UTRECHT UNIVERSITY

Assessing the performance of 5th Generation District Heating and Cooling Systems in European Energy Contexts

MASTER THESIS

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Abstract

Due to the emerging awareness of climate change and its accompanying consequences, there is an increasing need for carbon-neutral energy systems. Fifth-generation district heating and cooling system (5gDHC) is a new carbon-free technology, with high potential. However, it is still in its development phase and there is no consensus among scholars about the exact definition and performance of 5gDHC. So, in order to benefit the most from this new potential energy system, more research is needed on its performance, to see whether it can replace alternative solutions.

This study conducts three assessments, of which all determine one or more performances of 5gDHC. First, the technical performance of four case studies is evaluated with developed key performance indicators (KPIs). Secondly, the environmental and economic performance is determined with a cost-benefit analysis (CBA) and compared with a 4gDHC and a domestic gas boiler (DGB) alternative. Lastly, the social impact is assessed with a multi-criteria analysis (MCA).

The results of the KPI analysis show that the case studies score relatively well on developed KPIs. One of the main focus points is now the use of renewable thermal energy, rather than renewable electrical energy. However, future research is needed to test the KPIs on multiple other energy systems.

Secondly, the CBA shows that the environmental costs of 5gDHC are substantially lower than alternative solutions. However, the levelized cost of energy (LCOE) of 5gDHC is much higher than the alternatives, due to a very high CAPEX. If the environmental costs and the LCOE are combined, the 5gDHC costs come closer to the alternatives but are still higher.

Lastly, the MCA shows that the social impact of a 5gDHC is significantly lower than the alternative solutions. However, future quantitative research on this impact could help give a more complete answer.

To conclude, the 5gDHC shows some real potential for the (near) future. Compared with alternatives it scores well on the environmental and social impact. However, from an economic point of view, the 5gDHC is currently substantially more expensive than alternatives. This makes the technology probably, without subsidies or funding, not an economically viable solution. However, 5gDHC is a new technology and costs potentially can decrease tremendously with the learning and experience curve. Furthermore, considering the rapid demand for renewable solutions for heating and cooling systems, because of climate change and the rising gas prices, 5gDHC has a large potential for being one of those solutions.

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4gDHC	Fourth Generation District Heating and Cooling
5gDHC	Fifth Generation District Heating and Cooling
ATES	Aquifer Thermal Energy Storage
CAPEX	Capital Expenditures
CBA	Cost-Benefit Analysis
CHP	Combined Heat and Power
DDF	Demand-Drivenness Factor
dB	Decibel
DGB	Domestic Gas Boiler
DH	District heating
DHC	District Heating and Cooling
DHW	Domestic Hot Water
GHG	Greenhouse Gasses
HP	Heat pump
KPI	Key Performance Indicator
LCOE	Levelized Cost of Energy
MCA	Multi-Criteria Analysis
OPEX	Operational expenditures
PV	Photovoltaic
UHI	Urban Heat Island

1 Introduction

Climate change is one of the major challenges that raised awareness in the last decades, but especially in the following ones, the world will face its impact. The last IPCC report states that the influence of humans on global warming is unequivocal and 1.5°C warming of the earth is unavoidable due to the emission of greenhouse gasses (GHGs) in the past 100 years (IPCC, 2021). A 40-50% reduction of 2010’s emissions level is needed to make sure we do not exceed the 1.5°C global warming temperature. In order to combat climate change, 190 countries, including the EU and its member states, signed the Paris agreement in 2015, which is an international treaty and has the goal to limit global warming up to 2°C (European Commission, N.D.).

Energy use in the built environment is responsible for approximately 36% of the GHG emission and 40% of energy demand in Europe (European Commission, 2021; Buffa, Cozzini, D'Antoni, Baratieri, & Fedrizzi, 2019). Around 70% of this energy usage is for heating and cooling (Rousselot & Pinto Da Rocha, 2021).

In the following decades, energy consumption for heating will most likely decrease due to more efficient heating technologies and better building insulation (IEA, 2020). This improved insulation in combination with other phenomena, for example, global warming and the urban heat island (UHI) effect, can also lead to the overheating of buildings (Dengel & Swainson, 2012). Especially, for sun-oriented small apartments, this can be a problem, and a potential danger for older people, who are more vulnerable in warmer conditions (RVO, 2018). Because of these threats, increasing temperatures in the summer, and cooling systems becoming more affordable for more people, space cooling is a growing trend (IEA, 2020). The Dutch Top sector Knowledge and Innovation (TKI) Urban energy, has calculated that in 2030, the cooling demand will increase by 34% relative to 2020 levels (TKI Urban Energy, N.D.).

In the Netherlands, 92% of the households use gas for heating (CBS, 2021). However, to achieve the Paris climate goals, the Dutch government set national targets to get rid of natural gas in heating systems in the built environment before 2050 (Government of the Netherlands, 2019). For 2030, the aim is to accomplish this in 1.5 million houses and reduce CO_2 emissions by 3.4 Mton. This means that, on average, 200.000 residents need to become gas-free every year. To meet these targets, new suitable gas-free alternatives are necessary.

A promising natural gas-free thermal energy solution to reduce GHG emissions is the district heating and cooling system (DHC) (Lund, et al., 2014; Lake, Rezaie, & Beyerlein, 2017; Werner, 2017; Buffa, Cozzini, D'Antoni, Baratieri, & Fedrizzi, 2019). DHC systems are a shared energy system, that consists of a network of pipes. Through these pipes, it delivers heating and cooling to customers from one or more energy sources (Lund, et al., 2014). DHCs are currently in their 4th generation, with their main principles to use renewable sources and medium temperature district heating (70^o), to combat climate change and reduce energy losses (Lund, et al., 2014).

As the Paris agreement is already 5 years ago and the energy transition, including the heat transition, is still far away from the net-zero emission scenarios for 2050, pressure on the energy systems is still increasing (IEA, 2021). So, to keep up with the energy transition goals, new initiatives and technologies need to be tested and deployed.

Nowadays, 5th generation DHCs (5gDHCs) are being developed by several companies and institutes and are also already operating in different (pilot) projects around Europe (Buffa, Cozzini, D'Antoni, Baratieri, & Fedrizzi, 2019; Boesten, Ivens, Dekker, & Eijdems, 2019). The main intent of this new generation is to become more efficient and sustainable. Compared to previous generations, 5gDHC has several different characteristics.

Firstly, it operates at a close to the ground temperature, in order to reduce energy losses and having the ability to recover low-temperature sources (Buffa, Cozzini, D'Antoni, Baratieri, & Fedrizzi, 2019). Secondly, it uses a 2-pipe bi-directional network. If heat is demanded it withdraws water from the warm-water pipes and releases it back to the cold-water pipes, and vice versa (Bünning, Wetter, Fuchs, & Müller, 2018). Thirdly, the energy supply is circularly decentralized with prosumers, instead of linear centralized with separate producers and consumers (Boesten, Ivens, Dekker, & Eijdems, 2019; von Rhein, Henze, Long, & Fu, 2019). Lastly, the exergy flows are demand-driven, so energy is only delivered at the location of the demand (Allen, Henze, Baker, & Pavlak, 2020). This differs from conventional networks that need to operate on the temperature of the highest demander in its entirety. However, some critics say 5gDHC is rather a complementary technology than a new generation (Lund, et al., 2021).

Already some research has been done on the performance of 5gDHC. Regarding the technical performance, several studies have determined the potential of different energy sources, such as geothermal (Meibodi & Loveridge, 2022; Zeh, et al., 2021), solar thermal (Calise, Cappiello, d'Accadia, Petrakopoulou, & Vicidomini, 2022; Quirosa, Torres, & Chacartegui, 2022). Also storage (Boesten, Ivens, Dekker, & Eijdems, 2019) an high-level control and monitor systems (Wirtz, Kivilip, Remmen, & Müller, 2020; Bilardo, Sandrone, Zanzottera, & Fabrizio, 2021; Taylor, Long, Marjanovic, & Parisio, 2021; Wirtz, Neumaier, Remmen, & Müller, 2021) are important features of 5gDHC which are discussed in the literature.

On the environmental performance, mostly CO_2 reduction assessments have been done. For example, for a 5gDHC with groundwater (Schibuola & Tambani, 2022), using CO_2 as a refrigerant (Nagano, Kajita, Yoshida, & Amano, 2021), or a retrofitted DHC (Gillich, Godefroy, Ford, Hewitt, & L'Hostis, 2022).

In previous literature, 5gDHC does not perform well on the economical aspect. Most of the critics emphasize that 5gDHC is a too expensive solution compared to for example previous generations (Foster, Love, Walker, & Crane, 2016; Buffa, Cozzini, D'Antoni, Baratieri, & Fedrizzi, 2019; Gudmundsson, Schmidt, Dyrelund, & Thorsen, 2022)

On the social impact, not much research has been done yet. However, a study by Schibuola & Tambani (2022) showed a positive effect of 5gDHC on the UHI effect.

1.1 Research problems

As there is a need for new carbon-free energy systems, the performance of 5gDHC should be assessed in order to see whether this is a viable and profitable solution, to replace conventional heating systems. Although, several scholars have researched the performance of 5gDHC. There are still some untouched parts in this field of literature.

Firstly, on the technical aspect, no performance indicators used are assessing and compare different systems on how they perform on the new 5gDHC characteristics. Boesten et al. (2019) propose that future research should focus on integrating these characteristics into existing energy models. With a top-down 5gDHC indicator analysis, a broader view can be given of the performance of DHCs on being 5gDHC and how they differentiate from previous generations.

Secondly, by looking at this bigger picture, it is also important to determine the impact and potential of 5gDHCs, in different contexts. As discussed before, only a limited amount of research has been done on the environmental, economic and social impact of 5gDHC. That is why, bottom-up analyses, such as a cost-benefit analysis (CBA) and a multi-criteria analysis (MCA) could contribute to this field of research, by comparing 5gDHC to alternatives with these analyses. These assessments combined should give a clear overview of the current performance of 5gDHCs.

1.2 Research questions

Based on the research problems previously discussed, this study will therefore aim to answer the question:

What are the technical, environmental, economic and social performances of 5gDHC systems in different energy system contexts?

In order to answer this question, the following sub-questions will be answered:

- Sub-question 1: *What are the technical performances of existing DHCs based on 5gDHC performance indicators?*
- Sub-question 2: *What are the environmental and economic performances of a 5gDHC in comparison with existing energy systems?*
- Sub-question 3: *What is the social impact of a 5gDHC in comparison with existing energy systems?*

Scope

As different climates have different heat and cooling demands, the performance of a DHC is highly dependent on its geographic location. This study focuses on central Europe, with a relatively mild climate. Furthermore, the year assessed is 2021, which is important for the year specific heating and cooling demand, but also the inflation taken into account during the economic assessment.

2 Theoretical background

2.1 District Heating and Cooling

District heating and cooling (DHC) is a solution to reduce GHGs and dependency on fossil fuels for heating and cooling the built environment (Boesten, Ivens, Dekker, & Eijdems, 2019). Lund et al. (2014) describe a district heating system as: “District heating comprises a network of pipes connecting the buildings in a neighbourhood, town centre or an entire city, so that they can be served from centralised plants or a number of distributed heat producing units” (p. 1).

DHCs have energy producers (energy suppliers) and consumers (energy demanders) (Boesten, Ivens, Dekker, & Eijdems, 2019). Producers are mainly centralized heat or cooling sources, e.g. combined heat and power plants (CHPs), gas boilers, aquifer thermal energy storage (ATES) systems, or solar thermal sources. The consumers consist mostly of dwellings, but also commercial buildings, data centers, and offices. The energy flow is linear, which means it is going in one pipe from the supplier to the customer and goes back to the producer via another pipe to be heated up or cooled down again. District heating has gone through several developments, which are described as generations. The characteristics of these generations are shown in Figure 1.

