Transforming the Ulaanbaatar Heating Sector

Technology options for decarbonisation

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On behalf of:
Federal Ministry
for the Environment, Nature Conservation, Nuclear Safety and Consumer Protection
of the Federal Republic of Germany

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Disclaimer

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Summary of key findings

The current state of the Ulaanbaatar heating sector presents a unique opportunity to initiate a transition towards a decarbonised heat supply and wean itself off coal-based power and heat. As the coldest capital in the world, experiencing temperatures down to as low as minus 40°C, the demand for heat is high. While the coal-based heat generation capacity is old with some plants operating beyond their expected lifetime, the rapidly growing population makes it challenging for the existing heat generation capacity to satisfy the rising demand. The heat and power sectors, tightly coupled from their generation in combined heat and power plants (CHPs), are responsible for the largest share of greenhouse gas (GHG) emissions. A decision to upgrade and/or expand the CHP capacity to meet the growing demand risks to lock the city into coal dependency for decades to come. Now is therefore a critical moment, and a unique opportunity, to steer the sector away from fossil fuels by introducing low-carbon heating technologies.

Previous research has shown that full electrification of the Ulaanbaatar heating sector could lead to its decarbonisation by 2050. However, such scenarios would lead to a notable increase in electricity demand, locking in the dependency on coal-based CHP and extending the timeline for decarbonisation. In this study, we investigate whether there are other feasible decarbonisation options beyond full electrification, and their potential cost implications. Such an option is the application of solar assisted ground source heat pumps (SAGSHP), a hybrid technology combining ground source heat pumps (GSHP) and solar thermal collectors that generate heat from both technologies and maximises the efficiency of the heat pump. We compare a less electricity intensive decarbonisation scenario with the application of large-scale SAGSHP as the main heating technology to a fully electrified decarbonisation scenario informed by previous research.

The implementation of the less electricity intensive technology leads to a decrease in electricity demand by 28% compared to a scenario of full electrification of heat supply. Even though the more capital-intensive technology (SAGSHP) increases fixed costs by 30%, the cost savings from the lower electricity demand offset that difference, leading to 9% lower total costs. This is due to a less electricity intensive scenario requiring 22% less installed power capacity, 23% lower grid expansion costs and 28% lower variable costs.

These findings imply that in the particular case of Ulaanbaatar, full electrification may not be the optimal route for decarbonisation of the heating sector. The major increase in electricity demand would place a heavy burden on the power sector, leading to high costs for capacity, transmission and distribution expansions. The highly coupled heat and power sectors means that electricity production largely responds to the heat demand, resulting in significant inflexibilities in the system which limit the ability to increase the penetration of renewables and thus also the decarbonisation of both sectors. As such, a key challenge is to gradually phase down CHP while increasing the participation of renewables in a tightly coupled system. The application of heating technologies which are more efficient and maximise the direct use of renewable heat can reduce the burden on the power sector while gradually decoupling the heat and power supply sectors. Doing so could untap flexibilities that are locked within the system and facilitate the increased penetration of renewables and the decarbonisation of the energy supply.

Based on the results from the scenario analysis, we identify three key transformations which need to take place to enable the decarbonisation of the Ulaanbaatar heating sector. Those include: (1) Enhance energy efficiency by improving building envelopes and expanding the district heating network, (2) Expand the renewable energy power capacity to improve access to electricity and untap system flexibility, and (3) Integrate novel, renewable energy-based heating technologies.

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Abbreviations

ASHP	Air-source heat pump
CHP	Combined heat and power
COP	Coefficient of performance
DEH	Direct electric heating
GHG	Greenhouse gas
GSHP	Ground-source heat pump
HP	Heat pump
SAASHP	Solar assisted air-source heat pump
SAGSHP	Solar assisted ground-source heat pump
WSHP	Water-source heat pump

1 Introduction

1.1 Background

Ulaanbaatar is the coldest capital in the world and relies almost exclusively on coal for heating, making its heating sector the main contributors to the city's GHG emissions. On the national level, the buildings sector consumes more than 40% of the energy produced in the country (Savickas, 2020). According to latest available data from 2015, the energy sector was responsible for 52% of national GHG emissions, with 43% of it coming from the building sector (Ministry of Environment and Tourism et al., 2018; Nascimento et al., 2020). The extremely harsh conditions in winter, with temperatures dropping as low as -40°C and with a heating season lasting for roughly eight months, Ulaanbaatar requires a robust and reliable heat supply (Savickas, 2020).

With an immense supply of cheap, state-owned coal, almost all heat and electricity generation is coal-based (Carlisle and Pevzner, 2019). While a large part of the population is connected to the district heating network supplied from coal-fired combined heat and power (CHP) plants, rapidly growing informal housing districts, so called *gers*, lack access to central heating making them dependent on raw coal burning. The city's heating sector as such faces two key challenges to decarbonise its energy supply: Firstly, the co-generation of heat and electricity complicates the decarbonisation of the heat supply as it requires the decoupling of the two sectors. Secondly, the low density of the growing ger districts make them unsuitable for district heating systems and other decentralised ways of supplying heat must be considered. Options currently available require substantial infrastructure development and urban design solutions.

Despite such challenges, the current status of Ulaanbaatar's heating sector provides a unique opportunity. The ample solar and wind resources in the region provide great potential for the wide use of renewables. At the same time, the current heating infrastructure is old with some of the plants operating beyond their lifetime. The rapid urbanisation generates a steadily growing demand for heat, making the current capacity insufficient to meet the projected demand (Savickas, 2020; WBG, 2020). The sector is thus facing an urgent need to both upgrade and expand its heating capacity. To take advantage of this opportunity is therefore critical to develop a technology pathway for the decarbonisation of the heat supply, and to avoid investments in new coal-reliant technologies which would lock the sector into high-emitting fossil fuel technologies for the foreseeable future.

The question remains, however, what such a technology roadmap should look like. Previous studies have found that the available renewable energy resources in the region would be sufficient to meet the heat demand, but stops short of recommending full sector decarbonisation and maintains a partial dependency on coal-based CHP (Stryi-Hipp et al., 2018). But there is a certain gap in the existing research which so far has not considered the full range of decarbonisation technologies available. In this study, we perform a comprehensive technology mapping exercise with the aim to identify available decarbonisation heating technologies which could also reduce the overall power demand.

1.2 Building on previous research

The calculations in this study build on the results of a previous study where various pathways to achieve decarbonisation of the Ulaanbaatar heating sector are investigated (Stryi-Hipp et al., 2018). In that analysis, a cost-optimisation modelling exercise of supply and demand of the power and heating sectors is performed, aiming to identify the cost-optimal technology mix to achieve decarbonisation by 2050.

The (Stryi-Hipp et al., 2018) study relies on the electrification of the heating sector, and develops three different scenarios which vary in terms of energy generation constraints. Two of those scenarios chose to phase out the use of CHP plants by relying on local (Scenario 1) and/or regional (Scenario 2) wind and solar electricity generation, as well as storage capacity and different levels of imported electricity. Scenario 3 considers a maximum of 20% of the electricity demand being still fulfilled by a new coal-fired CHP plant.

The modelling exercise in (Stryi-Hipp et al., 2018) considers two main electricity-based heating technologies: electric resistive heating and air-source heat pumps (ASHPs), but overlooks renewable thermal energy and other types of heat pumps which could deliver heat in a more energy efficient manner.

This study aims to fill that gap through exploring those and other heating technology options, individually and combined in hybrid systems, while also considering the effect that they could have on the overall electricity demand. In **section 2** we perform a technology mapping exercise where various decarbonisation options are assessed in terms of their suitability in the Ulaanbaatar context, as well as their role in energy efficiency for the sector.

Based on the outcome of the analysis in section 2, we identify the technology options which would allow for full decarbonisation of the Ulaanbaatar heat supply by 2050 whilst minimising the electricity demand for heat generation. In **section 3**, three scenarios based in varying heating technology portfolios are developed and analysed based on electricity demand and cost implications.

In **section 4**, we identify key transformations that would need to take place in order to implement the suggested technology options, based on the results from the scenario analysis in section 3. These transformations are then linked to key enablers which could support their implementation. This section aims to provide a basis for policy and decision-making towards decarbonisation of the Ulaanbaatar heat sector.

Section 5 aims to identify further research gaps and future research needs.

2 Decarbonising the heat supply

When considering options for the decarbonisation of the heat supply, it is important to take a holistic approach. Not only is it important to investigate various technology options, but also their requirements in terms of context and their impact on other sectors, such as the power sector. Even though there might be several technologies which could decarbonise the heat supply, they may have various impacts on the decarbonisation of other sectors, as well as important cost implications.

First and foremost, a reduced demand for heat is the cheapest and most environmentally friendly way of mitigating emissions as it minimises the need for generating and distributing heat in the first place. Moreover, energy efficiency measures allow for the costs and scale of other mitigation measures to be minimised. A first priority should therefore be the consideration of energy efficiency measures. These are investigated in section 2.1.

Secondly, the remaining heat demand needs to be decarbonised through the substitution with zero emissions technologies. In order to identify the more advantageous technology options to fulfil the electricity demand, various decarbonisation technologies are explored and compared considering the local context. In the technology mapping exercise in section 2.2, we investigate the suitability of available decarbonisation technologies based on the following characteristics:

- Efficiency
- Performance in severe cold climates
- Space requirements
- Costs

2.1 Energy efficiency

By reducing energy needs in buildings and decreasing energy losses in the heating network, significant emission reductions can be achieved before focusing on decarbonising the remaining energy demand.

2.1.1 Building envelope

Energy efficiency measures on the demand side could deliver significant heat, emissions, and costs savings by reducing the overall demand for heat. Existing buildings in Ulaanbaatar are inefficient and deep retrofit programs therefore offer a relatively large mitigation potential. Poorly insulated pre-cast panel buildings from the 1970s to the early 1990s make up a large share of the building stock, while the traditional ger tents host about 60% of the population (Stryi-Hipp et al., 2018). Improving the efficiency of gers is challenging and a migration from gers to standard buildings is likely to be a more efficient measure.

In terms of existing buildings, studies have estimated that up to 50% of the heat demand could be saved through deep retrofits (GIZ, 2017). This not only results in vast energy, emissions, and variable cost savings, but also network-wide investment savings as a lower energy demand would result in a lower peak heat demand. As a result, lower peak capacities of renewable-based heating technologies would need to be installed to satisfy the heat demand of buildings.

As this study is building on modelling results from (Stryi-Hipp et al., 2018) we base the residential heat energy demand on data and assumptions provided in that study (Stryi-Hipp et al., 2018). As demonstrated in Figure 1, while overall energy heat demand increases over time as a result of a growing population and an increased living area per capita, about 45% of that demand is avoided by 2050 compared to in a frozen scenario where the heat demand per square meter of building area remains the same[1]. Such energy savings are achieved through the introduction of deep retrofits and improved standards for new buildings.

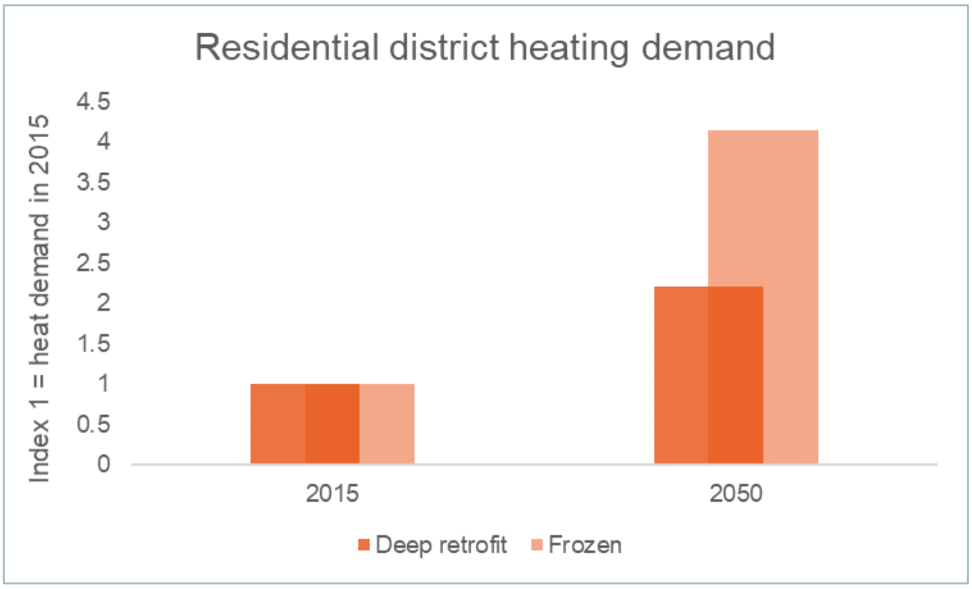

Figure 1. Residential heat demand of Ulaanbaatar in a frozen scenario compared to a deep retrofit scenario.

2.1.2 District heating

Following a growing rural-to-urban migration, the Ulaanbaatar population is rapidly increasing, and so to the city's heating demand. The current district heating network, serving about 55% of the population, is facing capacity constraints, limiting the number of new buildings that can be connected to the system. Meanwhile, an estimated 5-6% annual increase in district heating demand is expected over the next decade. While facing such issues, the existing district heating network is old and inefficient with the oldest parts of the network dating back to 1959.Due to lack of investment over the past decades, large parts of the system are in urgent need of replacement or upgrading. Overall, the technical losses of the district heating network are above 19%, much higher than the 9% in Harbin which is the coldest provincial capital of China with similar climatic conditions as Ulaanbaatar (WBG, 2020). Measures to reduce the losses of Ulaanbaatar's district heating network could thus contribute to significant heat and GHG emissions savings. In addition to that, however, a more modern district heating network is a requirement for the long-term transformation to a low-carbon heating system.

Supplying heat for space and water via a district heating network is a proven and widely applied technology, allowing for a higher energy efficiency of the overall system (Savickas, 2020). District heating has proven more cost-effective than heating buildings in a decentralised manner and can be supplied with heat from various sources, including renewable energy-based technologies (IRENA, 2020). The ability to integrate renewables, however, will be largely reliant on the type of district heating network. There are four generations of district heating networks which have evolved and improved over time.

[1] The frozen scenario assumes that no retrofits are made and that new buildings are built according to the current status of existing buildings. The deep retrofit scenario is based on calculations in (Stryi-Hipp et al., 2018) where linear interpolation has been used to estimate the growth between provided data points.

The first generation of district heating systems was predominantly deployed pre-1930 and uses high temperature steam as the heat carrier. Due to the high temperatures, the system has high losses.

The second generation, deployed between the 1930s and the 1970s, distributes pressurized water at temperatures above 100°C and is also inefficient due to this high temperature and the additional energy required to pressurise the water. This type of district heating network was used in Soviet-based systems and can still be found in countries outside the former Union of Soviet Socialist Republics.

The third generation of district heating networks has been deployed since the 1970s and is still in use in many places. Although pressurized water is still the heat carrier, it operates at a temperature between 70-95°C and has thus lower losses than the first and second generation.

These systems have been developed to distribute heat generated from fossil sources. A key issue with these systems, in addition to inefficiency and safety issues, is that they are incompatible with the integration of non-fossil heat sources due to their high supply temperatures. Renewable heat is generated at lower temperatures, requiring district heating networks to be adjusted to be compatible with lower supply temperatures. Although the third generation of district heating allows for the integration of electricity and renewable based technologies such as large-scale heat pumps and solar thermal, they typically require some type of booster technology to reach the required supply temperatures. That makes it difficult to fully decarbonise the system (Lund *et al.*, 2014).

The fourth and latest generation of district heating operates in a smarter manner and at lower supply temperatures of about 50-60°C. This allows for a more efficient and full integration of variable renewable resources such as waste heat and solar thermal (IRENA, 2020). Studying the economic benefits of lower distribution temperatures for district heating show a high sensitivity to cost reductions. This uncertainty means there have been few economic incentives to shift to low temperature systems. As such, traditional high heat distribution temperatures constitute a key barrier for the integration of renewable and recycled heat to district heating systems. The upgrading and refurbishment of old district heating networks is therefore an essential step, not only to reduce losses, but also to facilitate a wider adoption of renewable heating sources (Averfalk and Werner, 2020).

Considering that Ulaanbaatar's current system operates with supply temperatures above 100°C during the coldest months of the year (Epp, 2021), the upgrading and expansion of the city's current network is a prerequisite to the long-term wide integration of renewable-based heating technologies, and the eventual phase out of fossil fuels. In 2020, the World Bank Group initiated a five year project aiming to improve the efficiency of the district heating network and expand its capacity (WBG, 2020). The project aims to, in addition to other measures, upgrade parts of the system to reduce losses. It is however yet unclear whether those upgrades will allow for lower supply temperatures and the integration of renewables to the system.

2.2 Technology mapping

Energy efficiency measures could contribute to significant energy demand reductions, but full decarbonisation would require the phasing out of all fossil fuels in the energy heat supply mix. In identifying potential decarbonisation technologies, we group technologies by which energy carriers they use. Those include electric technologies, local renewables, hybrid systems, and hydrogen, biomass and wastes. Electric technologies are considered decarbonisation technologies under the condition that the electricity they consume exclusively comes from renewable resources. In this analysis those renewable resources include wind and solar energy.

2.2.1 Electric heating technologies

Electric heating uses electricity as the energy carrier to generate heat in two key ways, namely through resistive heating or by extracting heat from the environment.

Direct electric heating

Electric resistive heating, referred to as direct electric heating or direct electrification in this report, converts electric energy to heat through resistance. Direct electric heating is a fully commercialised technology and widely deployed globally. Its efficiency is typically estimated to close to 100% as all electric energy is transformed to heat. Efficiency losses can occur, depending upon the primary energy use, and the way the electricity is generated.

Direct electric heating is technically suitable in any type of climate, but the level of emissions mitigation is ultimately dependent on the emissions intensity of the electricity supply. In regions where renewable energy resources are scarce, direct electric heating may put significant pressure on the electricity supply. Therefore, other more efficient options may be more suitable under such conditions.

Direct electric heaters are easy to install and does not require significant refurbishment. In terms of costs, capital and installation costs are low but variable costs may become high. Because direct electrification is significantly less efficient compared to heat pumps, a shift to direct electric heating could significantly increase the electricity demand, and the operating costs would ultimately be dependent on local electricity prices (Energy Transitions Commission, 2019).

Even though direct electric heaters are technically applicable in most building types, their relative inefficiency compared to other electric heating technologies (e.g., heat pumps) make them an unpreferred option in most cases. However, in old or temporary buildings, the comparably high investment costs of other technologies may make direct electric heaters a preferable temporary option. For instance, as ger residents are expected to increasingly move to standard houses over time, direct electric heaters could be a more economically feasible option for decarbonising the heat supply in ger tents in the short-to medium term. Nevertheless, direct electric heaters could also play a role for other building types, particularly as other heating technologies may be unable to satisfy the heat demand during very cold days. Under such conditions, direct electric heaters could serve as an auxiliary heating source to meet the peak demand.

Heat pumps

As with direct electric heaters, also heat pumps are operated with electricity. The key difference is that heat pumps do not convert electric energy into heat, but instead uses the electricity to extract heat from the environment. By pumping a refrigerant through a closed system, heat can be transferred from an environment of low temperature to an environment of higher temperature (Figure 2). As such, a heat pump can deliver energy several times higher than the amount of energy added to the system. The electric energy is needed to operate the compressor. By comparing the ratio of heat energy delivered to the amount of electric energy consumed, the coefficient of performance (COP), determines the efficiency of a heat pump. The COP can be affected by several factors, including the type of heat source and heat sink, the comfort preferences in the heated space and the difference between the environment temperature and the target temperature of the heated space (Carroll, Chesser and Lyons, 2020). As a result of the high efficiency of heat pumps, their installation result in emission reductions, even if the electricity should be generated from fossil gas (Buck et al., 2022).

