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RENEWABLE ENERGY SOLUTIONS FOR HEATING SYSTEMS IN MONGOLIA

Developing a strategic heating plan

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Abbreviations

AOI	area of interest
AQI	Air Quality Index
BTES	borehole thermal energy storage
CHP	combined heat and power
COP	coefficient of performance
DH	district heating
DHW	domestic hot water
EE	energy efficiency
CSP	concentrated solar power
ETC	evacuated tubular collector
FPC	flat plate collector
GHG	greenhouse gas
GIS	geographic information system
GW	gigawatt
GWh	gigawatt hour
GWp	gigawatt peak
HOB	heat-only boiler
kt	thousand tonnes
kW	kilowatt
kWh	kilowatt hour
kWp	kilowatt peak
LPG	liquefied petroleum gas
Mt	million tonnes
MW	megawatt
MWe	megawatt electrical
MWh	megawatt hour
MW_{th}	megawatt thermal
$\mu g/m^3$	micrograms per cubic metre
NAMA	Nationally Appropriate Mitigation Action
NO_2	nitrogen dioxide
NO_x	nitrogen oxides
NREC	National Renewable Energy Center (Mongolia)
PJ	petajoule
PM	particular matter
$PM_{2.5}$	particulate matter less than 2.5 micrometres in diameter
PM_{10}	particulate matter less than 10 micrometres in diameter
PTES	pit thermal energy storage
SHP	strategic heating plan
SO_x	sulphur oxides
SO_2	sulphur dioxide
TPES	total primary energy supply
TW	terawatt
TWh	terawatt hour
WACC	weighted average cost of capital
Wp	watt-peak
W2E	waste to energy
3GDH	third-generation district heating
4GDH	fourth-generation district heating

Executive summary

The current heat supply in Mongolia is highly reliant on district heating and individual household heating fuelled by domestically produced coal. The coal provides an economical option for the supply of heat to the population but is also a main cause of many challenges in the country. Local pollution due to coal usage is high in cities, causing respiratory-related health issues. It also challenges Mongolia's aim to reduce greenhouse gas (GHG) emissions in line with its Nationally Determined Contribution (NDC) and thus hinders the pace of meeting the global climate change targets set in the Paris Agreement. Most buildings in Mongolia have low energy efficiency, and their heat supply systems are also inefficient. Furthermore, a large share of the population has relatively low purchasing power, which implies that upgrading heating systems and integrating more renewable supply is not a simple pathway. Finally, the population of the country is increasing rapidly, only adding to these problems if the current heating-related challenges are not addressed. Mongolia, however, also has large potential sources of renewable energy - especially wind, solar and geothermal energy.

A strategic heating plan (SHP) is a techno-economic assessment that shows how municipalities, districts, cities or countries can transform their heat supply from fossil-based sources through the integration of renewable energy resources. In the case of Mongolia, IRENA developed a detailed SHP covering the city of Ulaanbaatar to leverage the existing district heating network with the utilisation of locally available renewable energy heat sources, as well as renewable electricity from solar and wind. The assessment comprises detailed mapping of the heat demand of buildings and a detailed energy system analysis of the district heat supply. Since most of the pollution from the heating sector in Ulaanbaatar is generated in informal settlements ("*Ger*" areas) where district heating systems may not be possible, options for individual heating are explored. Less detailed mapping of heat demand in the towns of Khovd and Tsetserleg was also undertaken, but a detailed energy analysis was not possible due to limited availability of data.

The SHP applies the concepts of "energy efficiency first", smart energy systems and fourth-generation district heating. This means that energy efficiency has a significant role, and integration with renewable electricity generation and more efficient district heating systems have an important role too.

The SHP for Mongolia creates a model that spatially maps the heat demand in buildings. The reason to focus on the spatial aspects is that the density of heat demand is crucial in determining the feasibility of developing new - or expanding existing - district heating networks. Highly dense areas in terms of heat demand, such as built-up urban areas, are relevant for district heating, while in rural areas with low-density heat demand, supply of district energy is more costly. Heat demand in new buildings has also been estimated based on the projected population increase and the subsequent need for more buildings. Energy efficiency measures were considered for existing buildings, reducing the demand for heating by approximately 47% compared to the status quo. Regarding renewable energy sources for district heating, the assessment focuses on geothermal, solar, wind and energy from waste incineration.

A comparative heating system assessment was conducted for Ulaanbaatar as the major city and an exemplary case study for heat demand in Mongolia. The assessment involved the formulation and evaluation of three cases: a Reference 2020 case, 2050 long-term case and 2030 short-term case. The Reference 2020 case was established to illustrate the current fossil fuel-based heat supply systems. The 2050 long-term case was formulated to include a Baseline fossil fuel-based system and a 100% Renewable system. From the long-term case, a 2030 short-term case was established through a backcasting approach, also consisting of a fossil-based system and a renewable-based system.

The formulation of the Renewable 2050 system considers several essential enabling interventions. Implementing energy efficiency measures in buildings is crucial, as it reduces the need for additional heat supply capacity. Not including the efficiency measures would keep the heat demand high and require a significant energy input to balance. Lowering the heat demand in buildings would also have further benefits for heat supply. For example, this would make it possible to achieve lower supply temperature in district heating systems, hence reducing heat losses and improving the efficiency of the supply side. It would also benefit renewable energy sources, such as low-temperature geothermal or solar thermal, which typically provide lower temperatures than the current district heat supply from fossil fuels. In the Renewable 2050 system, the district heating network is improved in two ways: firstly, by gradually replacing old pipes with more energy-efficient pre-insulated pipes, and secondly by lowering supply temperature levels below 100°C, both of which help to reduce heat losses from around 17-18% to around 8-10%.

As regards heat supply, the primary strategy is to incorporate more renewables directly into district heating networks. Geothermal heat could be used to provide baseload heat in the winter months when other renewable sources are insufficient. In areas where geothermal energy is unavailable, industrial waste heat or heat pumps can be applied as alternative solutions, even though there are significant uncertainties due to lack of detailed geothermal investigations in the country. Another important technology is solar thermal collectors, which contribute renewable heat directly to the district heating supply. Waste incineration is also added, as this technology can be used as a significant method of treating waste in the country whilst also providing energy.

In addition to direct heat application in district heating networks, renewable electricity supply - mainly in the form of wind and solar power - could be implemented by increasing the use of air–water heat pumps and direct electric boilers in the heat supply, both for individual heating and district heating. Heat storage is also essential, as it can be used to balance the temporal difference between heat demand and renewable heat generation.

The results of the case study on Ulaanbaatar show that in the 100% Renewable system of 2050, a feasible supply mix for district heating would consist of 23% energy from waste incineration, 3% geothermal heat, 3% solar thermal, 42% air–water heat pumps and 29% electric heat-only boilers (HOBs). Compared to the Reference 2020 system, the Renewable 2050 system achieves a reduction of 55% in primary energy use, while the Baseline 2050 fossil fuel-based system would increase primary energy use by 9%. The implementation of the Renewable systems would significantly reduce annual CO_2 emissions from 6.5 million tonnes (Mt) in 2020 to 3.7 Mt in 2030 to 0.5 Mt in 2050. Looking at annual air pollutant emissions (SO_2, NO_X, $PM_{2.5}$ and PM_{10}), the reduction is also significant, from 81 900 tonnes in 2020 to 2 500 tonnes in 2030 and 1 000 tonnes in 2050 with the renewable energy systems. However, it should be noted that in the baseline fossil fuel-based system, flue gas cleaning is also included, having a significant impact on the reduction of air pollutant emissions. The cost of the district heating systems in the considered cases of 2020, 2030 and 2050 is susceptible to CO_2 costs. If CO_2 costs are omitted, the Baseline 2050 fossil fuel-based system and Renewable 2050 system are both more costly than the Reference 2020 system, but very similar to each other in annual cost at around USD 800 million per year. When the CO_2 costs are included, the Reference 2020 has a cost of USD 1.631 billion per year, while the 2050 fossil fuel-based system increases the cost to USD 2.22 billion per year and the Renewable 2050 system is only USD 852 million per year.

In individual houses and the *Ger* areas, the supply of heat is changed from coal-based stoves and HOBs to a mix of direct electric heating, air–water heat pumps and ground-source heat pumps, supplemented by solar thermal and air-to-air heat pumps. Transitioning to these technologies is estimated to reduce annual CO_2 emissions from 2.98 Mt in 2020 to 1.54 Mt in 2030 and 0.5 Mt in 2050. Air pollutant emissions are also reduced by 41% from 71.9 kt in 2020 to 29.4 kt in 2030; and to zero in 2050. The investment cost to achieve this reduction would increase from USD 22.8 million in 2020 to USD 125.95 million in 2030 and USD 194.23 million in 2050. However, taking a system perspective of the whole individual heating sector, this would provide considerable cost savings due to a reduction in fuel purchases and emissions, reducing total annual system costs from USD 858 million per year in 2020 to USD 568 million per year in 2030 and USD 362 million per year in 2050.

The SHP proposes several technological solutions that can be summarised into the following focus areas in terms of technological solutions:

Figure 1 **General recommendations by technology focus**

Implement energy effciency measures in buildings	**Set high thermal performance standards for new buildings and refurbish existing ones to improve their energy performance**
Expand and improve district heating systems	**Expand coverage of district heating systems in dense areas and lower the supply temperature level**
Expand renewable energy capacities	**Expand renewable energy utilisation in district heating systems such as geothermal heat, solar thermal, waste incineration and industrial excess heat; as well as renewable electricity for heating based on wind and solar energy**
Use heat pumps and electric boilers outside of district heating coverage	**Use ground and air-source heat pumps supplemented by electric boilers**
Use heat storages	**Use daily and seasonal heat storages depending on heat sources to balance demand and generation of renewable heat**

In the SHP, implementation challenges for renewable systems have been identified and are summarised in Figure 2.

Figure 2 **Challenges for implementation of renewable energy in district heating systems**

General

- Emissions from heating, transportation and industry sectors cause significant air pollution
- Inaqeduate local policies and investments for supporting renewable energy and strong support for coal development
- Large energy subsidies on the coal-based energy system result in low energy taxation
- Low-income households may not afford the cost of decarbonising their heating system
- Limited assessment of renewable potential for district heating

Energy efficiency in buildings

- High heat demand due to inefficient and insufficient thermal insulation in the building stock
- Buildings do not use heat metering as a measure for their heat consumption and billing
- There is a lack of financial incentives for building developers for the refurbishment and construction of energy-efficient buildings

District heating

- Expansion of the current district heating systems is geographically limited by the proliferation of *Ger* areas
- Current low heat tariffs represent a threat to district energy infrastructure cost-recovery
- Lowering of supply temperatures in Ulaanbaatar district heating can be achieved only after buildings are renovated to improve their energy efficiency

***Ger* areas**

- Limited data on energy demand in the *Ger* areas
- Lack of spatial planning as rural-to-urban immigration develops
- Overlooked planning of potential renewable powered rural heating networks

One of the major challenges to the implementation of the energy transition in Mongolia's heating sector is the low price of coal, which hinders the financial feasibility of renewable energy options. This could be solved by including externalities such as air pollution and the emission of GHGs in the heat tariff in the form of taxation. The increasing population is leading to a rapid increase in heat demand, which adds pressure to build more heat supply plants. Here, it is important to ensure that new buildings are energy efficient, for example through building regulation measures. Low heating tariffs is a major barrier hindering the implementation of energy efficiency measures in existing buildings since the cost of building renovation may not be recovered through the associated energy savings. This could be solved by introducing an appropriate tariff scheme based on consumption billing, and one that reflects the cost of the heat production.

Regarding new renewable sources, further investigation into geothermal and excess heat sources would be worthwhile for the district heating sector, as there are limited detailed surveys on the potential of these sources. Figure 3 shows recommended measures that could be implemented to promote renewable energy deployment in Mongolia's heating systems under four categories: general, energy efficiency in buildings, district heating and *Ger* areas.

Figure 3 **Recommendations for implementation of renewable energy in district heating systems**

General

- Target **increased investment** in renewable energy development and the decarbonisation of the heating sector
- Develop **enabling regulations** for renewable technologies in the Mongolian context
- Set ambitious, specific **targets for coal phase-out** to meet the 2050 vision
- Undertake **assessment of renewable potential** (*e.g.* geothermal potential)

Energy efficiency in buildings

- Provide heating installations with **energy meters and heat cost allocators**
- Implement measuring instruments to **assess development of heat demand** in buildings
- Improve **thermal insulation** in buildings
- Revise **construction standards** for new building regulations regarding energy efficiency measures
- Introduce **energy performance certificates** for new and renovated buildings

District heating

- Introduce **renewable energy solutions** (including thermal storage) that supply domestic hot water
- Create **district heating investment plans** supported by regulation to upgrade, increase capacity, and maintain district heating systems
- **Structure heating tariffs** to be composed of both fixed and variable costs
- Create district heating cost-covering systems by revising heating tariffs and ownership models

***Ger* areas**

- Investigate **heat pump potential** for buildings in *Ger* areas
- Assess the electrification of heating supply in *Ger* tents and plan alongside electricity distribution grid reinforcements
- **Improve insulation** capacity in *Ger* tents where possible

Assessment of renewable energy potential for district heating, such as geothermal energy, and the establishment of enabling regulations and ambitious targets to phase out coal in the heating system could be implemented to promote renewable energy usage in Mongolia's heating system. Improving energy efficiency in buildings through retrofitting the building envelop of existing buildings would decrease primary energy demand in the heating sector and make it possible to deploy locally available low temperature renewable energy sources for heating. Furthermore, the implementation of consumption-based billing and energy metering in buildings would further promote efficiency in the utilisation of heat at the building level.

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Introduction

Mongolia has a geographic area of around 1.5 million km^2. According to the National Statistics Office of Mongolia, the total population is 3.4 million, of which 2.3 million live in urban areas and 1.6 million live in the capital city Ulaanbaatar (National Statistics Office of Mongolia, 2022a). Thus, Mongolia is amongst the countries with the lowest population density in the world at around two persons per square kilometre. However, the population is growing at around 50 000-60 000 persons per year, which is equal to an annual growth rate of about 1.9%. A large share of this growing population is in informal settlement areas, called *Ger* areas,[1] which account for around 58% of the total building stock of Ulaanbaatar and add to the urbanisation of the country (Davaanyam and Gantsetseg, 2020). According to the 2020 census (National Statistics Office of Mongolia, 2021a) the total number of households in Mongolia was 897 400, of which 60.9% were houses, 38.2% were *Gers* and 0.9% were other dwellings. Within the housing category, around 50% were apartment buildings and 50% detached houses.

Mongolia has a large variation in ambient temperature over the year. For example, in Ulaanbaatar the maximum temperature reaches 33°C to 38°C while the minimum temperature reaches -33°C to -37°C (National Statistics Office of Mongolia, 2022b). Furthermore, the heating season in Mongolia is about eight months in most places, setting high requirements for heat supply systems in the country, which need to supply heat for long periods due to low ambient temperatures.

1.1 The current heating situation in Mongolia

In general, energy supply in Mongolia is dominated by coal. Figure 4 shows the total primary energy supply from 2015 to 2021, showing that more than 883 petajoules (PJ) out of 1 064 PJ were from coal in 2021 (National Statistics Office of Mongolia, 2022c), equivalent to over 80% of the total primary energy supply. Most of the coal is produced domestically and approximately 180 PJ of coal energy is consumed in combined heat and power (CHP) plants. Most of the coal exports peaked in 2019 at around 1 040 PJ and dropped to 800 PJ in 2020 (BP, 2022). The heating sector is almost entirely based on coal, both in district heating supply and individual households.

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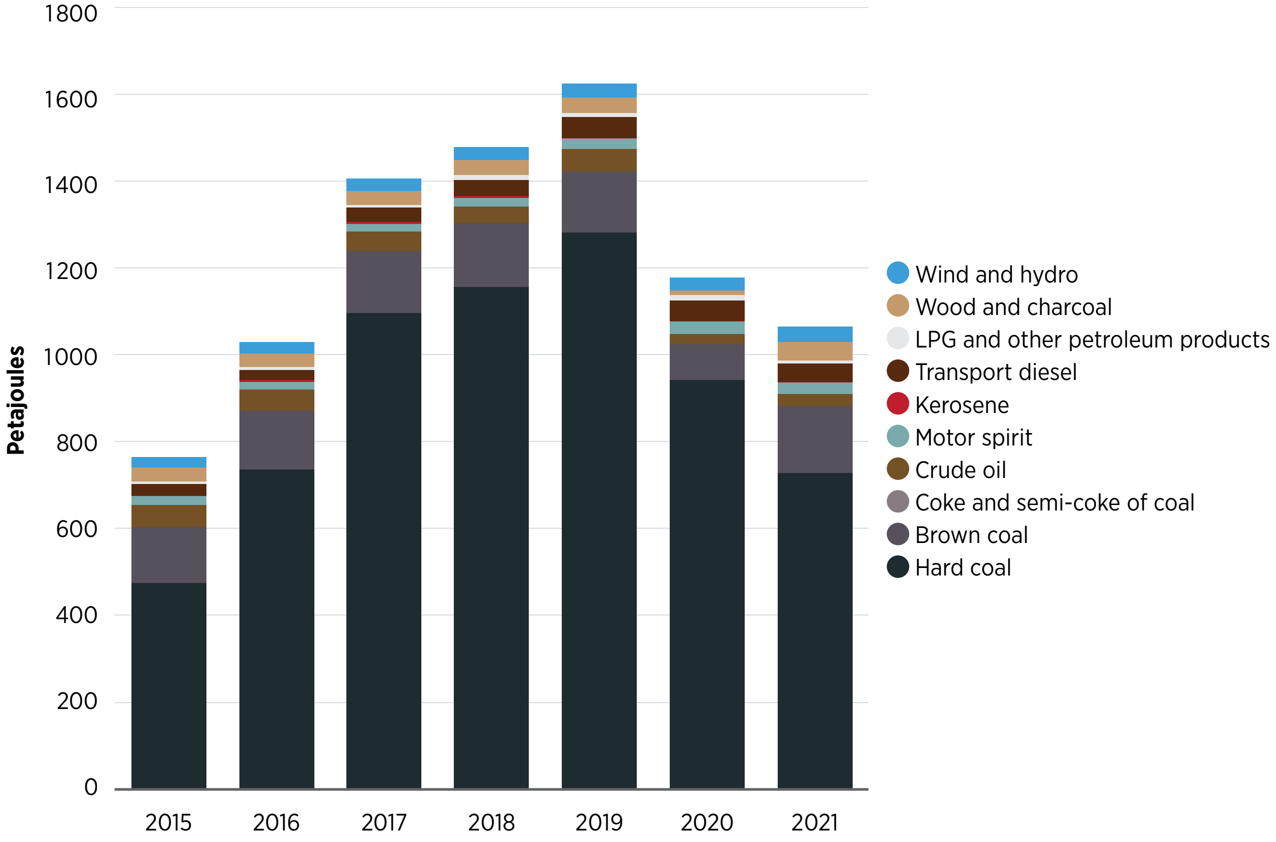
[1] The areas on the outskirts of Ulaanbaatar where the majority housing type is *Ger* tents. *Ger* tents are round, portable housing structures composed of a wooden frame with a felt covering, traditionally used by nomadic herders (Engel, 2015).

Figure 4 **Primary energy supply by source**



Source: National Statistics Office of Mongolia (2022c).

Note: LPG = liquefied petroleum gas

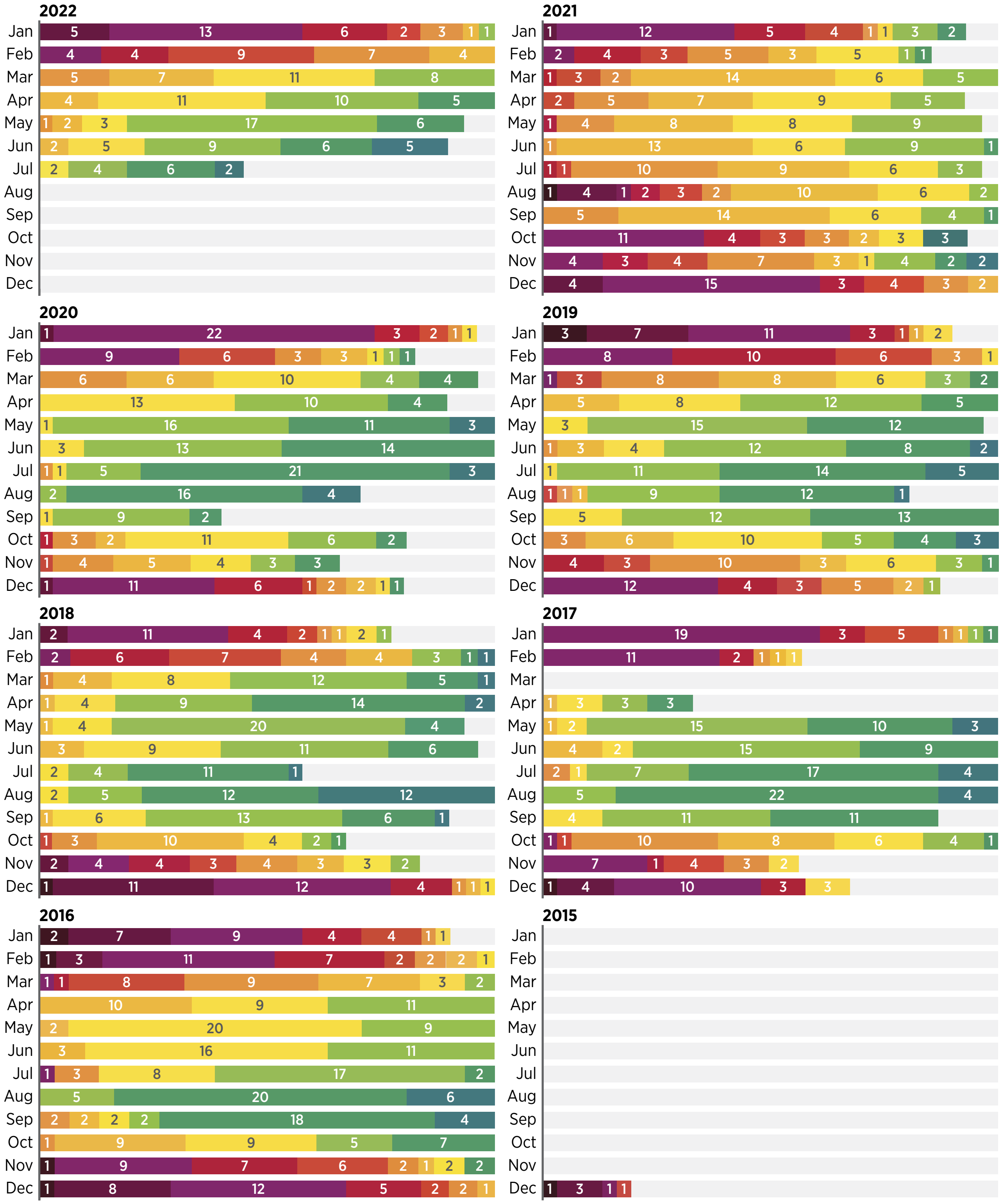
According to the 2020 census (National Statistics Office of Mongolia, 2021a), the heat supply technologies amongst households are distributed as follows, given as a percentage of households: 49.6% district heating, 41.3% fuel boiler heating, 7.1% low-pressure furnace and 2% electric heaters. The distribution varies between urban and rural areas, whereby the distribution for the two primary technologies is 57.5% district heating and 32.9% fuel boilers in urban areas, and for rural areas it is 12.2% district heating and 81% fuel boilers. Thus, it can be concluded that Mongolia has a relatively high share of district heating in urban areas, but still has the potential to expand it.

1.2 Main challenges and opportunities

1.2.1 Coal dependency

From an energy system perspective, Mongolia's primary energy supply is dominated by coal. Coal-fuelled CHP plants provide heat and generate electricity. The reliance on and availability of coal create critical challenges for advancing the country's efforts to reduce GHG emissions from the energy sector (Energy Sector Management Assistance Program, 2019). In addition, extreme air pollution levels are evident due to these heating systems' emissions, which contribute about 80% of the country's accounted air pollution. This condition is worsened by the geographic conditions in certain cities, such as the case of Ulaanbaatar and its temperature inversion layer (Batmunkh and Sato, 2014). During the winter of 2015 - 20, the average concentration of the three major sources of air pollution - $PM_{2.5}$, PM_{10} and SO_2, was up to 10 times higher than the limits recommended by the World Health Organization (WHO) (Asian Development Bank, 2021). Since the National Programme for Reducing Air and Environmental Pollution 2017–2025 has been implemented, the $PM_{2.5}$ concentration fell by 51% in 2019 - 2020 compared to the level in 2016 - 2020. Figure 5 shows the Air Quality Index (AQI) level for $PM_{2.5}$ in Ulaanbaatar; it is clear that many days are still at unhealthy, very unhealthy or hazardous levels in the Winter. For example, around 85 days were in these three categories from October 2021 to March 2022.

Figure 5 Days at AQI levels for $PM_{2.5}$ in Ulaanbaatar (US Embassy) in the period December 2015 to July 2022



AQI	0-50	51-100	101-150	151-200	201-300	300+
Air pollution level	Good	Moderate	Unhealthy for sensitive groups	Unhealthy	Very unhealthy	Hazardous

Source: World Air Quality Index (2022).

1.2.2 Energy systems with low energy efficiency

Three coal-fired CHP plants and about 100 heat-only boilers (HOBs) supply the existing district heating system, accounting for 98% of the district heat supply. These plants were commissioned in 1983 or earlier. In addition, a 348 MW_{th} HOB named Amgalan was commissioned in 2015.

Most of the district heat in *aimag*[2] and *soum*[3] centres is consumed by public organisations (schools, hospitals, kindergartens, *etc.*). These public organisations constitute around 70-80% of the total consumption in *aimag* centres and 95% of the total consumption in *soum* centres (Namkhainyam *et al.*, 2019a).

The energy efficiency of Mongolia's existing buildings and its district heating infrastructure need attention. Heat losses in the Ulaanbaatar district heating network are around 17%, which is relatively high compared to similar cities, which stand at around 6-9%. This results in factors, such as high heating demands, that require high supply temperatures due to poor insulation of buildings and district heating pipes. In recent years, many of the pipes in the Ulaanbaatar district heating system have been replaced, but still around 25% are from before 2000. The temperature level of the system is also relatively high, with a supply temperature of around 130°C, due to high temperature requirements in individual buildings.

The energy and building sectors, and their related infrastructure, are priority areas for Ulaanbaatar's Green City Action Plan (Municipality of Ulaanbaatar, 2019). The action plan acknowledges the challenge of a lack of financial resources slowing renovation activity, especially in *Ger* areas. In terms of energy, it considers that renewable energy promotion is on track, but energy efficiency in buildings in the Ulaanbaatar district heating area is a challenge, especially retrofitting pre-cast concrete panel apartments. Furthermore, there is a need for long-term investment planning strategies to increase energy efficiency in buildings and in the Ulaanbaatar district heating network (Energy Sector Management Assistance Program, 2019).

1.2.3 Large potential for renewable energy

Mongolia has enormous potential for renewable energy generation due to its rich geological history. Its energy system currently has 4.2% renewable penetration, but the potential to expand is significant. Its wind resource has been estimated at up to 1.1 terawatt electrical (TWe) with an electricity output of 2 550 terawatt hours (TWh) per year (Chen *et al.*, 2016).

Its solar potential has been estimated at 4 774 TWh/year based on a land area of 23 461 km^2 (Chen *et al.*, 2016). Mongolia has 270-300 sunny days a year, with an average sunlight duration of 2 250-3 300 hours available in most of its territories. Mongolia's annual average solar energy is 1 400 kilowatt hours per square metre (kWh/m^2) per year, with a solar intensity of 4.3-4.7 kWh/m^2/day.

As regards geothermal potential estimates, limited data are available in the form of underground temperature maps and site measurements (Namkhainyam *et al.*, 2019a). While this has not been comprehensively quantified, Mongolia has a significant geothermal potential characterised by the occurrence of hot springs in several parts of the country (Chen *et al.*, 2016). Around 43 potential geothermal areas are already exploited for heating, bathing and medicinal purposes in the country.

Figure 6 shows that the Uvurkhangai, Tuv and Ulaanbaatar areas are being considered for geothermal district heating. These areas have hot springs with relatively high temperatures and flow rates, and some are already being used to heat buildings and greenhouses. The four hot springs closest to Ulaanbaatar are estimated to have heating potential of 2.7 MW_{th} (Tseesuren, 2001).

Some pre-feasibility studies have already been conducted in areas with the most significant geothermal potential, such as in Tsetserleg, where a geothermal CHP plant with a capacity of 19MWe and 16.7 MW_{th} is envisaged, and exceeds the town's energy demand (Dorj, 2015). However, the potential for deep geothermal energy has not been assessed. Its potential for hydropower has been estimated to be 1.2-3.8 TWe. In relation to heating, there could be potential for biomass from forests in northern Mongolia and excess heat from industry, neither of which has been assessed in detail.

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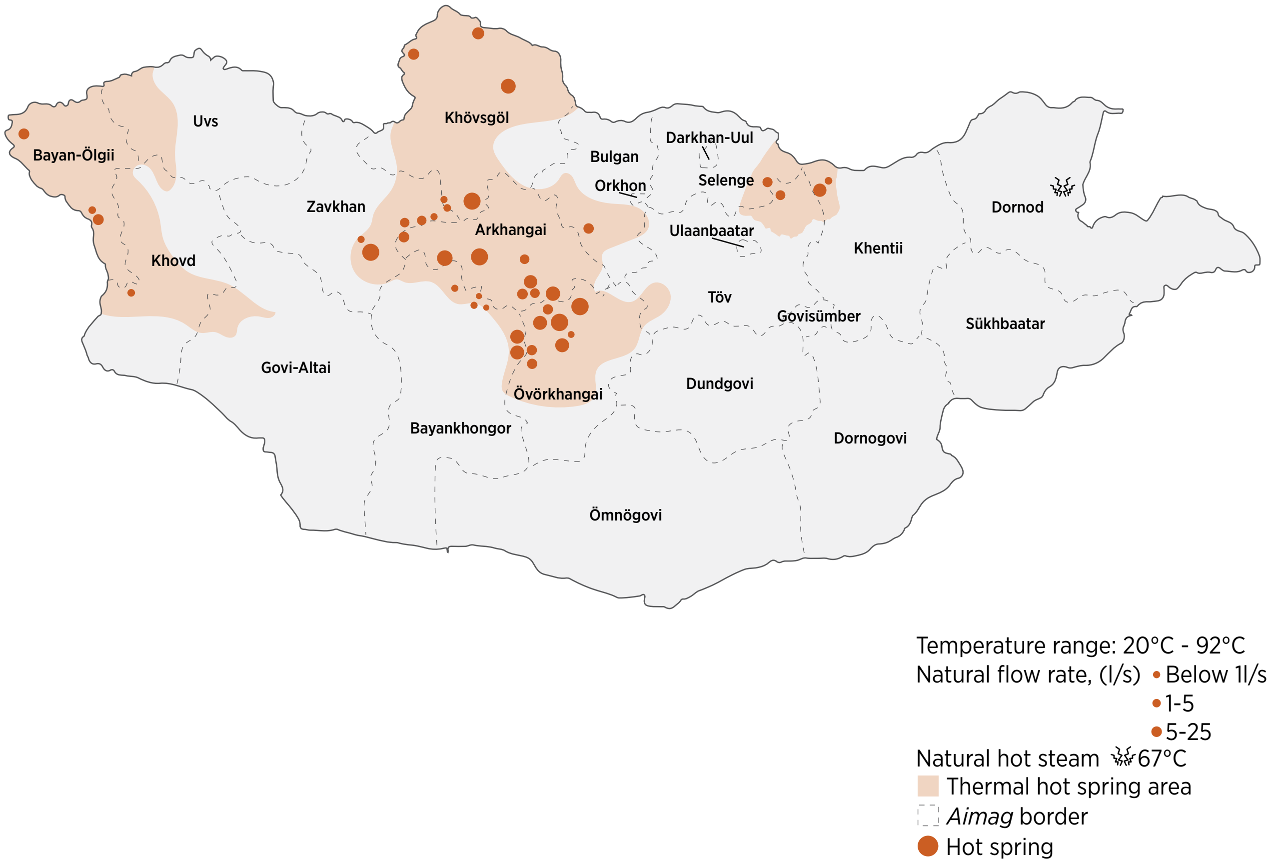
[2] The first-level administrative subdivision. Mongolia has 21 *aimags*.
[3] The second-level administrative subdivision. Mongolia has 331 *soums*.

Figure 6 **Map of geothermal hot springs in Mongolia**



Source: Tseesuren (2001).

Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply any endorsement or acceptance by IRENA.

1.2.4 Economic situation

Mongolia's economic situation has improved in recent years and since 2007 it has been classified as a lower middle-income country (Municipality of Ulaanbaatar, 2019). In 2011, Mongolia was one of the world's fastest-growing economies (Chatterjee and Baitha, 2022). Its GDP per capita increased from USD 1718 in 2009 to USD 4 040 in 2020 (World Bank, 2021). Development is noticeable in monthly average wages and salaries, which increased from USD 300 in 2009 to USD 1 220 in 2020 (National Statistics Office of Mongolia, 2022a). Furthermore, the average unemployment rate fell from 11.6% in 2009 to 7% in 2020, albeit slightly higher in urban areas at 8% in 2020 (National Statistics Office of Mongolia, 2021b). However, even with these significant improvements, the United Nations Development Programme (UNDP) still estimated in its *Human Development Report 2020* that 7.3% of the population are multi-dimensionally poor, while an additional 15.5% are vulnerable to being multi-dimensionally poor (United Nations Development Programme, 2020). The *Multi-dimensional Poverty Index* was introduced in 2010 and includes factors such as health, education and standard of living. Affordability is a serious issue considering Mongolia's average household income and living standards. The proportion of the population living below the national poverty line (USD 66.4 per month in 2018) increased in the last decade by about 6 percentage points, from 21.6% in 2011 to 27.8% in 2020, with rural areas around 3% poorer than the urban ones (National Statistics Office of Mongolia, 2021c). Energy poverty is especially evident in *Ger* areas and is the key challenge to developing renewable energy technologies at the household level. Mongolia is heavily dependent on the export of natural resources, especially coal, gold and copper, and the mining sector is the dominant economic sector in the country (Chatterjee and Baitha, 2022).

1.3 Climate targets

The climate mitigation target of Mongolia's Nationally Determined Contribution (NDC) is a 22.7% reduction in total national GHG emissions by 2030, compared to the projected emissions under a business-as-usual scenario for 2010. In addition, if conditional mitigation measures such as carbon capture and storage (CCS) and waste-to-energy technologies are implemented, then Mongolia could achieve a 27.2% reduction in total national GHG emissions. Alongside that, actions and measures to remove GHG by forests have been determined, setting the full mitigation target of Mongolia as a 44.9% reduction in GHG emission by 2030 compared to a 2010 business-as-usual scenario (Mongolian Government, 2019).

The Mongolian government set a target of 20% renewable share in the total energy production in 2020 and a 30% target for 2030 (Global Green Growth Institute, 2015). There is no specific target for 2050, but the government's Vision 2050 aims to increase sustainable production and smart consumption, implement climate mitigation measures, and enhance forest absorption of GHGs (Cabinet Secretariat of Government of Mongolia, 2020; United Nations Environment Programme & Ministry of Environment and Tourism Mongolia, 2021). These visions indicate that Mongolia aims to increase the deployment of renewables further than the 2030 goal. The new 2050 revival policy from 2021 includes expanding fossil and renewable production capacity and the construction of a natural gas pipeline from the Russian Federation to China through Mongolia (Congress of Mongolia, 2021). In 2019 the government banned the burning of raw coal[4] in Ulaanbaatar and has committed itself to reducing air pollution in Ulaanbaatar by 80% compared to the baseline year 2016 (Asian Development Bank, 2021). This reduction follows the National Programme for Reducing Air and Environmental Pollution target for 2025. Although the raw coal ban measure reduced daily $PM_{2.5}$ and PM_{10} mean concentrations by 40% during the heating season, the concentrations are still well above WHO standards for air quality (Soyol-Erdene, Ganbat and Baldorj, 2021). The city's air quality challenges concern GHGs such as SO_2, NO_2, O_3 and CO, which are monitored across the air quality monitoring network that reports to the Air Pollution Reduction Department of Ulaanbaatar municipality (Soyol-Erdene, Ganbat and Baldorj, 2021).

Other Mongolian energy efficiency targets are summarised in an action plan consisting of several objectives aimed at supporting green development. For the objective targeting the efficient use of natural resources while lowering GHGs emissions, the government targets are to reduce building heat loss by 20% in 2020 and by 40% in 2030 compared to 2013 (United Nations Environment Programme & Ministry of Environment and Tourism Mongolia, 2021).

1.4 Need for a strategic heat plan

Mongolia faces challenges related to coal dependency, an increasing population, high air pollution and high energy consumption in buildings. The country, however, also has large potential for renewable energy and ambitions to both increase renewables and reduce emissions; but to reach such targets, a broad analysis of the technological potential within the heating sector is needed, both in terms of supply and demand options. The concept of a strategic heating plan is therefore introduced and defined in Section 2.

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[4] Unprocessed coal extracted from a mine and yet to be put through washing processes. Raw coal is characterised by higher emission factors and decreased thermal efficiency when compared to processed types of coal, *e.g.* coal briquettes.

2

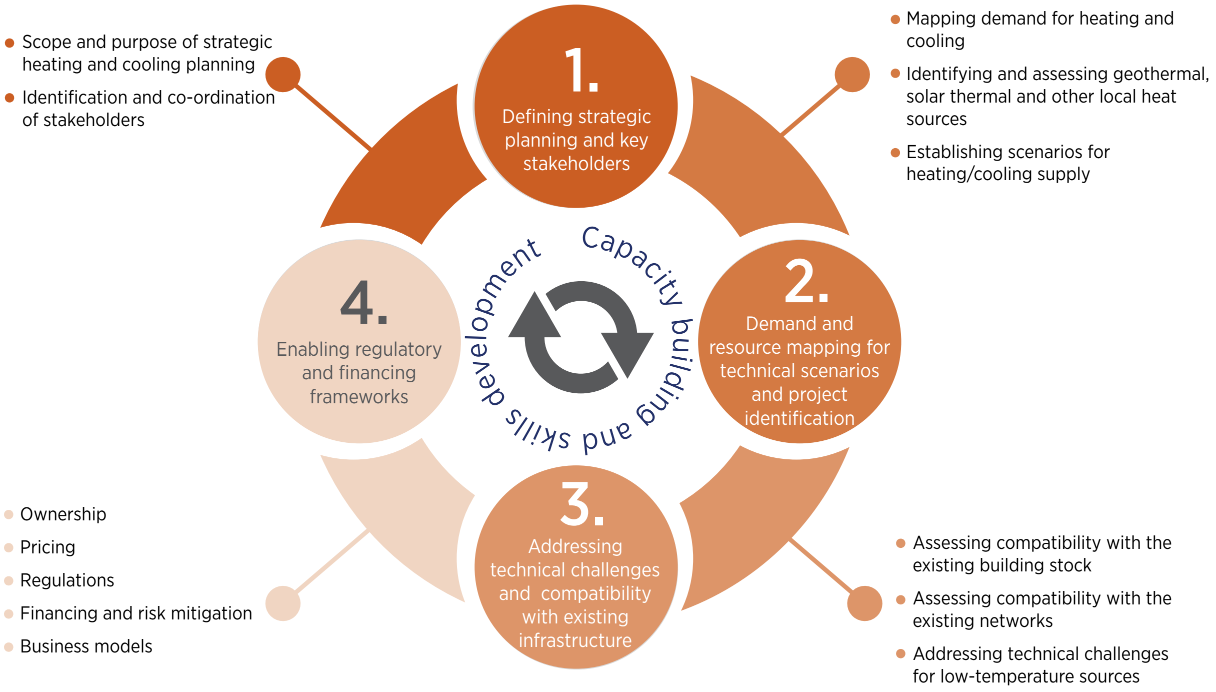
Strategic heating plan scope and methodology

This section defines and contextualises strategic heat planning for the Mongolian sustainable energy transition. It does this first by defining general aspects of strategic energy planning, smart energy systems and fourth-generation district heating; secondly by explaining the structure of the strategic heating plan (SHP), including its scope; and thirdly by detailing the applied methodologies.

2.1 Defining strategic heat planning in general

The purpose of an SHP for Mongolia is to support the decarbonisation of its heating sector. In general, scenario analysis is applied, investigating the various technological options within the heating sector and examining the technical and regulatory barriers to the options. The options include aspects of the whole energy chain, from renewable supply to energy efficient heating supply systems and energy-efficient buildings. In general, the SHP follows the four steps presented in Figure 7, based on the IRENA and Aalborg University report on integrating low-temperature renewables into district energy systems (IRENA and Aalborg University, 2021).

