into ongoing and future long-term planification processes.

Current approaches towards transition in the heating sector are typically characterized by an individual heating alternative approach. Increased standards for the energy performance of buildings, and support towards increased insulation of existing buildings, is used as a way to reduce heating and fuel demands and thus particle emissions. Regarding heat supply, individual heating alternatives either concern the replacement of inefficient stoves with more efficient biomass burners, or a resort to fossil fuels, which both have GHG impacts and have in the past been subject to limited access of supply and price shocks. On the other hand, individual alternatives relying on electricity, like building-scale heat pumps, are not yet accessible to certain sectors of the population. Moreover, the electricity needed for these would currently and come from a high share of energy produced from fossil fuels, which in turn can hinder climate change mitigation actions.

This report presents the development of an alternative solution. The scenario is designed and simulated in the form of a redesigned heating and energy system looking towards 2050, where district heating has a high market share and plays a large role in enabling cross-sectoral integration along with higher levels of variable renewable energy.

This approach used in the Heat Roadmap for Chile is based on the Heat Roadmap methodology, which has been in development since 2012, and has now been applied in over 28 countries [4–7]. The approach and methodology are based on a combination of spatial analysis and hourly energy system simulation, in order to combine both the local nature of heating and the national dynamics of the energy systems. A thorough spatial analysis of the heat demands is necessary to more accurately represent infrastructure costs and potential losses in a distribution grid and represent the local characteristics of (district) heating supply options. This is essential when considering district energy, since the cost of infrastructure to transport heat is relatively higher than the cost of transporting other forms of energy.

Subsequently, an energy system analysis approach is used to ensure that the synergies between heating and other components of the energy system are integrated into a more flexible and sustainable energy system, with a diversified and renewable supply. This is broadly in line with the Smart Energy System concept, which looks towards developing 100% renewable energy systems based on current available technologies [8][9]. In this way, the results demonstrate the impact of decontamination and increased energy efficiency in the heating sector based on a holistic design and assessment of the energy system. The results of this Heat Roadmap scenario allow for the quantification of the impact of implementing district heating along with renewable energy solutions as cleaner energy efficient alternatives are needed in Chile's future energy transition.

The results of this work were presented and discussed during 2 days of workshops and 2 days of bilateral meetings in Santiago de Chile in May of 2019. Participants included planners and policy makers from both local, regional and national government level; academics from engineering and regional development fields; civil society groups; and representatives from the private sector. During these events, preliminary results were presented and discussed for feedback. In addition, the models and data that have been developed for this project were presented at the energy mapping and energy modelling workshops, with the dual focus of allowing for targeted feedback, and providing a training activity before the resources were made publicly available.

2 Aims and Approach

The objective with HRCL is to demonstrate the potential of district energy on a nation-wide scale in order to reduce air pollution, increase the security of energy supply, and contribute to the reduction in GHGs. This is done by designing and simulating various long-term scenarios, and quantifying the impacts of having both more energy efficient infrastructures in the heating sector and more variable renewable energy and more flexibility in the (wider) energy system, provided by the integration of diversified supply sources and synergies across different energy intensive sectors.

The results of the Heat Roadmap methodology and scenarios can serve as a base for the further support and development of robust policies at the local and national level. These can support the development of radical technology changes that are necessary to ensure that the long-term energy planning objectives for Chile are met. In addition, the data, methods, models, and training materials developed can contribute to knowledge and capacity building initiatives to improve upon and generate such policy initiatives and allow for long-term planning.

The development of a long-term scenario that includes the development of district heating and implementation of renewables also allows for a quantified outlook, and vision towards the technical and market potential of different technologies. This in turn can play a role in bringing about more investments and support for the uptake of new technologies and infrastructures needed within the context of a cleaner and more efficient heating sector. For example, while the data and tools do not allow for feasibility-level assessments at a local level, they can help to guide an understanding of what areas should be targeted for (pre-)feasibility studies, and what types of supply options should be considered as options when designing local studies.

Furthermore, the long-term planning in HRCL provides an additional perspective on the available solutions that could complement and strengthen the existing plans proposed by the Chilean government towards meeting the country's renewable energy targets and the environmental decontamination goal of minimizing particulate matter emissions resulting from inefficient heating in urban areas.

Approach

Given the aims of Heat Roadmap Chile to incorporate both the local and national dimension of heating and integrate heating into a long-term energy system vision, the overall approach is underpinned by several approaches that together allow for the development of a Heat Roadmap. The approach and method are built on two main pillars: the development of a geospatial characterization of the heat demands, and an integrated analysis of the overall energy system. A depiction of this approach can be seen in Figure 1, and is further elaborated in Chapters 3 and 4 of this report.

Firstly, the use of a spatial heat demand model, named The Chile Heat Demand Map, allows for the identification of varying levels of heat demand densities around the country, and thus broadly maps areas in which district energy could be a potential solution. In addition, by having a spatial aggregation of the heat demands, it is possible to estimate the cumulative costs of the potential district heating grid at increasing levels of coverage of the heat demand and the associated energy losses that such a grid would encounter.

Following this, different scenarios of the energy system are developed and simulated using the results from the heat demand model, as well as other different sources such as the current energy balance, alternative scenario designs and projections to the year 2050, various system costs, and hourly energy demand and production profiles aggregated to a national level. Using the year 2050 facilitates the comparison of potential energy system designs while accounting for long-term considerations and projections, which provide a baseline for a long-term planning process. On the other hand, hour-by-hour simulations of the energy system allow for more nuanced analysis of how the different energy demands can be met.

This creates an understanding of how the synergies across the different energy sectors can be best exploited to allow for a more flexible energy system design with different variable renewable supply sources. This means that the heating system is designed in such a way that enables the integration of more renewable energy sources, while also allowing the electricity sector to be more flexible and further integrate these sources.

A simulation approach is chosen in line with the exploratory nature of the research conducted; the objective of HRCL is not to propose one optimal scenario, but rather to develop, quantify, and understand the mechanisms and ways in which district heating could contribute to the decontamination and decarbonisation of the Chilean heating and energy system. This is largely in line with a pragmatic and dialogue based model, in an effort to inform decision making rather than prescribe it [10].

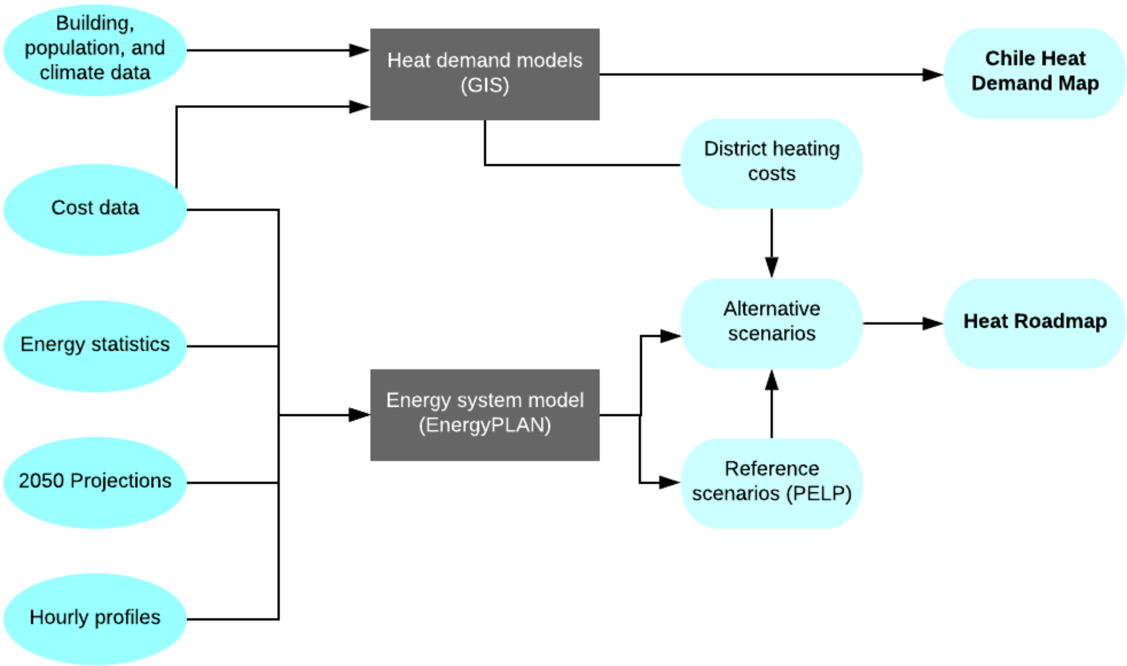


Figure 1. Data and model flow used under the Heat Roadmap Chile approach.

The development of different energy system scenarios considers functioning designs, where the supply can cover the energy demands throughout all the hours of the year, while meeting grid stability requirements. Although these different scenarios represent possible future alternatives, not all are necessarily in equal standing. The scenarios are all developed based on certain criteria and are assessed on the basis of multiple parameters rather than a single optimal indicator or constraint. The parameters considered in HRCL are a combination of the following:

- Primary Energy Supply (PES), defined as all energy that is used, before conversion, as input to supply the energy system, as indicator of the efficiency of the system
- CO_2 emissions that result from the energy system, indicating a level of decarbonization
- Socio-economic cost, to indicate the affordability and competitiveness of the various scenarios. This does not include the indirect costs and benefits on health due to particle emissions.
- Total particulate matter emissions resulting from the biomass' primary supply and its different combustion processes in the power and heating sectors.

Finally, it is important to note that the steps used to reach the Heat Roadmap scenario follow an iterative approach on the basis of the criteria mentioned above. This allows for a better identification of balanced solutions and an assessment of the trade-offs that occur by choosing different alternatives over the others. By means of this approach, a solution that is preferable over the others is identified while being grounded in comprehensive design criteria and a sound understanding of the compared scenarios.

3 The Chile Heat Demand Map

The Chile Heat Demand Map has been developed to create a geographic representation of the heat demands of buildings throughout the country. As no comprehensive database is available on the actual heat demand of the Chilean buildings, the demands presented in the map are estimated based on a (top-down) heat demand model. By mapping heat demands, it is possible to identify prospective areas where district heating could be technically feasible. Moreover, having a spatially explicit model of the district heating potentials allows for an economic analysis which can be further used as cost inputs for the expansion of district heating for the energy system analyses.

Map usage and methodology data

Before going deep into the models, this small section presents the correct usage of the map and principles on which the heat demand mapping bases its methodology. Visioning the national scope of this project, neither local or regional factors were considered, and coefficient weighting was chosen as mean and immediate practice when handling the available data for the study. Several sensitive hyper-local factors may have a considerable effect on the results presented in this report, hence it is encouraged to refine the tentative with more accurate data, if available. It is highlighted that this study shall be seen as a screening tool to be consulted for pre-feasibility studies at an early stage analysis of a potential area for district heating deployment. It provides the basic information needed to green light a project or narrow down potential district heating locations. The methodology shown however, intends to serve as mirroring and localized feasibility research with the correct implementation of local specifics and conceivably further accessibility to available information. Additionally, one must highlight the potential of this project deliverables when analysed on parallel with other ongoing Chilean projects aiming at identifying similar capacities e.g. potential district heating area distance to excess heat sources mapping identification and further economic viability assessment.

The methodology data sources show its own set of potentials and limitations which can be analyzed as the report progresses. As experienced from the data source selection, Chilean data availability and accessibility for the heating sector is limited. This, mainly due to the informal nature of the market of biomass fuel for heating purposes. Its consequent lack of measurability and traceability is known to be one of the nation's biggest challenge and having data as key element for planning and development, its improvement is essential. Moreover, although other databases were consulted for validation purposes, data interoperability represented a challenge due to data attributes lack of linkages and data format. Data's optimal potential is only leveraged when it is formatted to be interoperable and exchangeable at its generation stage amongst the different institutions involved on its gathering e.g. geo-coded building register linked to population census and utilities.

For the mapping presented in this report, floor area equals heated floor area, which differs from reality and undoubtedly influences heat demand density and further calculations taking this parameter as basis. Not only the ratio between constructed floor area and heated floor area are local, variant and unknown; but more importantly dependent on multiple technical, circumstantial, and socio-economic variables. Its assessment solely shall respond to a complementary analysis and be seen as extremely needed for the appropriate heat demand management and documentation.

Additionally, the regression model performed for the recording of data where insufficient census data takes departure on satellite data for both population and built-up areas. Taking satellite imagery interpretation as a condition, this means that the model by definition overestimates floor area where the dependent variables are located accordingly. When the results are summarized on a localized level, this issue becomes noticeable. Yet, when calculated heat demands are related to those floor areas, they show no crucial effect. Therefore, the regression model would not be as precise as the floor area model for rural/sparse areas where census data is not available – refer to Figure 5 and see *Región de Atacama* as example. For the object of this report which is to identify potential district heating areas in Chile, this particular effect is considered to have low incidence in the presented results, as the errors are mainly in low density areas.

Analytically, the 1 km^2 unit is used in order to simplify and facilitate mathematical and statistical calculations with disk space efficiency. Data consistency, uniformity and integrity are some of the benefits of working on a grid level, especially helpful for a nationwide level of analysis when operation overlaying is a key tool. However, apportioning attributes to a lower level of resolution causes drawbacks such as distorting vector data true representation of shape. Shape representation and location is specifically important when mapping heating since high heat demand can be represented by low heat densities on the grid, this for concentrated heat demands within the 1 km^2 analysis. The presented densities shall therefore not be interpreted as a homogeneously distributed measure along the 1 km^2.

3.1 Development of the Chile Heat Demand Map

To introduce the Chile Heat Demand map, a general overview of the model is presented in Figure 2. As seen in the figure, the method used to create the Chile Heat Demand Map revolves around four models in which data sources were used in a collective complementary system: a floor area model, a linear regression model, a heat demand model and finally, a district heating model which will be respectively explained in the following four subchapters.

In the process, when reaching the heat demand model, two outputs arise. The main one scales up to a 1 km2 grid, continues the process for the national heat demand model and serves as foundation for the Energy System Analysis chapter in 4.1. The secondary output from this process is a heat demand map on a block level. This product specific scale is per se not directly used, notwithstanding is perceived as a significant and enabler outcome for further deployments. Henceforth is added as one of the Heat Roadmap Chile deliverables.

The software used for the geospatial analysis performed is ArcGIS Desktop 10.6.1 and ArcGIS Pro 2.3.3 from ESRI Inc. (Environmental Systems Research Institute) which includes a rich analytical toolbox and modeling framework [11]. Additionally, scripts were used in ArcGIS toolboxes using Python language for the automation of processes and proper management of geographic data.

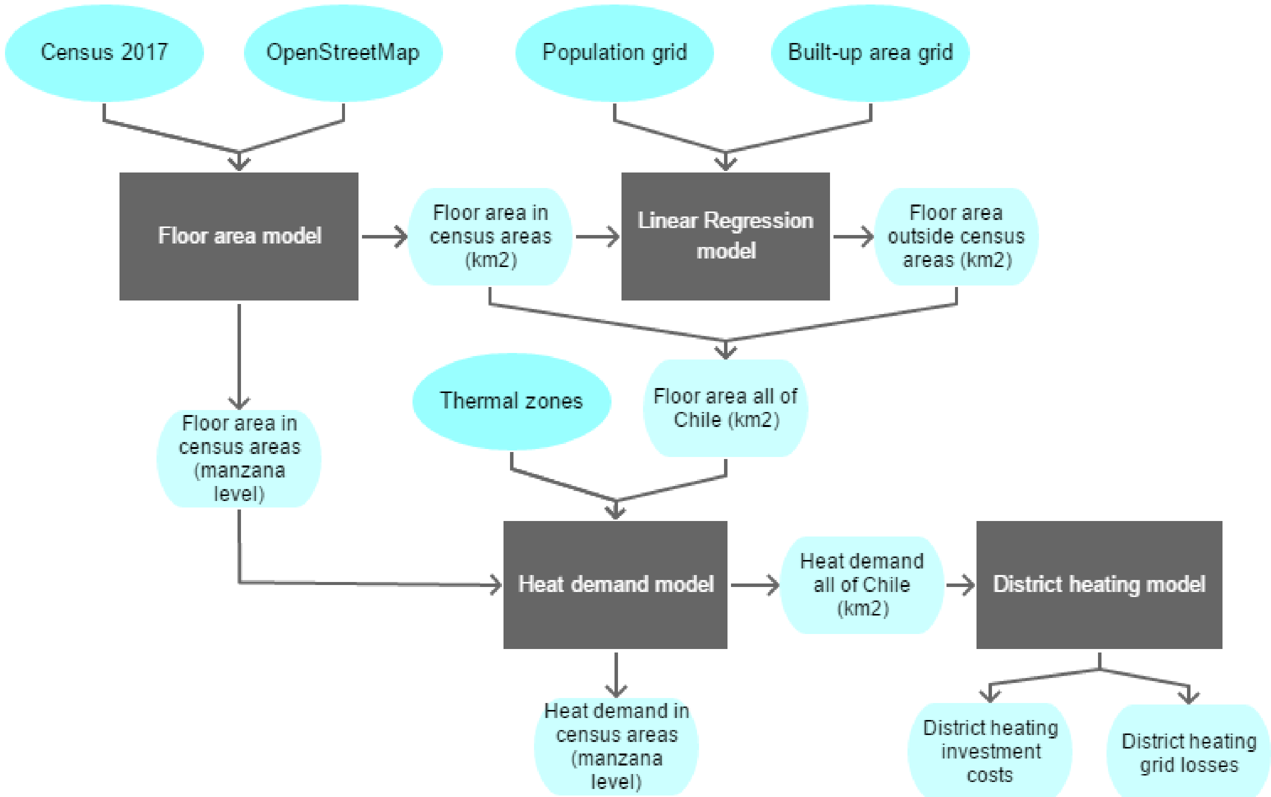


Figure 2: Heat demand map method flow chart

3.1.1 Floor area model

The starting point in the mapping process takes its point of departure using the obtainable inputs at the moment of its development. The 2017 Chilean national census provided by INE [12] is taken as the most accurate geographic representation of the number of people and buildings existing within a single or multiple urban/rural block area. Additionally, cartography is gathered for census blocks. By these means, non-georeferenced census database was then linked to georeferenced blocks through a block identification number (Manzana – Entidad {ID_MANZENT}). Both databases were obtained from the same source and were available for the entire nation.

High rise buildings represent the densest areas in the country, at the same time representing relevant heating demands and therefore potential district heating zones. However, due to the complexity of the floor area estimation for large (multistory) buildings, which neither population nor buildings data coming from the census would be able to predict in an accurate fashion, ©OpenStreetMap contributors (OSM) community driven mapping is simultaneously taken as a second source for the identification of large buildings [13]. Given the importance of such buildings and the reason that OSM buildings are considered a better floor area estimation for the available buildings within the country. Whereas census areas cover mostly the residential sector, OSM include buildings corresponding frequently to dense, non-residential areas. It is important to emphasize that OSM is data available under an Open Database License. The platform uses a variety of methodologies for its data verification and constant update, and as OSM is user driven the coverage of the country is relatively poor and mainly restricted to larger buildings.

Table 1 illustrates each input data specifications along with its attribute usage. As seen, both data sources denote certain potentials and limitations. Census data aggregation level and OSM buildings form a fairly strong spatial coverage. Regardless, the obvious challenge is the floor area estimation for census blocks starting off from the database attributes. To resolve this, an approach is used which includes the usage of the coefficients, both from *Corporación de desarrollo tecnológico de la Cámara Chilena de la Construcción* (CDT) and *Ordenanza general de urbanismo y construcciones del Ministerio de Vivienda y Urbanismo de Chile* (OUC) – refer to references at the table.

Table 1. Floor area Input data specifications

Data	Source (year)	Coefficient (year)	Format	Extent	Aggregation level	Attributes used
Census buildings	INE[1] (2017)	CDT[2] (2010)	.csv + .shp	Nationwide	Block(s)	# Buildings by type (House/Apartment)
						# Buildings by type (Collective/Particular)
						Rural/Urban
Census population	INE[1] (2017)	OUC[3] (2001)				# People
						Residential per capita built up area
©OpenStreetMap	OSM[4] (2019)	-	.shp		Building	# Floor levels Building area Building use

[1] Instituto Nacional de Estadísticas de Chile [12] [2] Corporación de desarrollo tecnológico de la Cámara Chilena de la Construcción [14] [3] Ordenanza general de urbanismo y construcciones del Ministerio de Vivienda y Urbanismo de Chile [15] [4] **©OpenStreetMap** [13]

The 2010 CDT report compiles an array of technical information regarding energy usages for various building typologies specific to Chile. Those typologies were researched for the study which aimed, amongst others, to characterize the different end energy usages within the Chilean residence sector. Table 2 describes the share for each building typology (1 -2 floor) within the nation, along with its correspondent average floor area. In the table, a national average of 77 m^2 floor area per building is seen on a general basis. Building typologies were assessed and weighted for further floor area selection in order to assign typologies to census attribute data, the coefficients for the typologies used are listed in Table 3.

Table 2. CDT Average floor area and share by building type

Data	Building type	# Floors		Total share (%)	Average floor area (m^2)
		1	2		
CDT	Detached house	29,4%	8,3%	37,7%	84
	Terraced house	5,7%	3,8%	9,5%	71
	Semi-detached house	24,0%	14,8%	38,8%	72
	Apartment	13,4%	0,7%	14,1%	76
Total		**72,5%**	**27,6%**	**100%**	**77**

Table 3. Floor area coefficients used for census buildings

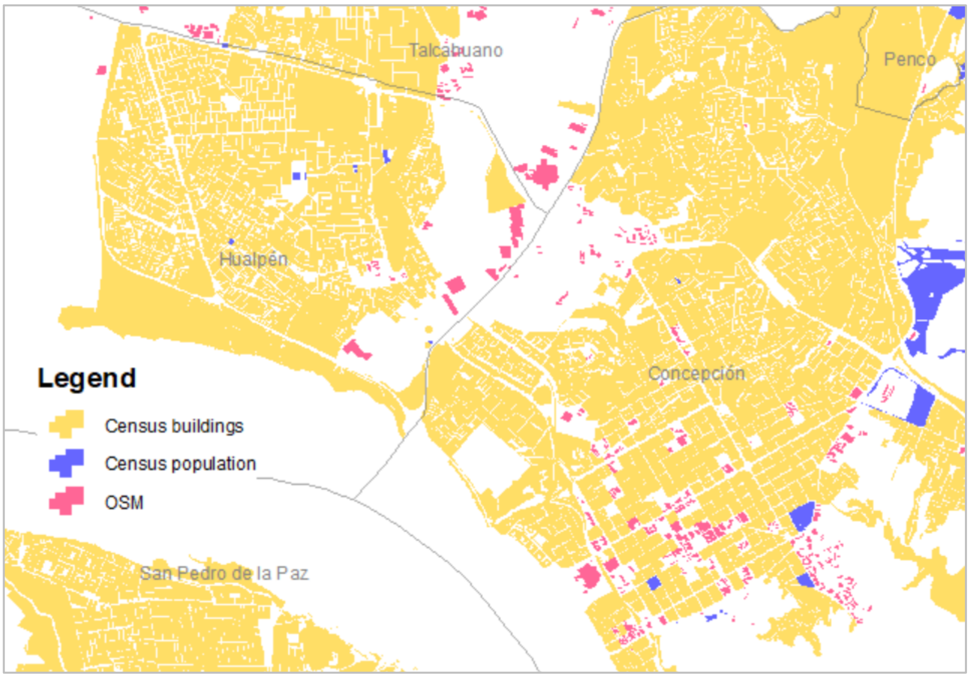
Building type	Floor area (m^2)
Rural house	108
Urban house	93
Apartment	76

Neither building typology nor usage were used in the floor area model due to the census input data aggregation level and lack of information regarding it, as the floor area model for census aggregates built up areas by block and various building typologies can exist within a specific block. However, for OSM buildings, typologies included the residential and industry sector. Regardless, no differentiation was performed when allocating the different coefficients for floor area used.

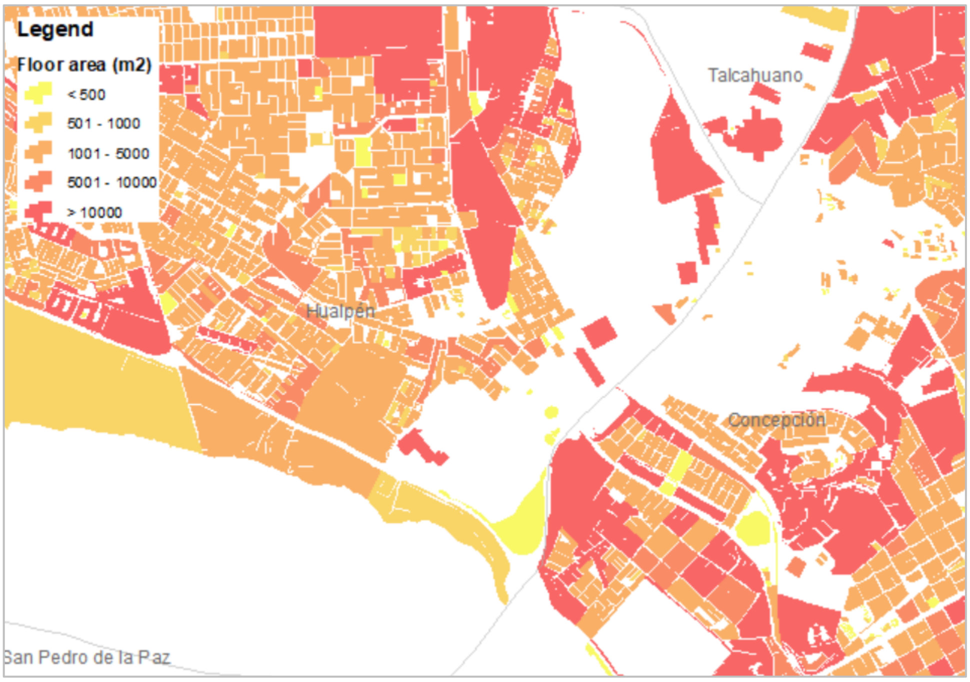
Later, in addition to these parameters, census population was also considered, so as to verify a coherent relation between people per building within a specific block. According to occupational base loads for residential buildings stated in Chilean building codes [15], a minimum of 20m^2/person is allocated for buildings corresponding to the size of the national average floor area.

According to the Chilean 2017 census [12], on average around 4 people inhabit a single building. Therefore, when population per building ratio exceeds this average, 20 m^2 floor area per person is used in order to refine the floor area estimation to not underestimate the floor areas of buildings with a higher than the average ratio. In practice, this means that if an apartment has more than 20 inhabitants, the floor area is estimated to be 400 m^2 instead of 76 m^2. Furthermore, an exhaustive spatial verification with the most updated base maps was carried out.

The following geographic representations portray the results of this approach. In Map 1, the spatial distribution on its aggregation level is portrayed for the input data in *the great Concepción* area. Results statistics show that of all the floor area estimation, 92% took census buildings as input, whereas 1% took census population. OSM accounts for 7% of the Chilean floor area estimation of this study. Simultaneously, Map 2 illustrates the estimated floor area using the graduated colors/color ramp shown in the map legend.

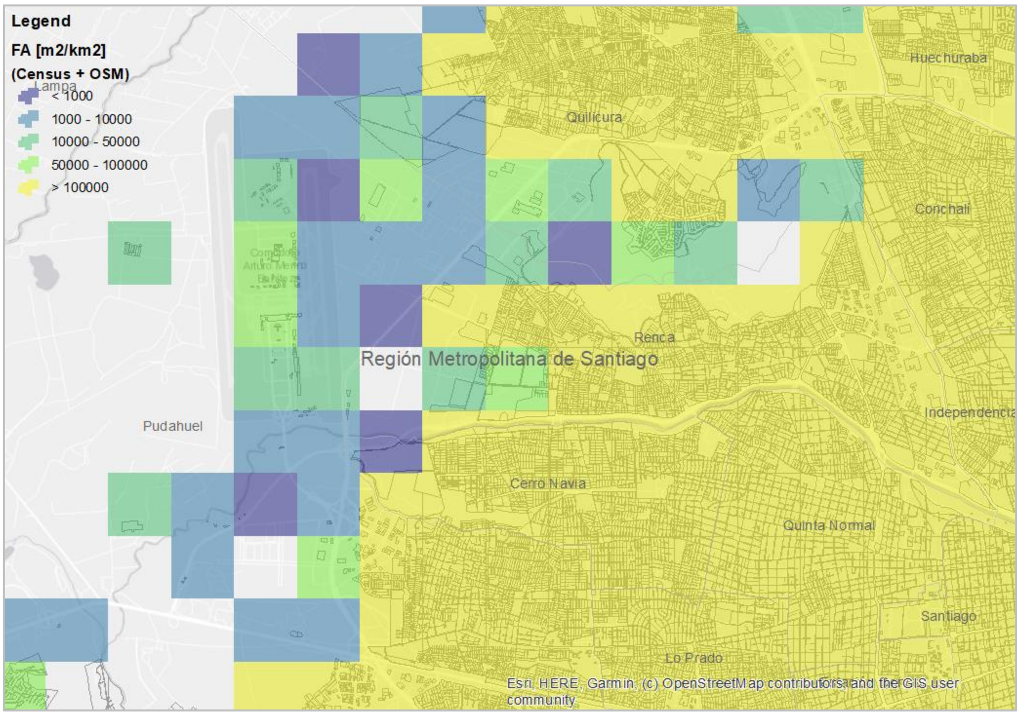


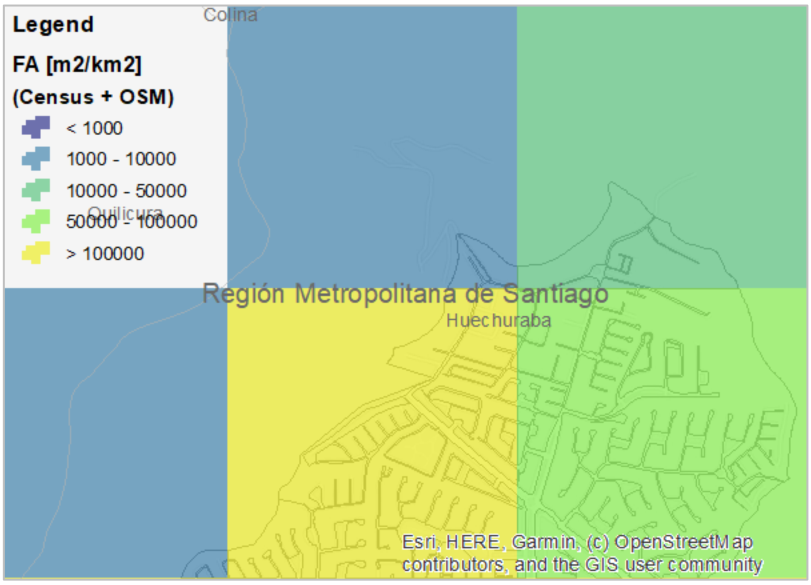
Map 1. Spatial characterization of floor area input data usage with different levels of aggregation



Map 2. Estimated floor area on manzana level

For the Chile Heat Demand Map, the floor areas on the manzana level – Map 2 – is available, but as these areas only cover parts of the country, a 1 km^2 grid model is developed as well. Thus, the output geographic representation of the floor area model was apportioned and summarized to a 1 km^2 grid for the whole country. One unit of km^2 will therefore become the unit of measurement for this study. This is done in order to reach the compatibility needed to be geo-processed jointly with the inputs needed for the linear regression model. On the final Chile Heat Demand geographic grid layer, the floor area model output is labelled as [a], refer to Annex 1. The latter is represented locally on Map 3 and the results of the model are further discussed in the subsequent chapters.