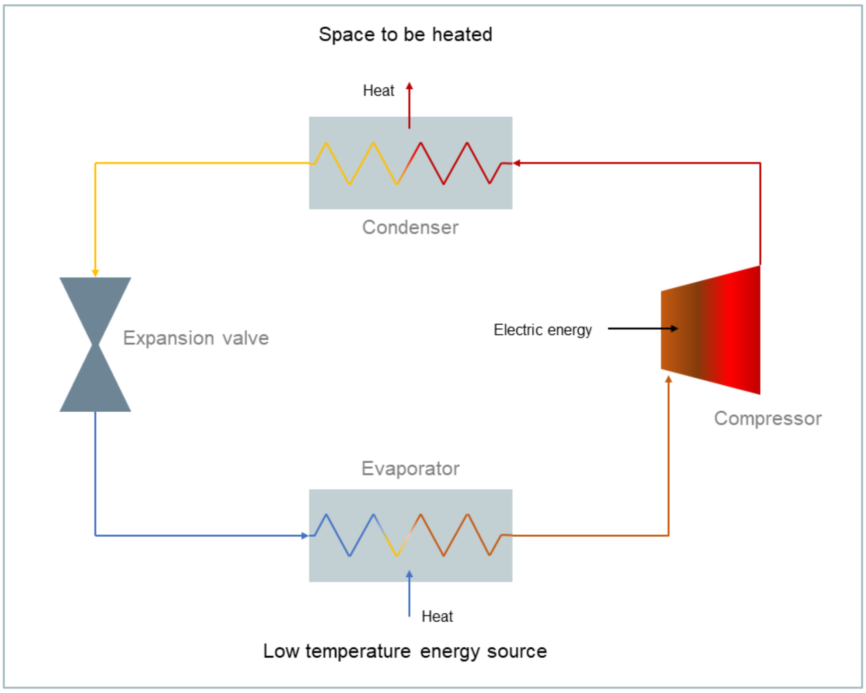

Figure 2. Schematic overview of a heat pump.

Figure reproduced from (Dincer and Erdemir, 2021).

A heat pump can extract heat from various environments including atmospheric air (air-source heat pumps (ASHP)), the ground (ground source heat pumps (GSHP)), or water (water source heat pumps (WSHP)). Depending on that environment and its context specific characteristics, the efficiency and suitability of the heat pump can vary significantly. The various types of heat pumps and their suitability in the Ulaanbaatar context is further explored in this section.

End of life emissions from refrigerants used in heat pumps

Heat pumps use refrigerants to transfer heat from an environment with lower temperature to a higher temperature environment. These substances have impacts well beyond their heat transfer properties as they can leak from the equipment or be released when a heat pump reaches its end of life. Chlorofluorocarbon-based refrigerants were phased out with the adoption of the Montreal Protocol in 1987 due to their ozone depleting properties. They were replaced with (HFCs), which had no impact on the ozone layer but were in turn powerful greenhouse gases with high global warming potential (GWP). The Kigali Amendment to the Montreal Protocol agreed a phase out of HFC-based refrigerants towards new substances that neither damage the ozone layer nor impact global warming. These new generation refrigerants are mostly hydrocarbon based, ammonia or carbon dioxide. To further improve climate performance of heat pumps, a formal system to recycle and properly dispose of refrigerants need to be in place, and equipment with low GWP-refrigerants should be prioritised.

The Mongolian Parliament recently passed a bill to ratify the Kigali Amendment, which is expected to happen before the end of 2022. This would mean that Mongolia would place efforts to adhere to the approved timeline for HFCs gradual reduction by 80-85% before 2045 (Unurzul, 2022). Table 1 presents a few examples of refrigerants and their GWP.

Table 1. Examples of refrigerants and their global warming potential (GWP). The use of CFC and HCFC in heat pumps are banned but presented for reference.

Refrigerant	Base	GWP
R-12	CFC	10,900
R-22	HCFC	1,810
R-134a	HFC	1,430
R-410a	Blended HFCs	2,088
R-600	Hydrocarbon (Butane)	3
R-717	Ammonia	0
R-744	CO_2	1

Source: (California Air Resources Board, 2022).

Air source heat pumps

Generally, the COP of an ASHP decreases as the temperature difference between the ambient air and the target temperature of the heated space increases, and thus decreases in colder climates (Carroll, Chesser and Lyons, 2020). As temperatures drop during the winter months, the ASHP needs to extract heat from colder air which decreases its efficiency. Although traditional ASHPs are operational down to about -20°C, new two-stage compression heat pumps have been successfully tested in ambient temperatures down to -40°C with a COP of above 1 which implies that it is more efficient than direct electric heating (Pillarisetti et al., 2019). One of the major concerns with using ASHPs in cold climates, however, is that frost formation can disturb its functionality. Several studies have investigated how this could be improved where one of the identified key strategies is the use of an external heat source to avoid frosting (Wang et al., 2021). Among available heat pump technologies, ASHPs face the most significant challenges related to efficiency and capacity limitations under cold climates (Van D. Baxter, Groll and Sikes, 2017).

Due to their low space requirements, ASHPs are particularly suitable for areas where space is limited such as high-density housing areas. It is important that the building is well insulated to maintain a comfortable indoor air temperature in cold climates, making improvements to the building envelope is necessary in many cases (Energy Transitions Commission, 2019). In terms of installation costs, although more expensive than resistive heaters, ASHPs have the lowest installation cost among other heat pump alternatives (Van D. Baxter, Groll and Sikes, 2017).

A pilot study in Ulaanbaatar tested a commercially available two-stage compression ASHP during winter in five modern style houses and two traditional ger tents. The results revealed that none of the households needed to use coal as back-up, despite the lowest recorded temperature of -39°C. In addition, even during the coldest days, all recorded COPs had remained above 1 (Pillarisetti et al., 2019). These results are indeed encouraging, particularly as the dwellings included in the study were not insulated, indicating that, if insulation were to be improved, even higher COPs could be achieved. The study identified outdoor temperature as the strongest contributor to the COP. In terms of costs, the study concluded that ASHPs are substantially (about 50%) cheaper to operate compared to direct electric heaters due to the higher efficiency and lower resulting electricity consumption. Using the coal and electricity prices at the time of the study, operating ASHPs was about 25% more expensive compared to coal boilers (Pillarisetti et al., 2019).

As has already been demonstrated by (Pillarisetti et al., 2019), ASHPs can operate in the Ulaanbaatar climate all year round, without the need for auxiliary heating. ASHPs low space requirements indicate this would also not be a barrier for their installation. However, its relatively low efficiency – only marginally more efficient than direct electric heating during the coldest days – would result in a significant rise in electricity demand should the current heating system be fully replaced by ASHPs. What is more, the risk of frost formation remains, which could disturb the system and require additional repair and maintenance costs, despite the technology having relatively low upfront costs.

Ground source heat pumps

GSHPs extract heat from the ground either through a vertical or horizontal borehole. The more stable ground temperature compared to ambient air makes their performance more stable and efficient compared to ASHPs (Wang et al., 2021). Typically, the COP of GSHPs ranges between 3 to 4 (GSHPA, 2021).

Depending on the type of borehole (horizontal or vertical) the space requirements and installation costs vary significantly. The horizontal type is typically installed at a depth of 1-2 meters and is as such less expensive to install yet requires more space. Its suitability in urban settings is therefore low. The vertical type requires boreholes at a depth of 50 to 150 meters which is more costly but requires less space. Because of the relatively constant temperature of the ground at depths below ten meters, vertical GSHPs can achieve a higher efficiency compared to horizontal GSHPs (Wang et al., 2021). In turn, the resulting lower electricity input needs results in lower variable costs in terms of electricity expenditures. In an pilot project in the Kharkhorin soum of Mongolia, it was found that the soil freezes up to 2.1 – 3.0 meters in depth, making vertical GSHPs the more suitable option (Savickas, 2020). The average minimum and maximum borehole depths for vertical GSHPs was investigated in a review of GSHP projects in severe cold regions of China where it was found that the average minimal depth varied within a range of 50-70 meters, while the maximal depth varied within a range of 120-150 meters (Lei, Tan and Li, 2018). However, one of the key weaknesses of GSHPs in cold climates is that, as the heat pumps extracts heat from the ground, the ground temperature gradually decreases over time unless heat is injected from an auxiliary source to compensate for the extracted heat. In the long run, this leads to a decreased efficiency of the GSHP. A GSHP system tested for an office building in northern China led to a significantly reduced ground temperature already after one year of operation, resulting in a declining COP year by year, and making the system unsuitable as a reliable heating source in the region (Liu et al., 2015).

As of 2020, the installed GSHP capacity in Mongolia was 2.5 MW and was mostly applied to public buildings. The installed capacity generates heat from a total of 457 boreholes with an average depth of about 105 meters and an average investment intensity rate of 3.16 million USD/MW. Ongoing pilot projects are generally concentrated to Ulaanbaatar as the capital has a higher concentration of expertise and potential to scale up projects (Savickas, 2020). Experience with GSHPs in China has shown that the highest suitability was found in cold climate regions (such as in provinces in the surroundings of Beijing), while the suitability in severe cold regions (such as Inner Mongolia) was lower due to a lower efficiency and longer payback periods (Lei, Tan and Li, 2018).

At first glance, GSHP systems show high quality characteristics ideal to the Ulaanbaatar context; they are able to operate in severe cold climates at a significantly higher efficiency relative to other electric heating technologies. But two key barriers make GSHP systems less attractive in the Ulaanbaatar context. Firstly, the building density of the urban area leaves little space to install GSHPs. Alternatively, large capacity GSHPs could be installed in dedicated areas with sufficient space to feed the district heating network and could thus make it an option for buildings connected to the district heating network. Secondly, previous studies show that there is a high likelihood that the installment of GSHPs in regions with high heat loads (i.e., in cold/severe cold climates) could result in a gradually decreasing soil temperature over time, leading to a decreasing system efficiency. For that main reason, GSHP system alone are not considered the optimal solution for Ulaanbaatar.

Water source heat pumps

In a WSHP system, surface or groundwater acts as the heat source. Due to the higher specific heat capacity of water compared to air, water can contain significantly higher amounts of energy per volume compared to air and can thus achieve higher COPs compared to ASHPs (Wang et al., 2021). Also the temperature of the water impacts the efficiency of the heat pump which increases if the temperature of the water is relatively stable (Carroll, Chesser and Lyons, 2020). As most surface water sources in Mongolia freeze in wintertime, WSHPs are not considered a suitable option in the Ulaanbaatar context (Savickas, 2020). We therefore do not investigate their potential further in this study.

2.2.2 Direct use of renewables

As an alternative to using electric energy to generate or extract heat, the direct use of renewable heat sources is an option for space heating. Its feasibility is dependent on the local availability of those resources. The key renewable heat sources available globally include solar and geothermal heat. As the geothermal resources in Ulaanbaatar are yet largely unexplored, we primarily focus on solar thermal heating in this section.

Solar thermal

Solar thermal collectors operate by transforming solar radiation into heat. The heat is transferred to an energy carrier such as water, solar fluid or air for heating end uses including space and/or water heating (Bassam, 2021). A key advantage of using a fluid carrier such as water is that the heated fluid can be stored and used at times when less solar radiation is available. The solar thermal collector is typically placed at the rooftop of a building from where the heated fluid can be circulated via a pipeline system to heat the building. There are four main types of solar collectors, namely unglazed absorbers, flat plate collectors, air heater solar collectors and evacuated tube collectors. They all differ in terms of technical characteristics, suitability in cold climates and upfront costs (German Energy Solutions Initiative, 2021).

Unglazed absorbers are generally cheaper than fossil fuel boilers but are limited in terms of capacity as they have a relatively low efficiency and can only achieve temperature levels within the range of 30°C to 40°C. Therefore, unglazed absorbers are typically used for purposes such as to heat pools and are not suitable in cold climates (German Energy Solutions Initiative, 2021).

Flat plate collectors are the most commonly used type of solar thermal collector for water heating in many countries. Although flat plate collectors are more expensive compared to unglazed absorbers, they have the advantage of achieving temperatures within the range of 60°C to 90°C (Bassam, 2021; German Energy Solutions Initiative, 2021).

Similar to flat plate collectors, air heater collectors use air in place of fluids to carry the thermal energy and are typically used to heat buildings directly without any storage unit. This type of collector is less efficient than a flat plate collector, yet relatively inexpensive (German Energy Solutions Initiative, 2021). Other advantages include less issues related to freezing, overheating and leaks when using air as the thermal energy carrier. However, due to their better performance as heat conductor, fluids are more suitable for hot water heating for homes (Bassam, 2021).

Evacuated tube collectors operate in a closed system isolated in vacuum and are therefore frost-proof. The system can achieve high efficiency levels and temperatures up to 120°C. The system also allows for the storage of heat in a hot water tank. Although the evacuated tube collector is the most efficient technology on the market, it is also the most costly type of solar thermal collector (Bassam, 2021; German Energy Solutions Initiative, 2021).

Based on this, the suitability of solar thermal collectors in severe cold climates is highly dependent on the type of solar collector. Due to its high efficiency, and ability to withstand frost, the evacuated tube collector is the most suitable option in severe cold climates. In addition, evacuated heat pipe systems are easy to install and require low maintenance. This is not the case for flat plate collectors which are more complex to install and maintain, requiring full replacement if parts of the system brakes. Depending on the heat load of the building and the available solar irradiance, solar heat collector systems may need an auxiliary heating system to deliver sufficient heat in colder climates. As solar energy is only available during the day time, solar thermal collectors can be particularly suitable to provide heating for buildings which are only used in day time, such as schools and office buildings (Bassam, 2021).

Solar thermal systems operate and have been tested in various cold climate contexts. In Daqing, a city located northwest of Harbin in northern China, a solar thermal (evacuated tube) system was simulated and field-tested in an office building with low night-time heating needs under severe cold conditions. The results showed that approximately 66% of the building's heat demand could be satisfied by the solar thermal system on a typical winter day (Liu, Jiang and Yao, 2014; Mussard, 2017). Another study in northern China found that up to 70% of the heat demand of a passive house could be met from solar thermal collectors in a severe cold climate, depending on its size and orientation (Jing et al., 2015; Mussard, 2017).

Ulaanbaatar receives relatively high levels of solar irradiance, even in wintertime. In 2019, the lowest irradiation reached 47 kWh/m^2 in December, and the highest, 218 kWh/m^2, in May (Pfenninger and Staffell, 2019). The average monthly irradiation from November to February was 65 kWh/m^2, while the corresponding value from May to August was 196 kWh/m^2. The case studies from severe cold climates in Northern China suggest that solar thermal collectors are likely to be able to deliver a significant share of the heat demand also in Ulaanbaatar. As can be seen in Figure 3 and Figure 4 which compares the climatic conditions of Harbin (located in a severe cold region of northern China) and Ulaanbaatar, showing that they have similar annual temperature and solar irradiation curves.

Solar thermal collectors could be particularly suitable for public buildings with little to no nighttime heat demand such as schools and office buildings but are likely to need an auxiliary source of heat to satisfy the full demand. Considering that rooftop space could be a limiting factor in terms of solar thermal deployment, large scale solar thermal collectors for district heating could be an alternative option. Large scale systems could thus be developed in the periphery of the city where more space is available. As such, solar thermal systems could be an efficient method to substantially reduce the energy demand from other sources, such as electric energy.

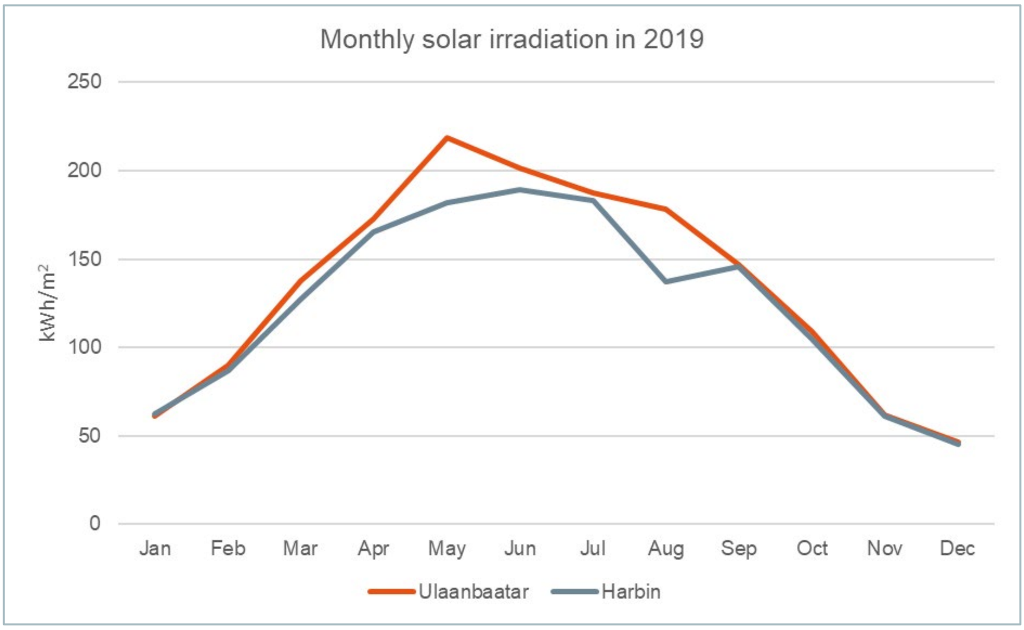

Figure 3. Monthly solar irradiation in 2019 in Ulaanbaatar and Harbin.

Source: authors' derived data from (Pfenninger and Staffell, 2019).

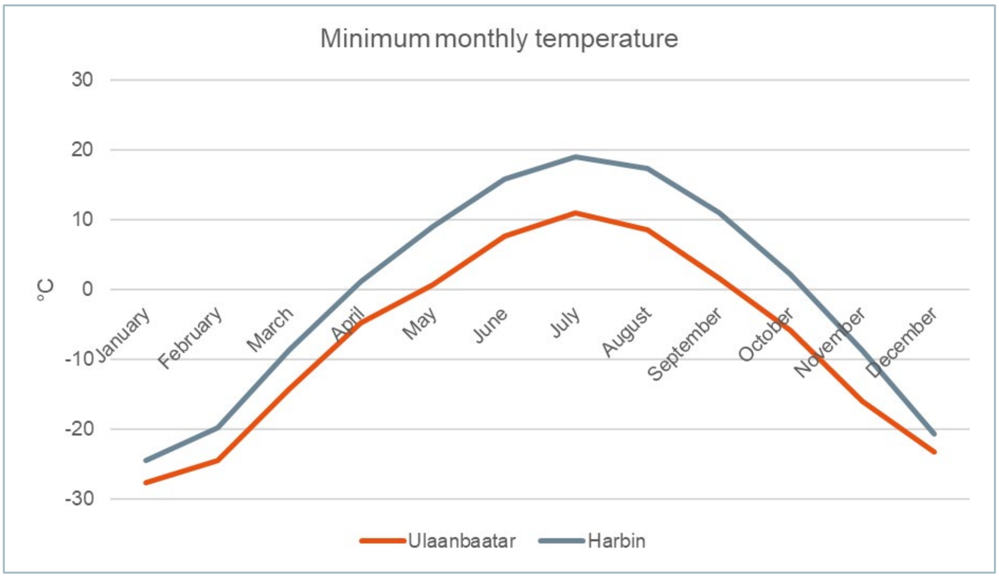

Figure 4. The minimum monthly outdoor temperatures of Ulaanbaatar and Harbin.

Source: (Climate-Data, 2021a, 2021b).

Geothermal

In areas with volcanic or tectonic activity, hot groundwater can be found which can be used directly for heating purposes. An example where that is widely used is in Iceland. As the hot groundwater can be found at quite shallow depths, the capital cost of direct geothermal heating systems can be relatively small (EPA, 2021). However, its application is evidently limited to locations close to geothermal sources. In the case of Mongolia, about 43 small hot springs across the country had been explored as of 2016. These have typically been used for end-uses such as bathing, health resorts and heating for greenhouses and buildings. Although a number of hot springs that could be used for space heating have been identified, the usage of those resources is expected to be limited to local communities (IRENA, 2016). To assess any potential resources within the Ulaanbaatar regional area, further scoping of available resources is needed. Geothermal energy is therefore not further considered in this study.

2.2.3 Hybrid systems

Hybrid heating systems refer to systems which combine more than one technology. This could be an efficient approach to maximise the integration of renewables by combining technologies to improve efficiency of the system and overcome technical barriers. For instance, the combination of a heat pump and solar thermal collector could both increase the efficiency of the heat pump while also saving electric energy. Moreover, under severe cold conditions, both a heat pump and a solar thermal system by themselves might not be able to meet the full demand in peak hours. In this section we explore the potential of low-carbon hybrid heating systems in the Ulaanbaatar context. We do so with a particular focus on solar assisted heat pumps (SAHPs) which combine heat pumps and solar thermal collectors.

