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A rapid-assessment model on the potential of district energy: The case of Temuco in Chile

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ABSTRACT

District energy systems (DES) offer an optimal solution for decarbonising the heating and cooling sector while attaining multiple additional benefits. The first step to analyse the potential of DES in both new and existing markets is through rapid assessments (RA). Currently, publicly available models lack rapid assessments of the technical-economic and environmental potential of DES. This RA model was developed within the framework of UNEP's District Energy in Cities Initiative to identify DES's potential spending low time and monetary resources. In this light, the study presents a model for conducting a rapid assessment applied to the case of Temuco, Chile. Results show that a total of 55 MW DH (district heating) capacity is required to cover the heating demand. A wood-chip boiler of 25 MW capacity and a gas boiler of 30 MW capacity are considered in the calculations. The total CAPEX of the project is around 25 billion CLP, with a NPV of 10.5 billion CLP and an IRR of 14%. The project is also estimated to achieve an annual reduction of 24,382 tons of PM10 and 23,692 tons of PM2.5. The model was validated against an independent study conducted by an international consulting company, and the results were found to be in close proximity with the study. Thus, the model can be an effective tool for performing rapid assessments of DES projects in the region and subjecting attractive projects to more detailed pre-feasibility analysis.

1. Introduction–The role of district energy in climate mitigation and local decontamination

Achieving the below 2 °C goal of the Paris Agreement, that is, a reduction in overall GHG emissions of 80-95% by 2050 compared to 1990 levels, requires a transformation of current energy systems. In doing so, one of the main challenges is the decarbonisation of the heating and cooling sector, which is currently responsible for around 50% of the final energy demand worldwide and is mainly reliant on fossil fuels. In the quest to decarbonise the heating and cooling sector, district energy systems (DES) have been considered an efficient, environmentally friendly and cost-effective method for heating and/or cooling buildings. DES are centralised heating or cooling generation systems that provide energy through networks of underground insulated pipes by pumping hot or cold water to multiple buildings in a district, neighbourhood or city. These systems create synergies between the production and supply of heating, cooling, domestic hot water and electricity. In this way, these low carbon integrated energy grids can also help achieve an abatement of GHG emissions and particulate matter (PM) mainly by: (1) replacing equipment in individual buildings with a more efficient central power plant and filtering systems; and (2) by making it possible to use high levels of affordable local renewable energy supplies through economies of scale, diversity of supply, flexibility of fuel sources, balancing supply against demand, and storage (not possible in individual heating and cooling systems). From a macro-economic point of view, introducing energy-efficiency measures in the building and energy sectors can also result in enhanced productivity and competitiveness: in the short term, through increased energy production, improved equipment performance, reduced operating times and shorter process cycle times; and in the long term, by lowering maintenance costs and reducing the wear and tear on equipment and machinery. Finally, DES can also contribute to energy

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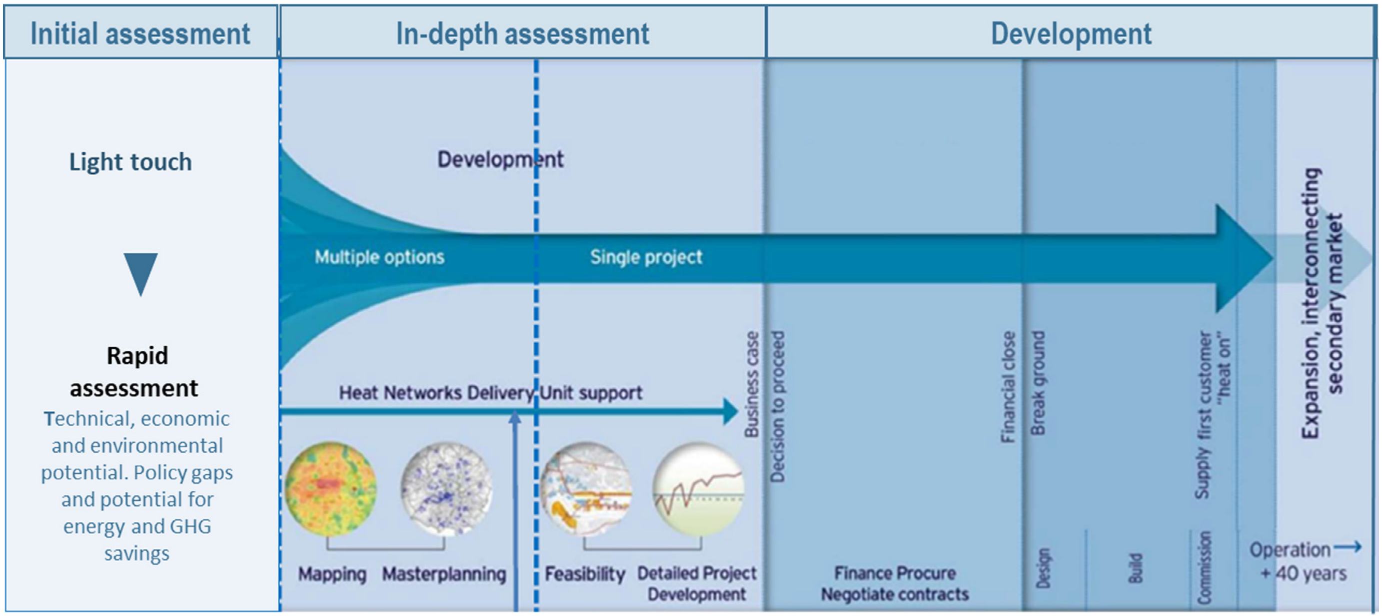


Fig. 1. Heat network development project lifecycle (Source–Adapted from DBEIS Heat Networks Delivery Unit).

access and security through the adequacy and reliability of resources and infrastructure.

This is particularly critical in developing countries such as Chile, where energy security plays such an important role in the social and economic well-being of a large portion of the population 3. In fact, around 70% of total energy consumption in an average city in central and southern Chile is used to cover the demand for heating and cooling. These needs are mostly met through inefficient and highly polluting woodstoves and/or individual gas boilers, particularly for space heating and cooking. Local air pollution is responsible for 3500 annual cases of premature death from cardiovascular diseases in the country, costing almost EUR 2100 million per year in medical expenses and lost labour productivity [1]. The concentration of PM2.5 in southern Chile, in cities like Temuco, is five times higher than the standards recommended by the World Health Organization. Improving air quality is therefore a major goal for the Chilean government, which was looking to address this issue through district energy. In the Heat Roadmap of Chile [2], which contributes to the discourse on heating sector and its role in the energy system clearly highlights district energy as a key technology in achieving the decontamination targets.

Rapid Assessments are the first step in project development, as they require very few resources and provide district energy high potential areas to focus on later stages. Local governments are uniquely positioned to advance district energy systems in their various capacities as planners and regulators, as facilitators of finance, as role models and advocates, and as large consumers of energy and providers of infrastructure and services. This RA model provides a excel tool and a users' guide to assess and map different areas of the city without having to undertake costly and lengthy feasibility studies to assess a project that may result non-bankable, as reflected in Fig. 1, adapted from [3].

Chile is one of the four pilot countries of the Global District Energy in Cities Initiative, an initiative lead by the United Nations Environment Programme that supports cities and countries in their energy transition by accelerating the development of district energy systems. In this context, a rapid assessment tool and methodology was developed to assist local government in the process of identification and preliminary evaluation of district energy projects. The lack of capacity of local governments to identify bankable projects is the first step and often the first barrier to develop district energy.

In light of this, the following study develops a model for conducting rapid assessments of DH potential, showcasing the case of Temuco in Chile, a city in the South of Chile with one of the highest pollution levels of in the country due to smoke emitted from wood burning during the winter [1].

1.1. State of the art in DH rapid assessment models

Scarcities of resources constrain the development of innovative ideas to solve common problems. The district energy rapid assessment provides an overview of the DH potential of a certain area from the technical, financial and environmental point of view and so help decision-makers and planners to allocate resources to deeper analyses in areas with greater potential. Aghamolaei et al. summarize the different methods and models that exist for these initial assessments, grouped in terms of environmental, economic, social, transportation and urban morphology [4]. The study shows that a multi-criteria analysis (MCA) is often used at the initial assessment stage. MCAs can be useful in identifying and comparing different policy options by assessing their effects on performance, impacts and trade-offs. This is the case for Ghafghazi et al., who ranks energy options in searching for the most beneficial solution for a district heating system in Vancouver [5]. Among the cases presented using a MCA are [6] and [7]. In the former, they use an MCA to offer a preliminary assessment of the potential of district heating in the city of Courtenay. They conclude that DES would be feasible and give recommendations to decision-makers in moving forward with DES. In the latter, the approach is used in the context of a rapid district heating and cooling potential assessment in five Indian cities, again using MCA. Sartor et al. also present a simple and effective methodology to provide accurate estimates of these parameters for CHP plants connected to the network [8]. On the other hand, studies like Weber et al. determine the optimum mix of technologies for DH that have the least environmental impact while meeting the demands of using mathematical optimization [9].