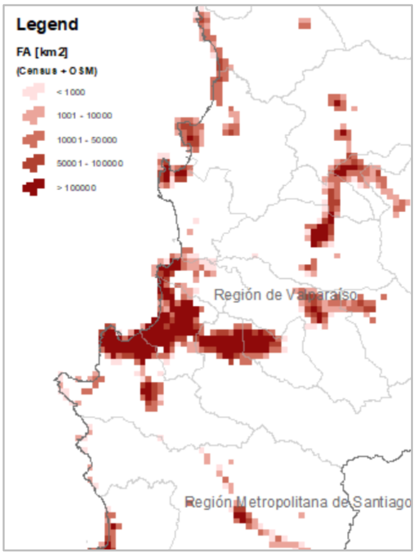




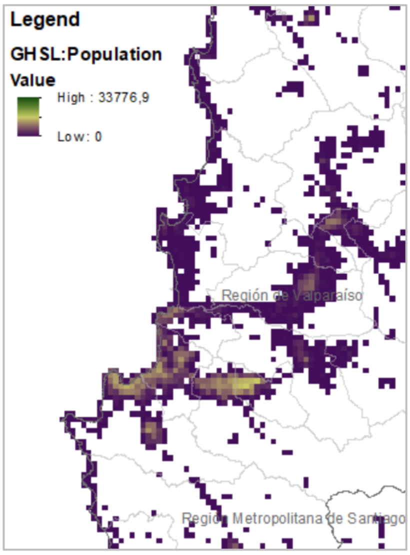
Map 3. Floor area model [1 km^2 grid] and localized apportioning

3.1.2 Regression model

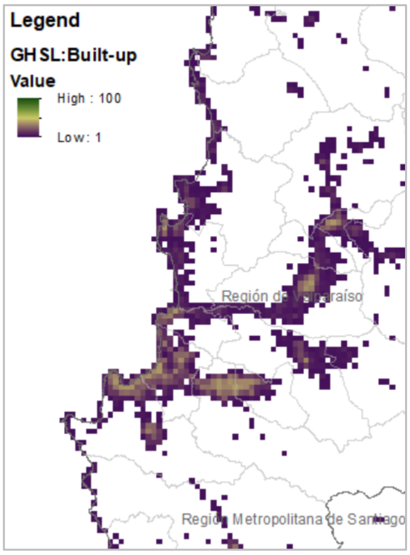
The linear regression model can be taken as the second/auxiliary floor area model, in order to complete areas not covered explicitly by the floor area model due to the different data sources limitations explained in 3.1.1. For a better demonstration of the scope and reach of the two models, a visual representation of *Valparaíso* region is presented in the three maps below. Map 4 shows the output km² grid coming from the floor area model, whereas Map 5 and Map 6 show the available grid data for population and built-up areas correspondingly. As it can be inspected on the above maps, there are zones where these last sources cover areas that are not covered by the floor area model shown in Map 4. Aiming at maximizing the scope and scale of this study, a linear regression model was employed in order to estimate floor areas not covered by the previous model.



Map 4. Floor Area model km² grid



Map 5. Population km² grid



Map 6. Built-up km² grid

Grid datasets were taken from the Global Human Settlement Layer (GHLS) framework that produces global spatial information on human presence in the planet. This grid data population dataset defines the amount of people within 1 km2 area whereas built-up area uses a 1 to 100 index describing built-up presence. Built-up index is calculated after global remote sensing data objective measurements, refer to GHLS methodology. Datasets operate on an open data basis supported by various partners and was obtained for the whole nation of Chile [16]. The geographic analysis tools within the ArcGIS environment used were Exploratory Regression (Spatial Statistics) and Ordinary Least Squares (OLS). The first tool aims at evaluating input combination looking at best fitted OLS models. Once this diagnosis is output, the variables were selected.

Later, the OLS tool was executed to generate predictions of a dependent variable in terms of its relationships to a set of explanatory variables. This means that the model considers the already existing relationships between all variables on the grid and learns from that to be able to predict the necessary variable in a certain km², having one or many explanatory variables as inputs. For this regression model, the explanatory variables used are population and build up areas whereas floor area is used as the dependent variable. The input datasets were transformed/normalized and outliers cut-off in order to be used avoiding biased results as possible. This, due to the complex relation between the variables which can be seen in the following scatter plots Figure 3 and Figure 4 and could be explained by generalizing relationships nationwide without any type of localized classification.

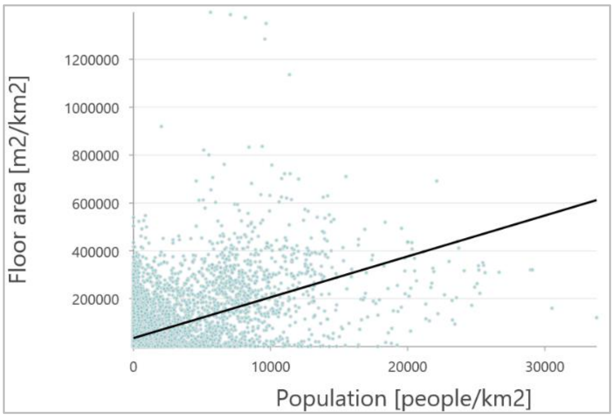


Figure 3. Population vs. FA relationship

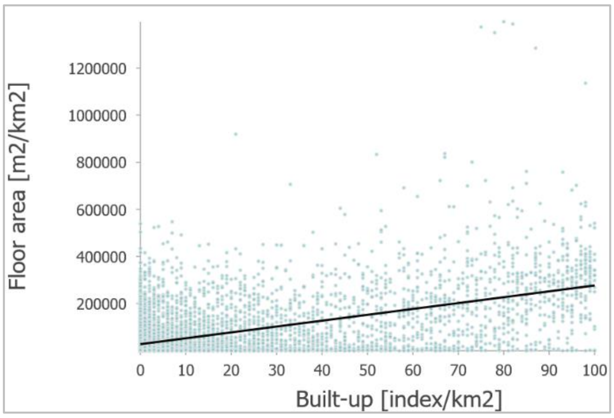


Figure 4. Built-up vs. FA relationship

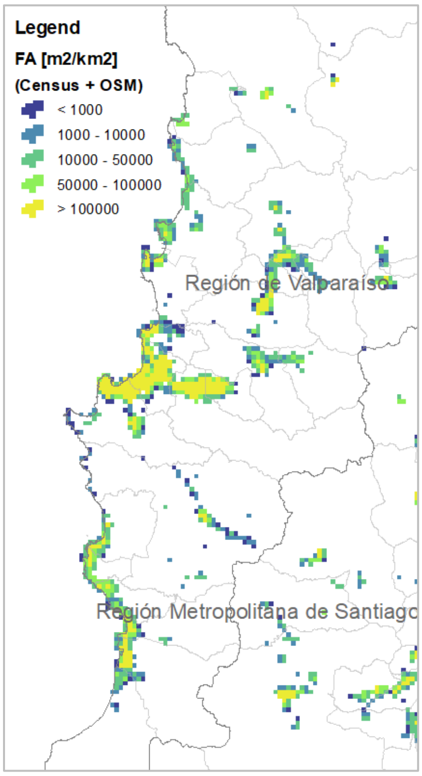
The OLS model yielded positive and statistically significant probabilities for the explanatory variables, both with $p < 0{,}01$ probality. This was expected since population and built-up area are to increase the dependent variable – floor area. Variable Inflation Factor (VIF); a measure of variable redundancy also returned a positive output. The model presents a $R^2 = 0{,}61$. The formula used for the floor area prediction starting off the explanatory variables is as follows:

$$\boldsymbol{FA}\left[\frac{\boldsymbol{m^2}}{\boldsymbol{km^2}}\right] = \mathbf{10918} + \mathbf{10.09} * \boldsymbol{Population}\left[\frac{\boldsymbol{People}}{\boldsymbol{km^2}}\right] + \mathbf{2255.4} * \boldsymbol{Built\_up}\left[\frac{\boldsymbol{Index}}{\boldsymbol{km^2}}\right]$$

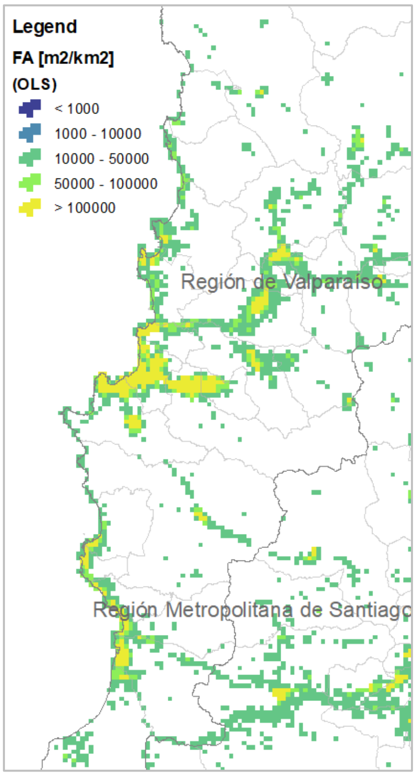
As a remark, it can be said that multiple other variables (e.g. average household income) could have been used for this model as to provide it with more relevant inputs for the dependent variable prediction. Although initial indications imply challenges and complications related to data interoperability. The use of the OLS approach and its easy replication means this type of analysis can be carried out in the future.

An exemplified geographic representation of the floor area selection is shown below through Map 7, Map 8 and Map 9 for the same *Valparaíso* region. A selection of the predicted floor area coming from the OLS was made for the areas where no data from the previous floor area model was found. Prioritizing this way, and using the census-based estimates when available, is considered to be the most accurate local data for the study.

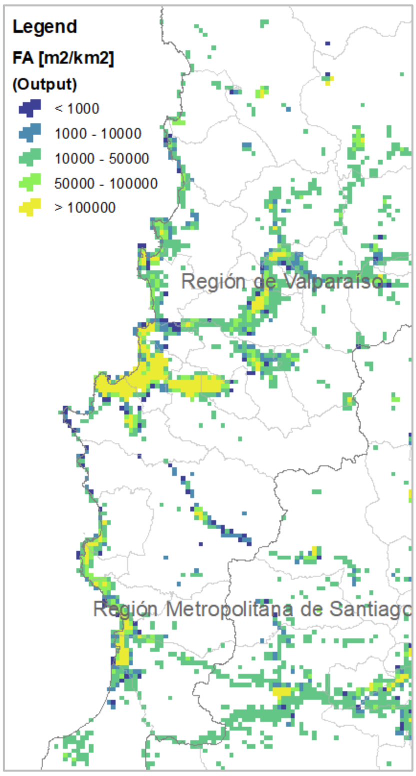
As seen in Map 8, OLS model was especially relevant for the rural areas where census data is missing. It can also be noticed with the aid of the map legends that in generally, OLS model overestimates floor area when compared to the previous floor area model. Lastly, an enhanced map with a considerably robust coverage of floor area estimation can be visualized in Map 9. On the final Chile Heat Demand geographic grid layer, regression model output and selected floor area are labelled as [b] and [ab] respectively, refer to Annex 1. The heat demand model will build on this floor area map in the next chapter.



Map 7. FA (Census + OSM)

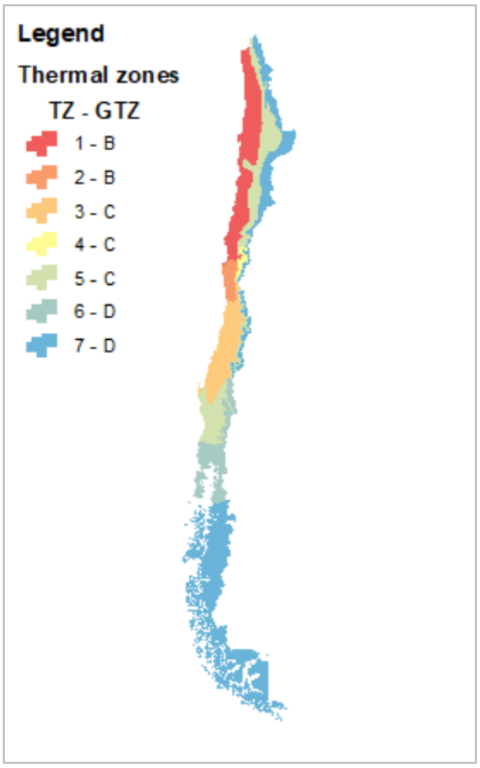


Map 8. FA (OLS)



Map 9. FA output

3.1.3 Heat demand model



Map 10. Chilean thermal zones [TZ] and thermal group zones [GTZ]

The heat demand model is next on the mapping methodology for this project, as seen in Figure 2. In the previous chapter, it was explained that the heat demand model will be further developed based on the floor area estimations.

Heat demands were calculated for each of the three scenarios seen in Map 7, Map 8 and Map 9. On the final Chile Heat Demand geographic grid layer, heat demand model output is labelled as [a_MWh], [b_MWh] and [ab_Mwh] respectively, referring to Annex 1.

Before explaining the calculation of heat demands, a brief overview of the parameters affecting those calculations has to be done. First and foremost, Chilean thermal zones have to be identified, and later a characterization of the Chilean building stock is foreseen.

As it is known, Chile has a rather diverse climate throughout the nation. A single municipality can have up to 4 different thermal zones each attributable to very different heat demands e.g. *Salamanca* municipality. Hence, each unit of measurement - 1 km^2 - was spatially attributed to a specific thermal zone for its heat demand estimation. Thermal zones in Chile are classified and categorized in groups as visualized in Map 10.

Now, when it comes to changes in building technology use, it can be said that those change respond to political implementations and building code regulations in the country. As suggested in the CDT report [14], in Chile, two of these milestones are clearly noticed. Buildings constructed before 2001, between 2001 and 2007, and buildings constructed after 2007. Each period corresponding to In addition to this, the 2010 statistics used in the report suggest that within the Chilean building stock, 86%, 13% and 2% relate to each one of those periods correspondingly. Later, CDT comprises within their study scope, an intuitive and rather detailed heat demand database for each specific thermal zone based on building floor area. The database includes heat demand changes when certain energy efficiency and retrofitting measures are implemented.

The heat demand model developed in this project, will have two scenarios based on the latter explained database. In the first one, no energy efficiency savings are included whereas in the second one, two measures are hypothetically implemented. At this point, it can be said that an optimistic building retrofitting was considered since the large majority of the building stock was constructed before 2001 and has no isolation whatsoever. Irrespective, it is considered vital to seek the potentials of heat demand with such reduction linked to current building stock renovations. Indeed, the importance of existing infrastructure represents a challenge for the heating and building regulation and policy in Chile. On average savings, 30% of the heat demand are reduced by the implementation of 5cm interior and exterior walls as an isolation measure.

Using all the parameters explained so far, coefficients from CDT were weighted and correspondingly used for the heat demand calculations. The yearly heat unit is kWh per m^2 and the coefficients are further explained in Table 4 for all Chilean thermal zones. Zone 1 and 2 have no energy efficiency savings measures (EESM) implemented.

Table 4. Weighted yearly heat demand coefficients [kWh/m2] taken from [14]

	Construction year												**w/o EESM**	**w/ EESM**
	< 2001				2001-2007				>2007					
	86%				13%				2%					
GTZ / TZ	A	B	C	D	A	B	C	D	A	B	C	D		
1	45,4	45,4			4,2	4,5			0,6	0,7			51	51
2	118,1	119,8			11,5	11,9			1,7	1,7			133	133
3	202,9		147,5		20,1		11,8		2,2		1,4		224	161
4	202,9		147,5		20,1		11,8		2,2		1,4		224	161
5	202,9		147,5		20,1		11,8		2,2		1,4		224	161
6	320,1			252,9	30,5			20,3	2,6			2,5	399	276
7	586,4			462,0	56,3			37,3	4,0			3,8	729	503

EESM: Energy efficiency saving measure, GTZ [A-D]: Thermal group zones, TZ [1-7]: Thermal zones

The EESM scenario is based on the selected floor area estimate calculated heat demand - [ab_Mwh]. On the final Chile Heat Demand geographic grid layer, heat demand contemplating savings is labelled as [ab_s_Mwh]. Total and annual implementation investment cost are included for this scenario, their respective labels on the annex are [ab_s_HS_USD] and [ab_s_HS_USD_yr], refer to Annex 1. These renovation costs were taken from the CDT report [14] which makes use of 2010 market reference costs. Albeit these costs are classified by building typology, area-based costs were taken as a mean to simplify the calculation per km^2.

Table 5. Total investment cost for EESM

	EESM	
	Exterior Isolation [5cm]	**Interior isolation [5cm]**
Unit cost ($/m^2)	7.312,00	6.296,00
($/m^2) Chilean currency – Chilean peso per m^2		

On the following figures, the calculated output data is aggregated for a more comprehensive understanding within the Chilean context. On Figure 5, aggregations by administrative regions for both floor area and heat demand is presented along with each respective density indicator. Data is sorted from most significant to less significant heat demand [HD] present on each region. When this tendency is compared to the floor area on the left, the effect of the different heating demands for each thermal zone is reflected. For example, looking at regions coded 7 and 15. On one hand, *Arica y Parinacota* region as the most northern of the country has most of its area on TZ1, which has the lowest heating demands as seen in Table 4. On the other, the centric *Maule* region responds mainly to higher TZ3 heating demands. Here, for this model even if relatively similar FA can be read, the dynamic influence of both variables - FA and HD coefficients by TZ - is highlighted.

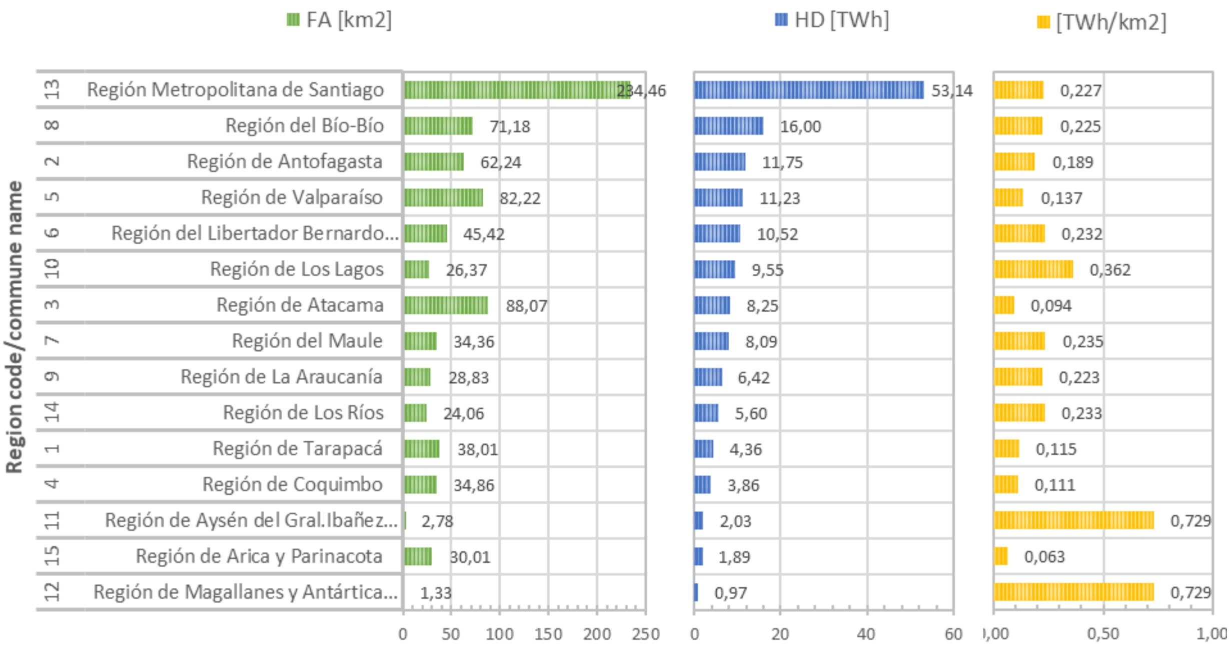


Figure 5. FA, HD and density region aggregation

Figure 6 on the other hand, illustrates an administrative commune aggregation where the highest demands are found. Together, these 41 - out of 346 total - sum up to 50% of the total Chilean national heat demand. Various communes on the top of the list are precisely more representative than the ones within the highest demand regions. Taking *Región del Bío-Bío [8] and Región de Los Ríos [14]* - rank 2 and 10 on a regional level - respectively as seen in Figure 5, along with its individual highest demand on *Concepción* and *Valdivia* commune accordingly, the latter accounts for ca. 30% more heat demand than *Concepción*. Ultimately, this merely points out the importance of a factual local district heating potential assessment even though its regional demand doesn't reflect its potential relevance.

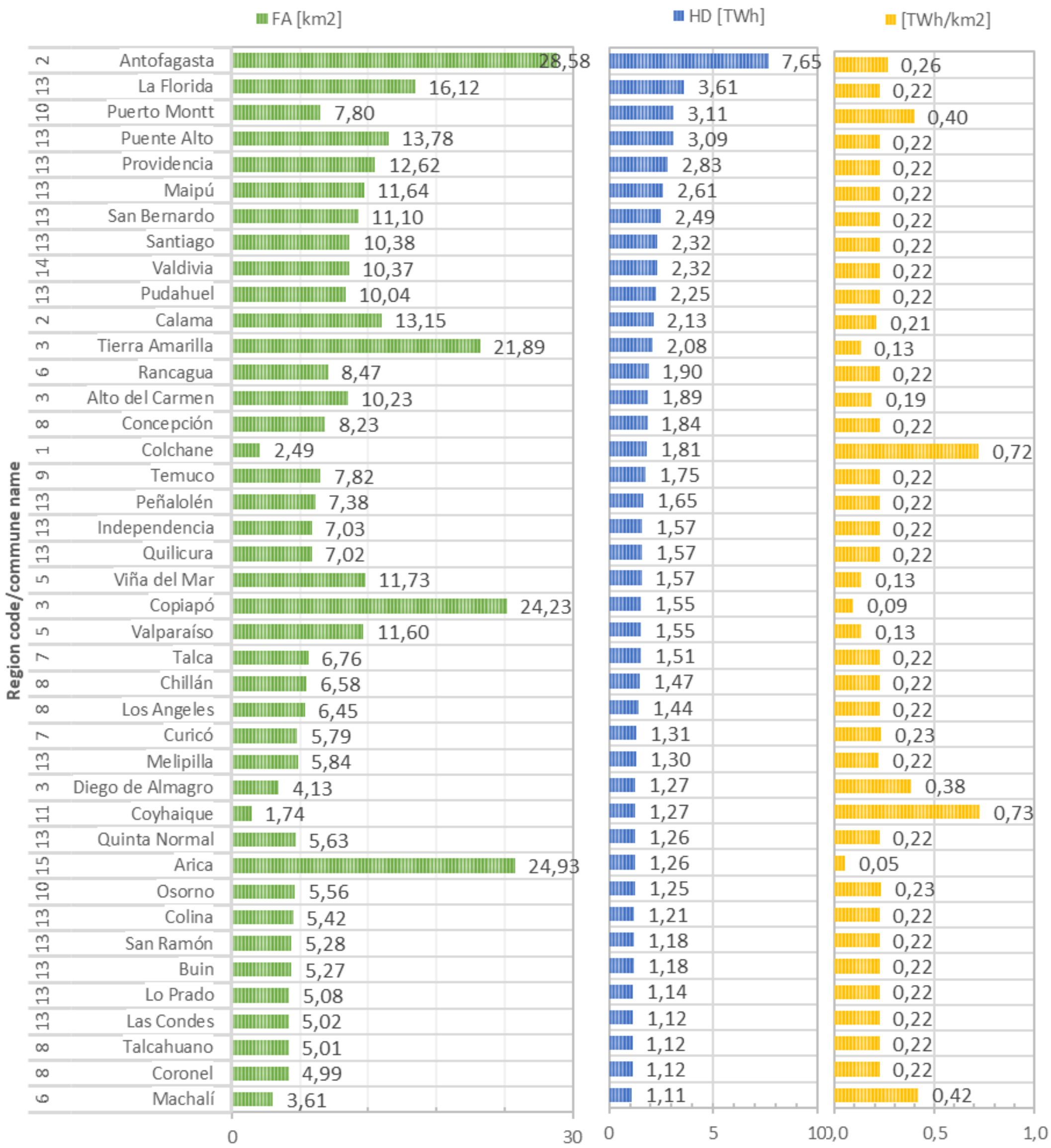


Figure 6. FA, HD and density commune aggregation

3.1.4 District heating model

The district heating model is based on the results of the heat demand mapping, where these are used to estimate the heat densities and physical district heating potential, district heating grid losses and investment costs for district heating.

3.1.4.1 Heat densities and physical district heating potential

The underlying assumption of viability is that district heating should be cheaper than the individual solution, given the perspective of a socio-economic cost, so that the regulatory framework can be designed to enable the best solution for society at large. This means the assessment is excluding taxes and subsidies but including the changes that happen to the costs of, for example, the industry and electricity sector, when DH is implemented. Important to note is that in this study, secondary benefits relating to improved health outcomes and avoided mortality are not directly taken into account in the Chile Heat Demand Map. When assessing DH potentials, a key parameter is the heat density of the area, which partly determines how competitive the DH solution is to individual alternatives.

Figure 7 shows how the main costs of DH supply relates to the density. In the example taken from [18], the individual/local heat generation cost is 20 EUR/GJ meaning that the cost for DH has to be lower than this level. As DH costs both consists of heat distribution costs and costs for energy, it is the total costs that needs to be lower. In very sparse areas, the heat distribution costs will simply be too high to compete with the individual solutions, where in dense areas DH will be feasible depending on the heat generation costs (“Ability to pay for recycled heat”). What the figure also illustrates is that the denser the area is, the lower the distribution costs will be, and thus the primary energy and recycled heat cost can be higher than in the sparser areas. The heat density mainly determines the length of the network, which influences both heat losses from the grid and investment costs of the grid. Moreover, the quality and temperature level of the DH network, as well as how it is operated will have an influence on the heat distribution costs as well.

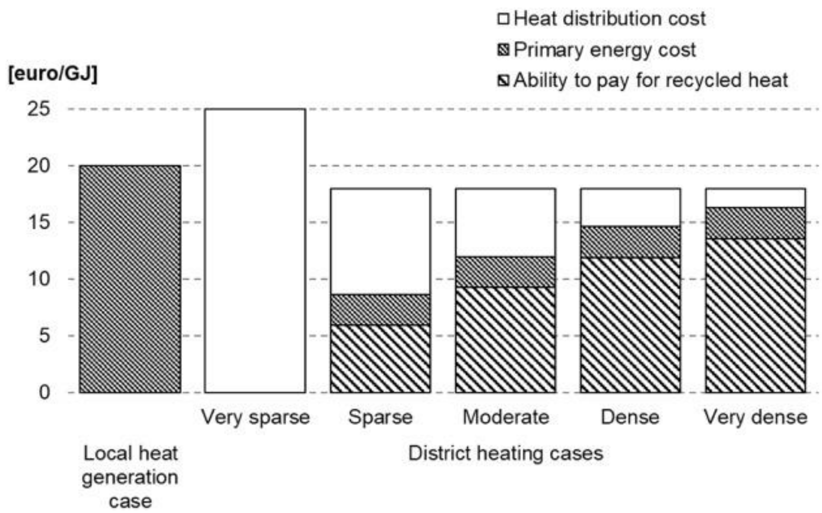


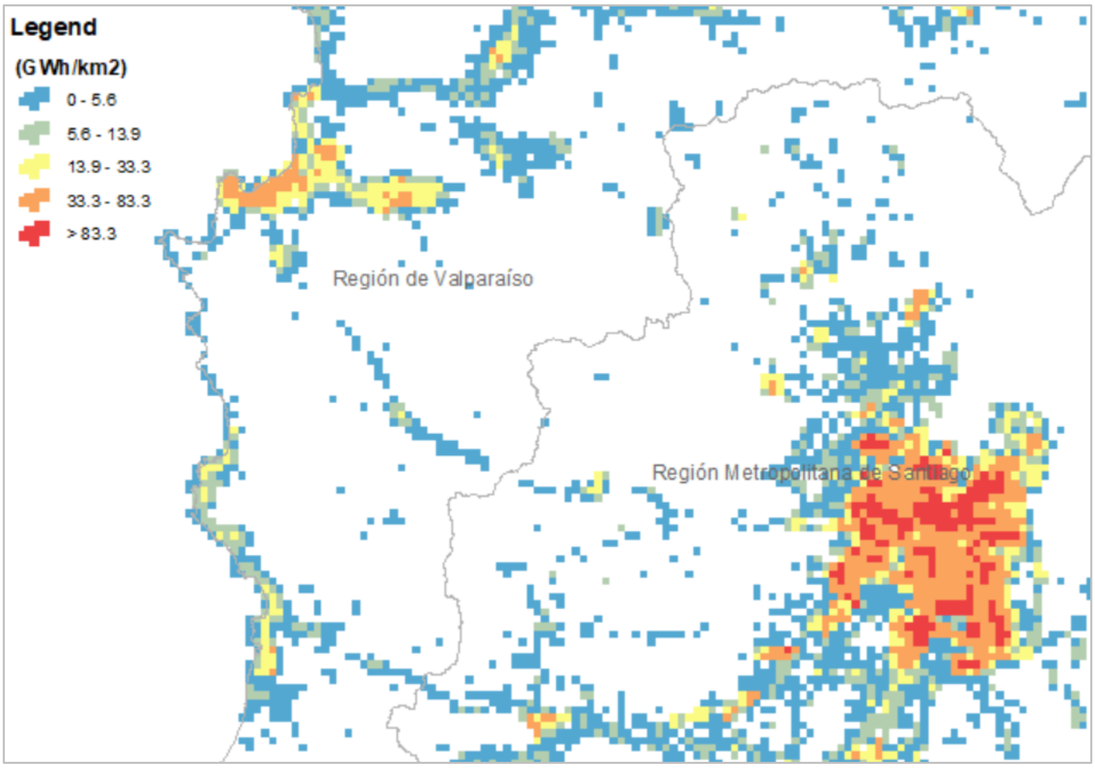
Figure 7. Example of the influence of heat density in relation to heat costs and individual solutions [17]

Using heat density as an indicator for DH potential, Table 6 shows the five heat density classes that have been used in this report. It is important to note, that these heat density classes are based on European experiences, so they must be used only as indicators of density as the Chilean situation is not directly comparable to the European, both in terms of layout of cities and heat demand of buildings.

Table 6: Heat density classes based on modified values from Persson et al. [17]

Heat density intervals		
Heat density class	**Heat density [GWh/km²]**	**Concentration of heat demands**
A	$0 < q_L < 5.6$	Very sparse
B	$5.6 \leq q_L < 13.9$	Sparse
C	$13.9 \leq q_L < 33.3$	Moderate
D	$33.3 \leq q_L < 83.3$	Dense
E	$q_L \geq 83.3$	Very dense

Yet, by using these heat density classes, an early overview of potential DH locations can be identified, as illustrated in Map 11. As seen in the example, primarily *Valparaiso* and *Santiago* cities can both be classified as dense areas, with a D-E heat density above 33 $\frac{GWh}{km^2}$. Leveraging the power of geographic location in order to use heat density maps in this way, can provide a good first estimate of finding the locations of potential areas for district heating.



Map 11. Heat density [GWh/km2] showing physical suitability for district heating

3.1.4.2 District heating grid losses

As a technology, district heating naturally adds heat losses to a system, primarily related to the distribution of heat in the district heating network. These network heat losses are related to parameters such as the spatial layout, the temperature and flow levels, and the type of pipes used in the network. As most of these parameters are unknown in the case of Chile, a simplification has been used to estimate the heat demands in all the areas of the heat atlas. The heat densities are used as proxy for the layout of the network, where network heat losses typically are lower in dense areas. Furthermore, it is assumed that the network is based on so-called 3rd generation district heating, with forward temperature levels of around 70-80 °C, with pre-insulated pipes. In Denmark, the 3rd generation district heating is wide-spread, and thus empirical data from Denmark is used.