Solar assisted heat pumps

In the previous section we described some of the challenges the different kinds of heat pumps can face in severe cold climates. A hybrid system can either use the thermal energy from the solar collector directly, or save the heat for short term storage (Mussard, 2017). This additional heat can therefore be used for several purposes, such as reducing frost risks, helping to balance the ground temperature, or providing additional heat to reduce electricity demand

Solar assisted air-source heat pumps

As discussed in section 2.2.1, the main challenge of the application of ASHPs in cold climates is the high tendency of frost formation which can disturb the performance of the heat pump. By using the heat from a solar collector in a solar assisted ASHP (SAASHP), the risk of frost formation can be significantly reduced or even eliminated (Mussard, 2017).

The increase in efficiency will ultimately be dependent on the level of solar irradiation and the ambient temperature. Generally, SAASHPs are suitable in urban areas as the only additional space required, apart from that of the heat pump, is space for the solar thermal collector which typically is placed on the rooftop of the building. Solar thermal systems might therefore face competition for rooftop space with solar photovoltaic (PV) systems, as those are one of the technologies that would also need to be deployed to decarbonise the power sector.

SAASHPs have been successfully piloted in various cold locations. A SAASHP combined with rooftop PV in a severe cold region in China achieved an average COP of 4, supplying parts of the heating needs of the building (Cao et al., 2016; Mussard, 2017). A study in Canada at a location with an average temperature of -7°C and a minimum temperature of -25°C achieved a seasonal COP of 3.0 with energy savings of about 40% compared to a conventional ASHP. The system was successful in delivering sufficient heat to meet the demand even in the coldest days, at a COP of about 2.2 (Van D. Baxter, Groll and Sikes, 2017).

Solar assisted ground-source heat pumps

Solar assisted ground source heat pumps (SAGSHPs) have been successfully tested in cold climate regions. The solar thermal energy can be used in different ways in the system; A parallel system which enables the independent use of both the solar thermal system and the heat pump system or storing the solar thermal energy as heat in the ground. By storing thermal energy in the ground, the efficiency of the heat pump can be improved while also overcoming long-term effects related to thermal soil imbalance (Mussard, 2017). By injecting thermal energy collected by the solar thermal collector into the ground, the performance of the heat pump can be maintained, or even enhanced (Mussard, 2017; Xu et al., 2021). It has been previously found that, ideally, solar collectors should be used both for supplying heat to the building and for maintaining the ground temperature in order to optimise the system (Reda, 2017). Several studies have shown that a SAGSHP system achieves higher COPs than a GSHP system, which results in reduced electricity consumption of the overall system. Moreover, the additional thermal energy provided by the solar thermal collector can reduce the required length of the boreholes, which can substantially cut down the initial investment cost of the GSHP (Xu et al., 2021).

In terms of applicability in the Ulaanbaatar context, similar limitations apply as for the individual technologies. Although vertical GSHPs require less space than horizontal ones, there might be limited space in highly dense areas. However, large-scale systems can be installed to supply heat to the district heating network**.** As GSHPs are significantly more efficient than ASHPs and direct electric heating, the electricity demand can be minimised and thus freeing up more rooftop space for solar thermal collectors. Nevertheless, solar thermal collectors could be centrally installed to feed into the district heating network.

The number of SAGSHP initiatives globally have increased rapidly since 2010 (Lei, Tan and Li, 2018). Several case studies have investigated the performance of SAGSHPs in various cold or severe cold locations – both through modelling simulation and pilot projects. Examples of such include (Rad, Fung and Leong, 2013; Emmi et al., 2015; Kegel et al., 2016; Mussard, 2017). A study conducted on a detached house in the suburbs of Harbin, China, between 2008 and 2009 tested a SAGSHP with seasonal thermal storage in the ground and found that 49.7% of the heat output could by supplied by solar thermal energy. This resulted in significant electricity savings compared to a system based on a GSHP exclusively and achieved a system COP of 6 and a heat pump COP of 4.3. All heat demand could be satisfied by the SAGSHP system, and no auxiliary heating was required. The system was optimised through working in different modes which prioritised solar thermal heat. Those results could be expected to be even higher now as the technology has advanced. The seasonal storage system injected excess heat from the solar thermal collectors to the ground during the non-heating season, which allowed for an increased heat pump COP in the heating season. Over the year, the soil temperature fluctuated, rising as less heat was required for space heating and thermal energy was injected to the ground, and decreasing as the space heat requirements increased. On an annual basis, the soil temperature slightly increased which may need to be monitored by decreasing the injection of solar thermal to the ground over time. The system used flat plate solar collectors with an area of 50 m^2 and borehole depth of 50 meters (Wang et al., 2010).

Another simulated system, tested in different cities of Canada, used the solar thermal energy either directly or stored in a water tank. Using the additional thermal energy supplied by the thermal collector allowed the length of the ground loop to be reduced by 15% compared to the original depth of 55 meters. However, the results varied across cities depending on the climate; a milder climate allowed for higher solar fractions[2] (Rad, Fung and Leong, 2013). The study also found that the oversizing of the solar collectors could affect the economic attractiveness, which proves the importance of prioritising energy efficiency measures before deploying innovative technologies.

Based on this backdrop, several cases studies suggest that SAGSHPs can operate and deliver significant efficiency gains even in severe cold climates. The optimal design of the system, however, must be carefully considered based on context specific parameters such as solar irradiance, outdoor temperature, the building stock's heat demand and existing heating infrastructure.

Hybrid heating systems at large scale

While the interest in hybrid technology systems for detached houses is rapidly increasing, so is the case for their application at large scale, supplying heat to district heating systems. The first such system was

[2] The solar fraction represents the share of the building's heat demand which is satisfied directly by solar thermal heat.

installed in 1988 in a small town in Denmark. By 2018, the number of large-scale systems had increased to 339 globally (Huang, Fan and Furbo, 2020).

Following issues extracting more heat from the ground than the storage provided using GSHPs for district heating in northeastern China, a large-scale SAGSHP was tested in the outskirts of Beijing. The system was to supply heat to 181 residential houses and one large office building. After some initial results, a system optimisation found that the system was most (cost) efficient when using 52.8% of the solar thermal energy for space heating. As the borehole heat exchange system accounts for roughly 50% of the investment costs, design optimisation can drastically decrease initial costs by making sure a fraction of the winter heat load can be covered directly by solar thermal heating. (Huang, Fan and Furbo, 2020).

Similarly, other studies have found that the lowest lifecycle cost of a GSHP system is obtained at the minimum borehole depth, and that the depth could be reduced by up to 41% by combining a GSHP with solar thermal collectors (Yeung, 1996; Lhendup, Aye and Fuller, 2014). Such a system has been simulated in the Ulaanbaatar context, where a SAGSHP system with seasonal thermal storage was tested. The system consisted of a small-scale district heating system supplying heat for 30 residential buildings. The simulation was optimised based on life cycle cost and GHG emissions through using the solar collector area and borehole length as the optimising variables. The results suggest that the system would be able to meet the full space heating demand without any auxiliary assistance, with an average heat pump COP of about 3.6. The initial investment cost of the system (excluding district heating costs) ranged between USD 0.208 – 0.265 million (Shah, Aye and Rismanchi, 2020).

2.2.4 Hydrogen, biomass, and wastes

Beyond electricity and local renewable resources, other carbon neutral energy sources such as hydrogen, synthetic fuels or biomass and wastes could be used to generate heat. In this section we discuss those options and their suitability in the Ulaanbaatar context.

Green hydrogen

The option of using green hydrogen for heating could indeed deliver zero emissions heat but would not be suitable in the Ulaanbaatar context due to its inefficiency compared to other technologies. Using green hydrogen for heat is an inefficient way of using renewable electricity, as it would be far more efficient to use that renewable electricity to either operate a heat pump or generate heat directly. As suggested in (Nilsson et al., 2021), direct electrification, when technically feasible, should be prioritised over the use of green hydrogen. Nevertheless, there could be circumstances under which green hydrogen for heating could be beneficial. As further discussed in (Nilsson et al., 2021), green hydrogen production could benefit from high shares of renewables in the power sector, where excess electricity as a result from production peaks coinciding with low demand can be used to produce green hydrogen, and by doing so, avoid curtailments in the power system. This is not expected to be the case in Mongolia in the near-term but could become so in the longer term, as higher shares of renewables are integrated to the power system. Quite conveniently, a gradual electrification of the heat sector, coupled with an expansion of the renewable electricity capacity to meet that demand (and the gap in supply as a result of the gradual phase out of the CHP plants) could result in such a scenario. Thus, green hydrogen produced from excess electricity could serve as a top-up fuel for other low-grade heating sources. For instance, it could be used as a back-up fuel in ger districts. Alternatively, should the supply temperature of the district heating system need to be increased during the coldest period of the year in order to deliver sufficient heat to meet demand, green hydrogen could be used as a top-up fuel to increase the lower supply temperatures generated from solar thermal and heat pumps.

Synthetic fuels

Using green hydrogen to produce synthetic fuels could be another way of heating homes, particularly those not connected to the district heating network. One important consideration of doing so is the source of CO_2 which is used as a feedstock to produce the synthetic fuel. Using captured CO_2 from fossil fuel combustion would not be a sustainable option since the CO_2 only would be recirculated into the atmosphere, whilst continuing to incentivise the combustion of fossil fuels. Instead, CO_2 would need to be sourced directly from the atmosphere using direct air capture technology. Direct air capture is not yet proven at commercial scale, and costs are still prohibitively high. Adding to that, efficiency losses incurred in the green hydrogen production, and synthetic fuels production and ultimate combustion would significantly affect overall efficiency and end up being a costly solution (Nilsson et al., 2021). We therefore discard the use of synthetic fuels for heating in this study, at least in the near- to mid-term future.

Biomass and waste

In (Stryi-Hipp et al., 2018) the potential of waste incineration in Ulaanbaatar was estimated to 19 MW of thermal capacity in 2050. It further suggested that another 30 MW could be obtained if the district heating supply temperature is lowered to 60°C. The 18.82 MW could supply 150 GWh of thermal energy per year, from 2030. A waste incineration plant could thus serve as a top-up to lower grade heating sources. Combustion of the waste in a CHP plant would further generate a power capacity of 52.1 MW. This could supply about 416 GWh per year from 2030. As such, the potential of waste incineration for heat generation is rather low – meeting about 1% of the heat demand in 2050.

Due to the limited supply, its use for heat generation might be limited to it being blended into the coal mix of CHP plants, which could further incentivise the use of coal-based heat. The use of sustainable biomass for decentralised heating in ger districts could lead to GHG emissions savings, but there are no quantitative estimates available to assess whether the available supply could meet the demand. In addition, the combustion of biomass in ger districts would continue to contribute to air pollution.

Generally speaking, and due to the limited supply of sustainable biomass, its combustion should only be considered when no other decarbonisation alternative can be found, and sustainable biomass should be prioritised in sectors where other alternatives do not exist. Based on that, we do not consider biomass a feasible decarbonisation option for the Ulaanbaatar heating sector. Nevertheless, the estimated available waste supply could contribute to a minor share of the heat generation mix.

2.3 Identification of an Ulaanbaatar heating portfolio that allows long-term decarbonisation at low electricity demand

Based on the energy efficiency measures investigated in section 2.1 and the technology mapping exercise in section 2.2, we evaluate the options to identify the most suitable technology mix and infrastructural set-up allowing for the full decarbonisation of the heat supply by 2050 while also minimising the electricity demand. The assessment is based on the technical and contextual parameters discussed and evaluated in the previous section and looks to derive high-level cost estimates, rather than a cost-optimal technological pathway.

2.3.1 Overall heat transmission and distribution infrastructure

Two key system approaches can be considered for decarbonising the Ulaanbaatar heating sector, namely a centralised and a decentralised approach (Figure 5). A centralised approach would aim to make use of, upgrade and expand the existing district heating network and decarbonise the heat supply centrally. In a decentralised approach, individual heating technologies would be installed to individual buildings, gradually making the district heating network obsolete.

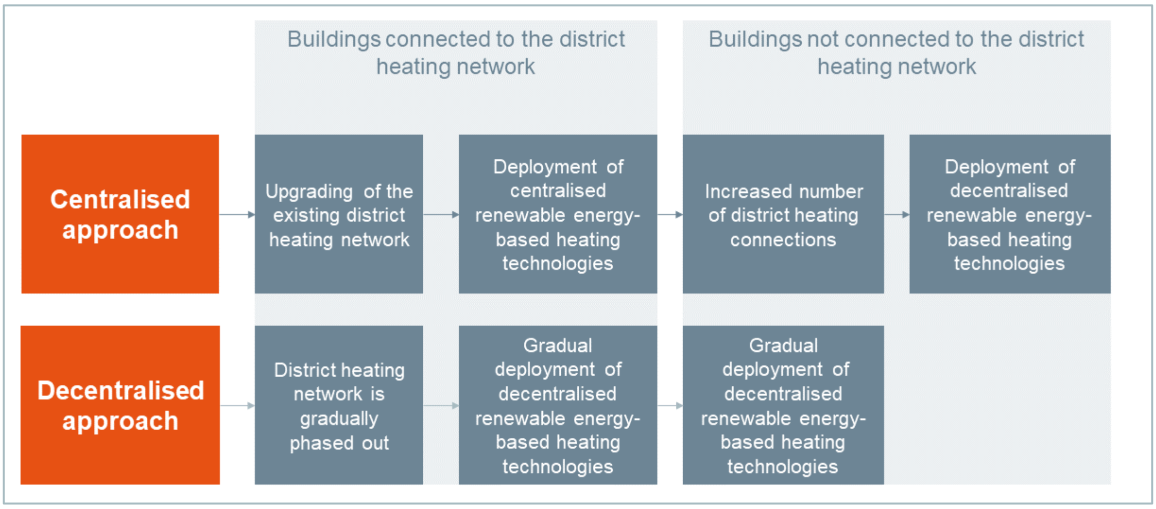

Figure 5. Concept of the decarbonisation of the Ulaanbaatar heat supply through a centralised versus a decentralised approach.

Drawing from the technological mapping exercise, we consider the maximum utilisation (and refurbishment) of the district heating network the preferred approach. This is considering that (a) district heating systems would allow for a higher system-wide energy and cost efficiency; (b) ongoing projects are already investing in the upgrading of the existing district heating network (as discussed in section 2.1.2); and (c) decentralised deployment of the most efficient technologies could be limited by space availability. It is important to stress that the upgrading and rehabilitation of the existing district heating network will be imperative for the transition to a decarbonised heat supply. While in the transitioning period CHP could serve as a top-up heating source, the district heating network would need to be upgraded to exclusively use heat and electricity from renewable sources in the longer term. It is yet unclear whether current upgrading projects aim to make the network compatible with a full renewable energy integration. Most likely, additional efforts would need to be in order to phase out CHP completely. Further, we assume that an expansion of the district heating network will take place over the years, as considered in the scenarios presented in (Stryi-Hipp et al., 2018) and analysed in Section 3. As presented in Figure 6, the projected district heating heat demand in 2050 increases substantially, by 124%, compared to 2015 levels. That is assuming all new buildings to host the growing population are connected to district heating. This not only means that the existing transmission network would need to be expanded, but also implies a considerable expansion of heat generation capacity.

But not all households are expected to be connected to the district heating network by 2050. Despite a large shift from gers to standard houses, about 6% of all households are projected to remain in ger areas. The decarbonisation of those will be reliant on decentralised solutions to phase out raw coal burning.

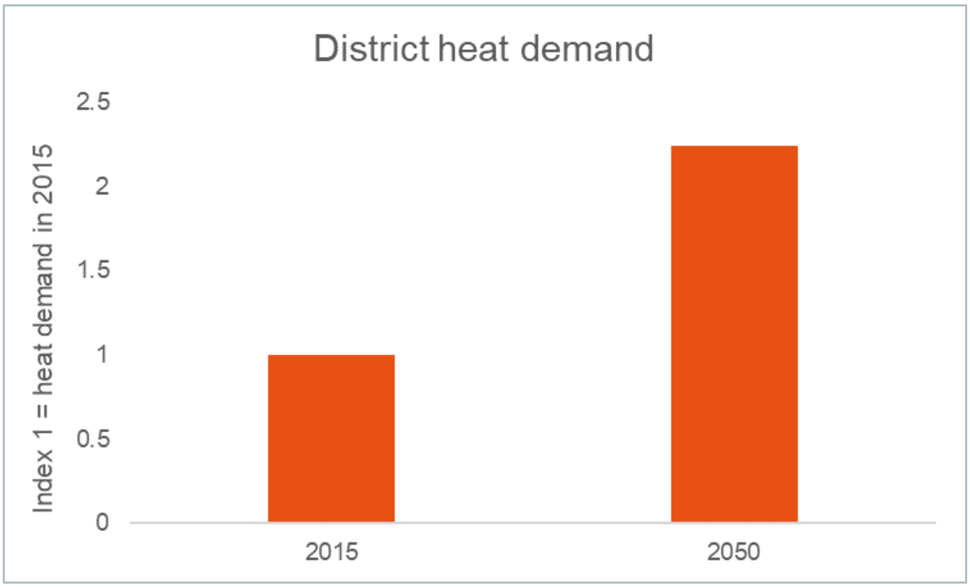

Figure 6. Projected district heat demand in 2015 and 2050.

Source: Authors' derived data using results from (Stryi-Hipp et al., 2018).

2.3.2 Centralised heating generation technologies

Assessing the available decarbonisation heating technologies at hand, several options could be feasible in the Ulaanbaatar context. Although the primary priority is the full decarbonisation of the heat supply, as we seek to minimise the electricity demand the most optimal solution would maximise the use of renewable heat sources. As suggested in the previous section, the most widely available renewable heat source in the surroundings of Ulaanbaatar is solar thermal, so we seek to maximise the use of solar thermal heat to the city's heat supply. But as the technology mapping suggests, additional heat sources would be needed to meet the heat demand. Therefore, heat pumps will play a leading role in the sector.

Due to its small space requirements and low investment costs, ASHPs does at a first glance seem like a good heat pump option. But due to the extremely low temperatures during Ulaanbaatar's heating season, their efficiency is significantly affected, which heavily increases the electricity demand of the ASHPs. GSHPs, on the other hand, can operate at an annual average efficiency of about 360%, if being assisted by solar thermal energy to maintain the soil temperature balance. A heating system supplied by SAGSHPs therefore appears to be the most suitable technology to supply the district heating network. Based on that, we identify the wide application of large scale SAGSHPs supplying heat to the district heating network as the least electricity intensive option for decarbonisation. The technological set-up is similar to what is suggested in (Shah, Aye and Rismanchi, 2020) but at a larger scale. For the buildings not connected to the district heating network, namely the ger districts, another technological set-up is suggested, as explained in the next section.

2.3.3 Decentralised heating technologies

Due to the low density of dwellings in the ger districts of Ulaanbaatar, district heating would not be a technically or economically feasible solution. Therefore, we consider decentralised heating technologies for those areas. The low energy efficiency of ger dwellings, and the objective of a gradual migration from ger dwellings to new apartment buildings make the deployment of expensive heat pumps and solar thermal systems unattractive. Direct electrification is therefore identified as the most suitable decarbonisation approach, which is similar to the conclusions in (Stryi-Hipp et al., 2018).

One of the key barriers of such transition is ensuring a reliable, affordable, and sustainable electricity supply to the ger areas. In a severe cold climate such as in Ulaanbaatar, a secure heat supply can become a matter of survival. The reliable supply of electricity is therefore a prerequisite to the electrification of the heat supply of the ger districts and would require improvements and expansions of the current grid infrastructure.

2.3.4 Industrial heat supply

As this study focuses particularly on the decarbonisation of the residential heat supply, we do not conduct any detailed analysis on potential alternative decarbonisation technologies for industrial heat supply. Instead, we build on the results in (Stryi-Hipp et al., 2018) where industrial heat is supplied from a combination of direct electrification, waste incineration and CHP. As we seek to fully decarbonise the heat supply, we keep the waste incineration but use direct electric heating for the remaining heat demand. Although other alternative decarbonisation solutions could be available, that analysis is outside of the scope of this study.

3 Scenario analysis

In this section, we derive high-level estimates of decarbonisation alternatives for the heating sector in Ulaanbaatar and analyse the potential impact of low and high electrification heating technology portfolios[3]. We compare the implications of doing so in terms of total electricity demand, expansion requirements, cost estimates and other metrics.

3.1 Approach and definition of scenarios

As mentioned in Section 1.2, the calculations in this study are based on data provided in Stryi-Hipp et al., and additional data collected from official statistics (Energy Regulatory Commission of Mongolia, 2021). The referred study is an exhaustive analysis of the energy system in Ulaanbaatar, which develops three scenarios to examine decarbonisation options of the energy system by 2050. In that analysis, a cost-optimisation modelling exercise of power and heating supply is performed subject to different assumptions and constraints, such as the reliance on imports and the use of regional renewable resources, amongst others.