Several feasibility-level analyses have been performed for various DH systems all over the world, such as [10], which analyses the potential and economic feasibility of utilizing excess industrial heat for DH in Sweden from a petrochemical cluster [11] analyses the feasibility of district heating and cooling to cover the heat demand in a tech park under Mediterranean conditions. Similarly, [12] presents a feasibility assessment of solar DH in China. A cost-benefit analysis of implementing a biomass boiler in central Chile to curb PM emissions [13] has also been performed with positive environmental effects at competitive

prices. These analyses however, are limited to certain supply technologies and do not provide flexibility to explore the environmental and financial impacts of different technologies.

Methods such as life-cycle assessments (LCA) and city mapping are deployed in some prefeasibility studies. LCA metrics gives decision-makers an overview of the impact of the potential interventions across the whole lifetime of the projects or period being assessed. Ristimäki et al studied the life-cycle design of DES for a new residential development in Finland. They conclude that the option with the highest initial investment is the best from an LCA perspective. They also show the strong connection between cost savings and emissions reductions and therefore how important it is to perform an LCA at the first stage of a project to develop more sustainable urban areas [14]. LCA can also be used to calculate the carbon footprint of an energy system during its whole lifetime. Yan et al. study an example in a district in Xuzhou and identify at what stage of the project carbon emissions will be the most extensive and where the focus should be placed in order to reduce these emissions [15]. Another study aimed to investigate the environmental and economic impact of one hot dry rock geothermal energy-based heating system in a life-cycle framework [16].

Likewise, in city mapping, a geographic information mapping (GIS)-based analysis can be used to design district heating. GIS makes it easier to assess the potential of a city for district heating by allowing the data to be crossed, for example, between heat sources and residential areas. A study by [17] focuses on using a heat atlas of Denmark with a GIS model of DH costs to assess the potential of district heating. DH covers 40% of the total built-up area in the country: the study showed the potential for increasing this area by 12-23%. In initial assessments, city mapping can be used to find the locations of all the clean heat sources that could be used for district heating. Su et al. used a GIS-based method to map heat sources and their potential for DES in the Stockholm City region. They concluded that nine clean sources could cover 100% of the existing district heating energy requirement in Stockholm [18]. They use a heat density map and a plot ratio map to propose a GIS-based method for determining potential DH areas with a specific focus on DH grid costs. The approach also allowed the length and diameter of transmission lines and their associated costs to be assessed [19]. Finney et al. demonstrate the opportunity to expand on existing DH systems in Sheffield in the UK using GIS and developing “heat maps” that locate existing and emerging heat sources and sinks [20]. Economic parameters should already be included at this stage to plan the investment and facilitate comparison with baseline scenarios. Some examples of this are [21] and [22]. The proposed techno-economic model by Pusat et al. provides a fast and easy evaluation of district heating systems, sharing useful results before detailed project planning. In the case of Fonseca et al., the model assesses the financial benefits of multiple urban design scenarios in a city in Switzerland. For an economic optimization the results show savings of up to 23% in emissions, 36% in primary energy and 11% in costs.

Thus, there are several district energy assessment methodologies that tackle different requirements, such as determining the right area for developing DH using GIS, detailed feasibility studies and some studies focusing specifically on determining the heat demand from buildings, a key factor in deciding the feasibility as demonstrated by [23, 24] and [25]. Though some studies of rapid assessments exist, such as [26], where several scenarios were analysed in Belgrade to replace the existing low efficiency DH system with renewable sources and improved network operation, a comprehensive model applicable to new markets where DH has never been implemented has not been addressed. A couple of rapid assessment studies have been performed in Quinto Burgos [27] and Coyhaique [28] in Chile following a bottom-up approach however the assumptions used in the study are not specific to Chile, instead rely heavily on global averages and inputs from the user. A District Heating Assessment Tool (DHAT) [29] developed by the Danish Energy Agency (DEA) also follows a similar approach. Though the tool can be used to analyse projects in any part of the world, it is dependent on the user’s ability to perform detailed analysis of the input variables and data. Rapid assessments need to be able to provide quick indications about the project’s potential at low cost, time and effort. The methodologies and tools covered in the literature review are limited when it comes to flexibility, project identification, time, effort and accuracy of the results when applied to Chile. Thus there is a need for a quick analysis tool with reliable built-in data for Chile that can be easily used by city planners to detect potential projects. In countries where DH is new, rapid assessments can boost the development of district energy projects by helping local governments identify bankable projects, and then motivate them to mobilize additional funding to undertake in-depth feasibility analysis and attract potential investors.

Hence, the aim of the District Heating Rapid Assessment model (DHRA) model is to support the preparation of rapid assessment analyses of DH projects in new areas and to determine if the technical, economic and environmental potential of a certain district heating scheme is suitable for moving towards a deeper analysis and/or prefeasibility study of the considered scheme without the need to assign scarce resources to the analysis of the as yet still uncertain potential for DH.

2. Numerical model

DHRA follows a bottom-up approach to engineering built as an Excel-based tool., It requires data from current building stocks and energy systems, climate data and the selection of DH generation technologies in order to calculate the techno-economic and environmental potential of DH in new markets. The energy demand is calculated based on data gathered from the building stock and individual technologies currently being utilized. This forms the baseline or business-as-usual (BAU) scenario. After identifying the total demand, desired DH generation technologies can be selected from a database. The model is then able to calculate the costs of developing the DH case and the potential savings in emissions of CO2, PM10 and PM2.5 through comparison with the BAU case. Financial indicators such as net present value (NPV), internal rate of return (IRR) and payback time (PBT) are calculated to determine whether the project is economically attractive. The modelling workflow is represented in Fig. 2.

The “General” inputs are required to identify the project and its main energy-related characteristics. For example, the “Indoor temperature” represents the temperature for desired thermal comfort. The higher the temperature, the greater the heat load. “Land surface” is the area that will be serviced by the DH system. “BAU scenario” inputs are required to create a baseline of the area’s current and future energy demand. The financial parameters will help to estimate the cost of heating and electricity currently being paid. “Heat price” represents the tariff and in the future will be used to calculate the revenue from selling heat generated by the DH system. “DH scenario” inputs establish the DH technologies that will replace current heating systems along with financial inputs to calculate the cost of setting up and operating such a system. The “Built-in” data covers various data points related to “Climate” that will be used to determine the heat load, “BAU and DH technology efficiencies” to determine the heat output produced, and “emission factors” to determine the emissions generated in both the BAU and DH cases. Finally, the total heating demand, the capacities of the DH technologies needed to cover this demand, the costs of setting up and operating the DH system and emissions savings are determined in the “Output”.

2.1. BAU scenario

2.1.1. BAU inputs

The baseline or BAU scenario will calculate the heating demand and the emissions generated from individual heating technologies. In order to create a baseline of the area’s current and/or future energy demand, it is necessary to identify existing space-heating technologies. This baseline is then used to calculate the peak demand and fuel consumption in