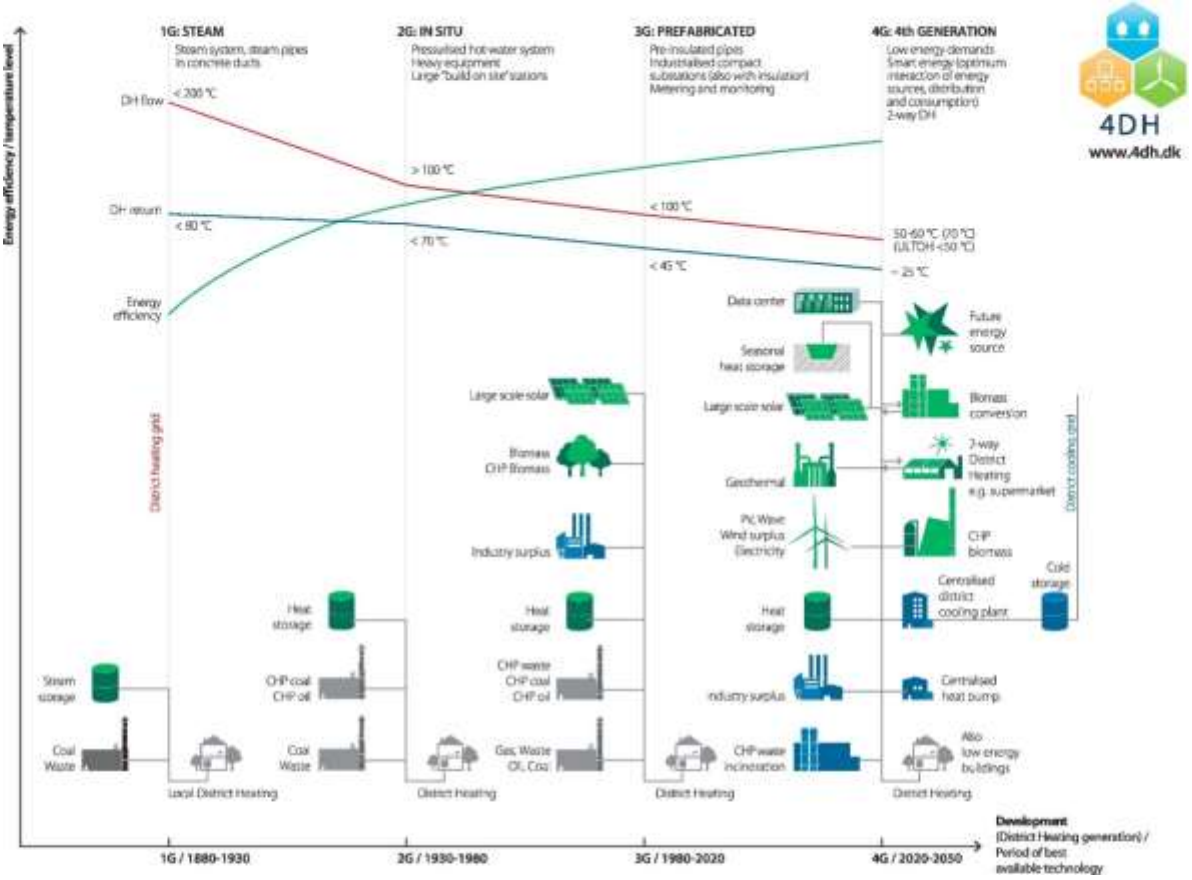

Figure 1. The generations of DHCs with the corresponding flow temperatures and energy efficiency (Lund, et al., 2018).

Previous generations

The development of the generations was predominantly characterized by the decline of the network temperature and the increase in energy efficiency. Regarding the heat sources, a shift towards more different types as well as more renewable sources addressed can be seen over the years.

District heating (DH) was used for the first time around 1880 (Lund, et al., 2014; Werner, 2017). 1st generation DH used coal as fuel and were built around centralized heat producers. The heat carrier was steam that reached up to more than 200ºC and was transported in concreted pipes. The consumers were mostly large heat users such as small urban industries, hospitals, or large residential centers. Although this concept dates from the late 1800s, these working principles are still used in the heating networks in New York City and Paris (Lund, et al., 2014; Werner, 2017).

From 1930, the second generation district heating is developed with a shift from steam to pressured hot water as heat carrier (Lund, et al., 2014; Werner, 2017). The temperature of the system is still above 100ºC. However, because of the lower temperatures and the usage of water instead of steam, the transition from the first to the second generation caused mainly an increase in operational safety and efficiency. The heating in this generation is in addition fueled by oil, and waste heat from power plants, which was the emergence of the CHP. This usage of CHP resulted in the reduction of primary energy and consequently the reduction of GHGs (Lund, et al., 2014; Werner, 2017).

The third generation was introduced around 1970. The major change was the shift to temperatures below 100ºC. The pipes in this generation were prefabricated and pre-insulated. This temperature decrease and new materials resulted in a large efficiency increase. In a few cases already geothermal and solar sources were used. Because of the prefabricated part of the system, the investment, as well as the operational costs, made dropped significantly.

In the fourth generation, the main focus shifted to the use of renewable energy (Lund, et al., 2014; Werner, 2017). In addition, temperatures were also lowered to medium temperature grids of around 70ºC, which simultaneously increased the efficiency. In the fourth generation, also district cooling was introduced making the system a DHC, instead of a DH. This cooling is mostly retrieved from geothermal, surface water and sewage water (Boesten, Ivens, Dekker, & Eijdems, 2019). However, the pipes used by the 4th generation system are not suitable for both heating and cooling, because of the temperature difference (Buffa, Cozzini, D'Antoni, Baratieri, & Fedrizzi, 2019). So, two different grids with both a supply and return pipe need to be deployed.

2.2 5th generation District Heating and Cooling

In line with the previous developments, several scholars, companies and institutes are recently developing a new continuation generation, in order to make DHCs more efficient and sustainable. Boesten et al. (2019, p. 134) present a definition for this new 5th generation DHC (5gDHC): “5GDHC is a decentralized, bi-directional, close to ground temperature district heating and cooling concept that is based on the principle of closing energy loops as much as possible and using renewable sources to bridge the gap between supply and demand.” This definition touches upon several different aspects between this new generation and its predecessors.

Firstly, the temperature of the system should be close to the ground temperature (Boesten, Ivens, Dekker, & Eijdems, 2019). These low temperatures will reduce energy losses during the energy transport (Buffa, Cozzini, D'Antoni, Baratieri, & Fedrizzi, 2019). Moreover, because 5gDHC operates at these low temperatures, it is able to utilize heat from additional sources, which are too low for conventional DHCs (e.g. waste heat from supermarket refrigeration, metro shafts, etc.).

Secondly, because of these low operating temperatures, 5gDHCs are able to convert the conventional 4-pipe system into a 2-pipe bi-directional system: one warm loop and one cold loop (Bünning, Wetter, Fuchs, & Müller, 2018). In this system, if heat is demanded it withdraws water from the warm-water pipes and releases, the cooled water, back into the cold-water pipes, and vice versa (Figure 2). As a result, the heat demand from one building can solve the cold demand from the other.

Additionally, besides a bi-directional pipe system, the energy supply is also decentralized. Every consumer delivers its waste heat or cooling directly back to the grid. That is why in 5gDHC the consumers are simultaneously producers, which makes them prosumers (Figure 2) (Boesten, Ivens, Dekker, & Eijdems, 2019). This decentralized energy production differs from the previous generations’ centralized linear energy supply.

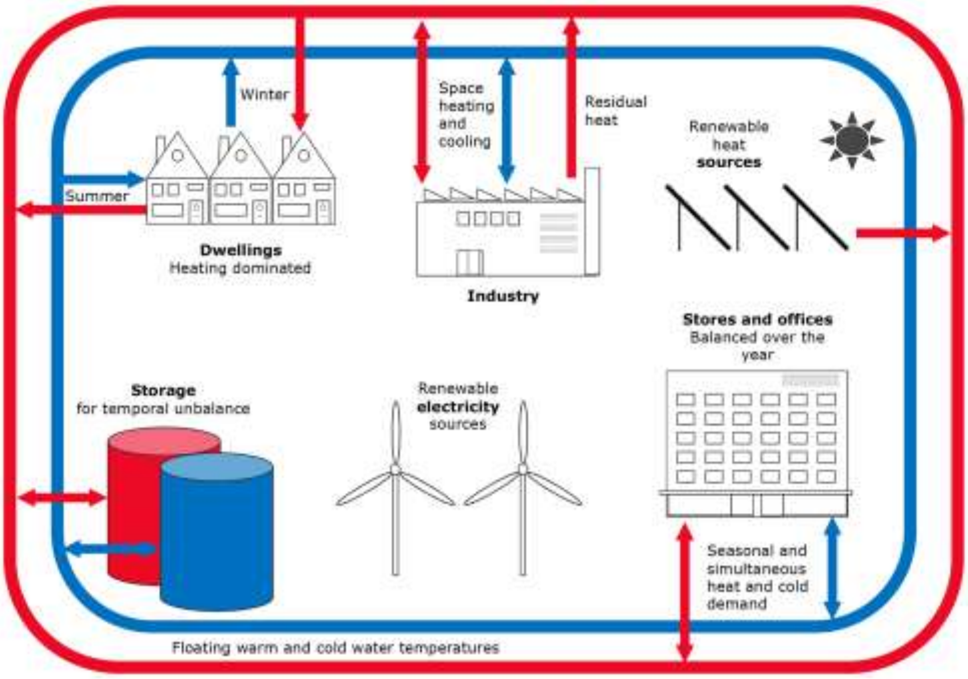

Figure 2. Schematic overview of a 2-pipe bi-directional 5gDHC (Boesten, Ivens, Dekker, & Eijdems, 2019).

Decentralized systems are most efficient with a different grid topology than centralized systems. In Figure 3, different topologies of a DHC grid are shown. The Radial grid is a conventional type of grid, where one energy producer delivers its heat linear. The ring grid allows the consumers to also provide back to the grid, so the energy can be used somewhere further down the loop (von Rhein, Henze, Long, & Fu, 2019). The Meshed grid can provide an even better exchange between de prosumers as there are more connection possibilities between them. The Ring and meshed grid are used for 5gDHC.

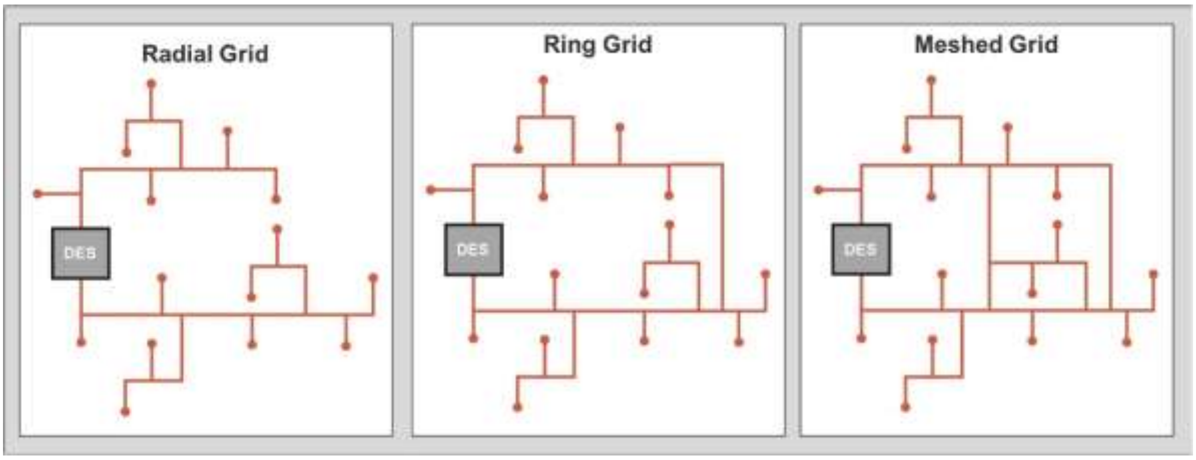

Figure 3. Different possible topologies of DHC grids (DES = District energy system) (von Rhein, Henze, Long, & Fu, 2019)

Lastly, with those decentralized grids, 5gDHCs have demand-driven exergy flows. This means that they try to bring only demanded temperature to the places that demand the energy at that time

(Allen, Henze, Baker, & Pavlak, 2020). If, for example, a building needs 40ºC, it is not efficient that the whole network needs to be upgraded to 40ºC. This energy on demand can be complex, so smart monitoring and algorithms need to optimize the system in such a way that it can minimize these exergy transportations. Due to this, a large part of the system can be operating at a low, ambient temperature, so it does not need expensive insulated pipes. In some literature, 5gDHC is also called ambient temperature DHC (Gudmundsson, Schmidt, Dyrelund, & Thorsen, 2022). This differs from previous generations, where the system needed to operate at the temperature of the highest demanding customer (Lindhe, Javed, Johansson, & Bagge, 2022).

5gDHC principles

Although 5gDHCs is not a broadly used term and already widely deployed. Multiple companies and institutes are developing and deploying (pilot) projects around Europe (Buffa, Cozzini, D'Antoni, Baratieri, & Fedrizzi, 2019). One of these projects is the Interreg North-West European project D2Grids. D2Grids has established five principles which try to embody a 5gDHC, in order to make it a definite and indisputable term (D2Grids, N.D.). The 5 principles are:

1. Closing the energy loop
2. Using low-grade for low-grade demand
3. Decentralized & demand-driven energy supply
4. An integrated approach of energy flows
5. Local sources as a priority

The first principle of a 5gDHC is defined to close the thermal energy loop within the energy system. The energy system should be completely self-sufficient and does not need energy from external sources. It is about the overall performance of the energy system. One of the challenges here is that this should be all year round, therefore energy storage plays an important factor. Another aspect of this principle, already previous mentioned, is the energy exchange between the end-users. So instead of conventional consumers, they are now prosumers.