A careful and detailed assessment of the results and the underlying assumptions of that study provides the basis to derive key parameters of the energy system that we use to enlarge the scope of the analysis in this study and estimate the impact of different electrification intensities of the heat supply. We do so through the development of three additional scenarios. By using the data provided in the cited study, we aim to maintain consistency and comparability of the results while exploring alternative configurations not examined in Stryi-Hipp et al. Similarly, and since we did not undertake an additional optmisation modelling exercise, the results of the quantitative analysis presented in this report should be understood within the boundaries of the assumptions of the modelling exercise performed in (Stryi-Hipp et al., 2018).

We carry out the analysis of the alternatives for decarbonising the Ulaanbaatar heating sector and, specifically, the implications of different levels of electrification by developing and comparing three scenarios:

[3] The heating technology portfolio referes to the mix of technologies used to satisfy the heating demand in 2050.

Scenario 1: Low-carbon scenario (LCS)

The first scenario is based on the recommended configuration from (Stryi-Hipp et al., 2018). This scenario represents a high electrification of the heat supply as ASHPs become widely deployed and supply the majority of heat in district heating networks for residential consumption, where direct electric heating would still need to meet peak demand and to generate heat for the industry and ger districts. This scenario does not include any technology to supply heat directly from renewable sources or hybrid systems. It relies on local renewable sources, namely solar and wind from within the city boundaries for electricity generation.

While it significantly reduces GHG emissions compared to the current energy system, this scenario does not represent a full decarbonisation option because it assumes the installation of a new CHP plant to supply heat to the district heating network and industrial heat consumption. For the purpose of this study, we refer to this scenario as the low-carbon scenario (LCS).

Scenario 2: High electrification decarbonisation scenario (HEDS)

The second scenario is a modification of the LCS aiming to achieve full decarbonisation. Since the LCS is still reliant on CHP to supply 14% of heat in 2050, we therefore modify that scenario so that the heat demand from CHP is electrified (Figure 8). The electrification is achieved through the wider application of the technologies already considered in the LCS, namely ASHP and direct electric heating for residential heating and direct electric heating in the industry. For this we rely on local and regional renewable energy resources, namely solar and wind from within and beyond the city boundaries.

The modification of the LCS scenario is necessary to make it comparable with other configurations that also lead to full decarbonisation. As the aim of this analysis is to investigate whether the application of less electricity intensive heating technologies could lead to overall cost savings for the full decarbonisation of the heating sector in Ulaanbaatar, the comparison of scenarios needs to take place under similar conditions; the scenarios being compared should lead to full decarbonisation.

This scenario constitutes the reference for full decarbonisation based on high electrification of the heat supply. For the purpose of this study, we refer to this scenario as the high electrification decarbonisation scenario (HEDS).

Scenario 3: Low electrification decarbonisation scenario (LEDS)

The third scenario is developed to represent an energy system configuration with lower electricity demand but equally achieving full decarbonisation of the heat supply and is informed by the technology mapping in 2.2. As explained in section 2.3, this scenario assumes a wide adoption of lower electricity intensive heating technologies, mainly through the installation of SAGSHPs to supply heat to district heating networks for residential consumption. Ger dwellings and industrial heat demand is still fulfilled by direct electric heating.

This scenario aims to investigate the implications of using a technology that has higher capital investment needs but with higher efficiencies to significantly reduce the electricity demand while achieving full decarbonisation of the heat supply by 2050. For the purpose of this study, we refer to this scenario as the low electrification decarbonisation scenario (LEDS).

The first two scenarios result in high electricity demand for the heat supply and serve as references to be compared with the third scenario (LEDS). Through the modification of the LCS into the HEDS we can compare the electricity demand in HEDS and LEDS under the common condition that they both lead to full decarbonisation. Table 2 provides an overview of the three considered scenarios and their heating technology portfolios.

Table 2. Overview of the scenarios considered and their respective heating technology portfolios.

Scenario name	Heat supply technologies in 2050
Scenario 1: Low-carbon scenario (LCS)	• ASHPs • Direct electric heating • Waste incineration • CHP • Thermal storage
Scenario 2: High electrification decarbonisation scenario (HEDS)	• ASHPs • Direct electric heating • Waste incineration • Thermal storage
Scenario 3: Low electrification decarbonisation scenario (LEDS)	• SAGSHP (solar thermal collectors and GSHPs) • Direct electric heating • Waste incineration • Thermal storage

3.2 Scenario results

The scenario analysis aims to provide a quantitative comparison of different technology portfolios for decarbonising the heat supply in Ulaanbaatar, as presented in the scenarios defined above, and their implications for electricity demand. Further, through the inclusion of high-level cost estimates, it intends to expose potential trade-offs between the selection of electric versus hybrid heating technologies and their implications and costs associated to increased electricity demand in terms of generation and transmission capacity in the power system.

For that purpose, the quantifications for each scenario consist of heat supply, electricity demand, and power capacity, storage, and grid expansion requirements. Additionally, we derive cost estimates associated to different components of the energy system relevant to the analysis, including heat supply, electricity generation, and grid expansion.

The analysis of the scenarios in this section focuses on the comparison of HEDS and LEDS as these two scenarios are comparable in terms of achieving full decarbonisation of the heat supply.

Unless stated otherwise, the data presented in this section are results from calculations carried out by the authors of this report.

3.2.1 Heat

Heat demand

The starting point for the analysis is the total heat demand in Ulaanbaatar in 2050. Total heat demand in 2050 is projected to be 14,724 GWh, which is concentrated in centralised buildings (buildings connected to the district heating network), representing 65% of the total heat demand. It is followed by the industry sector (23%) and decentralised (buildings not connected to the district heating network) dwellings (6%) (Stryi-Hipp et al., 2018). The three scenarios considered in this analysis assume the same total heat demand (see Figure 7).

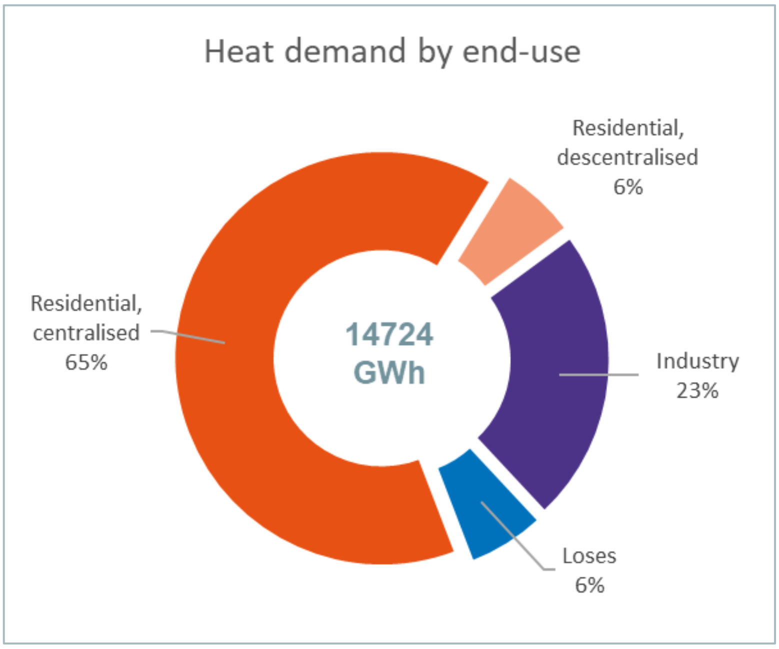

Figure 7: Heat demand in Ulaanbaatar in 2050 by end use. The same heat demand applied in all scenarios.

Source: Stryi-Hipp et al., 2018

Making the distinction between industry and residential heat demand is necessary due to the different supply temperature levels required for the two. The industry sector requires a higher supply temperature and can be fulfilled via direct electric heaters, CHP, and waste incineration plants. The residential sector demands a lower supply temperature that can be fulfilled by the same technologies that supply high temperature heat, as well as heat pumps and solar thermal collectors (Maruf et al., 2021).

The configuration of the city's building stock, with a large share of ger dwellings, leads to a need for both centralised and decentralised heating systems. Similarly, this set-up has implications for the technological choices to supply heat. Table 3 presents an overview of technological options to supply heat based on Ulaanbaatar's characteristics and from the outcome of the technological mapping exercise in section 2.2.

Table 3. Non-exhaustive overview of technological options of heat supply in Ulaanbaatar in 2050 by sector.

Technology	Residential – district heating	Residential – Ger areas	Industrial
CHP	✕		✕
Waste incineration			✕
Direct electric heater	✕	✕	✕
Air-source heat pumps (ASHP)	✕		
Solar assisted ground source heat pumps (SAGSHPs)	✕		

Heat supply

Based on that, the technological portfolios supplying heat makes the main difference between the three scenarios, resulting in various levels of electricity demand to supply the same amount of heat. Figure 8 shows the technology mix of heat supply for all three scenarios.

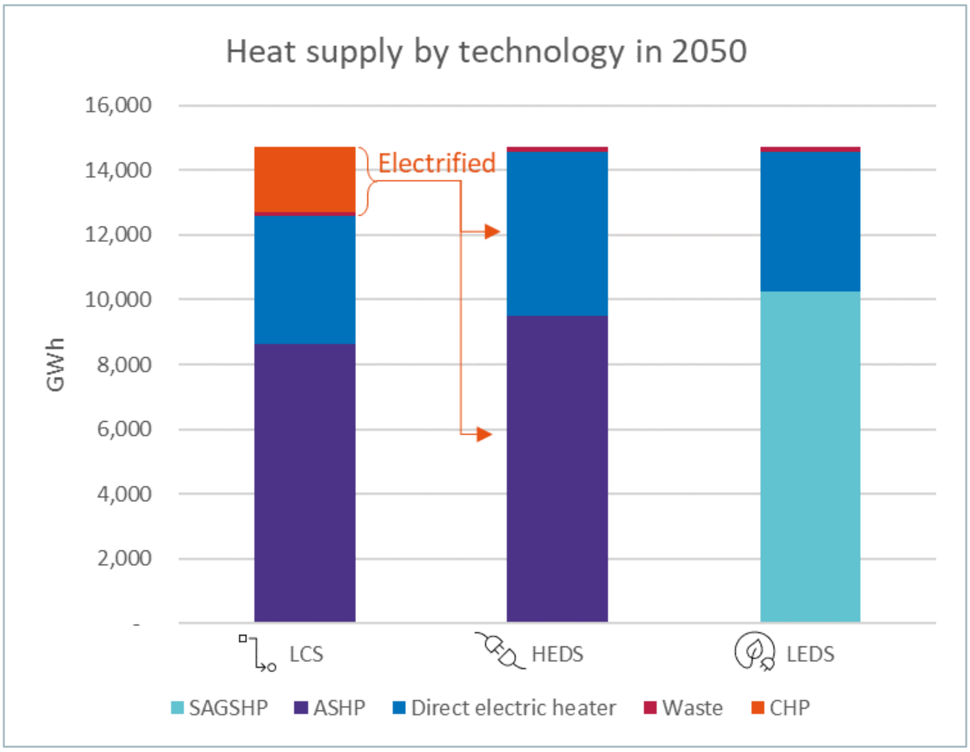

Figure 8: Technology mix of heat supply in 2050 per scenario. The technology portfolio of LCS includes coal-fired CHP. HEDS rely on more electricity intensive technologies than LEDS.

As the final goal is a decarbonised and reliable heating system, all three scenarios analysed in this study represent a profound transformation in the configuration of the heat supply in Ulaanbaatar by 2050 compared to the current state.

The LCS relies on the installation of a new CHP to provide 14% of total heat demand in 2050. Out of the three scenarios developed in (Stryi-Hipp et al., 2018), the study recommends the LCS configuration to supply heat demand in Ulaanbaatar in 2050. The recommendation to install a new CHP is based on the aim to reduce electricity imports while maintaining a secure energyy supply. Another important characteristic of this scenario is that the remaining heat supply is generated by electricity (59% ASHP and 27% direct electric heaters), under the assumption that other non-electric renewable energy technologies are not available to provide heat directly.

The HEDS takes the LCS as its reference with the key modification being the electrification of the 14% of heat supplied by CHP in the LCS. That electrification is achieved with additional deployment of ASHPs and direct electric heating, proportional to their contribution to the district heating (93% ASHP and 7% direct electric heaters). The heat supplied by CHP in the industry sector is fully replaced by direct electric heaters. The mentioned modifications result in the HEDS being almost fully electrified with 65% of heat supplied through ASHP, 34% through direct electric heaters, and 1% through waste incineration.

The LEDS takes the HEDS as its reference, but with the key difference of using large scale SAGSHP systems instead of ASHP and direct electric heating for centralised heating. This scenario assumes that part of the heat demand is met through non-electric renewable energy sources using solar thermal collectors. Direct electric heating is used to generate heat for decentralised residential dwellings and the industry heating technology remain the same as in the HEDS. While a district heating system relying entirely on SAGSHP might not be the ultimate solution for Ulaanbaatar, this scenario aims to maximise non-electric renewable heat supply paired with high efficiency electric heating to examine the trade-offs of lower electricity demand in the power system. This leads to a LEDS with a heat supply system consisting of 70% SAGSHP, 29% direct electric heating and 1% waste incineration.

Installed capacities

The installed capacity by technology across the three scenarios is derived through the technology supply mix and the utilisation factor[4] for each technology, as presented in Figure 9. Since no modelling exercise to mimic the operation of each technology was conducted, we assume that the utilisation factor by technology is constant across all scenarios to keep consistency and assure comparability. The utilisation factors of the CHP, waste incineration plant, ASHP and direct electric heater were obtained from (Stryi-Hipp et al., 2018). Due to lack of data, we assume that the SAGSHP operates similarly to the ASHP and thus with the same utilisation factor of 13%.

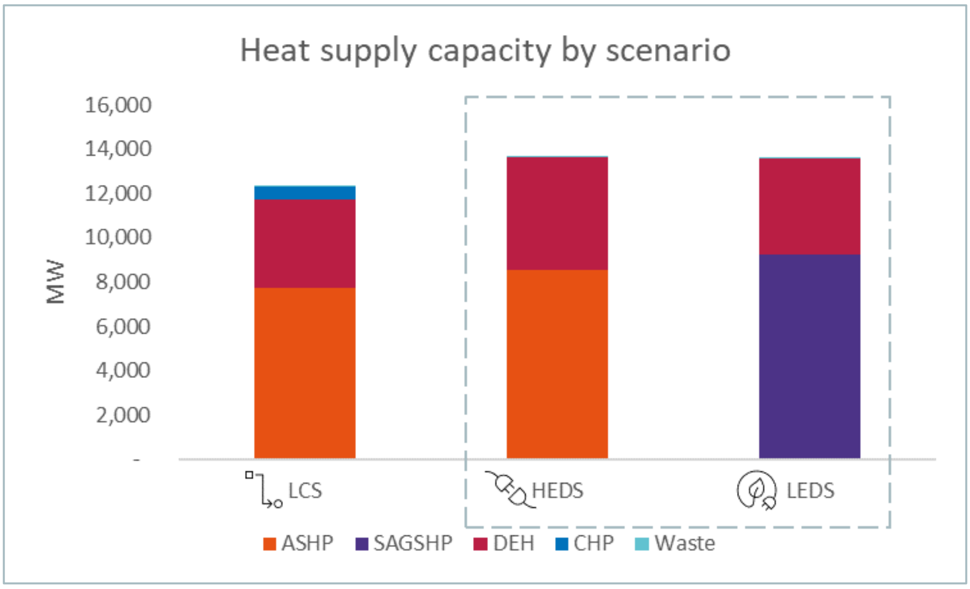

Figure 9: Installed capacity of heat supply technologies by scenario.

The HEDS and LEDS scenarios have similar total installed capacities, with the difference that the former is largely composed of ASHP and the latter of SAGSHP. Compared to the LCS, the total installed capacity of the two full-decarbonisation scenarios is 10% higher.

Cost estimates

The annualised fixed costs of the LEDS are 30% higher than the HEDS. This is explained by the difference in the capital expenditure (CAPEX) of the main heating technologies deployed in each scenario. While SAGSHP brings higher efficiency to supply heat, this system requires higher investment costs than conventional ASHP (Energy Saving Trust, 2021). Figure 10 shows the difference in levelised annual fixed costs to supply heat between the three scenarios.

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[4] Utilisation factor is the ratio of the energy produced by all units of a given thermal technology in a full year divided by the total energy that could have been produced if the thermal units of that technology were used at full capacity during the same year.

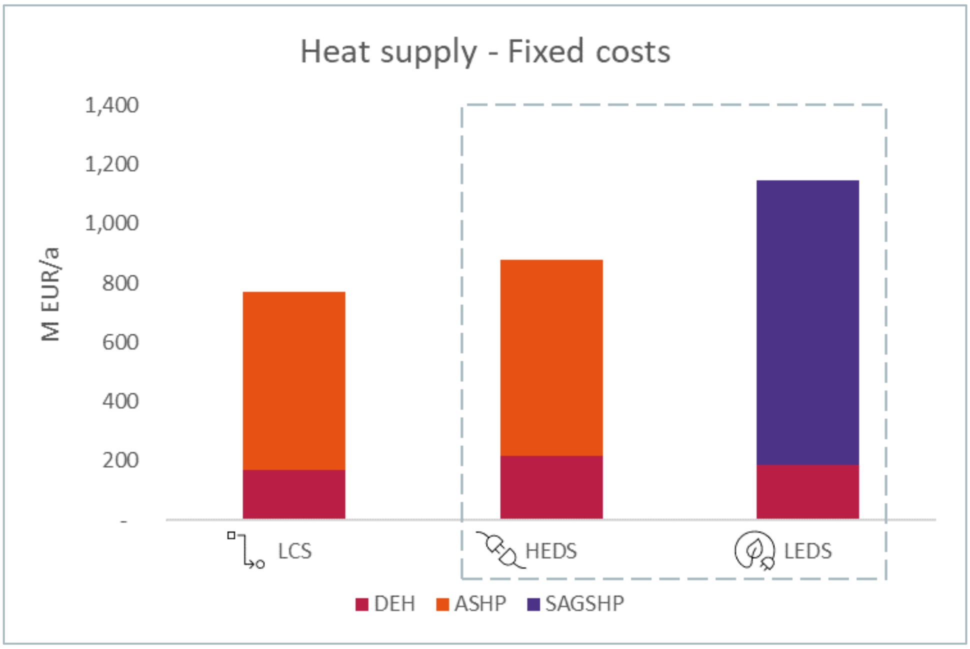

Figure 10: Estimates of the levelised annual fixed costs of heat supply by scenario and broken down by heating technology.

As total fixed costs are directly linked to the total installed capacity, the utilisation factor of each heating technology is a relevant parameter that will determine the total costs and consequently the cost effectiveness of the technology with respect to other options. Figure 11 shows that annualised fixed costs of the LEDS decreases as the utilisation factor of the SAGSHP increases. The figure shows that the current utilisation factor assumed for the scenario analysis (about 13%) leads to high fixed costs. However, it also shows that 13% of utilisation is on the side of the cost function where a marginal improvement of the utilisation factor can lead to significant reductions of annualised fixed costs. The uitilisation factor can be improved through optimised operation of the heat pump in conjunction with the optimised utilisation of the available solar energy with storage, and active response of the demand. Some studies suggest that modular small-scaled SAGSHP systems in Ulaanbaatar can reach up to 65% of utilisation (Shah, Aye and Rismanchi, 2020), however, this may decline when deployed at scale.