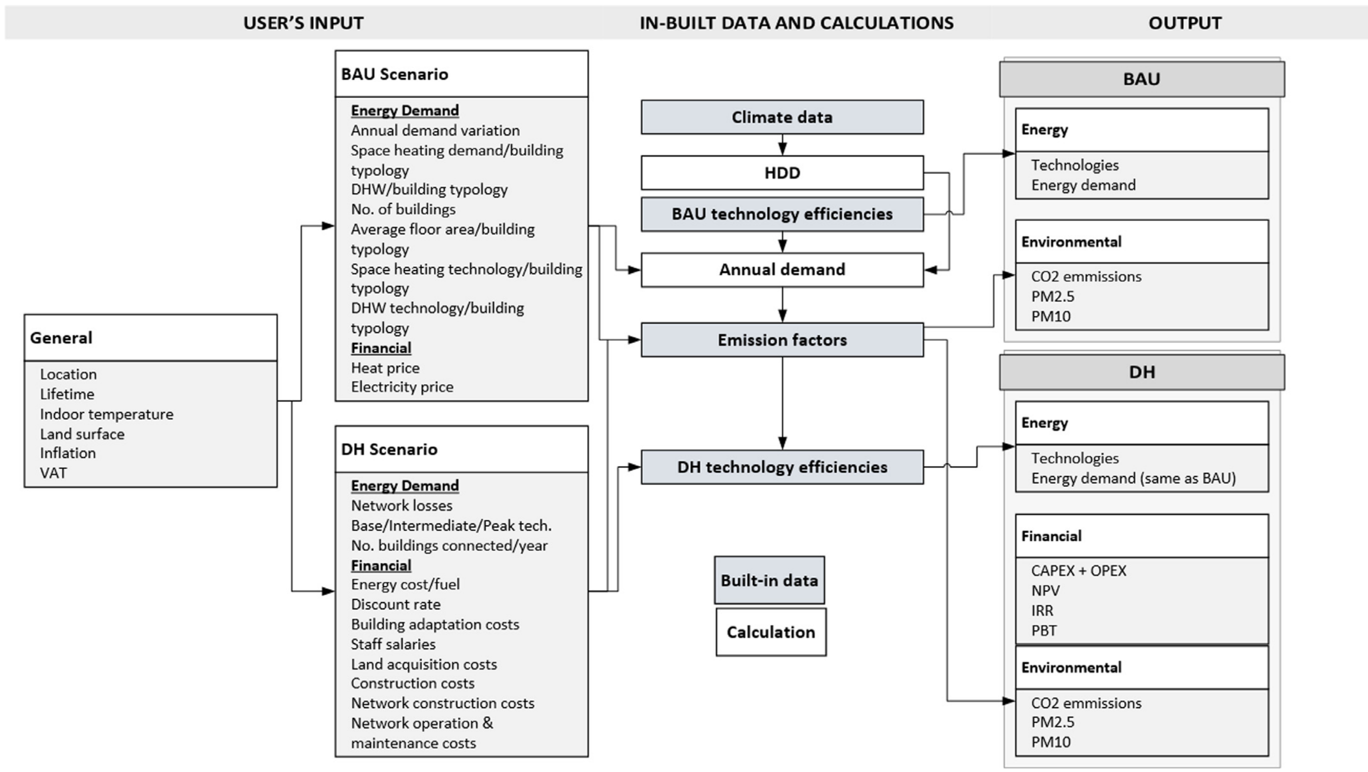


Fig. 2. Conceptual outline of the building stock model and the DHRA model.

Table 1
Energy demand inputs for case of Temuco (Aiguasol, 2020).

	Offices	Health	Education	Residential (SDB)	Residential (MDB)	Commercial
Annual heating demand	-	-	-	145	237	-
Average building area	-	-	-	62	57	-
Number of buildings/dwellings	27	39	112	8161	4789	260

the DH case and then create a benchmark between the BAU and DH cases. To characterize the heating demand, six different construction typologies are identified based on the building's use: office, health, educational, commercial, or residential (single- and multi-dwelling building, or SDB and MDB respectively). The distinction between residential SDB and MDB is provided in Appendix 1. (Definitions). In doing so, the first step is to establish the general aspects of the project in order to identify it.

The project selected for consideration here is a thirty-year project with construction beginning in 2022 and operations estimated to start in 2023 in the region of Temuco, Chile. The land area being serviced is 28,000,000 m2 with a set heating temperature of 18°C. The network losses are assumed to be 10%, which reflects the new efficient DES. The BAU heat price is 54.1 CLP/kWh (0.059 EUR/kWh).

Chile is split into seven different thermal zones, each with a different heating season. The model analyses a DES based in Temuco, which is located in zone 5 and has seven heating months. The distribution of heating seasons per thermal zone in Chile is provided in the Appendix. The annual space heating demand, average area and number of buildings/dwellings per building typology are required to calculate the total heating demand under BAU Table 1. provides values for these parameters, which are implemented in the model. The tool calculates the space-heating demand per building typology, $Q_{SH/building}$ using equation 1 where $Q_{SH/building/area}$ is the annual space heating demand per building per area, and A_{av} is the average building area. In the example of non-residential buildings in Temuco, the heating demand per building typology in kWh per year is directly provided as an input; Offices - 40,279, Health - 174,283, Educational - 24,907 and Commercial - 59,297.

$$Q_{SH/building} = Q_{Sh/building/area} * A_{av} \; [kWh/year] \tag{1}$$

A list of the individual heating technologies being implemented in the case of Temuco per building typology is given in Table 2.

The model then calculates the demand for each technology for space heating $Q_{SH/tech}$ using equation 2 where N_{type} is the total number of buildings/dwellings per typology. Finally, the total heating demand, Q_{total} is given by equation 3.

$$Q_{SH/tech} = \sum^{(Q_{SH/building} * N_{type})} * \left(\frac{1}{10^3}\right)[MWh] \tag{2}$$

$$Q_{total} = \sum^{Q_{SH/tech}} [MWh] \tag{3}$$

2.1.2. BAU calculations

The BAU calculations are made to assess the total heating generation and resulting emissions. The heat energy to be generated to cover space heating in the BAU case, $E_{SH/tech}$ is calculated by considering the heating demand per technology, $Q_{SH/tech}$ and the individual technology efficiencies, η_{tech} given in Table 2, using equation 4 and total system demand Q_{net} in equation 5.

$$E_{SH/tech} = \frac{Q_{SH/tech}}{\eta_{tech}} \; [MWh] \tag{4}$$

$$Q_{net} = \sum E_{SH/tech} \; [MWh] \tag{5}$$

Table 2
Individual heating technologies per building typology in the case of Temuco (Aiguasol, 2020).

	Efficiency	Offices	Health	Education	Residential (SDB)	Residential (MDB)	Commercial
Wood-chip stove	0.4	0	0	24	0	0	0
Wood-chip boiler efficient	0.6	0	0	24	0	343	26
Wood “Salamandra”	0.32	0	0	0	8161	0	0
Wood-pellet boiler	0.85	0	0	0	0	1794	0
Oil boiler	1	14	20	61	0	1541	208
Natural gas boiler	1	14	20	12	0	1111	26

Table 3
Emission factors for fuels.

Fuel	CO2 (kg/GJ)	PM10 (g/GJ)	PM2.5 (g/GJ)
Natural gas	56.15	3.59	3.59
Oil	71.3	1	1
Wood chips	113.94	1592	1547
Wood pellets	113.94	140.7	136.7

Once the net heating required to ensure the demand is fully satisfied has been identified, the model estimates the equivalent CO2, PM10 and PM2.5 emissions emitted from each individual technology and aggregates them to obtain the final net emissions. The average emission factors for each fuel used in Chile's BAU case is provided in Table 3 below. Emissions are then calculated using emission factors and equation 6 where $EM_{SH/tech}$ is the emissions per technology and EF is the emission factor. They are then aggregated in equation 7, where EM_{BAU} is net emissions in the BAU case.

$$EM_{SH/tech} = E_{SH/tech} * EF * 3.6 * \left(\frac{1}{10^6}\right) [t] \tag{6}$$

$$EM_{BAU} = \sum EM_{SH/tech} [t] \tag{7}$$

2.1.3. HDD and annual load profile

An annual daily average temperature profile for Temuco is extracted from the national climate database and is then automatically applied to the analysis. The heating degree-days (HDD) are then calculated based on the annual daily temperature profile and indoor set temperature. The HDDs increase with the increases in the set temperature for heating. In the case of Temuco, HDDs are only calculated for days that fall under the heating season, which begins in April and ends in October. Additionally, HDDs are only calculated for days when the ambient temperature is lower than the set temperature. Total HDDs in a year, HDD is calculated by aggregating HDDs per day, HDD_d using equations 8 and 9 where T is the set temperature and T_d is the average daily temperature.

$$HDD_d = T - T_d \left[degrees/day\right] \tag{8}$$

$$HDD = \sum HDD_d \left[degrees/day\right] \tag{9}$$

Based on the HDDs, the demand calculated in the BAU case needs to be for the district and across the heating season. Hence, space heating demand per day, $Q_{SH/d}$ is calculated using equation 10.

$$Q_{SH/d} = \frac{HDD_d}{HDD} * \sum Q_{SH/tech} [MWh] \tag{10}$$

The total demand per day, Q_d is then calculated using equation 11, where L_n is network thermal losses.

$$Q_d = \frac{Q_{SH/d}}{(1 - L_n)} [MWh] \tag{11}$$

2.2. DH scenario

Once the BAU scenario has been defined, the DH scenario can be calculated. The demand calculated from the BAU scenario has to be met by DH technologies. To this end, the first requirement in the DH scenario is to determine the total installed capacity for DH technologies, IC given by equation 12.

$$IC = \frac{Q_d}{24} [MW] \tag{12}$$

Up to three different DH technologies can be selected to cover the heat demand, base, intermediate and peak, which will collectively deliver the required heating demand to consumers, taking into account network losses. The technologies selected for the case of Temuco are wood-chip boilers as the base load and natural gas boilers as the peak load. The model allows the number of buildings connected each year to the DH network to be calculated, taking into account the gradual addition of consumers to the network (real cases), rather than assuming that all buildings are connected at the operation start year (Year 0). In the case of residential buildings, the number of dwellings is required as an input (not the number of buildings). In Chile, non-residential buildings are connected during the operation start year (2023), while 50% of residential buildings (both SDB and MDB) are first connected in 2024 and the rest in 2025. Then demand each year and cumulative demand are obtained using equations 13 and 14 based on the number of buildings connected to the network each year.