The second principle is about the quality of the energy sources. 5gDHC should have a temperature close to the soil temperature, which is also mentioned in the definition of Boesten et al. (2019). This means a relatively low warm temperature for heating and a relatively high cool temperature for cooling. This results in low-exergy systems. In this principle, this is referred to as low-graded energy. The meaning of the principle is not that high-graded energy is bad to use. However, in the case of heating and cooling buildings, it is not necessary, because the energy demand is low-graded. High-graded energy sources can be used for high-graded energy demand of, for example, industries.

The third principle is about the decentralization and demand-driven aspect of the system. These concepts are already discussed the previous chapter. Improving on this principle can be done by decentralizing the energy centers or installing heat pumps (HPs) at all the end-users buildings. Demand-driven and decentralized are both indirect indicators of efficiency.

The fourth principle is about the integration of different energy flows (e.g. industries, power grids, hydrogen conversions, solar plants, etc.) to the DHC, to avoid energy waste across sectors. This integration is also important to lower the needed power capacity of a system because it can manage peak loads better; peak shaving. With this principle, 5gDHC tries to maximize the efficiency of energy delivery and usage.

The last principle is about the local aspect of the energy system. If a system is more locally-oriented energy losses during transport are avoided. Furthermore, investments that would normally be outside the region (e.g. fuels), are not needed anymore. This means that the money stays within the region and stimulates the local economy. This can also lead to more local job opportunities.

2.3 Previous literature

Already some scholars have studied the performance or possibilities of 5gDHC. In this section, an overview will be given. First of all, the technical performance will be discussed, followed by the environmental performance. Additionally, the economic and social impact will be reviewed.

Technical performance of 5th generation DHC

On the technical part of 5gDHC, one of the characteristics is the energy exchange between the prosumers. For this self-exchange, there must be approximately the same heating and cooling demand. To overcome this challenge, the inclusion of different types of buildings will enhance this energy exchange, as different types of buildings have different demand schemes (Calise, Cappiello, d'Accadia, Petrakopoulou, & Vicidomini, 2022). Due to this, a larger variety of different buildings, allows 5gDHCs to be less depending on conventional energy suppliers. This can make 5gDHC more applicable in areas that don’t have large heating and cooling sources.

These sources are another important aspect of 5gDHCs. Geothermal energy is one of the sources with a large potential for 5gDHCs. Meibodi & Loveridge (2022) have written about the future role of geostructures in 5gDHC. Geothermal sources are maybe the most important energy sources for 5gDHC. It allows the system to be CO_2 neutral, flexible and resilient. Implementing large scale geothermal collectors can also enable a DHC to shift seasonal heating and cooling loads, as it also can function as (seasonal) storage (Zeh, et al., 2021).

Besides geothermal, also solar energy is an important potential technology for 5gDHCs. Because most of the 5gDHC systems only need electricity as fuel to operate, photovoltaic (PV) energy could offer 5gDHC the possibility to be more sustainable and less dependent on the electrical grid (Calise, Cappiello, d'Accadia, Petrakopoulou, & Vicidomini, 2022). A challenge for this is the possibility to store electricity, which is currently not commercially available on this scale. Studies show now that the implementation of PV can reduce the electricity consumption from the grid by 30% (Calise, Cappiello, d'Accadia, Petrakopoulou, & Vicidomini, 2022; Quirosa, Torres, & Chacartegui, 2022). Solar thermal energy in combination with heat storage can also overcome the problem of different seasonal demands (Boesten, Ivens, Dekker, & Eijdems, 2019).

This problem is also briefly mentioned in the previous chapter. It can be described as the mismatch in energy availability and demand between the seasons. In the summer, the system mainly needs to cool, so have a surplus of heat and in the winter vice versa. That is why thermal storage needs to be integrated into the network, to balance the energy demand over the year (Boesten, Ivens, Dekker, & Eijdems, 2019). Convenient manners to store thermal energy are with natural geothermal wells or artificial ATES systems.

Additional features of 5gDHC are the high-level control and monitoring systems of the network (Lindhe, Javed, Johansson, & Bagge, 2022). This is mainly due to the interactive exchange of heating and cooling between all the connections of the DHC. The network should know at every moment if a building demands heat or cooling, and if so if the waste energy can be used for another facility or if it needs to be stored. Moreover, these advanced control systems can also increase peak shaving (Lindhe, Javed, Johansson, & Bagge, 2022). Many scholars are studying the best optimalizations models for these high-level control and monitor systems (Taylor, Long, Marjanovic, & Parisio, 2021; Bilardo, Sandrone, Zanzottera, & Fabrizio, 2021; Wirtz, Kivilip, Remmen, & Müller, 2020; Wirtz, Neumaier, Remmen, & Müller, 2021).

Critics of the new generation state that the 5gDHC is more of a parallel development than the next generation because it is more of a complementary technology instead of a substitution (Lund, et al., 2021). The main argument of Lund is that (as seen in Figure 1) the efficiency of the evolution of the previous generation's energy efficiency increased. However, in the shift from 4gDHC to 5gDHC this is not a given. This is probably due to the larger amount of electricity that is needed with a 5gDHC.

Another study that compares 5gDHC with 4gDHC states that a 4gDHC scores better on the Reliability, Robustness and Resilience metrics (Gudmundsson & Thorsen, Low temperature or ambient temperature district heating? It all depends ..., 2021). Especially when there is a power failure in the system, a 5gDHC would not be able to cope with this, while a 4gDHC could switch to emergency thermal energy production.

Environmental performance of 5th generation DHC

The environmental performance of 5gDHC is also already assessed by several scholars. For example, Schibuola and Tambani (2022), found that a 5gDHC that uses groundwater as sources experience a reduction of 27% CO_2 emission reductions compared to building individual air source HPs and 39.5% fewer emissions than small air-source HPs combined with condensing boilers.

Furthermore, a 5gDHC that uses CO_2 as refrigerant emits 46% less CO_2 emissions compared to a 1gDHC, if groundwater is used (Nagano, Kajita, Yoshida, & Amano, 2021). When using river water, the decrease is 39% and when using sewage water it is 43%.

Another study focuses on a balanced energy network in the UK, which has retrofitted HPs to a conventional gas boiler network (Gillich, Godefroy, Ford, Hewitt, & L'Hostis, 2022). Besides the addition of HPs, nothing else on the network had been changed. The results of the study show a reduction of 13% in carbon emissions and 40% in gas usage.

Besides CO_2, other emissions are also important for determining the environmental impact. Therefore, took this study also the emission of other air pollutants into account.

Economic performance of 5th generation DHC

One of the main arguments used by critics are the costs of 5gDHC. In their review article, Buffa et al. (2019), also mention the extra capital investment involved with this new generation.

Gudmundsson et al. (2022) also did an economical assessment of the 5gDHC compared with 4gDHC. The study determines the Levelized cost of heat and the total efficiency of the system for two different case studies. Their results show that 4gDHC is the most viable solution. This result corresponds with the outcomes of another study, that also states that 4gDHC is more cost-effective than 5gDHC (Gudmundsson & Thorsen, Low temperature or ambient temperature district heating? It all depends ..., 2021).

Another case study in the Netherlands showed that per dwelling, an extra 5500 Euros is needed for a connection to a 5gDHC, compared to a traditional DH (Foster, Love, Walker, & Crane, 2016).

Social performance of 5th generation DHC

Not much research has been done yet on the social impact of 5gDHC. However, one increasing issue in cities is the phenomenon of UHIs (Deilami, Kamruzzaman, & Liu, 2018). This is the occurrence of increased temperatures in the urban areas, because of the heat-retaining concrete buildings and infrastructure. But also air conditioning (AC) increases the heat island effect, because they emit their heat into the urban environment. This increased temperature has a negative impact on the comfort and livability of the city. 5gDHC has a positive influence on this phenomenon because instead of emitting waste heat into the air, it is stored in thermal storage (Schibuola & Tambani, 2022). Groundwater HPs reduce the UHI intensity by 45% compared to air source HPs. Other social impacts of DHC are not yet discussed in the current literature. Another side effect of the UHI effect is the impact on urban energy consumption (Li, et al., 2019). It could lead to an increase of 19% in cooling energy and a decrease of 18.7% in heating energy.

3 Methodology

In this section, the methods that are used in this study will be elaborated on. It explains, what type of data is used, the analysis that has been conducted and the research boundaries.

The goal of this study is to answer the main research question. In order to do so, three sub-questions together try to give a comprehensive answer. Consequently, the sub-questions will be answered by three different assessments. An overview of the study is shown in Figure 4.

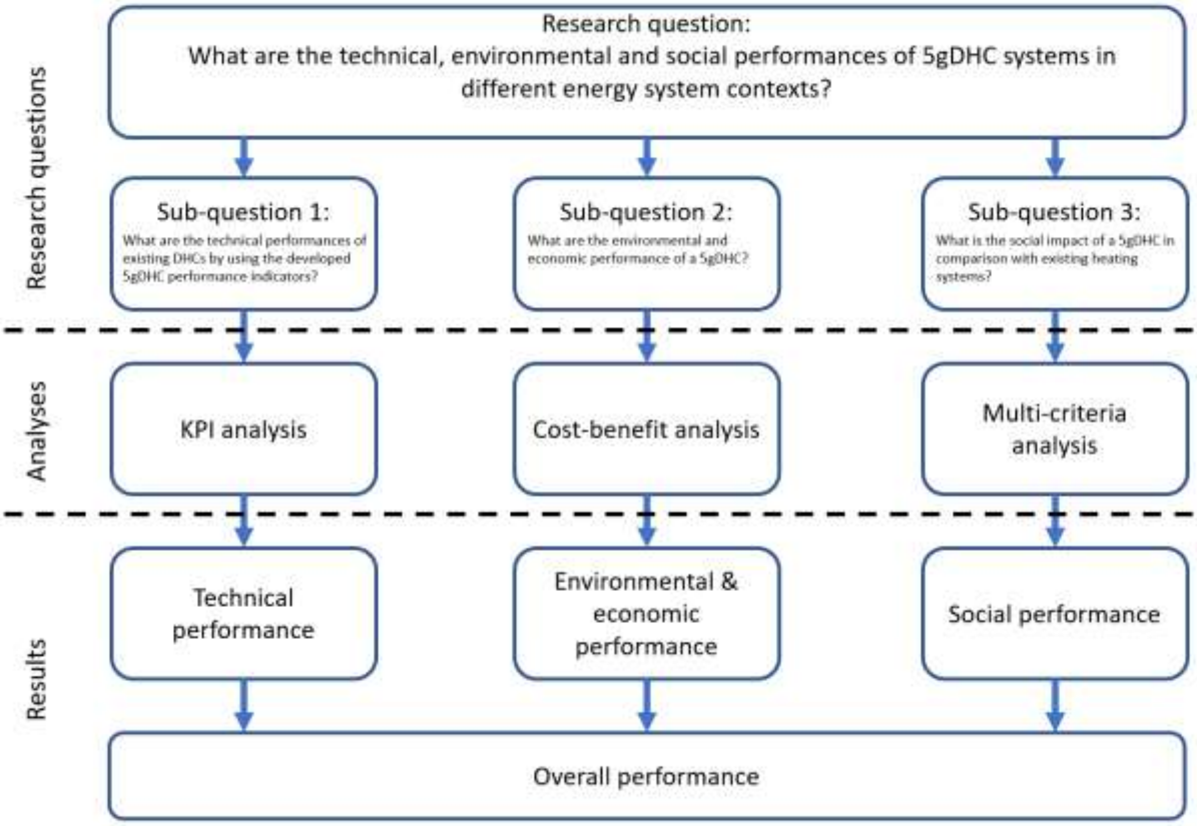

Figure 4. Schematic overview of research questions and corresponding methods.

First, to answer sub-question 1, several KPIs have been developed around the 5gDHC principles. These KPIs are tested on 4 different case studies. With this KPI analysis, the current performance of DHCs and their focus is shown.

Second, sub-question 2 is answered by a CBA. This CBA determined the environmental costs as well as the economic costs of a 5gDHC system and compares that to 2 alternatives.

Lastly, the third sub-question is answered by a MCA. In this MCA, the social impact of a 5gDHC will be assessed compared to 3 alternatives.

3.1 System boundaries

A DHC can be a complex system with several connections between sources and end-users. With these different stakeholders, it is important to define the boundaries of the system clearly. In Figure 5, the boundaries used in this study are shown.