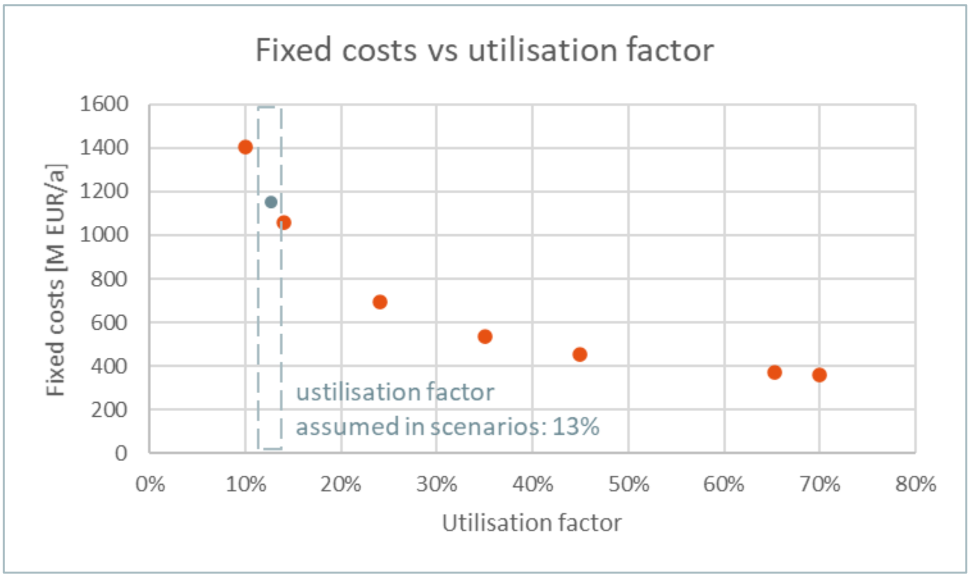

Figure 11: Sensitivity analysis of annualised fixed costs in LEDS as function of the utilisation factor of the SAGSHP to supply heat demand.

Studying the costs of electricity consumption as the main driver of variable costs of the heating technologies assessed in the scenarios, the variable costs in the LEDS are 28% lower than in the HEDS (Figure 12). That is a result of the direct use of solar heat and the efficiency gains of the SAGSHP system, resulting in around half of the ASHPs electricity consumption per unit of heat delivered. We assume that the electricity supply costs are 65 EUR/MWh on average, which is in line with historical trends. However, it is important to note that a deep transformation of the energy system analysed in this report would lead to disruptions of the electricity prices as well, which is not captured in this analysis.

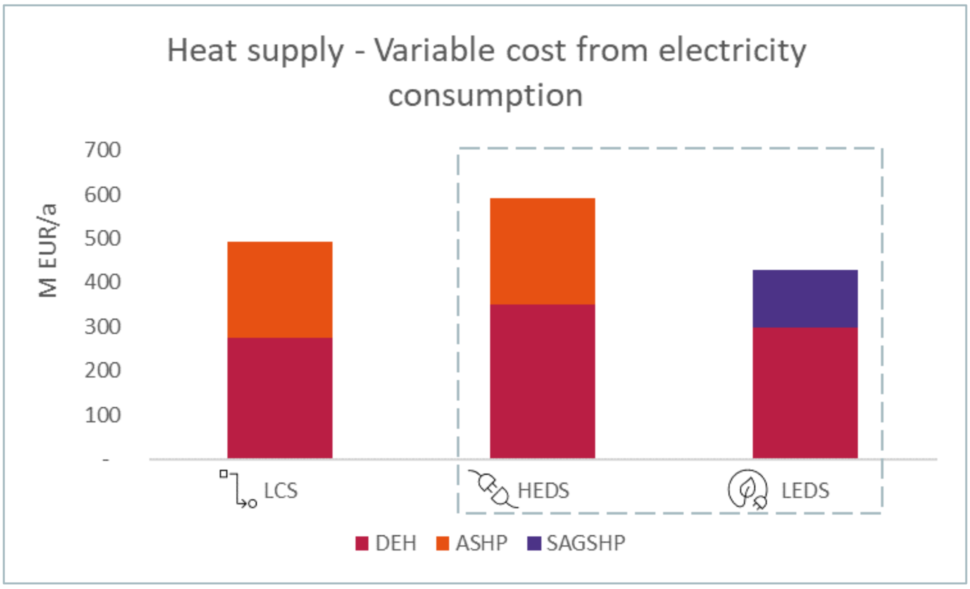

Figure 12. Estimates of annual variable costs of heat supply from electricity consumption by scenario and broken down by heating technology.

As a result, the high fixed costs of the SAGSHP (in the LEDS) are largely offset by the cost reductions from electricity consumption. Figure 13 shows that, when both fixed and variable cost components of heat supply are taken into account, the LEDS continues to have the highest levelised annual cost of heat supply, being around 7% higher than the HEDS and 18% higher than the LCS.

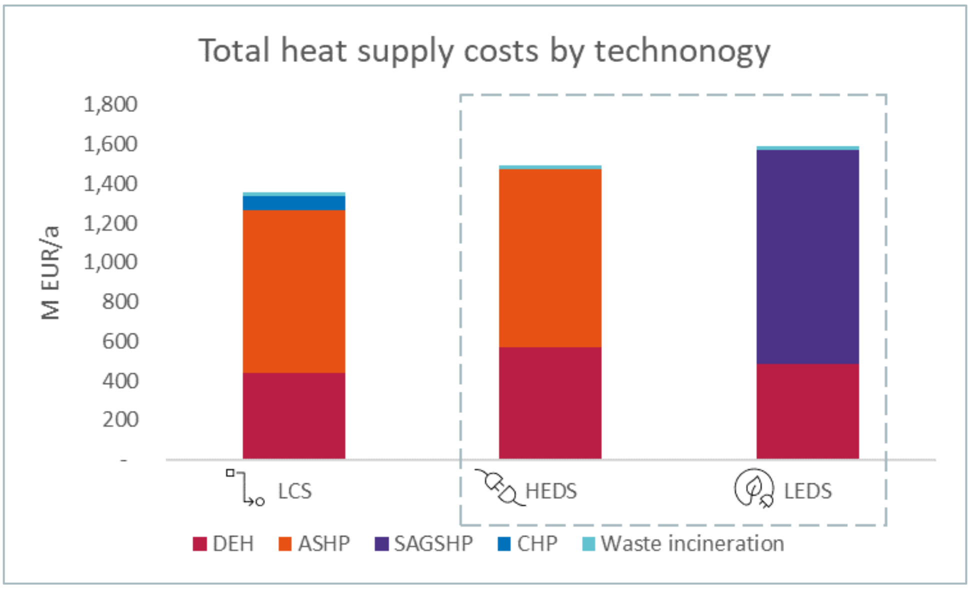

Figure 13. Estimates of the levelised annual total costs of heat supply by scenario and broken down by heating technology.

As might be expected, the more efficient heating technologies such as SAGSHP have larger cost savings the more expensive the cost of electricity. Figure 14 shows that, with an average electricity price of 105 EUR/MWh, the total heat supply costs of the LEDS will be the same as that of the HEDS. The relatively high electricity price in Ulaanbaatar, driven by high fuel costs and expensive electricity imports, make efficient heating technologies such as SAGSHP a more economically attractive decarbonisation option for the heat supply.

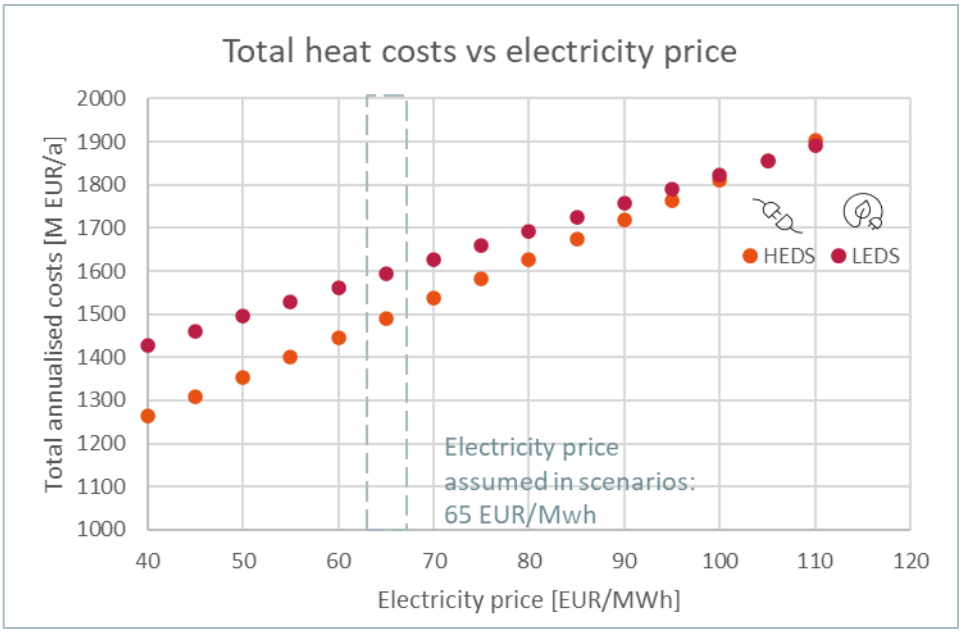

Figure 14. Sensitivity analysis of annualised total costs of heat supply as function of the electricity price.

To identify the total system costs, costs associated with the expansion of the power system required to meet the increasing electricity demand need to be estimated. In the next section, the impacts from an expanded renewable energy-based power system, including cost estimates, are further investigated.

3.2.2 Electricity

Total electricity demand

The total electricity demand of Ulaanbaatar in 2050 can be divided into direct end use of electricity in the residential, industry and mobility sectors and electricity consumption for heat generation. Figure 15 shows the breakdown of the electricity consumption by end -use, which shows that the largest contributor to electricity consumption is the generation of heat. For the purpose of this analysis, direct electricity consumption in end-uses in the residential, industry and mobility sectors are kept constant across all scenarios and is taken from (Stryi-Hipp et al., 2018).

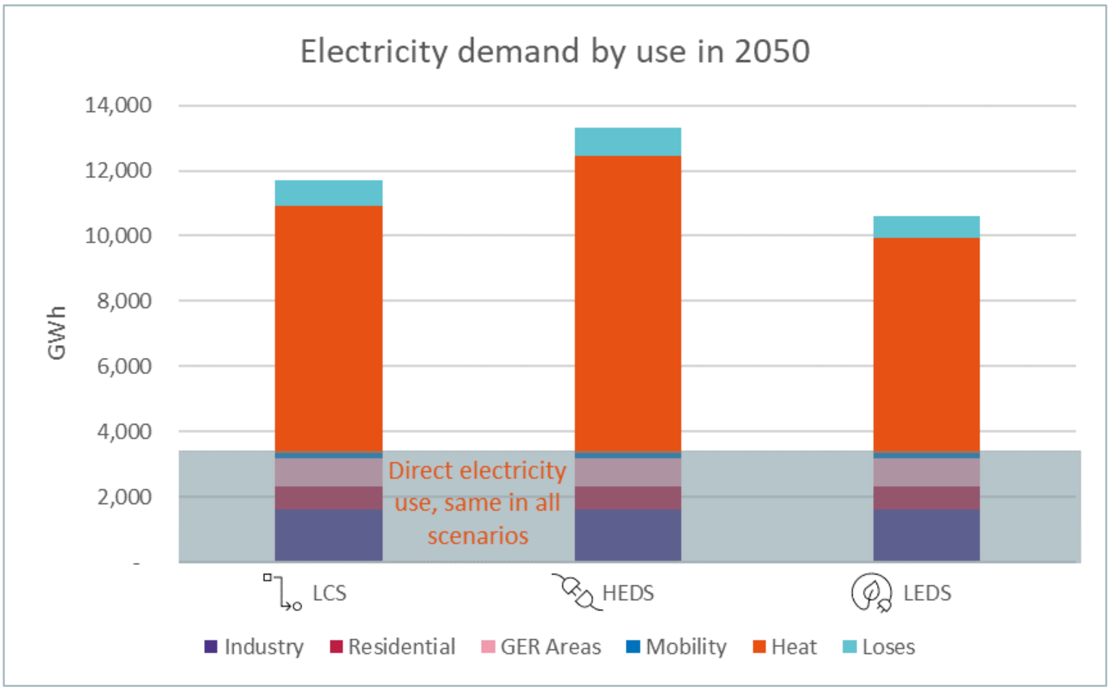

Figure 15. Electricity demand by scenario and broken down by use in Ulaanbaatar in 2050.

In the LCS, electricity consumption for heat production represents 65% of total electricity demand, which increases to 68% in the HEDS and is reduced to 62% in the LEDS. Compared to the LCS, total electricity demand increases by 14% in the HEDS driven by the substitution of CHP supply to other electricity-based technologies such as ASHP and direct electric heaters. In the LEDS, total electricity demand is reduced by 20% compared to the HEDS due to the heat being generated by more efficient technologies – requiring less electricity to deliver the same amount of heat. In this section we discuss the assumptions of different heat supply technologies and their implications on the electricity demand in more detail.

Electricity demand for heat supply

The electricity demand estimates suggest a substantial potential to reduce electricity demand in the LEDS. Compared to HEDS, the electricity demand for heat generation in the residential sector is reduced by 46% (Figure 16), and 28% reduction when also accounting for heat generation for the industrial sector (Figure 17).

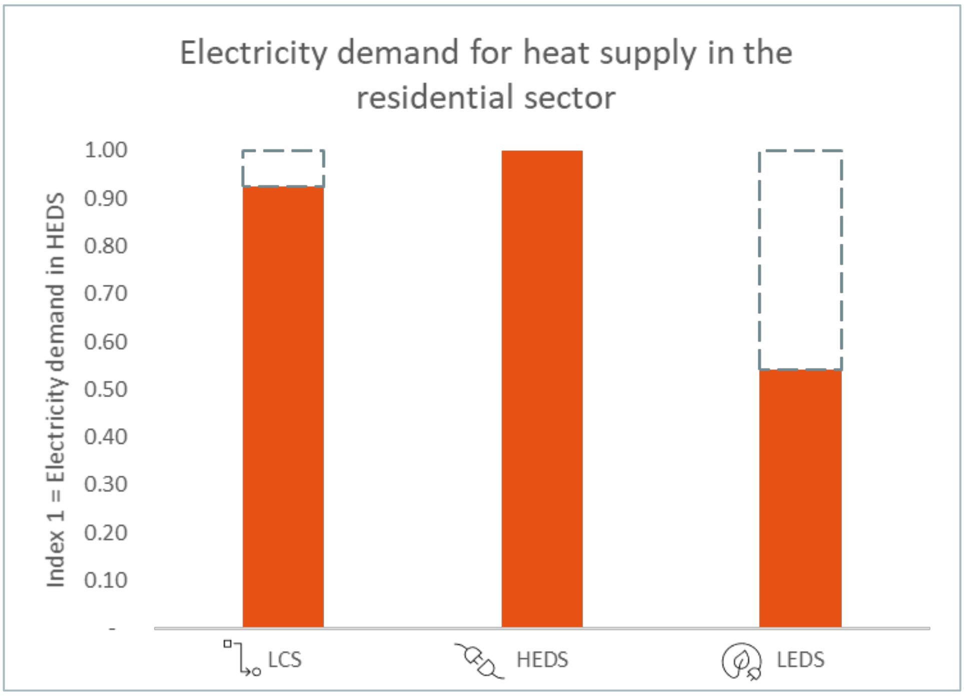

Figure 16. Comparison of electricity demand for space heating in the residential sector in 2050; comparison HEDS and LEDS.

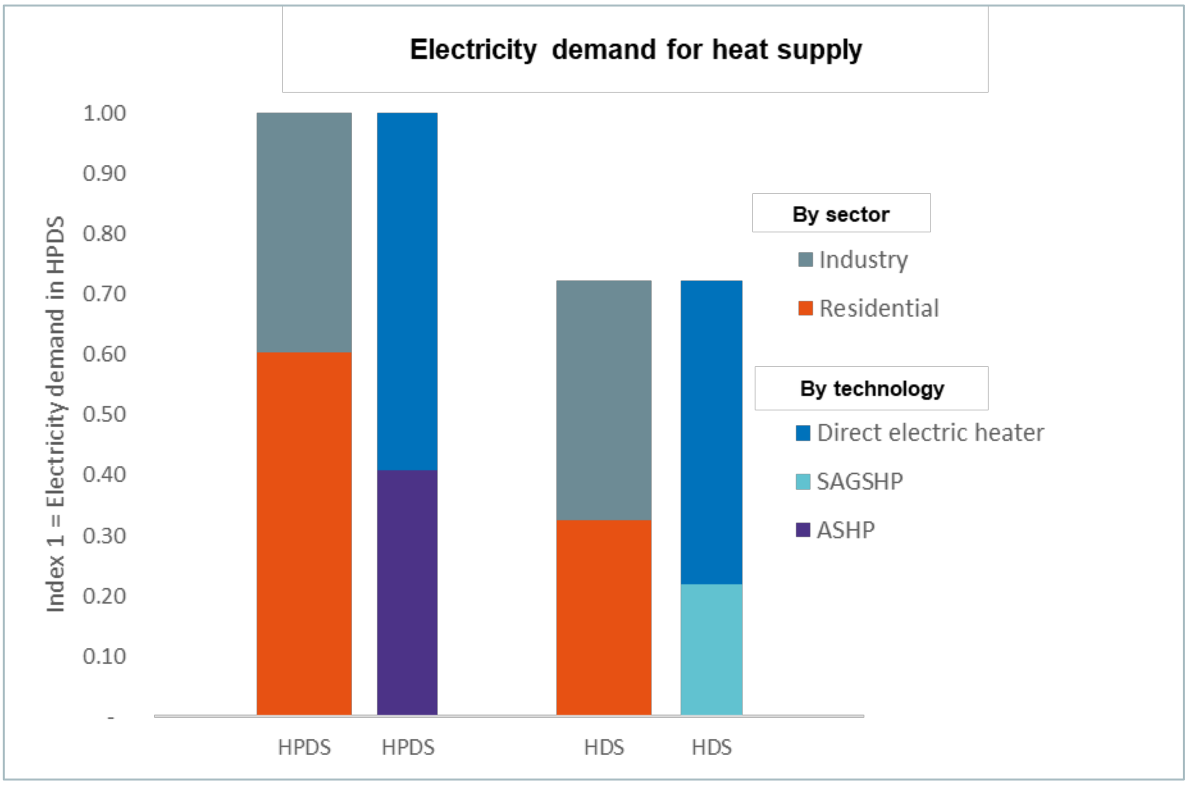

Figure 17. Comparison of electricity demand for heating in 2050 for HPDS and HDS scenarios by sector (residential and industrial) and per technology (Direct electric heater, SAGSHP and ASHP).

Electricity supply

The 20% reduction of electricity demand in the LEDS compared to the HEDS reduces the burden on the power system, leading to lower installed capacity requirements and, consequently, cost savings in the power system.

The deep transformation of the energy system is accomplished through the shift to a clean electricity supply. In the LCS, most of the energy for heat is supplied from renewables (38% solar PV and 37% wind), but coal-fired CHP is still needed for 18% of the generation share.

In the decarbonisation scenarios, however, the full demand is met with renewables, eliminating the need for CHP. In both the LEDS and the HEDS, it is assumed that the additional power generation comes from regional renewable resources beyond the geographical boundaries of Ulaanbaatar, mainly from wind and ground-mounted solar PV from the most resource-rich regions in the south. Power generation from wind resources account for 50% share in both scenarios, followed by 29% ground-mounted PV and 15% rooftop PV (Figure 18).

In order to keep consistency and comparability across scenarios, we assume that annual electricity imports are the same in all scenarios, representing 3% of total supply. Similarly, power generation from dispatchable waste incineration plants contribute to 4% of total supply in all scenarios. Keeping these parameters constant in the three scenarios makes them comparable in terms of energy security (low dependency on electricity imports aligned with the LCS).

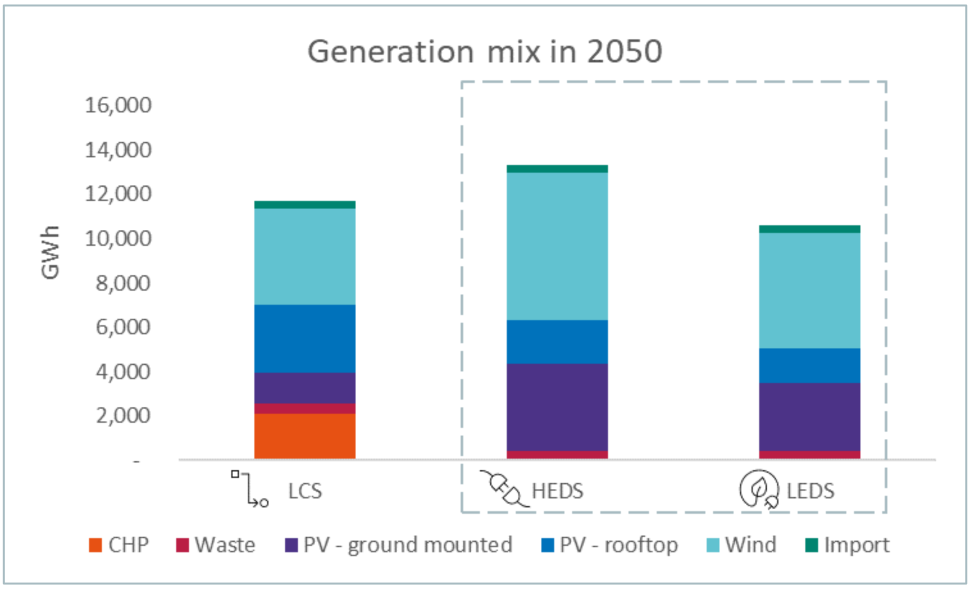

Figure 18. Power generation mix in 2050 by scenario and broken down by technology.