Hence, the demand calculated each year for the DH case, $Q_{SH/yr}$ is given by equation 13, where n_{type} is the actual number of building or dwelling connected.

$$Q_{SH/yr} = \frac{n_{type}}{N_{type}} * \left(Q_{SH/building}\right) * \left(\frac{1}{10^3}\right) [MWh] \tag{13}$$

Thus, the cumulative demand each year Q_{cd} is given by equation 14, where t is project year and PL is the project lifetime.

$$Q_{cd} = \sum_{t=0}^{t=PL} Q_{SH/yr} [MWh] \tag{14}$$

2.2.1. Finance and investment

The inputs required in the DHRA Model can be divided into: general financial parameters, CAPEX or capital expenditure and OPEX or operating expenditure.

2.2.1.1. General financial parameters.

The financial indicators calculated in the model are inflation, discount rate VAT etc. Inflation takes into account the progressive increase in price of goods and services throughout the project lifetime, the discount rate is the interest rate charged to financial institutions for short-term loans, and VAT is the general consumption tax assessed on the value added to goods and services Table 4. shows the values for such financial parameters for Chile.

2.2.1.2. CAPEX.

Capital Expenses (CAPEX) refers to the initial investment (typically included in Year 0), taking into consideration the DH technologies selected in “DH” and their respective prices and lifetimes, network investment, building adaptation, land, construction and abatement costs.

2.2.1.2.1. Network costs. Network costs include the costs of pipes, pumps and substations and installing them underground, connecting the heat generation centre to the demand centre. Network costs for new markets are calculated following the method envisaged by [30]. In this

Table 4
Economic parameter values for Temuco.

Parameter	Recommended value
Inflation	2%
Discount rate	10%
VAT	19%

Table 5
CAPEX inputs for Temuco (Aiguasol, 2020).

Parameter	Value (mil.CLP)	Value (mil.EUR)
Land	-	-
Construction	2536.05	2.79
Abatement	686.9	0.76

method, the DH network investment cost, C_n is found to be proportional to the heat density, and the final equation to calculate the cost is given by equation 15, where $C_a$is annualised distribution cost, and CCF the currency conversion factor from EUR to CLP.

$$C_n = C_a * CCF * Q_{net} \ \ [mil.CLP] \tag{15}$$

2.2.1.2.2. Building adaptation costs. Next, the building adaptation cost to DH, C_{BA} is calculated. This is the cost associated with preparing a building with systems that can connect to the DH system, for e.g. fitting radiators, pipes etc. Values for adaptation costs per building typology in Chile are provided in CLP/kW power ratings in the Appendix. These values do not include the cost of transfer stations in the buildings and the connection between the transfer station and the external DH system. The total building adaptation costs are then calculated using equation 16, where $C_{BA/type-power}$ is the building adaptation to DH cost per typology Table 5. provides CAPEX inputs for the case of Temuco.

$$C_{BA} = \sum \left(C_{BA/type-power} * \left(\frac{N_{type} * Q_{SH/building}}{365 * 24} \right) \right) * \left(\frac{1}{10^6} \right) [mil.CLP] \tag{16}$$

If the project lifetime is longer than the lifetime of some of the technologies, the cash flow will assume that the year N+1, N being the technology lifetime, the owner will purchase the same amount of installed capacity for that specific technology. This forms the Replacement Expenditure (REPEX) cost. Given that there is no prior DH market in Chile, there is no available data on DH technology costs. These DH technology prices were borrowed from the District Heating Assessment Tool, DHAT, developed by the Danish Energy Agency, DEA, for the Danish market represented in Table 6 [29]. This model was selected due to transparency in calculations and assumptions and constant update of the tool to reflect available best practices within the Danish DH experience. Hence, these values indicate the prices of such technologies for purchase in Denmark. To adjust the prices to the Chilean context, a purchasing power parity (PPP) rate is applied to convert Danish technology prices to the Chilean market. Updated PPP rates were obtained from the OECD statistical database and were found to be 52% for Chile (a 2007-2019 inflation rate and adjustment of 50% discount for new projects has been implemented while determining the PPP rate).

While calculating the DH technology CAPEX, the PPP value will be multiplied with the technology and investment CAPEX and OPEX costs

Table 7
Fuel prices in Temuco.

Fuel	Cost (EUR/kWh)	Cost (CLP/kWh)
Wood chips	0.012	11.25
Natural gas	0.075	68.1

to adjust the prices for Chile given by equation 17 where C_{tech} is the technology cost, for e.g. the cost of a heat pump or gas boiler etc., $C_{tech/MW}$ is the technology cost per MW capacity, and IC_{tech} is the installed capacity of each technology at PPP purchasing power parity.

$$C_{tech} = C_{tech/MW} * CCF * IC_{tech} * PPP \ [mil.CLP] \tag{18}$$

The DH network investment cost is also multiplied by the PPP factor and is changed to equation 18. Total CAPEX is then calculated using equation 19, where C_l is the cost of the land required to construct heat generation units, C_c is the cost of the obstruction of heat generation units and C_{ab} is the abatement costs.

$$C_n = C_a * CCF * Q_{net} * PPP \ [mil.CLP] \tag{18}$$

$$CAPEX = C_l + C_c + C_{ab} + \sum C_{tech} + C_{BA} + C_n \ [mil.CLP] \tag{19}$$

2.2.1.2.3. Energy Costs. Energy costs are the costs related to the fuel required to run the DH technologies. Local average energy prices for the fuels are required in the DH case to estimate the OPEX Table 7. provides the values utilised for Temuco.

2.2.1.6. OPEX. Operational expenses (OPEX) are costs along the whole lifetime of the project, due to the operation and maintenance of the system. This is calculated for the number of years defined for the project lifetime (30 years). It is divided into two parts: fixed OPEX and fuels. Fuels OPEX, $OPEX_{fuel}$ is the cost of fuel required annually to operate the DH systems based on the demand. Fuels OPEX is determined by multiplying the fraction of buildings connected to the network and the annual fuel price, C_{af} using equation 20 where n is the actual number of buildings/dwellings connected and N is the total number of buildings/dwellings connected.

$$OPEX_{fuel} = \frac{n}{N} * C_{af} \ [mil.CLP] \tag{20}$$

Total OPEX, $OPEX$ is given by equation 21, where fixed OPEX, $OPEX_{fixed}$ takes into account the costs related to the network, technology and the annual wages of employees described below.

$$OPEX = OPEX_{fuel} + OPEX_{fixed} \ [mil.CLP] \tag{21}$$

Absolute network operation and maintenance cost, $OPEX_n$ is calculated as a percentage over CAPEX. For Chile, a value of 1% is selected, which reflects typical network cost percentages in new projects based on the authors' own experiences. Next, technology OPEX that takes into account the operating and maintenance costs of the DH technologies, $OPEX_{tech}$ is calculated and equation is modified to incorporate PPP. The new equation to calculate tech OPEX is given by 22, where $OPEX_{fixed/MW}$ is the fixed OPEX per MW.

$$OPEX_{tech} = OPEX_{fixed/MW} * IC_{tech} * CCF * PPP \ [mil.CLP] \tag{22}$$

Based on other local/national utilities (e.g., power/street lighting/water utilities), estimates of professional profiles (e.g. station chief

Table 6
DH technology details.