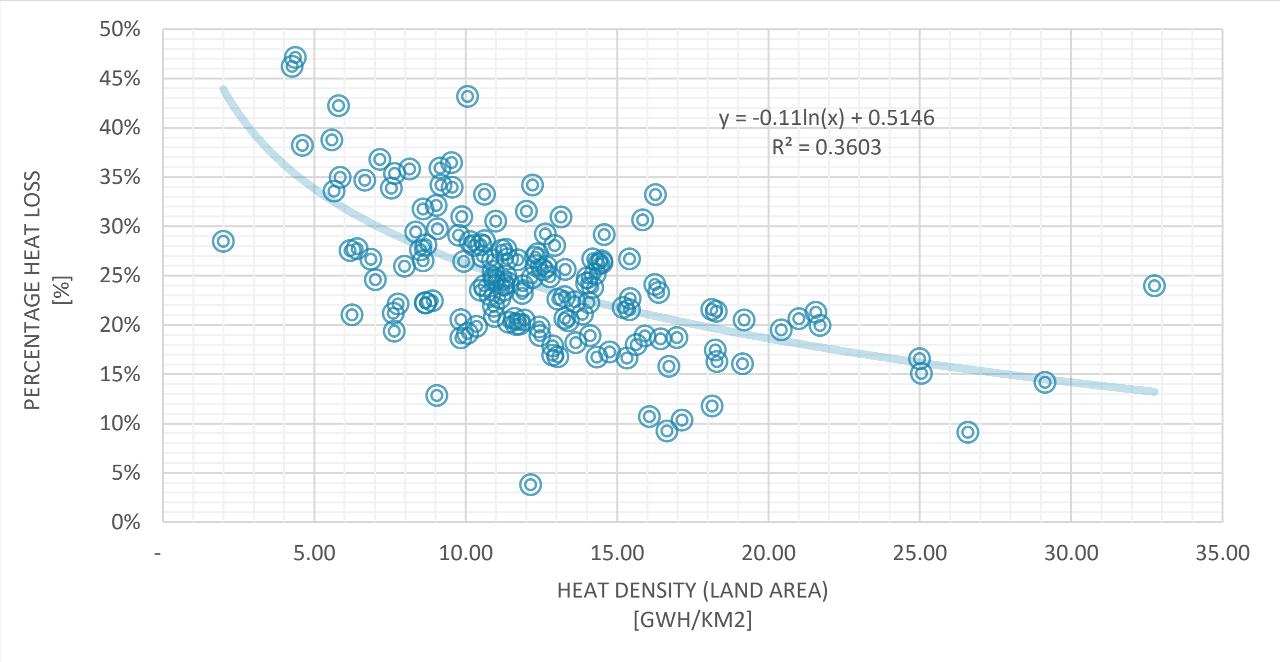


Figure 8. District heating network losses based on data from Danish district heating areas. The graph shows the relation between heat density (end-use) and percentage heat loss (percent of delivered heat) for 149 district heating areas.

Figure 8 shows the relation between heat density and heat losses in 149 Danish district heating. As seen from the figure, equation (1) can be used as a simple approximation, to estimate the heat loss based on the heat density in an area. From the R^2 value it is evident that there are large uncertainties in this method, and a large diversity between the performance of individual networks. This should thus only be used for broad planning purposes, and not detailed planning of a specific district heating area.

$$y = -0,11 * \ln x + 0,5146 \qquad (1)$$

It is important to note, that as equation (1) is based on heat demand from Danish buildings, which in general are better insulated than Chilean buildings. This means that the resulting percentage heat loss seems low compared to the heat demands, however in absolute numbers the losses are more significant.

3.1.4.3 District heating investment costs

One of the main cost components related to costs of district heating, is the investment costs in the district heating network, as this adds costs to a system, which needs to be balanced out by a more efficient supply system with lower heat production costs, than the individual alternative. The value for the investment cost estimates used in this report is based on an assessment made in the Heat Roadmap Europe project, but applied to the spatial density of Chile. Where the investment costs in heat distribution network, in relation to heat density was estimated using equation (2), which was derived from Figure 9.

$$y = 1970,7 * x^{-0.645} \qquad (2)$$

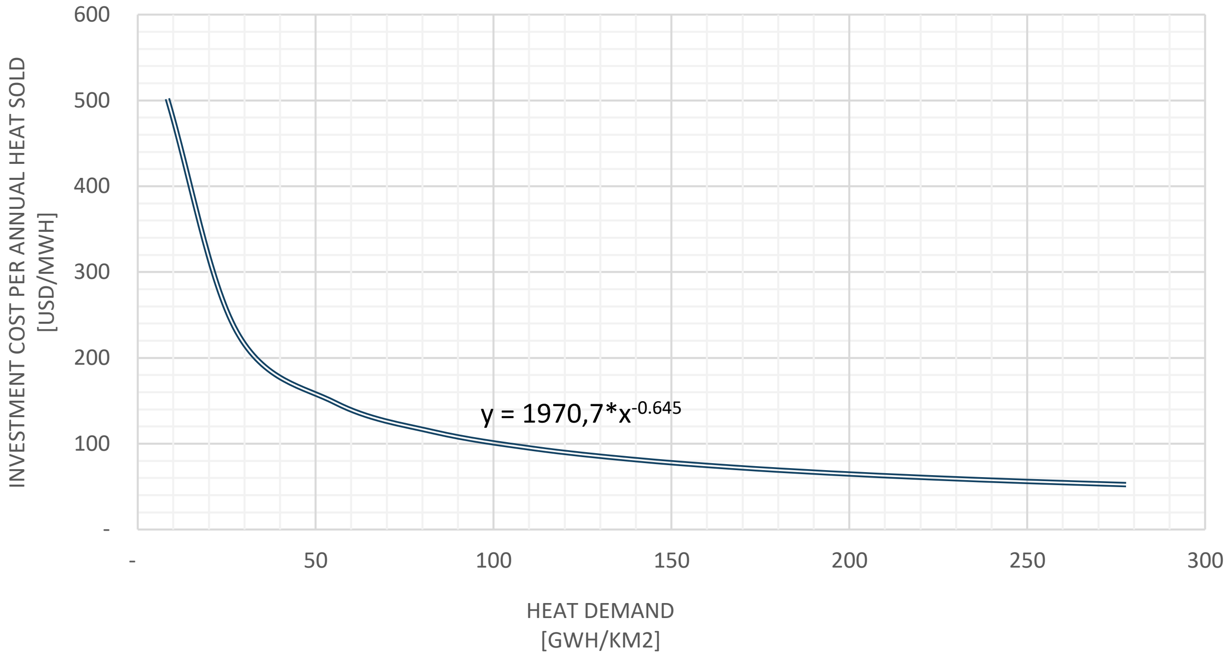
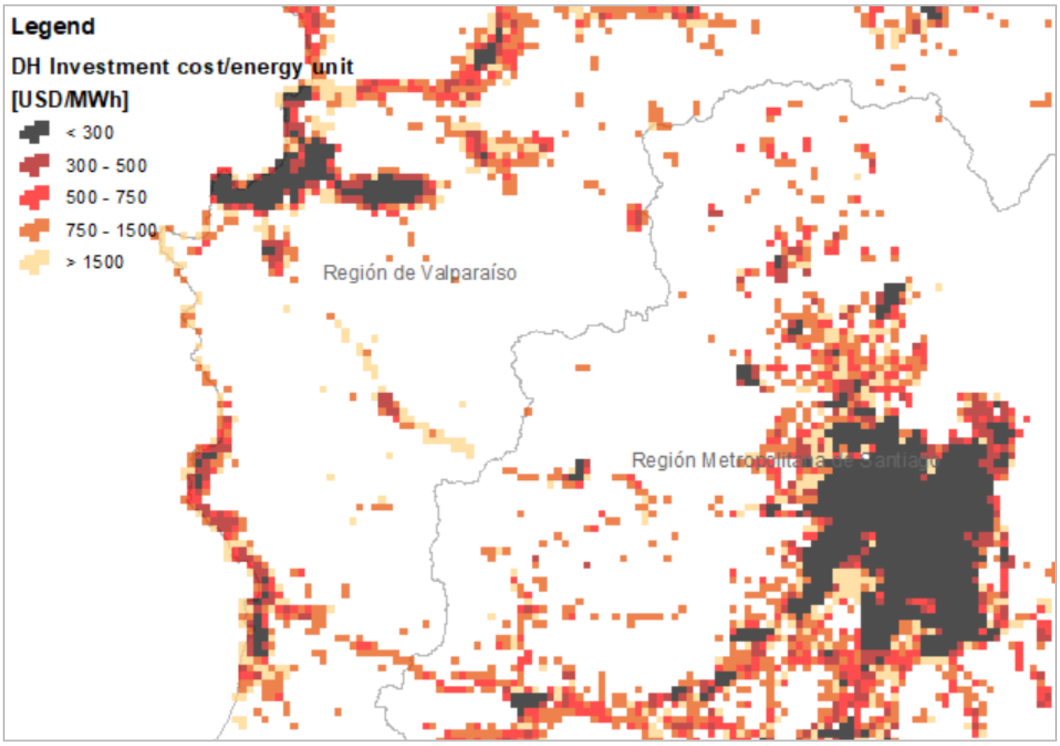


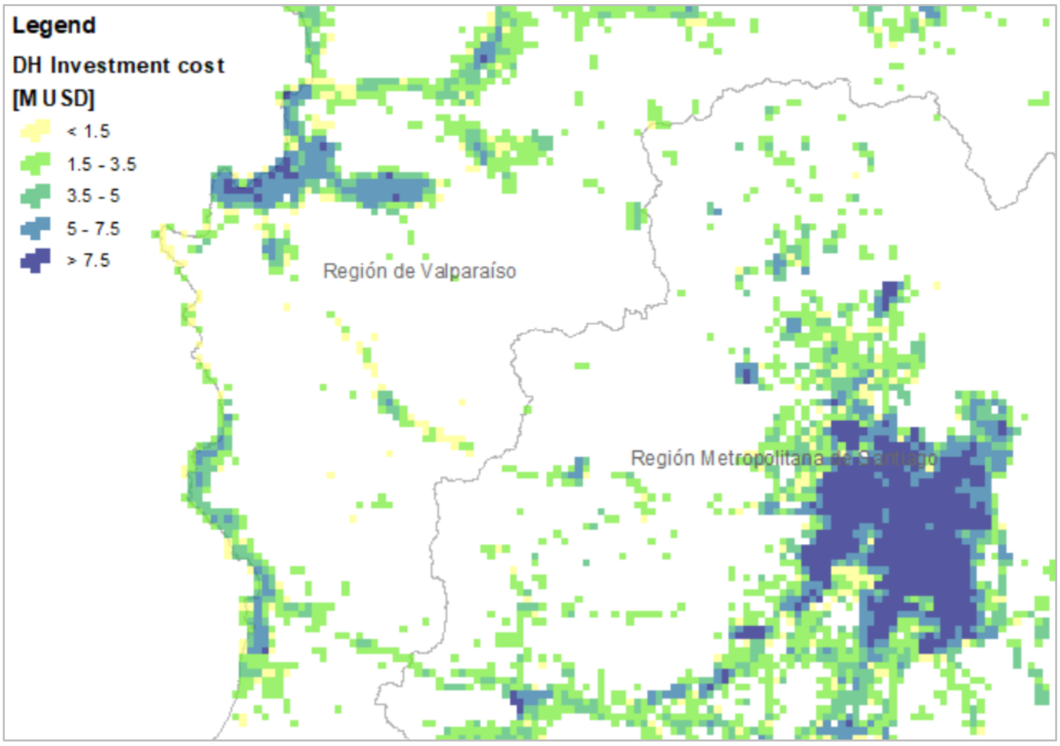
Figure 9. Investment costs per annual heat sold. Based on [18]

Figure 9 illustrates one of the main characteristics of district heating, that the investment costs per MWh of heat sold decreases with density, making district heating most feasible in dense urban areas. It is important to note, that the investment costs presented in Figure 9 only represents the investment costs in the distribution network for district heating, since other costs that are not geographically dependent, are added in the energy system analysis in Section 4.2.2. Moreover, it is also relevant to note that while this cost curve is used as the main input in the analysis, it mostly serves as a conservative estimate, given that the actual development of district heating investments in Chile might be subject to different labor costs and an initial learning process, which would result in some differences in the actual local costs.

Applying the cost curve from Figure 9 to the heat demand map visually illustrates this relation between density and grid investment costs, see Map 12. The map indicates, that in dense urban areas the grid investment costs fall below 300 USD/MWh, while in the low-density areas the cost can be more than 1500 USD/MWh. On Map 13, the total district heating investment cost in MUSD is shown, this indicating high investments in the dense urban areas, which is a function of the high demands in these areas. The total investment costs of district heating will be used in the mapping results, as this is one of the main inputs for the energy system analysis.



Map 12. District heating investment costs per km² in USD/MWh



Map 13. Total district heating investment costs per km² in MUSD

3.2 Mapping results

In this report, the results of the mapping are presented in two sections, the first showing the heat demands on different heat density levels for each region in the country and a second section showing the cost curves used to assess the district heating costs in the energy system analysis in Section 4.2.2. Results mainly include floor area and heat demands on Manzana/km^2 grid level and district heating costs on km^2 grid level. Both geographic datasets attributes are described in Annex 1 and its methodology is as explained in the previous chapters.

3.2.1 Heat demands on regional level

As the heat demands are georeferenced on a km^2 grid, the demands can be summarized on any level from national to city district level. In this section, the demands will be summarized on a regional level to illustrate the variation between regions. Table 7 shows the heat demands for each region split into the heat density classes from Table 6.

Moreover, the graphics pretend to show visually results of promising regions heat demands for district heating deployment analysis. These promising areas are classified as heat densities D and E according to Table 6. Total and percentage ratios are shown for the different density intervals in Table 7 and Figure 10 respectively. The biggest share potentials are as foreseen, for denser either southern regions as the bold and italicized ones coded 12, 11, 13 & 14.

Table 7. Heat demands [GWh/km2] for each Chilean region, by heat demand density intervals from Table 6.

RC	Region Name	A	B	C	D	E	TOTAL
1	Región de Tarapacá	915	1.092	1.197	974	182	4.361
2	Región de Antofagasta	1.680	2.246	2.856	1.940	3.023	11.746
3	Región de Atacama	2.451	3.335	1.978	485	0	8.249
4	Región de Coquimbo	1.546	1.401	787	128	0	3.863
5	Región de Valparaíso	2.789	2.682	3.440	2.318	0	11.228
6	Región del Libertador Bernardo O'Higgins	4.021	2.452	1.840	2.112	97	10.523
7	Región del Maule	1.732	1.622	1.938	2.793	0	8.086
8	Región del Bío-Bío	2.304	2.607	4.059	6.396	630	15.996
9	Región de La Araucanía	1.118	953	2.109	2.239	0	6.420
10	Región de Los Lagos	512	1.815	2.058	3.427	1.736	9.549
11	***Región de Aysén del Gral.Ibañez del Campo***	*2*	*49*	*129*	***898***	***948***	***2.026***
12	***Región de Magallanes y Antártica Chilena***	*0*	*0*	*0*	***0***	***973***	***973***
13	***Región Metropolitana de Santiago***	*3.848*	*3.827*	*5.026*	***22.402***	***18.040***	***53.143***
14	***Región de Los Ríos***	*1.020*	*649*	*814*	***2.010***	***1.106***	***5.599***
15	Región de Arica y Parinacota	620	830	393	46	0	1.888
TOTAL		24.558	25.562	28.626	48.169	26.734	153.649

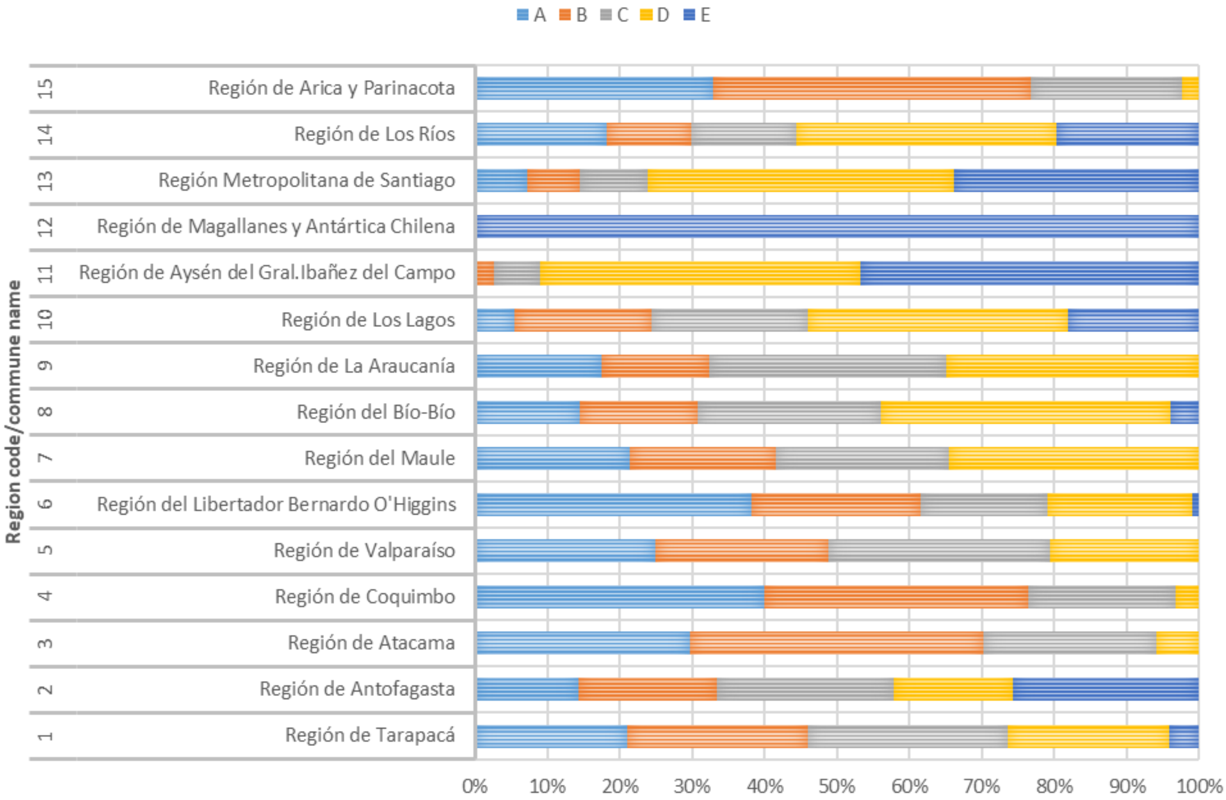


Figure 10. Categorized regional share of total annual heat demand according to Table 6

Zooming into these regions in Figure 11, when the total heating demand is compared to the demand allocated in both intervals D and E, those regions show a district heating pre-feasibility potential ranging from 56% in *Región de Los Ríos* to 100% in *Región de Magallanes y Antártica Chilena*. These combined percentages represent the share of the total annual heating demand market that could potentially be covered by district heating systems.

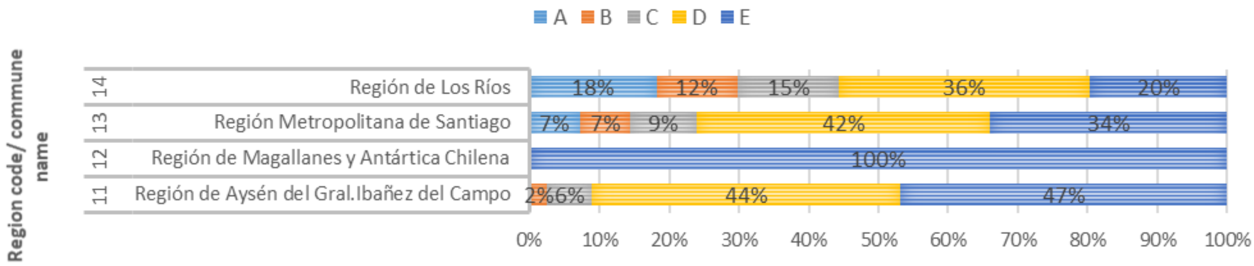


Figure 11. Zoom into highest potential regions share for DH systems

Now, it is known from Figure 6 that the highest demands and therefore potentials are not only found on a regional level, therefore this analysis was also performed for the highest heating demand communes in Chile. Having the context of the current Chilean heating energy sector where air pollution is highlighted as to be of major importance, it is considered therefore necessary to emphasize the findings on a commune level in contrast to the available PM measurement data exacted from the Air Quality National Information System of the Ministry of Environment [19]. This, taking advantage of the local aggregation level that a commune represents and the available measuring stations with validated data at the specific communes. In Figure 12, the classified communal heat density demands are represented on a bar chart with dual vertical axes, left and right representing HD density and PM annual mean concentrations, respectively. The WHO global thresholds for particulate matter pollution had been added to the graph in form of dash lines for reference purposes [20]. Additionally, to provide perspective amongst the different communes, the red rectangle comprising the major heat demand communes from Figure 5 is allocated to the right while on the left the gray rectangle gathers communes sorted largest to smallest in heat demand from left to right.

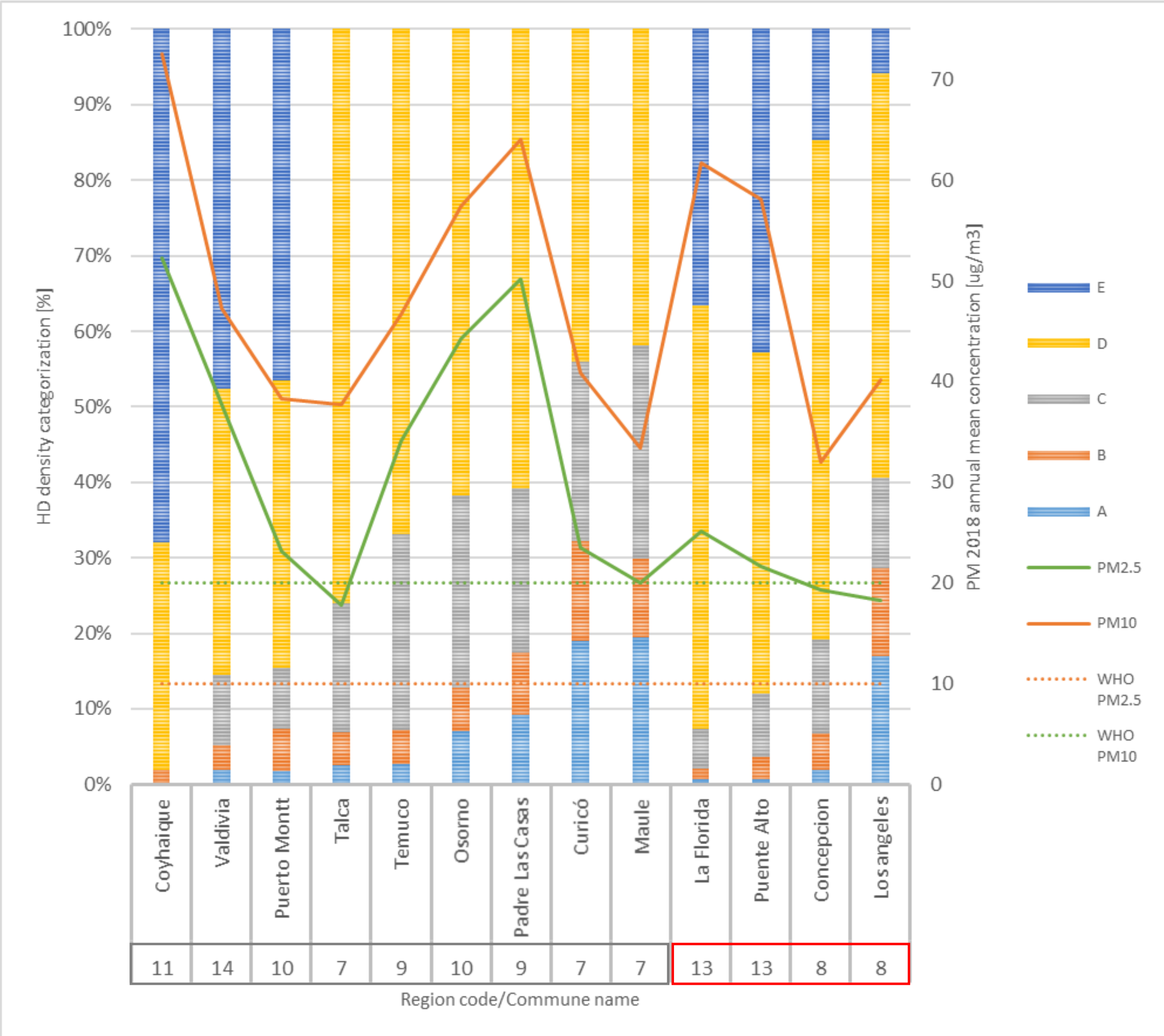


Figure 12. Categorized communal share of total annual heat demand according to Table 6

Looking at the bars, the graph in principle represents the communal district heating potential – categories D & E. The curves, on parallel show the potentials of district heating for PM abatement at a localized level. For the Chilean communes included in the graph, annual means for PM [PM2.5 & PM10] measurements exceed at minimum 60% WHO thresholds [20], and amongst the communes; the lowest heating share for potential district heating is 42% for *Maule* commune. The share goes up to 61% for *Padre de las Casas* commune, right where the highest concentrations of PM are observed. Concisely, Figure 13 indicates the importance of analyzing DH's advantages holistically at a localized level, and the necessary indicator scrutiny for assessing the potentials for a defined area. As a complement to the Figure 13 communal level overview, localized maps for the district heating potential found in the above mentioned communes are illustrated in Annex 2.

Another way to use the Chile Heat Demand Map, is to show curves for the relative district heating investment cost for each region, this is shown in Figure 12. As costs are derived directly from regional heating demand density, the difference between regions with high and low demand is reasonably visible on the curves. Curve smoothness would be subject to the amount of data available for that specific region. Regions with low heating demand are colored in maroon shades whereas high demand regions with blue shades. Maroon curves represent north Chile while blue ones central south Chile. Highest demand region curves coded 13, 8, 2 and 5 appear dotted on the figure.

Even though heating demands are the output of the series of calculations that have previously being explained throughout the report, the graph in a summarized way only emphasizes the importance of the geospatial/local dimension when talking about district heating, and the variation and similarities that exist. Looking at the relative cost at the lowest, Santiago de Chile as the densest region and Magallanes as one of the coldest have the biggest heating demands. Clearly, the ultimate heat density would respond to the two main drivers, floor area and climate. One take away from here could be the correct allocation of efforts needed that can more accurately gather data which can actually enhance output data quality.

High demand region curves tend to reach higher shares of annual total final heat demand for district heating grids steadily with the cost, distinctively from the substantial changes suffered on annualized investments seen in low demand regions. It is important to mention that these costs relate only to investments in district heating transmission and distribution grids, not the total cost of district heating installation.

This graph points out geographic locations where the biggest heating demand potentials that can further be exploited. Similar characteristics amongst the northern regions of *Tarapacá, Coquimbo and Atacama* are shown. Comparable scenarios can be seen between southern ones like for example *Araucanía, Aysén del Gral. Ibañez del Campo and Bío Bío* regions. These similarities can potentially be compared on a prior regional analysis so to seek helpful approaches for the developments.

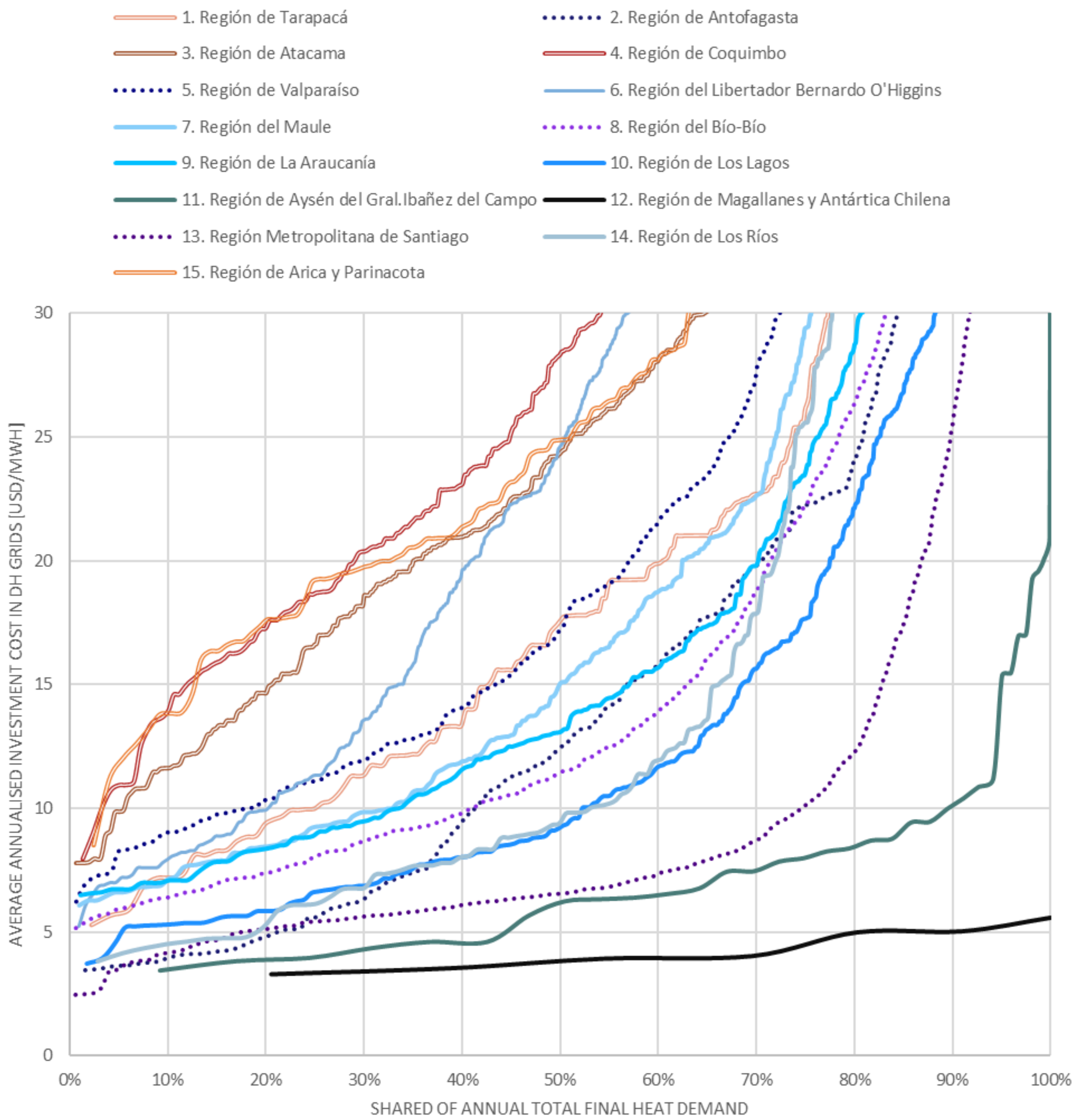


Figure 13. District heating investment cost by Chilean region

3.2.2 District heating potential for the energy system analysis

Similar to the previous section, this section will provide costs curves for district heating grid investment costs based on the mapping, however as these are used as inputs for the energy system analysis, they will be summarized on a national level instead of regional. In Figure 13, the district heating investment costs as percentage share of the heat market is shown.