Installed capacities and capacity factors

The total electricity demand and generation mix in each scenario lead to various levels of installed capacities. Taking the LCS as reference, the higher rate of electrification in the HEDS leads to an 18% increase in total installed capacity in 2050. In contrast, the less electricity intensive alternative to supply heat (using SAGSHP) leads to a reduction of 8% and 22% of the total installed capacity in LEDS compared to LCS and HEDS respectively (Figure 19).

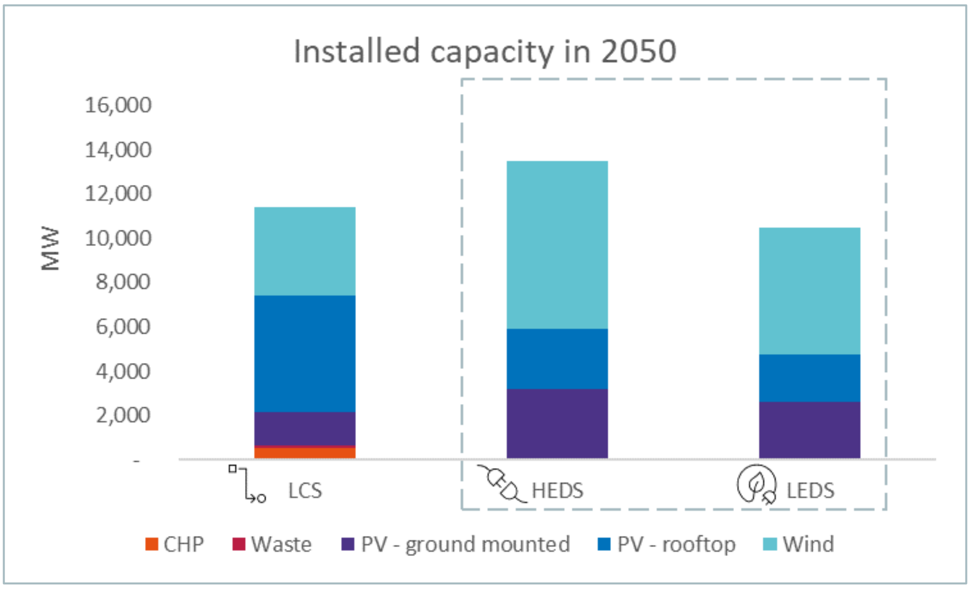

Figure 19. Installed capacity of power supply in 2050 by scenario and broken down by technology.

The installed capacities of each technology are a result of their expected total energy generation and the capacity factor[5] (in terms of full load hours). Since we do not conduct a modelling exercise to determine the capacity factor of each technology in each scenario, they are estimated as a function of the share of the technology in the generation mix and a share of the baseload technologies. The rationale behind this approach is that for non-dispatchable generation technologies, such as wind and solar PV, the capacity factor is affected by how much that technology is already contributing to the total mix; For example, the capacity factor tends to be higher in low penetration levels of renewable resources and tends to decrease with very high shares as a consequence of curtailments (Hirth, 2013). Additionally, the contribution of baseload technologies also affects the operation of non-dispatchable technologies by bringing flexibility or displacing its generation.

The estimation of capacity factors for each technology and scenarios (Table 5) is based on a detailed analysis of the energy modelling exercise conducted in (Stryi-Hipp et al., 2018). The capacity factors resulting from the analysis are in line with the original study, which shows robustness of the approach.

Table 4. Capacity factors of each power generation technology by scenario

Technology	LCS	HEDS	LEDS
CHP	44.2%	44.2%	44.2%
Waste incineration	44.2%	90.2%	90.2%
Wind	12.4%	14.1%	10.4%
Ground mounted PV	10.3%	9.1%	13.7%
Rooftop PV	6.7%	8.2%	8.1%

It is important to note that the resulting capacity factors of renewable-based generation technologies are considerably low compared to the potential of the resources. For example, the potential of wind resources in the South of Mongolia should yield a capacity factor of around 38%, which is much higher than the 10-14% obtained in the scenarios of this study. Similarly, the expected capacity factor of solar

[5] The capacity factor of a technology indicates how much of the full capacity that technology is used in a given period of time. This indicator is typically affected by system operation and the availability of the fuel/resource to generate electricity.

PV is 22%, more than double than the obtained 6-14% in the scenarios of this study (Pfenninger and Staffell, 2019). Nevertheless, we use the low capacity factors resulting from the calculations to be consistent with the results in Stryi-Hipp et al., and to guarantee comparability across scenarios. Additional modelling exercises are needed to assess in detail the impact of high shares of variable renewable energy in the operation of the electricity system and its repercussion on capacity factors.

Low capacity factors are a result of significant curtailments of renewable power generation, which is in turn reflected in high installed capacity requirements. Curtailments are a signal of low integration of renewables into the system and can be minimised through the optimisation of system operation or improving the flexibility of the system, such as increasing the storage and transmission capacity.

Besides high curtailments of renewable energy, the high shares of variable renewable resources (i.e., solar and wind) also have impacts on the reliability of the system. Power systems with high shares of variable renewable energy require additional resources to bring flexibility to respond to fluctuations in the power generation and to guarantee a reliable supply. Figure 20 shows the storage requirements of each scenario, which are estimated as a function of the share of variable renewable energy in the system, and the participation of dispatchable generation sources such as thermal power plants and imports.

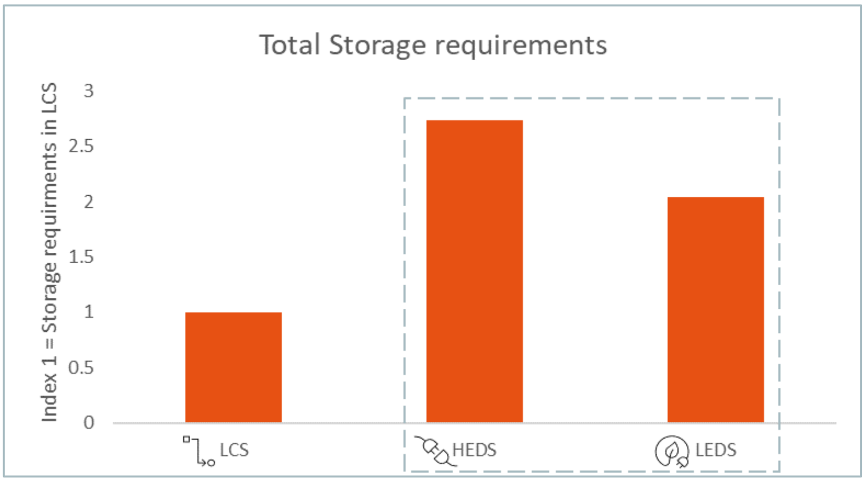

Figure 20. Total electricity storage requirements by scenario. The y-axis is indexed, where 1 corresponds to the total storage requirement in the LCS.

The comparison of the LCS and HEDS in terms of storage requirements highlights the importance of dispatchable generation units to guarantee a reliable supply of heat. By constraining the installation of new coal-fired CHP, the HEDS requires more than 150% more storage capacity compared to that of the LCS. The LEDS requires 25% less storage capacity than HEDS due to lower power generation requirements. However, the generally high storage requirements in the HEDS and LEDS indicate additional challenges in implementing those scenarios.

It is important to note that the high storage requirements required in the scenarios is also related to the limitation imposed to imports. Power imports from other regions and/or countries can increase the flexibility of the system and facilitate the integration of high shares of variable renewable energies (De Vivero-Serrano et al., 2019). Figure 21 shows how the increase in share of imports in total electricity supply reduces the burden on the storage capacity in the scenarios. By increasing annual imports to 25% of total supply, storage requirements could be reduced by more than 90% in 2050, and 15% of imports can reduce storge requirements by half in both scenarios compared to the current assumption of 3.5% imports in both scenarios. A full decarbonisation scenario with high shares of imports require that the electricity imported also is generated with low-carbon technologies which come with additional barriers. The analysis of those, however, is not part of the scope of this study. The assumption of limiting imports to very low levels is chosen on the basis of ensuring energy security and to keep consistency with the reference scenario (Stryi-Hipp et al., 2018).

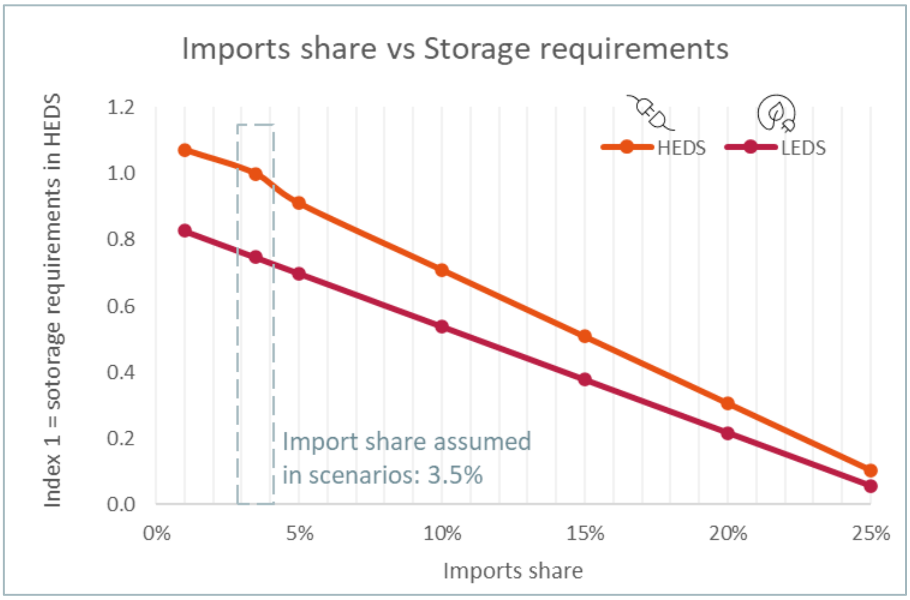

Figure 21. Sensitivity analysis of storage requirements as function of imports share for HEDS and LEDS. The y-axis is indexed, where 1 corresponds to the total storage requirements in HEDS.

A detailed reliability assessment of the system with high penetration of renewables is needed to understand the role of electricity imports and storage technologies in the road to full decarbonisation of the energy system. While the results presented above highlight the importance of greater flexibility with imports and storage, a more detailed analysis of reliability is beyond the scope of this report.

In this respect, and in the context of full decarbonisation of the power system, the reliability of supply, energy security and the risk of dependence on electricity imports must be weighed against the cost-effectiveness and the feasibility of maintaining a reliable security of supply, e.g., by installing large amounts of storage capacity. The integration into regional electricity grid (supranational) could bring substantial benefits in this regard.

Cost estimates

Electricity supply costs are calculated based on the total installed capacity per technology in each scenario. Taking the LCS as reference, the increase in electricity demand in the HEDS leads to an increase in annualised electricity generation costs of 41%. In contrast, the reduction of electricity demand in the LEDS leads to a reduction of total electricity supply costs by 22% compared to in the HEDS. Compared to the LCS, the LEDS has 10% higher total costs despite lower electricity demand and lower total installed capacity needs. This difference is mainly due to a selection of technologies that are more expensive than CHP (see Figure 22). The savings in electricity consumption from selecting more efficient technologies to supply heat in the LEDS partly compensates the higher technology costs of SAGSHP to supply heat in that scenario.

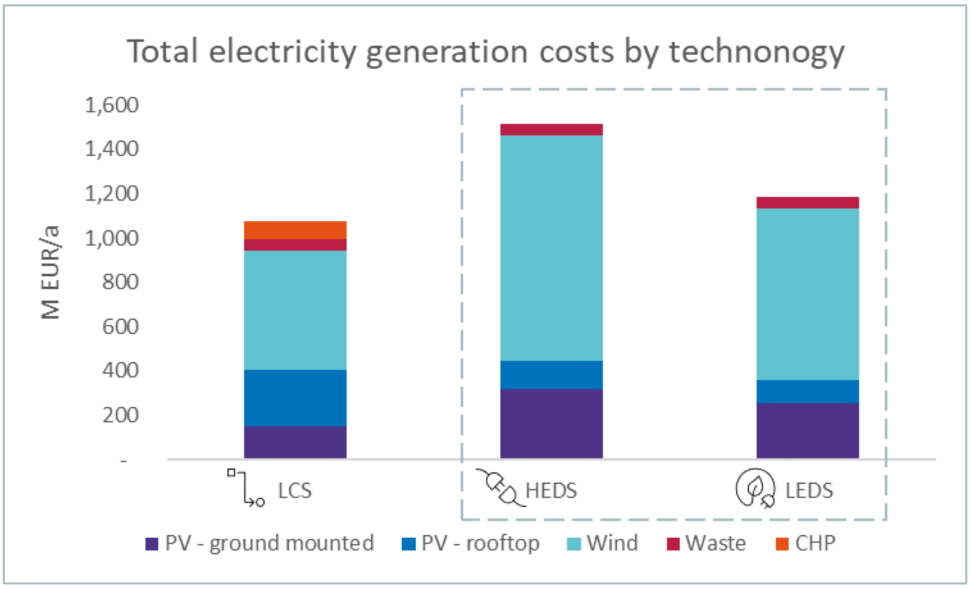

Figure 22. Estimates of the levelised annual total costs of electricity supply by scenario and broken down by heating technology, excluding storage costs.

The full decarbonisation of heat and power supply of Ulaanbaatar requires the use of renewable potentials from other regions beyond the boundaries of the city. In an attempt to capture the impact of exploiting renewable energy resources in other regions and transport it to Ulaanbaatar as electricity, this study aims to estimate the cost implications of expanding the electricity transmission grid.

The cost estimates of transmission expansion are based on the following assumptions across all scenarios:

- All imports require an expansion of the grid
- All wind power generation is transported to Ulaanbaatar from other regions
- Half of the electricity generation from ground mounted PV is transported to Ulaanbaatar from other regions
- The capacity expansion of the grid is scaled to accommodate all new installed capacity in other regions (i.e., minimise renewable curtailments due to grid congestion).
- The South-Gobi region is taken as the reference region to perform the cost estimates of grid expansion. That location is selected based on its high availability of renewable energy resources and other studies suggesting the need to expand the grid in that direction (Asian Development Bank, 2013)
- The high-level parameters needed to estimate the cost of the expansion including distance and reliability are obtained from a technical study conducted to determine the feasibility of a South-Gobi transmission network to transport significant amounts of power to Ulaanbaatar (Asian Development Bank, 2013). Due to the lack of cost data, transmission costs were obtained from the top end of cost estimates of high voltage transmission lines in other geographies to keep the approach conservative (Ho et al., 2021).

As expected, higher total electricity generation coming from renewable resources in the HEDS leads to a sharp rise in costs related to transmission grid expansion - nearly 90% higher compared to in the LCS. The savings in electricity consumption in the LEDS leads to around 23% savings in grid expansion costs compared to in the HEDS (Figure 23). Similar to the costs savings in power supply capacity, the cost savings in transmission expansion partly compensates the higher costs of heat supply in the LEDS.

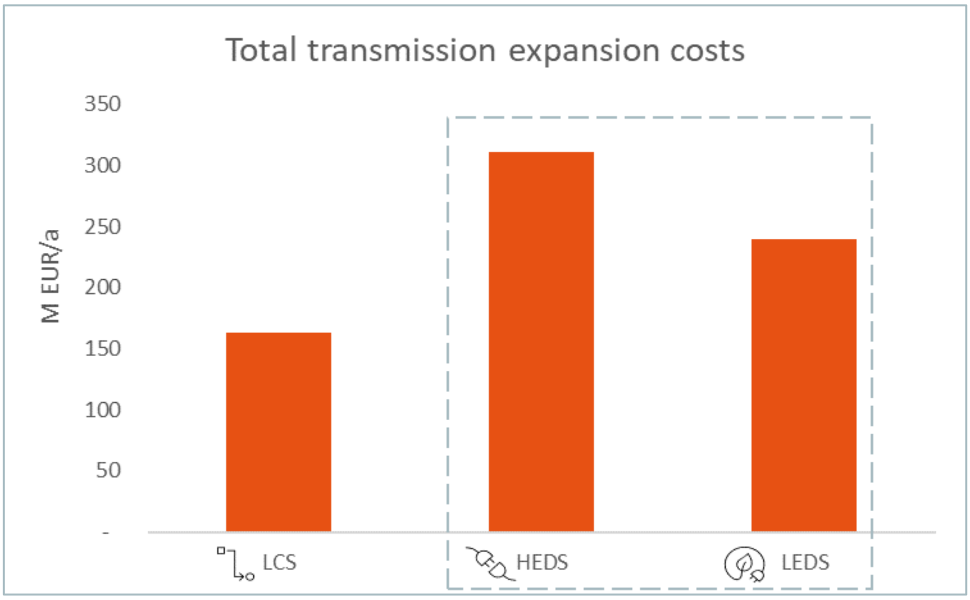

Figure 23. Estimates of the levelised annual costs of electricity transmission by scenario.

Interestingly, increasing the share of imports in the total electricity supply can reduce transmission expansion costs (Figure 24). While increased imports requires grid expansion, it also increases flexibility in the system which facilitates the integration of renewables into the system. As a result, renewables can yield higher capacity factors that are reflected in less capacity additions in distant resource-rich locations, which reduces the transmission expansion costs needed to transport this electricity.

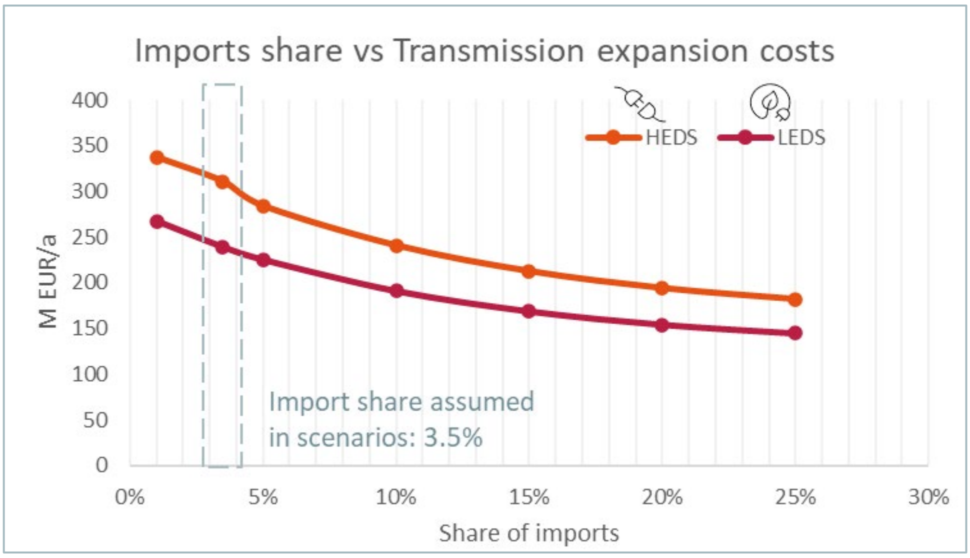

Figure 24. Sensitivity analysis of annualised transmission expansion costs as function of electricity imports.

3.2.3 Total cost estimates

A comprehensive view of all components of the energy supply cost reveals potential trade-offs between electricity and heat supply. The comparison of the two full decarbonisation scenarios in terms of costs and their components shows the importance of analysing the effects of decarbonisation based on high electrification (HEDS), versus alternatives that use renewable energy directly for heating (LEDS).

Although the LEDS has higher heat supply costs than HEDS due to deployment of a more costly technology (i.e., SAGSHP), the electricity savings in the LEDS are higher due to the more efficient heat generation. This efficiency gain offers greater costs savings in the expansion of the electricity system than the additional costs of investing and operating more efficient heat supply technologies. As a result, the annual levelised cost of the LEDS is 9% lower than that of the HEDS (see Figure 25).