DH technology	Investment		Fixed O&M		Variable O&M		Lifetime	Thermal efficiency
	mil.EUR/MW	mil.CLP/MW	EUR/MW	CLP/MW	EUR/MWh	CLP/MWh	years	
Gas boiler	0.06	28.86	1979.25	952019	1.11	534	25	1.03
Chip boiler	0.1901	91.43	0	0	5.778	2779	20	1.08

engineer, senior engineer, skilled technician, technician), number of employees and their expected monthly salaries is required. The tool calculates the total annual expenses and adds it to the OPEX. Equations 23 and 24 are used to calculate the total staff expenses where $C_{a/person}$ annual fee per person, C_m is the monthly fee, C_{an} is the total annual fee and N_e is the number of employees. Staff salary values used for the case of Temuco are provided in the Appendix.

$$C_{a/person} = C_m * 12 \left[CLP/person\right] \tag{23}$$

$$C_{an} = \left(\sum C_{a/person} * \; N_e\right) * \left(\frac{1}{10^6}\right) [mil.CLP] \tag{24}$$

Finally, total fixed OPEX is calculated using 25.

$$OPEX_{fixed} = OPEX_n + OPEX_{tech} + \sum^{C_{an}} [mil.CLP] \tag{25}$$

2.3. DH additional calculations–DH fuels, cash flow and annual emissions

2.3.1. DH fuels

The heat energy and emissions generated in the DH case based on the technologies selected is calculated. The heat energy generated by base load ($Q_{base/d}$) and peak load ($Q_{peak/d}$) per day is calculated as follows using equations 26 and 27, where is P capacity at which technology operates to meet the demand, Cap_{base} is the base load capacity Cap_{peak} is peak load capacity.

$$Q_{base/d} = P * Cap_{base} * 24 = Q_d \; if\left(Q_d \le Q_{base/d} * 24\right) [MWh] \tag{26}$$

$$Q_{base/d} + Q_{peak/d} = \left(Cap_{base} * 24\right) + \left(P * Cap_{peak} * 24\right) \quad if \; (Q_{base/d} < Q_d \le IC * 24) \; [MWh] \tag{27}$$

The peak load kicks in when a (1) peak load has been selected and (2) the demand is higher than the base and intermediate capacity combined. Hence, the total heating generated by base and peak load technologies in a year, Q_i is given by equation 28, where $Q_{i/d}$ represents cumulative heat generated by base and peak load technologies in a day and i represents base, and peak technologies.

$$Q_i = \sum Q_{i/d} \; [MWh] \tag{28}$$

If a combined heat and power or CHP unit is selected as a base load technology, the electricity produced per day, El_d is calculated using equation 29, where η_{el} is electrical efficiency and the total electricity produced, El is given equation 30.

$$El_d = Cap_{base} * 24 - Q_{base/d} * \eta_{el} \; [MWh] \tag{29}$$

$$El = \sum El_d \; [MWh] \tag{30}$$

Once the output of the generation technologies is calculated, the quantity of the respective fuel input needs to be determined, taking into account DH technology efficiencies. This represents the efficiency of the technology to convert fuel into heat, for example, the efficiency of the heat pump, gas boiler etc. The equations for calculating the required fuel input for heat only E_{HOU} and CHP units, E_{CHP} are given by equations 31 and 32 respectively, where Q_{HOU} is the heat supplied by a heat-only unit, Q_{CHP} is the heat supplied by the CHP unit and η_h is thermal efficiency. Here, CHP and the heat-only unit or HOU correspond to heating generated from the base technology and peak technologies respectively.

$$E_{HOU} = \frac{Q_{HOU}}{\eta_h} \; [MWh] \tag{31}$$

$$E_{CHP} = \frac{Q_{CHP}}{\eta_h} + \frac{El}{\eta_{el}} \; [MWh] \tag{32}$$

The fuel or energy consumption is multiplied by the energy costs to determine the annual fuel price, C_{af} when the system operates at full capacity. It is given by equation 33, where C_e is the fuel cost per unit of energy.

$$C_{af} = E_{HOU} * C_e * \left(\frac{1}{10^9}\right) [mil.CLP] \tag{33a}$$

$$Q_i = \sum Q_{i/d} \; [MWh] \tag{33b}$$

2.3.2. Cash flow

Cash flow is determined for the project's lifetime, where by the financial indicators are calculated (i.e. IRR; PBT and NPV).

Heating generation per year refers to the total heating to be generated each year, Q_t taking into account the number of buildings connected, annual demand variation and network losses. This is calculated using the equation 34.

$$Q_t = \frac{Q_{SH/yr}}{\left(1 - L_n\right)} \; [MWh] \tag{34}$$

The revenue is generated, R from the heat sold at a given heat price, C_h and, if a CHP is selected as a DH technology, the electricity sold at the given electricity price, C_{el} is also included. It is calculated by equation 35.

$$R = \left(\left(Q_t\right) * C_h * \left(\frac{1}{10^3}\right) + \left(El * C_{el} * \left(\frac{1}{10^3}\right)\right)\right) * \left(\frac{1}{10^6}\right) [mil.CLP] \tag{35}$$

To calculate the project's cash flow, the CAPEX, OPEX and revenue are totalled. The inflation index is taken into account to find the nominal cash flow. The cash flow (real prices) is determined using equation 36, where $CF_{net}(real)$ is net cash flow at real prices.

$$CF_{net}(real) = R - CAPEX - OPEX \; [mil.CLP] \tag{36}$$

To find the present value of the cash flows, nominal prices need to be taken into account by introducing inflation index, ii. Hence, the inflation index is calculated for the length of the project lifetime using equation 37, and the real prices are converted to nominal values by multiplying them by the inflation index where t is the project year and i is the inflation rate.

$$ii_{t+1} = ii_t * \left(1 + i_{t+1}\right) [\%] \tag{37}$$

Next, the net present value (NPV), internal rate of return (IRR) and pay-back time (PBT) are calculated. Standard equations for calculating these economic parameters are given by equations 38–40 respectively where t is project year, CF_t is cash flow in year t, CF_0 is cash flow in year 0, r is discount rate, Y_{CF^-} is last year with negative cumulative cash flow, and CCF^+ is first positive cumulative cash flow. The values of NPV and IRR will determine whether the DH project is technically, economically and environmentally attractive or not. For an attractive project the NPV value needs to be positive, while the IRR should be higher than the discount rate. The PBT, on the other hand, gives an indication of when break-even can be achieved.

$$NPV = -CF_0 + \sum_{t=1}^{PL} \frac{CF_t}{(1+r)^t} \; [mil.CLP] \tag{38}$$

$$0 = -CF_0 + \sum_{t=1}^{PL} \frac{CF_t}{(1+IRR)^t} \; [\%] \tag{39}$$

$$PBT = Y_{CF^-} - \frac{CCF^-}{CCF^+ - CCF^-} [years] \tag{40}$$

2.3.3. Annual emissions

After knowing the energy demand, the model estimates CO2, PM10 and PM2.5 emissions generated from each DH technology and aggregates them to obtain the final emissions. The emission factors considered in the model for CO2, PM10 and PM2.5 are given in Table 3. The model

then calculates the CO2, PM10 and PM2.5 emissions by using equation 41, where EM_{DH} is net emission in the DH case.

$$EM_{DH} = \left(\sum EF * E_{HOU} * 3.6 + \sum EF * E_{CHP} * 3.6\right) * \left(\frac{1}{10^6}\right) [t] \quad (41)$$

The annual emission savings $EM_{saved/year}$ are calculated systematically through the heating generation per year. The emissions savings each year from installing DH systems can be obtained by using equation 42. Here, the emissions from DH case are subtracted from the BAU case for each year of the project's lifetime to obtain the yearly savings. The cumulative savings over the project lifetime, $EM_{saved/total}$ are obtained by summing up yearly savings represented by equation 43. The model also generates graphs that represent the emissions in the BAU and DH case along with the savings.

$$EM_{saved/year} = EM_{BAU} - EM_{DH} \; [ton/year] \quad (42)$$

$$EM_{saved/total} = \sum EM_{saved/year}[ton] \quad (43)$$

3. Results

When introducing these inputs to the DHRA Model, the tool can be validated by comparing it with the prefeasibility study of Temuco City, performed by Aiguasol LATAM (Aiguasol Latam 2020). This case study was selected from among many other case studies because it contained the most detailed analysis done in the field over a period of two years and had several national and international validation stages, including a review of the district energy by the cities' technical experts and partners. The model was also calibrated against the DHAT tool, leading to the applied adaptation factors in the energy demand.

The project is a 30-year lifetime district heating system, including heating and domestic hot water (DHW), and setting a comfort temperature of 18°C. It consists of a base load supplied by a wood-chip boiler and a gas boiler for peak load and is expecting to connect 448 anchor clients, 8,161 houses (Single-Dwellings) and 4,789 apartments (Multi-Dwellings) in a 3-year period. Even though the prefeasibility study considers both heating and DHW supply, the DHRA model only evaluates the heating demands for district heating systems and no accumulation, so the technical results only compare the heating potential.