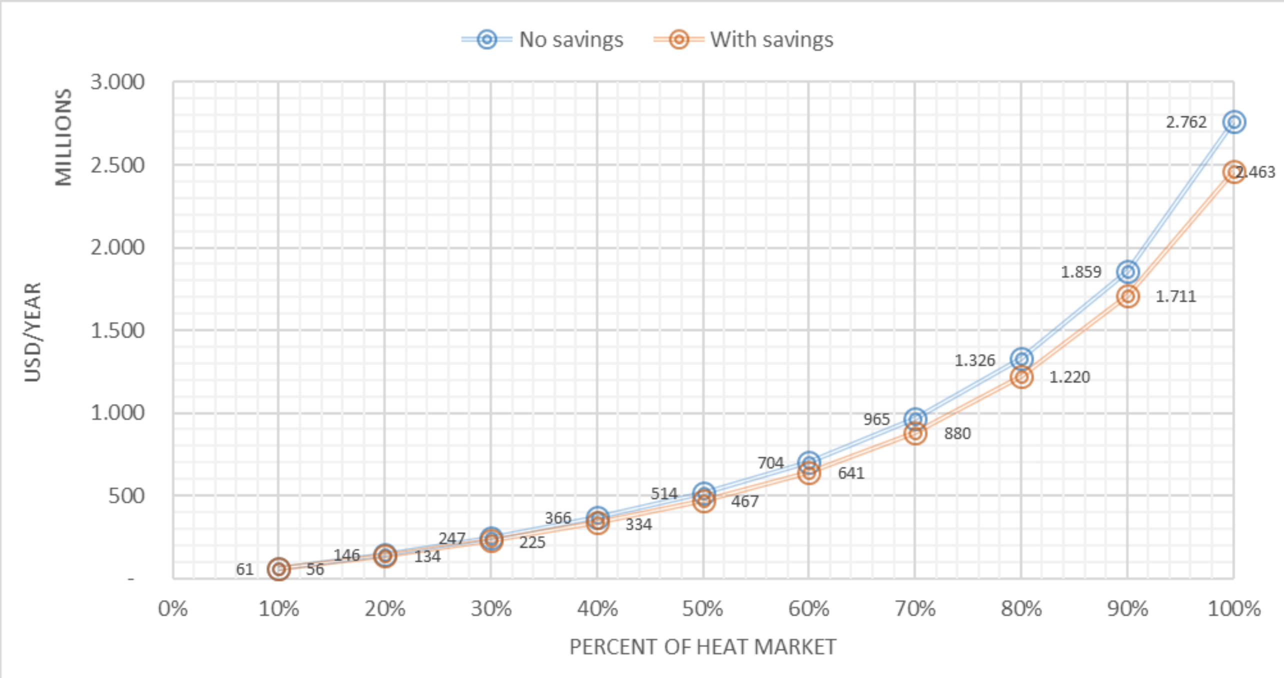


Figure 14. District heating investment costs in MUSD/a in relation to market share for scenarios without and with savings

Figure 14 shows the same result, but in relation to the heat demand instead of the market share. Here the difference between the scenario with savings and with no savings is clearer than the previous figure. With a saving scenario both the investment in district heating is lower, but also the cost related to supplying the heat will be lower, as smaller production capacities are needed.

Figure 15. District heating investment costs in USD/year in relation to heat demand for scenarios without and with savings

4 Heat Roadmap Scenario

In this chapter, different scenarios of the energy system are developed and simulated using the inputs from *Planificación Energética de Largo Plazo* (PELP) conducted by Chile's Ministry of Energy and the results from the heat demand model, as well as various other sources and projections to the year 2050. This approach facilitates the comparison and development of potential energy system designs while accounting for the long-term considerations needed to align with equally long-term planning process. The creation of multiple scenarios in conjunction with the replication of the PELP reference scenarios, rather than simply one optimized scenario, is an important tool in being able to create a comparative understanding. Doing this, it can become clearer how new infrastructures and the synergies across the different energy sectors can be best exploited to reach a more a more sustainable energy system, which can effectively aid to reach Chile's environmental and energy goals.

4.1 Energy System Analysis

Identifying the potential of introducing new technologies and infrastructures in future energy systems requires a holistic analysis of how such systems will function, and effectively simulate what they will look like in order to assess their suitability. This process involves quantifying how the scenarios will be (re-)designed considering different supply sources, conversion technologies and storages in order to meet the energy demands at any point in time. In the Heat Roadmap Chile scenarios, the energy system analysis is conducted by means of modelling the Chilean energy system in 2050 using the energy system analysis software EnergyPLAN (version 14.2).

EnergyPLAN is a deterministic model that optimizes the operation of a given system based on user-defined inputs and outputs, such as the demands and capacities for various technologies, resulting in a detailed simulation of their hourly interactions and energy resource demands, the system costs, and annual aggregates of the total primary energy consumption, energy production, and the amount of CO_2 emissions resulting from the energy system operation [21]. These then enable the assessment of how efficient and resource or emission-intensive the energy system will be.

Since EnergyPLAN is an hourly tool that covers the entire national energy system, it is specifically designed to enable the identification and analysis of potential synergies between different energy sectors – including the electricity, heating, cooling, industry, and transport sectors. This is particularly relevant for the Heat Roadmap methodology, since it considers the heating sector as a key and integrated part of enabling a transition in the wider energy system.

The value of EnergyPLAN as a simulation tool is in its ability to allow for user-defined (normative) scenario designs, meaning that it facilitates the development and comparison between different alternative scenarios. This is deeply rooted within the concept of a dialogue model for planning, where the role of energy systems modelling is to inform, present (quantifies and qualified) options, and facilitate participatory dialogue and deliberation between stakeholders[10].

To simulate the operation of the Chilean energy system, different parameters and data sources were considered. These included the hourly time-series distributions for electricity demand and temperature data, production profiles for the different plants, aggregated data for energy consumption and production, system costs, etc. A summary of these parameters and their data sources can be seen in Table 8.

Table 8. Modelling inputs and data sources.

	Data type	Sources used
Time series	Electricity demand	Energia Abierta SEN [22]
	Temperature data	Servicios Climaticos DGAC [23]
	Hourly production profiles	Energia Abierta SEN [22]
Aggregate data	Production capacities	PELP[3]
	Energy balance	Balance de Energia [24] & IEA [25]
	Energy demands & projections	PELP [3]
	Fuel and CO2 prices	PELP [3], Biomass reports [26,27]
	Investment costs	PELP [3], [28] and Technology catalogues [29–31]
	Emission factors	DEA technology catalogues [29,30], for CCS [32]
	Energy potentials	[3,25,33]

The first step to set up the energy system analysis using hourly simulations with EnergyPLAN was to obtain time-series data for the different energy demands in the system and the production profiles for the different types of plants and renewable sources.

In the case of the heating demands, these hourly distributions were derived from temperature data in different representative locations according to the thermal zone groups defined in [14]; namely, using measured temperature data from Antofagasta, Santiago and Puerto Montt each representing the aforementioned thermal zone groups [23]. The temperature data was reinterpreted as heating degree-hour calculations with a reference temperature of 17°C. These calculations were then rescaled according to the heat demand shares for space heating and domestic hot water (DHW) identified in [14], so that in periods with null heat degree-hours the baseload heat demand for DHW would be considered. Thermal inertia in buildings was also accounted for by taking 6 hour moving-average on the time-series distributions, which were then normalized and aggregated according to the share that each of the thermal zone groups represent from the total heat demand in the country.

These estimations were then used as the hourly distributions for both the district heating and individual heating demand, as no further measured data of these was readily available. This approach is likely to underestimate a coincidence factor in any potential district heating systems but provides a more conservative approach than trying to estimate these factors without context-specific data in the country.

The hourly profiles for the electricity demand and production were considered from available data sources corresponding to the Sistema Eléctrico Nacional (SEN) [22], since this system covers over 99% of the Chilean electricity sector [34]. The hourly distributions for each power plant and generation units were aggregated as a whole to estimate the hourly electricity demand profile. Similarly, an aggregation by individual plant types, such as wind, solar and hydropower, was also conducted to identify the hourly profile of each renewable energy source, at a national level. This hourly distribution is a key dataset in order to simulate and analyze the interactions between the electricity demand and fluctuating supply sources in the form of variable renewable energy, which should then be balanced appropriately in the broader design of the energy system scenarios.

The energy system scenarios described in Section 4.2, including the references and the Heat Roadmap alternatives, are mostly grounded from the *Planificación Energética de Largo Plazo* (PELP) conducted by Chile's Ministry of Energy [1]. This analysis contains different future projections for developments in energy demands, electrification in the transport and heating sectors, fossil fuel prices, technical potentials for new renewable energy generation, electricity interconnection, costs of externalities, and investment costs for key renewable generation technologies, battery storage and carbon capture storage (CCS) for coal based power plants. Additionally, this analysis also estimates the resulting energy production and installed electricity generation capacities for different energy system configurations based on a combination of these projections, which outline future alternative developments in the country's energy system. These yearly projections and results were then aligned and linearly extrapolated from 2046 towards 2050, as a way to adhere to international climate planning and ambitions; particularly given the Paris Agreement and commitments.

The energy system models for the scenarios then used these hourly distributions in combination with existing analysis. In conjunction with this, the heat demand model results from the analysis presented in Chapter 3 were also considered, which enable a better representation of the countrywide heating demand and provide further insight with respect to the costs and grid losses to be encountered when incorporating different levels of district heating into the system. In addition to this, the energy balances from [24] were used to identify the different shares of fuels in the overall system and to identify other energy uses like the fuel consumption in the industrial sector and the potential of any excess heat from this sector. Furthermore, assumptions pertaining technology specific parameters and costs – not considered under the PELP – were gathered from the technology catalogues in [29–31], while local biomass prices were obtained from [26,27].

Departing from the development of the energy system models, a series of parameters and criteria were used to assess how the different system alternatives will function and be able to quantitively compare their performance once district heating, diversified heating supply sources, and more variable renewable energy are included into them. This is fundamental, as it allows for an evidence-based national outlook and a deeper understanding of consequences of changes in the energy system which work towards a long-term energy transition. The main principles and criteria used for this analysis are outlined in the following sections.

4.1.1 Particulate matter as an indicator of decontamination

The objective of decontamination is to reduce the amount of total particulate matter (PM) emitted to the air by means of inefficient burning of logwood and other combustible sources. This is done in order to reduce health hazards and improve the air quality in urban areas. The analysis conducted identifies such PM reductions by relating it to the primary biomass supply consumed by the different types of plants in the heating and electricity sector, and their related emission factors, based on the different combustion technologies and their associated particulate matter control systems. This considered the amount of total PM emission by amount of fuel as a simplified factor – as specified in [29,30] – of 0,3 *g/MJ* for the case of centralized cogeneration plants and 10 *g/MJ* for individual biomass boilers, respectively. The combination between biomass quantity and its combustion process to quantify particulate matter emissions is important HRCL, since decontamination is envisioned as a shift from inefficient individual heating technologies towards district heating in high heat density areas, and more efficient individual technologies in rural areas with lesser concentration of heat demand. As a result, this allows for more efficient control over particulate matter emissions, without necessarily reducing the overall amount of biomass consumed in the country, but rather shifting the production towards more efficient units such as those found in district heating systems.

4.1.2 Primary Energy as an indicator of energy efficiency

Primary energy supply is defined as all energy that is used, before conversion, as input to supply the energy system. The goal of energy efficiency is to maximize the effectiveness of the energy that is used, and in doing so reduce the total amount of energy that is needed to cover the demands of an energy system. In HRCL, this translates to reducing the primary energy supply. In other words, this approach ensures that the total resources in the energy system are minimized, and not just that the minimization of energy at other individual phases such as during transformation or distribution stages. This in turn ensures minimizing the amount of total energy and fuels consumed, which typically leads to cost and CO_2 emission reductions and, therefore, a more decarbonized energy system.

4.1.3 Socio-economic energy system costs

A critical outcome of developing a Heat Roadmap for Chile is being able to quantify the benefits that a redesigned energy system scenario could provide in terms of transitioning towards cleaner, more efficient heating solutions such as those provided by district energy. This quantification can be reflected in the costs and potential savings that different system scenarios have between each other. This can then be viewed under the perspective of how it would look like for society at large, and towards what direction the supporting public funding, policies and regulations should aim at with respect to a given alternative. Consequently, the quantification of the socio-economic costs of the energy system means that even if the total costs are lower, it is likely to implicitly require an (internal) redistribution of costs and benefits to provide an equal or lowest-cost solution for all involved stakeholders.

Given that the HRCL scenario's primary aim is to create an understanding of how cleaner energy systems can be designed and planned in the long term, there is an intrinsic implication that a sustainable cleaner future is highly valued, and the importance of time value of money is low. For this reason, a social discount rate of 6% is considered in the cost reporting of the scenarios. It must be noted that this discount rate is used to annualize costs around the year in which the scenario modeling is conducted for comparing the different alternatives to each other, rather than for a cashflow analysis around a specific business case. In terms of the specific costs considerations, these included the investment costs for different energy conversion and storage technologies, heating infrastructure, operation and maintenance costs, fuel prices, costs of environmental externalities, as well as the technical lifetimes of the above in order to facilitate an annualized comparison.

The socio-economic costs considered include a cost for CO_2, but do not include a cost for the (indirect) health or environmental impacts of particulate emissions. This is partially due to the specific complications that are associated with the impact assessment and valuation of PM [2],[35]. While the PM emissions in future scenarios are quantified, further research would be required in order spatially re-allocate the benefits and do full assessments on impact reduction and health benefits.

The scope of these costs is specifically designed to include the costs not only for the heating sector, but also the electricity, transport and industry sectors, and thus conceived to include different key sectors in the analysis and present a comprehensive overall outlook of the energy systems' economics. While these do not fall under the direct focus of the study, this allows for the inclusion of benefits and costs that arise due to the increased interconnection and synergies that develop between the heating and other sectors.

4.1.4 Precautionary principles and use of proven and available alternatives

The energy system analysis done in Heat Roadmap Chile follows a scenario designing approach, rather than an optimization approach. This means that in order to construct the scenarios for the future, normative choices are employed to create technically viable simulations, and these are then assessed according to the indicators described above.

The design choices used when constructing and modeling energy systems follow an exploratory approach to define the range of technologies to be considered and how this can be best used within the system's constraints. While designing the Heat Roadmap scenario for Chile, this means that the design of the future energy system follows some explicitly assumptions about what kinds of technologies can be considered. These choices are mainly based around the use of proven technologies and potentials, rather than relying on completely radical improvement or innovations of yet-to-be-proved future technologies.

Although the final Heat Roadmap scenario may represent a radical change compared to the current energy system, it also represents a conservative alternative since the technologies needed in such a system are already mature and proven to adequately function at high market shares in different countries. Thus, it is important to note that the key aspect of understanding the consequences is centered not around the need for technological innovation, but rather the need for improved knowledge, data, planning practices and informed policy making that could ensure the transition towards a cleaner energy system that meets specific societal development targets.

Following this approach, a notable outcome in the design of the Heat Roadmap scenario is that biomass is used as a main fuel in the energy mix of the electricity and heating sectors, reaching comparable levels of utilization to the reference case. This is done without challenging the need for air decontamination from wood combustion, since the redesign of the heating system yields a feasible yet substantially less emission-intensive solution towards meeting air decontamination targets. In turn, this could facilitate the uptake of district heating since it does not necessarily stand on the way of an existing and well-established market like that of biomass.

Another important consideration in the design of the Heat Roadmap is that the energy system does not rely on carbon capture storage (CCS) as an option for decarbonization. This means that the decarbonization of the energy system needs to happen by shifting away from the fossil fuel share in the primary energy mix and by increasing the supply with renewable energy sources.

If new technologies do develop, these can then lead to faster rates of decontamination and decarbonization, more efficiency, or decreased costs, but the underlying norm to Heat Roadmap Chile is that these technological developments are not a pre-requisite for the transition towards a cleaner energy system to happen. For the remaining technologies, the same principles apply. Some learning and improvements are expected, but the measures and technologies considered in the development of the heat roadmap scenario are all proven and well-established.

4.2 Scenario development

To assess the potential energy system designs, a number of scenarios were considered in which different assumptions regarding the prospective developments of technologies in the energy system were taken into account. As seen in Figure 16, the scenarios considered built upon those originally presented in the Ministry of Energy's PELP, working towards further integrating the district heating and variable renewable energy potentials, and ending in the Heat Roadmap Chile scenario. The development and assumptions behind these scenarios are explained in the following sections.

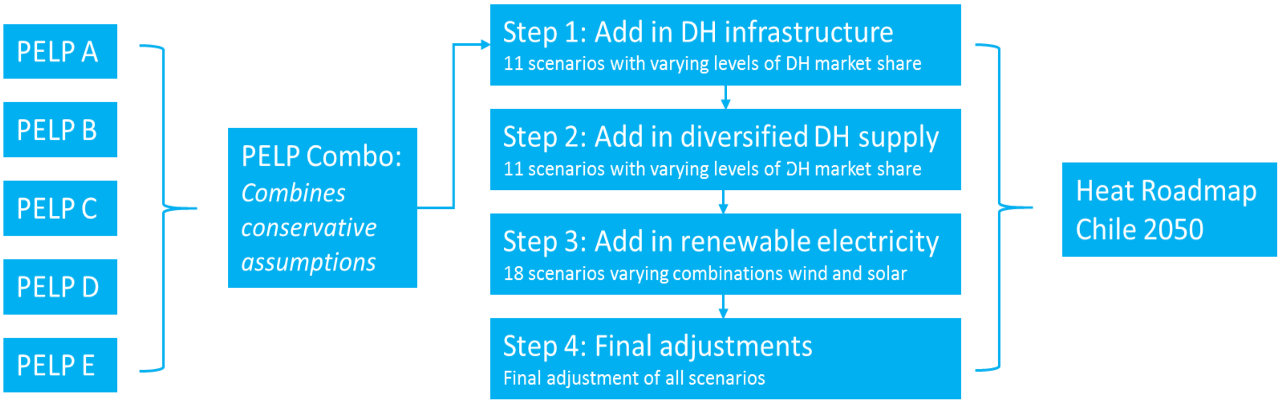


Figure 16. Overview of the energy system scenarios.

4.2.1 Reference Scenarios

Five main scenarios of potential energy system designs have been initially considered as a frame of reference for any alternative scenarios, based on the study developed for Chile's Ministry of Energy, "Proceso de Planificación Enérgetica de Largo Plazo" [1]. These scenarios represent different future developments, according to different factors such as technology changes, projected energy demands and costs assumptions. As mentioned, since the PELP scenarios are only developed towards 2046, the yearly projections and results were then aligned and linearly extrapolated from 2046 towards 2050, as a way to adhere to international climate planning and ambitions (in particular the Paris Agreement).

In order to have a common ground of analysis, a combination scenario ("Combo"), which is composed of the PELP assumptions, is both considered as the departure point for the development of the Heat Roadmap Scenarios and as the primary of the reference scenarios to function as a point of reference for comparison.. Moreover, this allows for a general understanding of the outcomes caused by specific changes in the energy system or in the level of investments needed, and their effect on the energy system's performance. The Combo scenario combines the most precautionary assumptions available for the different factors, in order to ensure a conservator approach and that the design of the final scenarios is robust even in the face of disadvantageous developments of eg. technology developments.

Table 9 shows an overview of the main assumptions pertaining to each of the 5 different initial reference scenarios and the additional combination reference scenario used hereafter as a primary reference in the HRCL analysis.

Table 9. Main considerations for the different scenarios representing Chile's energy system [1].

Factors	Scenario A	Scenario B	Scenario C	Scenario D	Scenario E	Combo
I. Social investment cost factors for power plants	Including factor and carbon capture storage (CCS)	Current market trends	Including factor and CCS	Including factor	Including factor	No CCS
II. Energy demands	Low	High	Medium	Low	High	High
III. Technology changes in battery storage	High	Low	Medium	Medium	High	Medium
IV. Environmental externalities	Current	Increased	Current	Current	Increased	Increased
V. Investment costs for renewables	Low	Low	Medium	High	Low	Medium
VI. Fossil fuel prices	Medium	High	Low	Low	High	Medium

The factors mentioned in Table 3 can be summarized as followed, all based on in [3,14]]:

I. Social investment cost factors for power plants: The costs for electricity generation plants may include a factor to account for costs related to implementation in certain regions. Additionally, coal power plants may include CCS units which would further increase investment costs. Finally, investment costs may also be assumed to have no external cost variation.

II. Energy demands: High energy demands include a higher level of macro-economic growth and a higher electrification rate of both the transport and individual heating sectors, accompanied by energy efficiency measures. Low energy demands reflect projected economic growth rates along with current trends of energy efficiency measures. The medium energy demand case builds on the low case by also considering current rates higher rates of electrification in the individual heating sector.

III. Technology changes in battery storage: The different cases of battery storage technology development are reflected in terms of varying investment costs for Lithium-Ion batteries.

IV. Environmental externalities: Environmental externalities are reflected as the current costs of CO2 emissions and a future increased cost. None of the references include a monetization of health impacts from PM.

V. Investment costs for renewables: This include 3 different projections of the potential development of investment costs for different variable renewable energy technologies.
VI. Fossil fuel prices: This includes 3 different projections of the potential development of fuel prices for coal, diesel, fuel oil and natural gas.

In addition to the above, the Combo scenario also considers the potential for combined heat and power (CHP) identified by [33].

The different energy system configurations were replicated using EnergyPLAN and were adjusted to reach the same levels of electricity production by calibrating the installed capacities of the different energy sources. The exception to this was large scale dammed hydropower, which in these future scenarios has fixed production capacity and storage equal to present levels [36]; likely due to geographical restrictions and being close to its maximum available potential.

Similarly, the initial shares of technologies, defined in [3,14], covering the individual heating demands were adjusted to meet the estimated demands from the analysis conducted in Chapter 3. This approach was followed so that the representations of the energy system had enough energy production to meet the expected demand at any given point, despite some discrepancies in the initial reference capacities due to both the nature of the hourly simulations and the understanding of required capacity factors on an aggregate level. Moreover, by aligning the energy production in the reference scenarios, and then using the EnergyPLAN hourly modelling to determine the appropriate capacities that align to this levels, it is possible to have a better frame of comparison regarding the emissions related to fuel consumption resulting from the energy production process.

The adjustment of these system configurations and scenarios also meant that the overall system had to be balanced with respect to the amount of electricity imports needed and any excess electricity produced. In other words, the energy system models had to meet the limited electricity interconnection capacity constraints defined in [3], and had to keep any critical excess electricity production to a minimum – here set to at most 10% of the total electricity demand – so that grid stability is ensured.

The application of the abovementioned factors and adjustments throughout the different scenarios result in dissimilar energy system designs and costs, with the combination scenario presenting results within the range of the initial scenarios in terms of annual costs and energy consumption, and higher amounts of emissions caused by the different energy supply mix, as seen in Figure 15. These differences are mostly driven by the varying assumptions in investment costs and fuel price projections for each of the alternatives and different developments of the electricity demands.

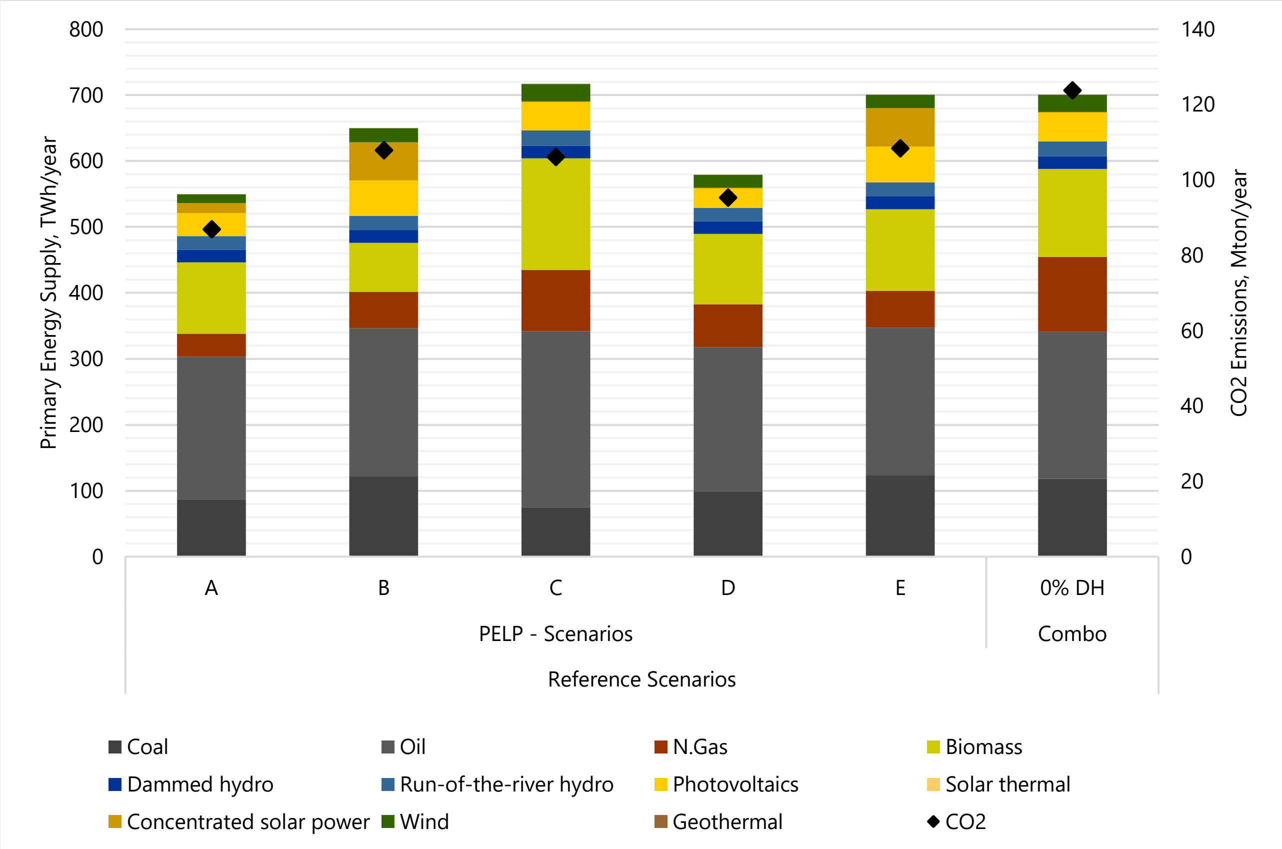


Figure 17. Primary energy supply for the PELP and combination reference scenario

4.2.2 Heat Roadmap Scenario Steps

The Heat Roadmap scenarios take as point of departure the combination scenario described in the previous section, as a basis for further redesign. A series of mid-step scenarios are developed in order to assess the impact of introducing district heating at different levels and diversifying the supply mix of the 2050 energy system. by modelling the inclusion of different elements stepwise and creating alternative scenarios in this stepwise manner, the role and impact of the different elements of the Heat Roadmap redesign become clearer.

This means that these steps **do not** represent a chronological order or series of prerequisites for national energy system transformation. The overall design of a long-term scenario is not necessarily synonymous with the trajectory at which a (local) energy or district heating system is expected to develop; rather, here of course the expectation would be that all the technologies discussed are implemented simultaneously, but at increasingly greater market penetration. However, in terms of creating an understanding of how the different elements that contribute to an energy system which includes district heating works, a step-wise approach is valuable, since it allows for the creation of multiple scenarios at each point, and an analysis of how the different elements of the system contribute.

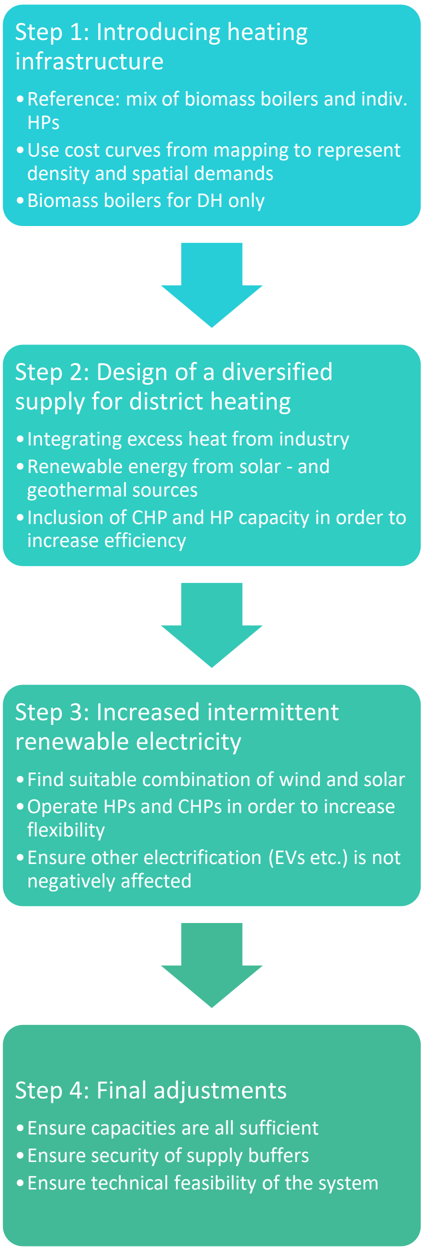


Figure 18.: Overview of Heat Roadmap Scenario design steps

Step 1: Introducing district heating infrastructure

Based on the results of the heat demand model produced in the mapping, an incremental increase of the heat demand covered by thermal distribution networks is simulated to make an initial determination of what the potential for heat distribution by means of district heating could be. In this initial step, the district heating systems are supplied only by boilers, and no additional effort is made to integrate further renewables into the energy system.

This step serves to integrate the cost of distributing thermal energy – which is inherently locally driven and therefore derived from a geospatial understanding – into the national-scale energy model simulation (see Section 3.1.4). The losses that occur in transporting heat in the district heating system are also included, based on the spatial analysis. In addition to the (distribution and transmission) costs from the mapping, costs for branch pipes and heat exchangers; heat generation capacity; and fuels for heat generation are included to the energy system costs. This results in the simulation of a system which has a functioning, albeit very basic supply in its district heating system. This simulation is done incrementally, using intervals of 10% of the heat market share as seen in Figure 16.

The main observation that can be gathered from considering the primary energy supply, shown in Figure 16, is that by using a boiler-only based system for the lower levels of district heating market saturation, there is an increase in efficiency compared to the combo scenario. This is mostly because in these high-density areas district heating is replacing a mix of inefficient biomass boilers, and electric heating based for a large part on (inefficient) thermal power generation. This is also evident from the decrease in CO_2 emissions as the market share for district heating rises, results from the non-renewables being used in the thermal power generation and are thus being displaces as electric heating if phased out.

However, at higher levels of district heating based on only boilers, the losses that occur as thermal energy is transported to less dense areas outweigh the benefits that are made from more efficient conversion. This increase in primary energy supply stands in for a simultaneous increase in costs (both from fuel – and from increased infrastructure investments). Based on this, a boiler-only district heating system can provide some benefits but does not represent the full (cost and energy) efficiency that district energy can provide.