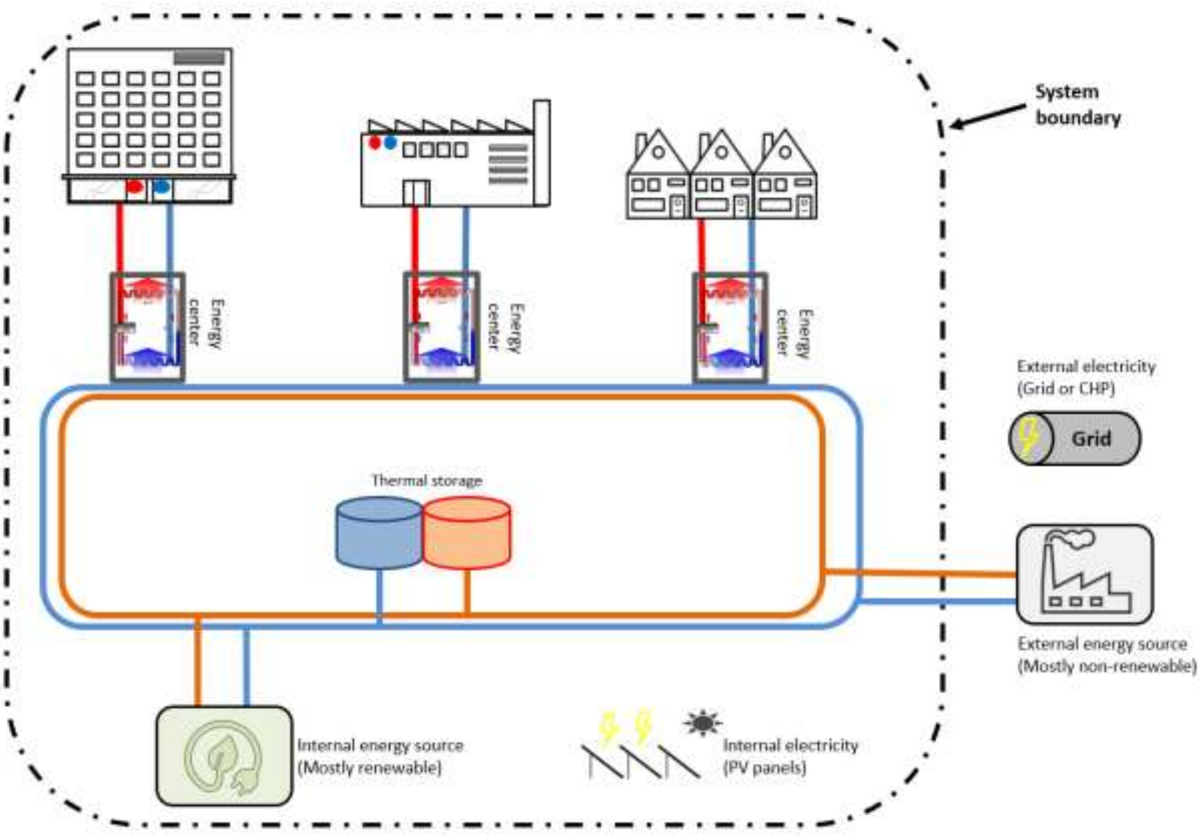

Figure 5.The system boundaries for the thermal energy of the DHC systems.

With regards to the sources, it assumed that all the energy from assets of the network operator are internal sources, so within the boundaries of the system. This means that the operator owns the energy production technology and does not have to pay an external party for this energy. These are mostly renewable energy sources (e.g. ATES or solar thermal panels). External energy is the energy that needs to be bought from an external party. For example, this can be from a wastewater treatment plant or biomass boiler.

The boundaries of the end-users lie at the point where the energy enters the building. Most of the time, this means that the boundary lies at the wall of the customers. However, a customer can also have a HPs inside, for example, a booster HP to cover the domestic hot water (DHW) demand. In that case, the system boundary is located after these HPs in the building. The energy centers are the location where the HPs and or chillers are, that heat up or cool down the water. These are also called sub-stations.

For electricity also the sources that are assets of the DHC operator are seen as internal sources. All the electricity that is bought from the national grid is considered external.

3.2 Key Performance Indicators analysis

In order to answer sub-question 1, key performance indicators (KPIs) are developed to quantify the five principles of 5gDHC. The indicators are tested on 4 case studies, which are also explained in this chapter. Finally, the decision trees are discussed, which are made to make the scores of the KPIs more intuitive.

Indicators

In this section, per principle, the developed KPI(s) and the corresponding formulas are shown and explained.

Closing the loop

The first principle is about the self-sufficiency of the system and the re-use of energy through exchange between end-users, and storage. The KPI shows the percentage of the demanded energy that is provided by energy sources within the system. Extracting the energy supplied from external sources from the demand, shows the part that is internally produced, so to what extent the system is self-sufficient. The KPI can be quantified with Formula 1.

Formula 1. $$KPI_1 = \frac{E_{demand} - E_{supply\_external}}{E_{demand}} * 100\%$$

Where E_{demand} is the total thermal energy demand (heating, DHW and cooling) of the system [kWh] and $E_{supply\_external}$ is the total final external energy flow into the system (through system boundaries) for heating, DHW, cooling [kWh]. It is defined as all energy purchased from external parties.

An ATES system is in this KPI described as an external source if the ATES is unbalanced. This means that energy extraction is more than the energy injected in the ATES system, so it will be slowly depleted. This injection can be the return flow of the network or recharged by for example solar thermal energy.

Using low-grade for low-grade demand

The second KPI is about the amount of low-graded energy used. The KPI is therefore the share of low graded energy of the total energy (formula 3).

Formula 2. $$KPI_2 = \frac{\sum E_{Low\_graded}}{\sum E_{Supply}}$$

Where $\sum E_{low\_graded}$ is the amount of the low graded energy used by the system [kWh], $\sum E_{supply}$ is the total amount of energy used (thermal and electric) [kWh]. For KPI 2, low graded energy is energy from sources with a temperature lower than 50°C. Furthermore, electricity is indicated as high-graded energy. Because of this, a system will never score 100%, because there is always electricity needed for pumping the water to transport in the system and the IT that is used for this.

Decentralized & demand-driven energy supply

The third KPI is about the efficiency of the system. This KPI is divided into two sub-KPIs: the demand drivenness factor (DDF) for the heat and cold pipes (formula 3 till 5). This KPI shows if the temperature average of the system is near the ambient temperature. The second KPI is the amount of sub-station operating per end-user (formula 6). This will show the decentralization of the systems' energy generation.

Formula 3. $$DDFhot = \frac{\sum(L.T_{average})_{hot\ pipes\ +\ ambient\ loop}}{\sum L_{hot\ pipes\ +\ ambient\ loop}}$$

Formula 4. $$DDFcold = \frac{\sum(L.T_{average})_{cold\ pipes\ +\ ambient\ loop}}{\sum L_{cold\ pipes\ +\ ambient\ loop}}$$

Formula 5. $$KPI_{3.1} = (DDFhot - DDFcolc) - |\, T_{avg.Ambient} \,|$$

Formula 6 $$KPI_{3.2} = \frac{\#end-users}{\#active\ sub-stations}$$

Where $\sum L.T_{average}$ is the length times the temperature for different segments of the pipe system, $\sum L$ is the length of the different pipe segments, DDF_{hot} and DDF_{cold} are the DDFs of the hot and the cold pipes, $T_{avg.Ambient}$ is the average temperature of the ambient loop. The #end-users and #active sub-stations are the amount of connections to buildings and the number of energy centers within the system.

An integrated approach of energy flows

The fourth KPI is also divided into two KPIs. It determines the minimum load needed to be operational for heating as well as cooling. The first sub-KPI is for the heating part of the system (formula 8 and 9) and the second sub-KPI is for the cooling part (formula 10 and 11). It gives an indication of the oversizing of the system and if there is for example still room for expansion.

Formula 7. $$P_{minH} = \frac{E_{demand\ heating}}{8760(h)}$$

Formula 8. $$KPI_{4A} = \frac{P_{minH}}{P_{\ heating}} * 100\%$$

Formula 9. $$P_{minC} = \frac{E_{demand\ cooling}}{8760(h)}$$

Formula 10. $$KPI_{4B} = \frac{P_{minC}}{P_{\ cooling}} * 100\%$$

Where P_{min} is the minimum capacity that is needed to be operational. This can be calculated by dividing the total demand by the hours per year. $P_{heating}$ and $P_{cooling}$ are the installed capacity of the systems. With this, the KPIs can be calculated, which shows the percentage of the system that is operating on average every hour of the year.

Local sources as a priority

The last KPI is about the local aspect of the system. This KPI is divided into thermal energy and electrical energy. To calculate the locations of the energy sources for the thermal energy is needed: municipality, region, national or international (Formula 11). For electrical energy, the amount of energy from the grid and the amount of energy generated locally are needed (Formula 12).

Formula 11. $$KPI_{5\_Thermal} = \frac{E_{local,100\%} + E_{region,75\%} + E_{national,25\%} + E_{international,0\%}}{E_{ther\_Total}}$$

Formula 12. $$KPI_{5\_electrical} = \frac{E_{local,100\%} + E_{grid,0\%}}{E_{Elec\_Total}}$$

Where E_{XX}, is the Energy source per location. For the KPI of thermal energy, energy from the municipality is seen as local, energy from within 25km of the system is indicated as regional, energy from the same country is national and energy from another country is international. Here should be noted that international sources that are within 10km or 50km, need to be counted as Local or Region and not as international. For electrical energy, only two options are distinguished: locally generated and from the national grid. E_{XX_Total}, is the total supplied energy.

Case studies & data

The systems that are tested on the KPIs are five pilot sites of the European project D2Grids. These consist of Brunssum (Netherlands), Genk (Belgium), Bochum (Germany), and Paris (France). These systems are mostly still in the design phase, but data is already available via modelling and estimations. The Brunssum and the Paris sites are already in operation, however, both systems are not completely finished yet. They have still future upgrades planned, in order to perform better or connect more buildings to its network. For the Brunssum site this is referred to as the capitalization call (CapCall). The data needed for the KPIs is retrieved from the four pilot sites via Email. In Table 1, a summary is shown of some specifications of the systems. The full data templates of the systems are shown the appendix Table A. 1.

Table 1. Summary of the DHCs that are used as case studies.

	Brunssum Mijnwater system (* after the CapCall)	**Bochum MARK 51°7 - FUW GmbH**	**Genk Thor Park**	**Paris-Saclay**
Country	Netherlands	Germany	Beglium	France
Already operational [Y/N]	Yes	No	No	Yes
Amount of cusomter connections [#]	191	25	4	76
Total surface served [m2]	17,960	196,000	22,000	851,773
Type of consumers	Residential	Business	Business	Commercial, business & residential
lentgh of network [m]	10,843	5,850	1,430	11,850
Heat sources	ATES + heatpumps	Mine water system + heatpumps CHP	ATES + heatpumps	ATES + heatpumps Gas boilers
Heating capacity [kW]	435 (692*)	12,140	12,140	25,676
Cooling sources	Geothermal well	Geothermal well Configuration chillers	Geothermal well	Geothermal well Cooling towers
Cooling capacity [kW]	268	9,700	22,000	12,000
Annual heating demand (including DHW) [MWh]	1,130	14,059	1,104	26,282
Annual cooling demand [MWh]	187	8,122	915	6,941
Total energy demand [MWh]	1,317	22,181	2,019	33,223

Scoring

The scores of the KPIs are not for every KPI intuitive. Therefore, decision trees have been developed in order to standardize the scores. These decision trees are found in Appendix Figure A. 1 to Figure A. 8. These trees help to score the KPIs from 0 to 10, where 10 is always the best score. With these scores, the focus of the different DHCs is shown and an extensive summary per pilot site will be explained also qualitative why the particular pilot scores on the KPIs and how they can potentially improve.

After the KPIs are scored separately as well as in total, an analysis has been done on the current performance of DHCs. The average, minimum and maximum scores are calculated. Furthermore, by analyzing why systems score better or worse on certain KPIs, a better understanding has been obtained of the current focus and performance of existing DHCs and how systems can improve themselves.

3.3 Cost-Benefit analysis

In this chapter, the methodology of the CBA is discussed. First, a generic overview of a CBA is given. Next, the assessed environmental and economic indicators are explained. Later, the sensitivity analysis and the costs and prices used are elaborated on.

In order to assess how a 5gDHC performs compared to different alternatives on the environmental and economic performance, a CBA is conducted. A CBA is a tool that helps policymakers with decision making (Romijn & Renes, 2018). It indicates the effects, risks and uncertainties of a certain technology or policy. This analysis investigated how the 5gDHC performs on environmental and economic indicators. During the CBA, the DHC of Brunssum will be compared with alternative heating systems. A CBA consist of 7 steps (Romijn & Renes, 2018):

1. Problem analysis
2. Establish the baseline alternative
3. Define policy alternatives
4. Determine effects and benefits
5. Determine costs
6. Analyse variants and risks
7. Overview of costs and benefits

The first three steps are framing the problem and the alternative technologies. In this study, it is the 5gDHC and two alternative solutions; a 4gDHC system and an individual domestic gas boilers (DGB) alternative. Step 4 to 6 is the core of the CBA, where the effect, cost and benefits of the alternatives are measured. Step 7 gives an overview of the results (Romijn & Renes, 2018).