Figure 7 **Schematic framework of a SHP**



Source: IRENA and Aalborg University (2021).

In this SHP the focus is primarily on Step 2 - demand and resource mapping and modelling technical scenarios for renewable energy solutions in Mongolia. Chapter 5 is dedicated to addressing Steps 3 and 4, *i.e.* providing solutions to address the technical challenges and proposing the development of appropriate enabling frameworks, respectively. Step 1 (defining strategic planning and identification of key stakeholders) has been undertaken outside the scope of this report.

Case studies: SHPs in Denmark and Chile

SHPs can be carried out at different levels. Here we present two examples, the first is Aalborg Municipality the second is a national SHP for Chile.

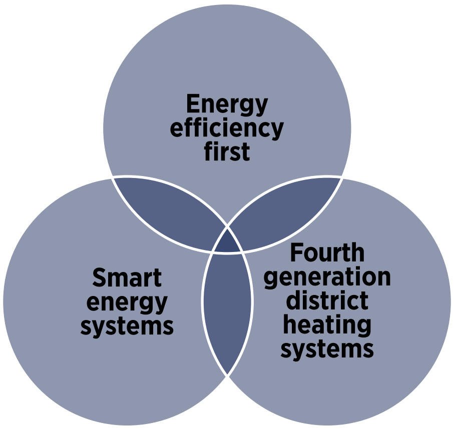
Aalborg Municipality is a Danish city with around 200 000 inhabitants. The city has worked since the early 1990s to reduce GHG emissions from its energy supply. The Aalborg Energy Vision 2050 is a long-term and strategic energy plan (including heating), which aims for the city to be fossil-free by 2050 at the latest. The current heat supply for Aalborg's district heating system is largely based on a coal CHP plant, but the plan is to phase out coal. The energy vision is based on the assumption that Aalborg will be independent of fossil fuels and will instead rely 100% on local renewable energy sources by 2050. Implementation requires a shift towards a coherent integrated energy system where the various technologies work together across supply types. The vision covers all energy-related sectors. It includes a future district heat supply based on various renewable and sustainable energy sources, including excess industrial heat, solar thermal, energy from waste incineration, heat pumps and geothermal energy (Lund *et al.*, 2019; Nielsen *et al.*, 2020).

The second example is the Heat Roadmap Chile case, which was created for a sustainable transition to green infrastructure in the Chilean context. Air pollution is one of the primary stresses in the current system, due to a predominant reliance on non-sustainable, inefficient and highly polluting biomass in the Chilean heating system. The roadmap includes novel practices for the Chilean context and showcases methodologies for pathway analysis and modelling current and future energy systems. The methodology combines local geographical analysis for the built infrastructure, potential savings from energy efficiency measures, and detailed all-sector hourly energy system analysis. The entire national energy system model allows for a 2050 scenario using proven and market-available technologies. By using this methodology, the roadmap showcases the tools available for energy system analysis and long-term planning, especially focusing on decarbonisation and pollution minimisation in the heating sector. The roadmap suggests widespread district heating using excess heat, energy efficiency measures and renewable sources to power heating systems. The study concludes that a 40% market uptake of district heating could reduce 99% of particulate matter pollution compared to current levels and potentially save almost USD 2.5 billion in public health costs. Moreover, district heating can securely and efficiently supply the heating sector while aiding sector coupling within the entire Chilean energy system (Paardekooper *et al.*, 2020).

Historically, different energy sectors have been planned and developed separately, *e.g.* electricity supply plans and heat supply plans. However, it is important to consider the synergies between the different sectors to find the best solutions for future decarbonised energy systems. In this SHP, the focus is mainly the heating sector; however, the integration of more renewables into the electricity system is also included, as the link between these two sectors will be strong in a future energy system where electrification of heating is a main factor in implementing the move to renewable energy sources.

Figure 8 presents three topics that will be the cornerstones in the cases presented in this report.

Figure 8 **Three critical aspects of this SHP**



The first topic is smart energy systems (SES), which have the following definition:

> ***"Smart energy systems are defined as an approach in which smart electricity, thermal, and gas grids are combined and co-ordinated to identify synergies between them to achieve an optimal solution for each individual sector and the overall energy system."***
>
> (Lund, 2014)

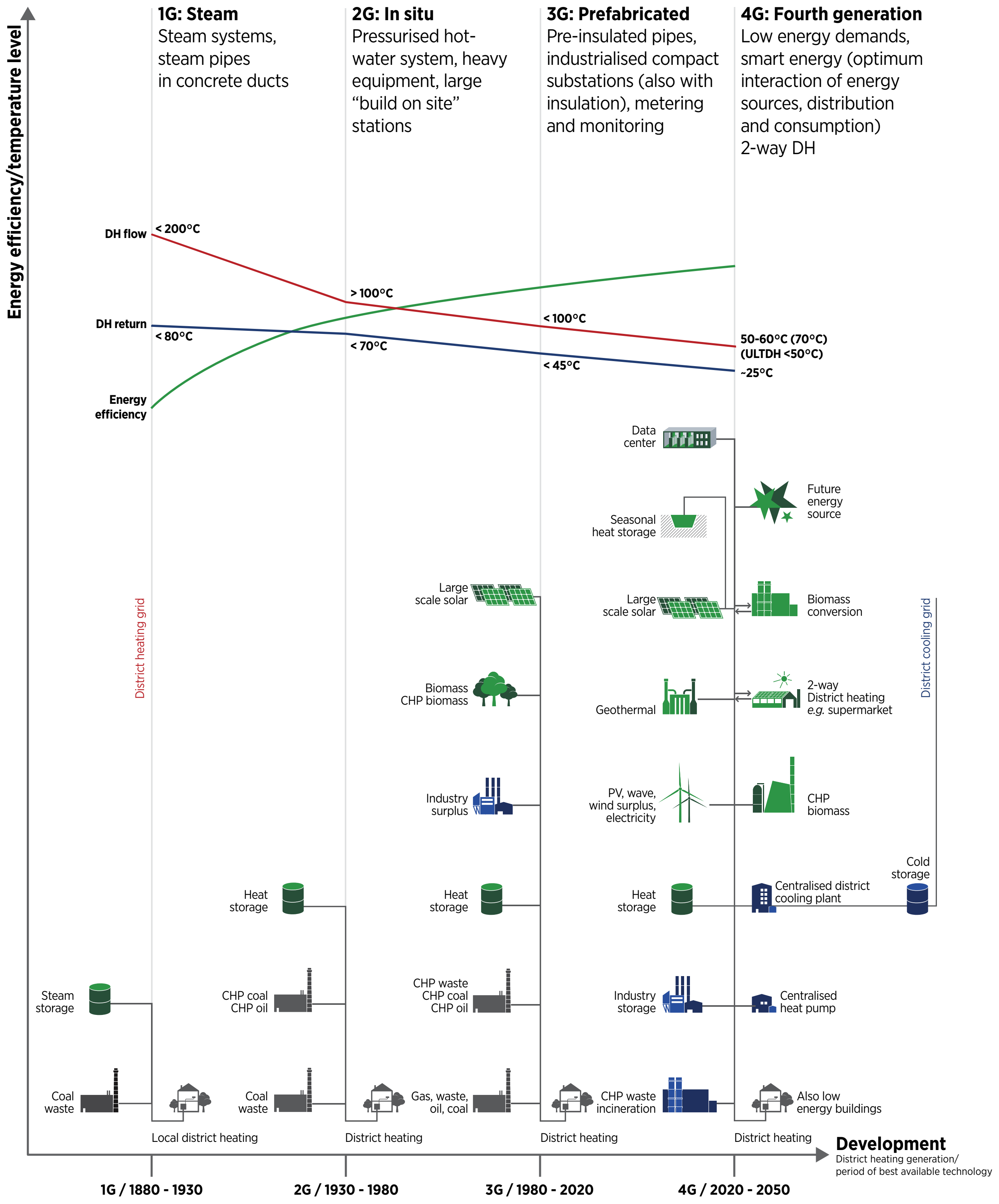
The concept of SES is essential for identifying the best solutions for the heating sector in Mongolia while also contributing to its national renewable targets. The solutions can be co ordinated using the SES approach and benefit both the heating sector and the whole energy system. Examples of such benefits are using heat storage, which is cheaper and more efficient than electricity storage. The heating sector can also be used to balance electricity markets by converting some of the excess electricity produced from renewable sources into heat when the production of renewables is high. Energy efficiency improvements in buildings enable lower temperatures in the district heating supply, which allow better use of surplus industrial heat. Thus, district heating is an integral part of the SES concept.

In future SES, while district heating has an important role to play, it needs to change to be competitive with other technologies. Figure 9 presents the concept of fourth-generation district heating, showing the general evolution of district heating systems from the first-generation systems to the modern fourth-generation systems. Fourth-generation district heating systems are defined as follows:

> ***"The 4th Generation District Heating (4GDH) system [is] defined as a coherent technological and institutional concept, which by means of smart thermal grids assists the appropriate development of sustainable energy systems. 4GDH systems provide the heat supply of low-energy buildings with low grid losses in a way in which the use of low-temperature heat sources is integrated with the operation of smart energy systems. The concept involves the development of an institutional and organisational framework to facilitate suitable cost and motivation structures."***
>
> (Lund *et al.*, 2014)

The common trend is that energy efficiency increases from generation to generation, owing to the use of more modern techniques in each part of the system. Supply temperatures are reduced significantly from steam-based systems to high-temperature water systems, towards ultra-low temperature systems where the supply temperature level is close to the actual temperature requirement in the buildings. The low supply temperatures result in a reduction in heat losses from the district heating network, increases in heat supply efficiency, and greater reliability and stability of the system. Furthermore, they also enable the use of multiple heat sources that are not feasible in systems requiring high supply temperatures. Lowering the supply temperatures also increases the efficiency of CHP plants and heat pumps, particularly the utilisation of lower-temperature heat sources and ambient heat sources using heat pumps.

Figure 9 **The concept of fourth-generation district heating**



Source: Lund *et al.* (2021).

Notes: DH = district heating; CHP = combined heat and power; ULTDH = ultra-low temperature district heating.

In Mongolia district heating systems can be classified as second-generation, all being coal-based boilers or CHP plants with relatively high temperatures and relatively significant heat losses from the networks.

The final topic is energy efficiency and the “energy efficiency first” principle, which is defined as:

> ***“‘Energy efficiency first’ means taking utmost account in energy planning, and in policy and investment decisions, of alternative cost-efficient energy efficiency measures to make energy demand and energy supply more efficient [...]”***
>
> (European Commission, 2018)

The energy efficiency first principle signals that it is essential to consider energy efficiency as part of planning future energy systems, as it affects the whole energy chain and will give more cost-efficient solutions over time. The energy renovation of buildings exemplifies the principle. Energy renovations directly reduce the heat demand of a building, and thus reduce the energy used to produce the heat. However, in the long term they will also reduce heat supply capacity, as energy renovations reduce the peak heat demand of the building. In a district heating area, the energy renovation of buildings has the same impact by reducing the need for heat supply and additional heat production capacity. But it also enables a reduction in the temperature of the heat grid. If the building is supplied by electricity, *e.g.* via heat pumps, energy renovation will reduce the need for electricity grid investment as well as additional electricity production capacity. The latter is very important in SES, as it will affect the need for investment in renewable capacity.

2.2 Scope of the plan

The scope of the SHP for Mongolia is to examine how the country’s heating sector, in socio-economic feasibility terms, can be modernised to fulfil the 2030 decarbonisation targets and reduce the problems with local pollution in cities, and in the long term achieve a renewable energy system by 2050. The plan achieves this by examining the country’s current and expected heating situation, and the potential for renewable energy supply and energy system efficiency improvement, both in the supply systems and the buildings.

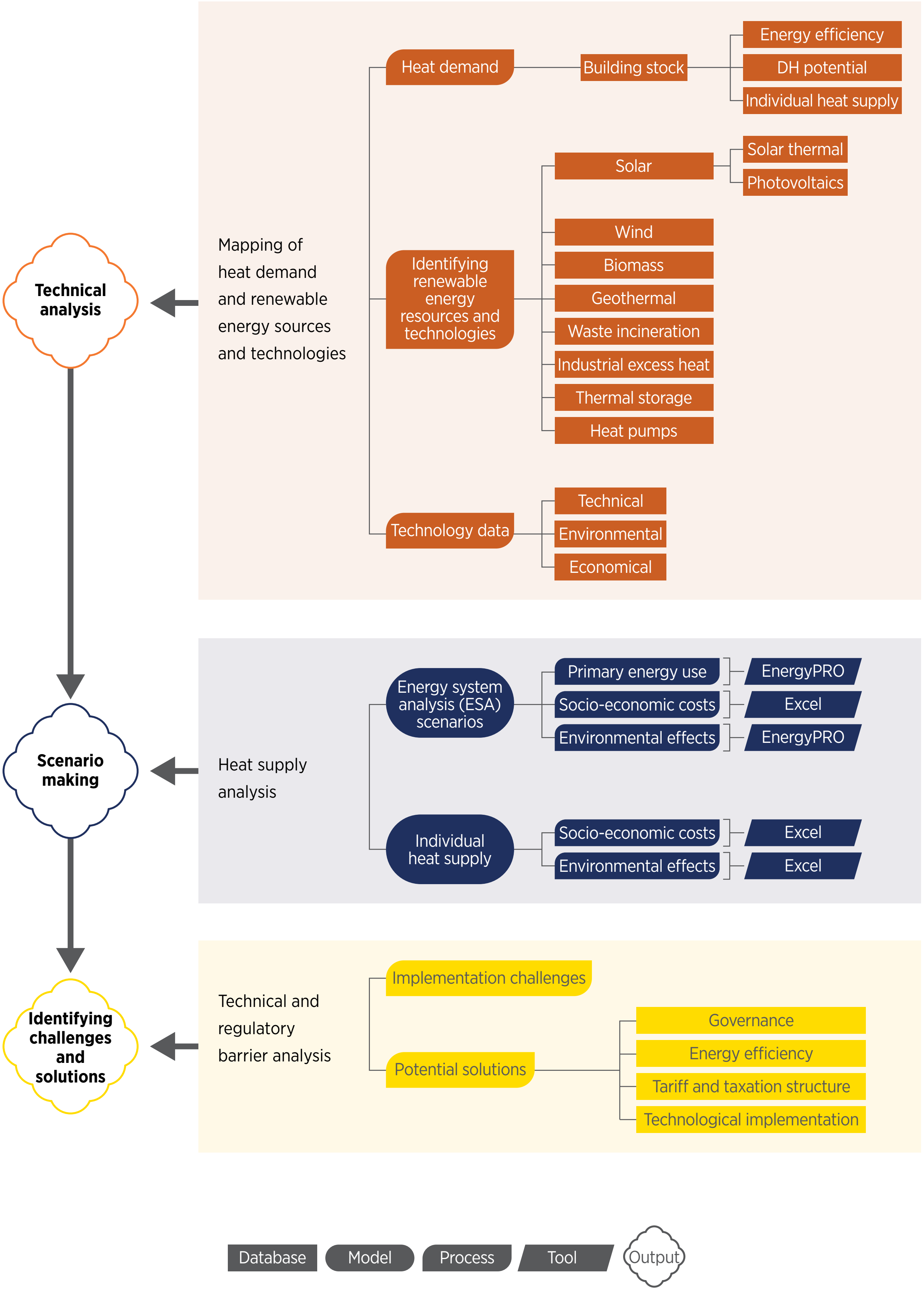
2.3 Methodology

This methodology section is divided into the overall methodology; the Ulaanbaatar case study and assessed cases; the spatial heat demand assessment model; demand projections; energy efficiency in the district heating systems; and background information on the technological data and costs used in the energy system analysis of both district and individual heating systems.

2.3.1 Overall methodology

Figure 10 illustrates the overall methodology and the connections between each part. The whole methodology can be split into three main parts, which are the mapping of heat demand and renewable energy sources and technologies; the energy system analysis; and the technical and regulatory barrier analysis. Each of the parts provides information which serves as input for the next step of the analysis. The mapping of heat demand and renewable energy sources serves as the basis of the energy system analysis, which then serves as the basis for evaluating the barriers.

Figure 10 Overall methodology for developing SHP



The section on mapping heat demand and renewable energy sources and technologies is the first to feed into the process. This section relies heavily on the geographical dimension of the study where building stocks are assessed for estimation of further heating demand. The demand is then split into district heating potential and individual heat supply with and without energy efficiency measures. This assessment is made for existing as well for new buildings. Various sources are used for the identification of renewable resources and technologies; their potential with their respective technical, economic, and environmental parameters is linked directly to the heat supply analysis.

The second part goes into the scenario making, where the output from the mapping section is used in a detailed heat supply analysis. The analysis is divided into an energy system analysis of the district heating system and an analysis of the individual supply outside district heating areas. The results of this part are the primary energy use, socio-economic costs and environmental effects of the transition to a renewable heat supply by 2050.

The third part deals with the analysis of technical and regulatory barriers related to the transition towards a 100% renewable heating system. This part is more general and is mainly based on literature review and inputs from workshops.

The rest of this section describes in detail the methodologies for mapping heat demand and renewable energy sources and technologies, as well as heat supply analysis. An additional general disclosure on the geographic information system (GIS) methodology is presented in Appendix A as a guide to the reader for its usage and conception.

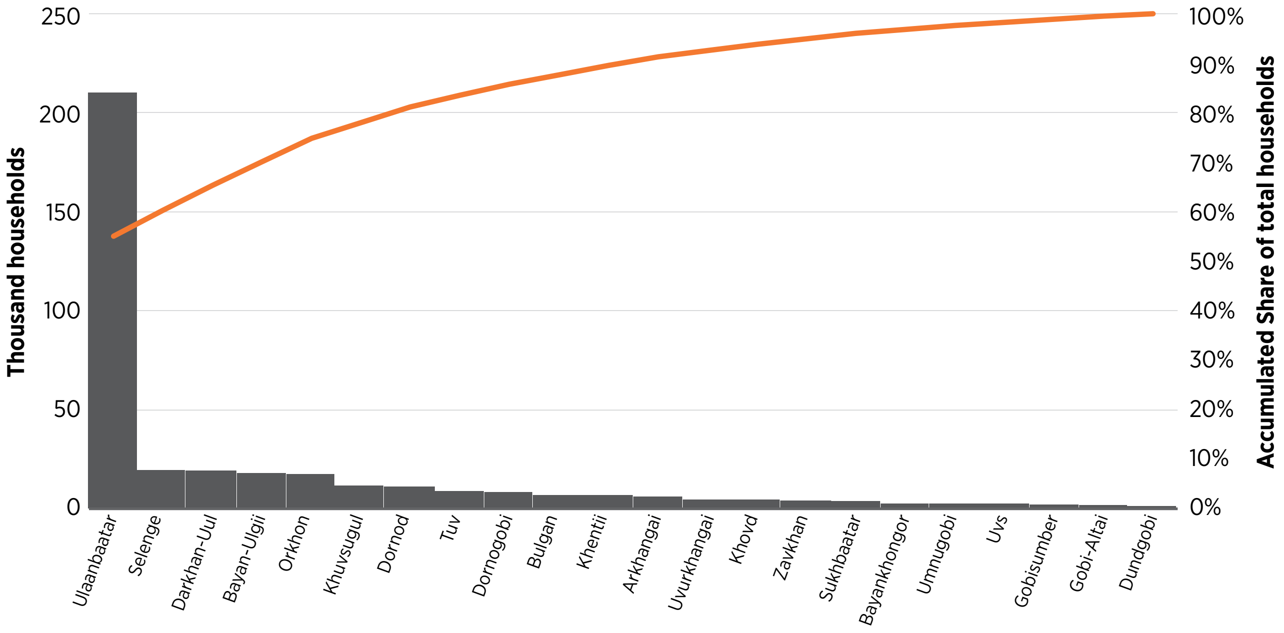
2.3.2 Ulaanbaatar as an exemplary case

Climatic conditions differ widely between regions in Mongolia. They directly influence heating demands and renewable energy potential, where colder regions have higher heat demands and sunny regions have high solar thermal potential. Therefore, in terms of geographical coverage, this SHP is divided into two main parts:

1. An exemplary case of a detailed energy system analysis of Ulaanbaatar, where the different relevant renewable technologies are implemented. Two less detailed cases showcasing solar thermal and geothermal potential in local district heating systems are also assessed.
2. A mapping of renewable energy potential related to the heating sector in Mongolia with a general scope.

Figure 11 shows the distribution of households among different regions. From the graph it is evident that around 55% of all the households in Mongolia are in Ulaanbaatar, while the other regions are all below 10% each. As such a large share of the buildings are situated in the capital, this is where the SHP will have its primary focus.

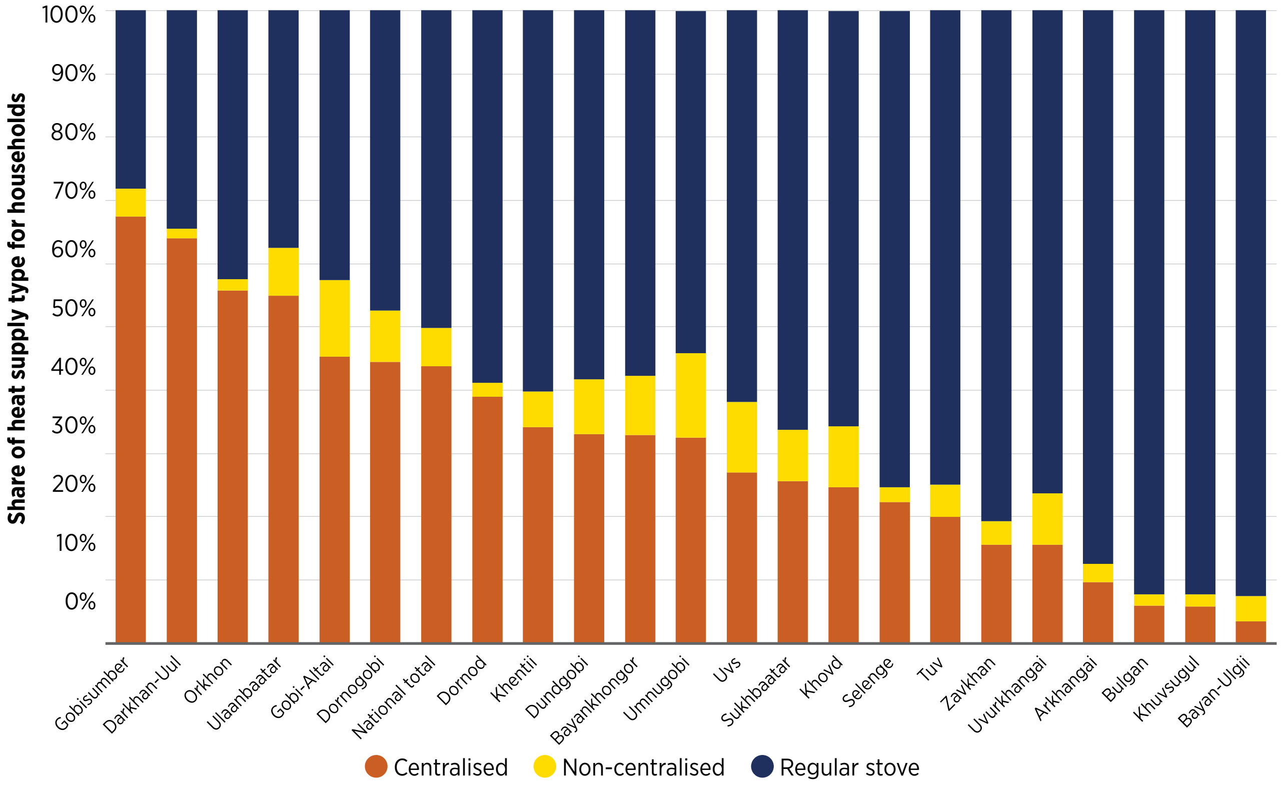
Figure 11 **Number of households in Mongolia by region in descending order from the most to the least**



Source: National Statistics Office of Mongolia (2011).

Even though the focus is mainly on Ulaanbaatar, most of the learnings from the detailed energy system analysis will be applicable to other parts of Mongolia as well. Figure 12 shows the share of households with either centralised, non-centralised (low-pressure stove or electric heating) or regular stoves (fuel boilers) as their heat supply. It is evident that district heating has a larger role in some regions, while other regions have very little. Some of the regions with highest district heating share are also some of those with the fewest households, *e.g.* Gobisumber and Gobi-Altai, which shows why heat density is an important aspect to include when estimating district heating potential and seeking the greatest impact.

Figure 12 **Share of heat supply type by region**



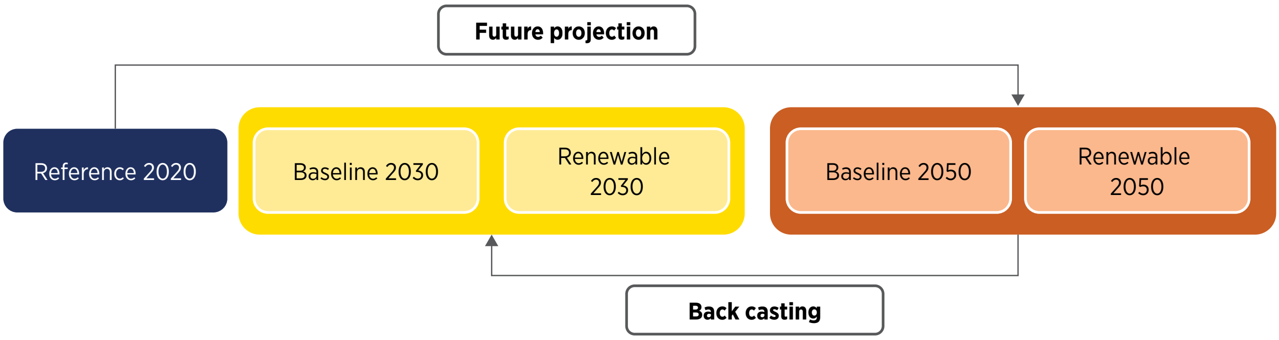
Source: National Statistics Office of Mongolia (2011).

2.3.3 Presentation of assessed cases

As part of the energy system analysis for Ulaanbaatar, this SHP developed a reference 2020 case as well as cases for both short-term and long-term timeframes; the 2030 short-term case and the 2050 long-term case. The 2050 case consists of a fossil fuel baseline system and a 100% renewable heating system. The focus is mostly on identifying challenges for shifting the Mongolian heating sector from a fossil-based system to a 100% renewable one. The 2030 case is a backcast of the 2050 case to serve as a short-term time step. The Renewable 2050 heating system does not aim to predict how the Mongolian heating sector will evolve, but rather serves as a benchmark for comparison with a coal-based baseline to 2050. The Baseline 2050 (coal-based) heating system and renewable 2050 are developed only for Ulaanbaatar.

Figure 13 provides an illustration of the different assessed cases. These cases are briefly discussed in the following sub-sections, while the results are further expanded in Section 4.

Figure 13 Assessed cases simulated for Ulaanbaatar in the energy system analysis



Reference 2020 case

The Reference 2020 case represents the existing heating structure in Mongolia. Heat demand is split into district heat demand and individual household demand. District heat demand includes space heating and hot water demand in buildings and spatial heat demand by industry. Individual heat demand includes heat demand for detached single family homes and tents in the *Ger* areas.

Long-term 2050 cases

For the analysis behind the 2050 case, two 2050 heating systems are modelled: a baseline fossil fuel-based system and a 100% renewable-based system. The Baseline 2050 system is a projection of the current coal-based heating system to 2050. The Renewable 2050 system is a 100% renewables-based system using a mix of renewable energy technologies, such as geothermal, solar thermal, large-scale heat pumps and waste incineration. The results are then compared for both systems regarding annual system costs, primary energy supply, GHG and particulate matter emissions.

Short-term 2030 case

Once the long-term 2050 case is finalised, it is then backcasted to create short-term case for 2030. This serves as a benchmark for the short-term implementation of measures such as energy efficiency improvements in district heating pipes, building renovations, expansion of renewable heat supply capacity and district heating. This helps energy planners ensure that future policies are aligned with a high-level, long-term goal.

2.3.4 Methodology description

A detailed methodology description is found in Appendix A. This includes an explanation of the estimation of heat demand and energy efficiency in buildings, with a focus on the geographic mapping of existing buildings, the assumptions behind the projection of population and heat demand to 2050, the energy efficiency of district heating networks and fourth-generation district heating, and the methodology behind the energy system analysis. The costs used in modelling the energy system are found in Appendix B. Finally, Appendix A also includes the analysis parameters for individual heating solutions.

3

Heat demand and renewable energy resources

This chapter describes the SHP's heat demand and renewable energy resource mapping step. First, the chapter presents the results of the heat mapping and then focuses on the relevant renewable energy source potential. As heat demand mapping is an essential part of heat planning, the focus of the SHP is stronger on this aspect. It is mainly to illustrate how maps can be used to assess district heating potential and serve as input for the energy system analysis of Ulaanbaatar in the subsequent chapter. The renewable resource sections are written with a broader Mongolia focus, supplemented with examples.

3.1 Heat demand in existing buildings and saving potential

The heat demand assessment is based on the GIS model described in Appendix A. Ulaanbaatar is set as the geographic delimitation and is therefore the area of interest (AOI) for this section. A total of 377 545 buildings are found from the sources within this delimitation. Approximately 75% of the building polygons are from OpenStreetMap, while the remainder are from the Microsoft building footprint database. Figure 14 shows the buildings footprints within the AOI, and the legend shows the source from which the building polygon was extracted.

Figure 14 **Building footprint in the area of interest**

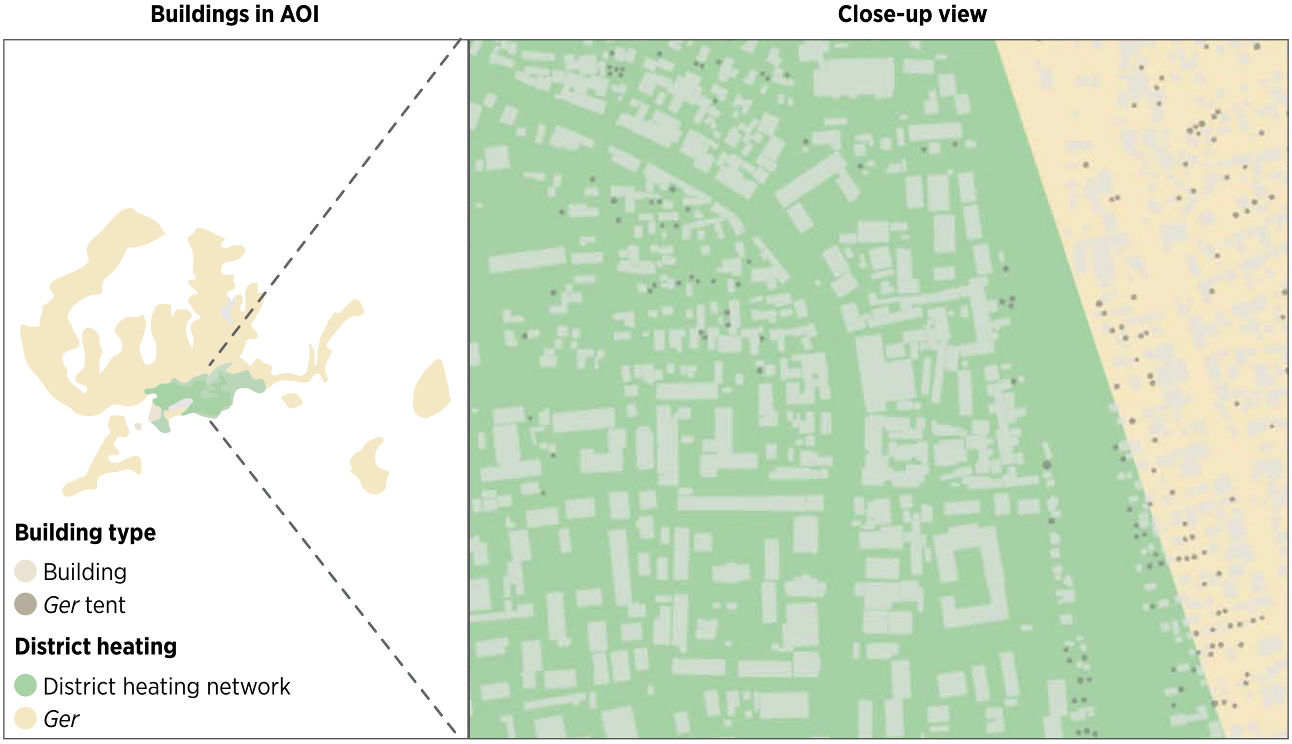
Note: AOI = area of interest.

Within the AOI, the model identifies two distinct types of area. The first is the existing district heating network area, and the second are various *Ger* areas that surround the network area. Note that various *Ger* areas can be found in literature and past reports; however, the best available geographically identified areas were used in this model. At a building level, *Ger* tents are differentiated from building structures. Of the total number of buildings identified, only about 11% are located within the district heating network area, while most of the building stock is found either in *Ger* or outer areas. This resonates with the ramified distribution of infrastructure characteristic of the AOI, while it challenges the available data, which imply that 50% of Ulaanbaatar households are connected to the network (Stryi-Hipp *et al.*, 2018) or 50% of the heat supply is via district heating (National Statistics Office of Mongolia, 2011). Therefore, this distribution of buildings as presented in the model, highlighting a potentially overlooked heat demand. Regarding building type, *Ger* tents account for approximately 20% of the geographically identified building stock in the AOI. The overview of the building counts is displayed in Table 1, while the geographical visualisation of the classification is presented in Figure 15.

Table 1 **Building counts in the AOI**

Area type	Building type	Count
District heating network	Building	38 306
	Ger tent	3 693
Ger	Building	252 472
	Ger tent	69 053
Other (within AOI)	Building	12 213
	Ger tent	1 808
Total		377 545

Figure 15 **Building and area classification in the AOI**

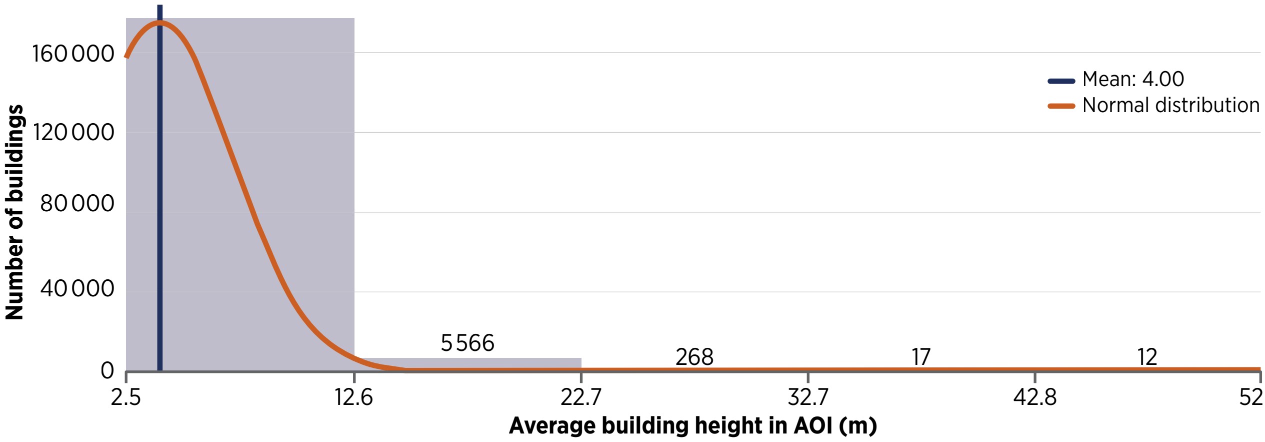


Note: AOI = area of interest.

For the volumetric estimation process, the Global Human Settlement (GHS) dataset for the AOI produces average building height estimates ranging from 2.5 metres to 52.9 metres, with a resolution of 100x100 metres. Around 50% of the height estimates in the AOI are between 2.5 metres and 12.6 metres, as seen in Figure 16. The histogram shows the estimated mean height of buildings to be 4 metres, and the standard deviation to be 3.23 metres. Within the whole extent of the AOI, the spread of the building height estimation concentrates the highest in the city centre, as predicted due to the relatively denser infrastructure and population of the area. After online visual inspection of the areas, however, in some of the outskirts of the city, the dataset seems to overestimate building heights. This is logical considering that *Ger* and outer city areas have dispersed, low building density and relatively lower building height when compared to the city centre where most commercial and high-density residential areas are established. From literature and local knowledge sources (Integration and Ekodoma Ltd., 2020; Stryi-Hipp *et al.*, 2018) it is known that building heights in *Ger* and outer areas fall within one to four floors. Therefore a conservative maximum threshold of 12 metres – considering a 3 metre ceiling height – is attached to the buildings located in these areas, whereas the height of *Ger* tents is set at 2.5 metres following standard *Ger* measurements.

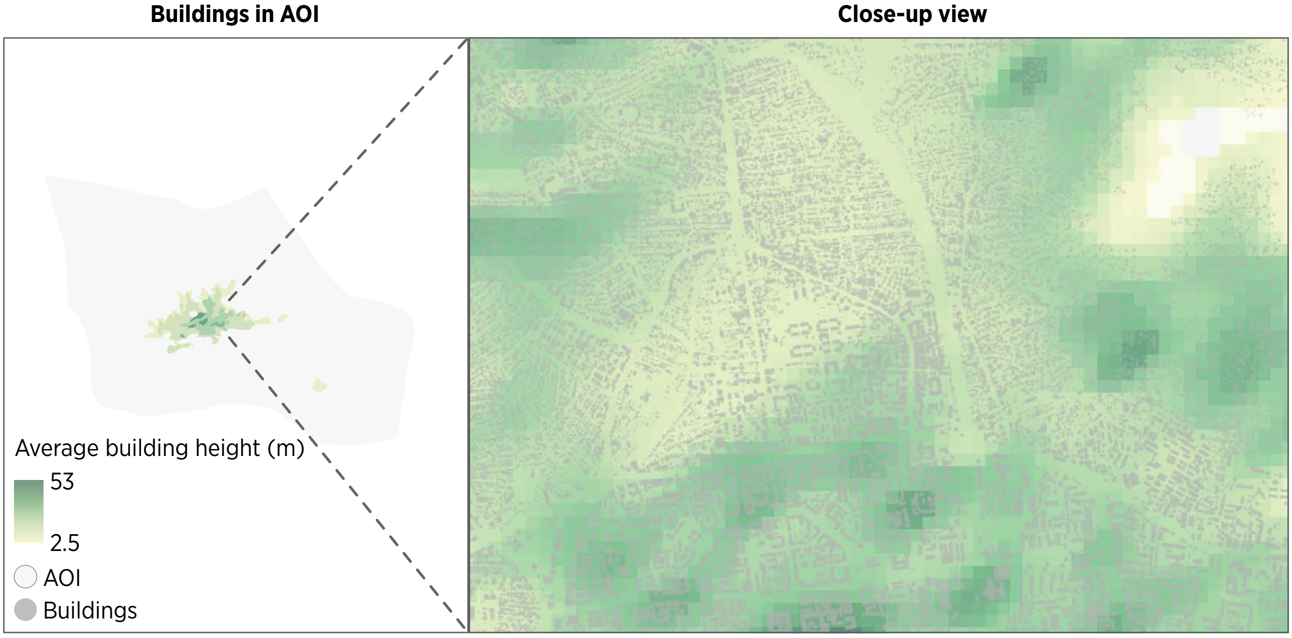
Figure 17 shows the raster dataset with average height estimation and building footprints within the AOI.

Figure 16 **Estimated building height in the AOI**



Note: AOI = area of interest; m = meters.