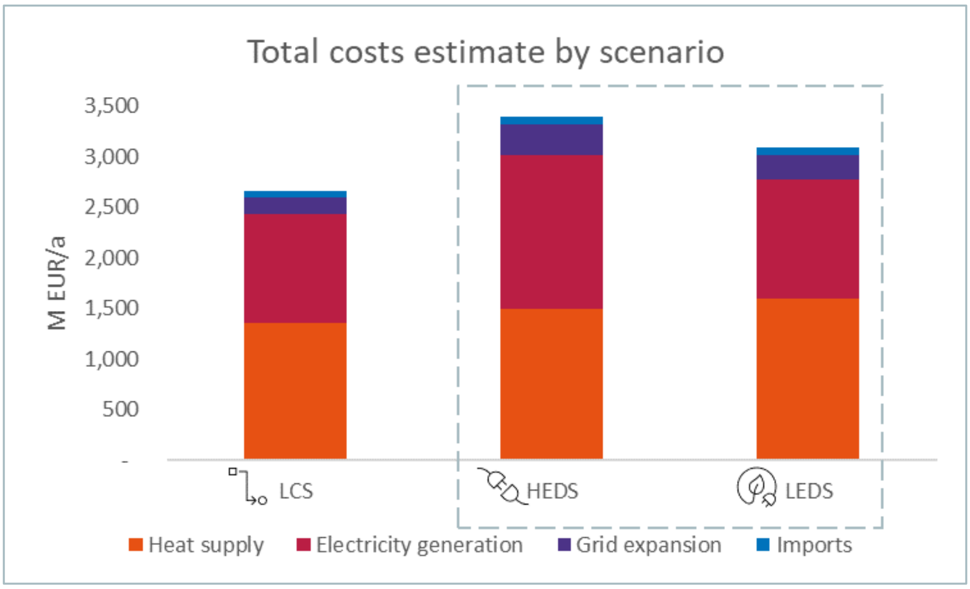

Figure 25. Levelised annual costs of all scenarios by cost component.

The annual levelised cost of the HEDS is 27% higher than that of the LCS. Replacing coal-based CHP plants in the LCS with more electricity intensive alternatives (HPDS) leads to a moderate increase in heat supply costs (10% increase) but a significantly higher increase in electricity generation and transmission costs (48% increase).

On the other hand, the LEDS, which replaces the coal-based CHP plant in the LCS has less electricity intensive alternatives, which leads to a higher increase in heat supply costs (18% increase) but considerably lower increase in electricity generation and transmission costs (15% increase). Overall, the annual levelised cost of LEDS is 16% higher than that of the LCS.

The cost estimate analysis indicates that greater investments in more expensive but more efficient heat supply technologies can lead to overall savings in total energy supply costs due to its resulting reduced electricity demand.

4 Transformations toward decarbonisation

Despite plentiful renewable resources, the transformation of the Ulaanbaatar heating sector to a decarbonised system poses a major challenge involving a multitude of actors. The transformation not only requires a shift to low-carbon technologies, but actions and coordination along the whole energy system, including supply, transmission, distribution, and the demand side. Measures taken in the short-term might influence investment decisions in the longer term, risking delays or even lock-in effects.

The current state of the Ulaanbaatar heating sector, reliant on old CHP plants operating beyond or approaching the end of their lifetime, presents a unique opportunity for the sector to steer into a new direction, away from reliance on fossil fuels. Doing so now could save emissions as well as costs. Investments in the upgrading of existing CHP plants in the near-term would prolong their lifetime and delay the integration of renewable-based technologies

A useful instrument in starting such a transition is the development of a vision for the heat sector, laying out the main objectives and the potential ways to get there. By involving the various actors in the sector, important considerations can be taken into account early on in the process. The vision can then be developed into a clear strategy, providing detailed targets and milestones. The strategy can further point to specific policies and programs and identify existing gaps such as investment needs.

Although this study is largely technology -focused, we identify three key transformations based on the results of this analysis, needed to achieve the transition of the heat sector. The transformations are discussed in more detail in this section and include:

- Enhance energy efficiency by improving building envelopes and expanding the district heating network
- Expand the renewable energy power capacity to improve access to electricity and untap system flexibility
- Integrate novel, renewable energy-based heating technologies

Although this study does not aim to develop specific policy recommendations, we identify key enablers linked to the transformations, as presented in Table 5. The transformations can serve as a basis for the development of a vision and a strategy, as well as the identification of relevant policy instruments.

Table 5. List of transformations and their corresponding key enablers.

Transformation	Key enablers
Enhance energy efficiency by improving building envelopes and expanding the district heating network	• Deep retrofit programs • Improved building codes • Coordination among operators of the district heating network • Public-private partnerships • Installing metering devices in all households/buildings • Introduction of consumption-based billing • Access to international climate finance
Expand the renewable energy power capacity to improve access to electricity and untap system flexibility	• Studies on optimal local and regional locations for renewable power generation • Expansion and reinforcement of transmission and distribution network • Renewable support mechanisms

Expand the renewable energy power capacity to improve access to electricity and untap system flexibility (contd.)	• Incentivise and remunerate flexibility in the system (e.g., storage, demand side response, flexible power generation, etc.) • Market access and regulatory framework to prosumers • Regional grid expansion and integration (multilateral power exchange) • Transfer subsidies from coal-based heating to electricity-based heating. • Re-modernisation program of obsolete CHP based on long-term visions
Integrate novel, renewable energy-based heating technologies	• Access to finance/public-private partnerships for piloting and demonstration • Subsidies and tax reliefs • Identification of suitable locations for renewable-based heating capacity • Development of a vision/strategy • Coordination among heat suppliers • Access to international climate finance • Capacity building, re- and upskilling of existing workforce

4.1 Enhance energy efficiency by improving building envelopes and expanding the district heating network

A full decarbonisation of the heat supply in Ulaanbaatar starts with the deep retrofitting of the building stock

As discussed in section 2.1, energy efficiency measures are vital in the overall transition to a decarbonised heating sector. Not only could it save resources and cut emissions in the short-term, but it would also reduce the burden on required investments in renewable-based technologies. As a substantial part of the Ulaanbaatar population live in energy-inefficient ger tents, the expansion of standard housing should be a key priority to allow for a gradual migration from ger tents to standard housing. New buildings should be built according to highest available efficiency, including insulation and energy efficient appliances. Making sure new buildings are energy efficient will be a key priority as the population of Ulaanbaatar is expected to grow substantially in the medium to long term, and new buildings are expected to make up the majority of the building stock in the medium term. In the meantime, deep retrofit programs for existing buildings can reduce the heat demand and put less pressure on the currently limited heat generation capacity.

Further energy efficiency potential can be incentivised through the introduction of a consumption-based billing system

In terms of the district heating network (DHN), the revenues of the Ulaanbaatar operators are currently below cost-recovery levels, making investments in standard maintenance, upgrading and expansion financially unfeasible (Yun Wu et al., 2019). This has resulted in an inefficient and deteriorating district heating network, with the government having to indirectly subsidise district heating by providing economic support for general maintenance of the network. Ulaanbaatar district heating prices in 2014 were 10 to 20 times lower compared to prices in Eastern European cities, and estimates suggest that heat tariffs would require a 130% increase to reach cost-recovery levels (Yun Wu et al., 2019). Although prices are low from an international perspective, heating prices in Mongolia are relatively high compared to income levels and are therefore subsidised (Savickas, 2020). Large energy consumption subsidies that are not designed with elements to reduce consumption may, on the contrary, discourage energy efficiency, further increase energy consumption and, consequently, exacerbate the financial viability of the operation of the district heating network. A shift from the current flat-rate billing system to a consumption-based billing system is one design element that could address this counterproductive effect, incentivising energy efficiency while increasing revenues for operators.

In addition to the upgrading of the district heating network, the growing population, and ger-to-standard housing migration will demand an expansion of the district heating network to reach more customers. Due to the multitude of actors in the Ulaanbaatar district heating system, its upgrading and expansion will require the engagement of all actors involved to develop a common vision and co-ordinate investments and long-term planning towards a more efficient and sustainable system. The national government could take on a leading role in putting actors together and developing a long-term vision for the district heating network.

The scenario analysis shows that the savings in electricity consumption from selecting more efficient heating technologies are reflected in lower power supply and transmission expansion costs, which compensates the higher technology costs of SAGSHP systems to supply heat. The trade-off between heat and electricity supply costs is a principal element to consider when planning the pathway to decarbonise the energy supply in Ulaanbaatar. Such savings could also be utilised to improve the infrastructure challenges mentioned above.

4.2 Expand the renewable energy power capacity to improve access to electricity and untap system flexibility

Full decarbonisation of the Ulaanbaatar heat supply will require the expansion of the renewable energy power capacity

To ensure the full decarbonisation of the heat supply, the increased electricity demand resulting from the electrification of the heat supply will require an expansion of the renewable energy power capacity. That will involve the exploration of local as well as regional renewable resources, including wind and solar. The maximisation of local resources should be prioritised in order to minimise the costs associated with grid infrastructure development but may be restricted by factors such as land space requirements for solar thermal collectors. At the same time, the scenario analysis shows that the introduction of a hybrid heating technology which maximises the use of direct renewable heat could reduce the burden on the expansion of the power sector. To further identify optimal locations and cost estimates for the expansion of the renewable energy power capacity, additional modelling exercises are needed which include the analysis of the spatial dimension.

Reliable and affordable access to electricity is a precondition for the electrification of ger districts, requiring an improved and expanded electricity grid infrastructure

Although, in this study, we expect a significant migration of people living in ger dwellings to standard buildings, such transition will require time and some residents will remain in ger dwellings, even in the long term. The current practice of generating heat through direct coal burning is not only highly inefficient, but also generates vast amounts of GHG emissions and air pollution. At the same time, ger households do not benefit from government's subsidies to the district heating and end up spending several times more money on coal for heating compared to district heating consumers during the winter, increasing the social inequality gap (Yun Wu et al., 2019).

Switching to direct electric heating, a low capital intensive and easy-to-install technology, could bring health benefits and significant reduction in GHG emissions resulting from the generation of heat in ger dwellings. A prerequisite for doing so, however, is ensuring a reliable and sustainable supply of power. The severe cold climate in Ulaanbaatar means that, for a fully electricity-based heating system to work, reliable and uninterrupted access to electricity becomes a basic necessity. Ensuring reliable and affordable access to electricity is thus likely to become a key driver in terms of consumer's willingness to shift to direct electric heating. To this point, policy initiatives such as electric heating initiatives and night-time electricity subsidies have shown poor results as residents are reluctant to depend on an unreliable electricity system which is frequently interrupted by power outages and voltage drops, particularly during extremely cold conditions when heating is most needed (Carlisle and Pevzner, 2019). The improvement of the electricity access in the ger areas should therefore be prioritised. From the technology perspective, the deployment of direct electric heating could be initiated within the near term.

A system with high shares of variable renewable energy penetration requires untapping and exploiting all flexibility sources locked within the system

A reliable operation of a power system with significant amounts of variable renewable energy generation requires the exploitation of all flexibility sources available. Although the scenarios analysed show that this flexibility can be provided by battery storage, the scale and magnitude required to maintain a reliable system may make these scenarios not realistically implementable.

A realistic implementation of an energy system with very high shares of variable renewable energies must be complemented with other flexibility sources such as grid interconnections, active demand response and smart electrification of end-use sectors. As showed in the scenario analysis, strengthening the transmission grid in a way that allows for greater imports and exports of electricity can increase the flexibility of the system, facilitate the integration of renewables, and reduce the burden on storage to maintain a reliable operation of the system.

A higher import share in a decarbonised electricity system can be harnessed through the participation in a regional energy exchange. In this sense, the risks of a weakened energy security (e.g., dependency on energy imports) should be weighed against the costs of maintaining a reliable system operation.

In addition to reliability issues, system flexibility also has economic implications on the path to decarbonisation. Significant curtailments of renewable energy sources as a result of their limited integration into the system may affect their cost-effectiveness, which could be an obstacle to the full decarbonisation of the energy system from an economic point of view, despite its technical feasibility.

All flexibility sources should be assessed in detail and recognise the potential they have to contribute to the integration of renewables. Besides battery storage and grid interconnections, other flexibility sources include active response to the demand, seasonal storage such as hydrogen production and usage, and the smart integration of end-use sectors.

4.3 Integrate novel, renewable energy-based heating technologies

The current state of the Ulaanbaatar heating sector makes a unique opportunity to steer the sector into a new direction which would allow for long-term decarbonisation while also bringing important health benefits to the population

The old and limited CHP heat generation capacity of Ulaanbaatar is struggling to satisfy a growing demand driven by increased urbanisation. This has led up to a critical moment where the city's heat sector could take considerably different approaches. The development of new CHP plants would exacerbate existing issues linked to the mismatch of power supply and demand and lock-in coal dependence for several decades to come.

What is more, the long expected lifetime of a CHP plant would mean that an expanded capacity would lock the city into coal dependency for at least another 30 years (Kelly, McManus and Hammond, 2014).

That would not only have strong negative implications for the climate and achieving the Paris Agreement, but also for the health of the population. The continuation of a CHP-based heat and power system would continue to generate vast amounts of pollution, putting the health of the city population at risk. Not only would that mean increasing rates of premature deaths, but also an economic burden on the healthcare system. Economic and social costs should therefore also be part of the cost-benefit assessments of technological investments on the heating and power infrastructure.

The benefits of a renewable-based solution to supply heat go beyond trade-offs and cost savings, it also supports the gradual decoupling of the supply of heat and power to decarbonise the energy sector

The benefits of a decarbonised solution for heat supply that is less reliant on electricity go beyond the overall cost savings, especially in the context of Ulaanbaatar. Ulaanbaatar's current energy system relies almost entirely on coal-based CHP to generate heat and power, making heat and electricity supply strongly coupled. This means that electricity production largely responds to heat demand, not electricity demand, resulting in significant inflexibilities in the system which limit the ability to increase the penetration of renewables in the system and thus also the decarbonisation of both sectors. What is more, the CHP-based system has resulted in the country exporting power at very low or even negative prices and importing power at high prices depending on the scale and timing of the mismatch of the heat and power demand (Nilsson et al., 2021).

In that sense, the strong coupling of heat and power supply is a key structural challenge that would be observed in the transition process, not in the ultimate goal of achieving full decarbonisation. In other words, the challenge is not to run a system with low or no participation of CHP, the challenge is to gradually phase down CHPs while increasing renewables in a system that is highly coupled.

The gradual deployment of heating technologies that also use renewable energy directly for heating, such as SAGSHP, reduces the burden on the power supply while supplying heat, thus gradually decoupling the heat and power supply sectors. The steady decoupling of the sectors untaps flexibilities that were locked within the system, ultimately leading to an increased penetration of renewables and the decarbonisation of the energy supply. By reducing the electricity consumption and maxmising "free" heat from renewables, variable costs can be reduced. The cost effectiveness of these systems falls on the high capital expenditures and the risks associated with an innovative technology (technology and investment risks), which can be mitigated through international climate finance.

Small-scale pilots of low-carbon heating technologies could provide important knowledge needed for the development of a vision and strategy.

Prioritising the above-mentioned transformations including energy efficiency measures, heating infrastructure and the expansion of the power sector could allow for the introduction of novel, low-carbon heating technologies which would then in turn avoid the need for additional CHP and ensure the phase out of existing CHP in the long term. While the realisation of energy efficiency measures could significantly reduce the heat demand and thus avoid the acute need for heat capacity expansion, a window of opportunity to test novel systems at small-scale could be provided.

Small-scale piloting of renewable-based heating technologies could be a useful first step to gain more knowledge on the functionality of such systems, as well as for capacity building. Small-scale piloting should include a set of technologies suggested by the literature and, for instance, provided in this study. Such pilots should involve various actors from the public and private sectors, representing the full system of landowners, power and heat generation, transmission and distribution. The pilots would also present a good opportunity for capacity building and developing local expertise. That should involve the re- and upskilling of current employees in the heat sector in order to allow for a just transition. Further, pilot projects could provide a good target for international climate finance.

Based on the pilot results, different technology options can be evaluated and inform the development of a long-term strategy according to inputs and experience from all involved actors. Such vision could subsequently be transformed into a heating sector decarbonisation strategy where specific policies are developed to steer the transition.

The list of transformations provided in this section should not be seen as a step-by-step process, but rather as developments that should be carried out simultaneously. By doing so, progress in each transformation contributes to short-term benefits while enabling the first steps of change towards a long-term decarbonisation of the Ulaanbaatar heat sector.

5 Limitations and future research needs

In this study, we build on existing modelling results to investigate a potential pathway for the full decarbonisation of the Ulaanbaatar heat sector. As the results are not based upon a sophisticated optimisation modelling, they can only be understood as indicative values. To gain a better understanding of the potential of the suggested pathway, a number of factors should be considered in future research.

First, an optimisation modelling exercise taking into factors such as local, regional, and national power generation capacity, including the required development of transmission and distribution networks can provide an increased understanding of the cost implications. Ideally, such a modelling exercise should also consider the influence on the power sector from other sectors and their decarbonisation.

Second, more details on how a SAGSHP could perform in the Ulaanbaatar context could improve the accuracy of the estimated electricity demand for heating. By carrying out pilot studies of the technology in Ulaanbaatar, actual measurements of indicators such as the coefficient of performance (COP), solar fraction and thus also the required solar thermal collector area could be attained. Further, the required depth of the GSHP boreholes could be identified. Such data could enable a more detailed analysis of the costs of the system. In addition, potential cost reductions as a result of scaling should be further investigated.

Third, this analysis does not include cost estimates for the upgrading and expansion of the district heating network. Further research and data on the requirements additional to ongoing projects is necessary to estimate the financial needs for that.

Fourth, this analysis does not investigate alternative technologies for low-carbon industrial heat generation. Future studies could fill that gap through similar analysis directed at the industrial sector.

Lastly, although this study analyses a future in which the district heating network of Ulaanbaatar is fully run on SAGSHPs, that is an extreme scenario and might not be the most feasible option. Instead, this report is aimed to serve as an entry point and provides arguments for hybrid heating technologies to become part of the bigger picture.

Methodological annex

Calculation of electricity demand for heating

The electricity demand for heating is estimated for the year 2050 in order to evaluate the situation once full decarbonisation is achieved. It is calculated based on the efficiencies of each technology and thus estimates the electricity consumption of each scenario and technology portfolio required to deliver the same amount of heat. The calculations of technology efficiencies are based on annual values in terms of heat demand, average solar fraction, and heat pump coefficient of performance (COP). Data from previous studies in the Ulaanbaatar context are used as presented in Table 6.

Table 6. Input data for the calculation of electricity demand for heating.

Input parameter	Unit	Data	Source
Solar fraction	%	30%	(Shah, Aye and Rismanchi, 2020)
COP GSHP	-	3.6	(Shah, Aye and Rismanchi, 2020)
COP ASHP	-	2.6	(Stryi-Hipp et al., 2018)
Efficiency direct electric heater	%	92%	(Stryi-Hipp et al., 2018)

We apply a simple methodological approach with the aim to derive high-level estimates on electricity demand for heat supply (see Figure 26, Figure 27 and Figure 28). For the centralised heat demand, the electricity demand is derived depending on the portfolio of technologies and their respective efficiencies. For example, in the LEDS, electricity demand is derived by applying the estimated annual average solar fraction and the annual average heat pump COP. The electricity demand for decentralised buildings remains the same across all scenarios as the technology mix does not change. Electricity demand for heat supply in the industry sector is different only in the LCS as it also includes CHP as a technology option, contrary to the HEDS and LEDS.