Indicators

The effects and benefits of a CBA are the indicators on which the alternatives are assessed. Afgan et al. (2000) propose sustainability indicators for an energy system assessment. Four main categories are provided: Resource indicators, environmental indicators, social indicators, and economic indicators. For this study, the environmental and economic indicators are assessed within the CBA (the social are determined in the MCA. The indicators are shown in Table 2.

Table 2. Indicators for the CBA.

Category	Indicator	Abbreviation	Unit
Environmental	$CO_{2\ \mathrm{Equivalent}}$ emission coefficient	K_{CO2}	Tonnes and €/kWh
	Air pollutants emission coefficients	K_{XX}	Kg and €/kWh
Economic	Capital expenditures	CAPEX	€/kW
	Operational expenditures (fixed and variable*)	OPEX	€/kW(h*)
	Levelized cost of energy	LCOE	€/kWh

Environmental Indicators

The environmental indicators show the impact of the different technologies on the environment. Within this study, this is translated by the emissions of GHGs and other air pollutants.

CO2e emission coefficient

The equivalent emission coefficient is the indicator that assesses the overall impact of GHG emissions. It is calculated by combining the different energy sources of the system. From these sources, the primary CO2 equivalent emissions are calculated with the emission factors (Formula 13).

Formula 13 $$K_{co2} = \frac{\sum_i E_i K_{CO2,i}}{Q}$$

Where K_{CO2} is the amount of CO_2 emitted by the system per energy produced in kg/kWh. E_i is the energy source “i” input in kWh and k_{CO2} is the corresponding CO_2 emission factor of that energy source kg/kWh. Q is the total energy produced in kWh by the system.

Local air pollutants

Besides the CO2e, the emissions of other air pollutants are assessed. The assessed selection is made by the inclusion of pollutants in the shadow costs report of CE Delft (2018). An overview of these shadow costs as well as the presence of these pollutants by the combustion of biomass and gas are shown in Table 3 (European Environment Agency, 2021). Differently from the CO2e emission, which has mainly impact on a global level, these pollutants have an impact on a local level (Khomenko, et al., 2021). They can cause health issues for humans and other hazardous threats to nature.

Formula 14 $$K_{XX} = \frac{\sum_i E_i k_{XX,i}}{Q}$$

Where XX is the air pollutant assessed. K is the amount of the pollutant emitted by the system per energy produced in kg/kWh. E_i is the energy source “i” input in kWh and k_{XX} is the corresponding emission factor of pollutant XX of that energy source kg/kWh. Q is the total energy produced in kWh by the system.

Furthermore, as the impact of these pollutants is mainly locally, the electricity from the grid is not taken into account in this indicator, because the electricity from the grid is not generated locally, so the effect is also not locally (Ivančić , Romaní, Salom, & Cambronero, 2021).

Economic Indicators

The economic indicators are the financial part of the CBA. It first evaluates two straightforward indicators; Capital expenditure (CAPEX) and operating expenditures (OPEX). These two are also necessary to calculate the last indicator, the levelized cost of energy (LCOE). With these indicators, the attractiveness of the technologies for investors is assessed.

Capital expenditure

The CAPEX include all the investments that are needed in acquiring and installing the assets for starting a new system. This can be the project engineering, materials, financing costs, etc. The CAPEX is calculated with formula 15.

Formula 15 $$CAPEX = \frac{I_{total}}{P}$$

Where I_{total} is the sum of all the different costs that are associated with the installation and deployment of the system in Euros. P is the capacity of the system in kW. So, the CAPEX is in Euros per kW.

Operating expenditures

The OPEX are the costs that are involved during the operations of a system. These costs include maintenance, fuel, labour, etc. These costs can be divided into fixed and variable OPEX. The fixed OPEX are the costs that are always needed, for example, labour. These costs are fixed per capacity that is installed, so are measured in Euros per kW installed. The variable OPEX are the costs that can variate annually, which are mainly fuel costs. These depend on the heating demand which variates annually due to different weather conditions. These costs are therefore in Euros per kWh. The OPEX can be calculated with the formulas 16 and 17

Formula 16 $$OPEX_{Fixed} = \frac{OC_{fixed}}{P}$$

Formula 17 $$OPEX_{Variable} = \frac{OC_{variable}}{Q}$$

Where OC_{fixed} is the fixed costs in Euros, $OC_{variable}$ is the variable costs in Euros, P is the capacity of the system in kW, and Q is the energy demand in kWh. The $OPEX_{fixed}$ is in Euros per kW and the $OPEX_{variable}$ is in Euros per kWh.

Levelized cost of energy

In order to compare the economic impact of the different alternatives, the LCOE measure is convenient to use (Blok & Nieuwlaar, 2016). This metric calculates the revenue per unit of energy that is required to recuperate the CAPEX and the OPEX of an energy system. It is the ratio between the total levelized cost of the system over its lifetime and the total produced energy and can be calculated with formula 18.

Formula 18 $$LCOE = \frac{I * \alpha + OM}{E}$$

Where I is the CAPEX, OM is the OPEX, and E is the annual energy production of the system. α is the capital recovery factor, this factor is a function of the lifetime of the system and the discount rate, shown in formula 19.

Formula 19 $$\alpha = \frac{r(1+r)^n}{(1+r)^{n-1}}$$

Where r is the discount rate in percentages and n is the lifetime of the system in years. The discount rate is the interest rate of the project. As the discount rate can have a big impact on the final LCOE, it has been the topic of many discussions for example in the IPCC report (Fischedick, et al., 2011; Nuclear Energy Agency, 2018). They state that also the social-environmental impact should be taken into account. In addition, projects that receive subsidies or other types of funding, mostly do not care that much about high future value, as those projects mostly will be experimental to see if a certain technology works or to become more sustainable. Therefore, during this study, in the CBA, a low discount rate of 3% is used.

Sensitivity analysis

Because of the several uncertainties in the financial assessment, a sensitivity analysis is performed.

First, an analysis is done on the LCOE with different discount rates for all the alternatives. The rest of the variables stayed the same during this analysis. With this, the impact of different discount rates is shown.

Second, another sensitivity analysis has been performed. This analysis used a random values generator for variables that are uncertain over time, for example, gas prices, CAPEX and OPEX. The random values are produced based on the assumption of a nominal distribution, where the mean is the value of the base scenario and the standard deviation is based on assumptions. This analysis shows the probability of different outcomes if several variables are changing. The analysis ran 500 simulations per model.

Determine costs

Environmental costs

Environmental costs are most of the time very hard to measure, as it is not a real price that needs to be paid, but a value that is given subjectively. However, with the rise of attention to the environment in the last decades, several institutes have tried to estimate this price on different environmental impacts. For emissions, these are shadow prices, which are measured in €/kg emitted pollution. In Table 3, the different costs for the polluted emissions used in this study are displayed, retrieved from the CE Delft (2018).

Table 3. The shadow costs and the presence of air pollutants during combustion (CE Delft, 2018; European Environment Agency, 2021).

	Shadow costs [€/kg]		**Emitted by combustion**	
Air Pollutant	**Lower**	**Upper**	**Biomass**	**Natural gas**
CO2	€ 0.01	€ 0.05	X	X
CFC	€ 22.10	€ 45.70		
PM2.5	€ 56.80	€ 122.00	X	X
PM10	€ 31.80	€ 69.10	X	X
NOX	€ 24.10	€ 53.70	X	X
SO2	€ 17.70	€ 38.70	X	X
NH3	€ 19.70	€ 48.80	X	
NMVOS	€ 1.61	€ 3.15	X	X
CO	€ 0.07	€ 0.15	X	X
CH4	€ 0.02	€ 0.03		
Cd	€ 798.00	€ 1,831.00	X	X
As	€ 703.00	€ 1,228.00	X	X
Pb	€ 3,967.00	€ 6,596.00	X	X
Ni	€ 75.00	€ 225.00	X	
Hg	€ 24,770.00	€ 53,630.00	X	X
CH2O	€ 19.30	€ 40.00		

In the table 3, there is a lower and upper scenarios shown. These scenarios are created because of the uncertainties of valuing the environmental impact of the pollutants (CE Delft, 2018). With these scenarios a range can be estimated where the actual result should be somewhere in between.

Inflation

Because many of the prices and costs data are from previous years, there should be a correction for inflation. For the environmental shadow costs, CE Delft (2017) suggest that you should use the inflation of the consumer price index. As most of the data of this study is from 2021, the price difference between the year of the older data and the average of 2021 is taken. For the environmental shadow costs, this is 2015. The inflation of the consumer price index in 2021 relative to 2015 is 110.39% (Appendix Figure B. 2) (CBS, 2022b).

Economic costs

For the economic impact analysis, some assumptions and results from different sources are used in order to calculate the CAPEX, OPEX and the LCOE for the different alternatives. For the DGB alternative, assumptions from articles and websites are used (Table 4) and for the 4gDHC assumptions of the article of Ivančić et al. (2021) and Kim & Weidlich (2017) are used (Table 5).

Table 4. Assumptions for the individual domestic DGB alternative.

DGB	Heating	unit	source
Gas prices	€ 0.05	€/kWh	Trading Economics (n.d.)
CAPEX	€ 137.5	€/kW	Trinomics (2020)
OPEX fix	2% of the CAPEX	€/year	Fraunhofer Institute for Systems and Innovation Research (2016)
OPEX var	Fuel price	€/year	Gas prices * heating demand
Lifetime	20	year	lin et al. (2021)

Table 5. Assumptions for the 4gDHC alternative.

4gDHC	Heating	Cooling	unit	Source
CAPEX	€ 1,139	€ 789.7	€/kWh	Ivančić et al. (2021)
OPEX fix	€ 119.76	€ 61.95	€/kW/year	Ivančić et al. (2021)
OPEX var	€ 0.03	€ 0.03	€/kWh/year	Ivančić et al. (2021)
Lifetime	30	30	year	Kim & Weidlich (2017)

For the 5gDHC, financial data from the Brunssum DHC is used. This data is only 4 months old because the system is only operating for that time at the moment. This data contains only winter months. It is assumed that the winter months are 140% of the average demand profile (NieuweStroom, N.D.). This study corrected for this, by dividing the winter months by 140%, and used that as the monthly average. Moreover, because of the substantial higher energy prices at the beginning of 2022 (Jan, Feb, Mar), also a correction of 20% is extracted from the OPEX, as the rest of the data is from 2021 or before (CBS, 2022a). The assumed input is shown in Table 6.

Table 6. Assumptions for the 5gDHC alternative.

5gDHC	**Heating & Cooling**	**unit**	**source**
CAPEX	€ XXXXXXX	€	Internal documents[1]
OPEX var	€ XXXXXXX	€/year	Internal documents[1]
Lifetime	30	year	Kim & Weidlich (2017)

For the 5gDHC designed, the addition of the CapCall is only affecting the investment costs. It is assumed that this is an additional 2 million Euros, which results in a CAPEX of € XXXXXX[1].

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[1] Known by the author, you can contact jibbebertholet@gmail.com for inquiries.

3.4 Multi-Criteria Analysis

In this section, the methods of the MCA are explained. First, an introduction to MCA is given, including the alternatives and indicators used in this study. These indicators are later briefly elaborated on.

For the social impact of a 5gDHC system, an MCA is conducted. An MCA is a method to explore multiple objectives of actors involved in a decision (Beinat, 2002). It is originally used to compare various alternatives on different criteria and to select the best alternative from this set. Beinat (2002, p. 7) states that: “In MCA a solution is never good or bad in absolute terms. It is such only in relation to the revealed objectives of the people who have the role and responsibility of making the decision or to influence the process”. An MCA is always subjective because it requires an explicit judgement of what is most important and less important, and accordingly, the weighting will be adjusted (Dodgson, Spackman, Pearman, & Phillips, 2009). To conduct an MCA several steps need to be taken.

First of all, the decision and the aim of the analysis need to be clear and established (Dodgson, Spackman, Pearman, & Phillips, 2009). For this study, it is to compare 5gDHC with alternatives on their social impacts.

Secondly, the different criteria and alternatives need to be identified (Dodgson, Spackman, Pearman, & Phillips, 2009). In this assessment, the alternatives are a 5gDHC, 4gDHC, 4gDH and a system with DGB. Table 7 shows some characteristics of the alternatives.

The different indicators (criteria), used in this study are shown in Table 8 with their corresponding type of social impact.

Table 7. A summary of the different alternatives used in the MCA and their characteristics.

	5gDHC	**4gDHC**	**4gDH**	**DGB**
Based on	Brunssum pilot (D2Grids)	Ivančić et al (2021)	Ivančić et al (2021)	Assumptions
Heating sources	ATES + HPs	Biomass ATES + HPs	Biomass ATES + HPs	DGB
Cooling sources	ATES	ATES	Domestic AC units	Domestic AC units
Fuel needed	Electricity	Biomass Electricity	Biomass Electricity	Gas Electricity
Maturity of the technology	New	Medium	Medium	Old

Table 8. The social impact indicators used in the MCA and the corresponding type of impact.