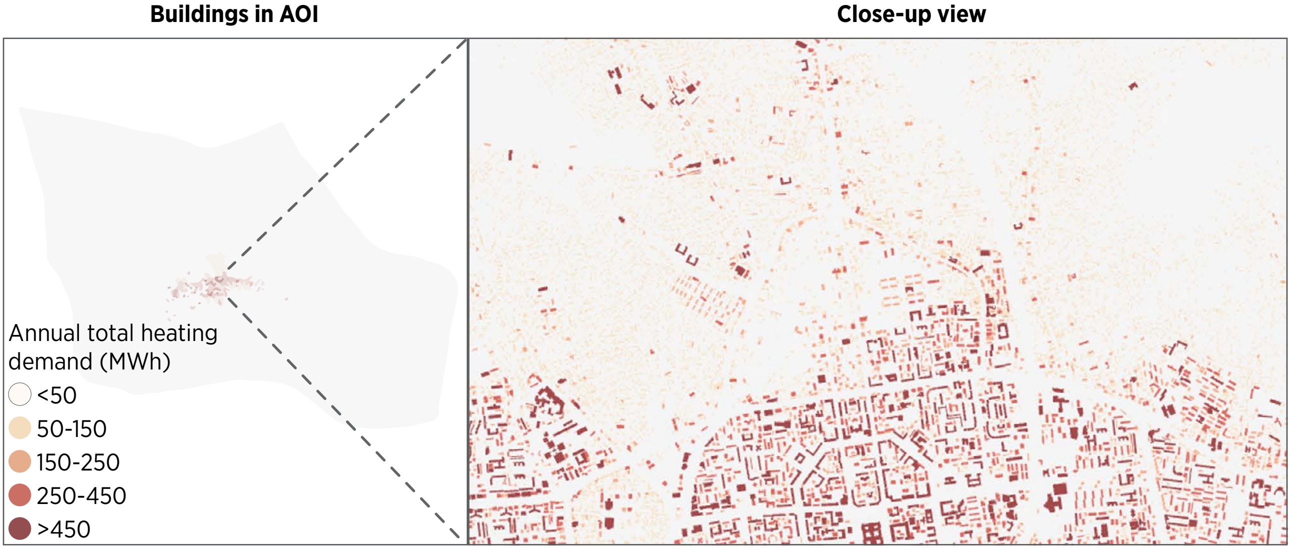
Figure 17 **Average building height 100x100 metre resolution in the AOI**



Note: AOI = area of interest.

The last part of the model's geometric calculation is the building surface area, which is then used for the building heat demand calculation alongside the AOI's corresponding climate and thermal resistance parameters of the building envelop (explained in Appendix A). The calculation applies to all buildings regardless of their location; however, no domestic hot water (DHW) is calculated for *Ger* tent building types. A map showing the calculated building-level total heating demand, *i.e.* combined space heating and DHW, is shown in Figure 18. The legend (colour intensity) represents annual total heating demand in MWh.

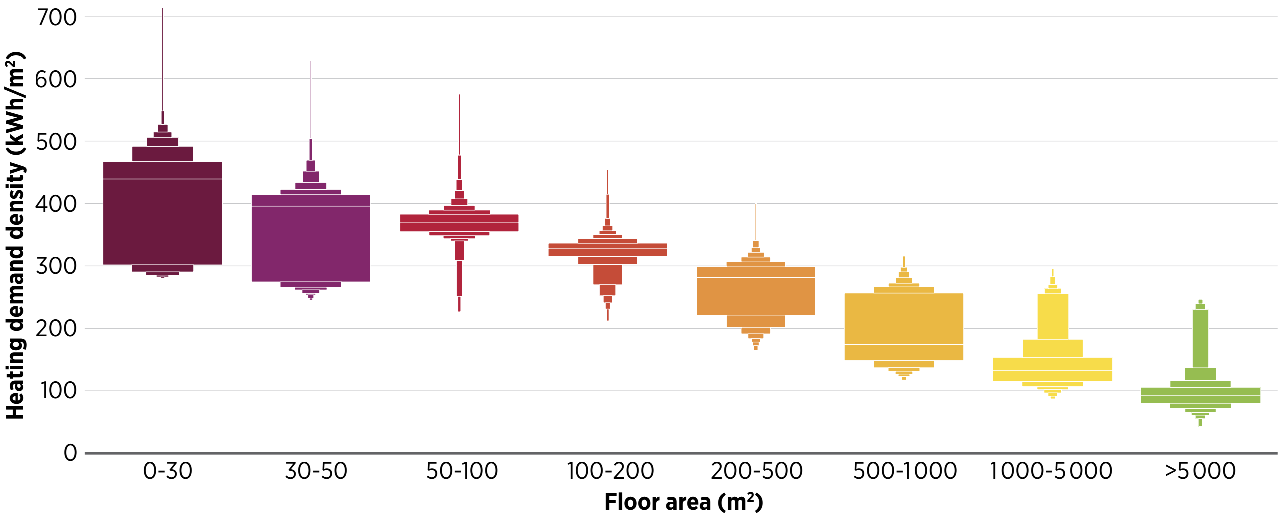
Figure 18 **Annual total heating demand in buildings**



Notes: AOI = area of interest; MWh = megawatt hour.

When plotting the individual demand spread, a tendency for a reduction in heating demand density is seen as the building increases in size. This tendency is also seen in the validation datasets included in Appendix A. The mean values for the different floor area categories are also aligned to the building validation datasets found in literature. It is important, however, to stress that the heating demand of the model is directly linked to the geometric properties of the building. Thus, since the model showed an overestimation of average heights in outer city areas, and an underestimation of them in inner city areas, this could result in reduced floor areas in the inner-city buildings. This estimation translates into the same propensity on the calculated heating demand where the lowest heating demand densities are seen in the highest building sizes. The smallest buildings with the highest heating demand density are the ones located in outer city areas or *Ger* areas. The visualisation of this pattern can be seen in Figure 19.

Figure 19 **Modelled heating demand density**

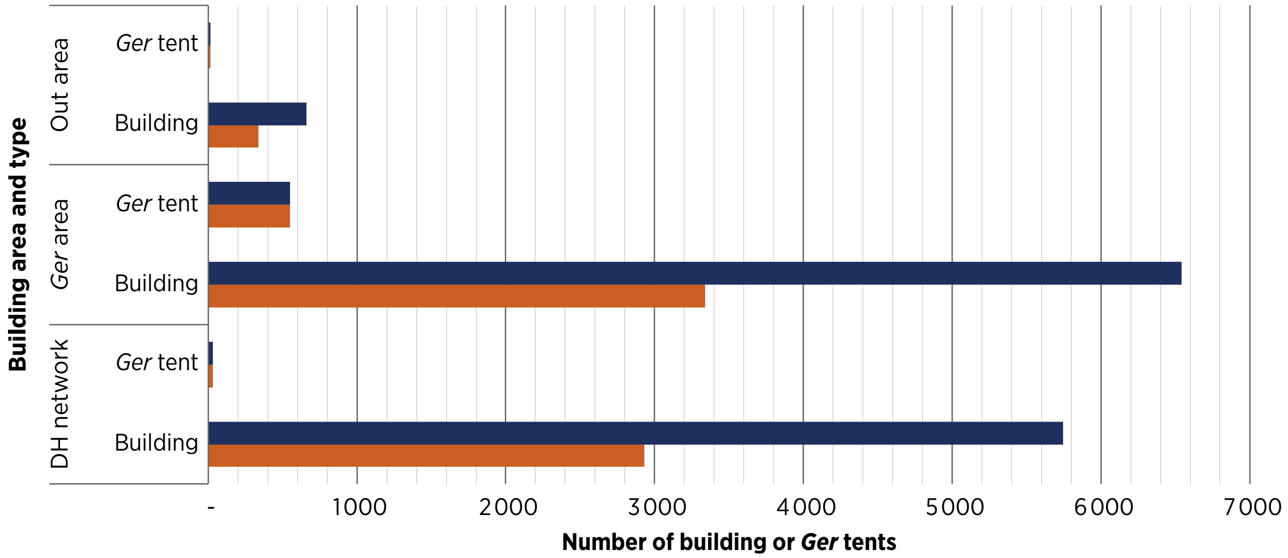


Notes: kWh/m² = killowatt hours per square meter; m² = square meters.

These demands are estimated for the current building stock, meaning the building stock identified through the GIS methodology. The next step in the methodology is to calculate the potential energy efficiency at a building level, which will be used to assess the future heating demands of the current building stock. As described in Appendix A following the previous studies, a total potential reduction in heating demand of 47% is applied to the space heating and DHW demand of the buildings. This applies to all buildings regardless of their location, except *Ger* tents where no energy efficiency is applied. Note that *Ger* tents account only for space heating demand.

The following chart shows the heating demand saving potential from energy efficiency by building area and type. The greatest potential for energy efficiency savings is seen in buildings located in the *Ger* areas. These areas vary widely in density and geographical distribution of heating demand. Overall, the current district heating network area accounts for around 2.5 times the total building floor area found in *Ger* areas. However, when these two are compared, they show a parallel demand which is explained by the difference in heating demand density along floor area categories (see Figure 20).

Figure 20 **Energy efficiency saving potential by building area and type in Ulaanbaatar**



	DH network		*Ger* area		Out area	
	Building	*Ger* tent	Building	*Ger* tent	Building	*Ger* tent
● No EE	5 745	30	6 544	552	661	15
● EE	2 933	30	3 342	552	338	15

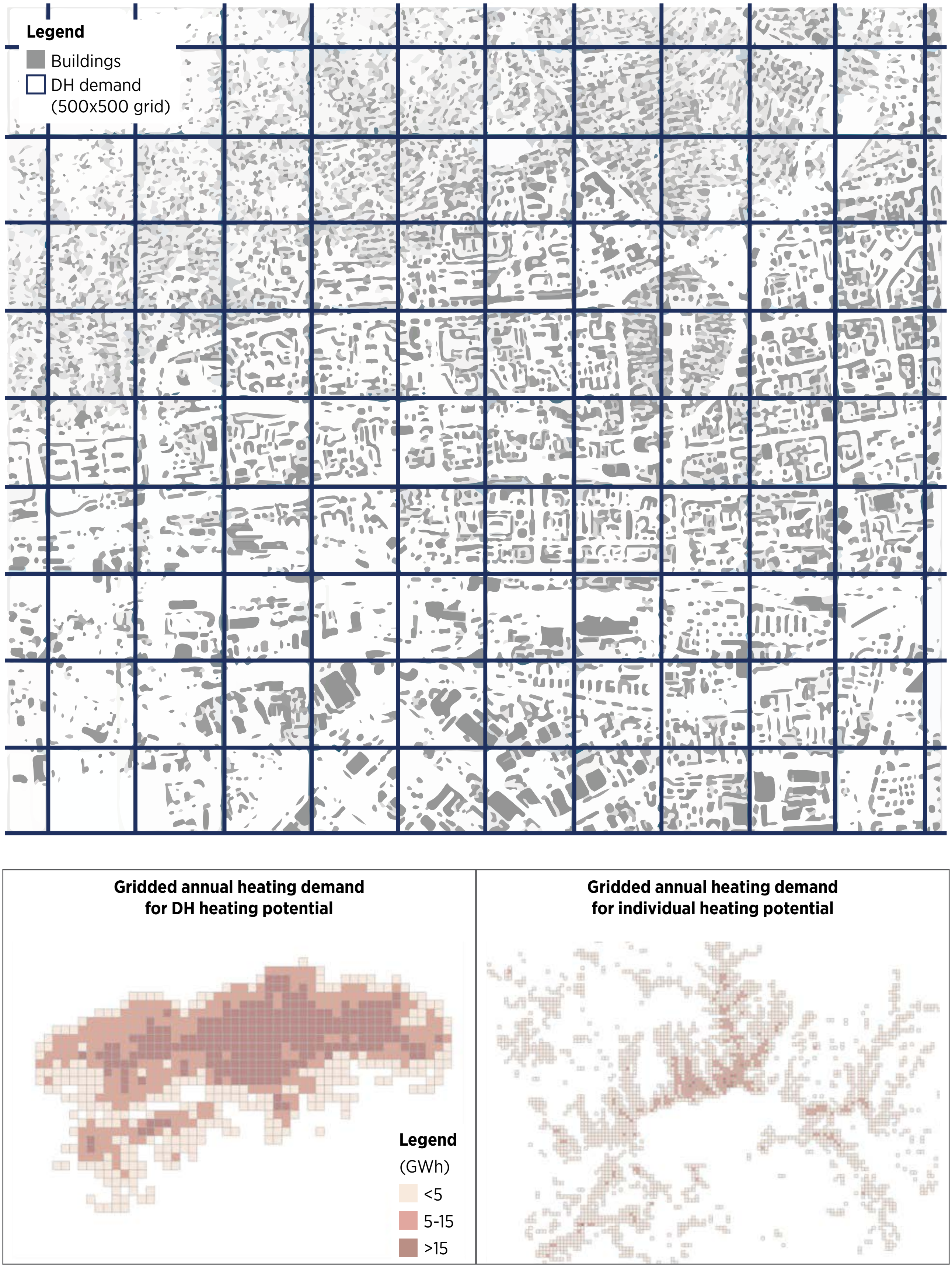
Annual heating demand = SH +DHW [GWh]

Notes: DH = district heating; DHW = domestic hot water; EE = energy efficiency; GWh = gigawatt hour; SH = space heating

The building demands are then aggregated on a grid level for the heating supply assessment where two different subsets of demands are created. The first subset is the aggregated heating demand inside and within a 1.5 km distance from the current district heating network. The second subset is the outer demand considered for individual heating potential. The grid size used is 500x500 metres following the validation and methodology described in Appendix A. For Ulaanbaatar, the resulting grids (district heating potential and individual heating potential) have 743 and 2 876 pixels respectively, each of them measuring 0.25 km^2 or 25 hectares.

The resulting gridded aggregated demand for both subsets is visualised on the left and right side of the lower graphic of Figure 21, respectively. The demand for individual heating supply is aggregated and shown on a grid scale only for visualisation purposes; its heating supply is assessed in Section 4.1.2.

Figure 21 Aggregated gridded demand split in Ulaanbaatar



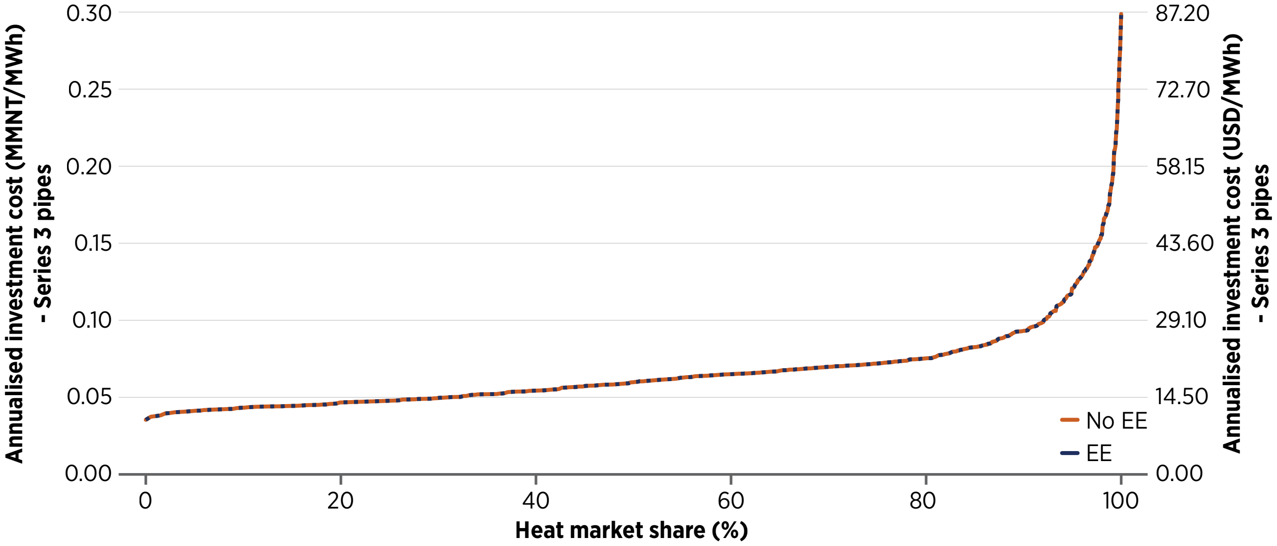
Notes: DH = district heating; GWh = gigawatt hour.

3.2 District heating potential for the energy system analysis

This section provides the cost curves for district heating grid investment based on the mapping outputs for the Ulaanbaatar case chosen as the AOI seen in Section 3.1. It uses the output from the regression model for district heating investment in potential district heating areas described in Appendix A. Figure 22 shows the district heating investment costs as a percentage share of the total heat demand shown in Figure 21, both with and without energy efficiency savings.

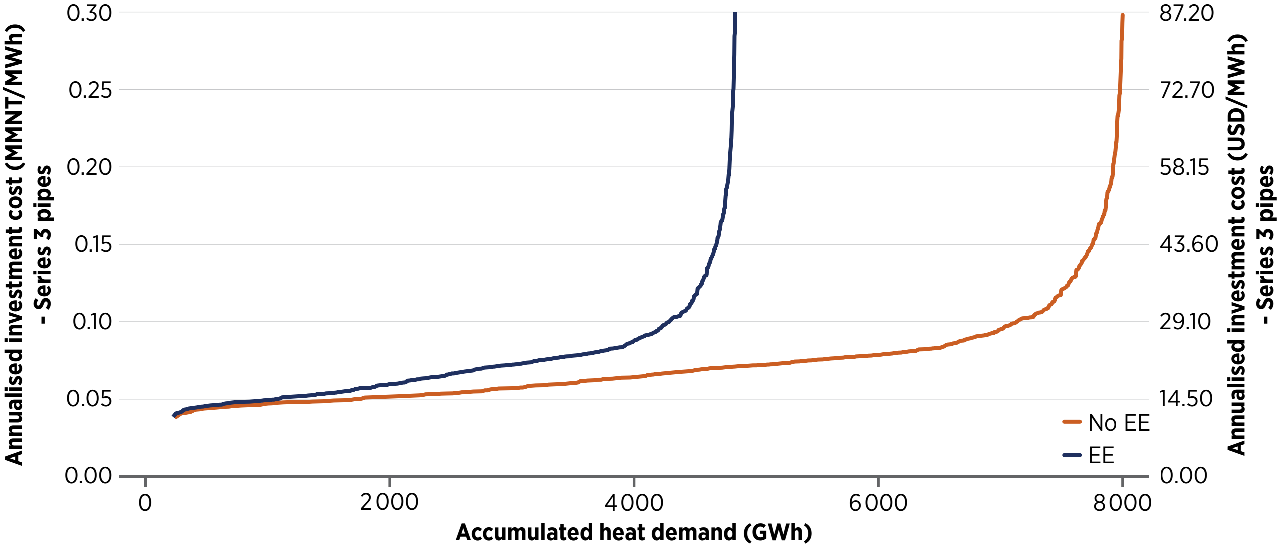
In parallel, Figure 23 shows the same result for heat demand instead of market share. Here, the difference from including energy efficiency savings in buildings is even more apparent. When including savings from energy efficiency, not only is the investment in district heating pipes lower, but also the cost relating to supplying the heat falls as smaller production capacity is needed.

Figure 22 District heating investment cost in relation to heat market share



Notes: EE = energy efficiency; MMNT = million Mongolian tugrik; the costs are based on Series 3 pipes, described in Appendix A.

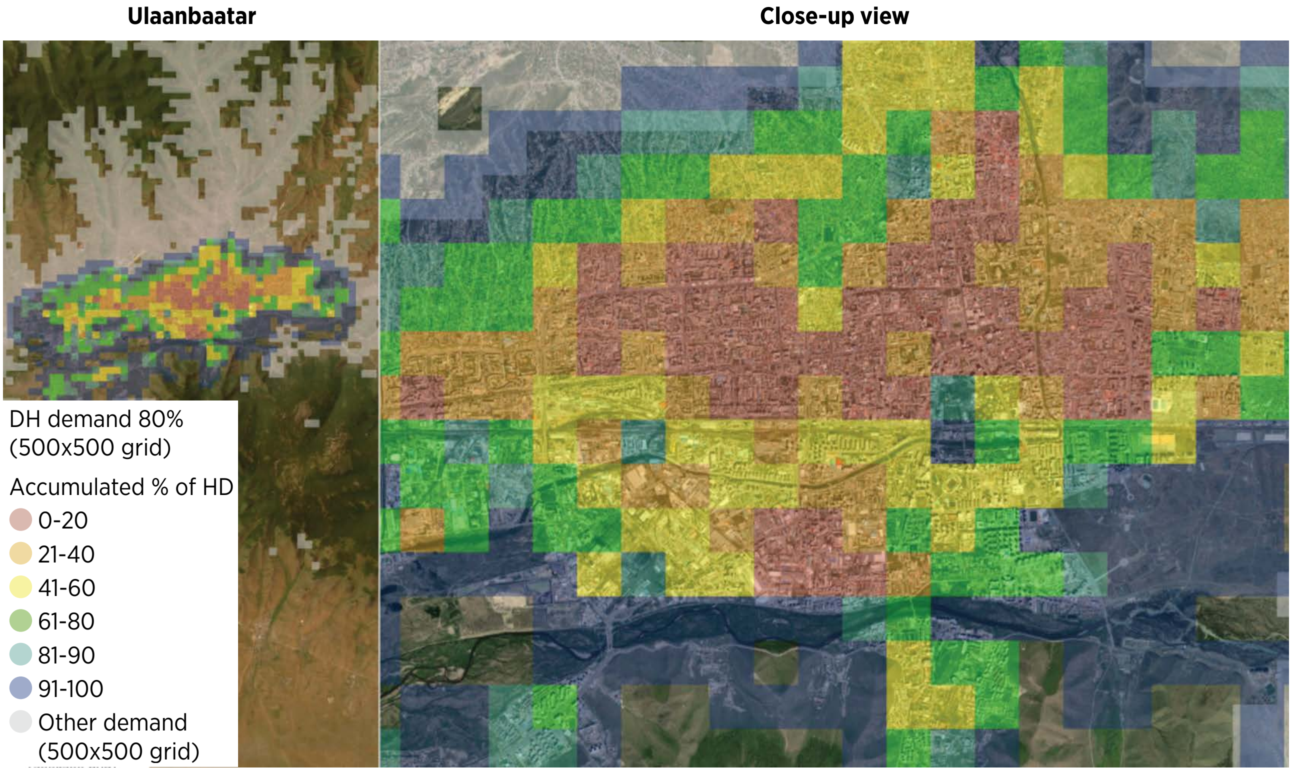
Figure 23 District heating investment cost in relation to accumulated heat demand



Notes: EE = energy efficiency; MMNT = million Mongolian tugrik; the costs are based on Series 3 pipes, described in Appendix A.

By assessing both graphs and focusing on investment costs as the district heating potential indicator, an estimate can be made of the extent of the heat market share that can be supplied with district heating. As seen, district heating costs perform linearly until they become exponential in relation to the provided heat market share. This also relates to the heat density being served, from denser and cheaper to less heat-dense areas where the technology becomes more expensive. Between 0% and 80% the costs grow linearly; after 80% heat market share, they become exponential and relatively much more expensive as they approach the totality of the heat market. Therefore, the cut-off point for district heating's share of the heat market is set at 80%. The map shown in Figure 24 displays how the heat market share looks on a spatial scale in Ulaanbaatar. Here, the potential geographical locations for district heating are identified and categorised according to heat market share at the grid level, from the best and cheaper locations (red) until the district heating cut-off is made at 80% (green). It is important to note that the heat market excludes *Ger* areas.

Figure 24 **Ulaanbaatar potential geographical locations for district heating**



Ulaanbaatar

Close-up view

Note: DH = district heating; HD = heat demand.

The heat market share of 80% for district heating is an input for the Ulaanbaatar energy system analysis in Section 4. The district heating heat losses are calculated accordingly, based on the methodology described in Appendix A for Series 3 pipes installed in 3GDH systems. The overview of the parameters for the district heating share is shown in Table 2.

Table 2 **District heating input for energy system analysis**

District heating *excluding *Ger* areas	Total investment cost [million MNT]	Heat demand inc. losses [MWh]	Heat demand exc. losses [MWh]	Heat demand with EE measures, excluding heat losses [MWh]
80%	4 634 560 or (USD 1.33 billion)	7 632 119	6 809 680	3 554 094

Notes: EE - Energy Efficiency; MNT - Mongolian tugrik; MWh = megawatt hours.

3.3 Individual heating demand

The remaining heating demand outside district heating potential areas (Figure 21) is then summarised for its individual heating supply assessment in Section 4.1.2. The split of this demand with and without energy efficiency savings is seen in Table 3. The buildings were categorised by the numbers of floors per building, so to identify single family, and multi-family buildings as shown in Table 4.

Table 3 **Distribution of heat demand in buildings outside district heating, including *Ger* tents**

Individual heat demand distribution		
Ger tents	439 780	MWh
Buildings without EE savings	6 297 538	MWh
Buildings with EE savings	3 215 764	MWh
Total *Ger* tents	54 531	units
Total buildings	210 518	units

Notes: EE = energy efficiency; MWh = megawatt hours.

Table 4 **Distribution of heat demand outside district heating divided into multi- and single-family buildings**

Individual heat demand distribution of buildings		
Single-family buildings without EE savings	5 995 650	MWh
Multi-family building without EE savings	301 888	MWh
Single-family buildings with EE savings	3 061 609	MWh
Multi-family buildings with EE savings	154 155	MWh
Single-family buildings	208 105	units
Multi-family buildings	2 413	units

Notes: EE = energy efficiency; MWh = megawatt hours.

3.4 Heat demand in new buildings

Given the population increase in Mongolia, the number of buildings is also expected to increase. The long-term heat demand of new buildings is almost impossible to map spatially, so instead the demand of new buildings is added to the demand found through the mapping of existing buildings. In this report, only an assessment of the heat demand for new buildings in Ulaanbaatar has been carried out as an input to the energy system analysis. However, based on projections for the rest of the country, this aspect also needs to be addressed for other cities when making local heat plans.

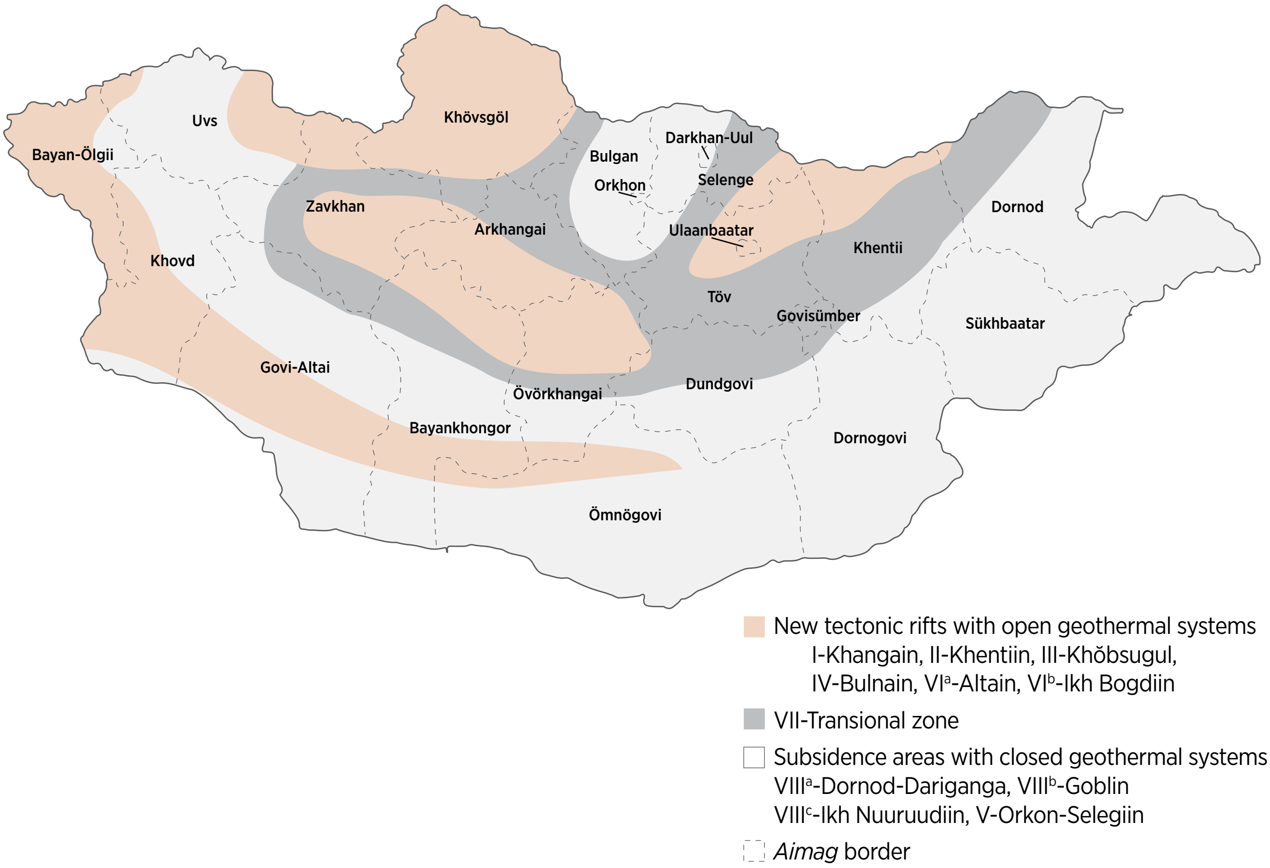
The heat demand of new buildings in Ulaanbaatar is based on the city masterplan (Stryi-Hipp *et al.*, 2018). Here the demand from new buildings is expected to add around 6.6 TWh/year in 2050 to the existing district heating demand. It should be highlighted that this is a relatively large increase, as the heat demand in existing buildings connected to district heating in 2050 is expected to be 3.5 TWh/year, when energy efficiency measures are fully implemented.

3.5 Geothermal

A potential renewable heat source for the heating sector in Mongolia is geothermal energy. However, this resource has yet to be fully explored and developed. Comprehensive geothermal surveys have not been performed; current studies focus on hot springs, but an assessment of deep geothermal resources at 1-3 km depth has not been comprehensively carried out. A geothermal plant uses the energy from reservoirs deep in the subsurface to supply heated water to the surface. This heat is typically extracted using a heat exchanger or a heat pump if the water temperature needs to be boosted to district heating level. The heated water is brought up to the surface and is then returned to the ground to maintain the reservoir (Danish Energy Agency, 2020a). The depth of the reservoirs is completely site-dependent and a thorough sub-surface investigation needs to be done to map them accurately.

Most detailed studies on the geothermal potential in Mongolia have been done in the Khangai region of the country. However, preliminary assessments indicate that Mongolia has significant geothermal potential besides the Khangai region. As indicated on the map in Figure 25, Mongolia's geothermal resources are mainly distributed in Khentii, around the Khubsugul Mongol Altain plate forms, and in the Dornod-Dariganga and Orkhon-Selenga regions (Tseesuren, 2001).

Figure 25 **Geothermal potential in Mongolia**



Source: Tseesuren (2001).

Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply any endorsement or acceptance by IRENA.

Many geothermal studies focus on connecting nearby *soums* and *aimags* (Tseesuren, 2001). Mongolia's geothermal resources have been utilised directly by shallow drilling (typically <100 m) in rural areas for heating, washing and recreational purposes. The largest geothermal resource available is located in Shargaljuut, Bayankhongor province, with a capacity of 6 MW_{th}. It has been estimated by Jigjidsuren, Naidan and Mustafa (2006) that a binary-cycle geothermal plant can be established here. The other location with geothermal potential is in Arkhangai province, with the Tsenkher springs having a potential of around 2 MW_{th}.

Most of the data available on geothermal potential in Mongolia are scattered across the western and central parts of Mongolia and are very limited in coverage. Therefore, it is essential to conduct a deeper investigation of the available geothermal resources more broadly, *e.g.* near Ulaanbaatar. This is to ensure secure investment in geothermal plants for district heating since the energy from the geothermal plants in remote locations cannot be transported over longer distances due to energy loss (Institute for Energy Research, 2022). A study done in Tuv province near Ulaanbaatar demonstrated the use of ground-source heat pumps with a solar collector to heat individual buildings such as kindergartens and other schools. The study mentions that the use of ground-source heat pump systems is rising in Mongolia for space heating.

However, the potential for geothermal heat of temperatures above 60°C is often found in aquifers at depths of 1-3 km. These geothermal sources can be used directly for district heating purposes in low-temperature networks and can be boosted to the required temperature in case of high-temperature networks. However, a prerequisite would be that the district heating system reduces its supply temperature below 100°C, otherwise geothermal becomes expensive. The efficiency of geothermal plants depends on the relative temperatures of the geothermal resource and district heating system. Table 5 shows an example of the efficiency of different geothermal options. In general, the deeper the geothermal source the higher the temperature, and the lower the district heating temperature, the higher the efficiency. However, this must be examined locally. As seen in the table, the district heating temperatures here are 70-80°C, which makes geothermal sources more efficient than where the district heating temperatures are higher.

Table 5 **Efficiency of different geothermal options**

	Total efficiency, annual average
Geothermal heat-only plant with:	**net (%)**
Electric heat pump, depth 1 200 m. DH temperature 80/40°C	460
Electric heat pump, depth 2 000 m. DH temperature 80/40°C	844
Electric heat pump, depth 1 200 m. DH temperature 70/35°C	548
Electric heat pump, depth 2 000 m. DH temperature 70/35°C	1 185

Notes: The total efficiency is calculated as heat output divided by energy input. Energy input is the input to the heat pump and auxiliary electricity to pumps *etc.*; DH = district heating; m = metres.

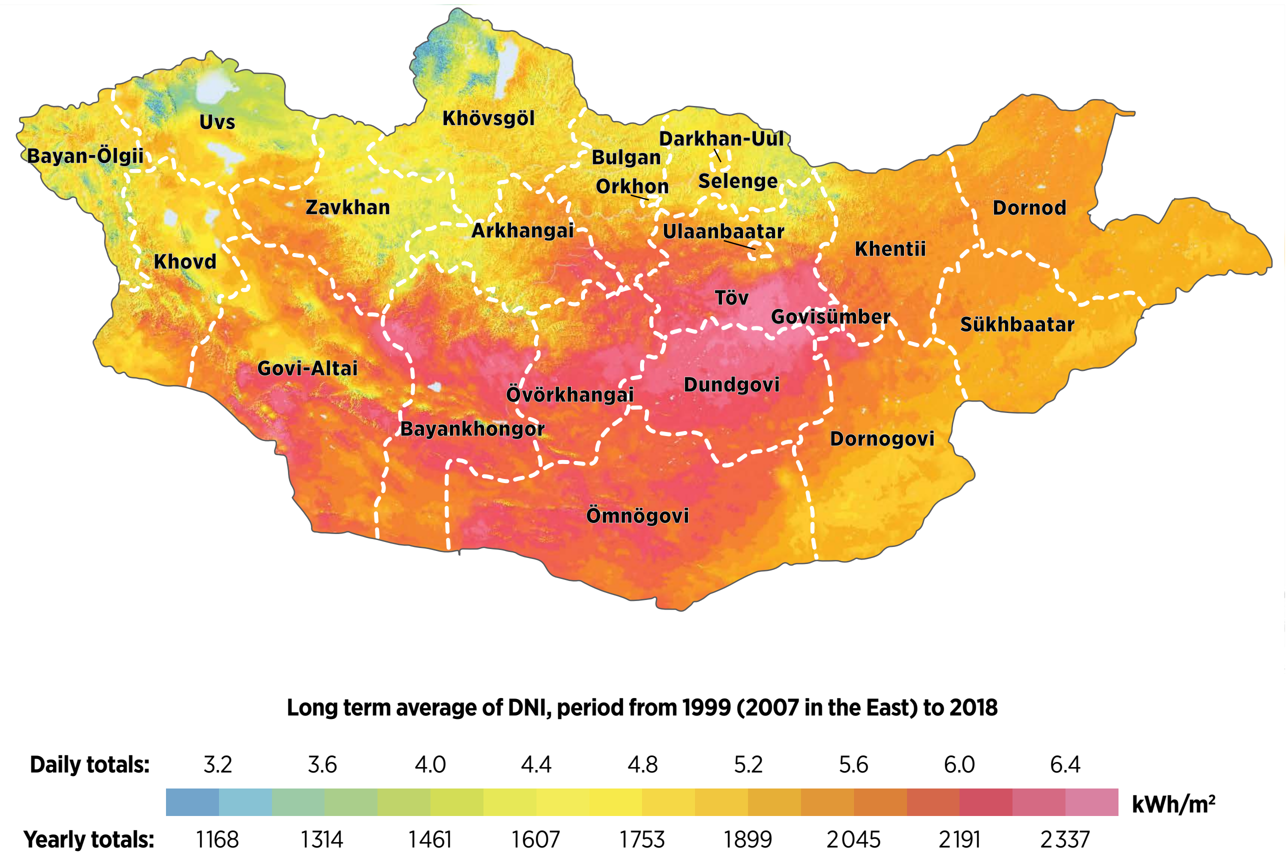
Source: Danish Energy Agency (2020a).

3.6 Solar potential

3.6.1 Solar thermal collectors

The technology to gather solar thermal energy for district heating purposes is typically divided into flat plate collectors (FPCs), evacuated tubular collectors (ETCs) and concentrated solar power (CSP). The most common type used in district heating is the FPC technology and will also be the focus of the following description. The purpose of solar collectors is to provide optimal conditions to absorb heat energy from the sun. The absorber typically consists of either aluminium or copper sheets, where a fluid is circulated in pipes behind the absorber. The fluid is heated by the absorbed heat. The absorber is covered by a glass layer for protection and the back of the solar collector is insulated to reduce heat losses. The heat from the fluid is transferred to the district heating system through a heat exchanger. The input to the solar collectors is solar radiation, which is highly dependent on weather conditions, seasonal variations and the location on earth. The closer to the equator, the more solar radiation is available. In Figure 26 the average solar irradiance for Mongolia is presented. Here, it is clear that the southern regions of Mongolia have a higher solar irradiance, but the other areas also have high potential.

Figure 26 **Map of solar irradiance for Mongolia**



Source: World Bank (2020).

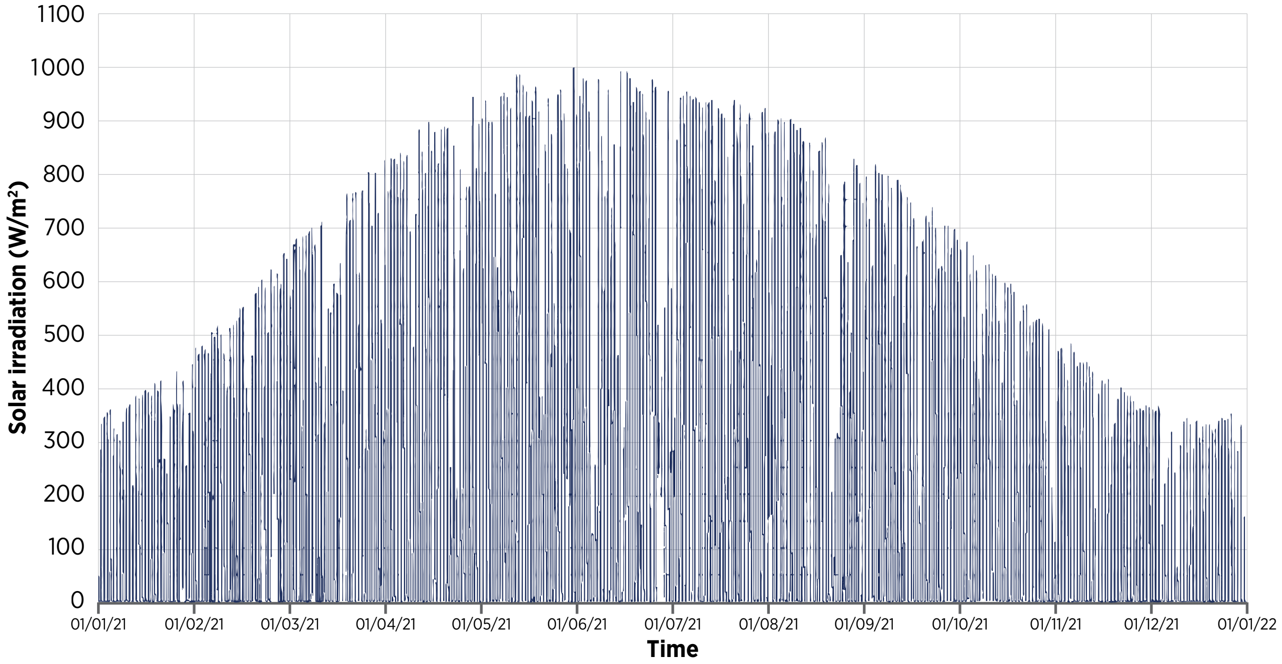
Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply any endorsement or acceptance by IRENA.

Notes: kWh/m^2 = kilowatt hours per square metre; DNI = direct normal irradiation

The solar irradiance changes over the year, typically with a higher solar irradiance in the summer. Figure 27 presents the hourly solar potential times series for the Ulaanbaatar region. The solar irradiance follows the length of the day, and thus there is always a significant difference between day and night; however, in the summer months, it is clear that the potential is much higher than in the winter months.