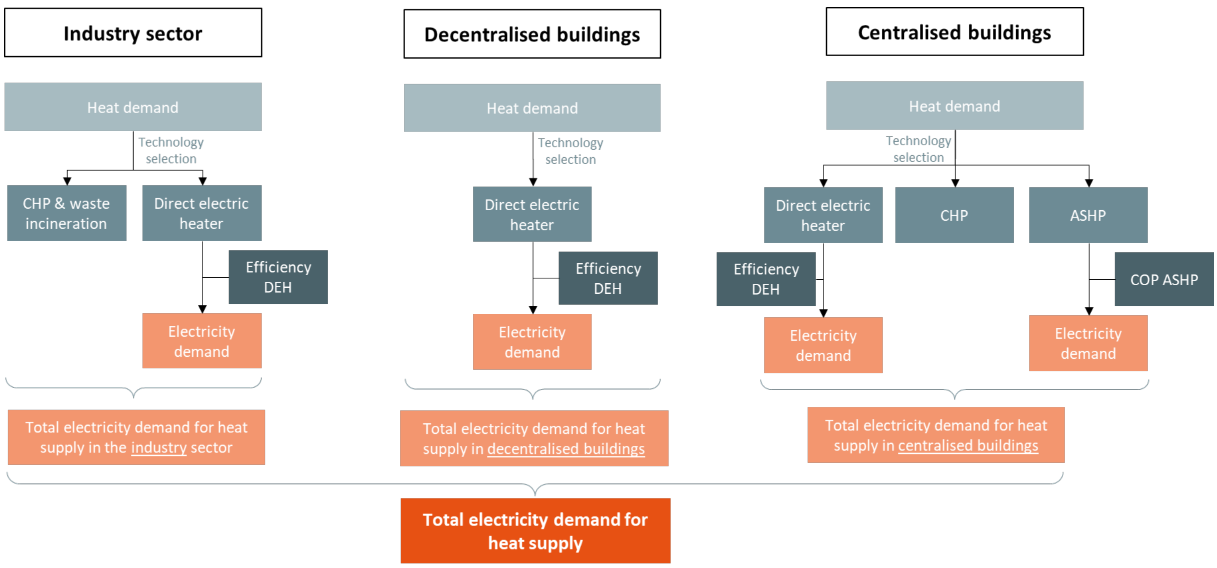

Figure 26. Methodological overview of the estimation of electricity demand for space heating for the LCS scenario.

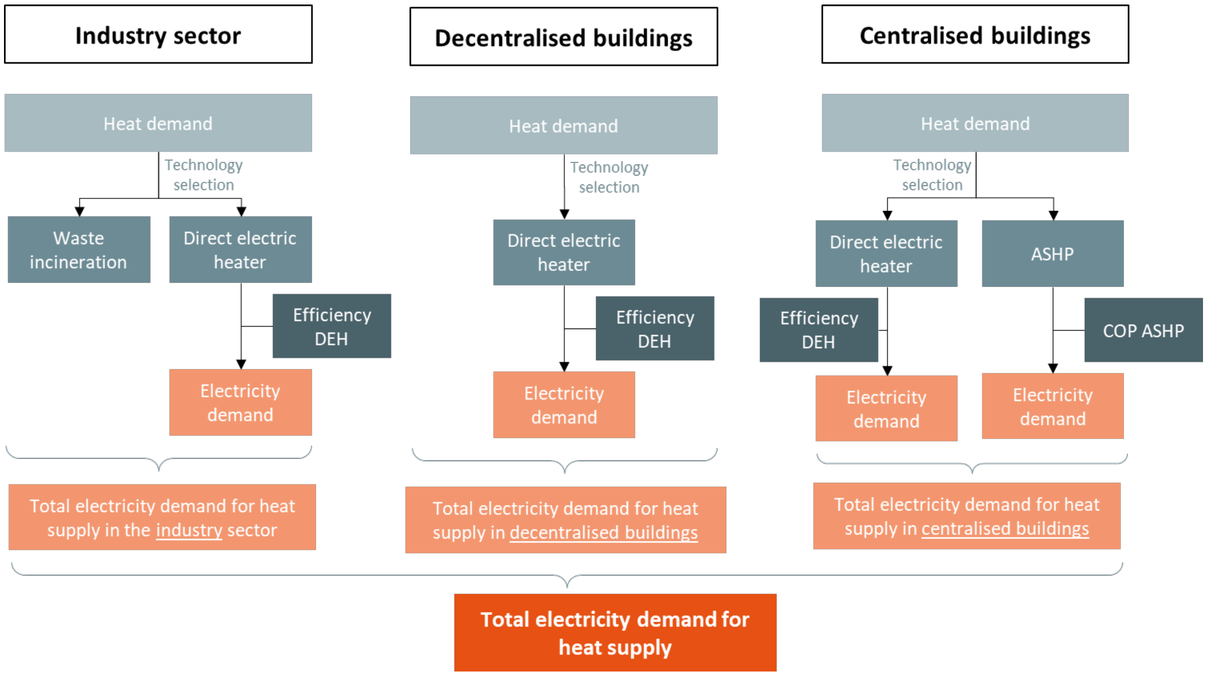

Figure 27. Methodological overview of the estimation of electricity demand for space heating for the HEDS scenario.

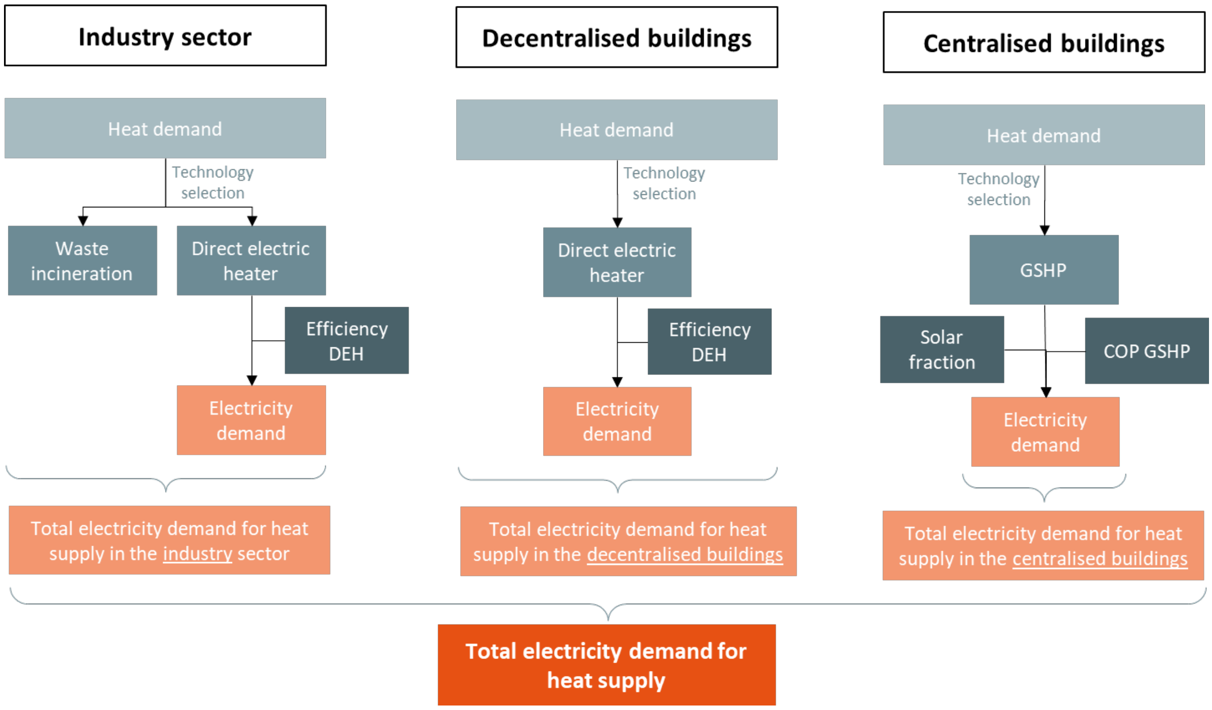

Figure 28. Methodological overview of the estimation of electricity demand for space heating for the LEDS scenario.

6 References

Asian Development Bank (2013) *Mongolia: Updating the Energy Sector Development Plan*. Available at: https://www.adb.org/sites/default/files/project-document/81826/43079-012-tacr-01k.pdf (Accessed: 3 June 2022).

Averfalk, H. and Werner, S. (2020) 'Economic benefits of fourth generation district heating', *Energy*, 193, p. 116727. doi: 10.1016/j.energy.2019.116727.

Bassam, N. El (2021) 'Chapter Seven - Solar energy: Technologies and options', *Distributed Renewable Energies for Off-Grid Communities (Second Edition), Elsevier*, 2, pp. 123–147. doi: https://doi.org/10.1016/B978-0-12-821605-7.00015-5.

Buck, M. *et al.* (2022) *Regaining Europe's Energy Sovereignty - 15 Priority Actions for RePowerEU*. Available at: https://static.agora-energiewende.de/fileadmin/Projekte/2021/2021_07_EU_GEXIT/253_Regaining-Europes-Energy-Sovereignty_WEB.pdf.

California Air Resources Board (2022) *High-GWP Refrigerants*. Available at: https://ww2.arb.ca.gov/es/resources/documents/high-gwp-refrigerants (Accessed: 25 April 2022).

Cao, C. *et al.* (2016) 'Research on PV/T - Air Source Heat Pump Integrated Heating System in Severe Cold Region', *Procedia Engineering*, 146, pp. 410–414. doi: 10.1016/j.proeng.2016.06.422.

Carlisle, S. and Pevzner, N. (2019) *Mongolian Energy Futures: Repowering Ulaanbaatar - Challenges of radical energy sector decarbonization*. Available at: https://iicec.sabanciuniv.edu/sites/iicec.sabanciuniv.edu/files/2020-11/Mongolian Energy Futures%2C Repowering Ulaanbaatar.pdf.

Carroll, P., Chesser, M. and Lyons, P. (2020) 'Air Source Heat Pumps field studies : A systematic literature review', *Renewable and Sustainable Energy Reviews*, 134(July), p. 110275. doi: 10.1016/j.rser.2020.110275.

Climate-Data (2021a) *Climate Harbin (China)*. Available at: https://en.climate-data.org/asia/china/heilongjiang/harbin-3488/ (Accessed: 22 December 2021).

Climate-Data (2021b) *Climate Ulaanbaatar (Mongolia)*. Available at: https://en.climate-data.org/asia/mongolia/ulaanbaatar/ulaanbaatar-490/ (Accessed: 22 December 2021).

Van D. Baxter, P. E., Groll, E. and Sikes, K. (2017) *Cold Climate Heat Pumps Improving low ambient temperature performance of air-source heat pumps*. Available at: https://info.ornl.gov/sites/publications/files/Pub46296.pdf.

Dincer, I. and Erdemir, D. (2021) 'Heat Storage Systems for Buildings. Chapter 3 - Energy Management in Buildings', *Elsevier*, pp. 91–113. doi: 10.1016/B978-0-12-823572-0.00004-7.

Emmi, G. *et al.* (2015) 'An analysis of solar assisted ground source heat pumps in cold climates', *Energy Conversion and Management*, 106, pp. 660–675. doi: 10.1016/j.enconman.2015.10.016.

Energy Regulatory Commission of Mongolia (2021) *STATISTICS ON ENERGY PERFORMANCE* . Available at: http://admin.erc.gov.mn/uploads/files/statisticseng.pdf (Accessed: 3 June 2022).

Energy Saving Trust (2021) *Air source heat pumps vs ground source heat pumps*. Available at: https://energysavingtrust.org.uk/air-source-heat-pumps-vs-ground-source-heat-pumps/#:~:text=The main difference between the,absorb heat from the ground. (Accessed: 27 May 2022).

Energy Transitions Commission (2019) *Mission Possible - Sectoral focus: Building heating*. Available at: https://www.energy-transitions.org/publications/mission-possible-sectoral-focus-building-heating/#download-form.

EPA (2021) *Geothermal Heating and Cooling Technologies*. Available at: https://www.epa.gov/rhc/geothermal-heating-and-cooling-technologies#Direct-Use-Geothermal (Accessed: 7 December 2021).

Epp, B. (2021) *“Reducing the level of harmful air pollutants is vital”*, *Solar Thermal World*. Available at: https://solarthermalworld.org/news/reducing-level-harmful-air-pollutants-vital/ (Accessed: 23 March 2022).

German Energy Solutions Initiative (2021) *Solar Thermal Energy*. Available at: https://www.german-energy-solutions.de/GES/Redaktion/EN/Text-Collections/EnergySolutions/EnergyGeneration/solar-thermal-energy.html (Accessed: 6 December 2021).

GIZ (2017) *Case Study: Thermo-Technical Rehabilitation (TTR) of Apartment Buildings, UB, Mongolia*. Available at: https://www.unescap.org/sites/default/files/CaseStudy_MN_Ulaanbaatar_ThermoTechRehabilitationApartmentBuildings_2017.pdf.

GSHPA (2021) *Domestic Ground Source Heat Pumps*. Available at: https://www.gshp.org.uk/ground_source_heat_pumps_Domestic.html#:~:text=For every unit of electricity,of its use of electricity. (Accessed: 27 May 2022).

Hirth, L. (2013) ‘The Market Value of Variable Renewables: The Effect of Solar and Wind Power Variability on their Relative Price The Market Value of Variable Renewables The Effect of Solar and Wind Power Variability on their Relative Price’, *Energy Economics*. doi: 10.1016/j.eneco.2013.02.004.

Ho, J. *et al.* (2021) *Regional Energy Deployment System (ReEDS) Model Documentation: Version 2020*. Available at: https://www.nrel.gov/docs/fy21osti/78195.pdf (Accessed: 3 June 2022).

Huang, J., Fan, J. and Furbo, S. (2020) ‘Demonstration and optimization of a solar district heating system with ground source heat pumps’, *Solar Energy*, 202(March), pp. 171–189. doi: 10.1016/j.solener.2020.03.097.

IRENA (2016) *Renewables Readiness Assessment: Mongolia*. Available at: http://www.irena.org/-/media/Files/IRENA/Agency/Publication/2016/IRENA_RRA_Mongolia_2016.pdf (Accessed: 7 August 2018).

IRENA (2020) *Integrating low-temp renewable sources into existing district energy networks & buildings*, *Webinar*. Available at: https://www.youtube.com/watch?v=G-dPdGGolh8 (Accessed: 23 December 2021).

Jing, Y. *et al.* (2015) ‘The Application of Solar Indirect System in Passive House in Cold Region and Severe Cold Region of China’, *Energy Procedia*, 70, pp. 699–703. doi: 10.1016/j.egypro.2015.02.178.

Kegel, M. *et al.* (2016) ‘Energy End-use and Grid Interaction Analysis of Solar Assisted Ground Source Heat Pumps in Northern Canada’, *Energy Procedia*, 91, pp. 467–476. doi: 10.1016/j.egypro.2016.06.180.

Kelly, K. A., McManus, M. C. and Hammond, G. P. (2014) ‘An energy and carbon life cycle assessment of industrial CHP (combined heat and power) in the context of a low carbon UK’, *Energy*, 77(1 December 2014), pp. 812–821. doi: 10.1016/j.energy.2014.09.051.

Lei, Y., Tan, H. and Li, Y. (2018) ‘Technical-economic evaluation of ground source heat pump for office buildings in China’, *Energy Procedia*, 152, pp. 1069–1078. doi: 10.1016/j.egypro.2018.09.123.

Lhendup, T., Aye, L. and Fuller, R. (2014) *Performance analysis of ground-coupled heat pump integrated with unglazed solar collector.* In: Proceedings of the 52nd annual conference, australian solar energy society (Australian Solar Council) Melbourne, Australia.

Liu, H., Jiang, Y. and Yao, Y. (2014) ‘The field test and optimization of a solar assisted heat pump system for space heating in extremely cold area’, *Sustainable Cities and Society*, 13, pp. 97–104. doi: https://doi.org/10.1016/j.scs.2014.05.002.

Liu, Z. *et al.* (2015) ‘Investigation on the feasibility and performance of ground source heat pump (GSHP) in three cities in cold climate zone, China’, *Renewable Energy*, 84, pp. 89–96. doi: 10.1016/j.renene.2015.06.019.

Lund, H. *et al.* (2014) ‘4th Generation District Heating (4GDH). Integrating smart thermal grids into future sustainable energy systems.’, *Energy*, 68, pp. 1–11. doi: 10.1016/j.energy.2014.02.089.

Maruf, N. I. *et al.* (2021) 'Classification, Potential Role, and Modeling of Power-to-Heat and Thermal Energy Storage in Energy Systems', *Elsevier*, pp. 1–27. Available at: https://arxiv.org/ftp/arxiv/papers/2107/2107.03960.pdf.

Ministry of Environment and Tourism *et al.* (2018) *Third National Communication of Mongolia*. Available at: https://unfccc.int/sites/default/files/resource/06593841_Mongolia-NC3-2-Mongolia TNC 2018 pr.pdf.

Mussard, M. (2017) 'Solar energy under cold climatic conditions: A review', *Renewable and Sustainable Energy Reviews*, 74(December 2016), pp. 733–745. doi: 10.1016/j.rser.2017.03.009.

Nascimento, L. *et al.* (2020) *Renewable heating virtual Article 6 pilot. Ground source heat pumps in Khovd, Mongolia*. NewClimate Institute. Available at: https://newclimate.org/2020/01/29/renewable-heating-virtual-article-6-pilot-ground-source-heat-pumps-in-khovd-mongolia/.

Nilsson, A. *et al.* (2021) *Green Hydrogen Applications in Mongolia - Technology potential and policy options*. Cologne and Berlin. Available at: https://newclimate.org/2021/09/24/green-hydrogen-applications-in-mongolia/.

Pfenninger, S. and Staffell, I. (2019) *Renewables Ninja*. Available at: https://www.renewables.ninja/.

Pillarisetti, A. *et al.* (2019) 'Advanced household heat pumps for air pollution control: A pilot field study in Ulaanbaatar, the coldest capital city in the world', *Environmental Research*. doi: 10.1016/j.envres.2019.03.019.

Rad, F. M., Fung, A. S. and Leong, W. H. (2013) 'Feasibility of combined solar thermal and ground source heat pump systems in cold climate, Canada', *Energy and Buildings*, 61, pp. 224–232. doi: 10.1016/j.enbuild.2013.02.036.

Reda, F. (2017) *Solar Assisted Ground Source Heat Pump Solutions Effective Energy Flows Climate Management*, *Scientia medica italica. English ed*. doi: 10.1016/s0002-9610(35)90953-9.

Savickas, R. (2020) *Energy Efficiency in Developing Countries*. 1st Editio. London and New York: Routledge Taylor & Francis Group. Available at: https://www.taylorfrancis.com/chapters/edit/10.4324/9780429344541-20/integration-low-carbon-technologies-district-heating-systems-developing-countries-cold-climatic-zones-romanas-savickas.

Shah, S. K., Aye, L. and Rismanchi, B. (2020) 'Multi-objective optimisation of a seasonal solar thermal energy storage system for space heating in cold climate', *Applied Energy*, 268(December 2019), p. 115047. doi: 10.1016/j.apenergy.2020.115047.

Stryi-Hipp, G. *et al.* (2018) *Energy Master Plan for Ulaanbaatar*. Freiburg. Available at: https://www.researchgate.net/publication/357636013_Energy_Master_Plan_for_Ulaanbaatar_Mongolia_Final_Report_Energy_Master_Plan_for_Ulaanbaatar_Mongolia_Final_Report.

Unurzul, M. (2022) 'Parliament adopts Bill to ratify Amendment to the Montreal Protocol', *Montsame*, 19 January. Available at: https://montsame.mn/en/read/287367#.

De Vivero-Serrano, G. *et al.* (2019) 'Transition towards a decarbonised electricity sector - a framework of analysis for power system transformation'. Available at: https://newclimate.org/wp-content/uploads/2019/10/Report_Transition_Towards_A_Decarbonised_Electricity_Sector_A2A_2019.pdf.

Wang, X. *et al.* (2010) 'Experimental study of a solar-assisted ground-coupled heat pump system with solar seasonal thermal storage in severe cold areas', *Energy and Buildings*, 42(11), pp. 2104–2110. doi: 10.1016/j.enbuild.2010.06.022.

Wang, Z. *et al.* (2021) 'State of the art on heat pumps for residential buildings', *Buildings*, 11(8). doi: 10.3390/buildings11080350.

WBG (2020) *Project Information Document (PID)*. Available at: http://www-wds.worldbank.org/external/default/WDSContentServer/WDSP/IB/2011/03/25/000001843_20110329141118/Rendered/PDF/P1217550PID0ap1or0InfoShop0March25.pdf.

Xu, L. *et al.* (2021) 'Hybrid ground source heat pump system for overcoming soil thermal imbalance : A review', *Sustainable Energy Technologies and Assessments*, 44(November 2020), p. 101098. doi: 10.1016/j.seta.2021.101098.

Yeung, K.-W. D. (1996) *Enhancement to a Ground Loop Heat Exchanger Design*, *Angewandte Chemie International Edition, 6(11), 951–952.* University of Washington.

Yun Wu *et al.* (2019) 'Paving The Way to a Sustainable Heating Sector: A Roadmap for Ulaanbaatar Urban Heating', *World Bank Group*. Available at: http://documents.worldbank.org/curated/en/361331554753311754/Paving-the-Way-to-a-Sustainable-Heating-Sector-A-Roadmap-for-Ulaanbaatar-Urban-Heating.

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