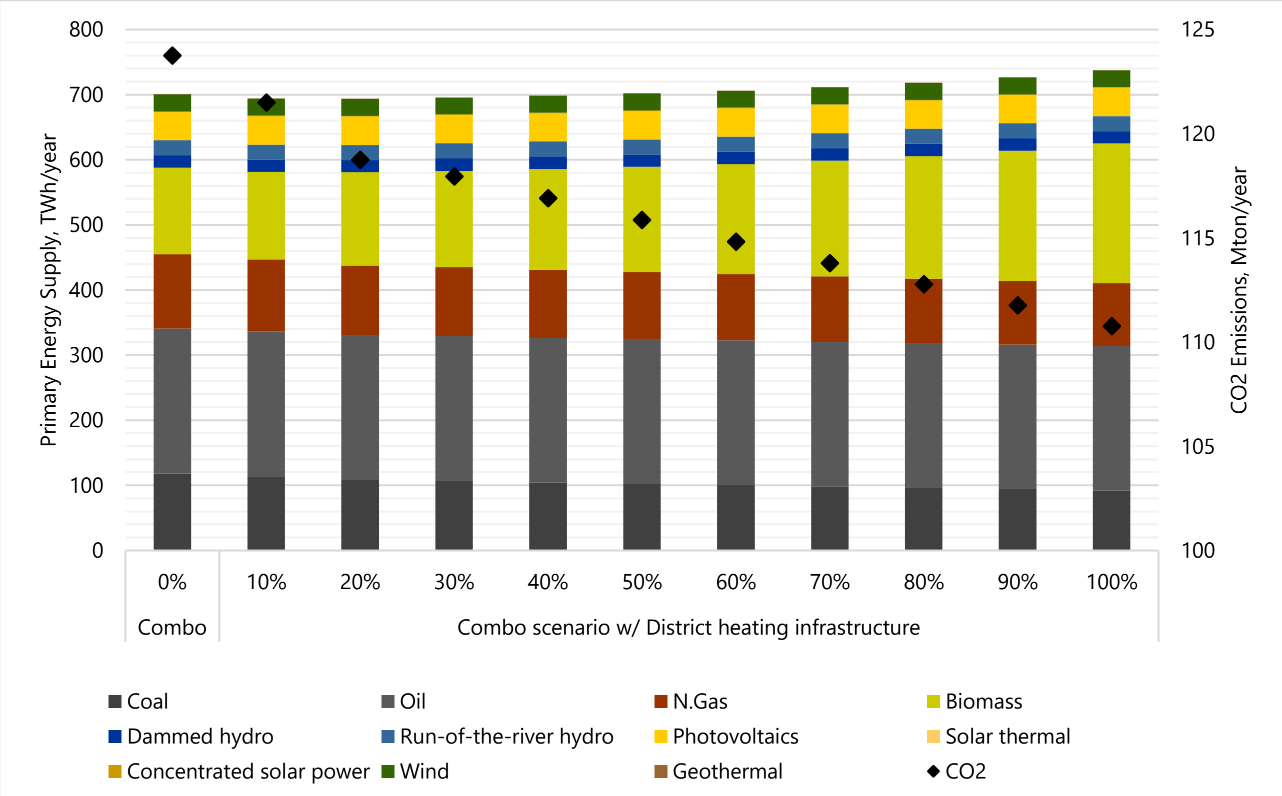


Figure 19. Step1: Effects of introducing district heating infrastructure on the energy supply in 2050.

Step 2: Design of a diversified supply for district heating

In order to consider the different supply options that can exist within modern district heating systems, different technologies to supply heat to the district heating system are implemented to complement the boiler-only setup in Step 1. This allows for the simulation of the benefits that district heating can have in terms of using more efficient technologies than boilers; namely by efficiently integrating available heat from other sectors and renewable energy sources; linking the thermal and electricity sectors through the use of CHPs and large-scale HPs, and implementing large-scale storage, which serves as a cheaper alternative to electric storage. This step considers several elements that combined represent a diversified supply mix.

a. Integrating excess heat from industry;

In order to estimate a maximum potential and recovered potential for excess heat [37], a generalization was made based on previous studies; notably, the most recent Heat Roadmap Europe (HRE) [4][38]. In that study, it was possible to geographically determine the positions of industrial excess heat sources and extrapolate the volumes of excess heat available based on the type of industry and data available from the European Union Emissions Trading Scheme (EU ETS). These excess heat potentials were then combined with geographical, temperature, and temporal constraints in order to give the maximum available potentials. However; since district heating does not typically extend to the full technical potential of the market share, only part of this excess heat is finally used in the Heat Roadmap Europe scenarios.

To tie this estimates with the industrial excess heat potential in Chile, the ratio between fuel consumption inputs in the Chilean industrial sector and recoverable potential for industrial excess heat determined in HRE were analyzed, showing a very strong correlation – as seen in Figure 17 – between what can be taken from the national energy balance and the levels determined through the spatial and industrial analysis. This estimation excluded the mining sector, which does not have a substantial presence in the HRE countries, and due to the geographical constraints, that do not facilitate the recovery of heat from this industrial subsector.

Based on this, the level of recoverable excess heat is estimated at about 3.9 TWh/year. Since this is one of the cheapest options of available heat, this is typically used to its full recoverable potential. It is important to note, however, that his estimate is used as proxy for the amount of excess heat that should be included in the system. Currently, there is a high degree of uncertainty as to what the actual amounts excess heat available are, since this assumption is not an actual identification of the existing and spatially feasible alternatives of recoverable heat. Further studies would be needed for a more accurate representation of the actual excess heat potential and recoverable excess heat available and could be integrated into both the mapping and the modelling.

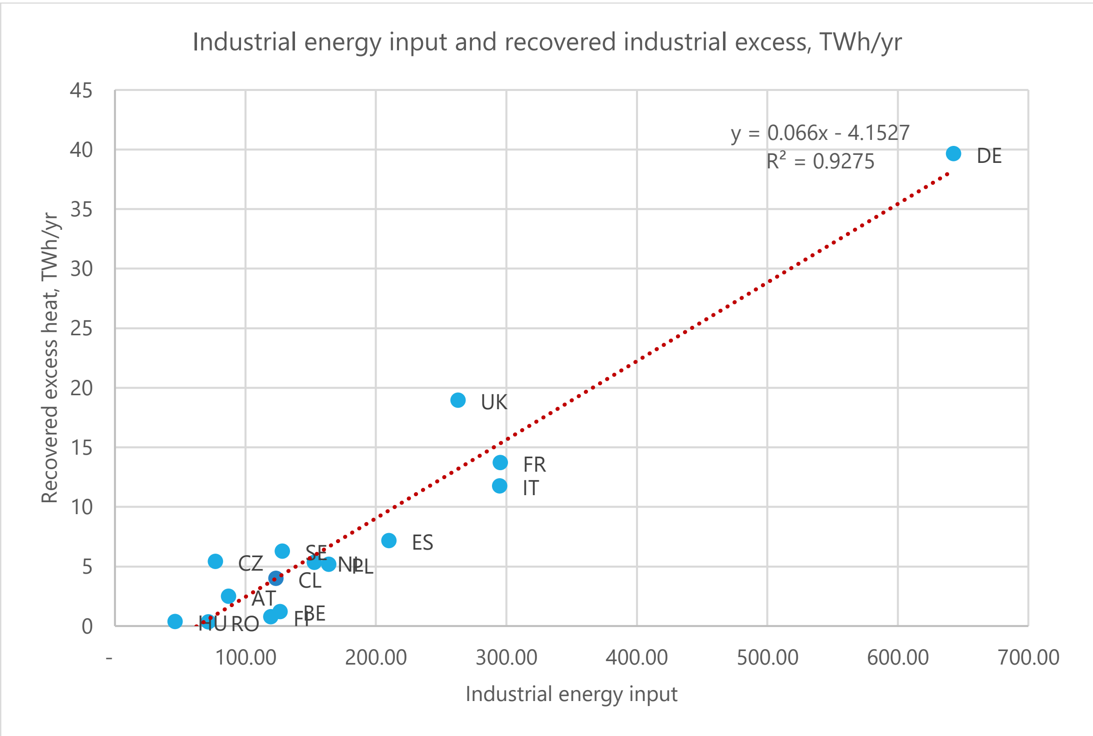


Figure 20. Correlation between industrial energy input - excluding mining - and the recoverable excess heat.

b. Renewable energy from solar- and geothermal sources

For the case of both solar thermal and geothermal energy available as base load supplies for district heating, half of their respective total potential defined in the PELP projections were assumed [1]. These, however, are conservative assumptions of these potential sources. In the case of geothermal, the actual potentials identified in the PELP projections are linked to high temperature sources more suitable for electricity generation. In the case of district heating, shallower sources with lower temperatures and in close proximity to urban centers could potentially be available but are not accounted for in the original PELP estimation of the potentials. Given that limitation, an assumption of the geothermal district heating potential amounting to about 1 TWh/year, equivalent to half of the actual geothermal potential for electricity, was considered as a conservative estimate. Similarly, the potentials for solar thermal energy, estimated at around 0.28 TWh/year, consider a spatial availability mostly linked to photovoltaic production. This real potential could be an underrepresentation of the possible use of solar energy for baseload heating, under the assumption that solar thermal could more adequately cover energy demands related to heating in certain geographical regions than photovoltaic would. Thus, the spatial potential was defined in terms of the area required for PV, from which then the solar thermal areal requirements and it's respective energy potential was derived. Also for these sources, further studies that can give a district energy specific and better quantified potential and a better geo-referencing for these sources could be used to create more refined allocation models, and develop the Heat Roadmap Chile scenario further.

In addition to the inclusion of these potentials, for the national modelling long-term storage was not deemed necessary since the climatic variation in Chile means that there are no instances where the 'baseload' heat sources such as industrial excess heat, geothermal and solar thermal are enough to cover the full heat demand. However, there may of course be exceptions at a local level. Thus, these potentials can provide a useful and likely conservative estimation for the national potential for excess and direct renewable heat sources, but also call for further analysis to reduce the uncertainty of how much more of this potential capacity can be used in tandem with the design of diversified heating sources available.

c. Inclusion of CHP and HP capacity in order to increase efficiency

For the district heating system to be able to provide efficiency and flexibility to the energy system, the available power plant capacity should undergo a transformation so that it can use the residual heat more efficiently during the process of energy conversion. This calls for a shift towards cogeneration (CHP), where the power plant production can cover both electricity and heating demands. This ensures a high degree of flexibility in hours when the heating demand is high and the electricity demand is low or when other electricity generation units are not online, so that the dual capacity of the plants can be used to their fullest. In addition, the inclusion of these CHP plants comes in tandem with the introduction of short term thermal storage, set to cover about 48 hours of the heat demand [39].

In a similar manner, large-scale heat pumps (LSHP) could add a high degree of flexibility to the system. Heat pumps can convert electricity efficiently to thermal energy, which means that in hours were there are significant amounts of variable renewable energy production above the electricity demand, this excess could be used within the heating sector to supply the corresponding demand covered by the heat pumps.

Both of these capacities are set in the different simulations so that they can both balance heat and electricity, and contribute maximally to the flexibility of the system, and are used to operate part load where necessary. This also allows for a reduction of the overall system costs at different levels, since the energy supply can be used more efficiently, translating into a reduction of fuel costs despite additional investments on new heat capacity.

The capacities were set to the maximum that was technically possible; in many cases there was an economic argument to reduce the capacities slightly and in doing so reduce total annual cost – but the heat supply was then substituted with biomass boilers. Given the overarching objective to reduce air pollution from biomass combustion, and the overall comparability of cost efficiency compared to the reference scenarios, the normative decision was made to maximize CHP/LSHP capacity (and thus minimize boiler utilization).

Step 3: Increased intermittent renewable electricity

After considering the introduction of diversified heating supply sources in Step 2, more renewable energy sources are considered for electricity production. The added flexibility provided to the energy system by the use of electric heat pumps and the intersectoral synergies between heating and electricity allow for a higher degree of intermittent renewable production to be put into play.

This led to an analysis of different sources based on their countrywide potentials, described in [1]. Namely, these included a very significant increase in the use of geothermal energy – even if only using half of the resources identified in the maximum potential for the generation of electricity. In addition, this included simulating increasing capacities for onshore wind and solar, while other variable renewable energy sources were not looked further upon, as the potentials present a higher degree of uncertainty and are logistically more complicated to introduce (as is the case with ocean energy and offshore wind).

The complementarity of using these sources must also be noted since the production by each of these types of variable renewable energies might be in direct competition with the other for given hours of the day, despite there being hours where one these resources might be available while the other is not. This complementarity must also be viewed with respect to the demands in other sectors and the interactions with the other infrastructures in the energy system, described in the previous steps. For instance, in hours were these renewable sources are not available, the heating demand will not necessarily be covered with heats pumps but rather by running combined heat and power plants or district heating boilers instead.

In the results, this translates to higher degree of utilization and expansion of the wind energy potential over solar. This is due to the hourly availability of the resources, which in the case of solar PV production is limited to only sunlight hours during the day and has high seasonal variations. This also opens the discussion of how the spatial potential of solar energy can be best utilized, since a different balance between the areal use of PV plants and solar thermal plants could lead to a different utilization of solar resources to cover baseload demands in the heating sector, and also enable thermal energy storage as an option.

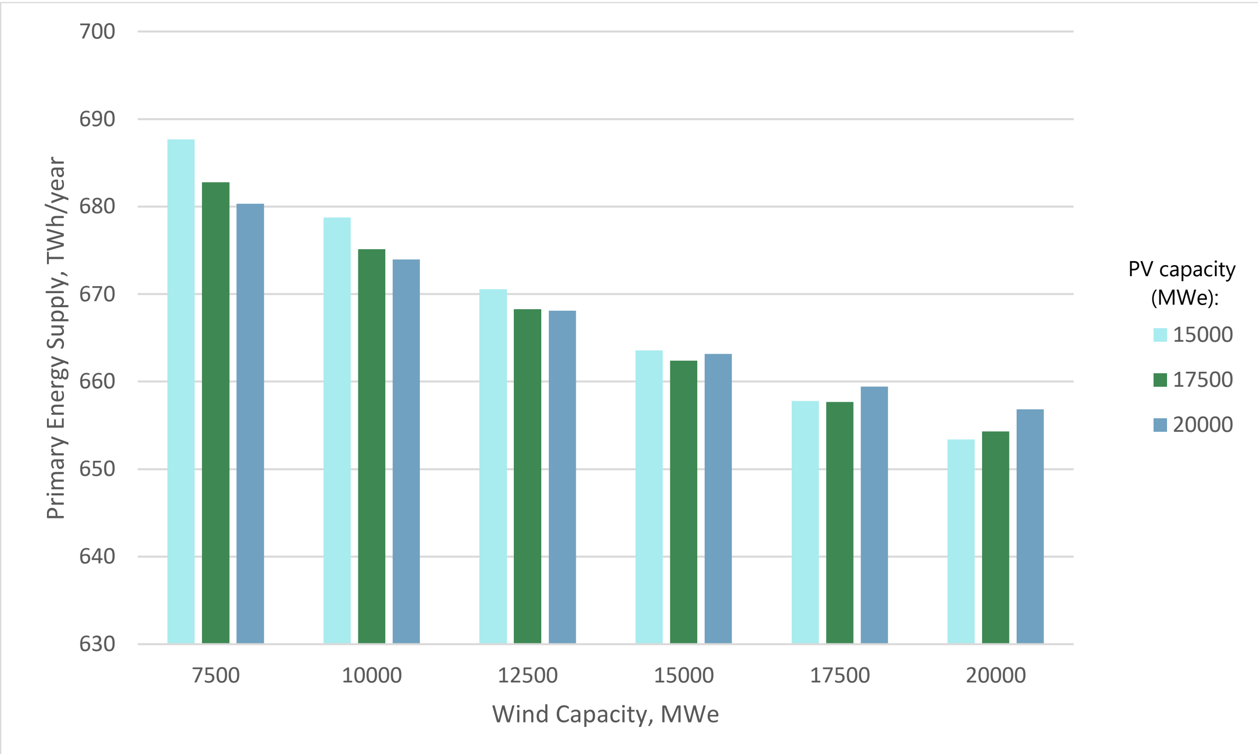


Figure 21. Increasing penetration of wind and photovoltaic capacity and its effect on primary energy supply.

Step 4: Final adjustments and coal phase-out

The last step leading towards the final Heat Roadmap Chile scenario, consists of an adequate balancing of the energy system. Finally, several final alterations were made to all scenarios to ensure alignment and security of supply buffers. Coal was removed from power production in all the non-reference scenarios, in order to be better aligned with current government ambitions to phase out by 2040. Biomass consumption was capped at the highest level considered in the Reference scenarios (PELP C). All district heating was supplemented with boiler capacity to cover the peak hour of demand and a 10% security of supply buffer; in addition, short term storage (equaling 48 hours of average demand) was implemented. Similarly, an additional 10% buffer is added for the condensing power plant capacity. This means that the production capacities are adjusted to cover the demand within the given system constraints, while ensuring a relatively low amount of excess production. The main production capacities are also adjusted so that these have enough capacity to serve as buffer for any changes in the demands.

These adjustments also enable to keep the resulting energy system scenario in line with the approach and guiding design principles mentioned in Sections 2 and 4.1, and used throughout the modelling of the scenarios. In turn, an adequate interpretation of the final scenario and its results can be achieved. The results of this final adjusted scenario are presented in detail in Chapter 5.

5 Results for the Heat Roadmap Scenario

The results of the Heat Roadmap scenario mentioned in Section 4.2.2 are presented in the following sections. The first of these outlines the market share for district heating and resulting heating supply mix and its components, showing how the implementation of district heating in a future energy system will be designed, and how it will be supplied with distinct sources such as excess heat from industry, renewable heating, and with efficient conversion technologies like CHP and large-scale heat pumps. Then, the flexibility and impact of having cross-sectoral synergies is analyzed in terms of its effects in the electricity sector, namely by enabling the use of more variable renewable capacity to come into play. Finally, the broader effects of having a redesigned energy system are presented, showing the benefits in improved air-quality, energy efficiency, societal costs and security of supply.

5.1 Supply technologies and energy carriers for heating

District heating in urban areas

Based on the combination of the results of the Chile Heat Demand Map, and energy system analysis, different levels of market share for district heating were modelled. In the Heat Roadmap scenario, district heating plays a big role in the heating sector, covering about 40% of the heat demand. This potential is unlocked by using multiple supply sources and benefiting from the integration of the energy sectors. On an annualized level, the use of diversified supply sources for district heating allows for cost savings that offset the initial expenditure in district heating infrastructure. This enables a market uptake up to a level where no additional cost benefit is gained from expanding the coverage of the heat demand with district heating. As seen in Figure 19, a share of about 40% of district heating can be reach in residential and service sectors providing optimal cost reductions as compared to the reference scenario with no district heating. Nonetheless, it is important to note that the range of feasible options for implementing district heating at no additional costs compared to the reference scenario can reach about 60% of the heat market.

In perspective to the mapping, this market share covers almost all of the 'Dense' (D) and 'Very Dense' (E) heat density classes described in Section 3.1.4, assuming that the densest areas would be where the district heating is implemented. This represents a radical shift from district heating projects, to city-wide networks – and assumes that district heating systems will cover (substantial parts of) urban areas.

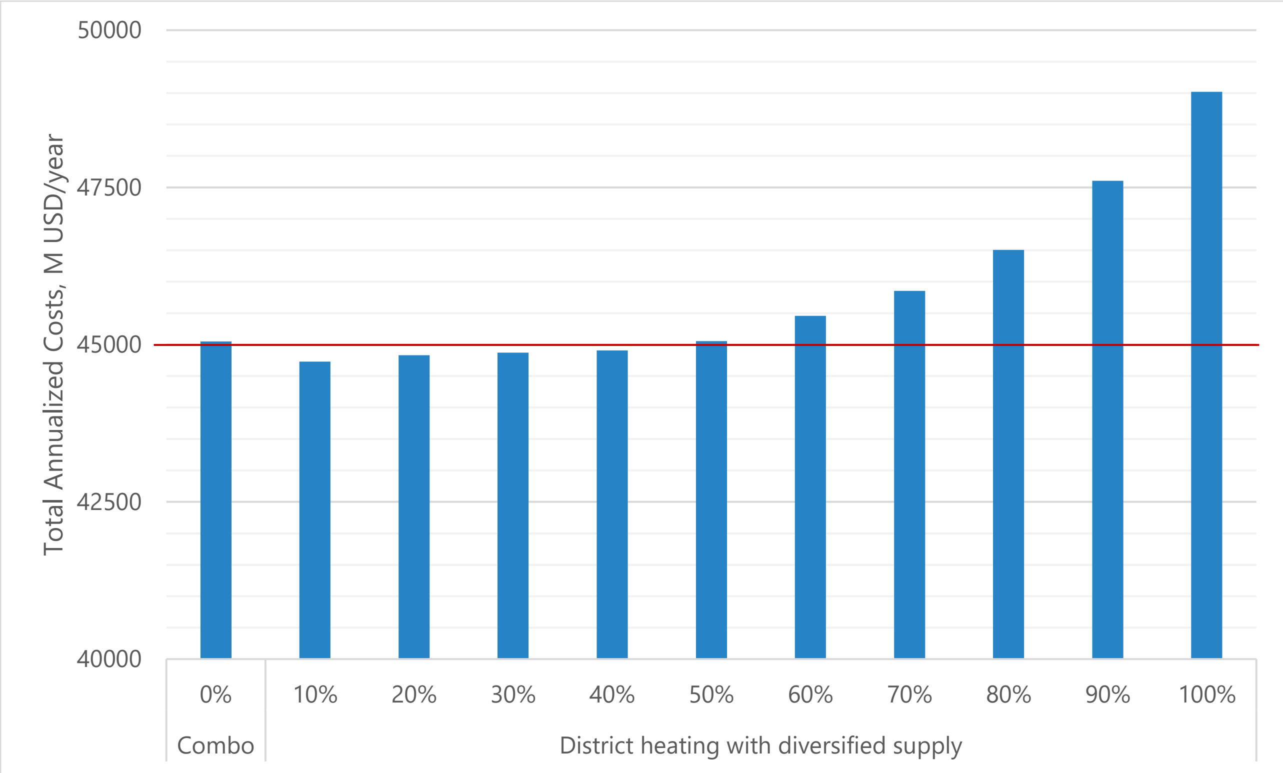


Figure 22. Step 2: Total annualized costs for the energy system with district heating with diversified supply sources.

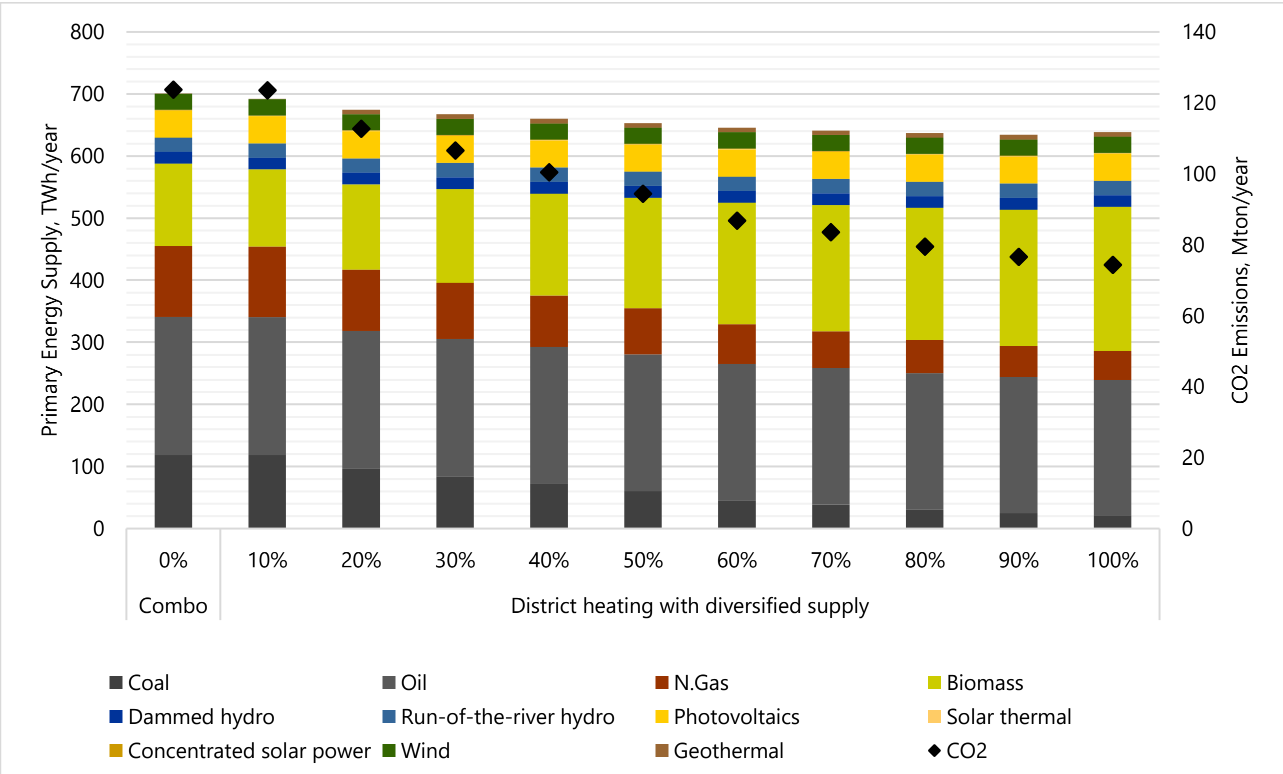


Figure 23. Step 2: Primary energy supply for the energy system at different penetration levels of district heating.

This level of market penetration for district heating is highly dependent one of the design parameters and assumptions used in the Heat Roadmap Chile project. The inclusion of diverse sources for district heating, rather than heat-only boiler systems, results in a scenario where a more complex, diversified, and realistic future district heating system is simulated. This fundamentally increases the efficiency of the system, reduces the costs, and allows for a higher level of socio-economically viable. By designing the system in a way that allows for the incorporation of efficient heat sources; integrating different renewable (thermal) energy sources and creating an interconnection between the thermal and electricity sectors, the co-benefits and synergies that district heating provides can be made more explicit.

5.1.1 District heating supply

The resulting supply mix for district heating is efficient and provides a high degree of flexibility to the energy system. A summary of these supply sources and their respective shares can be seen in Figure 21. Among the supply sources considered, cogeneration plants constitute the largest share of the district heating production covering about 60% of the supply, equivalent to a heat production of about 28 TWh/year. This share is then followed by the supply coming from large-scale heat pumps and excess heat from industry, which cover around 20.7% and 10.7% of the district heating supply, or about 9.6 and 5.0 TWh/year respectively. Heat-only boilers produce approximately 7.5% of the heat supply, representing a production of about 3.5 TWh/year. The remaining 1.2%, equal to a supply of about 0.6 TWh/year, is covered by baseload renewable heat from geothermal and solar thermal sources.

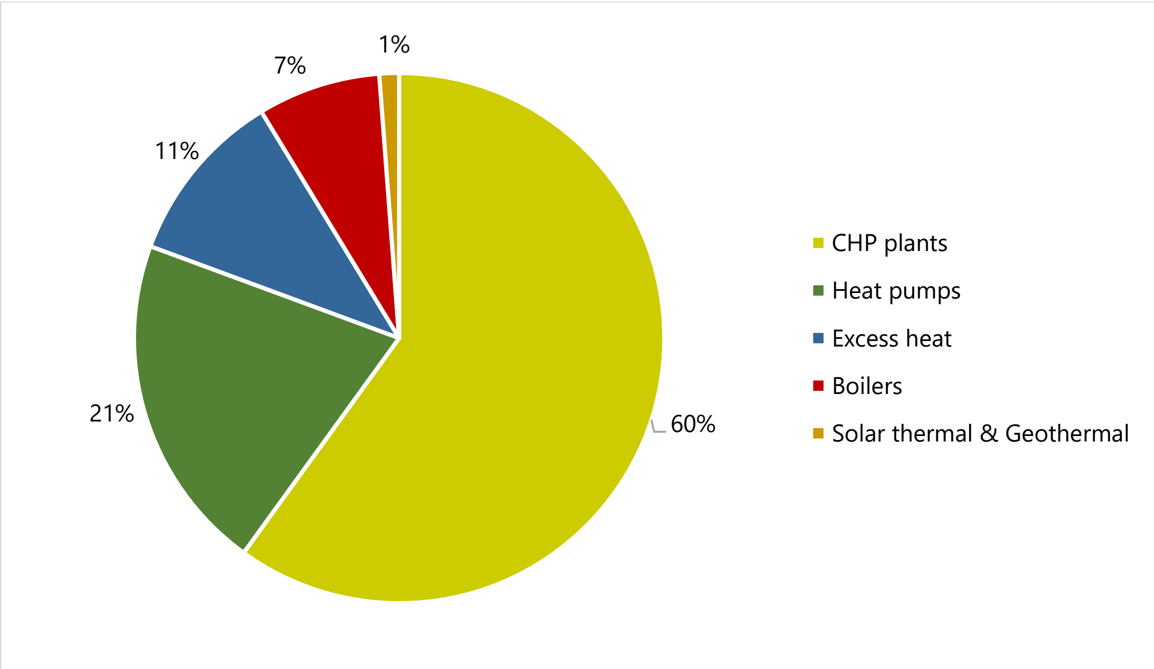


Figure 24. District heating supply mix in the HRCL scenario.

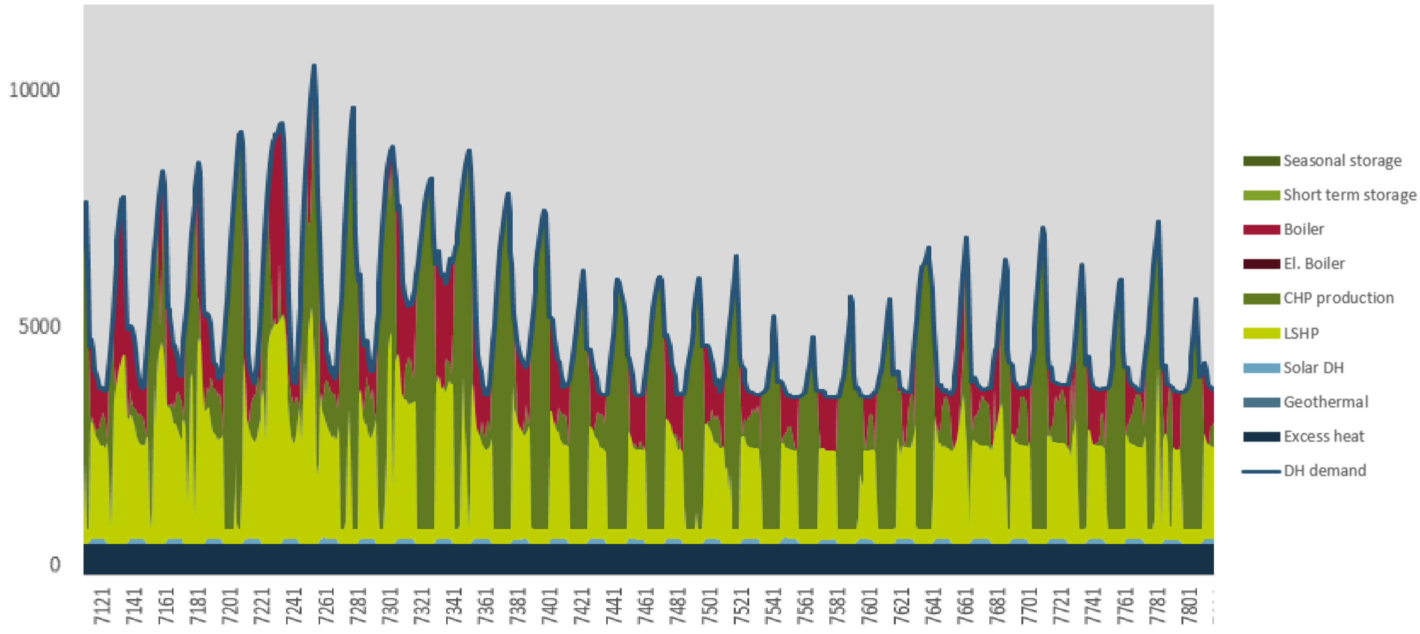


Figure 25. Extract from the hourly profile of DH production in the HRCL 2050 scenario

In terms of the hourly operation of the district heating system, Figure 22 shows an extract of 700 hours, during the transition from winter to spring. As is clear, the heat demand fluctuates on a daily basis (primarily because the demand for hot water is higher during these times) but is also respondent to how temperatures change overall. In order to respond to this and ensure that heating is provided in all hours, the different types of heat sources have differing hourly profiles in terms of their operation, depending on if they provide a more baseload, flexible, or back-up role in terms of their operation.

5.1.2 Baseload heating with excess and direct renewable heat sources

In the HRCL scenario, an emphasis is placed on designing an efficient and renewable district heating sector. One way of establishing the synergies across the heating sector and other energy sectors is by utilizing the potential of residual excess heat from industrial processes as an available energy source for the district heating supply. This has a secondary key advantage that these three supply options are not available unless the infrastructure (in the form of district heating) exists to unlock them – meaning that they directly contribute to the increased efficiency of the energy system, and can substitute fuels and processes associated with PM and GHG emissions.