In most district heating systems, solar collectors are designed to cover around 10-25% of annual heat demand (Danish Energy Agency, 2020a). However, this varies; and with seasonal storage, some examples show coverage of up to 40-45% of annual heat demand. The output of solar thermal collectors is hot water with varying performance over the year. The performance is related to the temperature of the fluid in the collector, the weather, the type of fluid, the flow, and the tilt of the collector. Figure 28 illustrates the efficiency as a function of the temperature difference between the ambient temperature and the working fluid. Thus, solar thermal collectors have limitations in the colder winter months in Mongolia. In colder climates, anti-freezing agents are typically added to the fluids in the solar collectors. If the anti-freeze agent is insufficient, heated water from the storage tank or district heating can be circulated to keep the collectors frost-free.

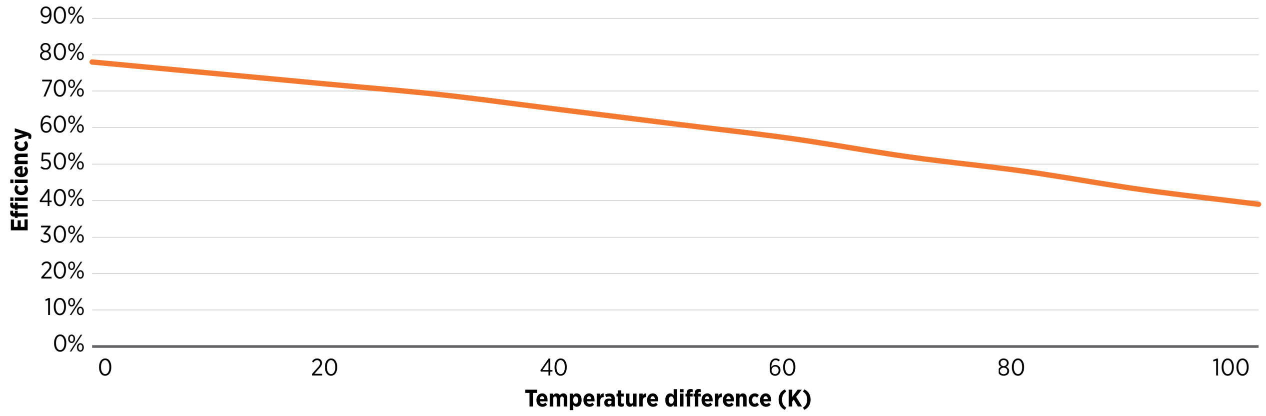
Figure 27 **Solar energy profile of Ulaanbaatar**



Source: Uwe P. *et al.* (2017).

Note: W/m² = watts per square metre.

Figure 28 **Relationship between temperature difference and efficiency of FPC**



Source: Uwe P. *et al.* (2017).

Notes: FPC = flat plate collector; K = degrees Kelvin.

In general, solar as a heat source should be considered for district heating systems with high fuel expenditure, as the main benefit of solar systems is that they replace part of these fuels. Thus, solar thermal is relevant in the case of Ulaanbaatar. In systems with a cheap baseload heat source, *e.g.* excess industrial heat or geothermal, it can be challenging to incorporate solar thermal.

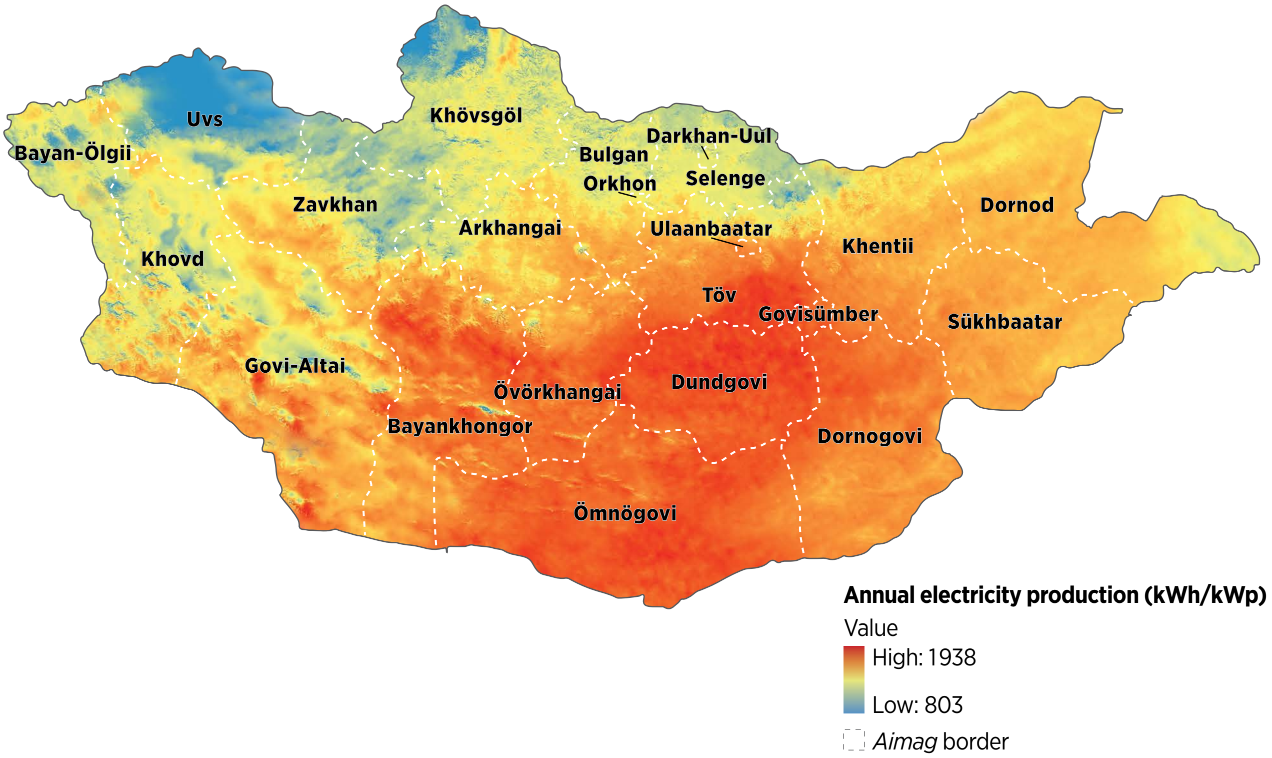
3.6.2 Solar photovoltaics

A solar photovoltaic (solar PV) cell is a semiconductor which generates electricity when solar irradiation hits the cell. The electricity generation capacity of the solar cells depends on the intensity of solar irradiation on the module, the angle at which the module has been set up, the spectral distribution of the solar radiation and the module temperature (Danish Energy Agency, 2020a). Solar PV modules can utilise direct and diffuse radiation, which enables the orientation of the modules in any way possible.

Figure 29 presents an estimated annual electricity production for solar PV in relation to a set installed capacity, whereby the potential is high especially in south and central regions of the country.

Mongolia has great potential for ground-mounted solar PV systems that can be connected to the main electricity grid; the electricity can further be used in heat pumps or electric heating either for district heating purposes or individual buildings. One of the challenges with solar PV and solar thermal collectors in Ulaanbaatar is that of air pollution (*i.e.* particulate matter) blocking part of the solar radiation, reducing their production; this has not, however, been examined in detail. Therefore, it is a prerequisite that the actual solar radiation on site is measured, and that the pollutant emissions from heat and electricity production are reduced if they pose a significant problem, to enable solar technologies to produce optimally. Alternatively, the PV systems need to be placed outside the city and connected to the main electricity grid. In the Ulaanbaatar masterplan (Stryi-Hipp *et al.*, 2018) it is estimated that there is sufficient area for around 2 gigawatt peak (GWp) roof-mounted PV and 1.5 GWp ground-mounted PV.

Figure 29 **Map of solar PV potential showing annual electricity production per kWp**



Note: kWp = kilowatt peak.

Source: World Bank (2020).

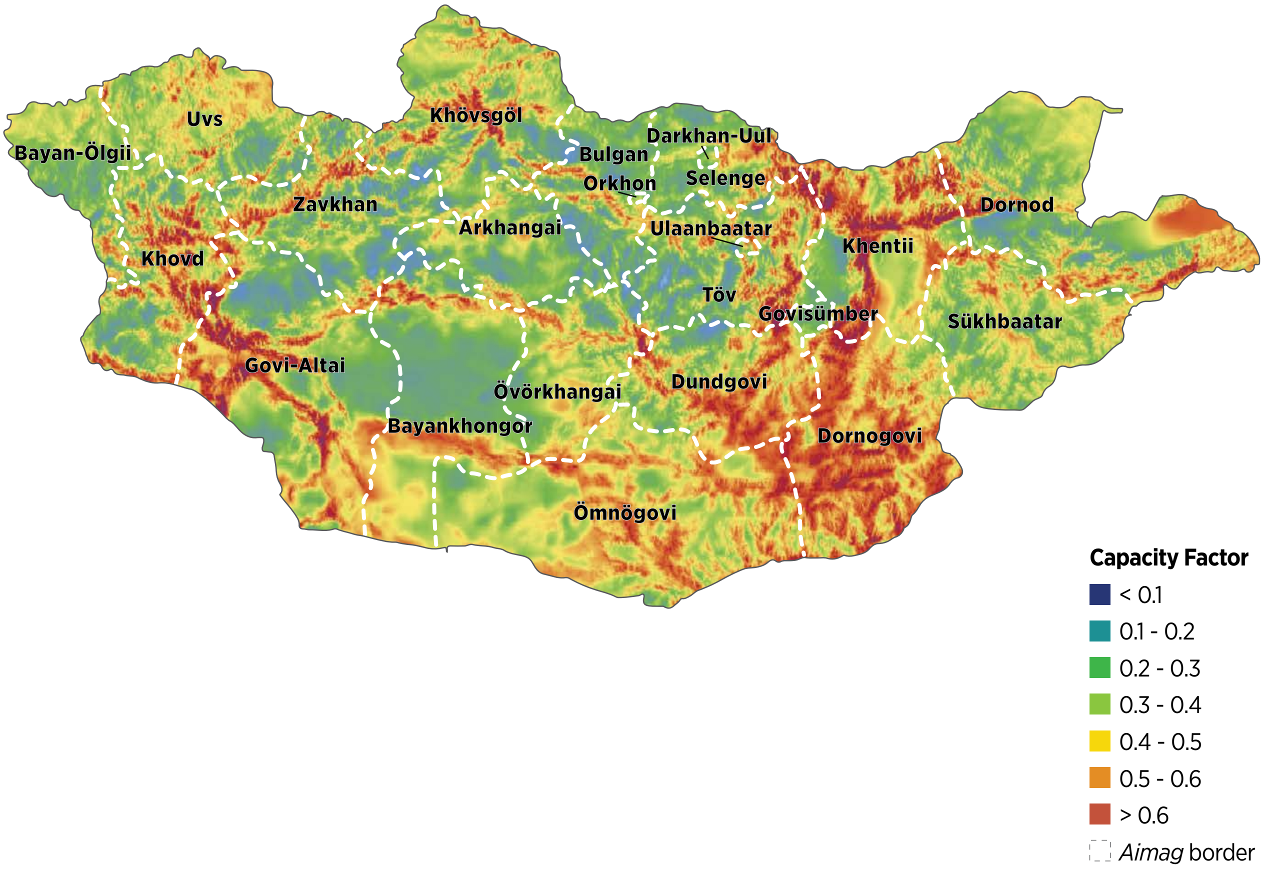
Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply any endorsement or acceptance by IRENA.

3.7 Wind potential

Wind turbines capture the kinetic energy of the wind to generate electricity. The energy from the wind is captured by the rotor blades, which in turn rotate the generator through a shaft. The average wind energy is dependent on the prevalent wind speeds where the wind turbines are located. The amount of wind energy harvested has increased globally in recent years since there has been much development and investment in the sector, leading to the technological improvement of wind turbines (Danish Energy Agency, 2020a).

Mongolia is subject to a westerly wind flowing across its territory, and the western and central parts have a topographical advantage over the rest of the country. Many factors affect wind energy utilisation, the key aspects for Mongolia being ambient characteristics of the mid-latitude westerly wind flow and the progression of weather systems. Areas with a lower elevation have maximum wind potential, with a higher frequency of high wind speeds in the summer months starting from March. Wind energy can be harnessed to its full potential when the wind farm is planned in the dominant wind direction and with lower topographical variations due to low surface roughness in the upward trend. Figure 30 presents the estimated capacity factors for wind turbines in Mongolia. Capacity factors indicate the gap between the nominal and the estimated power production of a wind turbine; if the capacity factor is 1, it means the plant is producing all the time. Hence, the higher the capacity factor the better, and for onshore wind turbines, a capacity factor above 0.3 is considered reasonable, which means that Mongolia has good wind resources.

Figure 30 **Estimated capacity factor for wind turbines in Mongolia**



Source: Global Wind Atlas (n.d.).

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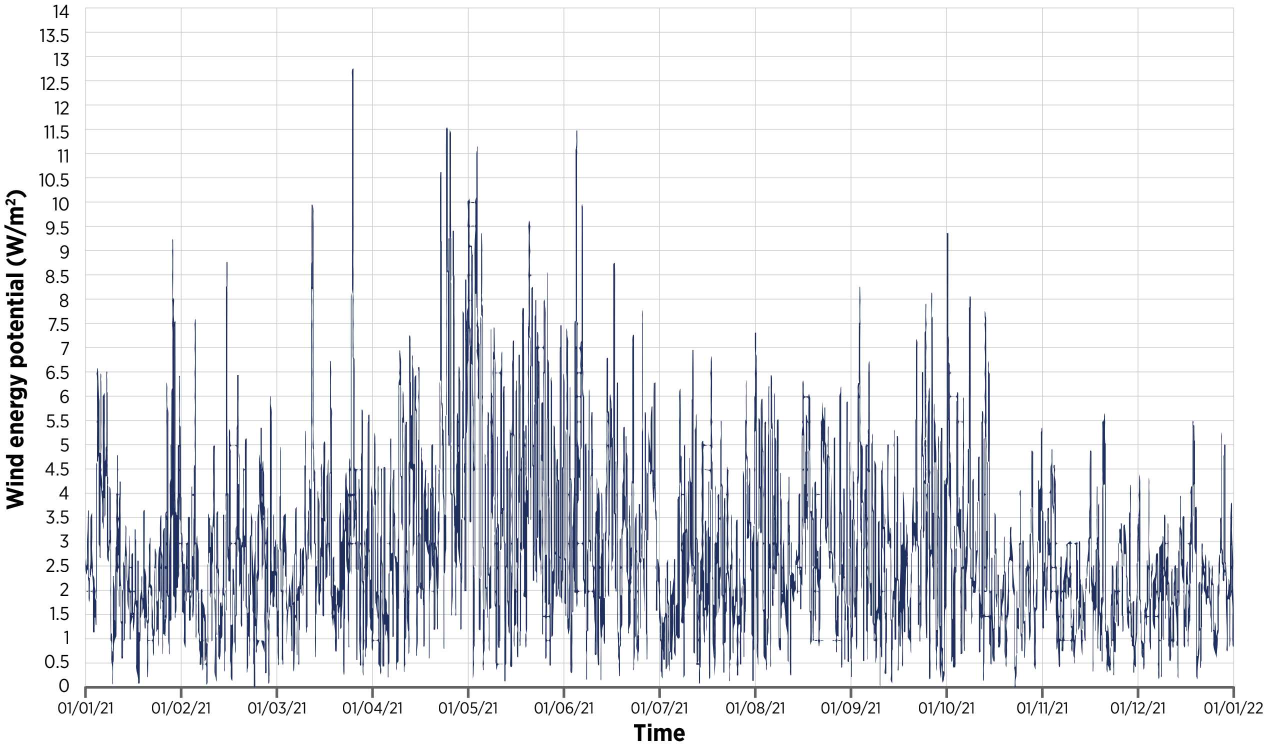
While other parts of Mongolia have moderate potential for the development of wind farms, for the city of Ulaanbaatar it is assumed that just 1% of the land available can be utilised (Stryi-Hipp *et al.*, 2018). This is due to existing wind speeds, availability of land for building wind farms and environmental concerns. Figure 31 presents the wind profile used for Ulaanbaatar.

Figure 31 **Wind energy profile of Ulaanbaatar**



Source: Saha *et al.* (2014).

Note: W/m^2 = watts per square metre.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3.8 Bioenergy

Bioenergy generally consists of biomass (residues from wood industries, wood chips [from forestry], straw and energy crops) and biogas (Danish Energy Agency, 2020a). Biomass resources are a renewable alternative to coal; however, as biomass sources are limited in Mongolia, it is essential to restrict their use to a sustainable level. Additionally, the inefficient use of biomass also adds to local pollution, which is another reason for limiting biomass use in cities. Therefore, biomass should mainly be considered a backup for hours with little production from other renewable sources. The different biomass resources have other properties in terms of humidity, granularity, ash content and composition, and density, and can be used interchangeably in a biomass plant.

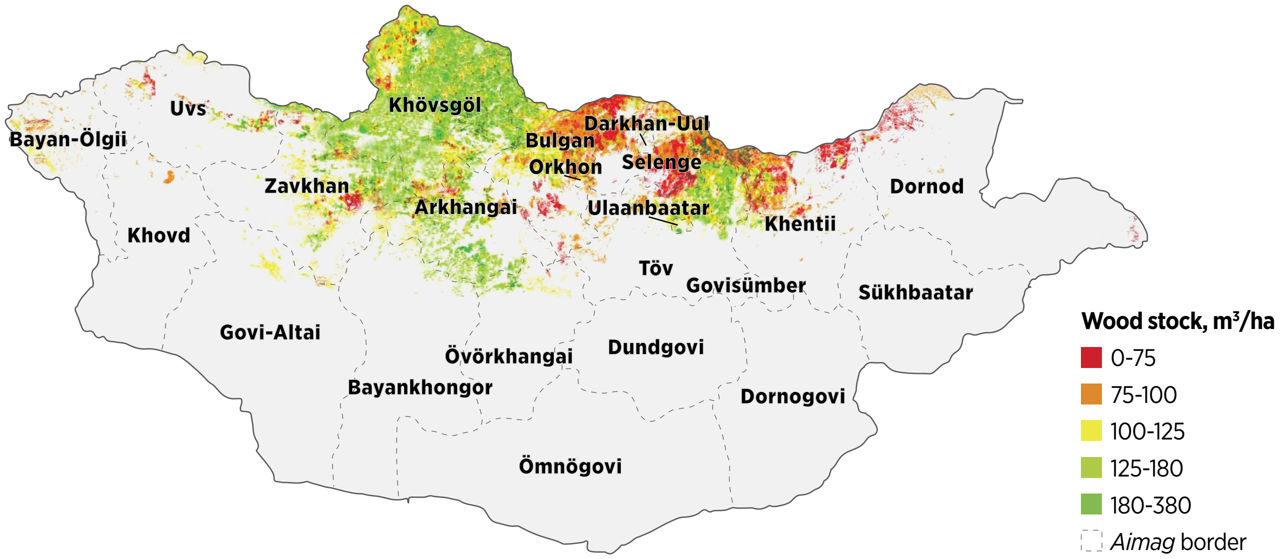
Wood is the most favourable form of biomass to use, especially in the form of pellets, as it has a higher energy density and low emission content of ash, nitrogen and alkaline metals. Wood biomass should mainly be in the form of waste from timber, paper and other industries, to ensure its sustainable use. When using biomass for energy generation, fuel quality must be the focus. This is because a high moisture content of the biomass will increase CO and PAH (polycyclic aromatic hydrocarbon) content.

Multiple studies have been done on the classification of forests in Mongolia, which are divided into two categories: the northern coniferous types, which include boreal, montane and mixed forest-steppe; and the shrubs of the desert, which include saxaul shrub forests. This reflects Mongolia's varied climate across its landscape. The country's forest resources are slow to grow (Erdenechuluun, 2006). The most feasible biomass resource for Mongolia's heating sector is solid wood waste and mill waste residues, including sawdust and chips. A study concludes that the potential to use this waste as biomass has not been explored yet; hence, the necessary technology and infrastructure need to be evaluated (Batmunkh and Ganzorig, 2005).

This means it is essential to assess the amount of woody biomass available for energy generation, as little information is available on the waste produced by timber and other industries. A study states that the Mongolian forest has an abundance of deadwood, which amounts to 46.5 m^3 per hectare and 40% of the total growing stock volume (Battuvshin and Aruga, 2022). Woody biomass is not being utilised at a macro scale and is used by households in small to medium-sized boilers.

All studies conducted on the use of biomass in Mongolia point towards its use in rural areas. As indicated in the map in Figure 32, most of the resources are concentrated in the north.

Figure 32 **Distribution of forest resources in Mongolia**



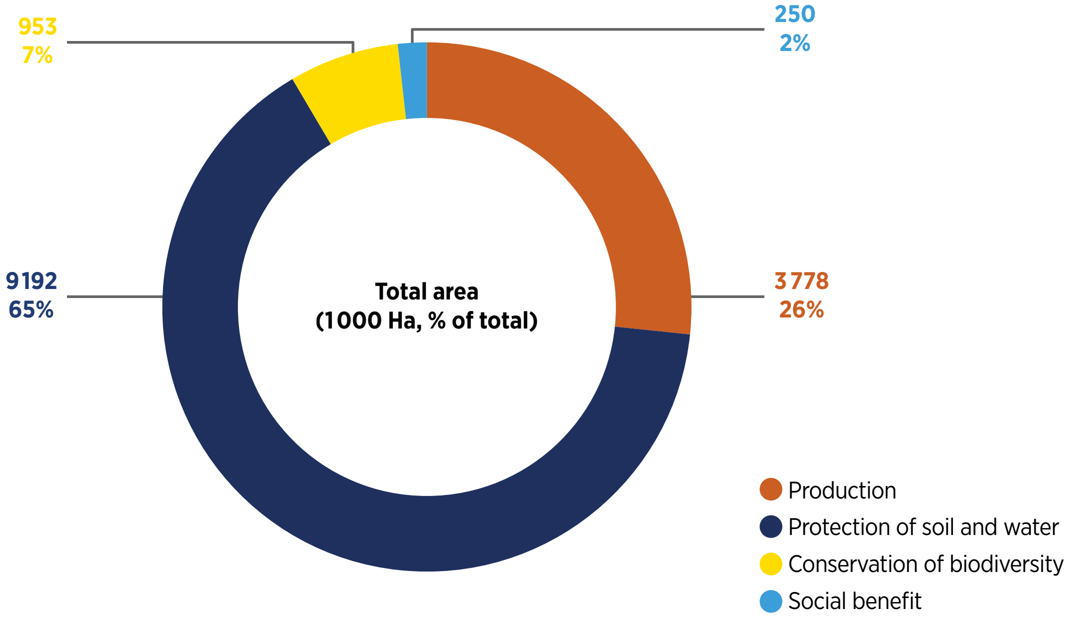
Note: m^3/ha = cubic metre per hectare.

Source: Tsogtbaatar (2017).

Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply any endorsement or acceptance by IRENA.

Good potential is also identified near Ulaanbaatar, with wood stock of 125-180 m^3 per hectare. The government of Mongolia has divided the forest resources into three zones for better management, and 7% of the forests are classified under the utilisation zone for timber harvesting. With permits from the government, timber can be harvested legally for use. According to the latest FAO report on global forest resources (FAO, 2020) only around 26% of the forest can be classified as for production purposes, whereby the rest is protected for biodiversity, soil and water as well as social benefit (social services). The specific distribution of these is shown in Figure 33.

Figure 33 **Forest areas in Mongolia by FRA2020 category**



Source: FAO (2020).

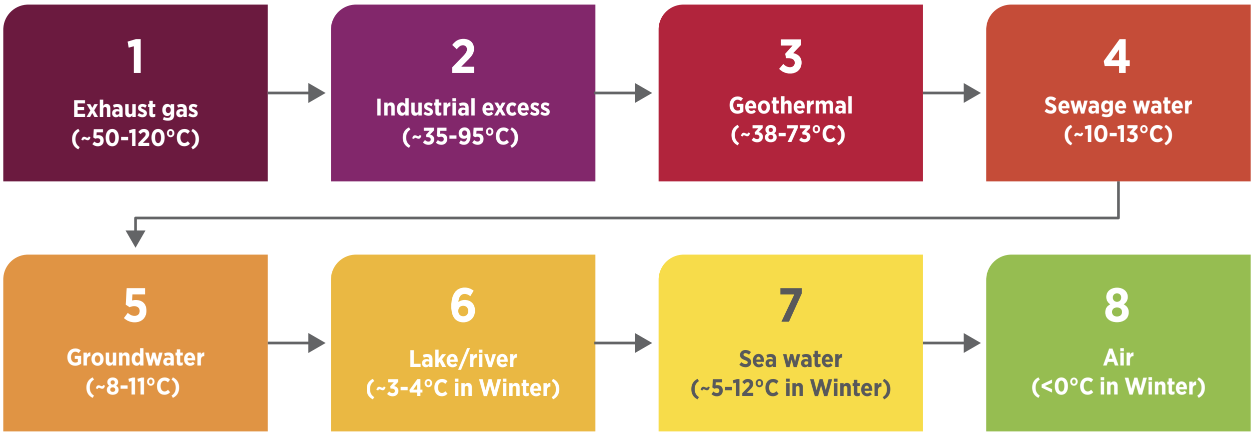
Note: Ha = hectare.

3.9 Heat pumps and alternative heat sources

Heat pumps basically move heat from a low-temperature heat source to a higher-temperature heat sink in a closed loop. In general, there are two types of heat pumps: 1) compression heat pumps utilising electricity or a combustion engine to drive the thermal process; and 2) absorption heat pumps using high-temperature heat to drive the thermal process. Heat pumps can be used at different scales, and to distinguish heat pumps applied in district heating from those applied in households, typically the term large-scale heat pumps is used for heat pumps in district heating.

Compression heat pumps utilise two inputs: a heat source and electricity. The heat pump is typically used to boost a heat source with a low temperature to the required temperature in the district heating system. Figure 34 presents different heat sources for heat pumps, starting from the highest to the lowest temperature sources. The figure shows general categories, but is not exhaustive as any heat source could be utilised, *e.g.* abandoned coal mines as seen in Spain (Roberto Mayoral Fernández, 2021).

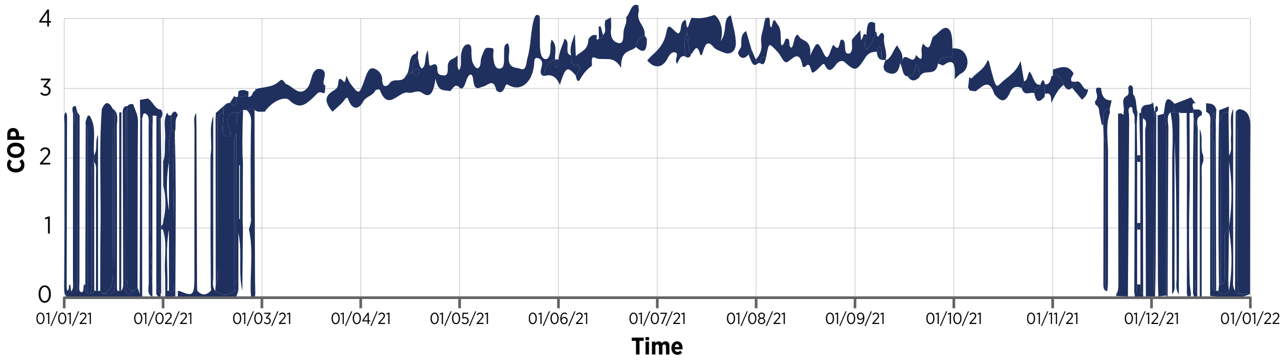
Figure 34 General overview of heat sources from higher to lower temperature



Based on: Komoszynska and Sørensen (2021).

The efficiency of heat pumps depends on their type. The efficiency of compression heat pumps depends on the source and sink temperatures and is given as the coefficient of performance (COP). Figure 35 shows the variation in COP over the year for Ulaanbaatar.

Figure 35 Variation in COP for air-source compression heat pumps in a typical year in Ulaanbaatar



Notes: When the temperature is below -20° C, heat pumps cut off; COP = coefficient of performance.

3.10 Waste incineration

In general, waste incineration plants for heat production can be divided into two groups: heat-only plants; and CHP plants. Waste incineration plants are like traditional heat production plants, but are included here as the heat is seen as a by-product of waste management. This also means that these plants typically have a relatively low heat production cost compared to other heat production plants that use traditional fuels. The input for waste incineration plants is generally municipal solid waste, and sometimes so-called green waste from parks and forests. The waste naturally has considerable variation as a fuel, as it is a mix of different types of waste with different chemical compositions and heating values. The typical capacity of a waste incineration CHP is 10-35 tonnes of waste per hour, which is a capacity of around 30-110 MW_{th}. Heat-only plants are typically smaller, with 5-15 tonnes of waste per hour and a total of 15-50 MW_{th}. The efficiency of waste incineration CHPs depends on their size, where small plants (35 MW_{th} feed) on average have an electrical efficiency of 21.6% and heat efficiency of 80.3%, while larger plants (200 MW_{th} feed) have an electrical efficiency of 22.4% and a heat efficiency of 80.2% (Danish Energy Agency, 2020a). In Ulaanbaatar waste incineration plants could be built both for the main district heating grid and for smaller HOB areas.

The Ulaanbaatar Waste Management Improvement Strategy and Action Plan (Ulaanbaatar City, IETC and AIT RCC. AP, 2017) states that 1.1 Mt of solid waste were generated in 2015. The waste is dumped in three disposal sites, of which only one is classified as a sanitary landfill. There are major gaps in both waste segregation, transport and recycling, which leads to improper handling of the waste. Of total waste arisings, 15% originates from apartments, 28% from *Gers*, 46.7% from business and government and 9.8% from roads and public areas. Most of the waste is food, plastic, paper, metal, glass, textiles and ash. In the winter 49% of the waste is ash related to heating. Therefore, introducing more renewables would also help to remove parts of the waste problem.

According to the Ulaanbaatar masterplan (Stryi-Hipp *et al.*, 2018), by using a daily quantity of 1.2 kg of waste per capita Ulaanbaatar city will in 2050 generate around 1.1 Mt per year. The underlying assumption here is that increased waste recycling will be counterbalanced by an increase in welfare, which typically generates larger quantities of waste per capita. The heat production potential from the identified waste quantities is 2.2-2.9 TWh depending on the type of incineration plant. In 2050 that would be sufficient to cover between 17-23% of the annual district heating supply.

3.11 Excess industrial heat

Excess (or waste) industrial heat can be defined largely as heat generated as a by-product of any industrial process. Excess industrial heat sources are typically related to processes such as boiler losses, heating/boiling, drying, evaporation, distillation, furnaces, melting, air compression, cooling, refrigeration and space heating. In conventional district heating systems, mainly energy-intensive industries (manufacture of cement, paper, glass, metals *etc.*) are considered as they have the required temperature level.

Table 6 presents an overview of typical industrial processes, industries and temperature levels. It has not been possible to identify any of these in the current project. However, it is strongly recommended to look into these heat sources, especially the higher-temperature sources, as they can have significantly lower heat production costs than the alternatives.

Table 6 **Overview of processes, typical industries, temperature level and medium**

Process	Typical industries	Temperature level (°C)	Medium
Melting	Metal, glass, ceramics and concrete	300-400	Flue gas
Furnaces	Cement and brick	200-250	Flue gas
Boiler losses	Refining, food and beverages	160-250	Flue gas
Other heating	Hardening, annealing and singeing	150-200	Cooling water and flue gas
Drying	Food, paper, chemicals, concrete and bricks	125-225 textile 30-40 scrubbing 80-100 average	Warm, humid air
Heating/boiling	Oil refineries, food and beverages, textiles, chemicals, concrete and metals	70-90	Water
Compression air	Food, chemicals, pharmaceuticals, refining, plastics, glass and machinery	60-80	Cooling water or air
Distillation	Oil refining, food and chemicals	40-60	Vapour
Evaporation	Food and beverages, pharmaceuticals and chemicals	35-50	Hot water
Cooling and refrigeration	Food and beverages, pharmaceuticals and chemicals	90% 20-40 10% < 140	Cooling water or air
Space heating	Manufacturing sector	20-30	Air

Based on: Huang *et al.* (2015).

In low-temperature district heating systems, low-temperature heat sources could also be relevant. In recent European studies (Persson *et al.*, 2020) there are examples of district heating systems using waste heat from refrigeration in food retail, wastewater treatment, metro stations, data centres and electricity transformer stations. These are also heat sources that could be relevant to Mongolia in the long term.

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3.12 Thermal storage

Generally, thermal storage for district heating can be grouped into short-term or long-term. Short-term storage is used within days, while long-term storage is used to store heat for several weeks or months. Short-term storage is very common, while seasonal storage is typically used to extend solar thermal use in district heating systems.

Hot-water tanks are used for short-term storage, in the form of steel, concrete or plastic (reinforced with glass fibre). The most common are steel tanks, with inlets and outlets at the top and at the bottom of the tank, respectively. In larger storage tanks, more distributed outlets are added to utilise the different temperature layers of the storage medium. The technology is well-known and applied broadly within the district heating sector. In Mongolia, short-term storage could be used in combination with heat pumps to integrate more renewable electricity into the heating system, *e.g.* between night and day.

There are three main long-term storage technologies: pit thermal energy storage, borehole thermal energy storage and aquifer thermal energy storage.

Pit thermal energy storage (PTES) is typically used for seasonal storage in smaller district heating areas, often in combination with solar thermal collectors. PTES is basically a large water reservoir for storing thermal energy. The technology is relatively cheap as it is a hole in the ground using a waterproof membrane and covered by an insulating lid. PTES has a relatively large land area requirement compared to other types of storage. PTES varies in size from 50 000 m^3 to 500 000 m^3, which equals around 5 000-40 000 MWh for a full charging cycle (Danish Energy Agency, 2018).

Borehole thermal energy storage (BTES) comprises tubes in boreholes and are typically operated in combination with heat pumps. BTES storage uses the ground as a storage medium instead of the water used in PTES. In a BTES the warm water is pumped into the tubes and is transferred to the surrounding soil and rocks. When the storage is discharged, cold water is pumped through the tubes and picks up the heat that was stored in the surrounding soil and rocks. BTES storage operates at low temperature levels, in the range of 0-30°C, but in some cases up to temperatures as high as 90°C. Therefore, these types of storage are more feasible in low-temperature district heating systems. BTES requires a relatively small land area, where the surface in some cases can be used for other purposes as well. In the Ulaanbaatar case study, BTES storage has not been included, but it could be an option in Mongolia.

In the case of Mongolia, it is mainly steel tanks and PTES options that are relevant; however, it could also be relevant to examine whether abandoned mines close to cities could be used for storage, as seen in Spain for example (Roberto Mayoral Fernández, 2021).

4 Case studies

This section of the report includes the three Mongolian case studies that have been studied in the SHP to varying levels of detail. The first case study is a detailed energy system analysis of Ulaanbaatar. Various factors such as the air pollution effects, the energy efficiency of different technologies and the total system cost are integrated in the analysis. The results relating to the existing district heating supply are initially presented, then the results outside the district heating coverage area are presented, and finally a discussion of the broader implications of the case study results is presented. The second case study is a simpler energy system analysis focusing on solar thermal implementation in the town of Khovd. The third case is a short review that focuses on geothermal heat in the city of Tsetserleg.

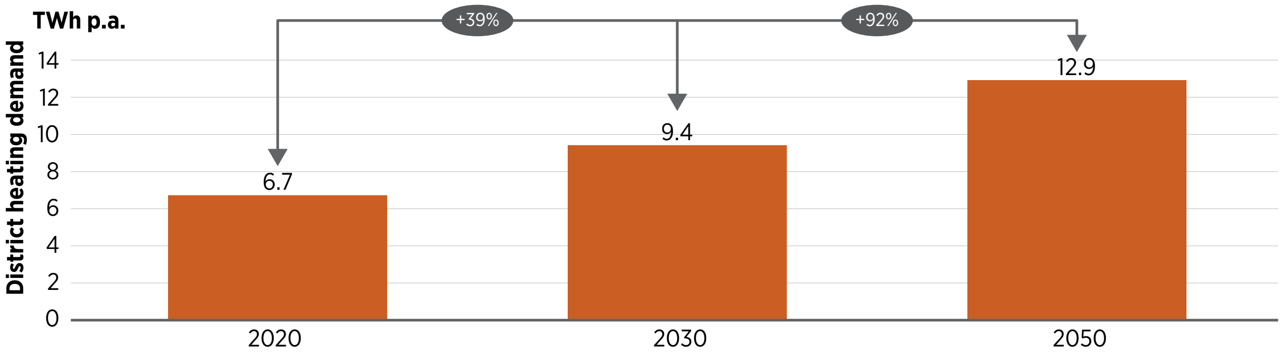
4.1 Case study 1: Ulaanbaatar

While the scope of this report lies mainly with the heating sector, it is important to realise that it is not a stand-alone sector in the energy system and including other sectors would enable cross-sectoral synergies to be assessed, such as waste heat recovery from industrial processes. This might not be apparent in a single sector analysis, which often leads to systems that are not socio-economically optimal. Hence a holistic energy system analysis would result in a more socio-techno-economically beneficial energy system that incorporates other sectors such as transport, industry and power, along with the principles outlined in this report for strategic heat planning and making use of the locally available resources and geographically distributed heating demands. With that said, the purpose of this section is to give insights into the dynamics of the Ulaanbaatar heating sector as one part of the energy system.

The overall approach to the scenario analysis, along with the cost and performance data that are applied in the analysis, are presented in Chapter 2 above. The resulting scenario configurations and results from the energy system analysis are presented in this section.

The projected district heating demand in 2050 is almost twice the level in the current system, as illustrated in Figure 36. The demand modelling behind this projection is presented in Chapter 3.

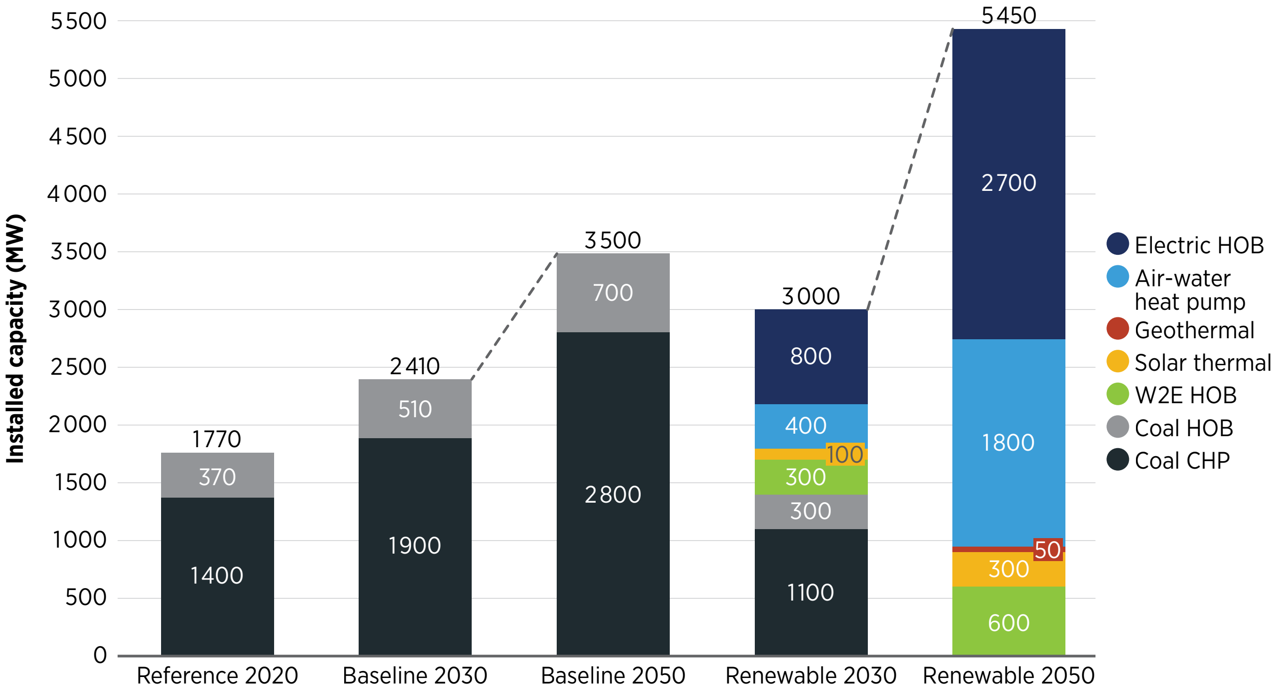
Figure 36 **The development of district heating demand in Ulaanbaatar from 2020 to 2050**



Note: TWh p.a. = terawatt hours per year.