Indicator	**Social impact**
UHI	Living comfort and health
Noise	Living comfort and health
Local employment	Individual Economic
Land use	Local Economic
Import shares	Local Economic
Volatile prices	Individual Economic
Air quality	Health

Thirdly, the criteria need to be scored for all the alternatives (Dodgson, Spackman, Pearman, & Phillips, 2009). Because it is very hard to put real numbers on most of the indicators, the scoring is done with a range from - - to + +. Where - - is a strong negative impact, - is a light negative impact, 0 is a neutral or no impact, + is a light positive impact and + + is a strong positive impact. The scoring is based on arguments, from articles, websites and logical rational thinking. Afterwards, the scores have been standardized and weights have been assigned to all the different criteria. These weights show how important the individual indicators are. With these scores and weights, the total score of the social impact of the alternatives is calculated. With the impact and the alternatives, an MCA matrix is made (Table 9).

For the MCA, the tool DEFINITE (decisions on a finite set of alternatives) is used. This program is made to improve decision-making (Janssen & van Herwijnen, 2006). And it provides several methods for the MCA, for example. it helps visualize the results.

Table 9. The MCA matrix for this study.

Analyzed Criteria	Weight-factor	Unit	**5gDHC**	**4gDHC**	**4gDH**	**DGB**
UHI		++/--				
Noise		++/--				
Land use		++/--				
Work employment		++/--				
Import shares		++/--				
Velocity prices		++/--				
Air quality		++/--				

Indicators

The social indicators cover the impact on society. These indicators are most of the time hard to quantify or measure. But they do have a certain impact on the local community in the area of the system.

Urban heat island effect

The UHI is the phenomenon that urban areas become significantly warmer than rural areas (Deilami, Kamruzzaman, & Liu, 2018). The urban environment absorbs heat during the daytime and radiates heat slowly during the night, so it does not cool down. This increase in urban temperature can affect human well-being as it can cause stress, lack of concentration, and even increase mortality, especially among elderly

Noise

Noise is, besides air quality the most hazardous environmental issue, which impacts human health and well-being (World Health Organization, 2018). Exposure to too much noise can result in high-stress levels and sleep disturbances. The increase in urban noises makes this an important rising social concern.

Local employment

Energy systems can create working opportunities. It can deploy different types of jobs. We can divide the jobs mainly into two different types. Namely, temporary jobs and permanent jobs. Permanent jobs have a more positive effect on the local community as these are more stable work opportunities.

Land use

Land use is another social impact that is assessed. It includes the land needed for the devices, the infrastructure of the systems, and also, the land that is needed for the fuels, for example cultivating biomass, is taken into account.

Import shares

Import shares are the share of the products, materials or fuels used that need to be imported from other countries or regions. The less distance they need to travel, the less GHGs are emitted. Furthermore, if the import shares are low, the money stays within the local or regional area, which has a positive impact on the local economy.

Volatile prices

Prices that are very uncertain over time are volatile, this is mostly a negative impact as the grid operator or the customers can not anticipate the prices for a longer period. For example, a crisis can increase the gas or electricity price, or the pollution or emission cost can go up, because of climate change.

Air quality

An increase in air pollutants will cause a decrease in air quality. Air quality has the most hazardous local impact on human health (World Health Organization, 2018). For example, $PM_{2.5}$ and PM_{10} are very small particulates, which can negatively affect human health by causing heart and lung diseases. In addition, NO_x, which consists of NO and NO_2, can cause smog. This mainly results in human health issues such as respiratory problems

4 Results

4.1 KPI analysis

Brunssum

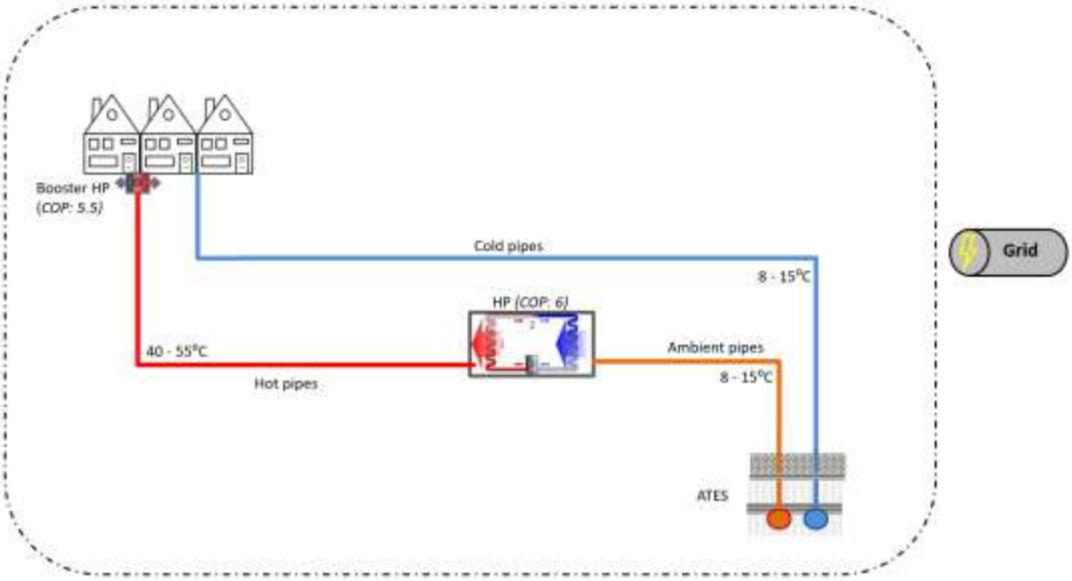

Figure 6. Schematic overview of the Brunssum system.

The pilot site Brunssum is managed by the company Mijnwater B.V. and lies in the south of the Netherlands. The pilot heats and cools three residential districts, with a total of 191 dwellings. A systematic overview of the system is shown in Figure 6. The network is relatively simple. It uses an ATES as thermal energy source and storage. After the ATES, the thermal energy is upgraded to the required temperate by HPs for covering the heating demand. The cooling supply is also done by the ATES but is directly pumped to the end-consumer (passive cooling) (Figure 8). The water from the ATES is between 8°C and 15°C, depending on the season. The hot circuit is between 40°C and 55°C. The cold circuit is respectively 8°C and 15°C, as it is directly from the ATES system. In all the houses booster HPs are installed for covering the DHW. All electricity that is used is currently extracted from the national grid. The Brunssum DHC is already operating, but there are still upgrades planned for the system. This upgrade of the system is called the Capitalization Call (CapCall). In this CapCall, the addition of two HPs is planned, as well as the installation of PV and PV thermal panels. The main goal of the CapCall is to balance the ATES system, as this is currently unbalanced.

The different KPI scores for Brunssum are shown in Table 10 and the standardized scores in Figure 7.

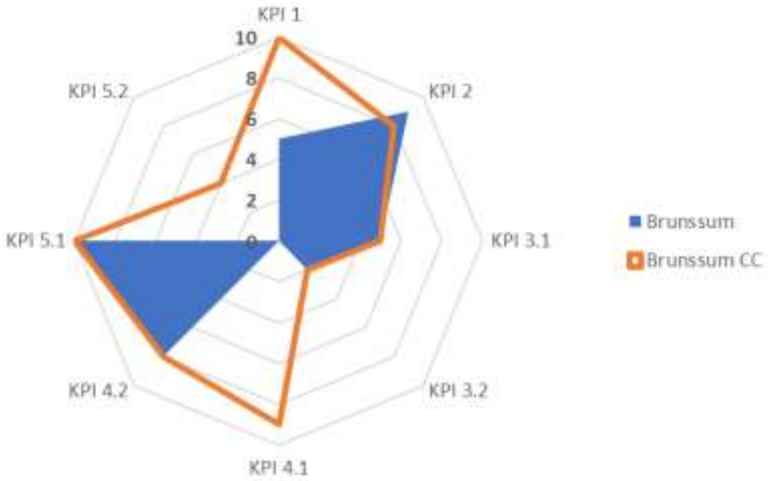

Figure 7. The standardized scores of the KPIs for the Brunssum DHC with and without the CapCall (CC).

Table 10. The results of the KPIs for Brunssum with and without the CapCall.

	Brunssum	CapCall
KPI 1	47%	100%
KPI 2	88%	76%
KPI 3.1	22%	0%
KPI 3.2	3%	4%
KPI 4.1	30%	19%
KPI 4.2	8%	8%
KPI 5.1	100%	100%
KPI 5.2	0%	39%

Closing the loop

Brunssum does not score very high with 47% self-sufficiency, KPI 1. This is due to the fact that the ATES system is unbalanced, which means that the system extracts more heat from it than it injects back in. This causes a gradual depletion of the source. However, with the PV thermal panels that are planned during the CapCall, the ATES will be balanced throughout the year, as it recharges heat during the summer. Because after the CapCall, the ATES will be balanced, all energy from it is considered from an internal source, so Brunssum will score 100%.

Low-graded energy

Brunssum scores 76.4% on KPI 2. All the thermal energy of the system is low-graded, however, the electricity used is almost a quarter of the total energy used. As electricity is high-graded, this penalizes the score. The ratio of electricity and thermal energy does change after the CapCall, so KPI 2 decreases marginally after the CapCall. But because of this, the standardized scores drop from a 9 to an 8.

Decentralized and demand-driven energy supply

The DDF of Brunssum is 26.9%. This is relatively high. This is because the hot pipes are on average 50°C. This is almost 40°C higher than the ambient loop. The scores on KPI 3.2 are very low with 3% and 4.2% (CapCall). This is because, for the 191 houses, only 2 energy centers are operating.

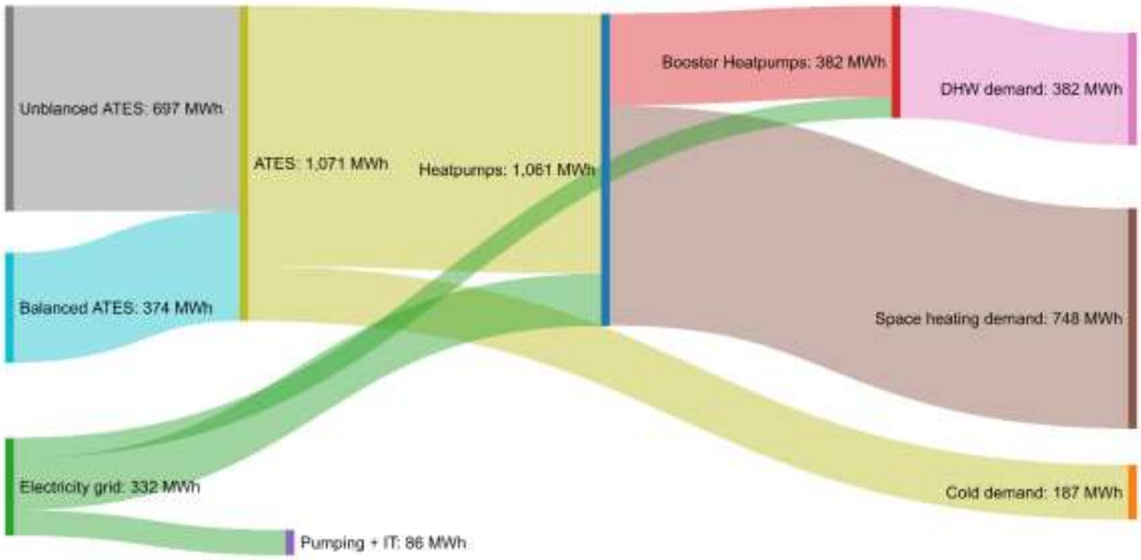

Figure 8. Sankey diagram of the Brunssum site.

An integrated approach of energy flows

On KPI 4.1 score Brunssum with 30% very high compared with the other systems. This means that on average, every hour a year the system runs at 30% of its capacity. This would score a 10 in the decision tree, provided that the other three conditions are met. However, in the winter of 2021, the Brunssum DHC could not meet the peak demand (Benneker, 2022). For that reason, the system scores a 0 on this KPI. A reason for this failure is that the system is not finished yet. With the CapCall, almost a third more capacity is planned for the system. After this upgrade, the KPI scores 19% on this KPI, but it is assumed that then the peak demands can be covered. For the cooling part, Brunssum scores lower with 8%.

Local sources as a priority

On thermal energy, Brunssum scores 100%, because all the energy comes from the local ATES system. On electricity Brunssum scores, 0% as all of the electricity comes currently from the national grid. However, with the CapCall, this will change to 38.9% as there are some PV panels planned.