For both excess heat from industry, geothermal, and solar thermal for district heating, the technical potentials assumed were found to be cost-effective and viable. The total available excess heat considered in this report assumes a direct correlation between the national consumption used for industrial process other than mining, and the utilization rates seen in EU countries. While this correlation seems a useful first indicator, the actual constraints and opportunities to use excess heat are not intrinsically considered by this approach. In addition, there is no direct consideration of the spatial allocation of these excess heat sources, and particularly at local level the use of residual heat from industrial process could be subject to geographical limitation and boundaries, as well as the temperature levels of the surplus heat in question. This means that a more detail spatial and technical analysis is needed in order to fully quantify the actual recoverable amounts of excess heat.

Similarly, the potentials for solar thermal and geothermal energy are inferred from renewable energy potentials and have not been subjected to a localized allocation analysis, in order to more accurately identify proximity to potential district heating areas. While a factor has been assumed, this is especially important for these direct renewable sources, since at a local level, they can play an important role in determining the viability of district energy in smaller (more rural) cities and towns, where the diversity of local sources may otherwise be limited.

In terms of their operation, as can be seen from Figure 22, the geothermal and excess heat sources are considered baseload, and provide the same amount of energy at all hours in the year. While this is a fair approximation of many systems, there may of course be regional differences (for example, if excess heat facilities partially close during weekends or holidays). The primary advantage of this type of operation is that since the marginal costs of running the installations are relatively low, and the operation is effectively full-load hours, the investment costs are relatively easily recovered, and these provide some of the cheapest sources of heat.

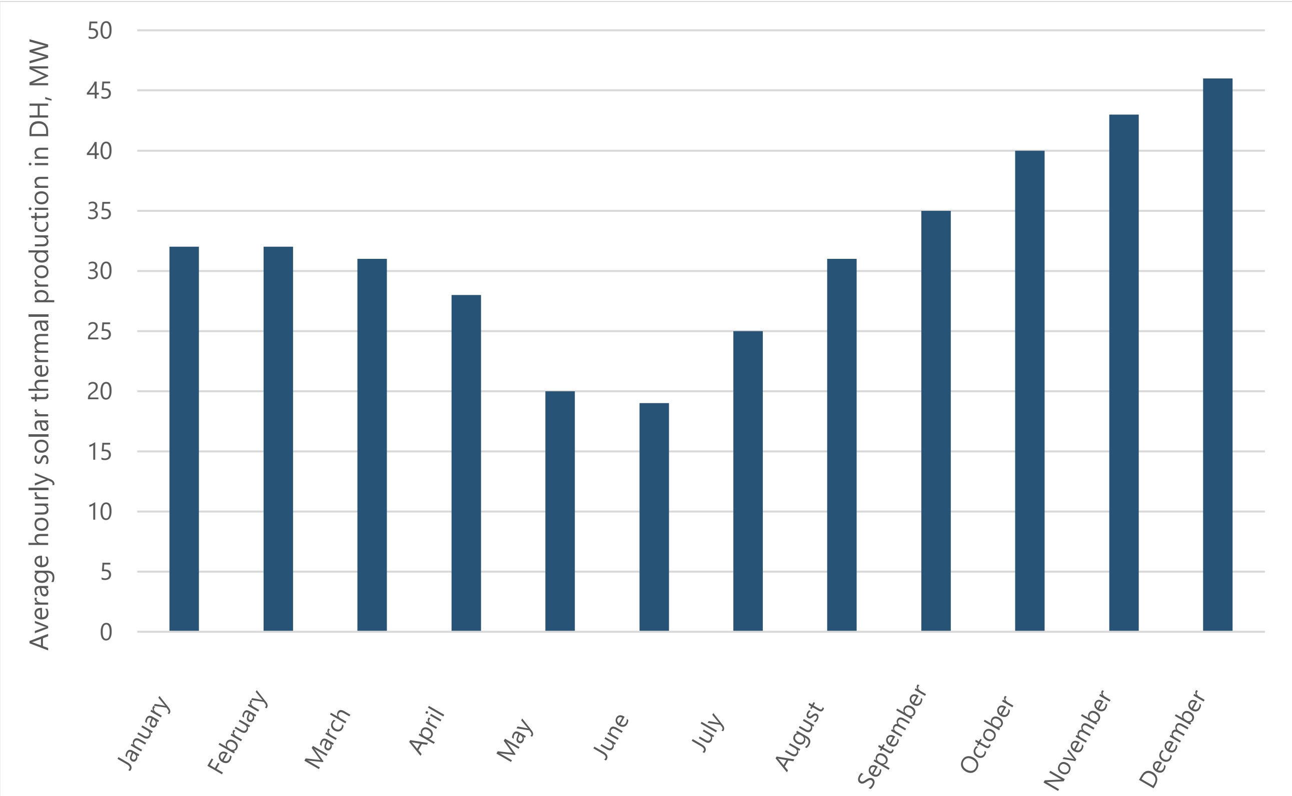


Figure 26. Average solar thermal production in DH per month in HRCL 2050

Solar thermal operates in a similar way, with the obvious caveat that it operates only at points where the sun shines. This leads to an overall lower production profile in the summer months (see Figure 24), but since the baseload heat demand (consisting of hot water demand in summer) still exceeds the conservative estimated potentials for industrial excess heat and geothermal, the installations can still be maximally utilized.

If this has not been the case, the role for (long-term) seasonal storage may be higher. While the cost-effectiveness for this was not established in the Heat Roadmap Chile scenarios, this is more likely to represent a limitation in the alignment between (national level) modelling and lack of local allocation than a true indicator that seasonal storage will not be cost-effective. For example, in cities where the level of excess heat is extremely high, and there is a large direct renewable potential, it may be possible that the cost of installing a large capacity and storage outweighs the cost of a flexible or peak boiler. However, these types of local allocation require a more detailed analysis of the exact (relative) locations of excess heat and renewable sources than was achieved here.

For the baseload heat sources, a main consideration throughout the development of the scenario design has been to use the (marginally) cheap and potentially available baseload heat sources as a way to reduce the cost of producing heat, and allow for efficiency and direct use of renewables in district heating, and contribute to the diversity of the district heating supply mix. This is done by designing the supply mix to include excess heat from industry, and conservative estimated amounts of geothermal and solar thermal heat as supply sources for the district heating systems.

5.1.3 Flexible supply through large scale heat pumps and cogeneration

One of the key benefits that district energy can provide is to support the further integration of (intermittent) renewable electricity, by creating an efficient and flexible link to the electricity sector [8,40]. Both the use of cogeneration and large-scale heat pumps in the HRCL scenario contributes to this, and together constitute over 80% of the district heating production (Figure 20).

The maximum technical potential for cogeneration if mostly determined by the electricity sector, in the sense that the proposed capacity in Heat Roadmap Chile represents a conversion and shift from thermal power production (typically in condensing mode) to cogeneration. In doing so, the overall efficiency of power production increases dramatically, from below 50% to 85%, especially in the cases where biomass is used. The maximum potential for large scale heat pumps is similarly relatively flexible, since they can be applied anywhere from oceanic fjords; local river systems; and in highly diverse applications to unconventional excess heat sources like sewage systems, hospitals, supermarkets and data centers [41,42]. The primary differentiator between these types of applications is the efficiency of the LSHP, so these latter applications have been disregarded in order to ensure a conservative overall efficiency.

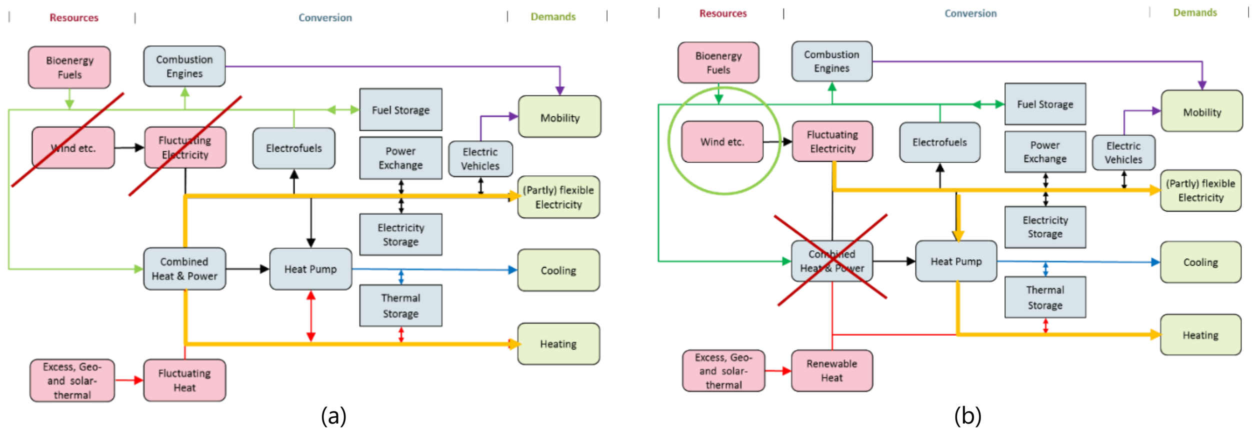


Figure 27. Diagrammatic overview of the energy system: (a) shows the system in hours of low intermittent renewable electricity and efficient cogeneration; (b) shows the system in hours of high intermittent renewable electricity.

In terms of their operation, the CHPs and LSHPs are largely driven by the availability of electricity on the power market, rather than only the heating market. In accordance with the Smart Energy System concept, the CHPs are set to operate in the hours where intermittent renewable electricity sources (like wind and PV) are not sufficient to fulfil electricity demands (see Figure 24). This means that the heat produced is a true by-product of electricity production and contributes to the efficient use of resources.

Simultaneously, because CHP plants are smaller, more decentralized and more flexible than electricity-only power plants [30], they can contribute to the further integration of intermittent renewable electricity in the hours that there is ample production (see Figure 24). In these hours, the cogeneration plants can easily be shut down and electricity demand fulfilled directly via intermittent renewable energy sources – provided that the district heating supply is diverse enough that there are alternatives to supply the heating sector. The dynamic between the electricity sector and (district) heating sector is further strengthened by operation of large-scale heat pumps, which can operate during those hours and fulfil the role of directing (renewable) wind or solar power into the heating system efficiently.

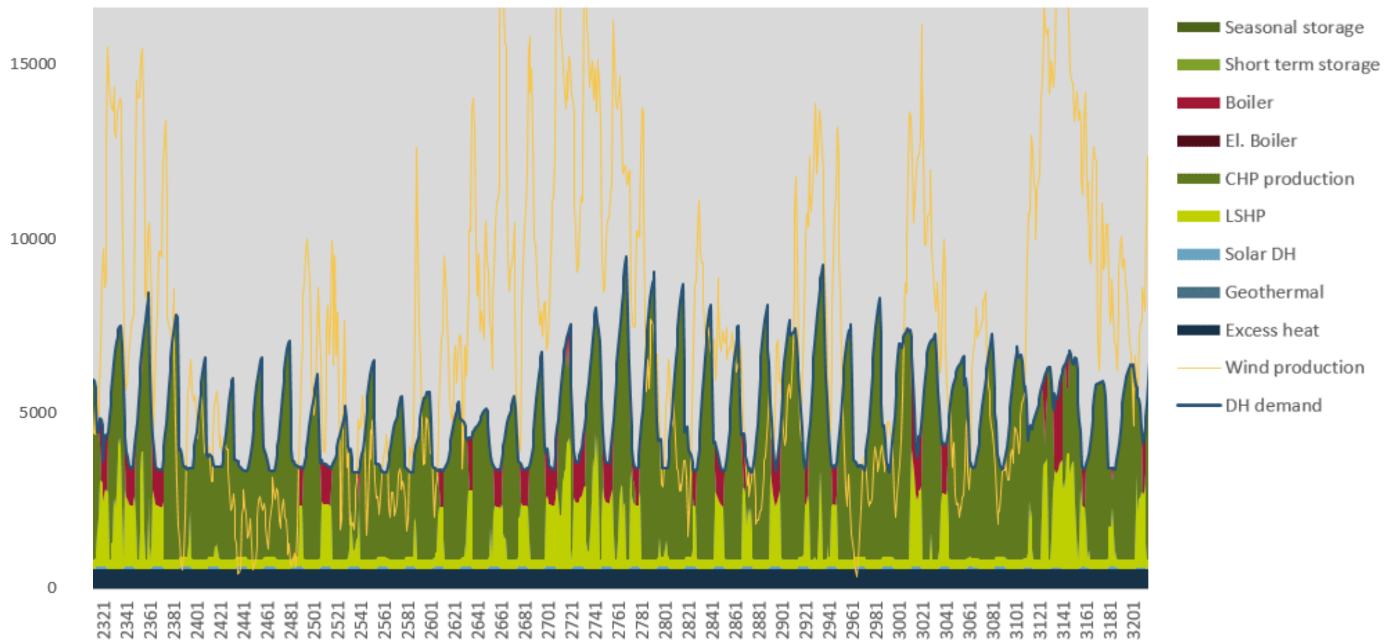


Figure 28. Extract of the hourly district heating and wind production in HRCL 2050

This dynamic is also visible when considering an extract of the district heating demands and production profiles, overlaid with the wind production profile in Figure 25. While this ignores the dynamics between electricity demand and other forms of renewables, it shows that in hours where wind production is relatively lower (e.g. hours 2370 – 2490), heat pump production is minimal, and cogeneration is high. Alternatively, when wind is abundant (e.g. hours 2700 – 2780 or 3110-3170), the operation of heat pumps is much higher.

This flexible operation means that both the cogeneration plants and the large-scale heat pumps are not expected to operate full load. Over the year, the aggregated large-scale heat pumps operate at about 25% of their full load hour capacity (with 125 hours at maximum capacity, 4665 hours at minimum capacity, and almost 4000 hours at varying part load levels). The aggregated cogeneration plants operate at almost 30% of their full load hour capacity (with only several hours at maximum capacity, do not produce any heat for 1372 hours, but spend the overlarge majority, with 7411 hours, operating at varying part load levels).

This flexible operation if both possible and advantageous because both LSHPs and CHPs can take advantage of lowering their marginal costs when the power sector allows, in order to recover their investments. When electricity is scarce, the sale of power is the primary role and income for the cogeneration producers, so the heat can be produced as a cheap by-product; however, when electricity prices are low there is no economic incentive to operate at full load, given the cost of fuel. This means that as long as the district heating supply mix is diverse enough and the heat is not required from cogeneration, operations can halt.

Conversely, for the large-scale heat pumps, marginal operation costs are lowest when electricity prices are low (typically due to a high level of intermittent renewables in the energy system at that point in time, so the ability to avoid high costs for electricity, and part-load or shut down operations allows for an easier recovery of overall investment costs. The addition of 48-hour storage further contributes to this flexibility and responsiveness and means that the specific combination between cogeneration and large-scale heat pumps can contribute to reducing the cost of producing heat and allow for an overall efficient and cost-effective district heating system.

As will be discussed in Section 5.2, one of the prominent reasons that district heating can contribute to the broader fuel- and cost efficiency of the energy system is through the ability to enable and support the indirect integration of more (intermittent) renewable electricity, while also producing cheap heat. The combination of cogeneration and large-scale heat pumps is a key function of this, by using flexible operation strategies to create an efficient and flexible link to the electricity sector. This complementary use of cogeneration and large-scale heat pumps in the HRCL scenario, which represents slightly over 80% of the district heating production, allows both for the cheap production of heat, while also ensuring the costs for installed capacities are covered.

5.1.4 Peak production through boilers

The direct combustion of fuels in heat-only boilers is used to provide 7.5% of the heat supply in the HRCL 2050 scenario (Figure 21). This capacity is set to be able to cover the full peak district heating demand, plus a 10% buffer to ensure security of supply at all times, and accurately represent the maximum required investment in back-up capacity.

Operationally, the use of boilers is mostly dominated by the extent to which it is economically advantageous, within the existing biomass limits. In the HRCL 2050 scenario; the overall use is only 7% of the full load hour capacity, with there being no heat produced by boilers in almost 6000 hour of the year. From hour to hour, boilers are the least favored option since the investment for the boiler capacity is relatively cheap compared to some of the other heat source technologies, but the marginal costs or operation are quite high.

This typically means that if any of the other sources can still be increased, this is preferred over the biomass boilers. This is also the reason that the heat-only boiler based systems modelled in the 1st step (Section 4.2.2) were far more expensive than the more diversified systems, which require more up-front investments but can produce heat much more cost-effectively and result in an overall cheaper system.

Since the boiler operation is very dependent on the other types of heat available, the sensitivity to other supply mixes is quite high. For example, under higher biomass potentials constraints, it seems likely that the potential for LSHPs would increase, and potentially also be used as peak capacity. Further options for investigation would be to consider the use of direct electric boilers; which are less efficient than heat pumps (and thus have a higher marginal cost) but can be a cheaper option if operating hours are low.

5.2 Integrating more renewable electricity

Based on the better integration between the heating and electricity sector, it becomes possible to install more renewable energy capacity. For both wind and PV, the maximum technical potentials were identified in [1], and the capacity finally integrated into the energy system modelling was determined through the complementarity analysis described in Section 4.2.2. The resulting power productions of both the HRCL 2050 and the Combo reference scenarios can be seen in Figure 30.

The main difference to notice between the two scenarios is that due to the increased flexibility in the system, is that the electricity from power plant production is hugely reduced, from 91 TWh/year to 22 TWh/year. Some of this production is replaced by (more flexible) electricity from cogeneration (22 TWh/year), but the majority is replaced by dramatically increased wind production (from 26 TWh/year to 68 TWh/year), and the full potential use of geothermal electricity production.

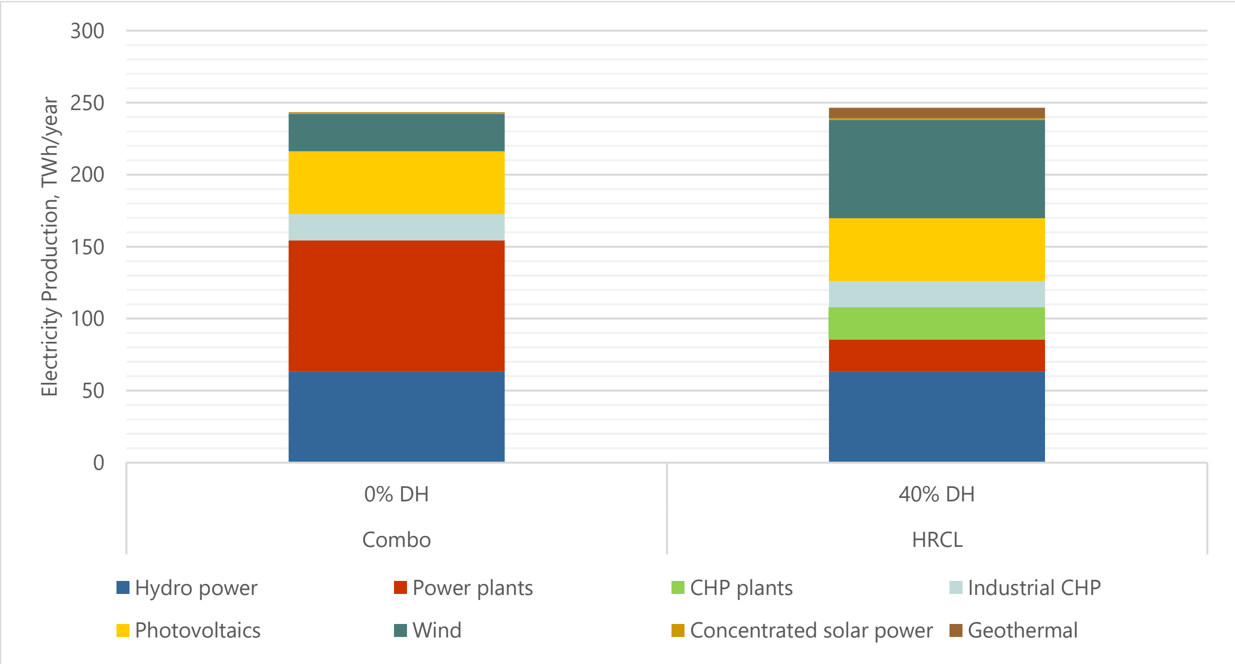


Figure 29. Total electricity production in HRCL 2050 and the Combination PELP scenario

The results of the electricity sector for the Heat Roadmap for Chile show that the design of the heating system – and the flexibility that a diverse and substantial district heating sector can bring with it – can have a dramatic effect on the wider energy system. This also shows why it is necessary to include the wider energy perspective in the planning of the heating sector and use an integrated perspective.

This also demonstrates the close link with decentralization of the power sector and cogeneration and the development of the district heating share, which are required to go hand in hand. Since the synergies between the heating and the electricity sectors allow for both much more efficient production of heat, but also a much higher penetration of renewable energy sources, it is neither possible to develop the district heating supply without a close concern for the electricity sector, nor vice verso, which makes the integrated energy system modelling of any heating sector (and specifically including district heating) necessary and valuable.

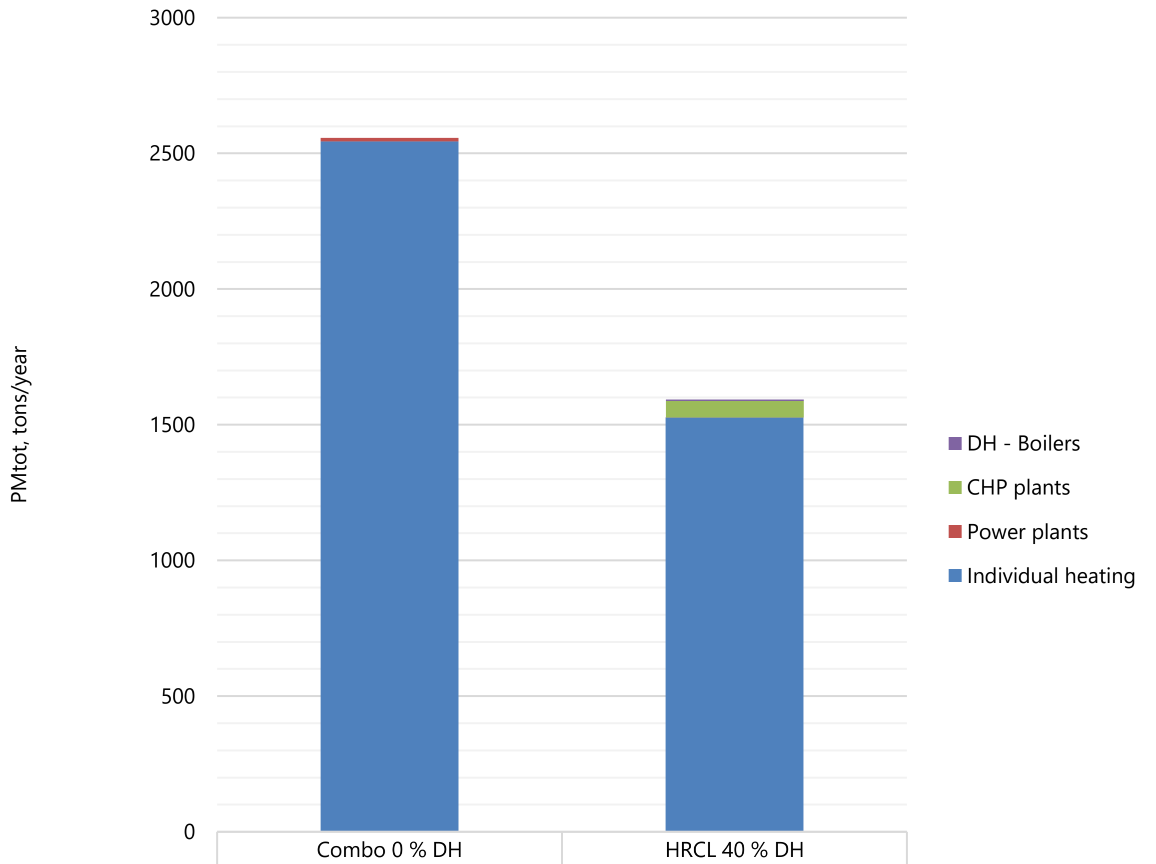
Overall, this results in a scenario for Heat Roadmap Chile where the renewable share in the electricity sector is over 90%, renewable and more than 90% is being produced outside of a traditional power plant installation This represents a very radical departure both from the current design of the electricity system, but also from the reference scenarios, but play a key role in reducing the fossil fuels in the energy system, which in turn allows for the reduction of imports of fossil fuels and a higher degree of decarbonization in the Heat Roadmap Chile scenario.

5.3 Quantifying the impact of increased energy efficiency

5.3.1 Improved air-quality

The main purpose of the HRCL project is to create an evidence-based roadmap to present an alternative scenario about the future of the heating sector and its role in Chile’s energy system and air decontamination plans. For this reason, the quantification of particulate emissions, particularly from the heating sector, is a key indicator in terms of the Heat Roadmap Chile’s performance in terms of fulfilling the strategic needs of the long-term energy ambitions.

The results from HRCL 2050 show that a 40% market share of district heating can reduce the PM emissions from heating and electricity by almost 40% in comparison to the Combo reference scenario Figure 28. This results in total PM emissions from heating in Heat Roadmap Chile of only 1600 tonnes per year. It should also be noted that this Combo reference already represents a very ambitious reduction in PM from heating but using the approach of increased thermal performance of buildings, electrification, and highly efficient biomass boilers without considering the option of district heating.



	Combo 0 % DH	HRCL 40 % DH
DH - Boilers	0	4.2012
CHP plants	0	60.4584
Power plants	13.2732	1.08
Individual heating	2544.12	1526.4

Figure 30. Total PM emissions per year by source in the district heating and electricity sector.

The results shown in Figure 27 also clarify what the different sources for PM emissions are in the different scenarios. Clearly, most of the PM reductions in the Heat Roadmap Chile scenario are the result of decreasing the use of biomass boilers at an individual level. Even though the assumed technologies are far more efficient than today (with PM emissions of approx. 10 mg/MJ, compared to anywhere between 20-1600 mg/MJ, or even higher today [2,29,43]),. However, the scale of the centralized biomass combustion units allows for better (and more cost-effective) flue gas and ash cleaning processes and dust filters to be available, so the combustion of biomass in a centralized district heating boiler or cogeneration plant has even fewer emissions, with centralized units emitting only approximately 0,3 mg/MJ [30]. This difference is the main driver behind the decrease in PM emissions in the Heat Roadmap for Chile, since the use of district heating also allows for the use of these much cleaner centralized combustion units.

The secondary mechanism in which PM emissions and the role of biomass change in the Heat Roadmap Chile is by shifting away from their use in the heating sector towards their application in the electricity sector (see Figure 28). Firstly, the inclusion of other heat sources in the district heating system (including excess heat, direct renewables, and the use of large-scale heat pumps) displaces the need for biomass in the heating sector. Secondly, the use of cogeneration means that the majority of the biomass being used in the district heating sector, is also contributing to the electricity supply. In conjunction with the other changes to the electricity sector described in 5.2, this means that the ongoing use of biomass can replace the use of fossil fuels, and thus reduce imports.

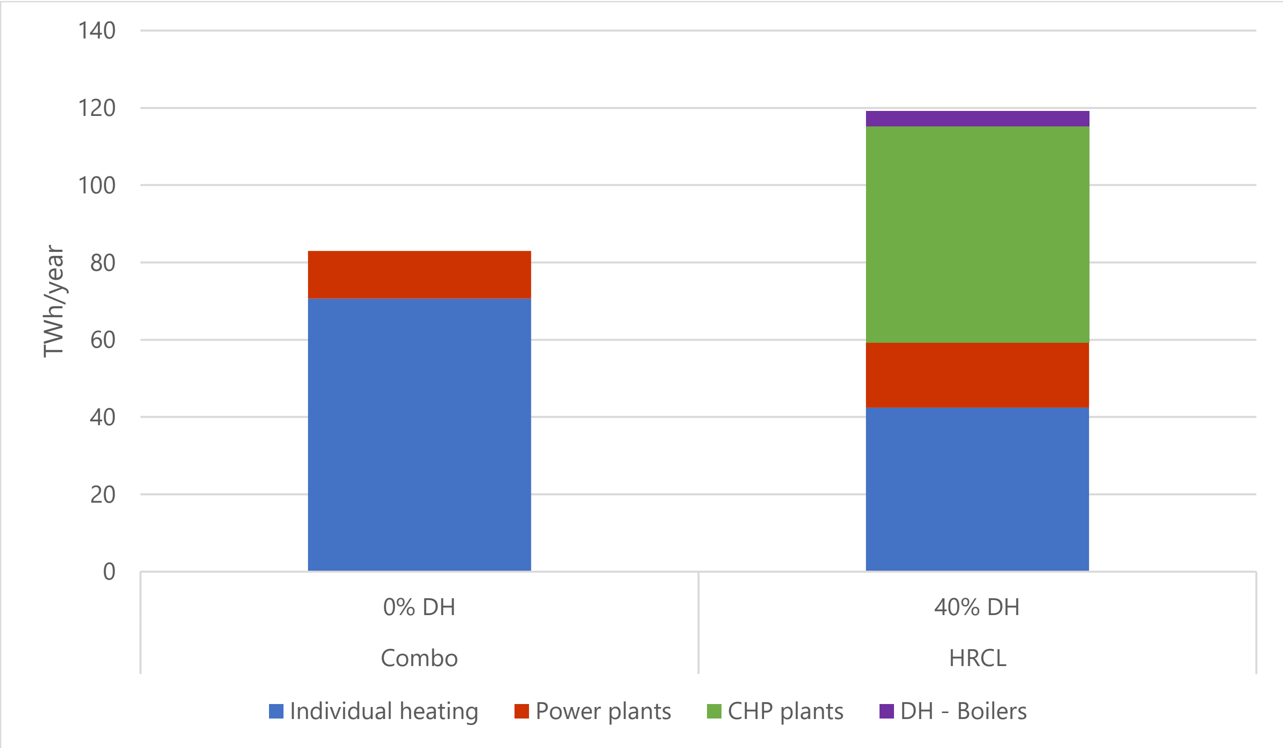


Figure 31. Biomass use in different conversion technologies in HRCL

This is an important perspective, because it means that decontamination and the reduction of PM emissions does not necessarily need to go hand in hand with the reduction of the quantity of biomass consumed; rather, the focus should be on how the biomass is converted. Since the use of biomass does have several strategic advantages (including its renewability, and the role the development of markets can play in ensuring the benefits of clean and renewable energy arise at close to the community), this is an important distinction to make when designing towards a clean and decontaminated heating and energy system.