The current heat supply system consists of a set of ageing coal-fired CHP and HOB units that may be replaced in the coming 5-10 years. Furthermore, the projected large increase in demand prompts a need to expand the supply capacity significantly. Building on the Reference 2020 case, the 2030 short-term case and the 2050 long-term case, two alternative pathways for development of the supply system have been investigated: a Baseline fossil-based system and a Renewable energy-based system. The assessed pathways only cover the district heating demand and do not consider demands from other energy sectors, such as the electricity demand of Ulaanbaatar. In that regard it would be highly relevant to carry out a broader integrated system analysis, to explore potential synergies across sectors. The resulting district heating supply systems of the two assessed pathways are illustrated in Figure 37.

Figure 37 **Installed heat capacity in the various assessed cases, by deployed technologies**



Note: CHP = combined heat and power; HOB = heat only boiler; MW = megawatt; W2E = waste to energy.

The Baseline 2050 system is a continuation of the existing system, except for the complete replacement of the existing coal plants with highly modern coal power plants with higher overall efficiencies and filtering of air pollutants such as $PM_{2.5}$ and PM_{10}. Coal CHP capacity is scaled according to the configurations. However, the adequate dimensioning of the CHP capacity could be dependent on the surrounding electricity system. Coal-fired HOBs are deployed to provide back-up capacity and to cover the remaining demand peaks. The coal-fired units that are deployed in the Baseline fossil fuel-based systems are provided with flue gas cleaning equipment that reduce the air pollution from coal firing significantly, but at an additional operation and maintenance (O&M) cost compared to plants with no flue gas cleaning.

The Renewable 2050 system is designed based on utilising renewable energy resources. The scaling up of the units such as solar and geothermal depends on the availability of land and the geothermal and solar potential. The capacity applied in this system is a precautionary estimation, and further feasibility studies would assist with estimation of local potential calculations. It can be seen that a higher capacity needs to be installed in the Renewable 2050 system as compared to the Baseline 2050 system. This is because of the additional installation of backup electric boilers which are expected to kick in when the renewable powered (wind and solar powered) air-water heat pumps as well as solar thermal collectors are not producing heat, due to the variable nature of wind and solar energy.

Mongolia has great renewable resource potential; this is covered further in Chapter 3. In addition to solar thermal and geothermal options, the assessed cases with Renewable systems explore the integration of electricity from wind and solar via air-water heat pumps, which can lead to an effective and flexible district heating system. The potential for large-scale air-water heat pumps is, however, limited in Ulaanbaatar due to the very low temperatures (below -20°C) that occur for around 1 400 hours during the winter. To enable the effective utilisation of heat pumps, as well as the other renewable sources deployed in the Renewable 2050 system, a 65 GWh seasonal heat storage (PTES) has been implemented to balance the variable renewable resources with temporal demand. PTES is a low-cost energy storage solution but has very high space requirements. PTES storage capacity of 65 GWh has an estimated volume of around 1 million m^3.

Around 500 000 m^2 of solar thermal collectors have been installed in the Renewable 2050 system. Solar thermal collectors are a relatively cheap option but have relatively large space requirements and typically rely on complementary heat storage to be feasible for large-scale deployment. However, this area works out to be only 0.001% of the overall area of Ulaanbaatar city, considering the region's overall area to be approximately 1 800 km^2.

The geothermal potential in Mongolia is rather unexplored with estimates ranging from 200-2 500 MW_{th}. The country is located on the Central Asian Orogenic belt, which is a region with a high concentration of geothermal resources. The exact locations and availability, however, remains somewhat unexplored. The Renewable 2050 system includes a conservative capacity of around 50 MW_{th} of deep geothermal in 2050.

The estimated waste-to-energy potential in Ulaanbaatar, as covered in Chapter 3, is fully utilised in the Renewable scenario via waste incineration boilers, and forms a baseload complemented by the geothermal plants. Both technologies have relatively high fixed costs and low operating costs, and require high capacity factors to become economically feasible.

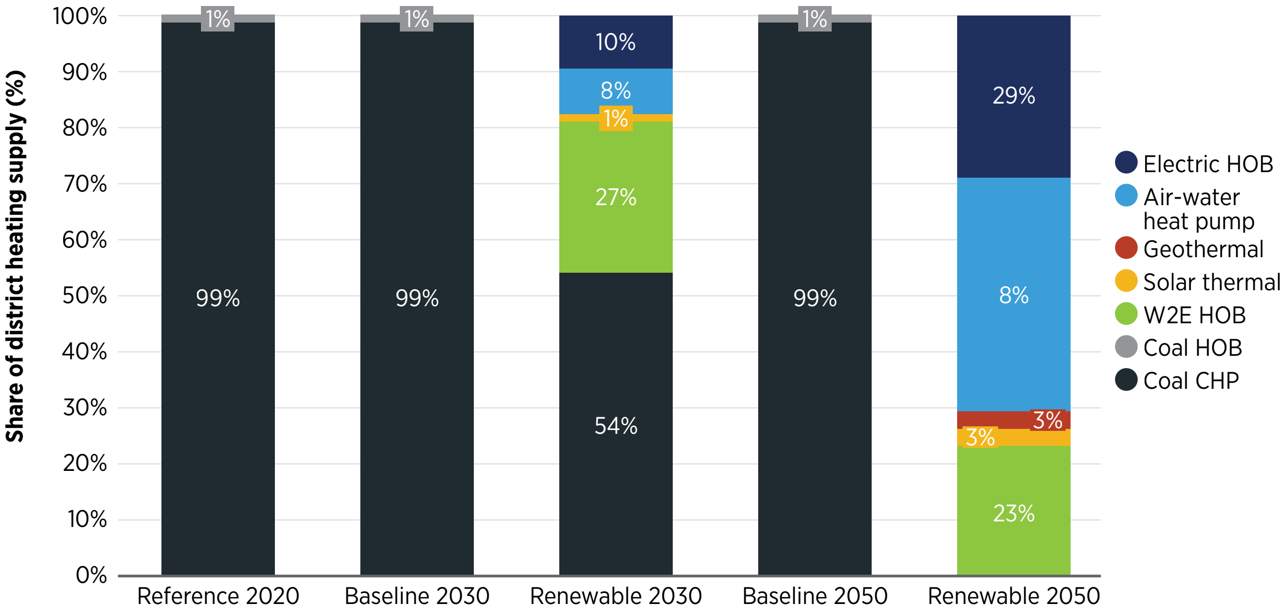
Around 1 800 MW_{th} of heat capacity from large-scale air-water heat pumps is installed in the Renewable scenario in 2050.

As waste-to-energy, solar thermal and geothermal cover the majority of the heat load during the summer, the heat pumps are limited to producing storage during this low-demand period, and see the majority of their operation during the heating season, albeit when temperatures are above -20°C. Electric HOBs are installed as the back-up to the system whenever the other supply options are not sufficient to meet demand. Electric HOBs have relatively low fixed costs, but high operating costs, and are usually operated as peak load units. The electric HOBs could be complemented with other HOB options, such as gas HOB or similar, depending on the availability of other resources.

Around 1 350 MWe of onshore wind and 750 MWe of solar PV are installed in the Renewable 2050 system to cover the full electricity demand of the heat pumps and electric HOBs. As the heat pumps and electric HOBs are not operating fully flexibly, there is a need to balance electricity production distributed via the grid. A broader integrated energy system analysis is vital to ensure the effective integration of wind and solar electricity into the heating system.

The relative distribution of the heat production from the supply units in the assessed cases is illustrated in Figure 38.

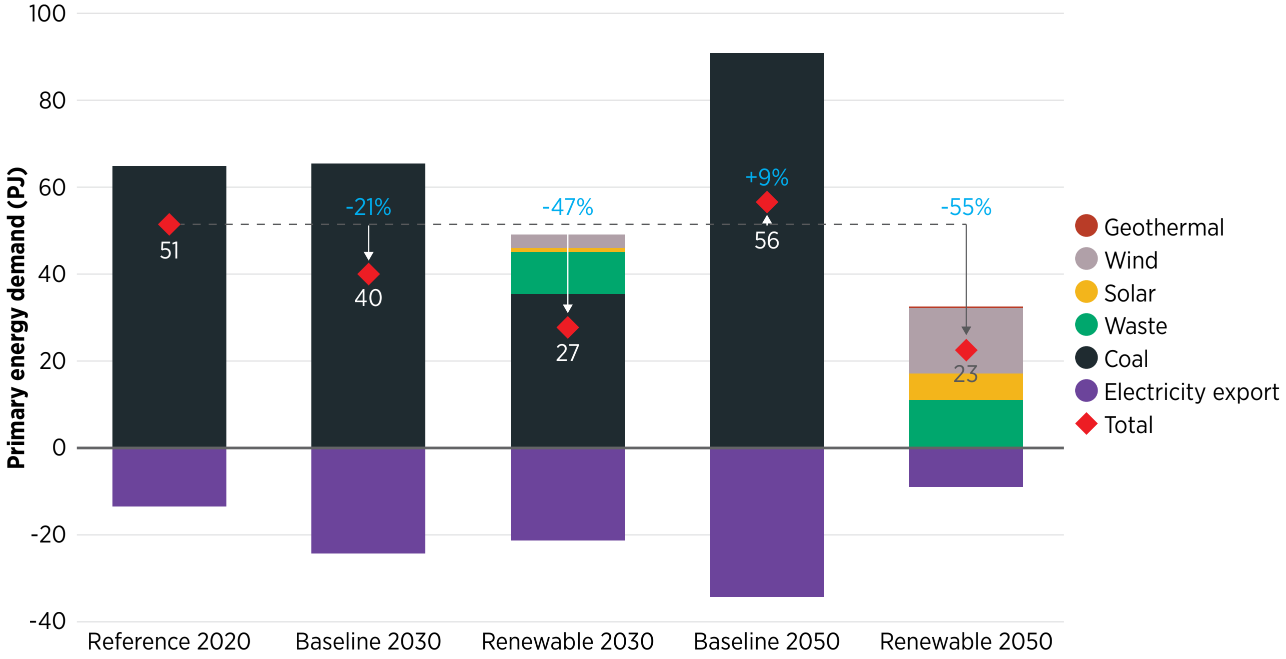
Figure 38 **The heat supply share of the deployed technologies in the 2020, 2030 and 2050 cases**



Notes: CHP = combined heat and power; HOB = heat only boiler; MW = megawatt; W2E = waste to energy.

An efficient district heating system results in lower primary energy demand. The Baseline system sees a slight decrease in coal consumption from 2020 to 2030, despite an increase in district heating demand. This is achieved through the replacement of the ageing CHP units, with highly modern coal CHP plants that have higher overall efficiencies. In 2050, coal consumption increases in the Baseline system by around 30% compared to the Reference 2020 case due to growing demand. The Renewable 2050 system is designed to be efficient, and results in a decrease in primary energy demand of around 30% despite a doubling of demand by 2050. The resulting primary energy demand for each scenario is illustrated on Figure 39, which includes an electricity import/export balance.

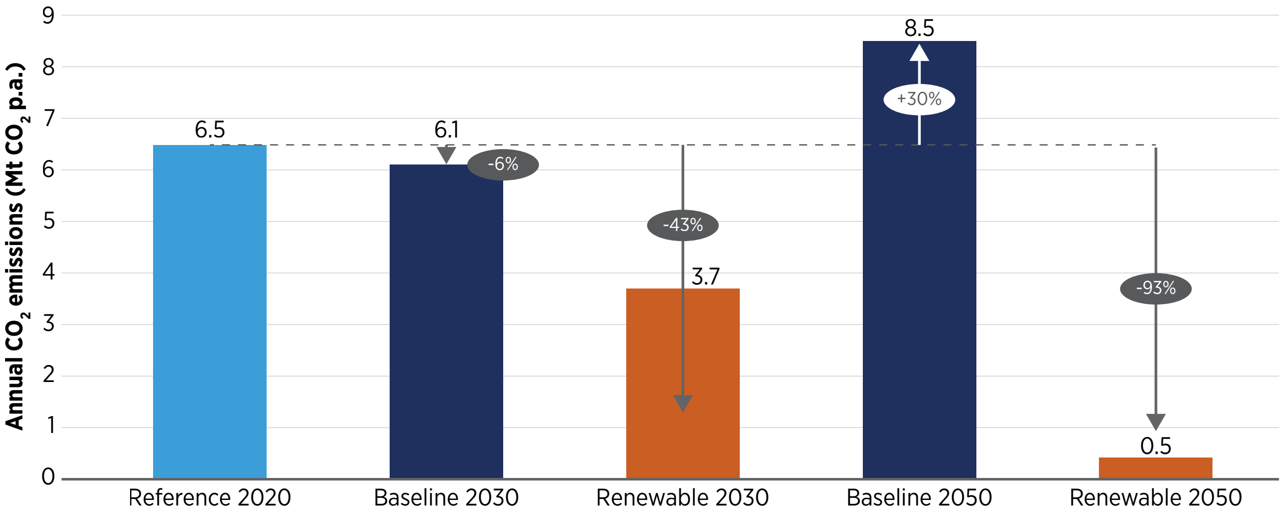
Figure 39 **Primary energy demand including electricity export balance for the assessed cases**



Note: PJ = petajoule.

The energy system analysis also includes a calculation of the resulting CO_2 emissions in each scenario. The Reference 2020 scenario results in annual CO_2 emissions of 6.5 Mt. The Baseline system sees a slight decrease to around 6.1 Mt CO_2 in 2030, due to new CHP units with higher efficiencies. In 2050 the emissions in the Baseline system increase to around 8.5 Mt CO_2. The Renewable 2050 system sees a drastic decrease in CO_2 emissions compared to the Reference 2020 case. By 2030 annual emissions decrease by 43% to approximately 3.7 Mt. In 2050 CO_2 emissions are reduced to 0.5 Mt and achieve a 93% reduction compared to the Reference 2020 case, with the waste-to-energy plants as the only remaining emitter. To achieve full decarbonisation, carbon capture, utilisation and storage (CCUS) can be implemented on these waste incineration units. The development of CO_2 emissions is illustrated on Figure 40.

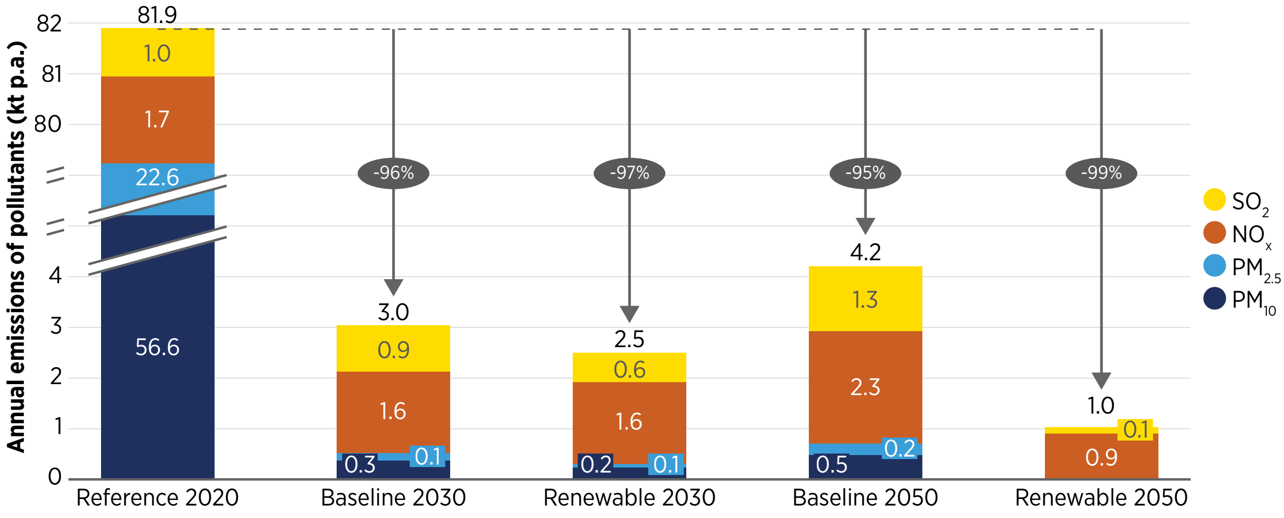
Figure 40 **The resulting annual CO_2 emissions in the assessed cases**



Note: $MtCO_2$ p.a. = million tonnes of CO_2 per annum.

Emissions of other air pollutants, including SO_x, NO_x and PM, fall drastically across all assessed cases as shown in Figure 41; however, this is related to a large degree of uncertainty surrounding the validity of the applied emission factors, which can be found in Table 11 in Appendix A. Modern and efficient coal power plants can reduce air pollution through the installation of a comprehensive pollutant filtering system, which can lead to large reductions compared to the existing CHP plants. However, the validity of the available data on pollution levels from the existing CHPs is uncertain. The Renewable 2050 system demonstrates very low emissions of air pollutants.

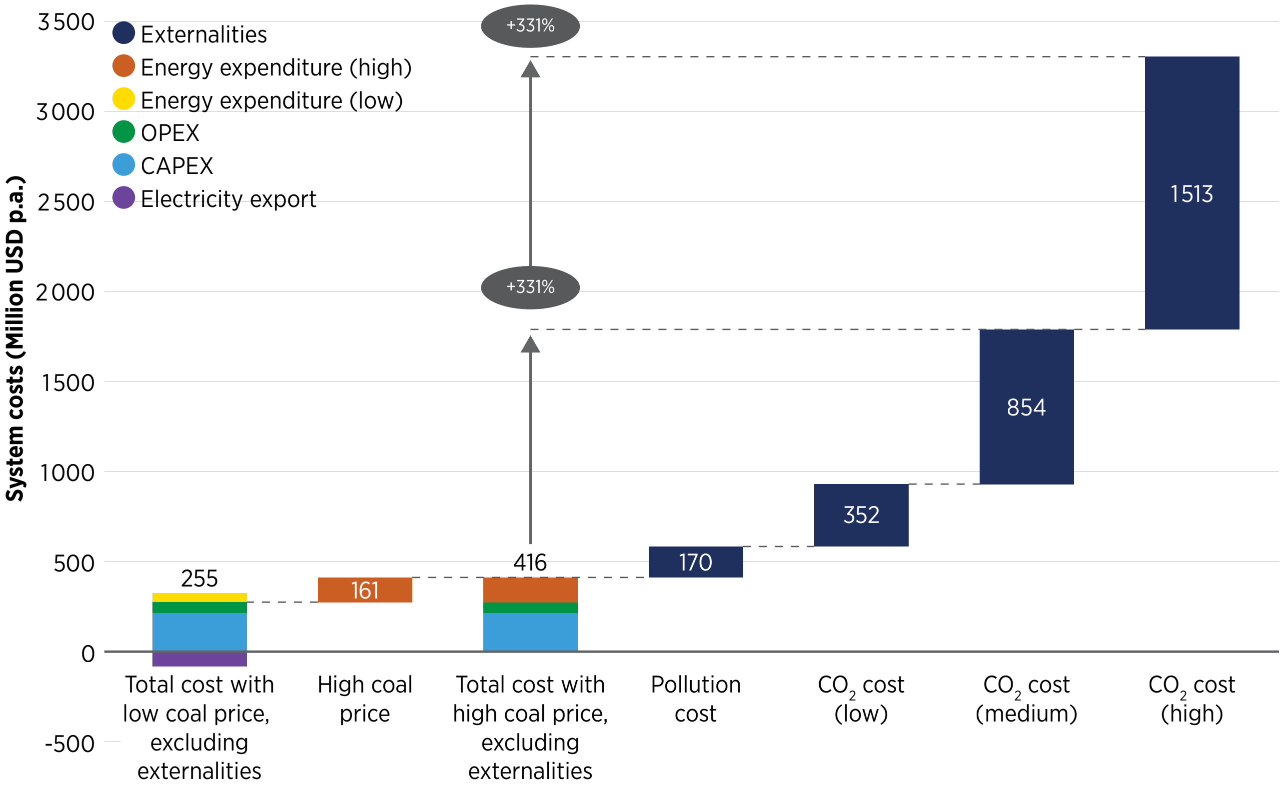
Figure 41 **The resulting annual emissions of pollutants from the assessed cases**



Notes: The y-axis is compressed between 4 kt and 80 kt per annum; kt p.a. = kilotonnes per year.

The cost analysis of the assessed cases relies on the costs related to various assumptions, which can be found in Chapter 3. In this study, the cost of coal and the cost of externalities are subject to considerable uncertainty. Figure 42 illustrates the impact of different cost assumptions on the Reference 2020 case. The system cost excluding the cost of externalities can be seen in the first three left-hand columns in Figure 43. The first column shows the cost of the system at the lowest screened coal price, and the third column shows the system cost with a coal price (high expenditure) from the International Energy Agency. The four right-hand columns show the cost of including externalities in the system cost. The actual costs of CO_2 are difficult to quantify, but this study relies on three studies on the cost of CO_2 emissions with three different cost levels. The figure shows the impact of applying each of these cost assumptions. For this study the low coal cost and the medium CO_2 cost have been applied.

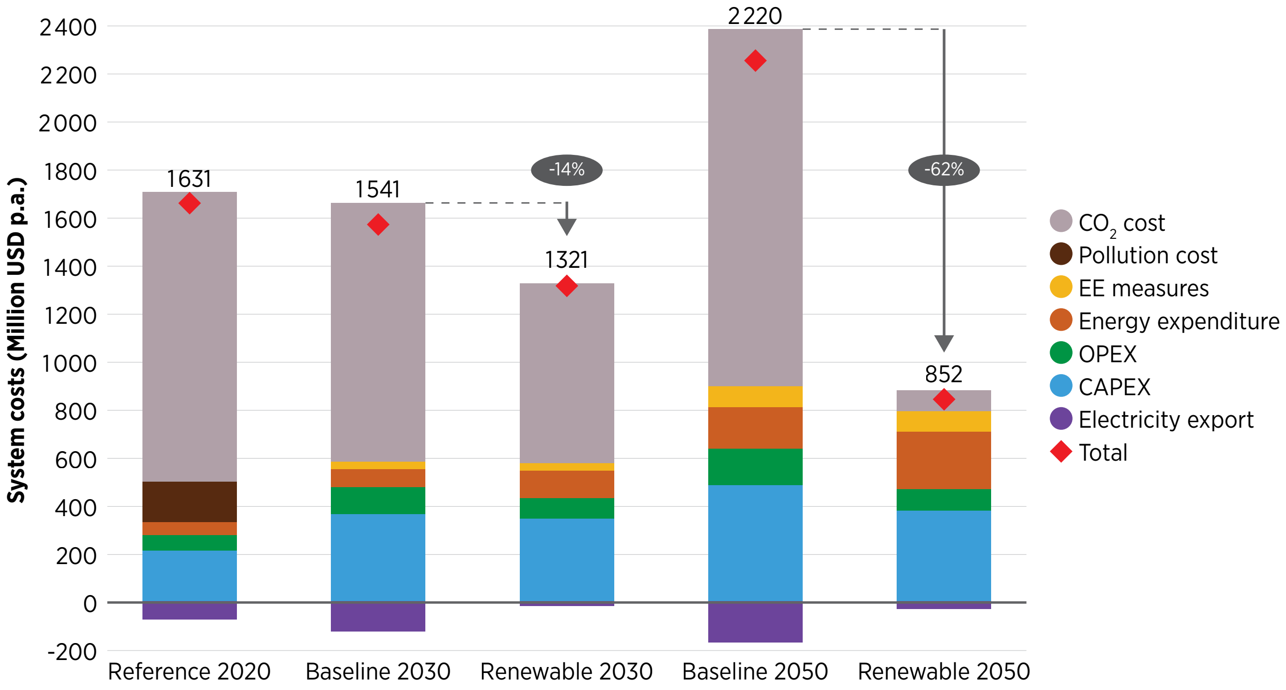
Figure 42 **The potential costs related to the Reference 2020 case**



Notes: The first stacked column represents standard costs excluding externalities and a low coal price. The second column is the additional cost from a higher coal price scenario. Cost of externalities are then added on top, for local pollutants and CO_2 emissions at a low, medium and high cost; CAPEX = capital expenditure; OPEX = operating expenditure.

The resulting system costs of the assessed cases are presented in Figure 43. The analysis shows that the Renewable 2050 system is the most cost-effective. This leads to system cost savings of around 62% compared to the Baseline 2050 fossil fuel-based system. The savings are mainly related to the cost of externalities, which are typically not accounted for in Mongolia today. This analysis shows that the Renewable 2050 system is a feasible alternative to the Baseline fossil-based district heating system in Ulaanbaatar. Furthermore, an integrated energy system analysis including other energy sectors can assist in identifying cross-sector synergies that could make the Renewable 2050 system yet more cost-effective.

Figure 43 System costs related to the investment and operation of the assessed cases by categories



Notes: Electricity export is an income in cases where export is applied; CAPEX = capital expenditure; EE = energy efficiency; OPEX = operating expenditure.

4.1.1 Discussion of alternative pathways

The Renewable 2050 system achieves almost complete decarbonisation of the heat supply in Ulaanbaatar, with waste incineration being the only source of GHG emissions. Completely excluding waste incineration from the Renewable 2050 system could lead to more expensive heat tariffs, all things being equal. Furthermore, other solutions would have to be implemented to mitigate the negative effects of landfills, including environmental pollution and production of methane, which is a potent GHG. Waste incineration technologies that are commonly applied in district heating supply include CHP and HOB technologies. A number of waste incineration HOBs with comprehensive flue gas treatment systems are deployed in the Renewable 2050 system, as they are a cheaper investment compared to CHP; however, both are valid and efficient options. Waste incineration units often operate as a baseload at very high capacity factors. This makes them viable options for carbon capture systems. Oxy-fuel combustion is a carbon capture technology that can prove to be more economically efficient than scrubber solutions. Oxy-fuel combustion requires comprehensive and costly retrofitting to existing plants, but can prove to be a viable option for new-builds where it can be integrated in the system design. The CO_2 can be utilised in CCUS value chains or stored in underground caverns to prevent their emission, which contribute to global warming.

Thermal storage is a viable solution to balance variable renewable energy solutions and is more cost-competitive compared to other storage solutions such as utility-scale lithium-ion batteries. In the Renewable 2050 system, a total storage capacity of about 65 GWh is deployed. This is a large capacity and has a total volume of around 1 million m^3. In comparison, the Danish town of Vojens has installed 200 000 m^3 of PTES in combination with a 70 000 m^2 solar heating plant. In combination, they provide energy for 2 000 out of 4 000 heating consumers in the district heating grid (Ramboll, 2015). This study identifies a 1 million m^3 PTES plant as an optimal size in combination with a total of 500 000 m^2 of solar heating, and 1800 MW_{th} of air-source heat pumps. The PTES integrates solar and wind electricity in the system, and a sensitivity analysis of the Renewable 2050 system shows that the PTES enables annual savings of approximately USD 42 million, corresponding to about 5% of the overall system cost, compared to a similar system with no thermal storage. The savings are mainly related to a reduction in operational expenditure from procuring electricity for electric boilers. A PTES plant of half the size (500 000 m^3) correspondingly results in savings of up to USD 20 million annually.

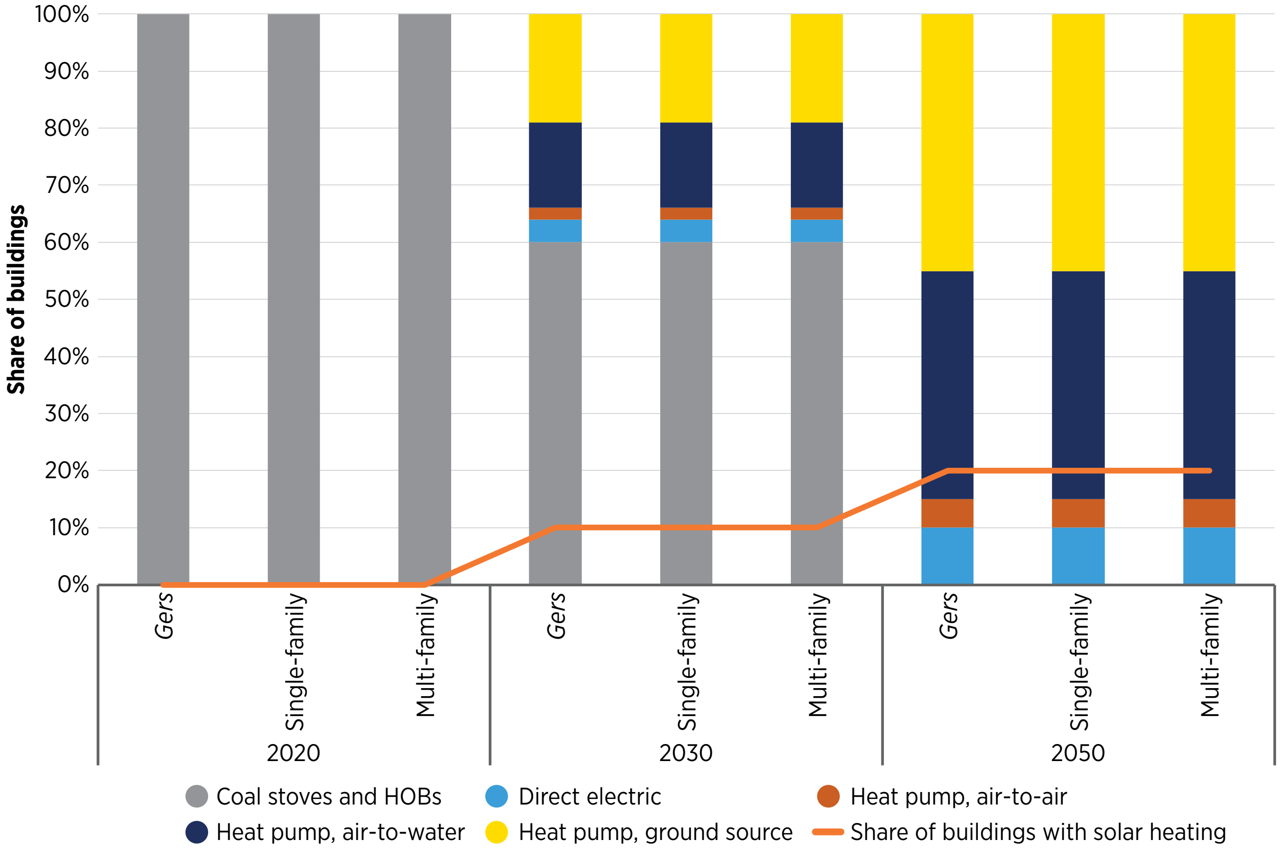
Other resources such as natural gas can potentially play a role in future district heating supply in Ulaanbaatar. CO_2 emissions and air pollution related to combustion of natural gas are significantly lower compared to the combustion of coal. An additional case has been investigated in this study, where 9.5 PJ of natural gas is fired in a district heating boiler and contributes to the supply in 2050. In this additional case, the Renewable 2050 system may be redesigned to integrate the gas boiler into the system. The gas boiler allows for optimising the operation of the electric boilers, so they can operate when there is no available electricity from wind and solar. The 9.5 PJ of natural gas supplies around 20% of the demand in the system. The CO_2 emissions related to the natural gas combustion are around 500 000 tonnes, which approximately doubles the emissions compared to the Renewable 2050 system. This achieves a reduction of about 5.5 Mt CO_2 compared to the existing system, corresponding to a reduction of 85%. This system with a natural gas unit achieves 70% renewables integration, and results in cost savings compared to both the Baseline 2050 and Renewable 2050 systems, when applying the medium CO_2 externality cost.

4.1.2 Individual heat supply outside district heating

The mapping of existing buildings in Section 3.3 shows the total number of buildings outside district heating to be 210 518 buildings and 54 531 *Ger* tents. Of the buildings, 208 105 are single-family dwellings. The heat demand in the buildings is expected to be reduced from 6.3 TWh/year in 2020 to 3.2 TWh/year in 2050 due to a gradual implementation of energy efficiency measures, while the *Ger* tents are assumed to be 0.4 TWh/year in both 2020 and 2050.

Figure 44 shows the transition of the existing buildings into a renewable supply, where the 2020 supply is dominated by coal stoves and HOBs, and a combination of the supply technologies presented in Appendix A are gradually implemented towards a 100% renewable supply in 2050. Here the main technologies are heat pumps and electric boilers in combination with 20% solar thermal in 2050. The heat pumps are split between ground-source and air-source heat pumps, as both are expected to have a role in the future energy system.

Figure 44 **Share of existing buildings by heat supply type outside district heating in transition to renewables**



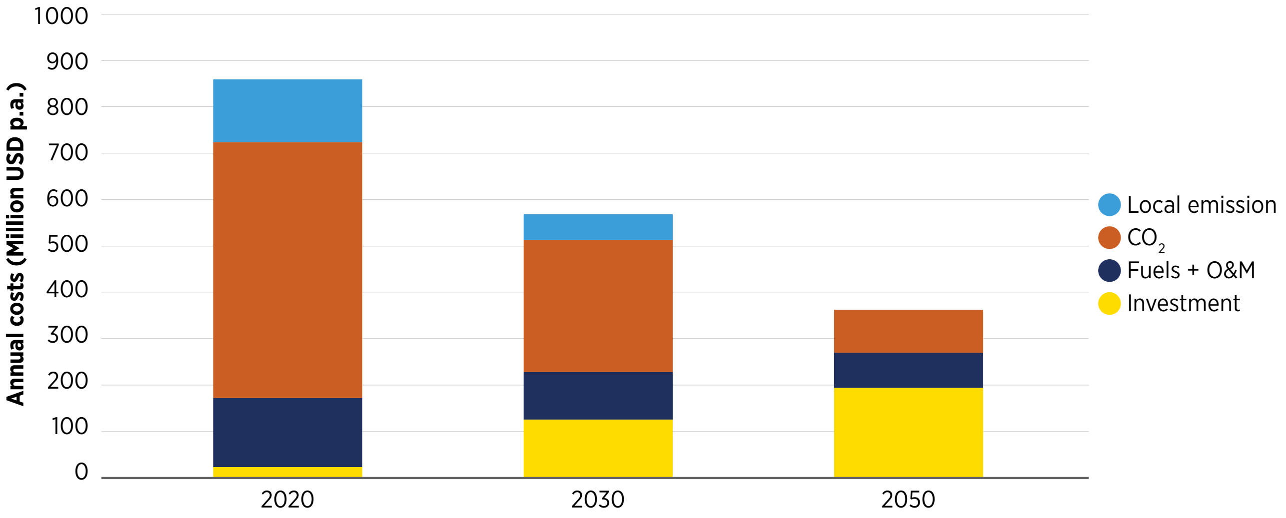
Note: HOB = heat only boiler.

Transitioning to these technologies is estimated to reduce the annual CO_2 emissions from 2.98 Mt in 2020 to 1.54 Mt 2030 and 0.5 Mt in 2050, and the air pollutant emissions by 41% from 71.9 kt in 2020 to 29.4 kt in 2030, and to zero in 2050.

Figure 45 shows the annual costs related to the transition of the supply outside the district heating coverage area. The investment costs would increase from USD 22.8 million in 2020 to USD 126 million in 2030 and 194.2 million in 2050. However, taking a system perspective of the whole individual heating sector, this would provide a considerable cost saving in 2050 due to a reduction in fuel purchase and emissions. The total annual system costs would reduce from USD 858 million per year in 2020 to USD 568 million per year in 2030 and USD 362 million per year in 2050. The reason for this reduction is that in the 2020 supply, USD 686 million per year are related to emissions, while in the 2050 system this cost is reduced to USD 92 million per year. The investment costs are significantly higher in the 2030 and 2050 systems, while the fuel and O&M costs are lower. It is also evident that if emission costs are not included, then the 2020 system is cheaper than the other systems, mainly due to the low prices for coal.

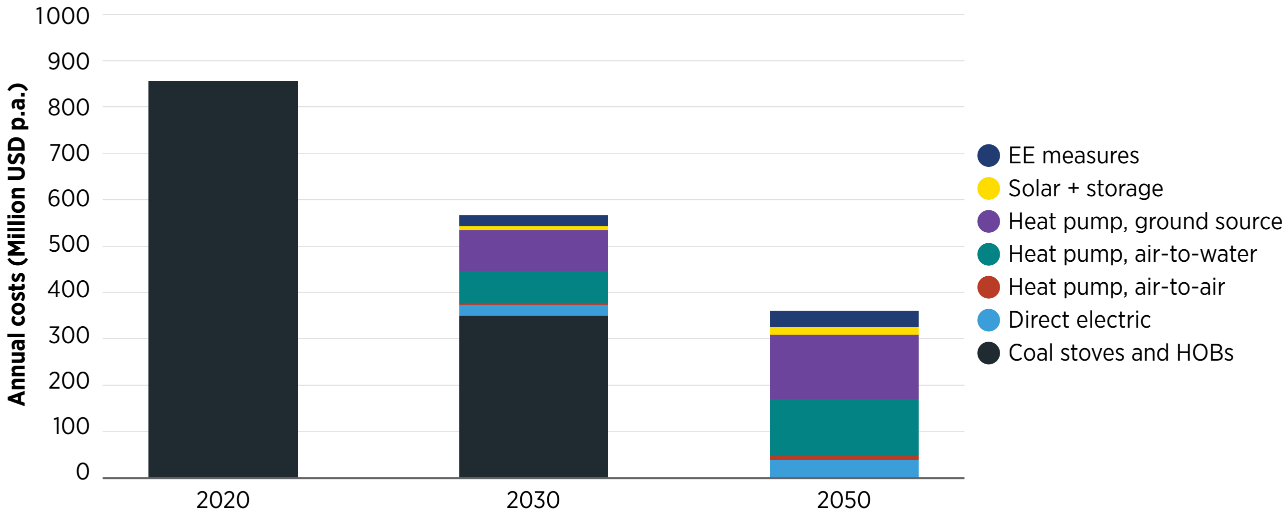
Figure 46 shows the same annual cost but split by technology. Here, the costs are mainly attributed to heat pumps and energy efficiency measures.

Figure 45 **Annual costs by cost category for existing buildings outside district heating area**



Note: O&M = operation and maintenance

Figure 46 **Annual cost by supply technology for existing buildings outside district heating area**

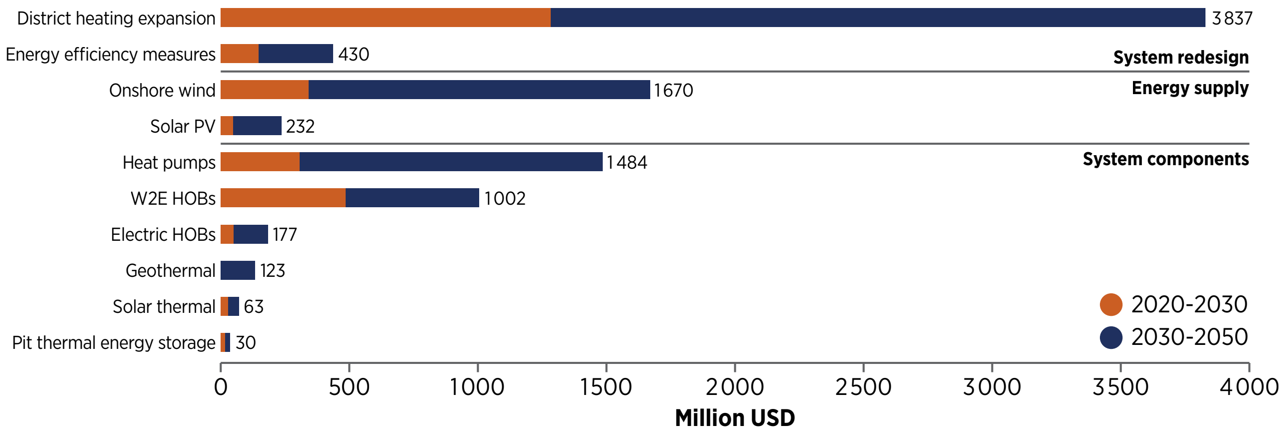


Note: HOB = heat only boiler; EE = energy efficiency.

4.1.3 Investment roadmap

In order to decarbonise the Ulaanbaatar heating sector by 2050, some investments need to be prioritised. The following two figures provide an indication of the major investments needed in terms of system components, renewable energy supply and system redesign measures such as energy efficiency improvements in buildings and district heating expansion. Figure 47 shows the major investments needed from 2020 to 2030 and 2030 to 2050 for centralised district heating, whereas Figure 48 shows the major investments for individual heating.