Table 8
Heat generation.

Heat generation	Aiguasol, 2020	DHRA model
Capacity to be reached (MW)	90.08	55.0

3.1. DH technologies and fuel consumption

A comparison is made between the calculated installed capacity by the DHRA model and the Aiguasol study as shown in Table 8. In terms of the design of the district heating system, the power calculated by Aiguasol 2020 is 39.4% higher than that of the DHRA model. The distribution of the capacity between the base and peak loads is represented by Fig. 3.

The deviation from Aiguasol Deep Assessment relies mainly on capacity estimates. Aiguasol models the building's demand for heating and DHW hourly, and the HDD methodology estimates the heating demands per day, so it flattens the peaks and the overall profile. This effect contributes directly to the capacity estimate because it depends on the peak aggregated demands. Taking this into consideration, the DHRA model underestimates the capacity, being the error acceptable within the low range [-20% to -50%] of variation for a Concept Screening in the processing industries, which can resemble the rapid assessment of district energy project developments [31].

The proposed set up is optimized to reduce the impact of CAPEX and OPEX in the business case through financial parameters. The wood-chip boiler of 25 MW ensures large annual full-load hours that benefit

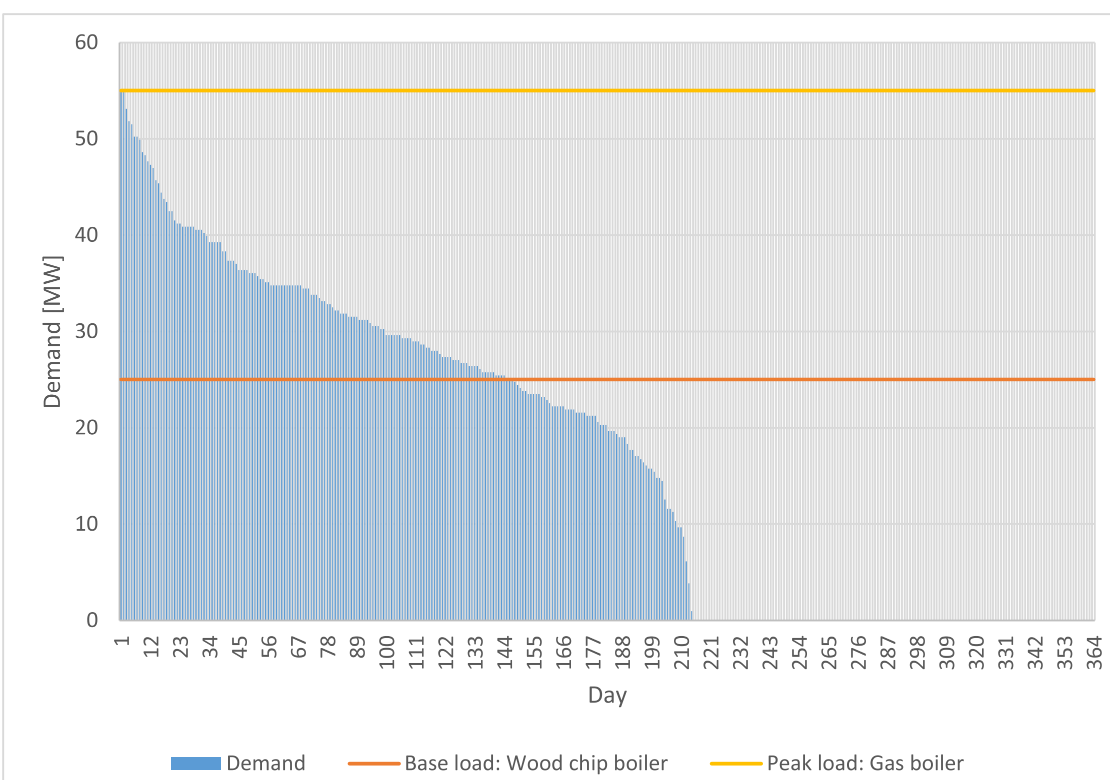


Fig. 3. Net installed capacity per technology and annual cumulative demand graph.

Table 9
DH fuel consumption.

Fuel	Energy consumed (MWH/year)
Wood chips	109,249
Natural gas	32,636

Table 10
Generation costs–Comparison of DHRA model with Aiguasol, 2020.

Generation cost	Aiguasol, 2020	DHRA model	Units
Base technology (Biomass boiler)	3521.8	2551.0	mil.CLP
Peak technology (Natural gas boiler)	368.7	1035.7	mil.CLP
DH network investment	16314.4	19096.7	mil.CLP

the systems from their smaller OPEX, whereas the gas boiler ensures the full supply of the demand. Due to the shape of the demand–that is, large differences between peaks and mean daily consumptions–the gas boilers ensure a lower purchasing price and flexibility during the few hours it will have to work during a year's operation.

Due to the cheaper fuels and operation costs, and despite having a lower installed capacity, the wood-chip boiler working as a base technology produces more energy than the natural gas boiler, at a ratio of 3:1. The fuel consumed by these two units per year is shown in Table 9.

3.2. Financial analysis

Only the costs of the main CAPEX components (base and peak technology and the distribution network) were compared. The pre-feasibility study by Aiguasol 2020 considers the supply of heating and DHW. Therefore, to compare the cost in this section, an "extra" demand was entered equal to the total power of the study (which corresponds to 64 MW + accumulation). Regarding the distribution network, a service area of 2.8 km2 is assumed. The results are presented in Table 10.

In relation to the main CAPEX costs of base and peak technologies, the tool taking into account the lower installed capacity per technology and different purchasing prices results in an underestimate of the cost of the base technology by 27.6% and overestimates the peak technology cost by 2.8 times. The network investment is overestimated by 7%. Other financial parameters calculated by the DHRA model are presented in Table 11.

With a fixed DH heat price provided as an input to ensure that the system cannot be more expensive than the ceiling BAU price, the project reveals a high internal rate of return of 14% and a net present value of 10,509 million CLP (11.55 million EUR). These numbers indicate the high financial potential of the area under study, which could eventually benefit from lower heating prices or be used as the core of an expansion of the system towards areas with lower profitability but larger emissions and greater levels of energy poverty.

Table 11
Key financial indicators to assess the DH project feasibility.

Parameter	Unit	Value
DH heat price	CLP/kWh	50
Capital Expenditure (CAPEX)-Year 0	mil.CLP	25,072
Operational Expenditure (OPEX)-Per year	mil.CLP	136
Net Present Value (NPV)	mil.CLP	10,509
Internal Rate of Return (IRR)	%	14
Payback Time	years	7

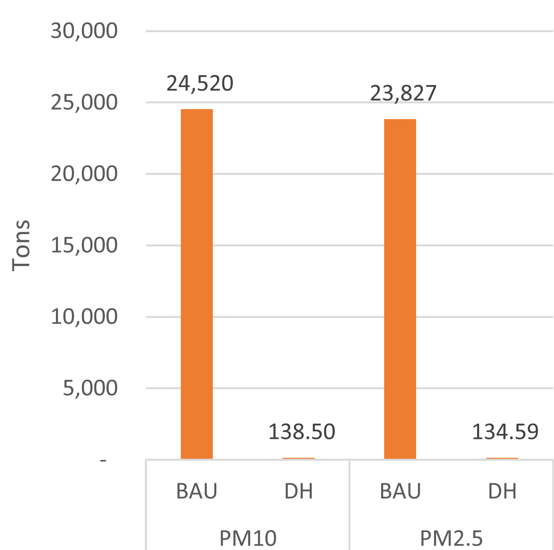
3.3. Emissions

In terms of the environmental results of the Rapid Assessment tool, it is worth mentioning that the business-as-usual scenario assumes that the heating systems in the residential sector in the south of Chile are mainly covered by inefficient wood stoves for SDB. The MDB and the educational centres use simple wood-chip boilers, while the health and commercial sector use natural gas boilers for heating. Using these technologies as the BAU scenario, the environmental results are presented in Table 12 along with the values calculated by Aiguasol.

Table 12
Emission savings per year.

Parameter	Aiguasol, 2020	DHRA model	Units
CO2 (BAU-DH)	17,020	19,985	mil.CLP
PM10 (BAU-DH)	575	698	mil.CLP
PM2.5 (BAU-DH)	528	679	mil.CLP

The deviations shown in Table 12 are a result of the differences in the energy required to heat the area under study. Smaller deviations than in these in the DH CAPEX set-ups have been found, indicating greater proximity. The larger savings can reflect a more conservative scenario in the BAU case in respect of Aiguasol' s set up, as the same abatement filters have been implemented in both methodologies, and the latter has a larger energy consumption in its BAU case. The overall emissions in the BAU and DH scenarios have been represented in Fig. 4 below.