5.3.2 Energy efficiency and fuel consumption

In terms of primary energy supply, the HRCL 2050 scenario uses approximately 13% less energy than the Combo reference scenario (Figure 29). Also when compared to the other reference scenarios, there is a marked increase in the use of wind power (more than doubling, and in many cases almost tripling the respective reference scenarios); while at the same time significantly of natural gas by 52

TWh/year and phasing out coal from thermal power plants. As mentioned, this results in a scenario for Heat Roadmap Chile where the renewable share in the electricity sector is over 90%, renewable and more than 90% is being produced outside of a traditional power plant installation

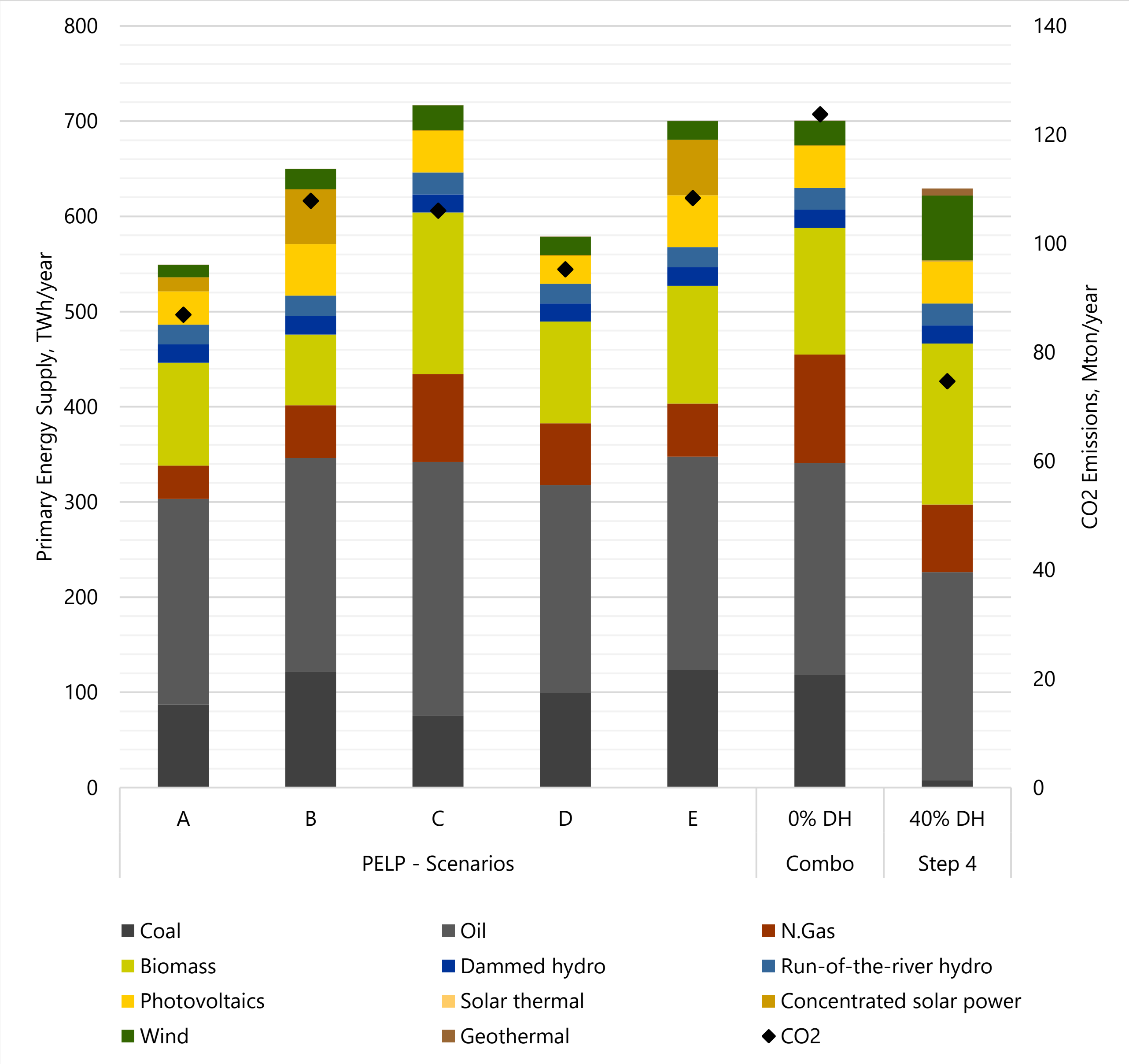


Figure 32. Total primary energy supply.

This efficiency and decarbonization results from several of the changes made in the Heat Roadmap Chile scenario, enabled by the widespread use of district heating. Firstly, the availability of an infrastructure to transport heat allows direct use of renewables otherwise not available, such as geothermal and solar thermal energy. This principle is similar for the use of excess heat sources from e.g. industry and heat from power production, in the form of cogeneration. If the heating infrastructure is not available to use these sources, they would otherwise go wasted and heat would have to be provided in an alternative way, leading to an inefficiency in the system. Secondly, the better integration of renewable energy sources discussed in Sections 5.1.2 and 5.2 allows for the substantial substitution of the (inefficient) combustion of fuels for electricity generation, further contributing to the overall efficiency and renewability of the energy system.

In terms of CO_2 emissions, the Heat Roadmap for Chile scenario has the lowest level compared to all the alternatives created in the PELP process including A, which assumed both CCS, higher developments in batteries, and lower investment costs for renewables than the HRCL scenario. Overall, this shows the potential of the HRCL scenario to contribute to the reduction of GHG emissions from energy.

This change in primary energy supply quantity and mix has several further impacts for how the energy system performs in terms of the strategic objectives identified for the Chilean energy system. Firstly, the reduction in fossil fuels results in less need for imports, ensuring a higher level of stability and strengthening the Chilean position with respect to international fuel price fluctuations and geopolitical considerations. Secondly, the increased use of renewables (including local biomass resources) results in the energy system making better use of local resources and further encouraging the potential for local benefits to arise from the local development of energy and energy technology markets. Finally, the developments of fuels and energy in the Heat Roadmap Chile scenario, without the use of CCS or a currently undeveloped level of battery development results in a more efficient and renewable system that is conceptually in line with the potential further development of a Smart Energy System, which in the long run supports and enables a full transition to 100% renewable energy.

5.3.3 Energy system costs

Overall, the results of the Heat Roadmap for Chile show very similar total socio-economic cost to the reference scenarios, and particularly the Combo reference scenario, which uses the same assumptions for power plant, renewable, and fuel costs. While there is a slight reduction in costs due to the redesign of the heating sector, when the scale of the energy system (including industry and transport) is included, the overall effect is more based on a shift of costs from fuel to investments, than a fundamental reduction (Figure 30).

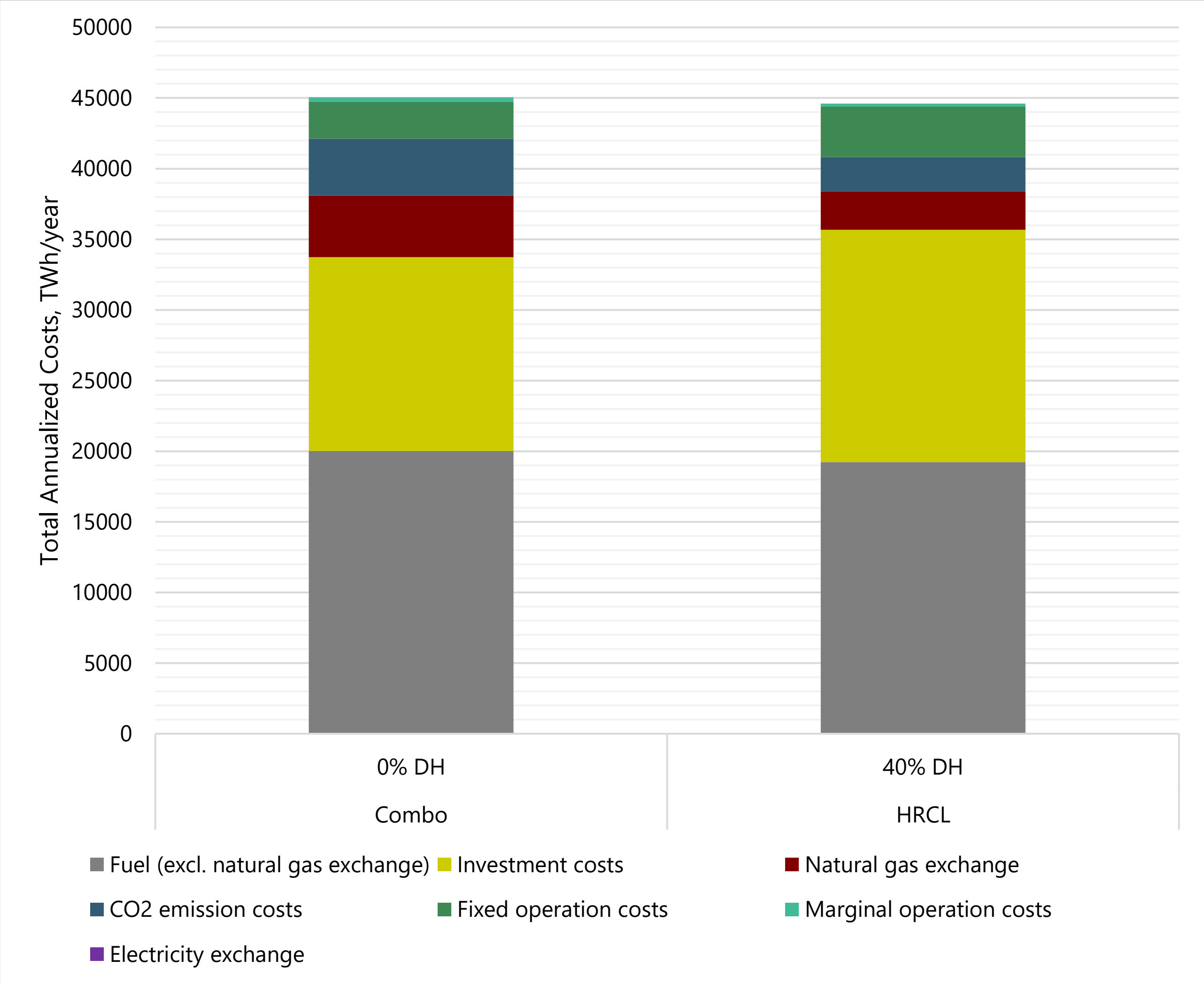


Figure 33. Total annualized energy system costs for all sectors (heating, electricity, transport, industry) for the HRCL 2050 and Combo scenarios

However, if only electricity and heating are considered, a cost reduction of almost 10% is achieved in the Heat Roadmap Chile scenario for those two sectors, which represents a significant potential impact. This shift is primarily because the changes in the Heat Roadmap Chile scenario are fully responsible for the decrease in natural gas and fuel costs exchange (representing a savings of 2927 million USD/year), a decrease in CO2 emission costs (representing a savings of 1346 million UDS/year). Conversely, the overall investment costs are higher in the HRCL scenario, increasing by 2024. In addition, the fixed operation costs (mostly associated with these new investments) is also slightly higher.

This change in costs shows that while there are substantial cost reductions to be made if looking only at the scale of the heating system, the overall impact of the Heat Roadmap Chile scenarios is also very strongly to move from fuel costs towards investment costs. Considering the results shown in Figure 31, it is clear that while the total amount of investments change, the technologies that require investment are also different.

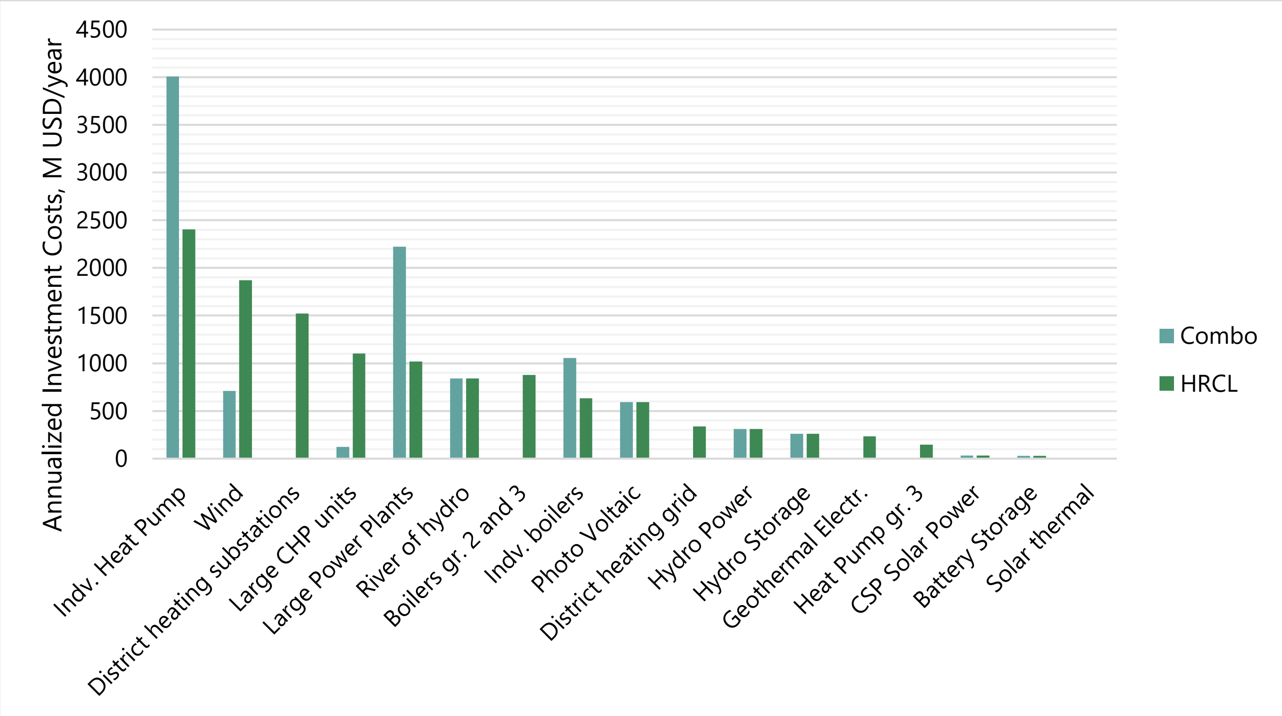


Figure 34. Change in investment costs for selected heating and electricity infrastructures and technologies, comparing HRCL and Combo

In terms of the required investment for the district heating, system, the transmission and distribution pipes do not actually represent the largest fraction. This is mostly because at an annualized level, the costs are spread over the lifetime of the infrastructure, emphasizing the need to take a long-term approach. The largest single category of required investments for district heating, on an annualized level, is the installations of substations in the form of local heat exchangers at the individual building level. This represents a large part of the required investment simply because the investment has to be made at every single building, and because the lifetimes are not as long as the other technologies associated with district heating.

Regarding supply technologies for district heating, substantial investment is required for both the installation of large-scale heat pumps, cogeneration (for district heating), and district heating boilers. It is important to note that while the required annual investments for these three supply technologies is within the same range, the final installed boiler capacity is about 4 times that of LSHPs, reflecting the per MW price and feeding into the discussion of the use of different district heating sources in Section 5.1.2.

The largest need for investment exists for individual scale heat pumps; which is primarily because the relative investment costs are high at smaller capacities, and they represent a substantial portion of the remaining 60% of the heating market. However, the required investments for individual heat pumps (and individual boilers) are reduced in the HRCL scenario, simply because a large portion of the heat demand is transitioned.

The final important shift regards the investments needed to enable the transition in the electricity sector that is proposed in the HRCL scenario as a result of the higher level of flexibility through the sector interconnections. The required investments for large power plants are obviously reduced, while the investments needed for (onshore) wind turbines is more than doubled.

While the overall system may be similarly priced, Figure 31 shows that the transition to a Heat Roadmap Chile based scenario would radically increase the amount of investment and market potential for some technologies (including district heating related technologies and wind power), while simultaneously reducing the need for others (such as large power plants, and of course the different fuel transporting industries). Since it is very differently structured it is likely to be necessary to reallocate costs and benefits from different stakeholder in the value chain. To enable this, encourage investments where necessary, and avoid stranded assets in the long run, it is important to have scenarios that can make these quantitative impacts explicit, and support a long-term integrated energy planning approach that can support this process.

5.3.4 Assessing the energy system's future uncertainty

The socio-economic feasibility of the Heat Roadmap Chile scenario has been assessed on the basis of a social discount rate of 6%, customary for the context of Chile. This socio-economic approach excludes taxes and subsidies, and maximizes the return to society at large, but does not necessarily represent the return that commercial actors are currently seeking in an undeveloped market for integrated energy systems in Chile. Similarly, this social discount rate assumption embeds an implicitly higher risk consideration than, for example, discount rates assumed in a European context, where a 3% discount rate is more common for social projects. In turn, this could potentially downplay the socio-economic value of implementing technologies for improving air quality and decarbonizing the energy system.

For that reason, a sensitivity analysis has been made to further assess the impact of discount rate assumptions when designing the future designs of the Chilean energy system. In this analysis, the suggested 6% discount rate assumption has been compared to assumed rates of 3%, 9%, and 12%. Correspondingly, a 3% discount rate represents a higher prioritization of implementing actions that affect the future design of a decontaminated and decarbonized energy system, while the latter two account for higher uncertainty and give less weight to the value of future money and its effect on the total costs of the Chilean energy system. In all cases, the comparison is done in an intermediate step towards the Heat Roadmap Chile scenario, namely Step 2 – as described in Section 4.2.2 – as this mid-step scenario provides a representation of the different market uptake levels for district heating and diversified supply sources. This comparison can be seen in Figure 36.

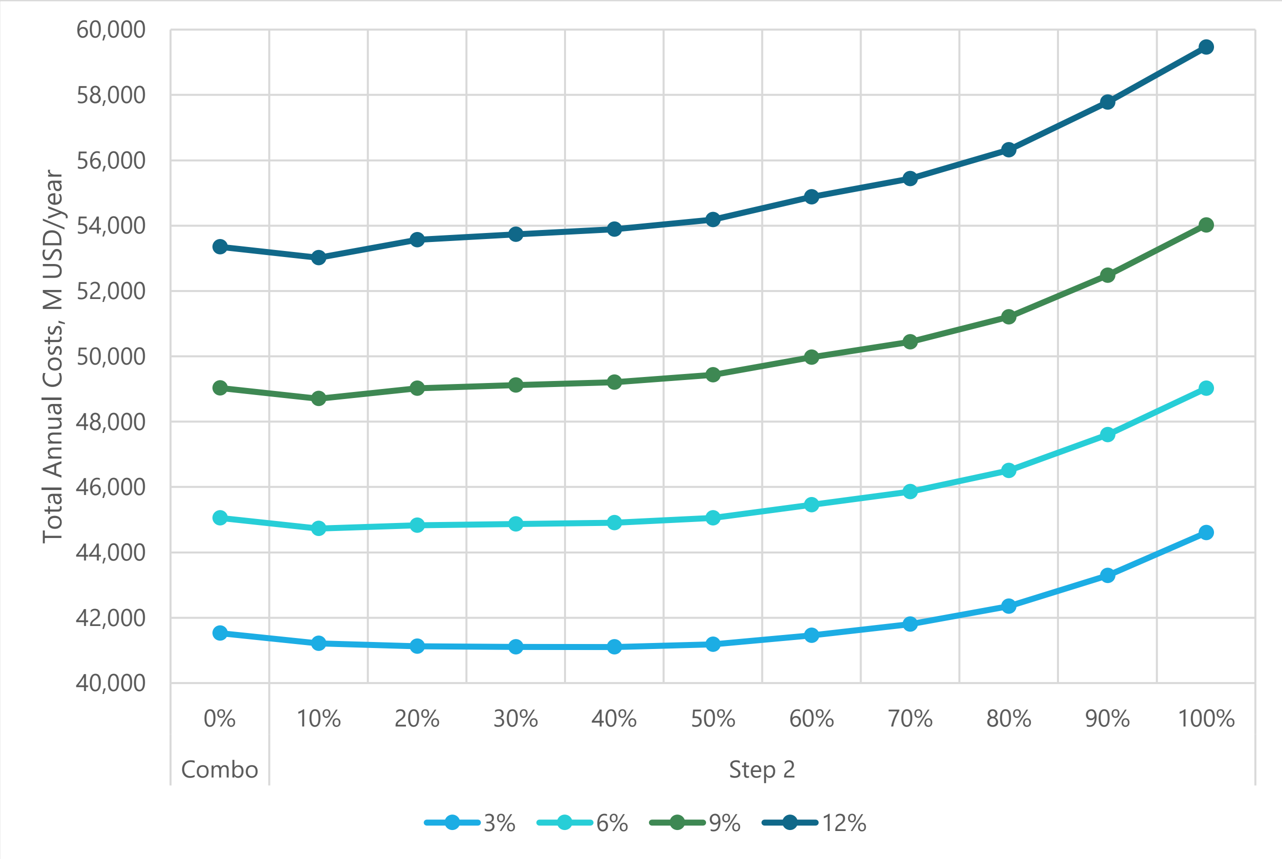


Figure 35. Sensitivity analysis of the total annual costs for the energy system with district heating and diversified supply sources considering different discount rates.

As seen in Figure 36 for all the discount rate assumptions considered, the implementation of district heating with diversified supply sources is socio-economically cheaper than a system with no district heating. For all cases, there is a district heating market uptake bandwidth with cheaper total annual system costs than that of the reference system. However, the analysis also indicates that these are less realizable with increasing uncertainty. These results provide a clear indication that even with high degree of uncertainty, implementing district heating would be an economically viable option even before considering any additional synergies with the power sector and the integration of variable renewable energy (considered in Step 3 and 4, as defined in the Section 4.2.2), which would make the potential even more significant in face of these assumptions. Moreover, although this analysis does not include taxes or subsidies relevant in a business economic calculation, it provides a hint that district heating can still be considered cheaper when prioritizing the value of money in the present, as seen with the 9% and 12% discount rate assumptions.

6 Recommendations and conclusions

The purpose of the Heat Roadmap Chile (HRCL) project is to create an evidence-based Roadmap to contribute to the discourse on the future of the heating sector and its role in Chile's energy system and air decontamination plans, as well as create data, tools, models, methodologies and knowledge contributing to further develop the long-term planning for the future of the sector. The recommendations in this section build on the Chile Heat Demand Map and the data and mapping developed to support it; the Heat Roadmap Chile 2050 Scenario, models, and alternative scenarios that were used for its development, and the valuable feedback from partners and participants during 2 days of presentations, discussions, and workshops and 2 days of bilateral meetings in Santiago de Chile in May of 2019. Participants included planners and policy makers from both local, regional and national government level; academics from engineering and regional development fields; civil society groups; and representatives from the private sector, including consultancy services and district heating operators.

Including district energy in a shift towards integrated energy planning

The discourse around energy and heat planning is grounded in a clear understanding of the problems that the current system poses, and impetus in order to resolve these. Health impacts from air pollution are evidenced, mostly related to the inefficient combustion of biomass for heating; in addition efficiency and decarbonization have been identified as a valid and effective way to deal with geopolitical challenges regarding fuel prices; and Chile has shown a strong realization for the need to address the role of energy in affecting the future climate.

Overall, the long-term transition from the current energy and heating systems to a future, cleaner, more efficient and renewable energy system can bring socio-economic benefits, but this will require deliberate and, in some cases, radical shifts away from certain technologies and towards others. This kind of radical transformation requires both the restructuring of value chains and reallocation of gains and losses between different sectors and stakeholders. In order to address these challenges within the context of a complex and interconnected energy system, a strong vision towards the (long-term) energy transition is necessary in order to outline a clear trajectory and overall aims for development.

Based on the work done in Heat Roadmap Chile, it is clear that there are quantifiable benefits to a Chilean energy system with a 40% market share of district heating. A diverse district heating system at this market share does not only address air pollution concerns but reduces the overall cost of the energy system and addresses national strategic energy objectives of reducing dependency on imported fuels and contributing towards CO_2 reductions. This means the planning perspective should embrace energy efficiency first principles, exploit the synergies that exist between the different sectors of the energy system, and introduce new infrastructures (like district heating) that can unlock the potential for more renewables and further flexibility for the energy system. In order to capitalize on these types of benefits, the long-term energy planning perspective must include an integrated energy planning approach, in order to recognize these cross-sectoral benefits and allow for a more cost-optimal transition.

This involves integrated planning practices that explicitly look across sectors and try to identify solutions that are best for the wider energy system, at both the local and the national level. For district heating specifically, this involves a national enabling framework that actively supports a market design for the heating and electricity sectors that rewards integration and efficiency and enables the development of (city-wide and diverse) district heating systems. At the same time, local integrated energy planning is required, given the inherently local nature of heating, to ensure that local potentials and resources for heating are linked and integrated with other urban and energy systems.

Recognizing and enabling the large potential for district heating nationally

In order to support the extremely rapid development of district heating that is necessary to transform the heating market and achieve the scenario proposed in Heat Roadmap Chile, strong national enabling frameworks are required. In addition to a strong national framework of integrated planning, for district heating specifically the creation of an enabling framework can take several forms. Based on the development of the Heat Roadmap for Chile, the experiences of developing district heating in other countries, and the workshops in May 2019, several recommendations can be made towards this process.

Firstly, the market design should be based on the understanding of district heating as an infrastructure and utility. Assuming it as such results in the idea that district heating is in its essence a natural monopoly, which can bring benefits at scale but also requires regulation and careful market design. While consumer or municipality ownership or control of natural monopolies is typically the most price-efficient ownership structure, regardless of what ownership model is used, to ensure that the benefits of a natural monopoly can be realized, it is important to ensure that it is framed within the right governance structure [44]. This should on the one hand serve to protect customers, and avoid monopolistic exploitation for those who have connected to district heating, but on the other hand also address the tendency of natural monopolies to underprovide, and ensure that coverage includes those who are already vulnerable to price fluctuations. Given the nature of district heating as a natural monopoly, it is not possible to let the market develop without any regulation or intervention and expect the potential benefits and advantages from district heating to be realized.

Other recommendations for the development of enabling frameworks are to specifically include district heating as a possibility in existing regulatory instruments, for example, decontamination plans (PDA). Depending on the location, the results from Heat Roadmap Chile show that district heating as a higher potential to reduce air pollution than the currently used approaches, and the ability to change district heating sources over time means it is a stronger solution than investing in, for instance, a natural gas grid, which may have to be replaced within the next 30 years. This can be in the form of preparing renovated houses for connection to district heating; directly connecting or providing zoning incentives. In this case, the inclusion of district heating can strengthen a neighborhood approach towards renovations and energy efficiency [45]. By being able to actively include the development of district heating into decontamination plans through integrated planning, the enabling framework can provide a shift from remedial actions to proactive and no-regret solutions.

Similarly, the option of specifically including regulation that can support the long-term development of district heating into the regulations surrounding the development of electricity capacity can provide an opportunity to develop an enabling framework. This can both be the case by strengthening the guidelines around existing and new power plant capacity; for example, modelled on a strengthened version of the EU's Article 14 of the Energy Efficiency Directive. This requires member states to identify areas where high-efficiency co-generation could take place – and subsequently to take steps where high potentials are identified. For Chile, specific regulations to encourage and support the development of cogeneration (and potentially also other efficient heat production processes) by using the regulation that already exists around distributed energy producers (<9MW). Since these are already envisioned to be a part of a more decentralized, flexible energy system that are more explicitly tied to their locality, and more flexibility around their energy selling contracts, this may be an opportunity to ensure their efficiency and further contribute to the local use of resources.

Overall, the role for the national government of Chile in recognizing and enabling the large potential for district heating should include the form of leading long-term, integrated energy planning processes that address the (strategic needs of the whole energy system and allow for a clear trajectory. In addition, for district heating specifically there is a large role in terms of creating an enabling framework for district heating that recognizes the natural monopolistic role of the infrastructure, but that also allows for its full socio-economic expansion. Suggestions for this are also to include district heating in existing planning instruments that are relevant to the diverse role that district heating has; for example, through decontamination plans and electricity capacity regulations.

Recognizing and enabling the large potential for district heating locally

Based on the Chile Heat Demand Map and Heat Roadmap Chile scenarios, it is clear that the market potential for district heating is extremely substantial. This means that the objective for many cities should be to look towards city-wide, diverse, efficient and renewable district heating systems, that fully cover the dense and very dense areas in cities. This level of district heating is not only cost-optimal, but also contributes to the decontamination, energy efficiency and renewability of the urban energy systems, while supporting local investments and the local use of resources.

At the local level, the policy and strategic processes should focus supporting pilots, and allowing for increased first-hand experience of district heating systems in order to kick-start implementation processes. However, these should be done within the overall perspective and objective of developing long-term, local, city-wide strategies. These should include local processes and policies to identify and capitalize on dense and very dense areas in terms of energy demands; other priority areas in terms of air pollution, and a diverse and multi-source potential supply that takes advantage of the local industries, geographies and resources. At the local level, the integration of district energy should in almost all Chilean cases both focus on starting the development of district heating, but also ensuring ongoing expansion so that the market potentials can be capitalized upon.

An important factor experience for supporting the development of integrated energy planning processes and instruments at a local level can be the development of specific innovation areas with lighthouse functions, to exchange of knowledge and experiences from other municipalities or regions through the creation of clear frontrunners. This is a model known and commonly used within the Danish context for renewable energy; for example, on the Renewable Energy Island of Samsø, which won a competition and was appointed in 1997 with the purpose of designing a 10% renewable energy strategy, trialing its implementation, and now exporting the lessons learned.

This type of approach can be particularly relevant for decontamination and district heating, since the advantages of scale that district heating has when coverage does include all the dense and very dense areas. For example, the benefits of district heating in terms of substituting inefficient biomass combustion are clearest when a city-wide approach is taken; with smaller pilots, the impact of air quality does not become clear if it is implemented in a few buildings spread throughout the city. Similarly, the complementarity and interaction of different sources for district heating are not always evident in smaller systems, where it may not be possible to integrate both large scale heat pumps and cogeneration facilities.

The objective of this would be to develop a competitive exemplary 'clean and warm city' to use as a case for other cities; both as a testing ground for technological solutions within a Chilean context, but also to develop stakeholder involvement and planning process innovations. The competitive nature of appointing such an initiative – even if the backing from the national level is based more in capacity support than financial support – is both the likelihood of identifying a front-runner and high-potential city, but also to allow multiple cities to generate ideas on how to fulfill the brief during the allocation process.

In terms of outcomes, the attraction for these types of innovation areas is that they can serve as a live 'testing ground' and allow for the better sharing of experiences and solutions. The advantage of serving a lighthouse function can also be the generation of interest – both in terms of collaboration with the private sector in order to test and showcase solutions, but also towards other regions and cities looking to learn from the capacities and experiences generated. This in turn can also develop into local employment, and the export of local expertise.

Broader developments in the heating market

Looking at the planning processes around heating and energy, it is possible to identify several underlying assumptions that need to be achieved in order to transform the heating and energy systems – regardless of the future energy scenarios. While these have not been discussed in depth in either the Chile Heat Demand Map or the Heat Roadmap scenario, they bear explicit discussing since they underpin not just these but also all the reference and alternative scenarios that are foreseen and discussed.

The first is the challenge and assumptions underpinning both the improved energy performance of buildings, but at the same time addressing any remaining issues of fuel poverty and encouraging increased standards for thermal comfort with regards to (space) heating and domestic hot water usage. This is an intrinsic part of the PELP scenarios, and in that of the Heat Roadmap Chile scenario in the long run – but also a key element in many short-term decontamination plans. Previous research shows that the increased energy performance of buildings is key to achieving efficiency and Smart Energy Systems and that there is no direct trade-off between heat savings and high levels of district heating implementation [4,6,46–50]. With this in mind, it is likely that energy renovations and more stringent building standards would efficiently contribute to better thermal standards, and it is strongly recommended to find broader ways to encourage the ongoing development of both the thermal efficiency of buildings, and the increased quality of life and health that thermal comfort provides.

Regarding individual heating, there is a cross-scenario assumption towards more efficient combustion and electrification is necessary. In the Heat Roadmap Chile scenario, the market potential for district heating is identified around 40% - which implicitly means that the remainder will still be provided through individual heating supply technologies. The preferred or optimal direction of these technologies was not specifically investigated in the Heat Roadmap Chile project, but should once again be considered from a long term, integrated energy system planning perspective. This means that the deployment of electrification should be seen also from the perspective of the electricity supply sector, and the use of biomass within the context of the fuel needs of other sectors. In order to ensure a long-term, sustainable transition in the heating sector outside of district heating the focus here should not be on moving towards fossil fuels but is likely to be a combination of the efficient combustion of biomass and electrification through (efficient) heat pumps.

A final consideration for all the scenarios is that bioenergy has a large role to play, since it has several key benefits (including the distinct advantages of being a local and renewable resource in Chile). However, current biomass markets do not supply in a way that ensures that the benefits of biomass are taken advantage of, and formalization and increased transparency was indeed identified as a key, if challenging, step towards this, regardless of specific solution within the heating or energy system. This is primarily to enable the identification of sustainable biomass potentials, and the increase in quality of processing, before combustion. While all future scenarios and expectations towards the future energy system in Chile, including the Heat Roadmap developed here, depend heavily on a biomass, but a transformation of the current market structure is needed in order to allow for the benefits of locality and renewability to be clear.