Bochum

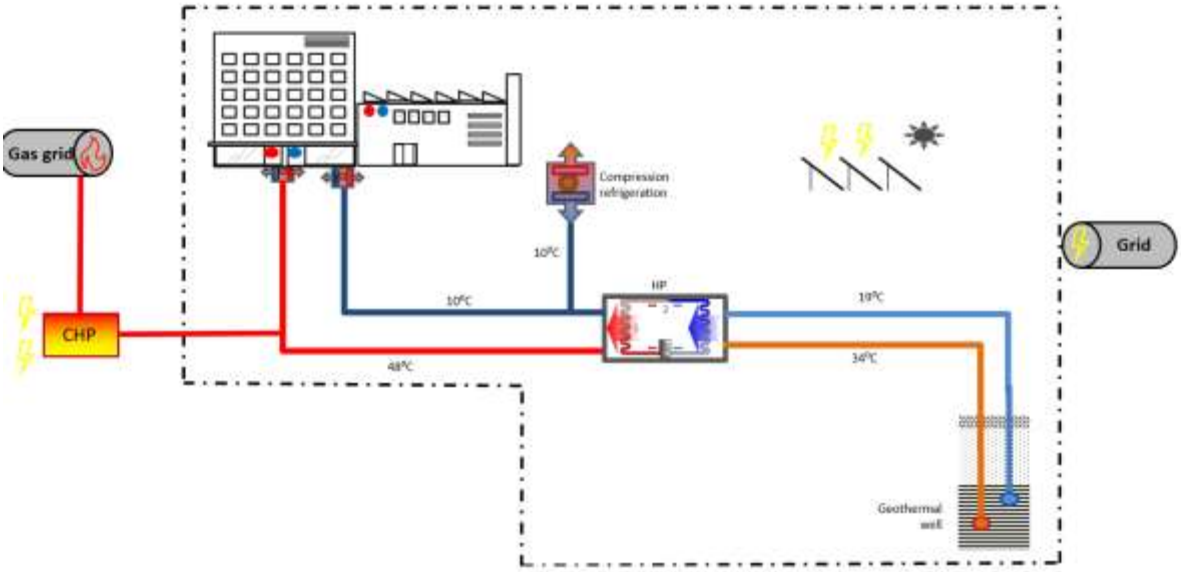

Figure 9. Schematic overview of the Bochum network

The pilot site of Bochum will be located at the former Opel plant, in the Rhine-Ruhr Metropolitan Region in Germany. In this former mining area, a broad mixture of businesses and offices are planned to be connected to the network, with a total of 25. Because of its history, there are mine shafts that are nowadays flooded with water. These shafts will function as an energy source as well as storage. Besides the mine water, they also use the heat of a CHP and the cooling of Compression refrigerators. For electricity, some PV panels will be deployed, but the largest share is extracted from the grid (Figure 11). The construction of the geothermal well has finished in April 2022, and end of 2022 the first customers will be connected. However, the data used is from the final design phase when there will be 25 end-users connected. The different KPI scores for Bochum are shown in Table 11 and the standardized scores in Figure 10.

Closing the loop

On the first principle, Bochum scores well. The 65% shows that almost two-thirds of the energy demand is covered by internal sources. This is because the mine water system delivers the largest share of thermal energy compared to the gas of the CHP.

Low-graded energy

The share of low-graded energy is 54%. this is lower than KPI 1, which is caused by the electricity that is also added to this KPI.

Figure 10. The standardized scores of the KPIs for the Bochum DHC.

Table 11. The results of the KPIs for Bochum.

	Bochum
KPI 1	65%
KPI 2	54%
KPI 3.1	21%
KPI 3.2	200%
KPI 4.1	31%
KPI 4.2	17%
KPI 5.1	84%
KPI 5.2	72%

Decentralized and demand-driven energy supply

On the DDF KPI scores Bochum a 6, with 21%. This means that the average difference between the ambient loop and the cold and the heat pipes is 21ºC. On KPI 3.2 they score very high with 200%, which is caused by the large amount of heating and cooling stations that will be located within the system, per end-user there will be 2 sub-station. This can be caused by the large buildings of the customers, which need more sub-station per building to cover the energy demand entirely.

An integrated approach of energy flows

On the capacity principle, Bochum scores relatively high with 31% (KPI 4.1) and 17.2% (KPI 4.2). This shows that they operate every hour of the year on average on almost one-third of their capacity for heating and 17% for cooling. It is now assumed that they can meet their peak demands, so then the network is probably good in peak shaving, through e.g. thermal storage.

Local sources as a priority

On the last principle, Bochum scores average. For the thermal energy, it scores 84%. Of the final thermal energy, only the heat from the CHP is counted as international. The heat and cooling from the mine water and the cooling from the Configuration refrigerators are both locally produced. For the electricity part, they produce 59% of the energy locally, this includes the electricity from the CHP as well as the electricity produced by their PV panels. This is, compared with the other systems, a high score.

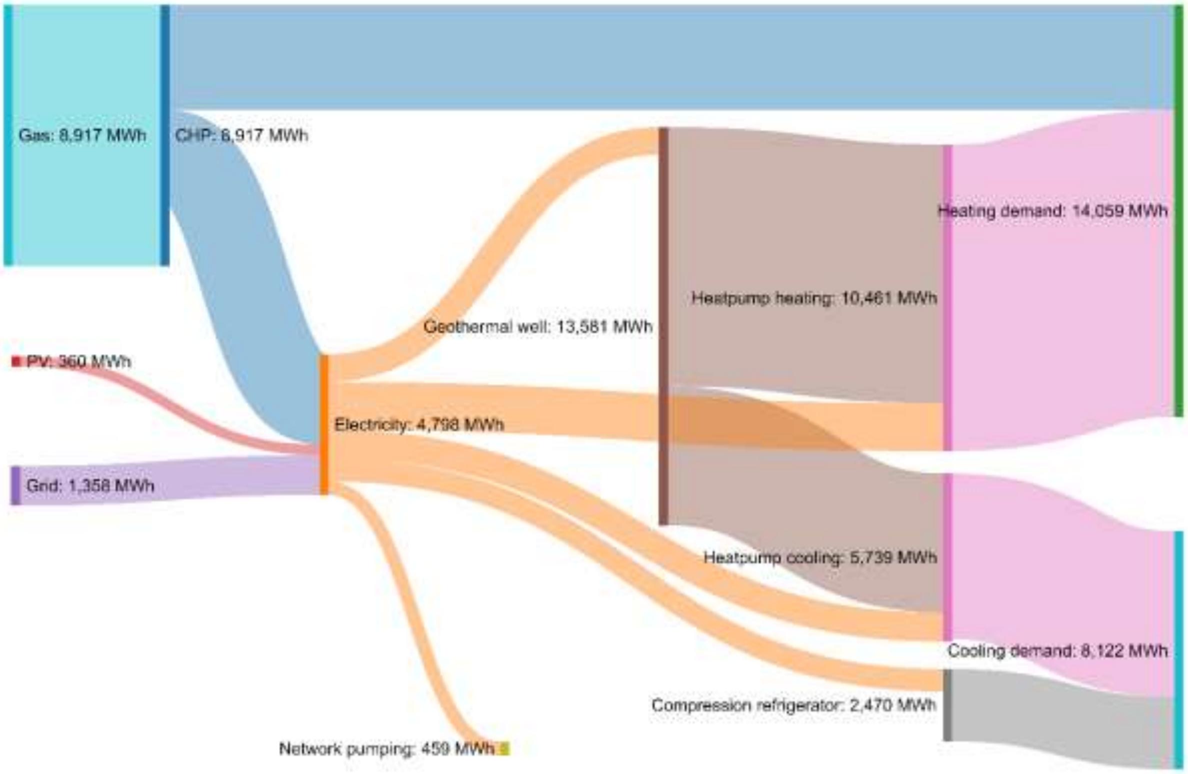

Figure 11. Sankey diagram of the Bochum system

Genk

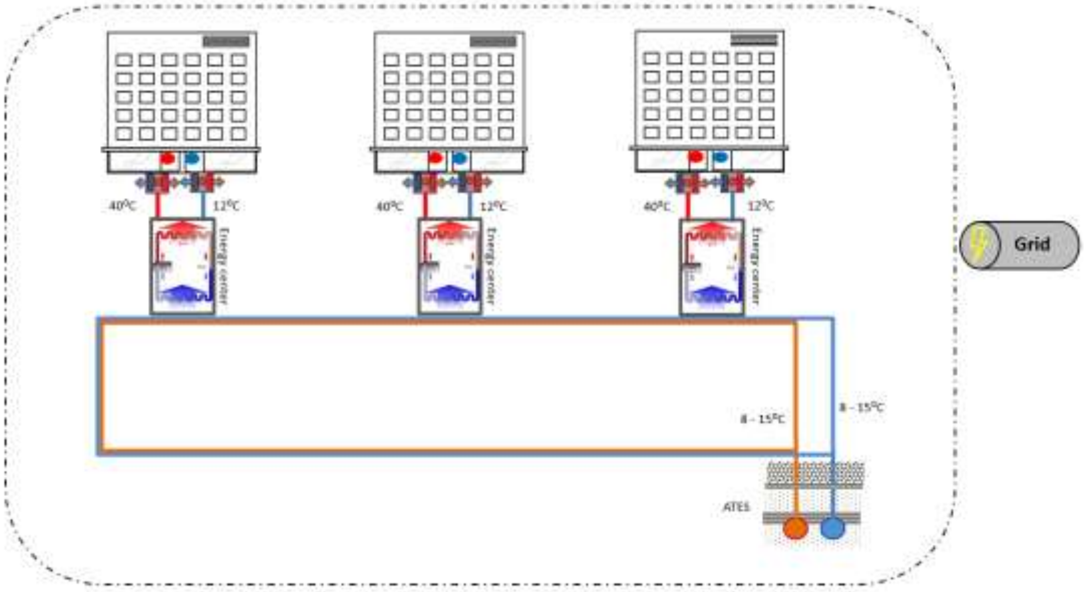

Figure 12. Schematic overview of the Genk network.

The Genk network is located in the north-eastern part of Belgium near the Dutch border. The system is still in its design phase and is planned to be operational within five years. There will be 4 buildings connected to the network, which are all large industrial buildings and offices. However, there are still some lots available in the area, where new buildings will be built in a later phase, which will also be connected. The system uses a geothermal well as thermal source (Figure 12 and Figure 14). This energy will be upgraded by HPs at the end-users buildings. Also, chillers will be installed but will only work as a backup for balancing the thermal well as too much heat will be injected back into it. In the later phase, besides the new construction of buildings, there will also be an expansion to another cluster of buildings, including the stadium of football club KRC Genk as well as two residential areas. With this addition of different types of buildings, it is expected that more exchange between end-users will be taken place and less heating and cooling from the ATES system is needed. However, the data used for this study will be limited by the 5 buildings planned for the first phase. The different KPI scores for Genk are shown in Table 12 and the standardized scores in Figure 13.

Closing the loop

On the first KPI Genk scores 100%, as all the thermal energy is from the ATES. The ATES is assumed to be balanced. In case the customers have a higher cooling demand than the system can inject back into the ATES, the network has backup chillers to rebalance it.

Low-graded energy

The second KPI shows the ratio of the electricity needed compared to the thermal energy of the ATES. Genk scores 75% which means that a quarter of the energy needed is electricity.

Decentralized and demand-driven energy supply

On KPI 3.1 Genk scores 8%, which means on average there is an 8ºC difference between all the pipes and the ambient temperature. For KPI 3.2 Genk has a score of 100%, as there are 4 end-users and 4 energy centers. This means that per customer the temperature can be customized according to their demand, which is the most demand-driven what a system can be.

An integrated approach of energy flows

For KPI 4.1 Genk scores 10%, which means that on average, every hour of the year the system is operating at 10% of its capacity. This relatively low score shows that it is designed for additional connections in the future. For KPI 4.2, it scores 17%., which can also still be higher if there will be more buildings connected in the future.

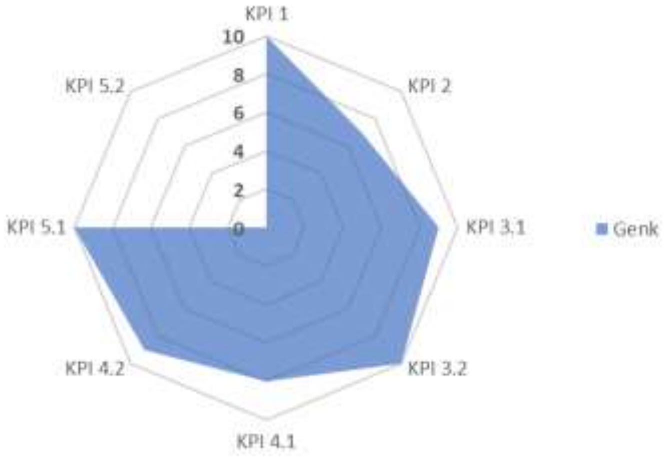

Figure 13. The standardized scores of the KPIs for the Genk DHC.

Table 12. The results of the KPIs for Genk.

	Genk
KPI 1	100%
KPI 2	75%
KPI 3.1	8%
KPI 3.2	100%
KPI 4.1	10%
KPI 4.2	17%
KPI 5.1	100%
KPI 5.2	0%

Local sources as a priority

For the last set of KPIs, Genk scores the maximum for thermal energy and the minimum for electricity. This is because the geothermal well is local and provides all the thermal energy, but all the electricity is from the national electricity grid.