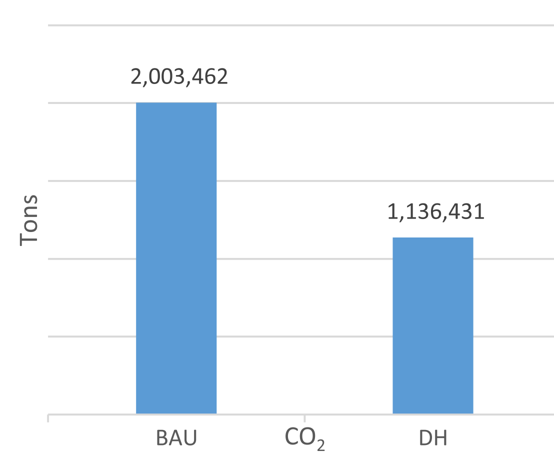


Fig. 4. PM2.5 and PM10 emissions in BAU and DH scenarios (left), CO_2 emissions in BAU and DH scenarios (right).

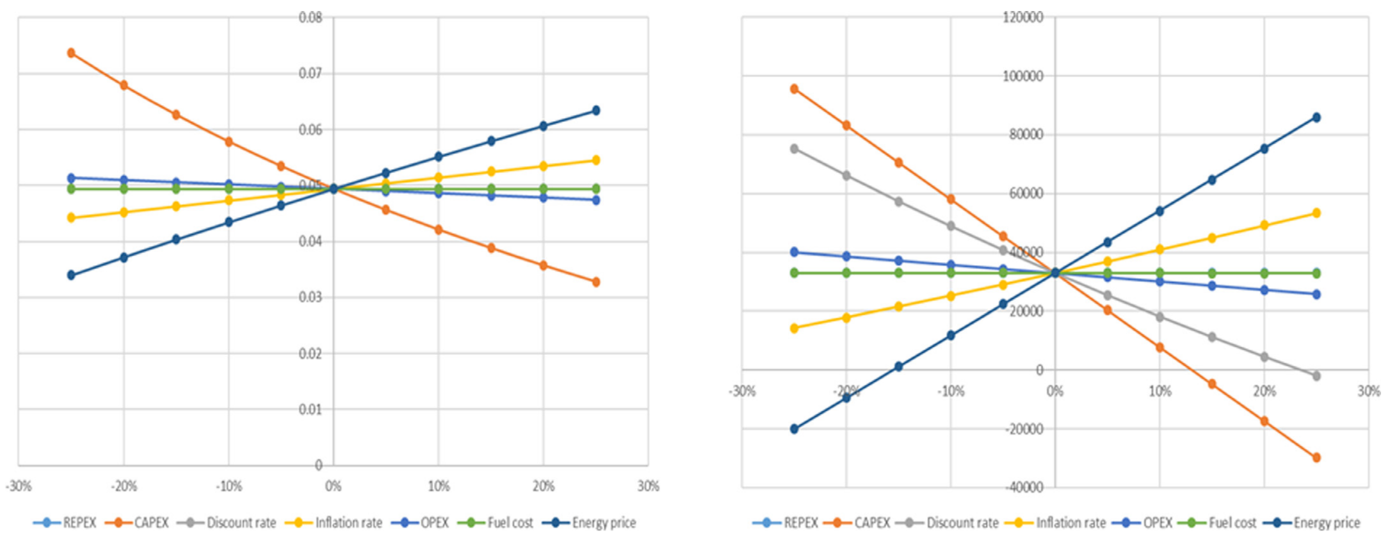


Fig. 5. Sensitivity analysis of financial indicators–IRR (left) and NPV (right).

3.4. Sensitivity

The DHRA model addresses uncertainties by including a sensitivity analysis of some of the most important input parameters, including CAPEX, REPEX, OPEX, fuel cost, discount rate, inflation and energy price. The parameters vary from -25% to +25% in increments of 5%, and the corresponding NPV and IRR values are determined. Graphs (see Fig. 5) are generated to capture these variations and the impacts of these variations on the project visually. This will ultimately help identify any potential obstacles in the project feasibility phase. The results indicate that the variations in CAPEX and the heat price have the largest influences on both NPV and IRR. A focus on the optimization of these areas can potentially create a better business case.

4. Discussion and conclusion

This paper presents a novel methodology to conduct a rapid-assessment on the technical, economic and environmental potential of a district heating in areas with no prior market. The model has been tested in the city of Temuco in Chile and the results show an overwhelming reduction in PM2.5 and PM10 emissions (99%) with the implementation of gas boiler and a wood chip boiler to service the heat demand in the area. This reduction, coupled with a 43% reduction in carbon emissions through the project lifetime, can significantly improve the local air quality and, therefore, improve the health of the residents. The financial results are also favourable with a positive NPV and the IRR being greater than the discount rate. This indicates the analysis can move towards a deeper pre-feasibility and feasibility analysis in order to assess whether the technology is suitable and the project should be constructed.

The sensitivity analysis has pointed towards a high level of influence for CAPEX and heat price assumptions. A deeper focus on the setting of technology prices and potential reductions in the heat price could bring similar financial, technological and environmental results, while improving the purchasing conditions of the final users. The model was also validated against similar studies performed by local technical firms.

The main deviations between RA model and Aiguasol can be summed as: lower capacity estimation (39%), lower district energy system cost (27%) but larger emissions potential than other studies (against in-depth study from Aiguasol). The main differences are explained in Table 13.

The difference in the district energy system mainly respond to the currency exchanges. Also, the proposed expenditures for the purchase and maintenance of the system vary. Due to the lack of a local DH market and operating experience, assumptions based on top-of-the-class technology and prices from mature DH countries as Denmark and the application of a PPP price-transfer appeared to be a promising solution that potentially could be expanded to other countries without a DH market,

Table 13
Synthesis of differences and consequences between the RA model and Aiguasol PF model.

Type	Differences	RA model	Aiguasol PF	Consequences
Technical-Environmental	Heating demand estimation method	Heating degree day method	Hourly peaks of temperature	The RA model flattens the demand curve, which affects the capacity dimensioning. This is a bias that systematically will output a lower capacity estimation in comparison with an in-depth study like the PF developed by Aiguasol, which dimensions consider the lower hour temperature of the year
	Efficiencies	Date basis, mainly Denmark	Detailed efficiencies from catalogues and others	The different efficiencies approach influences the dimensioning of the pieces of equipment, the local and global emissions estimation and the energy savings
	Network and accumulation losses	It does not consider accumulation losses	It consider specific network losses by the different sections (primary and secondary), and considers accumulation losses	The difference influences the dimensioning of the generation equipment and the network, the local and global emissions estimation and the energy savings
Economic	Biomass and generation technology costs	Data Bases, mainly Denmark	Detailed costs from quotes and local prices estimation	The RA model considers generation and distribution costs from a Danish DB, while Aiguasol quotes local equipment to the local market, and estimates the cost when imported
	Currency	Danish currency, adapted to Chilean currency from PPP	Different foreign exchange rates to Chilean pesos in different dates (US Dollar, Euro)	The difference of the currencies influence the final economical assessment due to the different exchange rates in time

allowing existing technological gaps that hinder the transfer and implementation of state-of-the-art sustainable heating solutions to be filled. Furthermore, the area against which the methodology was tested proved to be of high value in developing a first DH system in the area and allowing the later expansion and development towards areas of high energy density and/or pollution or energy poverty, as both energy and financial potentials are very high. The simplicity of the tested model has the potential to develop a large quantity of early studies to map the technical, economic and environmental potential of DH in different areas of a country without having to allocate large amounts of resources (time and money) and by ensuring competitiveness among projects. The energy reduction encountered compared to similar models is expected to raise the bar regarding project assessment viability and ensure the reliability and selection of higher potential cases under conservative energy assumptions in the early stages, so that scarce resources are mobilized towards projects with greater potential. The model also presents certain limitations, such as the fact that it is not able to account for individual potential energy efficiency improvements in the building stock. Still, the methodology presented does not intend to disregard projects based on purely financial indicators but to weight a project potential with different scenarios and to include environmental metrics to balance the financial indicators with emissions deployment.