Role of tools, data, models and methodologies

One of the key objectives of the Heat Roadmap Chile project has been to generate data, models, tools, that can support planning instruments and serve as an input to the discussion and knowledge-building taking place among lead actors in the heating and energy sectors; policy makers, planners, industry and researchers at both the local and national level. This is done from the conviction that better information contributes to forming a basis for more integrated planning. The data, models and free tools developed in this project are designed to empower others, including national and local planners, to be more involved in decision making, by being able to generate their own understanding, propose and discuss alternatives, and allow for a more nuanced discussion.

The development of the Chile Heat Demand Map, with national coverage, means that an initial screening of heat demand densities can be done for any area within the country and made available on the public app and associated training materials. Based on this, decisions about (more costly) bottom-up further analysis can be made, facilitating the process of identifying short term, medium term and long-term focus areas. This is especially powerful if the (public) layer is combined with other relevant national or local energy maps. In addition, the Floor Area model and Regression model that underpin it allow for further refining of the heat demand models in the case of better available data. As in cadaster data and heat consumption data for specific buildings.

Similarly, the development of a Heat Roadmap scenario for Chile (and the various other alternative scenarios that were a part of its development process) is based on the development of an energy system simulation model, using freely available data and the EnergyPLAN freeware. The EnergyPLAN models made for Heat Roadmap Chile are sophisticated in the sense that they model the full energy system; take into account the hourly variations of different demand and supply options; and allow for a high degree of user control – but are also accessible enough that lead users can use the training materials provided and start making additional designs.

For example, the Heat Roadmap Chile scenarios would benefit from the integration of more refined datasets where discussed; particularly regarding better district heating source allocation, and more information regarding the potentials of renewables like wave and tidal energy. In addition, alternative scenarios including the impact of cooling; the impact of transport; and looking towards full renewability, etc. could contribute to the discourse of long-term energy planning for Chile. These energy models are designed to be used to contribute to a reflexive approach on designing and visualizing scenarios for long-term energy planning and potential contributions to the reduction in national GHG emissions, by proving tools and data inputs that allow for concretizing the different alternative future energy systems, and allowing for their quantification.

The final note on the development of tools and data for heat planning is that since heating is in some ways very local, data can be scarce and difficult to collect. In these cases, national datasets can be very useful to support the development of local solutions either by providing data directly, or by allowing for benchmarks that can facilitate processes earlier on. since heating is in some ways very local, data can be scarce and difficult to collect. In these cases, national datasets can be very useful to support the development of local solutions either by providing data directly, or by allowing for benchmarks that can facilitate processes earlier on. In addition, the standardization of data and tools can allow for more widespread application and more secure and trusted decision results and can help prevent the need for the repetitive development of new solutions.

Some of these initiatives can involve the better alignment of already existing data; for example, commune codification is not standardized amongst the different Chilean institutional databases, special attention had to be taken when correlating data. Alternatively; datasets can be created in order to facilitate the process of energy planning. To take a Danish example, the development of technology catalogues and cost databases by the Danish Energy Agency [29–31] allows for easy analysis, and a good comparison between projects. This is especially strengthened by the national guidelines and methodology for socioeconomic calculations within the energy sector, outlined by the Ministry of Finance [51]. Similarly, both the Danish government and EU periodically bring out reference scenarios, similar to the work done in PELP, that are also explicitly designed to be used as a comparison point for other analysis [52,53]. The production of these kinds of datasets and methodologies allows for better (preliminary) analysis to be done in energy planning, and specifically in heat planning where data accessibility regularly poses a more comprehensive challenge.

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Annexes

Annex 1. Geospatial layer attribute description

Chile heat demand map

Heat demand grid layer

Attribute	Description	Descripción	Unit
OBJECTID	Internal ArcGIS feature number	Identificador interno de ArcGIS para el OG	-
Shape	Feature geometry	Geometría de OG	-
pop	Population	Habitantes	ppl/km2
built	Built up area index [Normalized range 0 - 100]	Índice de AC [Rango normalizado 0 - 100]	-
a	Calculated FA from databases	AC calculado de base de datos	m2
b	Calculated FA from regression model	AC calculado de regresión lineal	m2
ab	Selected FA	AC seleccionado	m2
TZ	Thermic zone	Zona térmica	-
GTZ	Group thermic zone	Grupo de zona térmica	-
a_MWh	HD density for a	DE para a	MWh/km2
b_MWh	HD density for b	DE para b	MWh/km2
ab_MWh	HD density for ab	DE para ab	MWh/km2
ab_loss_p	Heat loss percentage on grid for ab HD density	Porcentaje de pérdida de calor en red para la densidad de ab DE	%
ab_loss_MWh	Heat loss on grid for ab HD density	Pérdida de calor en red para la densidad de ab DE	MWh
ab_DH_USD_MWh	Investment cost per MWh for ab HD density	Costo de inversión por MWh para la densidad de ab DE con medida de eficiencia energética	USD/MWh
ab_DH_USD	Total investment cost for ab HD density	Costo total de inversión para la densidad de ab DE	USD
ab_DH_USD_yr	EAC for total investment cost for ab HD density	CAE para costo de inversión total para la densidad de ab DE	USD/yr
ab_s_MWh	HD density with energy efficiency savings for FA	DE con medida de eficiencia energética para AC de ab	MWh
ab_s_loss_p	Heat loss percentage on grid for ab HD density with energy efficiency savings	Porcentaje de pérdida de calor en red para la densidad de ab DE con medida de eficiencia energética	%
ab_s_loss_MWh	Heat loss on grid for ab HD density with energy efficiency savings	Pérdida de calor en red para la densidad de ab DE con medida de eficiencia energética	MWh
ab_s_HS_USD	Implementation cost for energy efficiency savings for ab	Costo de implementación de medida de eficiencia energética para AC de ab	USD
ab_s_DH_USD_MWh	Investment cost per MWh for ab HD density with energy efficiency savings	Costo de inversión por MWh para la densidad de ab DE con medida de eficiencia energética	USD/MWh
ab_s_DH_USD	Total investment cost for ab HD density with energy efficiency savings	Costo total de inversión para la densidad de ab DE con medida de eficiencia energética	USD
ab_s_DH_USD_yr	EAC for total investment cost for ab HD density with energy efficiency savings	CAE para costo de inversión total para la densidad de ab DE con medida de eficiencia energética	USD/yr
ab_s_HS_USD_yr	EAC for implementation cost for energy efficiency savings for FA	CAE para costo de implementación de medida de eficiencia energética para AC de ab	USD/yr
NOM_REG	Region name	Nombre de la región	-
NOM_PROV	Province name	Nombre de la provincia	-
NOM_COM	Commune name	Nombre de la comuna	-
CC	Commune code	Código de la comuna	-
CR	Region code	Código de la región	-
Shape_Length	Feature shape length	Longitud de geometría de OG	m2
Shape_Area	Feature shape area	Área de geometría de OG	m2

FA = Floor built area
HD = Heating demand
EAC = Equivalent annual cost where number of periods [n = 30] & [Discount rate = 0.03]
*All demands are yearly based

OG = Objeto geográfico
AC = Área construída
DE = Demanda energética
CAE = Costo anual equivalente en donde número de períodos [n = 30] & [Taza de descuento = 0.03]

Chile heat demand map

Heat demand manzana layer

Attribute	Description	Descripción	Unit
OBJECTID	Internal ArcGIS feature number	Identificador interno de ArcGIS para el OG	-
Shape	Feature geometry	Geometría de OG	-
FA	Feature floor built area	AC de OG	m2
BUILDINGS	Estimated number of buildings within the manzana	Número estimado de edificios en el OG	u
CLASS	Feature FA estimation database source	Fuente de datos para la estimación de AC	-
TZ	Thermic zone	Zona térmica	-
GTZ	Group thermic zone	Grupo de zona térmica	-
a_MWh	HD for FA	DE para el AC	MWh
a_s_MWh	HD with energy efficiency savings for FA	DE con medida de eficiencia energética para AC	MWh
a_s_HS_USD	Implementation cost for energy efficiency savings for FA	Costo de implementación de medida de eficiencia energética para AC	USD
Shape_Length	Feature shape length	Longitud de geometría de OG	m2
Shape_Area	Feature shape area	Área de geometría de OG	m2

FA = Floor built area
HD = Heating demand
All demands are yearly based

OG = Objeto geográfico
AC = Área construída
DE = Demanda energética

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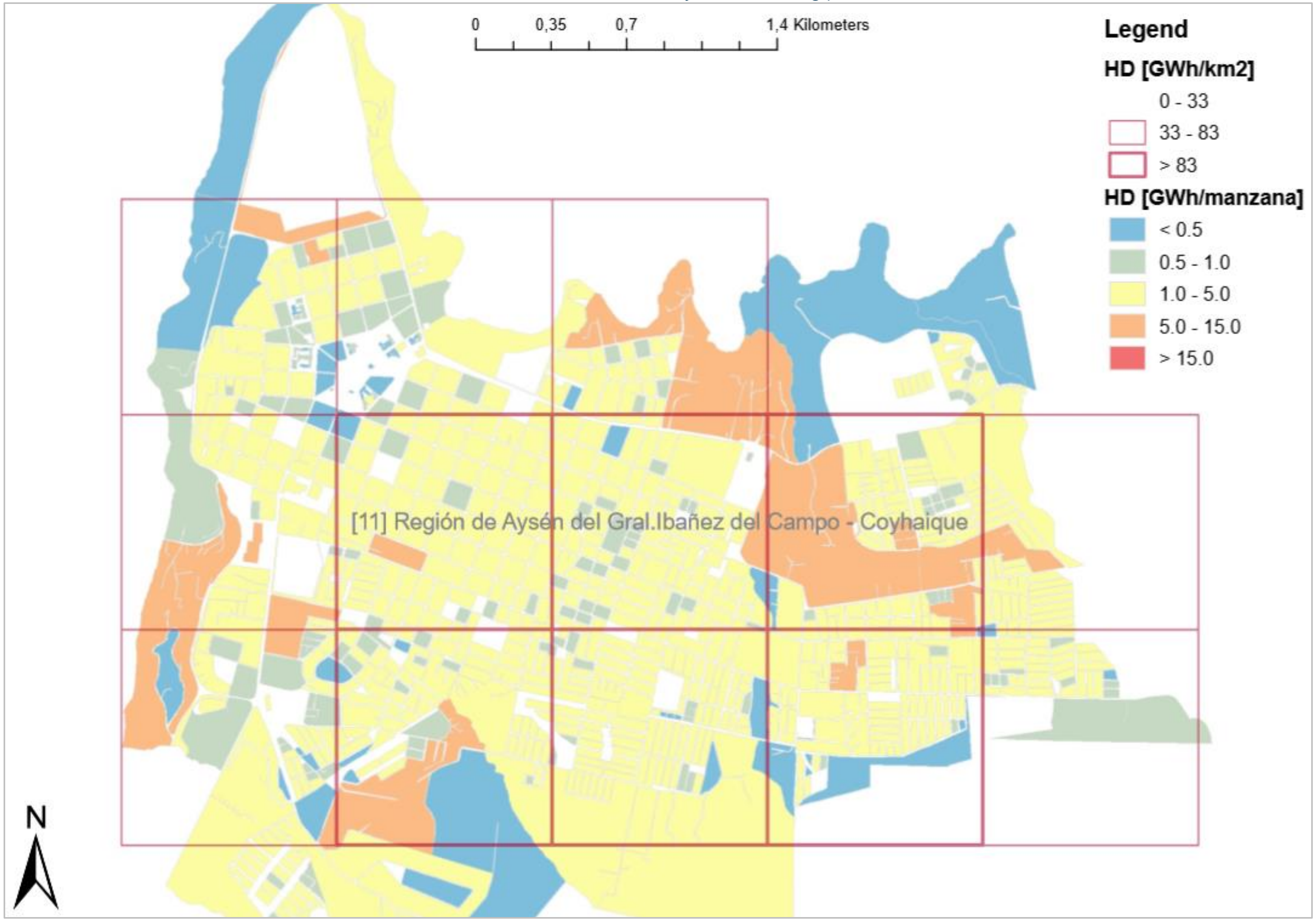
Annex 2. Localized communal-city district heating potential




0
0,5
1
2 Kilometers
Legend
HD [GWh/km2]
0 - 33
33 - 83
> 83
HD [GWh/manzana]
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0.5 - 1.0
1.0 - 5.0
5.0 - 15.0
> 15.0
[14] Región de Los Ríos - Valdivia
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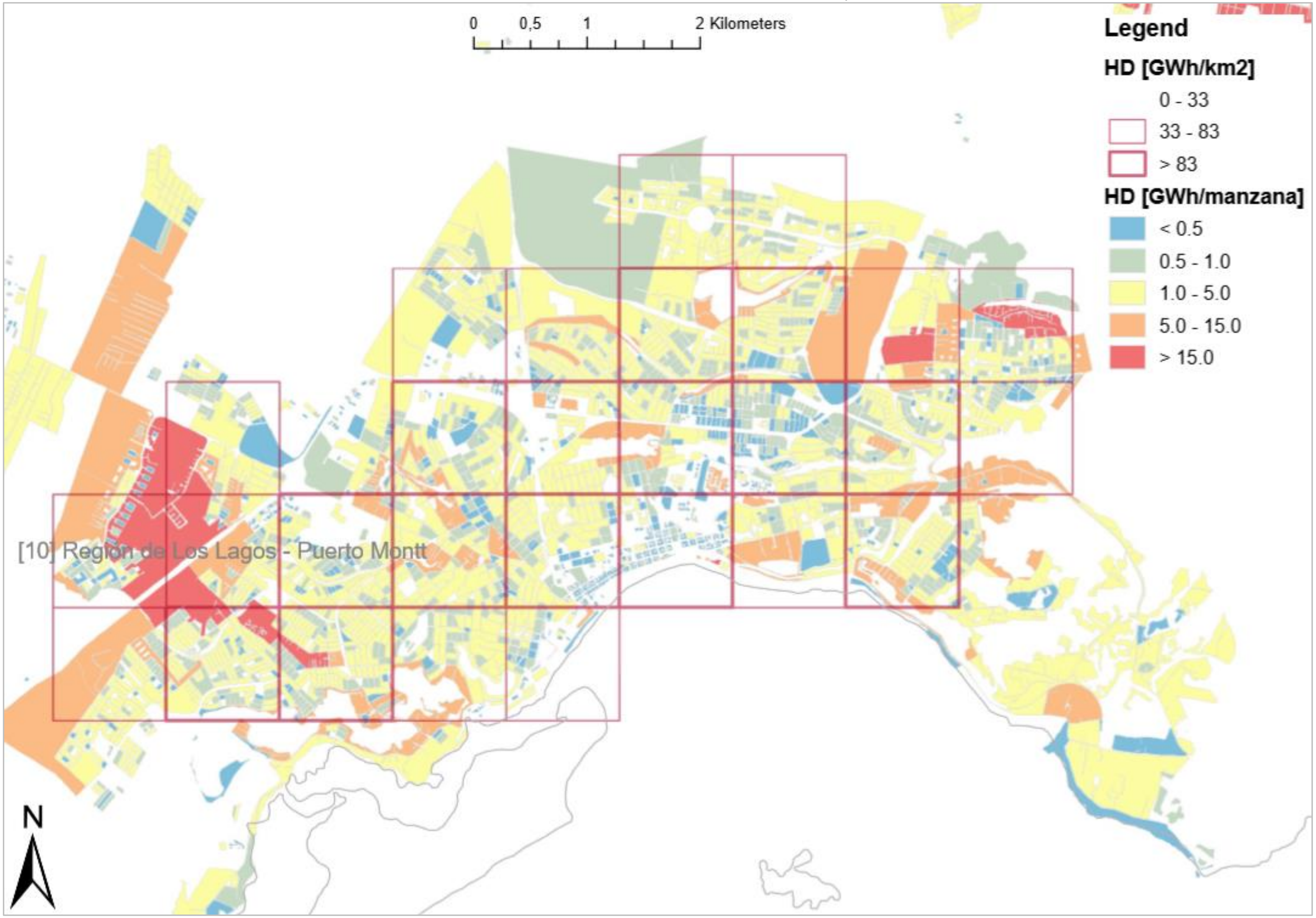
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Legend
HD [GWh/km2]
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33 - 83
> 83
HD [GWh/manzana]
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0.5 - 1.0
1.0 - 5.0
5.0 - 15.0
> 15.0
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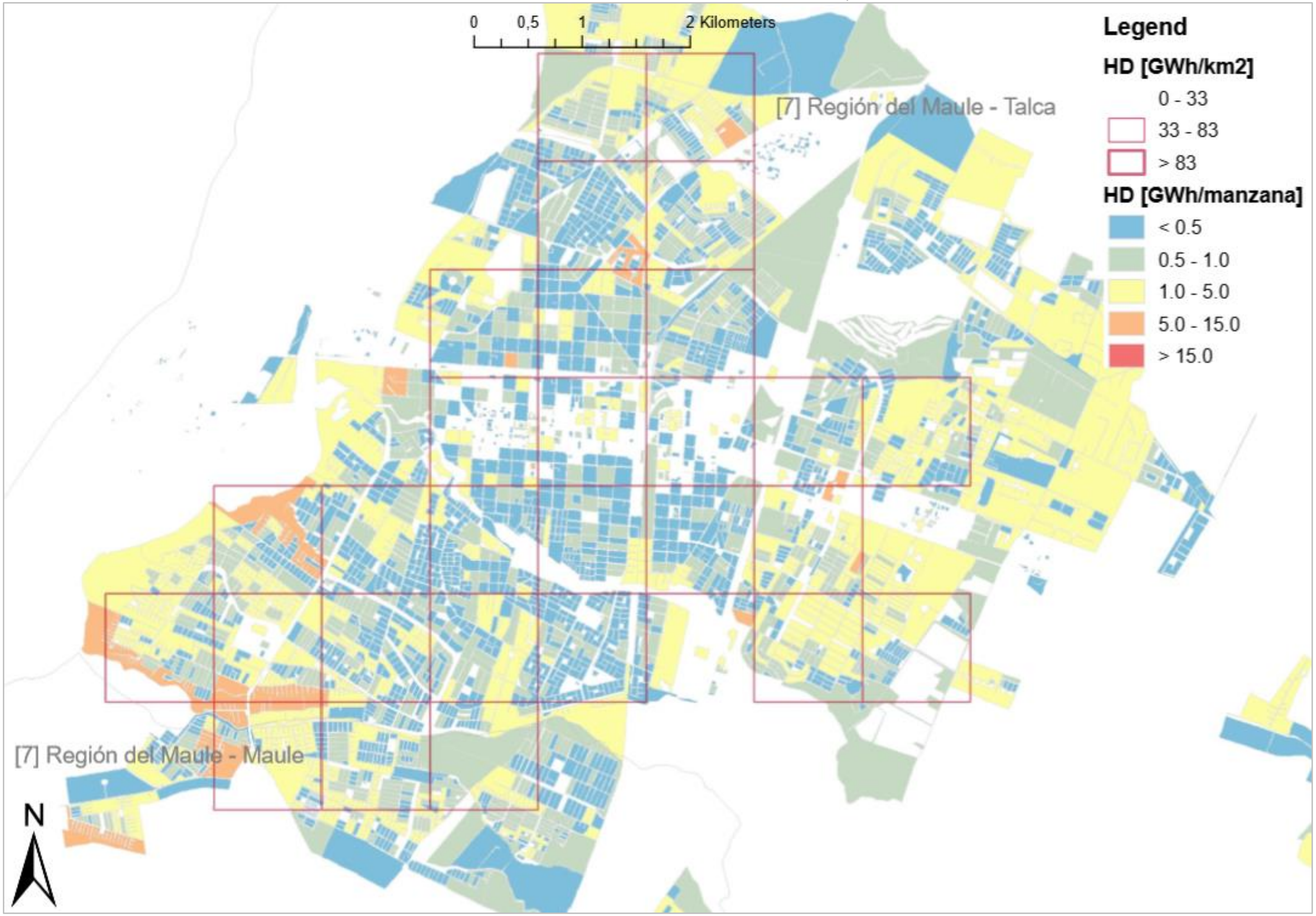
0
0,5
1
2 Kilometers
Legend
HD [GWh/km2]
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33 - 83
> 83
HD [GWh/manzana]
< 0.5
0.5 - 1.0
1.0 - 5.0
5.0 - 15.0
> 15.0
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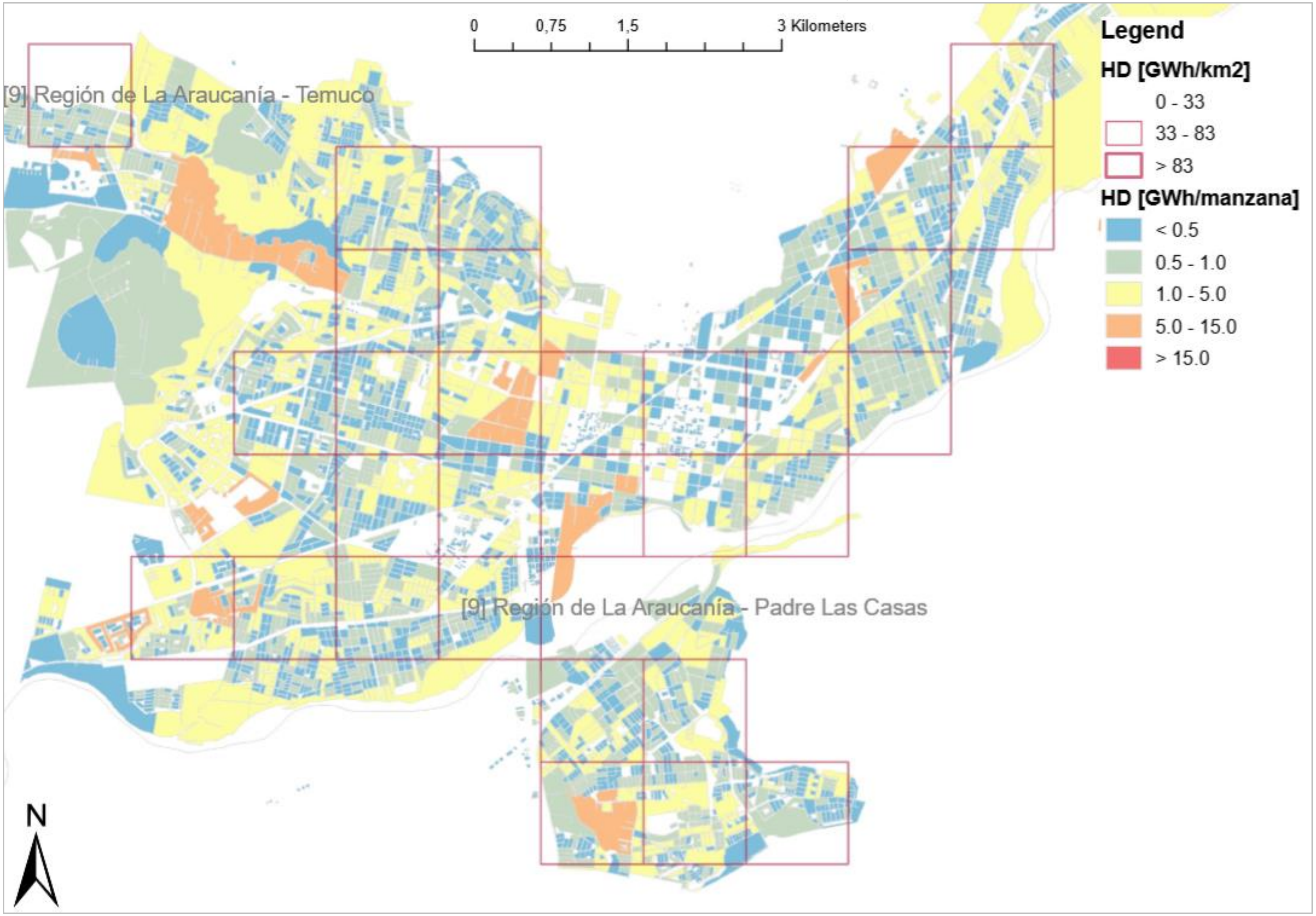
N



0
0,75
1,5
3 Kilometers
Legend
HD [GWh/km2]
0 - 33
33 - 83
> 83
HD [GWh/manzana]
< 0.5
0.5 - 1.0
1.0 - 5.0
5.0 - 15.0
> 15.0
[9] Región de La Araucanía - Temuco
[9] Región de La Araucanía - Padre Las Casas
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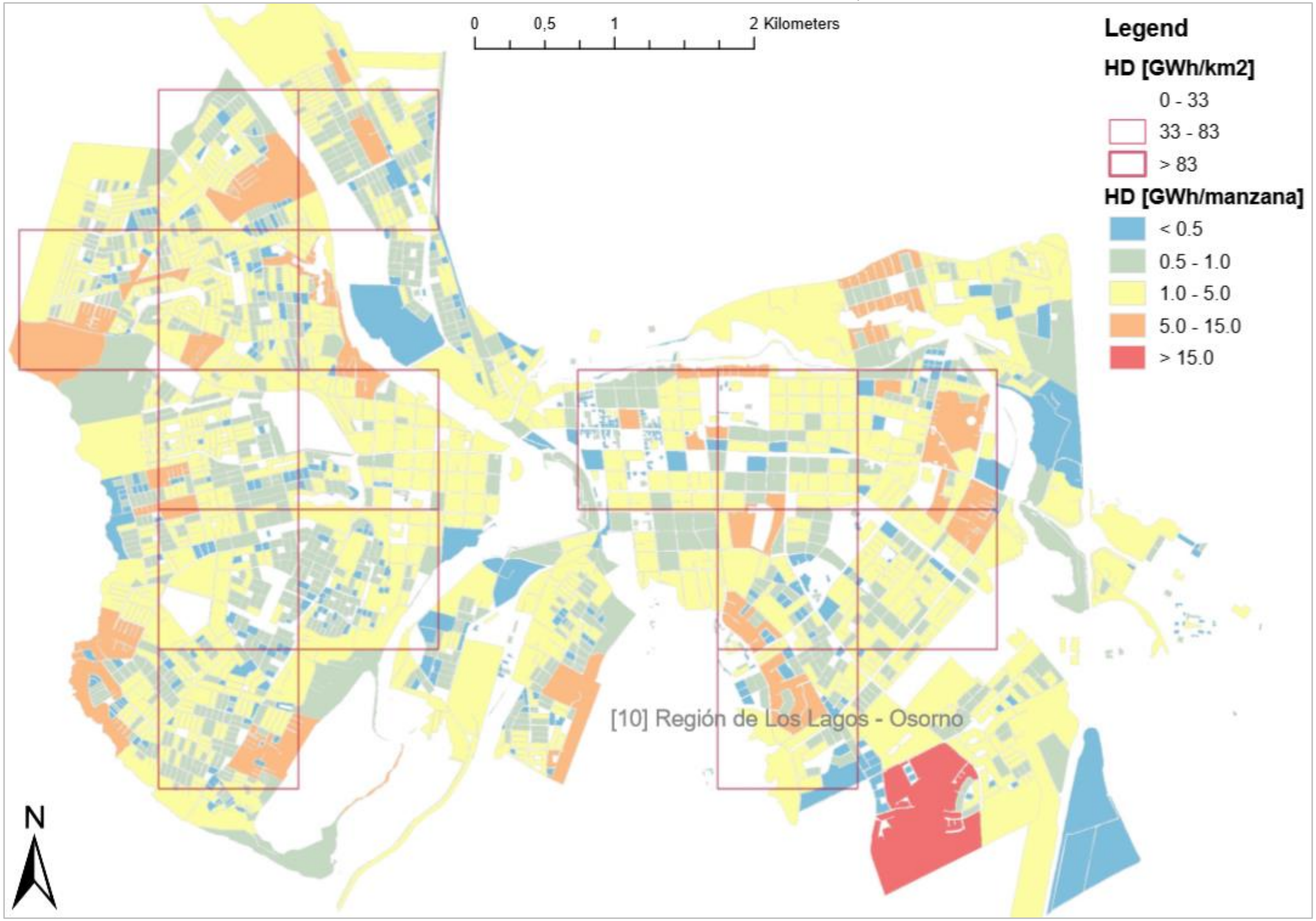
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Legend
HD [GWh/km2]
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> 83
HD [GWh/manzana]
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1.0 - 5.0
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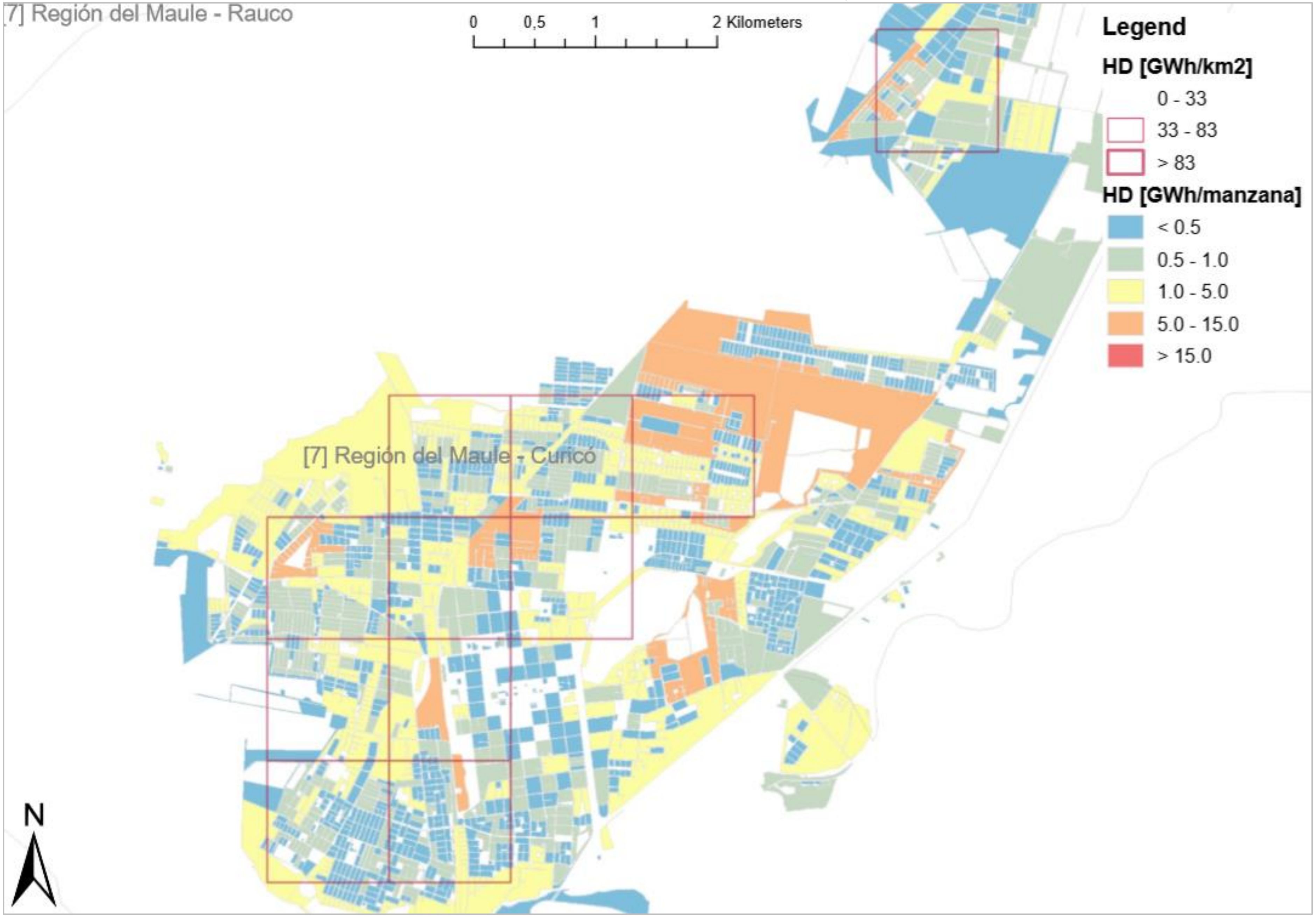
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1.0 - 5.0
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