Figure 47 **Major investments in Ulaanbaatar district heating to 2050**

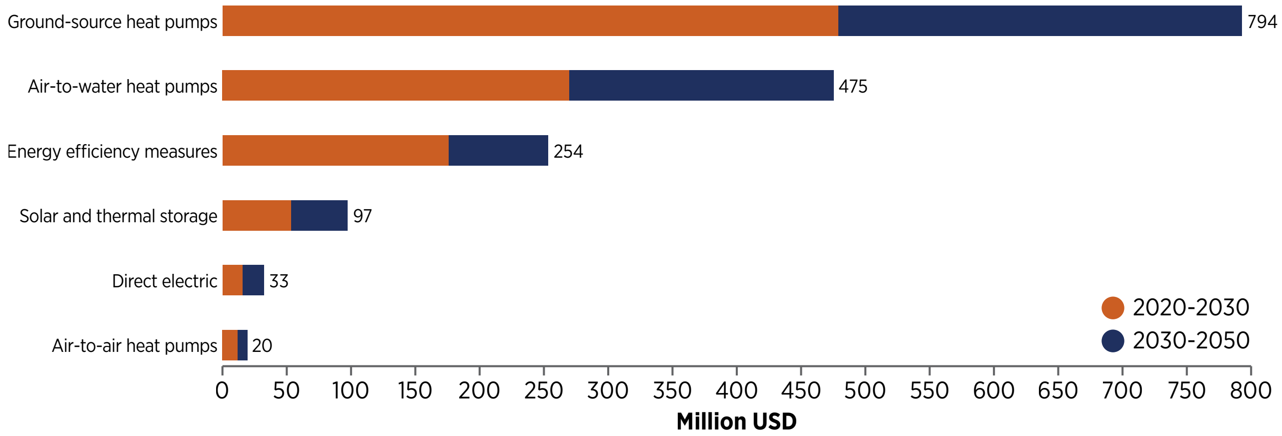


Notes: HOB = heat only boiler; W2E HOB = waste-to-energy heat-only boiler.

For the period 2020-2050, in terms of system redesign, around USD 3.8 billion needs to be spent on the district heating system. This includes both replacing old district heating pipes and the expansion of the district heating network to existing and new buildings. It is assumed that these investments are made gradually and linearly from 2020 to 2050. As detailed in Section 3.2, the analysis suggests that the district heating share in 2050 for Ulaanbaatar city (excluding *Ger* areas) should be expanded to cover around 80 % of all new and existing buildings.

District heating expansion is quite important for large-scale integration of renewable energy as it allows the maximisation of electrification on the supply side via heat pumps, for instance, hence integrating more renewables and lowering costs when coupled with other sectors. On the supply side, around USD 1.67 billion needs to be spent on onshore wind, most of which is invested later during the period 2030-2050 when coal is slowly displaced from the district heating network and the demand for electricity in the heating system increases. On the system components, air-source heat pumps constitute a major proportion of the total investment, followed by waste-to-energy HOBs. Figure 48 outlines the major investments in individual heat supply systems for the two periods.

Figure 48 **Major investments in Ulaanbaatar individual heating to 2050**



As seen from the figure above, regarding the system redesign, a total of USD 254 million needs to be spent on energy efficiency improvements of single-family and multi-family houses, and *Gers* up to 2050. Almost 70% of that investment needs to be made during the period 2020-2030 to ensure energy savings alongside renewable technology implementation.

From the technology side, as also mentioned in the previous sub-section, heat pumps (both ground-source and air-source) make up more than 80% of the individual heating supply, half of them installed before 2030 and the other half between 2030 and 2050.

4.1.4 Broadening of the case study results

The intention with the Ulaanbaatar case study is to show the technological shifts needed to transition towards a 100% renewable heat supply. In the other Mongolian cities, it would require a similar shift in technologies as presented in the Ulaanbaatar case study. However, as both heat demand and energy resources are different across the country, the results cannot be transposed from Ulaanbaatar to another city. For other cities it is important to investigate the same shifts as presented in the case study, but to a different degree.

To determine how much district heating should be built in other cities, the mapping of heat demand and heat densities is needed, as the high-density areas are most feasible for district heating. Heat demand will follow the outdoor temperature, so in colder areas it will be higher while in warmer areas it will be lower. In addition to the existing buildings, it is important to estimate how many new buildings will be built, and if these should be connected to district heating. As seen in the Ulaanbaatar case, this can be a significant addition to the existing heat supply; however, this will also be different from case to case.

The heat supply technologies will be like that of the Ulaanbaatar case study, but the local availability of different renewables and heat sources is an important factor. In some regions the solar potential might be higher than in Ulaanbaatar, so solar could provide a larger share in these areas. In cities colder than in Ulaanbaatar, direct electric heating might be required to a greater extent, as air-source heat pumps can struggle on the coldest days. In general, the electric heat supply solutions need to be positioned so that renewable electricity can be used in areas with very poor connection to the main electricity transmission system; local renewable electricity generation therefore needs to be expanded as well. In the Ulaanbaatar case study, excess heat from waste incineration is also a significant part of the baseload production; in other cases this could be replaced by, for example, geothermal energy or waste heat from other sources. The mapping of renewable energy sources shows that solar, wind and biomass should be available in many places, and as Mongolia is sparsely populated, the land requirements should not be an issue.

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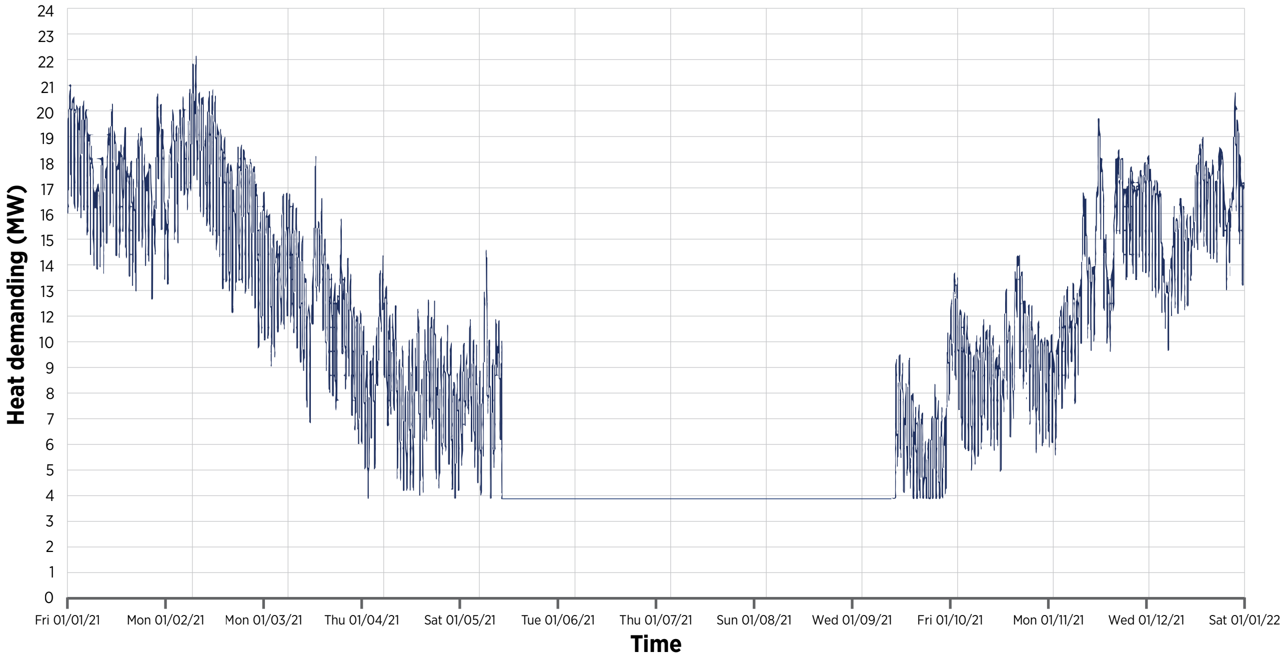
4.2 Case study 2: Integration of solar energy into the district heating supply of Khovd

The town of Khovd is situated in the western part of Mongolia. The existing district heating demand of Khovd is around 85.5 GWh/year, which is provided by a single coal-fired heat-only boiler of around 25 MW$_{th}$ heat output capacity. The peak heat demand for the city is around 22 MW$_{th}$, as shown in Figure 49. The heating season assumed for the analysis lasts from around mid-September till mid-May, whereas the non-heating seasonal demand remains almost constant at around 4 MW$_{th}$. This situation is very similar to most other Mongolian towns outside Ulaanbaatar. Therefore, it is relevant to examine the feasibility of replacing coal with renewable energy sources.

Figure 49 **Yearly temporal heat demand distribution for Khovd**



Source: Saha *et al.* (2014)

Note: MW = megawatt.

To incorporate more renewables in the existing heating system, a preliminary analysis of adding solar thermal and thermal storage was performed. Table 7 shows the techno-economic parameters used for the renewable components. In addition, a discount rate of 8.75% and a coal price of USD 11.96/t were used for the calculations.

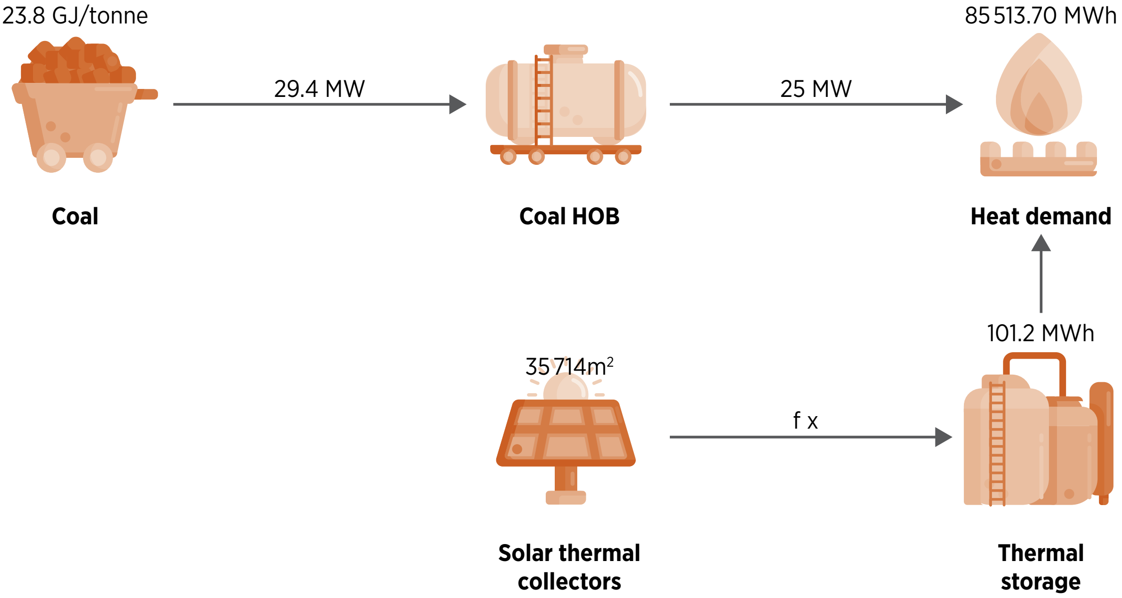
Table 7 **Techno-economic parameters for renewable components**

	Year	Round trip efficiency	Energy losses	Construction time	Lifetime	Investment	Fixed O&M	Variable O&M
Thermal storage		%	% per day	years	Years	Million USD/GWh	USD/MWh/year	USD/MWh output
	2020	98%	0.2%	0.5	40	3.30	95	0.00
Solar thermal	Year	Efficiency			Lifetime	Investment	Fixed O&M	Variable O&M
		%			Years	Million USD/MW	USD/MW/year	USD/MWh
	2020	65%			30	0.29	66	0.00

Notes: GWh = gigawatt hour; MWh = megawatt hour; O&M = operation and maintenance.

The new system was designed to implement solar and thermal storage to cover DHW demand during the summer months, reducing the need for coal burning and ultimately lowering CO_2, NO_x, SO_x and particulate matter emissions. Figure 50 shows a schematic diagram of the solar thermal collectors and thermal storage implemented in the Khovd case.

Figure 50 **EnergyPRO model overview**



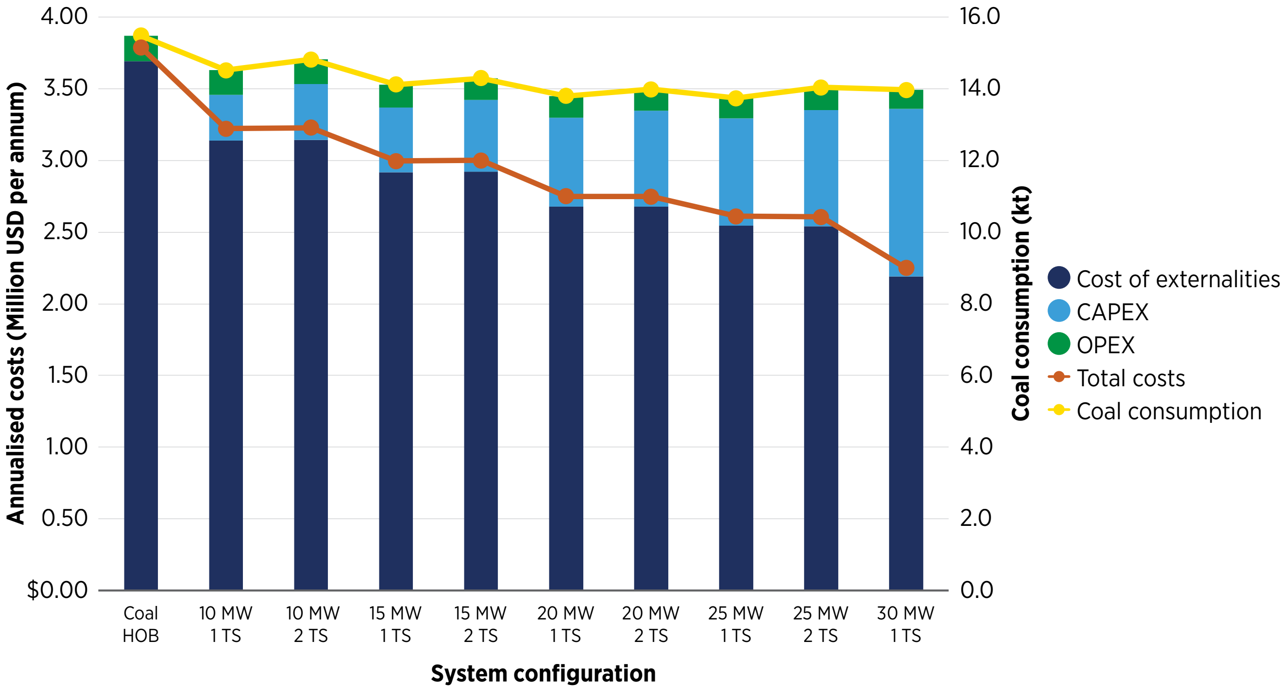
Notes: GJ = gigajoules; HOB = heat only boiler; m2 = square metre; MW = megawatt; MWh = megawatt hour.

The thermal storage utilised in this case study comprises large-scale hot water tanks that can store heat in the short-term - from a few hours up to two weeks. Large-scale hot water tanks are widely deployed in the Danish district heating grids located in 284 local district heating plants, with an average capacity of 3 000 m^3. This volume translates into a heat storage capacity of around 190 MWh.

The Khovd case study analyses the effects on total annualised costs and emission reduction when additional solar thermal and thermal storage capacity are included in the existing system. Figure 51 shows the effect on the total annualised cost when 10 MW_{th}, 15 MW_{th}, 20 MW_{th}, and 25 MW_{th} are added with one and two large-scale thermal storage water tanks, respectively. The effect of adding one or two thermal storage tanks can be seen with their respective solar thermal installed capacity.

Figure 51 shows that adding new renewable capacity decreases coal consumption as increasing amounts of solar thermal are introduced onto the system. This also causes a decrease in the overall cost of the system, the major chunk of which are external costs, mainly CO_2 costs. A CO_2 cost of USD 185/t was used with an emission factor of 94 kg/GJ for the coal-fired, heat-only boiler. The results indicate that the lowest-cost system is where an additional 25 MW_{th} with one thermal storage system is added, where additional thermal storage does not necessarily decrease coal consumption. However, the major benefits from adding renewables to the mix seem to come from the avoided emissions and the reduced monthly operating expenses, particularly in the summer months.

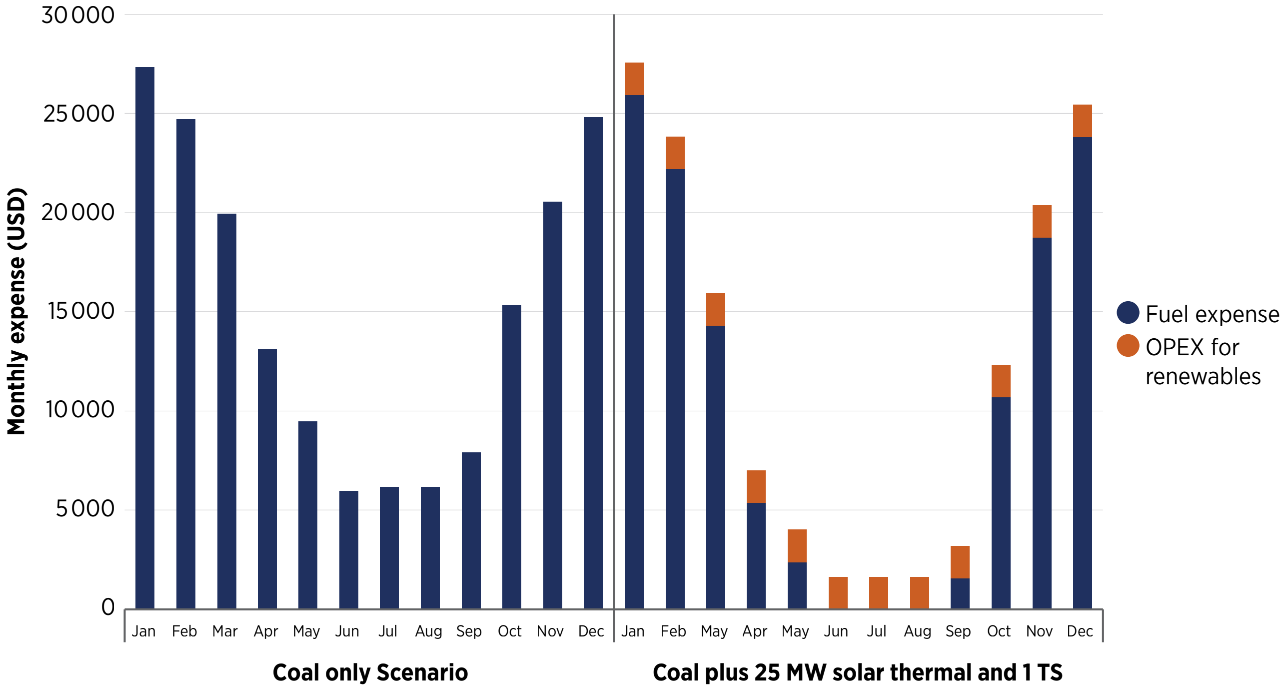
Figure 51 **Annual cost and coal consumption of different heat system configurations**



Notes: TS = thermal storage; CAPEX = capital expenditure; HOB = heat only boiler; kt = kilo tonnes; MW = megawatt; OPEX = operating expenditure.

Figure 52 below shows the monthly operating expenditure, comparing the coal-only system with the least-cost systems from Figure 51, *i.e.* an additional 25 MW_{th} of solar thermal with one thermal storage unit of 190 MWh. The results show a significant reduction in operating expenses for the summer months since solar thermal along with thermal storage capacity proves sufficient, and no coal is burned for most of the non-heating system. For the three summer months, the operating expenses decrease by almost 75% by adding solar heating compared with a coal-only system.

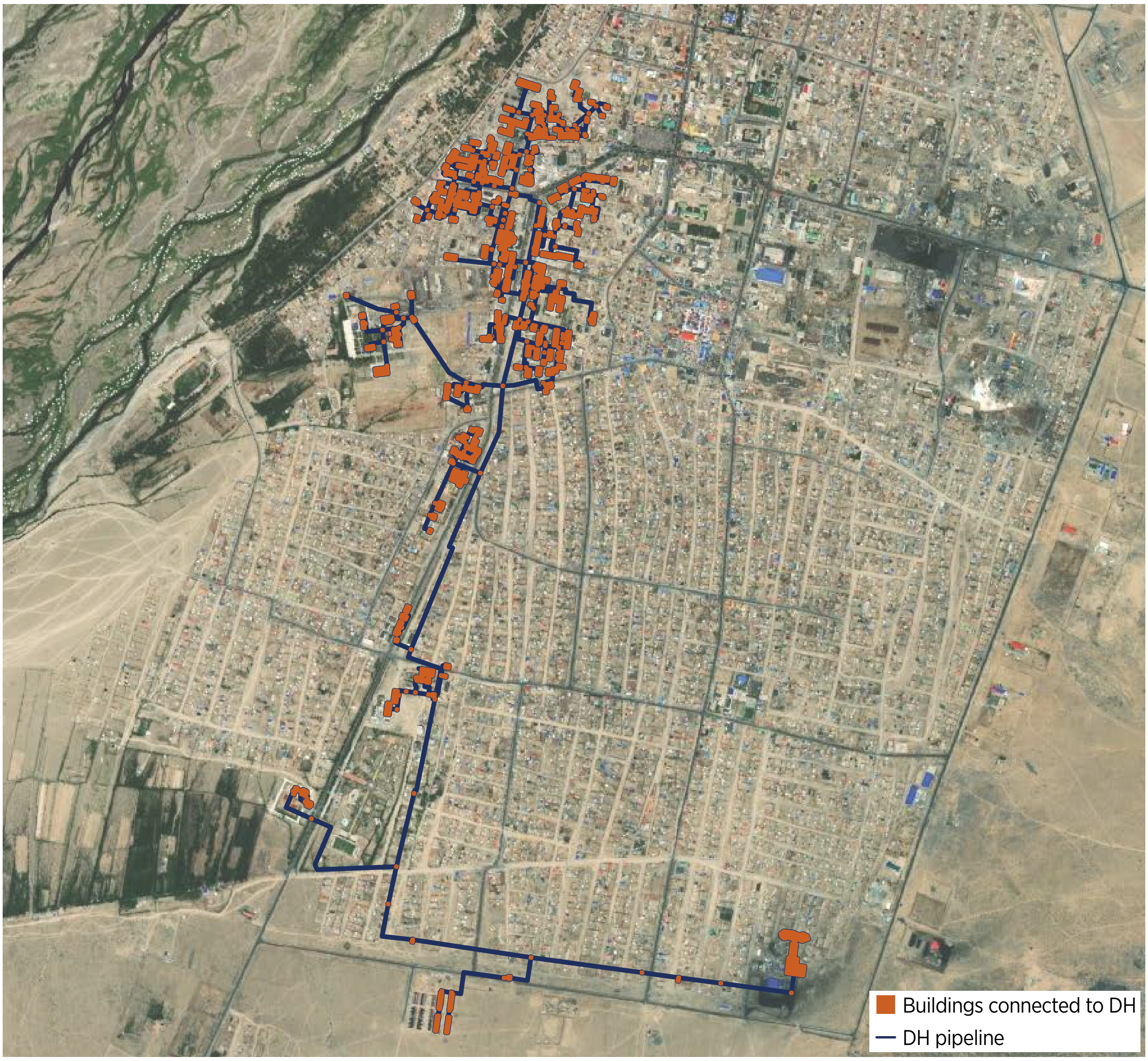
Figure 52 **Monthly operating expenses with and without solar heating**



Notes: MW = megawatt; OPEX = operating expenditure; TS = thermal storage.

The analysis presented above only covers the existing district heating system; however, there could also be potential to expand the district heating system. Figure 53 shows the existing district heating system of Khovd, which only covers part of the city.

Figure 53 **Map of the existing district heating system of Khovd**

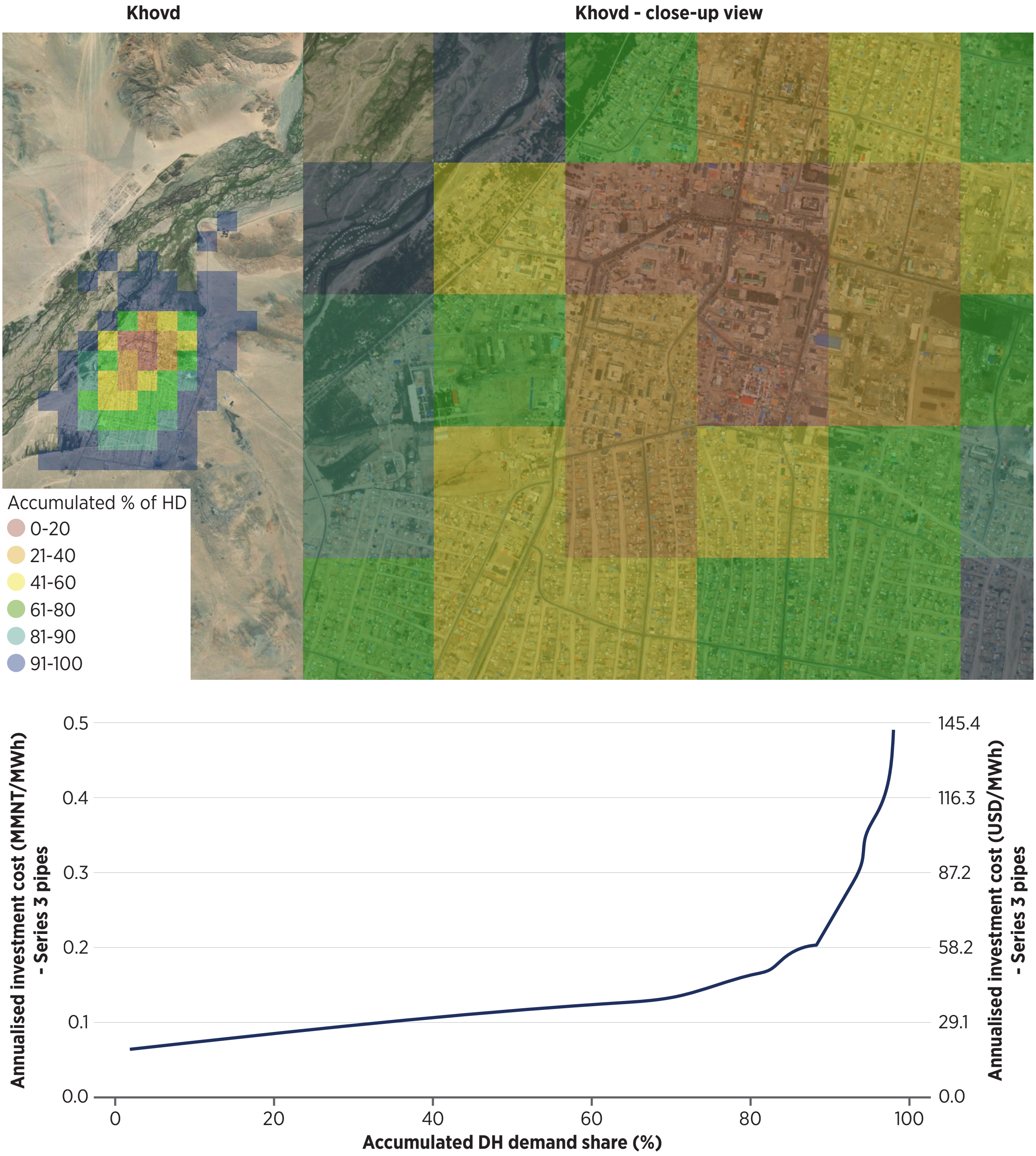


Note: DH = district heating.

Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply any endorsement or acceptance by IRENA.

District heating expansion has not been analysed in detail in this study, but Figure 54 shows a screening of the heat density of the city and the cost of expanding district heating from zero to 100%. The investment costs are relatively low for the first 40% of the heat demand and going up to 80% seems relatively affordable. Going to 80% equals a total heat demand of 195 GWh/year, excluding network losses, which is more than a doubling of the existing district heating demand.

Figure 54 Heat density of the Khovd and the cost of expanding district heating network



Notes: DH = district heating; HD = heat demand.

Disclaimer: This map is provided for illustration purposes only. Boundaries and names shown on this map do not imply any endorsement or acceptance by IRENA.

4.3 Case study 3: Geothermal heat in Tsetserleg city

An investigation into the geothermal resources and underground reservoirs in Tsenkher district has been carried out by the Geothermal Energy and Geofluids Group and the Earth and Planetary Magnetism Group of ETH Zurich, the Mongolian Academy of Sciences and the National Renewable Energy Centre in Ulaanbaatar to provide clean energy to the regional centre in the city of Tsetserleg (ETH Zurich, 2018). In this SHP, the case of Tsetserleg is used to show how the mapping of heat demand in buildings can be linked to specific renewable heat sources, in this case geothermal heat.

Given that Tsetserleg city is seen as a potential location for geothermal energy (ETH Zurich, 2018), the model described in Appendix A for district heating potential is applied to Tsetserleg to assess the building stock and estimate the heating demand of the city. However, since information regarding the city's current district heating system was not accessible, no energy system analysis is performed for a city level. The model identifies 5 632 buildings in the city, out of which 2 031 are *Ger* tents. The average building height ranges from 2.5 metres to 12.2 metres, with a median heating density demand of 280 kWh/m^2 in the buildings. All in all, the city's annual heating demand estimation is approximately 163 GWh, and 90 GWh when energy efficiency savings are applied. The total investment costs for an 80% (130 GWh) district heating share of the heat market are estimated to be MNT 169 million (USD 48 600), excluding *Ger* areas. The building stock used for this screening is seen in Figure 55, with the geographical locations for the district heating potential in Tsetserleg city also shown in the figure. Previous studies show that a geothermal CHP plant in Tsetserleg could reach 1.9 MWe of electricity production and 16.7 MW$_{th}$ of heat production. The local hot spring – Tsenkher – has a flow rate of approximately 10 litres per second and a temperature exceeding 80°C (ETH Zurich, 2018). If this renewable energy source is assumed to function as a baseload capacity, the plant could supply up to 146 GWh per year, which is larger than the district heating potential demand assessed in Tsetserleg. Therefore, this screening on the city's heat demands supports the conclusion of ETH Zurich (2018), implying that such a plant would exceed current heat consumption, which is generally lower than the heat supply, after network heat losses. However, inputs regarding the current district heating system and geoscientific measurements are needed to reach a greater understanding of geothermal potential in specific geographical locations.

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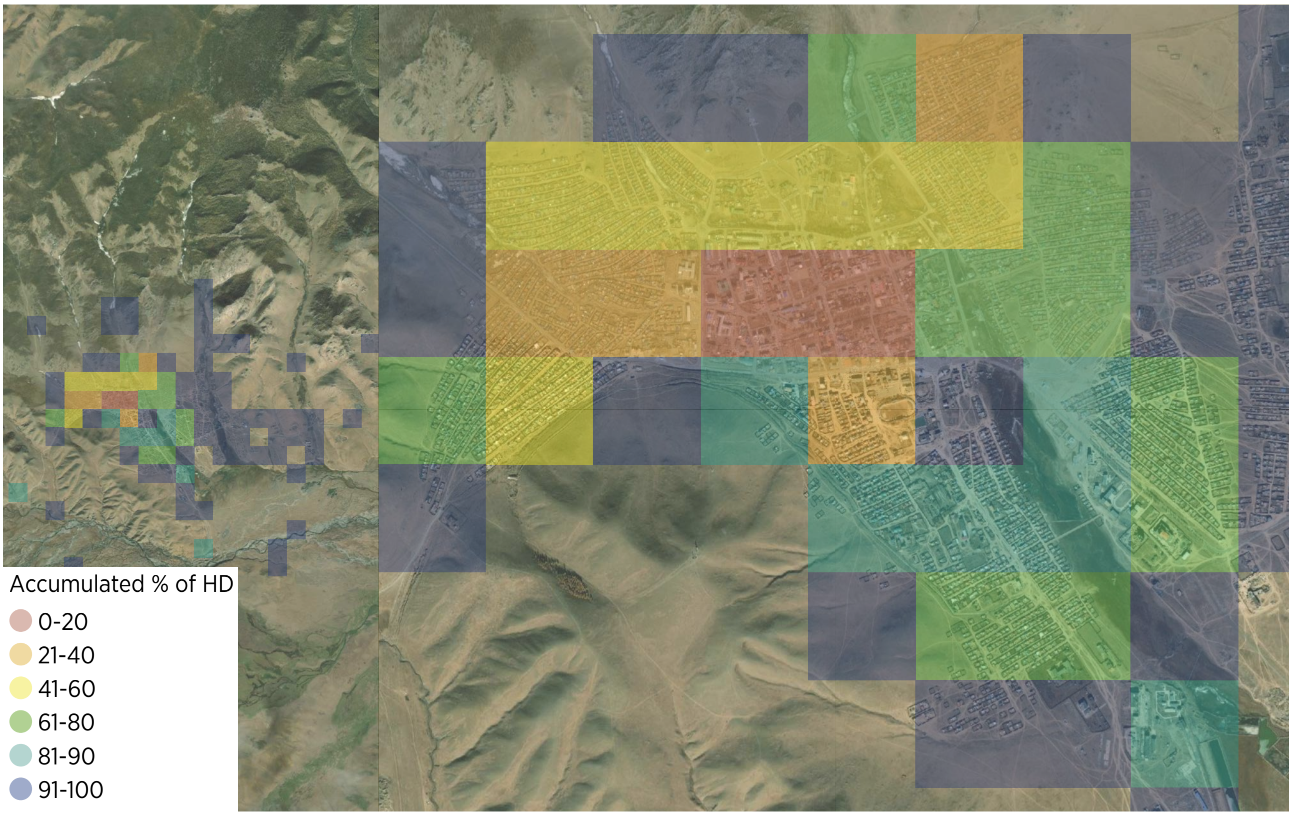
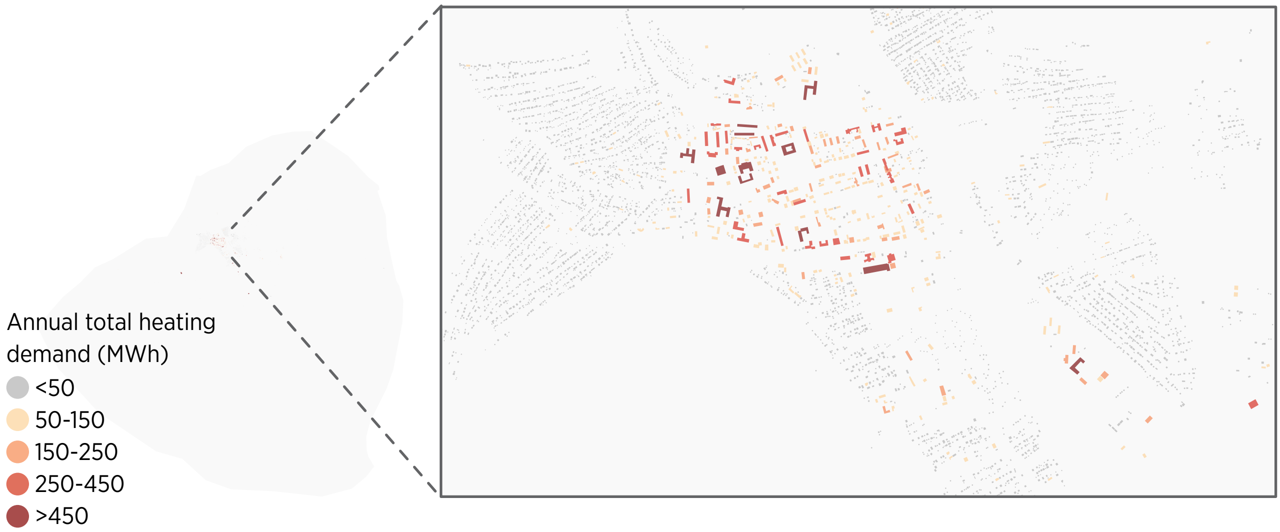
Figure 55 Geographical potential locations for district heating in Tsetserleg

Tsetserleg **Close-up view**



Buildings in AOI **Close-up view**



Notes: AOI = area of interest; HD = heat demand; MWh = megawatt hour.

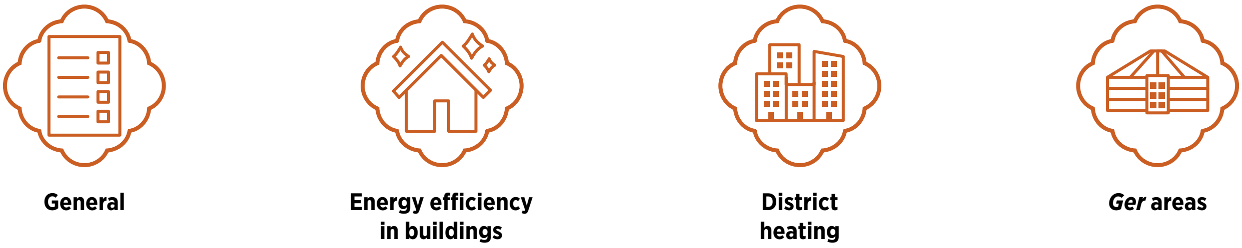
5

Technical and regulatory barriers, and recommendations

A compilation of the regulatory and financing frameworks working in the Mongolian context is provided in this section. It is based on the information taken from the project activities and other sources of information available through the literature review.

The 2030 and 2050 cases presented in this report require significant change in the existing heating system. Energy efficiency measures in buildings need to be implemented, both outside and inside the district heating system coverage areas. District heating systems should expand to cover a larger share of the heat demand, also due to increasing heat demand from population increase. Furthermore, large parts of the district heating infrastructure in Ulaanbaatar needs retrofitting to improve efficiency and allow the transition of the current system to lower supply and return temperatures. The district heating supply should change from a single fuel system towards a system combining several renewable energy technologies, such as waste incineration, heat pumps, electric boilers, solar thermal and potentially geothermal and excess industrial heat. As many of these sources have variable production, heat storage also becomes essential. Outside the district heating systems, buildings need to switch to heat pumps, electric boilers and solar thermal. The change towards a more electrified heating system requires increased renewable electricity production, primarily wind and solar PV. Technical and regulatory barriers must be addressed to allow these changes to be implemented. The following section presents the implementation challenges and solutions; both sections are divided into general, energy efficiency in buildings, district heating systems and *Ger* areas, as illustrated in Figure 56.

Figure 56 **Main structure of presentation of challenges and solutions**



5.1 Implementation challenges

The following list identifies the main challenges:

General

- The heating sector in Mongolia is characterised by significant air pollution which is as a result of coal-based heating supply, combined with low-efficiency buildings.
- Coal is the main fuel input for CHPs and HOBs in the current district heating systems. Besides being the primary source for air pollution, smoke accumulates and contributes to smog formation due to the thermal inversion effect of the city, which at the same time reduces solar energy potential.
- The recent ban on raw coal usage has contributed to a reduction in local pollution from the heating sector. This measure can be seen as a mitigating strategy while plans for decarbonisation and eventual complete coal phase-out are developed. However, detailed, reachable and actionable targets for decarbonising the energy system are largely lacking.
- Despite the formulation of some policies focusing on the decarbonisation of the energy sector in Mongolia, there is little focus on decarbonising the district heating systems. This could partly be as a result of the continued use of coal CHP plants as one of the major sources of heat supply to these systems.
- Large energy subsidies result in low energy taxation, causing the energy companies to have no incentive to switch to renewables and continuing the carbon cycle (Integration and Ekodoma Ltd., 2020). This underutilisation of energy taxation causes large environmental problems due to the widespread use of coal.
- The local support for renewable energy policies and investment in Mongolia is limited. Instead, strong support for coal power development exists (Edianto, Trencher and Matsubae, 2022).
- There is limited funding for renewable energy projects in Mongolia. During the period 2013-2017, financing for coal from foreign government-affiliated organisations amounted to around USD 1 billion, while the funding for renewables was less than a quarter of this (Natural Resources Defense Council, 2017).
- Due to the relatively low-purchasing power for many households, their ability to investment in the decarbonisation of their heating system is limited.
- The current ownership model of district heating systems, which is dominated by government-owned entities, focuses on providing cheap heat at the expense of recovering the operating costs. This limits further investment into the heating systems.

Energy efficiency in buildings

- Buildings and houses generally have low energy efficiency and insufficient thermal insulation, which results in a relatively high heating demand. With the current fossil supply, this also generates high levels of local pollution. This challenge is considerable for buildings dating from older construction periods, but also for new construction that does not comply with energy-efficient building standards.
- Buildings do not use heat metering as a measure for their heat consumption and billing. Space heating bills are based on the property area, while DHW is according to the number of people within the household. This disincentivises customers from making heat savings via their behaviour as well as adopting potential energy efficiency measures.
- The documentation and auditing of the building stock and its heating demand are not well documented. This represents a barrier for estimating not only current heat demand, but also future demand.
- Due to highly subsidised energy supply, there is a lack of financial incentives for building developers to construct energy-efficient buildings, as well as for building owners to undertake private renovations and retrofitting.

District heating

- The current district heating system is geographically limited by *Ger* area expansion located either on the fringe or between areas within the city. This limits the system's capacity for expansion and possible new connections to attractive district heating customers.
- There is a lack of investment in current infrastructure for optimal operation. Heating infrastructure is put under pressure by rapid growth in heating demand while needing repair and renovation.