The methodology was applied and tailored to the building stock of Temuco; nevertheless, the approach is transferable to other countries and regions. The application will, however, depend on the morphology of the stock, model purpose, and data availability. The results of the rapid assessment from the DHRA tool serve as a crucial step to inform local decision makers of the implementation of DH, as key technology to decarbonize their systems. The simplicity of the tool is also beneficial for this purpose. Hence, this tool serves as the first stepping stone in unlocking investments and mobilising resources in Chile and provides the necessary foundation required to take suitable projects to implementation. The DHRA model could be further developed by quantifying the multiple benefits of district energy, such as local job creation, avoided deaths through the reduction of PM2.5, and an increased public budget through the reduction of spending on health support due to air pollution.

Authors' contributions

SM and CC developed the core model in 2019-2020. CR and PL revised the model, tailored the model to the Chilean case study, collected the data and conducted the validation. TY supported in the development of the model in 2021. CC, SM, CR, PL and TY wrote the draft with contributions from all authors. JB collected the data and supported the validation. ZC provided feedback to the final.

Additional information

Ancillary information is not available for this paper.

Conflicts of Interest

The authors declare no conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of the data; in the writing of the manuscript; or in the decision to publish the results.

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Appendix 1. Definitions

Appendix 2. Table of symbols

Table 14
Distinction between single-dwelling and multi-dwelling buildings.

Name	Definition (i.e. building typology)
Single-dwelling building (SDB)	Single-family house or detached house–A house for a single family or household that is not attached to any other building. Semi-detached house, Twin house or Duplex–A house, typically with two separate entry doors (sometimes with one) divided into two parts and housing two separate owners or tenants; this can be side-by-side, or one above the other. Row house or Terrace house–A series of houses, often of similar or identical design, situated side by side and joined by common walls.
Multi-dwelling building (MDB)	Small multi-family or small apartment building–A building where multiple separate housing units (12 or less) for residential inhabitants are contained within one building or several buildings within one complex. Large multi-family home or large apartment building–A building where multiple separate housing units (more than 12) for residential inhabitants are contained within one building or several buildings within one complex.

Table 15
Heating season per thermal zone in Chile.

Thermal zone	Winter heating demand	Summer heating demand	Heating months
1	100%	0%	6
2	100%	0%	6
3	100%	0%	6
4	100%	0%	6
5	90%	10%	7
6	85%	15%	8
7	67%	33%	10

Table 16
Building adaptation costs.

Building type	Connection (CLP/kW)	Adaptation (CLP/kW)	Total cost (CLP/kW)
Buildings	15,426	46,875	62,301
Individual houses	350,444	482,678	833,122

Table 17
Staff salaries for plant operators in Temuco.

Employees	Monthly fee (CLP/person)
1	2,600,000
2	1,800,000
2	800,000
2	600,000

Symbol	Definition
A_{av}	Average building area (m^2)
C_a	Annualised distribution capital cost (CLP/GJ)
C_{ab}	Abatement cost (CLP/GJ)
C_{af}	Annual fuel price (mil.CLP)
C_{an}	Total annual fee (mil.CLP currency)
$C_{a/person}$	Annual fee per person (CLP/person)
C_c	Construction cost (mil.CLP currency)
C_e	Fuel cost per unit of energy (CLP/kWh)
C_{el}	Electricity price (CLP/kWh)
C_h	Heat price (CLP/kWh)
C_l	Land cost (mil.CLP)
C_m	Monthly fee (CLP/person)
C_n	Network investment cost (mil.CLP)
C_{tech}	Technology cost (mil.CLP)
$C_{tech/MW}$	Technology cost per MW capacity (mil. EUR/MW)
C_{BA}	Building adaptation to DH cost (mil.CLP)
$C_{BA/type-power}$	Building adaptation to DH cost per typology (CLP /kW)
Cap_{base}	Base load capacity (MW)
Cap_{peak}	Peak load capacity (MW)
CCF	Currency conversion factor (CLP/in-built currency)
CCF^-	Last negative cumulative cash flow (mil.CLP)
CCF^+	First positive cumulative cash flow (mil. CLP)
CF	Cash flow (mil.CLP)
C_{net}	Net cash flow (mil.CLP)
$CAPEX$	Total capital expenditure (mil.CLP)
E_{CHP}	Annual energy consumption CHP (MWh)
E_{HOU}	Annual energy consumption heat-only unit (MWh)
$E_{SH/tech}$	Energy generated per technology for heating (MWh)
EF	Emission factor (g/GJ)
El	Electricity supplied annually (MWh)
E_d	Electricity produced per day (MWh)
$EM_{saved/year}$	Emission savings per year (ton/year)
$EM_{saved/total}$	Total emission savings (ton)
$EM_{SH/tech}$	Emission per technology for space heating (ton)
EM_{BAU}	Net emissions - BAU case (ton)
EM_{DH}	Net emissions - DH case (ton)
HDD	Total HDD in a year (degrees/year)
HDD_d	HDD per day (degrees/day)
i	Inflation rate (%)
ii	Inflation index (%)
IC	Total installed capacity (MW)
IC_{tech}	Installed capacity for each technology (MW)
IRR	Internal Rate of Return (%)
L_n	Network thermal losses (%)
n	Actual number of buildings/dwellings connected (-)
N	Total number of buildings/dwellings per typology (-)
N_e	Number of employees (-)
n_{type}	Actual number of buildings/dwellings per typology (-)
N_{type}	Total number of buildings/dwellings per typology (-)
NPV	Net Present Value (mil.CLP)
$OPEX$	Operation expenses (mil.CLP)
$OPEX_{fixed}$	Fixed operation expenses (mil.CLP)
$OPEX_{fixed/MW}$	Fixed OPEX per MW (EUR/MW)
$OPEX_{fuel}$	Fuel expenses (mil.CLP)
$OPEX_n$	Network expenses (mil.CLP)
$OPEX_{tech}$	Technology operational expenses (mil.CLP)
P	Capacity at which technology operates to meet the demand (%)
PBT	Pay-back time (years)
PL	Project lifetime (years)
PPP	Purchasing power parity (%)
Q_{base}	Heat supplied by base load annually (MWh)
$Q_{base/d}$	Heat supplied by base load per day (MWh)
Q_{cd}	Cumulative demand each year for DH case (MWh)
Q_{CHP}	Heat produced by CHP unit (MWh)
Q_d	Demand per day (MWh)
Q_{HOU}	Heat supplied by heat only unit (MWh)
$Q_{i/d}$	Cumulative heat generated by base and peak technologies in a day (MWh)
Q_{net}	Net heating to be generated in BAU case (MWh)
$Q_{peak/d}$	Heat supplied by peak load per day (MWh)
$Q_{SH/building/area}$	Annual space heating demand per building per area (kWh/m2/year)
$Q_{SH/building}$	Space heating demand per building (kWh/year)
$Q_{SH/d}$	Space heating demand per day (MWh)
$Q_{SH/tech}$	Space heating demand per technology (MWh)
$Q_{SH/yr}$	Demand each year for DH case (MWh)

(*continued on next page*)

Q_t	Total heating to be generated per year in DH case (MWh)
r	Discount rate (%)
R	Revenue (mil.CLP)
T	Set temperature (°C)
T_d	Average daily temperature (°C)
Y_{CF^-}	Last year with negative cumulative cash flow (year)
η_{el}	Electrical efficiency (%)
η_h	Thermal efficiency (%)
η_{tech}	Efficiency of technology (%)
Abbreviations	
BAU	Business-as-usual
CAPEX	Capital Expenditure
CHP	Combined Heat and Power
CLP	Chilean Pesos
CO_2	Carbon di-oxide
DEA	Danish Energy Agency
DH	District Heating
DHAT	District Heating Assessment Tool
DHRA	District Heating Rapid Assessment
DHW	Domestic Hot Water
GIS	Geographic Information System
HDD	Heating Degree Days
LCA	Life Cycle Analysis
MCA	Multi Criteria Analysis
MDB	Multi Dwelling Building
OECD	Organization for Economic Co-operation and Development
OPEX	Operation Expenditure
PM	Particulate Matter
REPEX	Replacement Expenditure
SDB	Single Dwelling Building
VAT	Value Added Tax
WHO	World Health Organization
Subscript	
a	Annual
ab	Abatement
af	Annual fuel
an	Annual fee
av	Average
ba	Building adaptation
BAU	Business-as-usual scenario
c	Construction
cd	Cumulative demand
CF	Cash flow
CHP	Combined Heat and Power
d	Daily
DH	District Heating scenario
e	Energy
em	Employee
el	Electricity
h	Heat
HOU	Heat only unit
l	Land

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