- Current low heat tariffs represent a threat to the whole district heating infrastructure due to their lack of performance in achieving system cost-recovery to a balanced or positive level. Additionally, these subsidised tariffs for the connected users increase energy accessibility and inequality issues in unserved areas such as *Ger* areas.
- Actors in the Ulaanbaatar district heating context are diverse, but dispersed and disconnected across the whole district heating actor network. The disinvolvement of such actors poses a barrier to the strategic planning of the heating system (Energy Sector Management Assistance Program, 2019).
- The current district heat networks in Mongolia rely on high temperature supply. On the other hand, the SHP suggests lowering the supply temperature of the district heating network to below 100°C over time, in order to utilise the locally available renewable energy sources. Lowering the temperatures in the Ulaanbaatar district heating would be a challenge in the current situation and should only be done when buildings are renovated to a level where they can be heated with reduced district heating temperatures. It should also be underlined that in very cold winters, it may still be necessary to increase temperatures above 100°C. However, in general the benefits of reduced temperatures make it a key focus point for the future.

***Ger* areas**

- The lack of spatial planning and redevelopment strategies in the *Ger* areas is a challenge as rural-to-urban migration develops. District heating generation for *Ger* areas is poorly regarded due to the uncertainty of their development.
- Actors representing these areas are scarce, which is a barrier to their participation in the strategic planning of rural heating development. In addition, there is limited documented information about the energy demand in the *Ger* areas, leading to estimations of their magnitude, location and distribution.
- The *Ger* areas are considered low-income areas, which usually represents a challenging panorama for renewable business strategies yet a viable target for public subsidies and other forms of financing for increased affordability, such as energy communities in which citizens collectively organise local renewable production.

5.2 Potential solutions

The following potential solutions to the challenges are proposed.

General

- In Ulaanbaatar, current efforts focus on introducing energy performance certificates for new and renovated buildings, which will be integrated in the building permit process. The initiative should be expanded to existing buildings and eventually be part of a nationwide strategy that enables audits and metrics.
- Decision making should consider the use of different instruments such as energy system modelling for scenario assessment. The use of the system's socio-economic indicators can aid the alignment of specific Mongolian environmental goals while promoting low-cost environmental and societal energy systems.
- Robust institutional capacity is key for supporting energy planning. Hence, strengthening skills through capacity building at relevant institutions is needed in terms of financial, technological and planning skills. This capacity development addresses improving the production, performance and deployment of energy.
- Investments in the Mongolian energy sector should be targeted primarily at renewable energy development and the decarbonisation of the heating sector, as they align with the current climate priorities of the government.
- Regulation for renewable technologies should be implemented in the Mongolian context. This regulation should encompass a framework for addressing technology barriers, cost-recovery analysis, quality standards, impacts of the introduced technology, financial and fiscal measures including subsidies, grants and a reduced levy on renewable technologies and projects (Jayawardena, Rivera and Ratnayake, n.d.).
- Ambitious specific targets for coal phase-out should be introduced into the 2050 vision. This as a complimentary goal as the share of renewable energy increases following the investment roadmap.
- Significant investment should be allocated to renewable potential exploration, specifically for technologies that are not fully or thoroughly assessed in Mongolia such as geothermal, as this could provide valuable baseload production in future district heating systems. In addition, it should cover the potential for low-temperature

sources for future district heating systems, namely waste heat from industry and commerce, and waste-water treatment plants, amongst others.

- Privatisation or community ownership of new energy developments could be a viable solution. A thorough assessment of possible ownership models for the Mongolian context should be developed. Experiences from other countries where non-profit or consumer-owned forms of ownership are favoured should be considered.
- As the suggested changes are fundamentally different from the current energy supply in Mongolia, a public campaign to improve knowledge of transitioning to renewables is also recommend. Such a campaign should focus on both public and private stakeholders, as well as high-level decision makers in Mongolia.

Energy efficiency in buildings

- To encourage energy savings and manage heat demand at the user end, heating installations with energy meters and heat cost allocators should be provided. This will also assist with better energy planning.
- The adoption of assessing and measuring instruments would further enhance understanding of the development of heat demand in buildings. This can come in the form of a rating or classification system for buildings, as well as the implementation of energy auditing, and should be allied directly to a measurable indicator aligned with the national climate targets.
- Thermal retrofitting of buildings, such as whole-house retrofits, better insulation and double window glazing, can help retain heat and keep the indoor climate comfortable (Geels *et al.*, 2017).
- The implementation of strict regulations surrounding building codes could support efforts toward energy efficiency measures in buildings.

District heating

- For district heating systems served by HOBs (which are usually turned off during the summer months when space heating is not required), renewable energy solutions can be introduced initially to supply DHW during the months the HOBs are turned off, and later expanded with the inclusion of thermal storage to cover more space heating load during the winter with clean energy.
- Regulations should enable the establishment of investment plans that not only concern the upgrading and increased capacity of district heating systems, but also the maintenance of these investments throughout their lifetime so as to ensure their operability and stability (IRENA and Aalborg University, 2021).
- Regulations and the infrastructure should enable district heating billing to be measured based on consumption rather than on the heated space to promote energy efficiency (Energy Sector Management Assistance Program, 2019). In this case, the tariff structure for heating could be composed of two elements: fixed and variable costs. The fixed costs include all the investment in equipment and consider its depreciation. Variable costs are based on the actual heat consumption. An example of a variable tariff scheme is being implemented in Aalborg, Denmark, where the plan is to phase out coal CHP plants. The situation is similar to the one in Mongolia, where the primary fuel used for CHP is coal (medium-quality lignite), (Djørup *et al.*, 2020).
- To ensure that the new tariffs set are applied uniformly, third-party inspection of the district heating companies can be done to verify that there is no variation in the costs. This will ensure impartial inspections. (Energy Community Secretariat, 2021).
- Heating tariffs should be revised so that they are cost-covering with respect to the system. This will allow investment in new technologies when the supply is balanced. When reviewing tariffs, it is important to consider the impact on low-income households to avoid increasing energy poverty.

***Ger* areas**

- In *Ger* areas heat pumps and their potential for heat supply need to be investigated as this would help to reduce local emissions. They could be supplemented with photovoltaics, solar heating and heat storage. As these solutions are very investment heavy, some sort of subsidy scheme or financial support would require.
- Only about 5% of *Ger* area households have electric heating. Increasing this share is important but needs to be planned together with electricity distribution grid reinforcements.
- *Ger* tents suffer heavily from heat loss since they are not adequately insulated. They lose about four to five times as much heat as regular houses. If possible, measures should be taken to improve their insulation.

6

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Appendix A

Detailed methodology description

Heat demand and energy efficiency in buildings

This section presents the GIS methodology used for mapping current heat demand with a focus on estimating heat demand at the building level. The output of this methodology is the aggregated grid-level heat demand and the identification of the optimal share of district heating based on its investment costs, as presented in Chapter 3. This is the foundation for the energy system analysis performed in Chapter 4. Visualisations for each step of the methodology are shown for an enhanced appreciation of both the scope of the analysis and its resolution.

The methodology uses a variety of tools both for geographic and non-geographic analysis. The software used for the geospatial analysis is ArcGIS Desktop 10.6.1 and ArcGIS Pro 2.9.5 from ESRI, Inc. (Environmental Systems Research Institute), and QGIS 3.22.3 from QGIS Developing Team. These GISs include rich analytical toolboxes, modelling and visualising frameworks. Moreover, the robust geographical analysis was performed in Python standalone coding scripts using open-sourced Python libraries for geospatial and non-geospatial data management, analysis and process automation.

The methodology follows a collective, sequential and complementary system as shown in the following step-by-step list:

- Geographic delimitation – area of interest (AOI) identification.
- Geographic building footprint and geometric estimation.
- Heat demand estimation at the building level.
- Validation of heat demand estimation using Ulaanbaatar district heating network data.
- Heat demand energy efficiency estimation at the building level.
- Grid level district heating potential assessment.

Geographic delimitation – AOI identification
This step consists of the AOI identification. The city of Ulaanbaatar is identified to delimit the geoprocessing scope of the model geographically.

Geographic building footprint and geometric estimation
Once the AOI is defined, the building identification starts by using open input data for a building footprint and further volumetric estimation. The input data are taken from different sources: OpenStreetMap (OSM) where data is crowdsourced (OpenStreetMap contributors, 2021), and Microsoft (MS) building footprints where building footprints are identified via Machine Learning pattern recognition algorithms applied on satellite data that for Central Asia have a false positive rate of 2.2% (Microsoft, 2022). These two sources are used in a supplementary way; however, OSM building footprints are prioritised when geographically overlapping data are found since OSM's resolution is assumed to be finer. A spatial join algorithm is used to match the AOI area to the buildings intersecting it.

Additionally, the Global Human Settlement Layer (GHSL) GHS-BUILT-H R2022A (Pesaresi and Politis, 2022) from the GHSL Data Package 2022 is used for the building height estimation. This referred dataset includes the spatial distribution of building heights that use regression models on different data structures such as Digital Elevation Models, Digital Surface Models, NASAs topographic Mission and Sentinel-2 global data, amongst others. The dataset uses data for 2017-2018, as released in 2022, and has a resolution of 100 m x 100 m on a grid level. The geoprocessing in this step includes a reprojection and crop of the global dataset using the AOI geometry, followed by a zonal statistics method for joining the average net building height (Pesaresi and Politis, 2022) in metres to the buildings using the median as the statistic measure for the join. The level of resolution of this dataset is considered indicative as there are expected errors when working with globally averaged datasets, whose level of accuracy will highly depend on the geographical location and building density where they are utilised. Nonetheless, the dataset is the closest available estimate of building heights for their volumetric estimation. Building footprints in the model receive the estimated height from the Raster dataset, for the model to perform geometric calculations including floor area, building perimeter, and lastly building surface area.

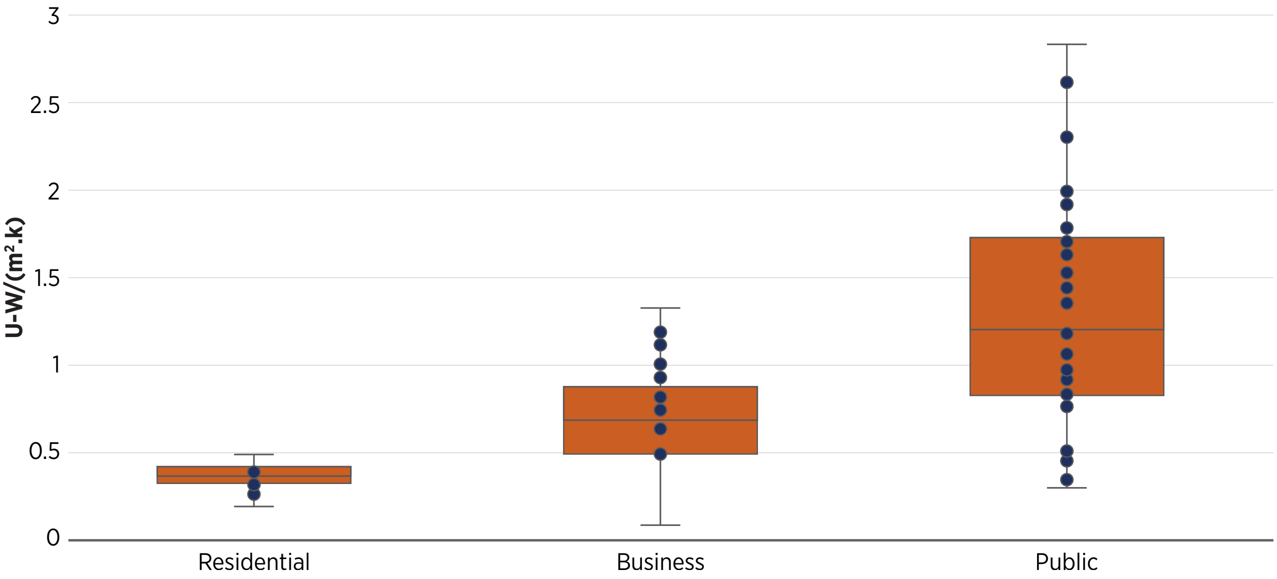
The buildings within the AOI are also classified by geographically identifying the district heating network, Ger areas, and outer areas where data are available for such categorisation. From the buildings, it is important to identify the Ger tents since they show characteristics distinct from other building structures. Therefore, an extra step is added where Ger tents are identified by the type of geometry they are geographically drawn in the building footprint dataset.

At the end of this geographic processing, each building footprint is properly classified and geometrically identified assuming the building as a cubical geographical entity. The building's surface area is then used for the heat demand estimation at a building level.

Annual heat demand estimation at a building level

The surface area included within the surrounding exterior walls of the building is the point of departure for the model's annual heat demand estimation. There are two main components in this estimation: the building surface heat loss, *i.e.* the space heat demand, and the building DHW demand. The total surface heat loss calculation for the building uses an average sum of the thermal resistances of the layers of a building element. This means an averaged U value based on literature (Namkhainyam *et al.*, 2019b). Considering that the building usage is unknown in the model, it is decided to use the mean value for the residential sector, U = 0.47 Watt per square metre per Kelvin (W/(m^{2}K), as the category is deemed more critical for the heating system (see Figure 57). It is important to mention that in the model, floor area equals heated area, and a ceiling height of 3 metres is used for calculating the number of floors corresponding to each building's estimated height.

Figure 57 **Calculated averaged U-value**



Source: Cases studied in Namkhainyam *et al.* (2019b).

Notes: U = insulation performance; W/m^2.k = watts per square metre per degree Kelvin.

The heat loss calculation for the building uses additional climate condition parameters. Outdoor hourly temperature was retrieved for the AOI's bounding box using the Copernicus Climate Data Store API. The dataset used is ERA5 hourly data on single levels from 1959 to present (Hersbach *et al.*, 2018). A heating season from 15 September until 15 May, accounting for 8 months and 5 832 hours for the year 2019, is taken alongside an internal temperature of 20°C inside the building envelope. The DHW demand is calculated as a function of the building's heat loss: a conservative 43% of that demand is used based on literature available (Integration and Ekodoma Ltd, 2020), except for Ger tents where no hot domestic water demand is considered.

For this heating demand estimation, validations are performed. Table 8 shows the summary of the validation for the existing district heating network area, while a full description of the other levels of validation performed can be seen in Appendix C. For the buildings within the district heating area, the validation results show a slight underestimation of the modelled space heating demand, and an even slimmer overestimation of the modelled DHW demand.

Table 8 **Summary of the validation output**

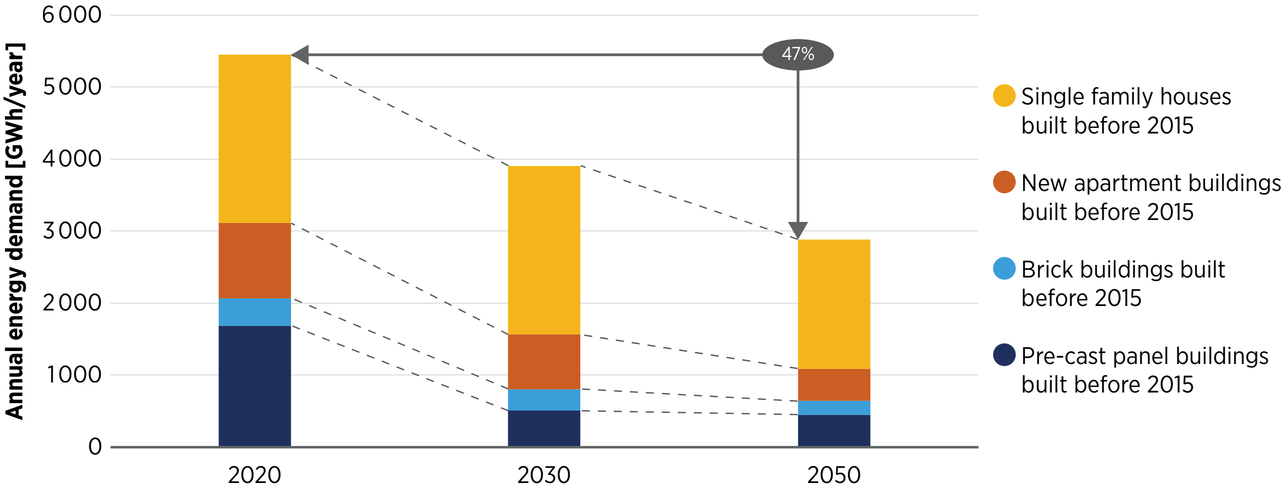
Annual heat demand [MWh]	Model	Validation	Percentage difference [%]
Space heating	2 154	2 172	0.8%
Domestic hot water (DHW)	926	923	-0.3%
Total heating demand	3 080	3 095	0.5%

Notes: DHW = domestic hot water; MWh = megawatt hour.

Heat demand with energy efficiency estimation at a building level

The existing building energy efficiency potential is estimated to be 47% in 2050 based on average values in the Ulaanbaatar masterplan (Stryi-Hipp *et al.*, 2018) (see Figure 57). In the literature referred to, the study for the estimated annual heating demand includes different types of building built before and after 2015 alongside their prognosis for 2020, 2030 and 2050. The estimates in the study are calculated according to the 2009 developed building code norms and standards (BCNS) of the construction sector in Mongolia, regulated by the Ministry of Construction and Urban Development. The referred to norms aim for a higher energy efficiency by determining precise building thermal parameters according to the building's usage. Moreover, they regulate the establishment of an energy performance certificate for buildings (Ministry of Construction and Urban Development, 2009). The estimates were gathered for buildings built before 2015 and can be seen in Figure 58. In the model, an average of 47% energy efficiency savings is applied to the space heating demand and consequently to the DHW demand of the buildings. However, no energy efficiency is applied to Ger tents in the model due to the lack of data on the future efficiency measures in this specific type of building.

Figure 58 **Heating demand estimation for existing buildings in Ulaanbaatar**



Notes: GWh/year = gigawatt hour per year.

The investment cost of energy efficiency measures has not been included in the Ulaanbaatar masterplan, so to estimate these the Ulaanbaatar energy audit report from 2013 (Malek, Zahradnok and Tauschova, 2013) has been used. Here different types of energy efficiency measures have been evaluated for different typical types of building in Mongolia. Table 9 shows the summary of the costs from the report for brick apartments, pre-cast concrete, a school and two types of single-family houses. For each of these, the energy efficiency potential and associated costs have been assessed in terms of walls, roofs, windows, floors and other measures. In the SHP for Mongolia, the average costs for apartments and single-family buildings have been applied.

Table 9 Estimated average costs for energy efficiency measures

	Heat saving	Investment cost	Specific investment cost
	MWh/year	EUR/year	EUR/MWh
Brick apartment building	1 448	6 976	4.8
Pre-cast concrete (panel) apartment building	3 320	10 951	3.3
School - brick building	2 774	10 051	3.6
Single family house - combined timber and brick structure	73	563	7.7
			USD/MWh
Average apartment cost			6
Average single-family cost			12

Note: Exchange rate of 1.06 and a 1.23 inflation factor applied to convert to USD; MWh = megawatt hour.

Source: Malek *et al.* (2013).

Grid level district heating potential assessment

A grid level analysis is used for the district heating assessment where a 500 m x 500 m grid is chosen following the validation of grid-level output. For this process, buildings located within and in the vicinity of the current district heating system are separated from buildings outside this range. The first split will therefore be considered for district heating potential, whereas the second split is for individual heating assessment, taking into consideration the lack of connectivity of outer areas to the existing system.

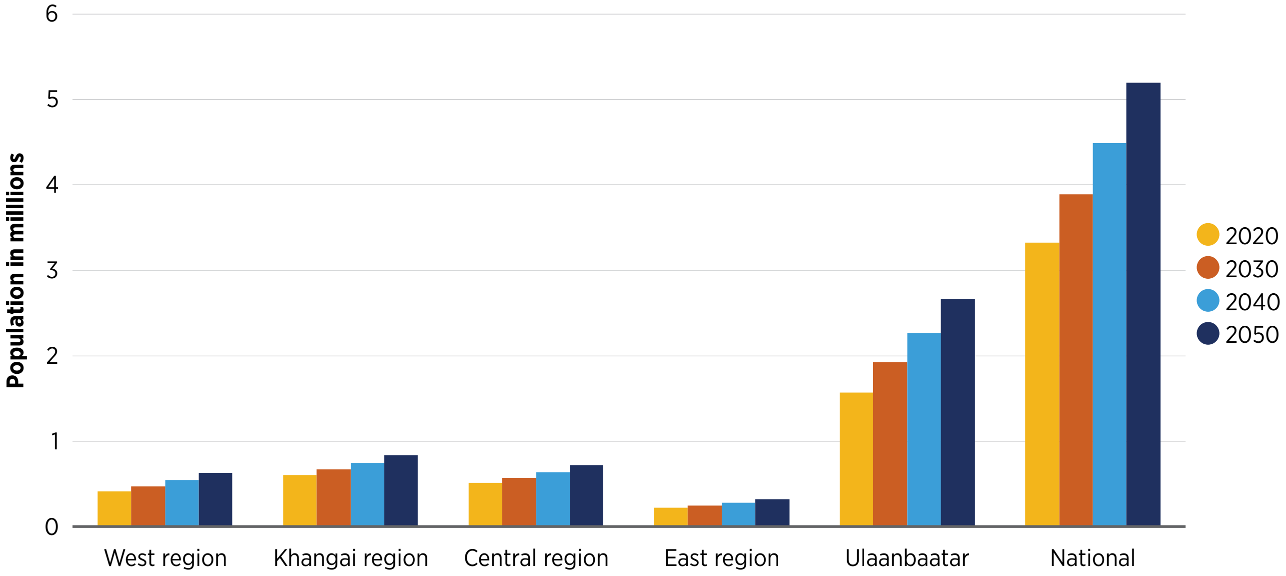
This is done by aggregating the individual building heating demands on the 500 m x 500 m grid to perform the district heating assessment. A geographic buffer analysis using 1.5 km offset from the current district heating system is used to identify the building split, and a polygon centroid-based spatial join is performed using both the building polygons and the grid vector dataset. The buffer analysis uses Euclidean distances, meaning the straight-line offset distance from the original geographical shape outwards. That way the aggregated heating demands translate into the grid dataset. The split of buildings set for individual heating assessment are also aggregated and mapped for visualisation purposes.

A remark must be made here for the reader to understand the geographic visualisations included in Section 3 of this report. Due to the somewhat extensive geographical extent of the study, the geographic visuals included in this report are split into two sides. On the left, a full extent of the map is shown aiming at portraying the whole scope of the AOI. And on the right, a close-up view of the previous depicts detail to a much more visible extent.

Projection of population and heat demand towards 2050

In addition to heat demand from existing buildings, heat demand from new buildings also needs to be estimated. This heat demand is related to population growth, which for Mongolia is presented in Figure 59. According to official population projections, the national population is expected to increase from 3.3 million to 5.2 million between 2020 and 2050. Around a 1.1 million projected increase will be in the Ulaanbaatar region, while the other regions have a projected increase between 100 000 and 200 000. In relative numbers, the population of Ulaanbaatar is expected to increase by 70% of the current population while the other regions are expected to have a growth of 40-50% of their current population.

Figure 59 **Projection of population growth from 2020 to 2050**



Source: National Statistics Office of Mongolia (2021c).

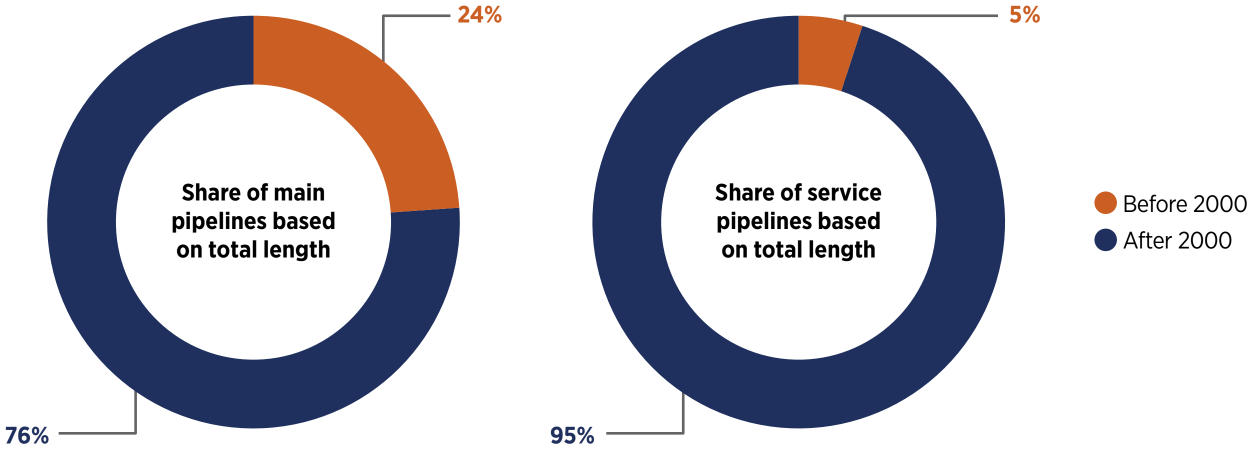
Population growth is an important factor in determining heat demand, but other factors also need to be included. In this report, the expected heat demand in new buildings for the Ulaanbaatar case is based on the assessment done in the Ulaanbaatar Masterplan (Stryi-Hipp *et al.*, 2018). In the masterplan the heat demand is divided into residential, entities and industry. For the residential potential the current average household size of 3.71 inhabitants is reduced to 3 inhabitants per household in 2050, while the living area per household is increased from 43 m^2 to 61 m^2. The average annual heat demand is assumed to be 158 kWh/m^2 for new apartments and 263 kWh/m^2 for detached houses. With the expected population increase and the expected heat demand per m^2, the anticipated heat demand is assessed for 2050. The expected number of new households is divided into 431 000 apartment buildings and 100 000 single family buildings. Also, the number of Ger tents is reduced to 50 000, which is around half of today's number.

Energy efficiency in district heating networks and 4GDH

Energy efficiency measures will largely be based on data from Ulaanbaatar district heating coupled with technical data on the efficiencies, costs and losses of different types of district heating pipes.

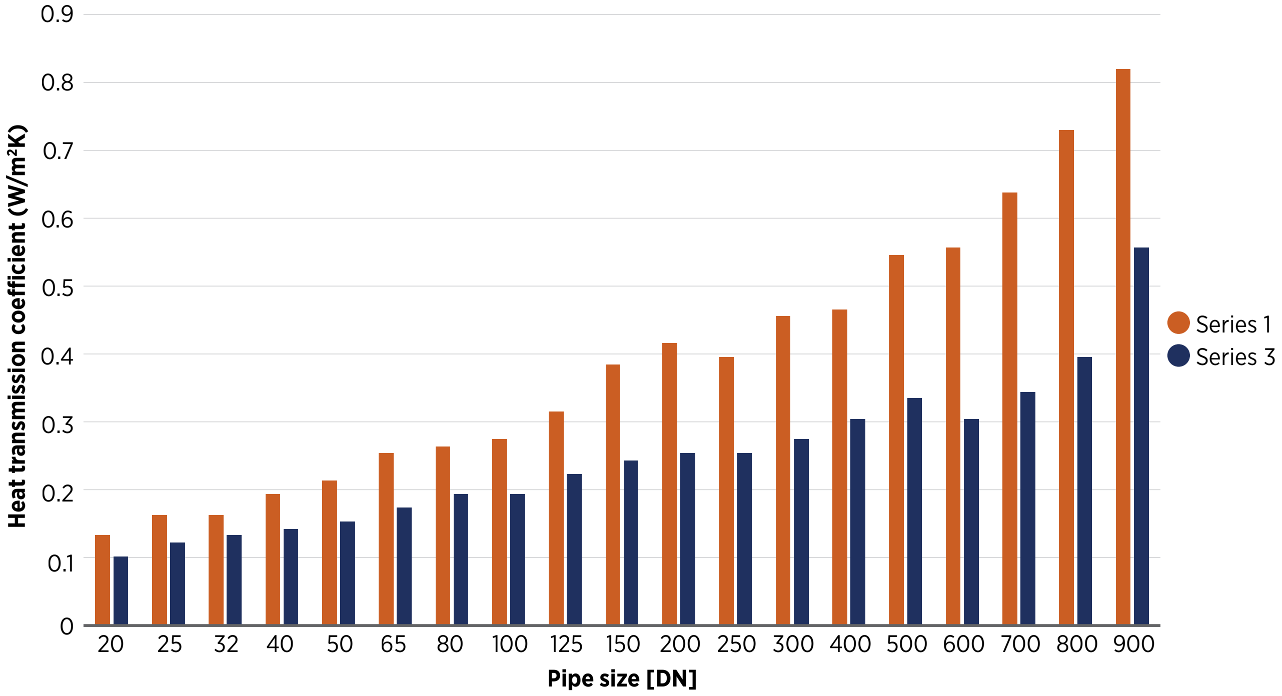
The current district heating network in Ulaanbaatar has a design temperature level of 150/70°C and a peak load operating temperature of 132/65°C. Figure 60 shows the age distribution of the district heating pipes, where a large share of the pipes has been either built or renovated since 2000. Overall network heat losses have been reduced from 19.6% in 2017 to 18.1% in 2021.

Figure 60 **Age distribution of district heating network**



In general, district heating pipes need to be replaced after approximately 30-40 years, which means that the last 24% should be replaced before 2030 and the whole system needs to be renovated before 2050. To increase the energy efficiency of the district heating grid in the long term, one option is to use modern pre-insulated pipes, which have lower heat transmission coefficients and thus lower heat losses per pipe (see Figure 61). The figure shows the heat transmission coefficients for Series 1 and Series 3 pipes, which are both modern pre-insulated pipes. The difference is mainly that Series 1 pipes have higher heat transmission coefficients and heat losses, and thus choosing Series 3 pipes would be an efficiency improvement over Series 1. The pipes used in Mongolia are typically steel, post-insulated, and due to data scarcity, it is assumed that these are similar to Series 1 pre-insulated pipes.

Figure 61 **Heat transmission coefficient for Series 1 and Series 3 pipes**

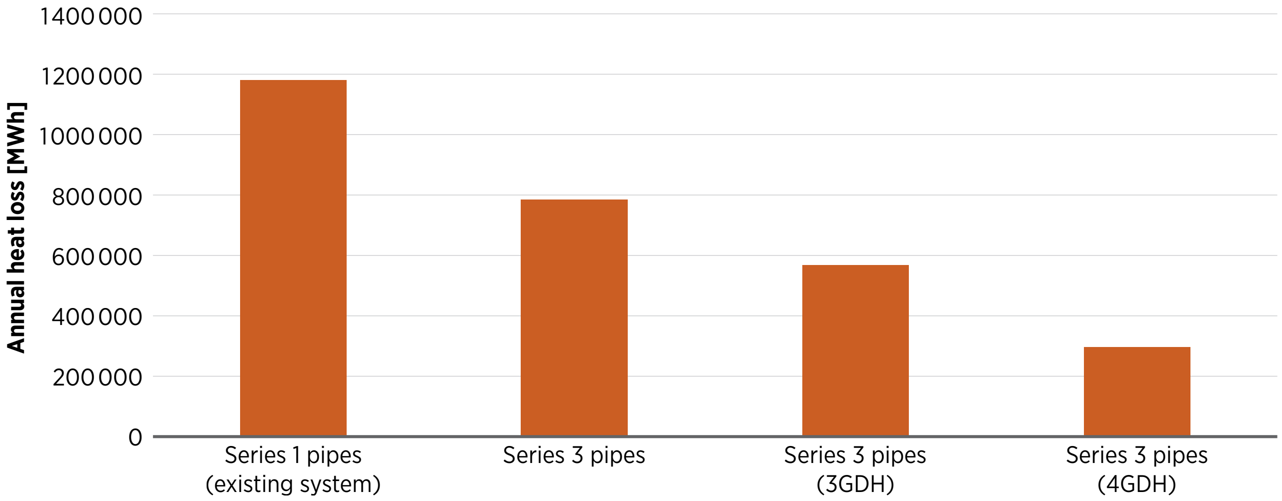


Notes: DN = diamatre nominel (internal pipe diameter in mm); W/m²K = watts per square metre per degree Kelvin.

Besides replacing the existing district heating pipes with Series 3 pipes, the energy efficiency of the district heating system could also be improved by lowering the supply temperatures in the system. Lowering the supply temperature level will reduce the heat losses in the district heating system and improve the energy efficiency of the heat supply units; however, it requires an energy efficient building stock, as the lower temperatures would not be sufficient to provide the heat needed for buildings with high heat demand. Thus, it is a pre-condition that energy efficiency measures are implemented in the buildings to enable the district heating system to lower its supply temperature level.

Based on the existing district heating system in Ulaanbaatar, the heat losses of the existing system and potential energy efficient systems have been estimated in Figure 62.

Figure 62 **Estimated heat loss for the existing district heating system in Ulaanbaatar for three energy efficiency improvement scenarios**



Notes: MWh = megawatt hours; 3GDH = third generation district heating; 4GDH = fourth generation district heating.

The estimation for the existing system heat loss is based on using the heat transmission coefficient for Series 1 pipes and the current temperature level. This gives an annual heat loss of 1 185 GWh/year; in the Ulaanbaatar 2018 Masterplan this number was estimated at 1 329 GWh/year. The lower number is reasonable considering the energy efficiency improvements since the release of the masterplan. The second column in Figure 61 shows an annual heat loss of 787 GWh/year if Series 3 pipes were used with the same temperature level as the current system, which is a reduction in heat loss of around 400 GWh/year. The next two columns show that reducing the system temperatures to 100/50°C for 3GDH systems or 60/25°C for 4GDH systems could further reduce the losses by 217 GWh/year and 488 GWh/year respectively, so that the total losses would be either 570 GWh/year for 3GHD or 298 GWh/year for 4GDH systems. So, theoretically by using Series 3 pipes and reducing the operating temperature to the level of 4GDH, the losses could be cut by 75% of the current system losses. A prerequisite for this is that the radiator systems in the buildings are sized for the lower temperature level in the district heating system – and that the heat exchanger installations in the customers' premises are sized for this.

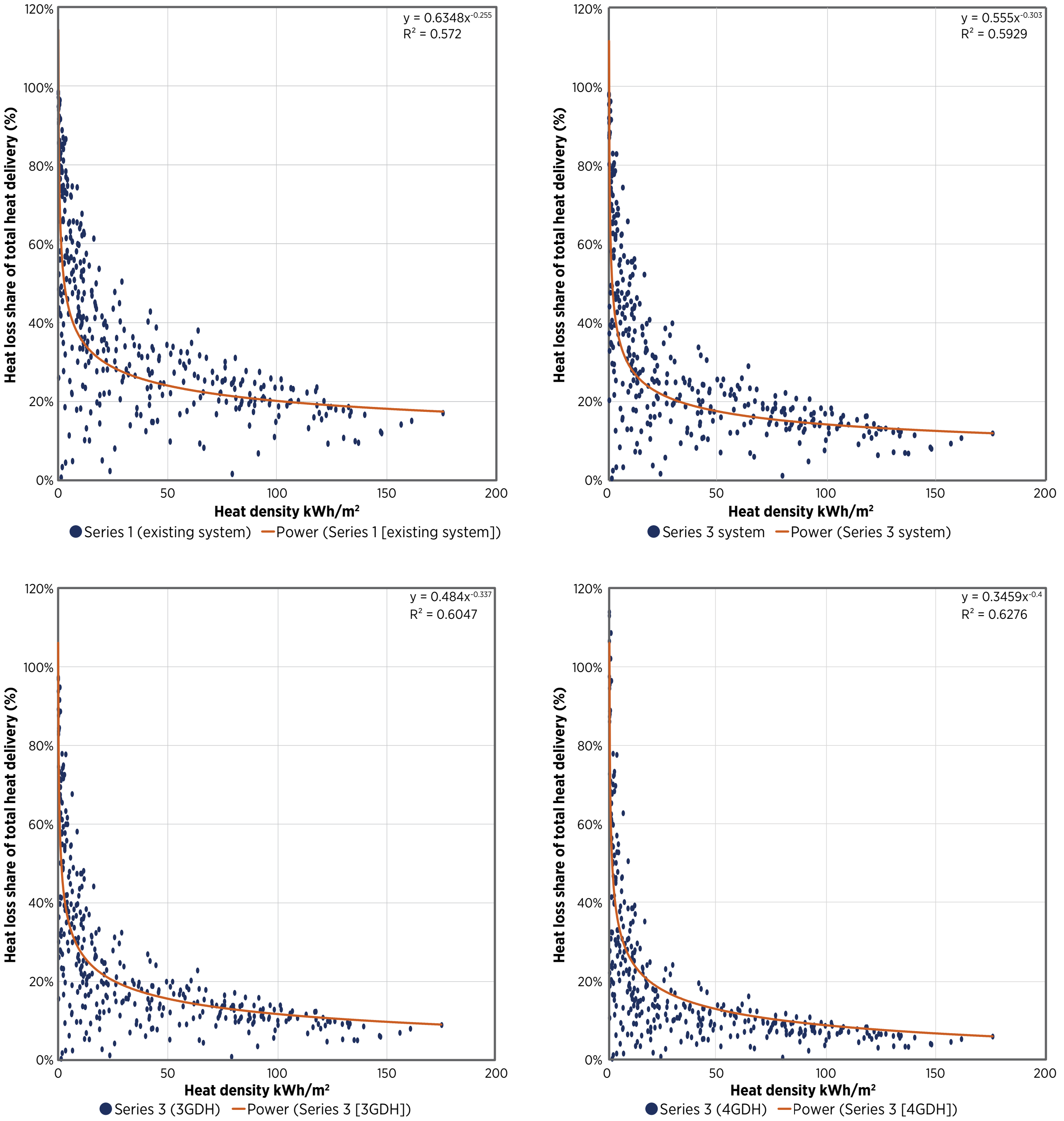
Based on the Danish experience, the cost of going from Series 1 to Series 3 pipes is an increase in investment of around 15%, which in Ulaanbaatar would mean an investment increase from MNT 3 658 313 million (USD 1.05 billion) to MNT 4 209 133 million (USD 1.21 billion). There are no direct costs from lowering the operating temperatures, but as mentioned previously it requires energy efficiency improvements in buildings, which can require significant investment.

Regression model of heat losses in potential district heating areas

A regression analysis was carried out to estimate the heat losses in areas without an existing district heating network. The result is a formula used together with the heat demand estimate model to estimate heat losses in a potential district heating area.

As explained in the previous section, the heat losses will depend on the type of pipes and the operating temperature level of the district heating system, and thus four different regressions have been done based on the four systems presented in Figure 63. The result of the regression analysis is presented in Figure 63, where the heat losses are reduced using more efficient Series 3 pipes, and by reducing the operating temperature levels to 3GDH and 4GDH levels. It is also apparent that there is a correlation between heat losses and the heat density, where the losses are relatively low in high-density areas and very high in low-density areas.

Figure 63 **Regression analysis of heat loss share compared to heat density under four efficiency scenarios**

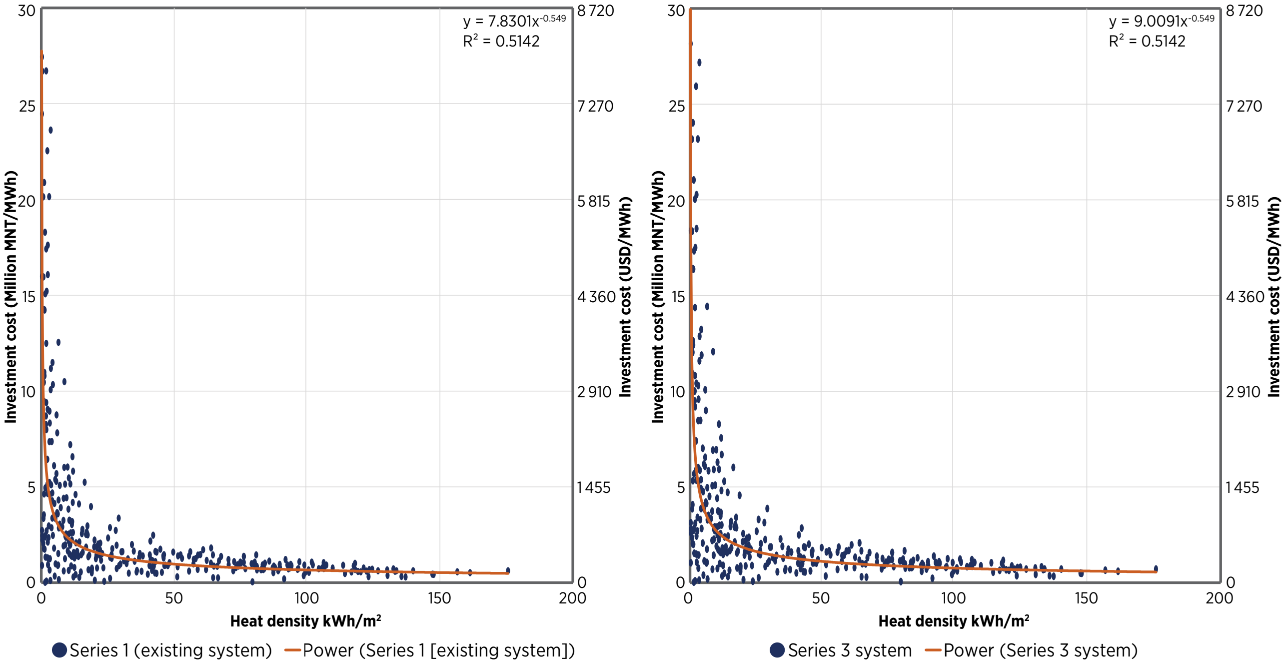


Notes: kWh/m² = kilowatt hours per square metre; 3GDH = third generation district heating; 4GDH = fourth generation district heating.

Regression model of district heating investment in potential district heating areas

Two more regression analyses were applied to estimate the district heating investment costs, which are presented in Figure 64. First, the graph for Series 1 pipes is presented followed by the same graph for a Series 3 system. The two graphs are similar, with the Series 3 pipes slightly higher in cost as expected. The general trend is that the higher the heat density the lower the specific cost per MWh, making district heating more feasible in high-density areas.

Figure 64 **Regression analysis of district heating network investment costs compared to heat density**



Notes: kWh/m² = kilowatt hours per square metre; MNT = Mongolian tugriks; MWh = megawatt hour

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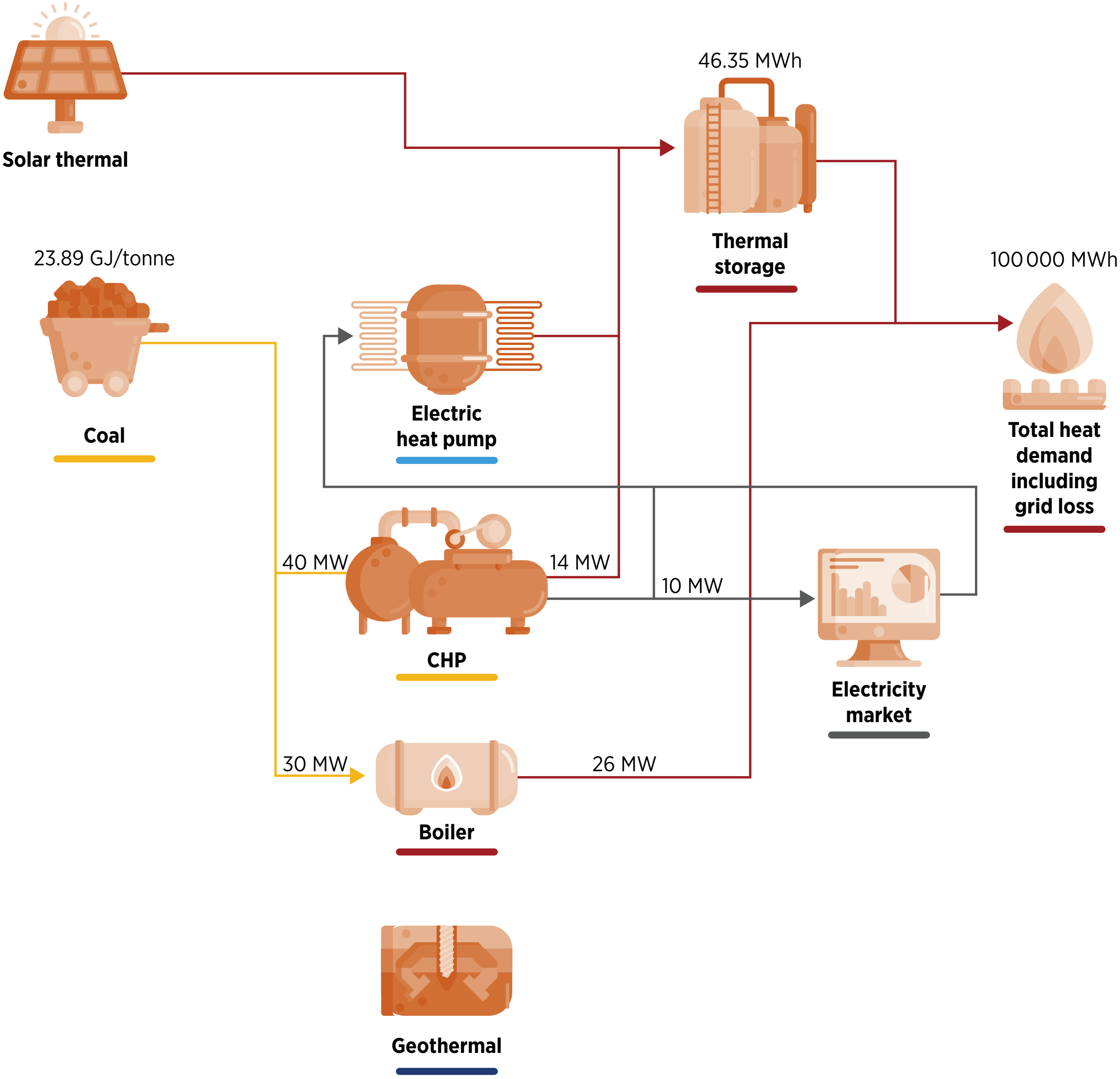
Energy system analysis of district heating

The energy system analysis is performed to simulate the hourly performance of the different cases and provide details on each case's costs and environmental impacts. There is a vast number of different tools for performing energy system analyses. In a recent review paper by M. Chang *et al.* (2021), 54 tools are compared in terms of their capabilities and scope. As this project is focused on the heating sector, especially district heating and renewable heat supply, the tool EnergyPRO is an adequate choice. The focus of EnergyPRO is detailed technical and financial analysis of district energy projects, and includes CHP plants, solar collectors, heat pumps, geothermal energy and seasonal storage, which are relevant in Mongolia. An example of a model set-up in EnergyPRO is presented in Figure 65. The set-up is highly adjustable and can be designed for any energy project, but generally includes fuels, conversion technologies, storage and heating demand, and external electricity markets.

Figure 65 **EnergyPRO model example**



Notes: CHP = combined heat and power; GJ = gigajoule; MW = megawatt; MWh = megawatt hour.

EnergyPRO also makes it possible to use hourly time series of external conditions, such as outdoor temperature, which enables a detailed simulation of the performance of, for example, heat pumps, solar thermal and heat storage. In the SHP for Mongolia this is especially important due to the large temperature variations over the year.

Technology data and costs for district heating

This section presents a description of some of the key technical specifications of relevant technologies. The presented information is applied to the energy system analysis and includes relevant operational details, such as efficiencies, typical sizes and restrictions. A variety of alternative heat sources can be deployed in district heating systems. In the baseline systems, a continuation of coal-fired district heating supply is investigated, albeit with the deployment of modern CHP plants and HOBs as opposed to the existing units.

In the renewables-based systems a variety of alternative heat supply options are investigated. Due to the limitation on available biomass resources, this study excludes the use of biomass technologies in the assessed cases. However, available waste resources, including biomass waste, are included. The available waste resources are based on estimations from the Ulaanbaatar Master Plan (Stryi-Hipp *et al.*, 2018).

Electric boilers and air-to-water large-scale heat pumps are included in the Renewable systems, in combination with onshore wind turbines and solar PV. Solar thermal collectors and deep geothermal are also included in the Renewable systems as well. Deep geothermal refers to geothermal sources at approximately 1.2 km depth. As described in Section 3.5, the potential for geothermal in Mongolia is relatively unexplored, and thus this is included to assess a case where geothermal heat sources are available. As many of the applied technologies have high efficiencies during the summer, when heat demand is relatively low, the potential for seasonal heat storage is investigated in form of PTES. Thus, the assessed district heating cases include the following list of technologies:

- Coal CHP
- Coal HOB
- Waste incineration CHP
- Waste incineration HOB
- Electric boilers
- Large-scale heat pumps, air-to-water
- Solar thermal collectors
- Deep geothermal, 1.2 km underground
- PTES (seasonal heat storage)
- Onshore wind turbines
- Solar PV.

Other technologies, such as gas boilers and gas CHP plants, could also be relevant in the future energy system of Mongolia, but these have been excluded from the main assessed cases due to uncertainties regarding the potential for development of a gas sector in Mongolia.

Each of the listed technologies is described, firstly in terms of technical specification and economic costs associated with investment, operation and maintenance, and subsequently costs related to fuels and emissions. A qualitative description of the heat sources and supply technologies can be found in Chapter 3.

Appendix B shows the technology cost and specifications used for each of the assessed cases, *i.e.* 2020, 2030, and 2050. Values related to the technology's efficiency, lifetime expectancy and investment costs are shown for both heat-only technologies, and electricity-producing combined technologies.

Table 10 shows the economic cost data assumptions related to fuels, electricity and emissions. The price of coal is added both at a low and high price level with its expected development towards 2050. The emissions factors are set the same in 2020, 2030 and 2050. A discount rate of 8.75% has also been assumed.

Table 10 **Economic cost data for fuels, electricity and cost of emissions and WACC assumptions**

Category	Unit	Values for different years			Reference
		2020	2030	2050	
Coal price (low)	USD/MWh	3	4	7	(Energy Regulatory Commission, 2022; IEA, 2022)
Coal price (high)	USD/MWh	21	13	11	(IEA, 2022)
Electricity price	USD/MWh	30	45	77	Estimated from (Energy Regulatory Commission, 2022)
CO_2 price (low)	USD/tonne	54			(Ricke *et al.*, 2018)
CO_2 price (medium)	USD/tonne	185			(Rennert *et al.*, 2022)
CO_2 price (high)	USD/tonne	417			(Wang *et al.*, 2019)
SO_x	USD/kg	1.07			(Wang *et al.*, 2019)
NO_x	USD/kg	1.09			(Wang *et al.*, 2019)
$PM_{2.5}$	USD/kg	2.11			(Wang *et al.*, 2019)
PM_{10}	USD/kg	2.11			(Wang *et al.*, 2019)
WACC	%	8.75%			(Nascimento *et al.*, 2019)

Notes: kg = kilogramme; MWh = megawatt hour; WACC = weighted average cost of capital.

Table 11 shows the emissions related to CHP plants and waste incineration plants. The CHP plants have been split into existing and modern coal plants, which have a significant difference in PM emissions.

Table 11 **Emissions performance of the CHP plants included in the energy system analysis**

Category	CO_2	SO_x	NO_x	$PM_{2.5}$	PM_{10}	Reference
	kg/GJ	g/GJ	g/GJ	g/GJ	g/GJ	
Existing coal plants	94.1	14.0	25.0	326	816	(Wang *et al.*, 2019)
Modern coal plants	94.1	14.0	25.0	2.1	5.3	(Wang *et al.*, 2019)
Waste incineration plants	42.5	8.3	79.0	0.3	0.7	(Wang *et al.*, 2019)

Notes: g/GJ = grammes per gigajoule; kg/GJ = kilogram per gigajoule.

Analysis parameters for individual heating solutions

Individual heating solutions is a broad term used for all the buildings that are not connected to the district heating network. In terms of individual heating solutions, various renewable alternatives are available to the existing coal stoves and HOB plants. In this SHP, the focus is on non-biomass-based heating, as biomass resources in Mongolia are limited, and burning biomass would give similar challenges as coal in relation to the local emissions. Thus, the following technologies are included:

- Coal stoves and HOBs
- Direct electric
- Heat pump, air-to-air
- Heat pump, air-to-water
- Heat pump, ground source
- Solar collectors thermal with storage.

Each of these technologies is described first in terms of technical properties, followed by a section on the economic costs associated with investment, operation and maintenance, fuels and emissions.

For each technology the expected level of development in 2020, 2030 and 2050 is assessed. Due to limited data availability for Mongolia, Danish data have been used for some of the costs, but data from Mongolia has been used where possible. Appendix B shows the technology and cost data for each specific technology used for individual heating solutions.

In addition to the technology-specific information, Table 12 includes general inputs that have been used for prices and emission factors. The electricity price is based on the average user tariff for the central region (Energy Regulatory Commission, 2022). A decreasing average CO_2 emission factor is assumed for grid electricity, as the 2050 electricity system is assumed to have a higher share of renewables.

Table 12 **General inputs for electricity prices, emissions and costs related to emissions**

Category	Unit	Values for different years			Reference
		2020	2030	2050	
Electricity price	USD/kWh	0.032			(Energy Regulatory Commission, 2022)
Average CO_2 emission factor (grid electricity)	tonne/MWh	0.600	0.449	0.380	2020: (Ritchie, Roser and Rosado, 2022) 2030: average of 2020 and 2050 2050: (Stryi-Hipp *et al.*, 2018)
CO_2 costs	USD/tonne	185			(Rennert *et al.*, 2022)
SO_x costs	USD/tonne	1 072			(Andersen *et al.*, 2019)
NO_x cost	USD/tonne	1 092			(Andersen *et al.*, 2019)
$PM_{2.5}$ costs	USD/tonne	2 110			(Andersen *et al.*, 2019)
Emission factors for coal briquettes used in stoves and HOBs					
CO_2	tonne/ tonne	1.37			(Namkhainyam *et al.*, 2019a)
NO_x	kg/tonne	1.40			(Namkhainyam *et al.*, 2019a)
SO_x	kg/tonne	6.00			(Namkhainyam *et al.*, 2019a)
$PM_{2.5}$	kg/tonne	9.60			(World Bank, 2009)
PM_{10}	kg/tonne	16.00			(World Bank, 2009)

Notes: kg = kilogramme; MWh = megawatt hour; kWh = kilowatt hour.

Appendix B Technology and cost data

Table 13 **Technical specifications and cost assumptions for district heating technologies and onshore wind and solar PV for 2020**

Technology costs and specifications for 2020								
Heat-only technologies								
Category	**Efficiency**	**Electric efficiency**	**Heat efficiency**	**Lifetime**	**Investment**	**Fixed O&M**	**Variable O&M**	**Reference**
	%	**%**	**%**	**Years**	**Million USD/ MW heat**	**USD/ MW/year**	**USD/ MWh**	
Heat pump	310%	-	350%	25	0.93	2 173	1.84	(Danish Energy Agency, 2020a)
Geothermal	467%	-	467%	25	2.88	23 791	6.20	(Danish Energy Agency, 2020a)
Solar thermal	68%	-	68%	30	0.29	66	0.23	(Danish Energy Agency, 2020a)
Electric HOB	99%	-	99%	20	0.08	1 162	0.98	(Danish Energy Agency, 2020a)
Coal HOB	95%	-	95%	25	0.77	35 524	2.13	(Danish Energy Agency, 2020a)
Electricity-producing technologies								
	Efficiency	**Electric efficiency**	**Heat efficiency**	**Lifetime**	**Investment**	**Fixed O&M**	**Variable O&M**	**Reference**
	%	**%**	**%**	**Years**	**Million USD/ MW heat**	**USD/ MW/year**	**USD/ MWh**	
W2E CHP	95%	20%	74%	25	9.32	223 788	29.64	(Danish Energy Agency, 2020a)
Onshore wind	-	-	-	27	1.22	15 209	1.63	(Danish Energy Agency, 2020a)
Solar PV	-	-	-	35	0.61	12 276	0.00	(Danish Energy Agency, 2020a)
Coal CHP	55%	19%	36%	25	2.60	42 424	3.72	(Danish Energy Agency, 2020a)

Notes: CHP = combined heat and power; HOB = heat only boiler; MW = megawatt; MWh = megawatt hour; O&M = operation and maintenance; PV = photovoltaic; W2E = waste-to-energy.

Table 14 **Technical specifications and cost assumptions for district heating technologies and onshore wind and solar PV for 2030**

Technology costs and specifications for 2030								
Heat-only technologies								
Category	**Efficiency**	**Electric efficiency**	**Heat efficiency**	**Lifetime**	**Investment**	**Fixed O&M**	**Variable O&M**	**Reference**
	%	**%**	**%**	**Years**	**Million USD/ MW heat**	**USD/ MW/year**	**USD/ MWh**	
Heat pump	315%	-	355%	25	0.83	2 173	1.84	(Danish Energy Agency, 2020a)
Geothermal	474%	-	474%	30	2.72	23 139	6.66	(Danish Energy Agency, 2020a)
Solar thermal	70%	-	70%	30	0.28	62	0.33	(Danish Energy Agency, 2020a)
Electric HOB	99%	-	99%	20	0.07	1 108	1.09	(Danish Energy Agency, 2020a)
Coal HOB	95%	-	95%	25	0.74	33 677	2.85	(Danish Energy Agency, 2020a)
Electricity-producing technologies								
	Efficiency	**Electric efficiency**	**Heat efficiency**	**Lifetime**	**Investment**	**Fixed O&M**	**Variable O&M**	**Reference**
	%	**%**	**%**	**Years**	**Million USD/ MW heat**	**USD/ MW/year**	**USD/ MWh**	
W2E CHP	93%	21%	72%	25	8.81	207 493	28.81	(Danish Energy Agency, 2020a)
Onshore wind	-	-	-	30	1.13	13 688	1.47	(Danish Energy Agency, 2020a)
Solar PV	-	-	-	40	0.41	10 320	0.00	(Danish Energy Agency, 2020a)
Coal CHP	90%	39%	52%	25	2.73	44 539	3.99	(Danish Energy Agency, 2020a)

Notes: CHP = combined heat and power; HOB = heat only boiler; MW = megawatt; MWh = megawatt hour; O&M = operation and maintenance; PV = photovoltaic; W2E = waste-to-energy.

Table 15 Technical specifications and cost assumptions for district heating technologies and onshore wind and solar PV for 2050

Technology costs and specifications for 2050

Heat-only technologies

Category	Efficiency	Electric efficiency	Heat efficiency	Lifetime	Investment	Fixed O&M	Variable O&M	Reference
	%	%	%	Years	Million USD/ MW heat	USD/ MW/year	USD/ MWh	
Heat pump	320%	-	360%	25	0.83	2 173	1.84	(Danish Energy Agency, 2020a)
Geothermal	494%	-	494%	30	2.59	21 618	6.37	(Danish Energy Agency, 2020a)
Solar thermal	73%	-	73%	30	0.26	65	0.38	(Danish Energy Agency, 2020a)
Electric HOB	99%	-	99%	20	0.07	999	1.09	(Danish Energy Agency, 2020a)
Coal HOB	95%	-	95%	25	0.66	30 309	3.20	(Danish Energy Agency, 2020a)

Electricity-producing technologies

	Efficiency	Electric efficiency	Heat efficiency	Lifetime	Investment	Fixed O&M	Variable O&M	Reference
	%	%	%	Years	Million USD/ MW heat	USD/ MW/year	USD/ MWh	
PTES	70%	-	70%	25	0.51	3.26	0.00	(Danish Energy Agency, 2018)

Electricity-producing technologies

	Efficiency	Electric efficiency	Heat efficiency	Lifetime	Investment	Fixed O&M	Variable O&M	Reference
	%	%	%	Years	Million USD/ MW heat	USD/ MW/year	USD/ MWh	
W2E CHP	94%	22%	72%	25	7.68	175 989	27.75	(Danish Energy Agency, 2020a)
Onshore wind	-	-	-	30	1.04	12 319	1.33	(Danish Energy Agency, 2020a)
Solar PV	-	-	-	40	0.32	8 039	0.00	(Danish Energy Agency, 2020a)
Coal CHP	90%	39%	52%	25	2.69	43 937	4.11	(Danish Energy Agency, 2020a)

Notes: CHP = combined heat and power; HOB = heat only boiler; MW = megawatt; MWh = megawatt hour; O&M = operation and maintenance; PTES = pit thermal energy storage; PV = photovoltaic; W2E = waste-to-energy.

Technology data and costs for individual heating

Coal stoves and HOBs are the primary technology used for heating outside district heating areas. As seen in Table 16, their efficiency is only 70%, but both have a low investment cost and a low fuel cost, making them the most attractive heating solution outside district heating, when not considering the emissions-related costs from local pollution and climate change effects.

Table 16 **Coal stoves and HOB technology and costs (same for 2020, 2030 and 2050)**

Category	Unit	Value	Reference	Assumption
Efficiency	%	70%	(Namkhainyam *et al.*, 2019a)	-
Technical lifetime	years	20	(Namkhainyam *et al.*, 2019a)	-
Investment cost	USD/MW	112 500	(Namkhainyam *et al.*, 2019a)	-
Fuel cost	USD/kWh	0.014	(Jun, 2021)	-
Fixed O&M	USD/MW	7 669	(Danish Energy Agency, 2020b)	50% fixed O&M

Notes: kWh = kilowatt hour; MW = megawatt; O&M = operation and maintenance.

An alternative to using coal stoves and HOBs is to replace them with direct electric heating solutions. As with all other electricity-based solutions, it is a prerequisite that the electricity supply also transitions into renewables; otherwise, the change would only reduce local pollution and not climate change effects. As seen in Table 17, direct electric heating has an efficiency of around 100%, which is not high considering the efficiency of power plants and network losses in the electricity supply. Thus, simply basing the future system on direct electric heating would cause challenges for electricity distribution and supply capacity.

Table 17 **Direct electric heating technology and costs**

Year	Category	Unit	Values for different years			Reference
			Gers	Single-family	Multi-family	
2020	Efficiency	%	100%			(Danish Energy Agency, 2020b)
	Technical lifetime	years	30			(Danish Energy Agency, 2020b)
	Investment cost	USD/MW	320 000			(Danish Energy Agency, 2020b)
	Fixed O&M	USD/MW	8 480	8 480	325	(Danish Energy Agency, 2020b)
2030	Efficiency	%	100%			(Danish Energy Agency, 2020b)
	Technical lifetime	years	30			(Danish Energy Agency, 2020b)
	Investment cost	USD/MW	320 000			(Namkhainyam *et al.*, 2019a)
	Fixed O&M	USD/MW	8 127	8 127	305	(Danish Energy Agency, 2020b)
2050	Efficiency	%	100%			(Danish Energy Agency, 2020b)
	Technical lifetime	years	30			(Danish Energy Agency, 2020b)
	Investment cost	USD/MW	320 000			(Danish Energy Agency, 2020b)
	Fixed O&M	USD/MW	7 420	7 420	278	(Danish Energy Agency, 2020b)

Notes: MW = megawatt; O&M = operation and maintenance.

Air-to-water heat pumps are a more efficient alternative to direct electric heating. As seen in Table 18, the average annual efficiency is around 260%, which means that the requirements for the electricity supply system are much lower than for direct electric heating. However, with air-to-water heat pumps it is important to note that their efficiency in the cold winter months is reduced, and thus they are often supplemented with heating elements that can supply peak demand when needed. The investment cost of air-to-water heat pumps is also higher than direct electric heating, which is typically offset by the higher efficiency.

Table 18 **Heat pump, air-to-water technology and costs**

Year	Category	Unit	Values for different years			Reference
			Gers	Single-family	Multi-family	
2020	Efficiency	%	260%			(Stryi-Hipp *et al.*, 2018)
	Technical lifetime	years	16	16	20	(Danish Energy Agency, 2020b)
	Investment cost	USD/MW	1 658 600	1 658 600	729 195	(Danish Energy Agency, 2020b)
	Fixed O&M	USD/MW	47 156	47 156	11 481	(Danish Energy Agency, 2020b)
2030	Efficiency	%	260%			(Stryi-Hipp *et al.*, 2018)
	Technical lifetime	years	16	16	20	(Danish Energy Agency, 2020b)
	Investment cost	USD/MW	1 401 151	1 401 151	576 686	(Namkhainyam *et al.*, 2019a)
	Fixed O&M	USD/MW	33 967	33 967	11 363	(Danish Energy Agency, 2020b)
2050	Efficiency	%	260%			(Stryi-Hipp *et al.*, 2018)
	Technical lifetime	years	16	16	20	(Danish Energy Agency, 2020b)
	Investment cost	USD/MW	1 192 345	1 192 345	456 347	(Danish Energy Agency, 2020b)
	Fixed O&M	USD/MW	32 123	32 123	11 076	(Danish Energy Agency, 2020b)

Notes: MW = megawatt; O&M = operation and maintenance.

An alternative to air-source heat pumps is to use a ground-source heat pumps, for which the technology data are presented in Table 19. Ground-source heat pumps have a higher average efficiency as ground temperatures on average are higher than outdoor air temperatures, especially in the colder months. However, the technology also has higher investment costs than air-to-water heat pumps. From an energy efficiency perspective, ground-source heat pumps are the most efficient alternative to district heating.

Table 19 **Heat pump, ground-source technology and costs**

Year	Category	Unit	Values for different years			Reference
			Gers	Single-family	Multi-family	
2020	Efficiency	%	345%	345%	320%	(Danish Energy Agency, 2020b)
	Technical lifetime	years	20			(Danish Energy Agency, 2020b)
	Investment cost	USD/MW	2 196 561	2 196 561	679 396	(Danish Energy Agency, 2020b)
	Fixed O&M	USD/MW	43 498	43 498	7 104	(Danish Energy Agency, 2020b)
2030	Efficiency	%	365%	365%	340%	(Danish Energy Agency, 2020b)
	Technical lifetime	years	20			(Danish Energy Agency, 2020b)
	Investment cost	USD/MW	1 976 905	1 976 905	577 487	(Namkhainyam *et al.*, 2019a)
	Fixed O&M	USD/MW	30 308	30 308	6 987	(Danish Energy Agency, 2020b)
2050	Efficiency	%	385%	385%	360%	(Danish Energy Agency, 2020b)
	Technical lifetime	years	20			(Danish Energy Agency, 2020b)
	Investment cost	USD/MW	1 779 215	1 779 215	490 864	(Danish Energy Agency, 2020b)
	Fixed O&M	USD/MW	28 464	28 464	6 700	(Danish Energy Agency, 2020b)

Notes: MW = megawatt; O&M = operation and maintenance.

Another heat pump technology with a higher efficiency is air-to-air heat pumps, as shown in Table 20; however, it should be noted that these can only be used as a supplement to other technologies as they can typically provide up to around 30% of the space heating requirement at room temperature. In the cold Mongolian winter, the efficiency will be much lower as it is related to the outdoor temperature, and another technology would be needed for DHW preparation.

Table 20 **Heat pump, air-to-air technology and costs**

Year	Category	Unit	Values for different years			Reference
			Gers	Single-family	Multi-family	
2020	Efficiency	%	460%	460%	485%	(Danish Energy Agency, 2020b)
	Technical lifetime	years	12			(Danish Energy Agency, 2020b)
	Investment cost	USD/MW	472 357	472 357	276 902	(Danish Energy Agency, 2020b)
	Fixed O&M	USD/MW	63 742	63 742	24 516	(Danish Energy Agency, 2020b)
2030	Efficiency	%	505%	505%	530%	(Danish Energy Agency, 2020b)
	Technical lifetime	years	12			(Danish Energy Agency, 2020b)
	Investment cost	USD/MW	449 263	449 263	263 365	(Namkhainyam *et al.*, 2019a)
	Fixed O&M	USD/MW	42 507	42 507	16 349	(Danish Energy Agency, 2020b)
2050	Efficiency	%	530%	530%	560%	(Danish Energy Agency, 2020b)
	Technical lifetime	years	12			(Danish Energy Agency, 2020b)
	Investment cost	USD/MW	406 408	406 408	238 242	(Danish Energy Agency, 2020b)
	Fixed O&M	USD/MW	39 538	39 538	15 207	(Danish Energy Agency, 2020b)

Notes: MW = megawatt; O&M = operation and maintenance.

A solar thermal collector is another technology that can be used as a secondary heat supply. The data for solar thermal collectors are presented in Table 21. A solar thermal collector is a renewable solution that produces heat directly from solar energy and can be used to reduce the need for heat production at the main heat supply unit. Due to the variation in solar potential over the year, solar thermal is typically only used to provide around 20-30% of the annual heat demand, such as DHW. As solar thermal collectors only produce heat during daylight hours, it needs to be supplemented with a heat storage, so the heat can be stored and used later. The data for small thermal storage tanks are presented in Table 22.

Table 21 **Solar thermal collector technology and costs**

Year	Category	Unit	Values for different years			Reference
			Gers	Single-family	Multi-family	
2020	Space requirement	m^2/kW	1.43			(Danish Energy Agency, 2020b)
	Production per m^2	kWh/m^2	790			(COWI, 2019)
	Share of space heat	%	10%	10%	0%	(Danish Energy Agency, 2020b)
	Share of DHW	%	65%			(Danish Energy Agency, 2020b)
	Technical lifetime	years	25	25	20	(Danish Energy Agency, 2020b)
	Investment cost	USD/MW	278 474			(COWI, 2019)
	Fixed O&M	USD/MW	13 237	13 237	3 157	(Danish Energy Agency, 2020b)
2030	Space requirement	m^2/kW	1.43			(Danish Energy Agency, 2020b)
	Production per m^2	kWh/m^2	790			(COWI, 2019)
	Share of space heat	%	10%	10%	0%	(Danish Energy Agency, 2020b)
	Share of DHW	%	65%			(Danish Energy Agency, 2020b)
	Technical lifetime	years	30			(Danish Energy Agency, 2020b)
	Investment cost	USD/MW	278 474	278 474	278 474	(COWI, 2019)
	Fixed O&M	USD/MW	12 127	12 127	3 419	(Danish Energy Agency, 2020b)
2050	Space requirement	%	1.43			(Danish Energy Agency, 2020b)
	Production per m^2	years	790			(COWI, 2019)
	Share of space heat	USD/MW	10%	10%	0%	(Danish Energy Agency, 2020b)
	Share of DHW	1	65%			(Danish Energy Agency, 2020b)
	Technical lifetime	1	30			(Danish Energy Agency, 2020b)
	Investment cost	1	278 474	278 474	278 474	(COWI, 2019)
	Fixed O&M	USD/MW	10 815	10 815	3 157	(Danish Energy Agency, 2020b)

Notes: DHW = domestic hot water; kWh/m^2 = kilowatt hours per square metre; m^2/kW = square metres per kilowatt; MW = megawatt; O&M = operation and maintenance.

Table 22 **Small thermal storage tank technology and cost (same costs for 2020, 2030 and 2050)**

Category	Unit	Value	Reference	Assumption
Technical lifetime	years	30	(Danish Energy Agency, 2018)	-
Investment cost	USD/kWh	217	(Danish Energy Agency, 2018)	50% of Danish cost
Fixed O&M	USD/kWh	18	(Danish Energy Agency, 2018)	-

Notes: kWh = kilowatt hour; O&M = operation and maintenance.

Appendix C
GIS Methodology

The mapping parameters and methodology data present their own subset of delimitations, assumptions and potential errors. Both data availability and accessibility for the Mongolian heating sector are limited, probably due to the lack of measurability and traceability, especially regarding non-connected district heating buildings where single heating solutions are used. This is combined with Mongolia's characteristic challenge of mapping non-permanent structures such as Ger tents. Through the support of the Mongolian Ministry of Energy, it was possible to gather data on the district heating network. These data were used to perform a validation at the building level for buildings connected to district heating, as well as regression analysis models for district heating investment costs and heat losses in the Mongolian context. For buildings not connected to district heating, other means of validation were used, such as previous reports and articles on building-level heat demand estimations in Ulaanbaatar city.

Based on the available data, the methodology was tailored to fulfil the objective of heat demand estimation at a building level with a focus on the geographical scale of the distributed demand within the AOI. Generalised coefficients for the thermal insulation of buildings were used, independent of their usage. Additionally, floor area equals heated floor area in the model's buildings. These parameters will be highly dependent on their technical and circumstantial parameters, amongst others of a local nature.

The largest errors are expected in areas with sparse infrastructure distribution, particularly areas with a low density of high-rise and low-rise buildings within the same grid area, since the input data homogenise building heights, thus overestimating in areas with sparse distribution, and underestimating in some denser ones. For the district heating assessment, a 500 m x 500 m grid facilitates the analysis by aggregating building-level heat demand. These aggregated densities, however, should not be seen as a homogeneously distributed heating measure in the designated geographical area.

All in all, the overall approach can be seen as a showcase of the potential for the geographical analysis of district heating assessments, as well as a replicable prefeasibility methodology that can be refined with further accurate data, if available.

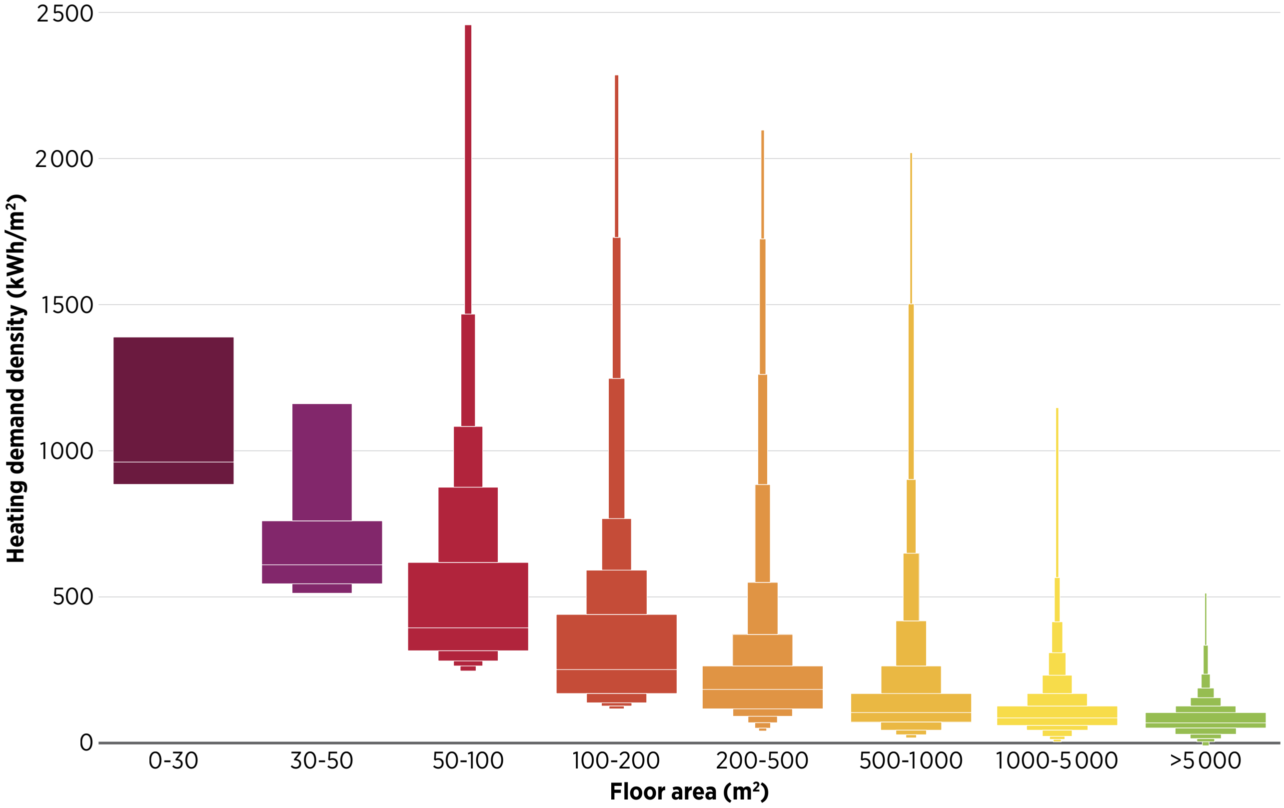
Validation of the heating demand model in Ulaanbaatar

Various types of validation were performed for the heating demand model. The first validation is on a systematic level, using Ulaanbaatar district heating network data. The second validation is on a building level, using values gathered from literature studies and previous reports addressing heating demand estimations in Ulaanbaatar. A third level of validation consists of an assessment based on the aggregated sum of heating demand using different grid resolutions. More on the validations follows:

- **System-level validation:** Datasets containing information about the current district heating system are used to validate the heating demand model. The datasets include information on building height, area and their peak heat capacity for both, space heating and DHW. To be compatible with the estimated values calculated by the model, the building peak capacity is translated into annual heat demand by estimating the peak capacity factors of the heating system based on full load hours operation – 8 760 hours. There are 13 010 buildings within the validation dataset, where a total of 9 158 are matched to the model for the validation, leaving around 34 000 buildings within the district heating network not matched for validation.

Once the match was created, the model's performance was assessed in a summarised form. Overall, the model overestimates the total heating demand by 0.5%. Figure 66 shows a whiskers plot of the spread of building heating demand density in relation to floor area building size category. Here, heating demand density responds to heating demand per unit of heated area, which is assumed to equal floor area in a building. From the plot, small buildings show up to 10 times the heating demand density of larger buildings for the validation dataset, considering the mean and the interquartile range of the distribution.

Figure 66 **Validation dataset for heating demand densities**



Note: kWh/m² = kilowatt hours per square metre.

- **Building-level validation:** Estimates are also gathered from the literature on the estimated heating demand per individual building, depending on their corresponding type. However, due to the unknown building type and heated area share of the total floor area in both validation and model datasets, the values are taken as indicative. Moreover, taking the heated area as a proportion of the total floor area, the values in Table 23 are expected to be larger than the ones seen in both the model and the validation dataset – see Figure 66.

Table 23 **Estimated individual heating demand per building type**

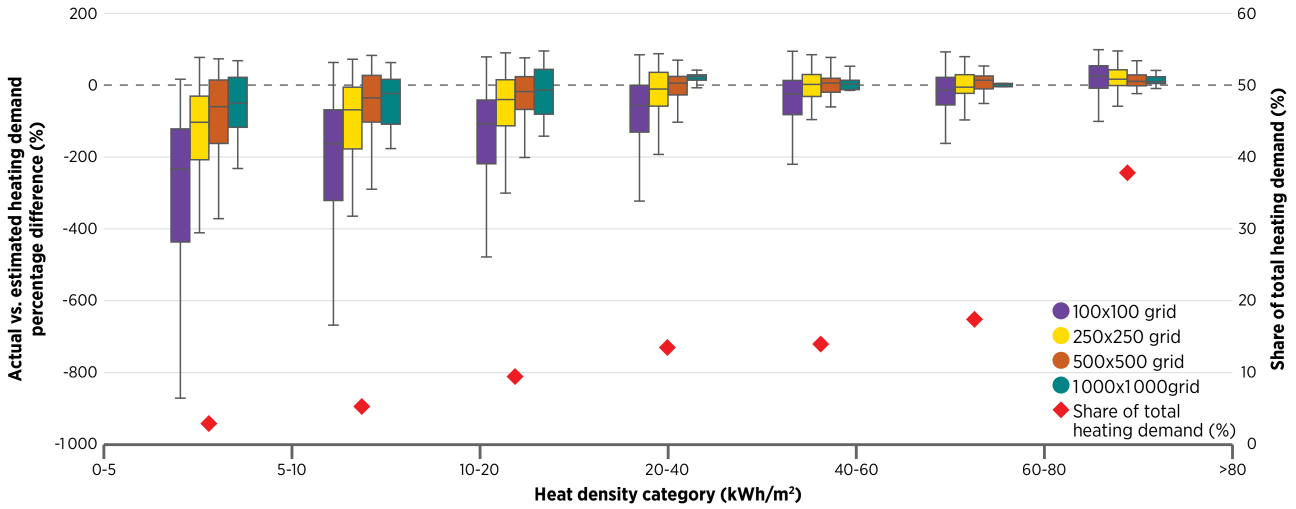
Type	Description	Estimated heat demand [kWh/m²]*
Buildings	Pre-cast	562
	Old brick	390
	Before 2015	350
	Public buildings	239
	Schools	217
	Kindergartners	284
Houses	Single family before 2015	405
	Public dwelling	500
	Other	500
	Ger area	432
Other	*Ger*	625

Source: Integration and Ekodoma Ltd. (2020); Stryi-Hipp *et al.* (2018).

Notes: *The estimated heating demand is considering heated area; kWh/m2 = kilowatt hour per square metre.

- **Grid-level validation:** This validation is performed to identify the best performing grid size of the model to be used in the district heating assessment, without compromising the scale of the analysis. This is done by testing grid sizes of 100, 250, 500 and 1 000 metres, and assessing their performance. Performance is measured as the total heating demand percentage difference by grid heat density category. The heat density category here responds to the total heat demand relative to each grid area. Results of the spread of this validation – see Figure 67 — show a weaker performance as the grid resolution increases, independently of the heat density category. The figure also includes a secondary axis showing the share of total heating demand per heat density category. Altogether the figure shows both weaker performance at a higher resolution, and a low share of heating demand in the lowest and worse performing heat density category.

Figure 67 **Grid and heat density validation**



Note: kWh/m² = kilowatt hours per square metre.