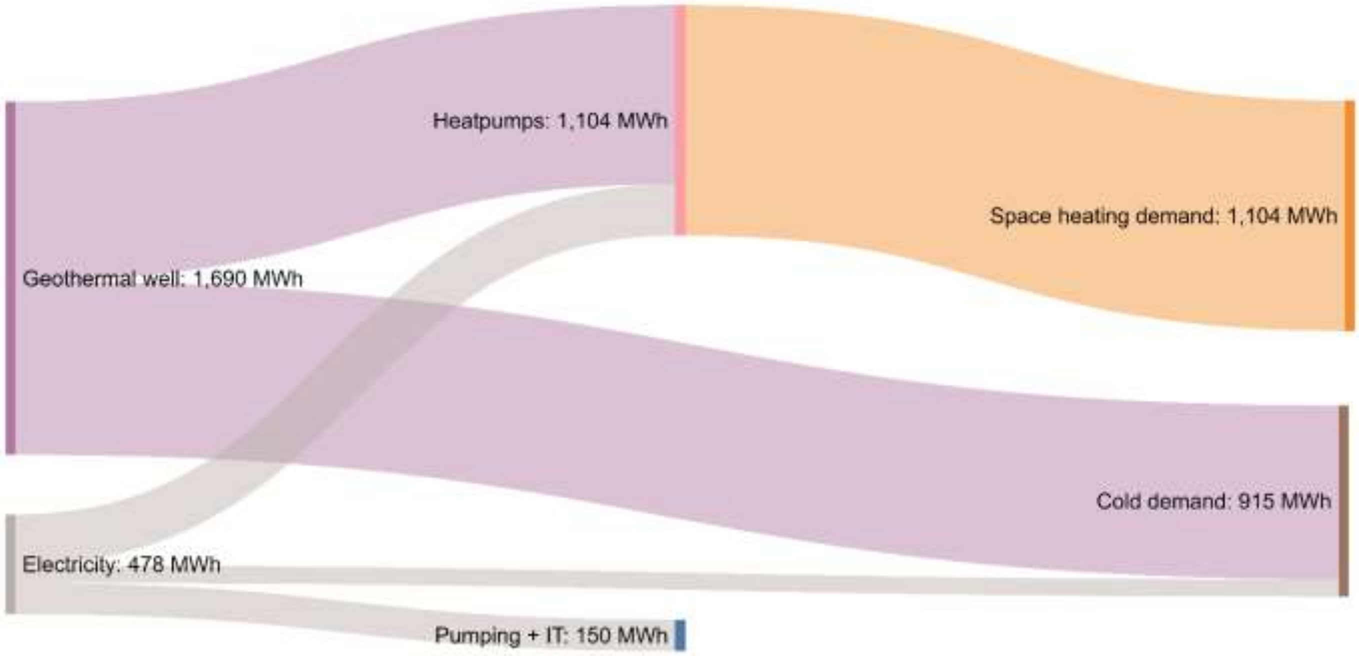

Figure 14. Sankey diagram of the Genk system.

Paris

The district heating and cooling network of Paris is located in the southern area Paris-Saclay. Paris-Saclay is a cluster of business and research buildings and a large university with a campus. Originally, the network used only gas boilers as its heat source and cooling towers as a cold source. These two sources were used in combination with HPs. Which cools down and heats up the water before it reaches the end-users. For DHW, also booster HPs are installed in the residential buildings within the network. Since the end of 2021, a geothermal well has been installed, for making the transition from a 3gDHC to potentially 5gDHC. This geothermal well is mainly used as a source and not as storage because the aquifer that is utilized is also a backup drink water reservoir for the residential area. This means it cannot be heated up any further. Paris-Saclay is still under construction and will be expanding in end-users. Today, there are 48 buildings connected to the DHC system. However, in 2027, it is planned that there will be 76 buildings connected. In Table 13 and Figure 16, the difference in the scoring of the system before and after the usage of the geothermal well is shown. The different KPI scores for Paris are shown in Table 13 and the standardized scores in Figure 16.

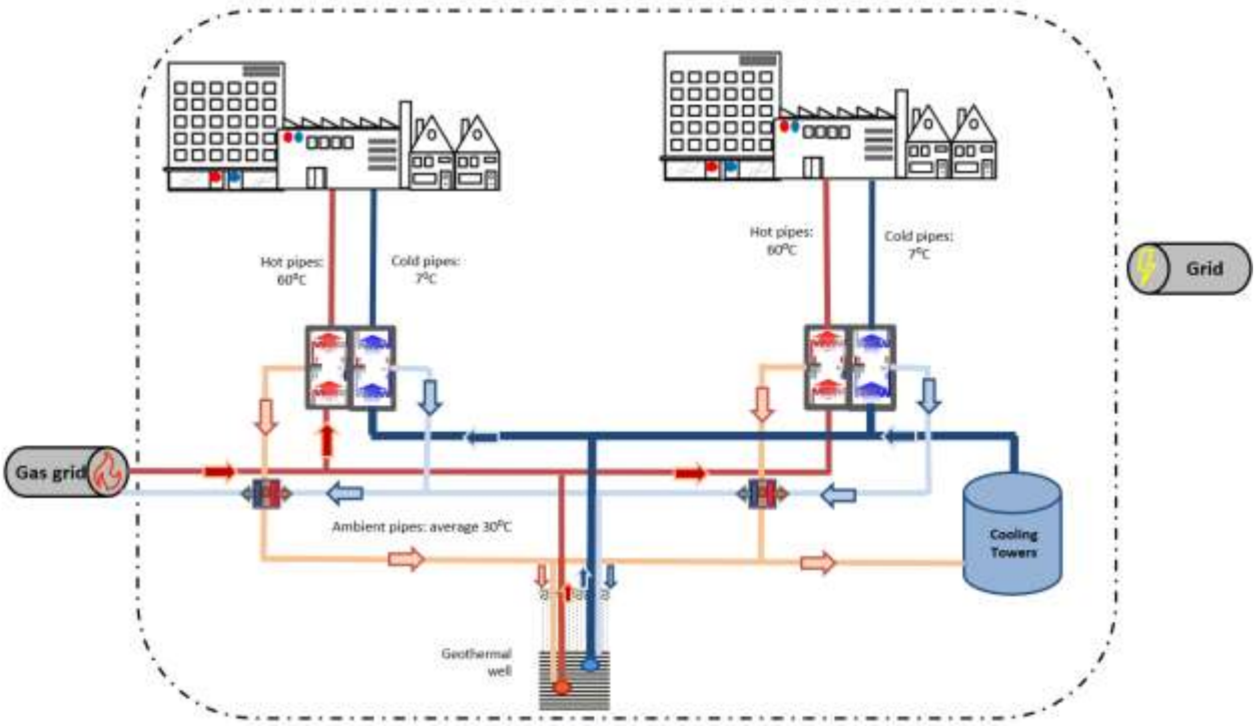

Figure 15. Schematic overview of the Paris network

Closing the loop

The Paris network scored originally 0% on the first KPI. This is because all the heating was done by the external gas boilers. The cooling is done by the cooling towers. These cooling towers are in reality internal sources, but because cooling towers emit waste heat into the outdoor environment, it is considered external, because it is the opposite of closing the loop. After the installation of the geothermal well, 84% of the energy will be from internal sources.

Low-graded energy

Before the geothermal well, the energy from the gas boilers and the electricity were high graded and the energy from the cooling tower low graded. In the other scenario, also the geothermal energy was added to the low graded energy. This results in a score of 11% before and 54% after the geothermal well.

Decentralized and demand-driven energy supply

On KPI 3.1, the Paris network scores the same for the situation before and after the geothermal well. With 1% the system scores a standardized 10 on this KPI. This is because the temperature in the ambient loop is relatively high, which causes it to be close to the hot pipe temperature, which is the longest, so has the most impact within the formula. For KPI 3.2, Paris scores 8% before the upgrade of the system and 15% after. This is because of the addition of several energy centers together with the geothermal well.

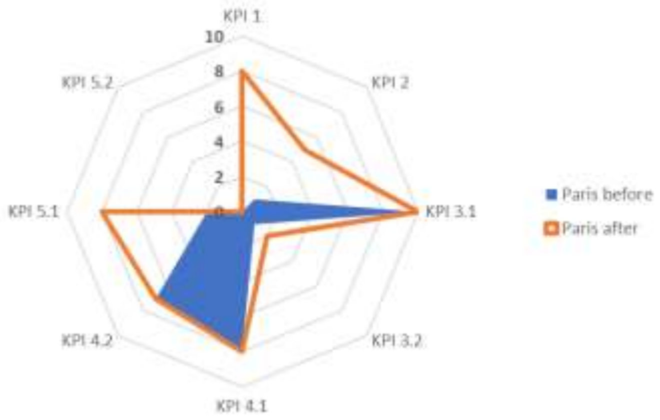

Figure 16. The standardized scores of the KPIs for the Paris with and without the Geothermal well.

Table 13. The results of the KPIs for Paris with and without the Geothermal well.

	Paris before	Paris after
KPI 1	0%	84%
KPI 2	11%	54%
KPI 3.1	1%	1%
KPI 3.2	8%	15%
KPI 4.1	12%	15%
KPI 4.2	7%	7%
KPI 5.1	17%	84%
KPI 5.2	0%	0%

An integrated approach of energy flows

On the capacity KPIs, Paris scores for the heating before the geothermal energy 13% and after 12%. This decrease is only marginal because, together with a capacity increase, also the energy demand increases in the after situation. The cooling capacity KPI scores 7% for both situations. Both KPI 4.1 and 4.2 show that there is still room for more connections to the network. This is also planned for the coming years.

Local sources as a priority

Before the geothermal well, the Paris grid was not very focused on local sources. Only 16.6% of the thermal primary energy was produced locally (cooling tower). Furthermore, all electricity was from the grid. After the geothermal well, the percentage of local energy has risen to 64.8%.

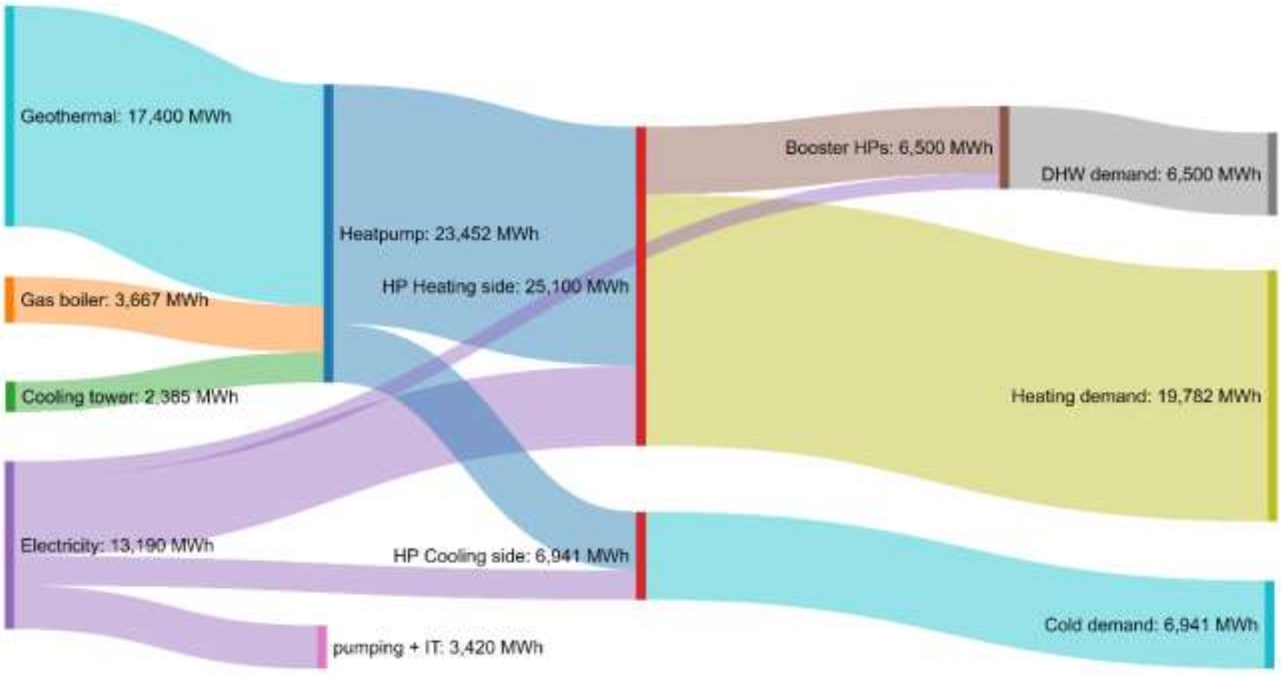

Figure 17. Sankey diagram of the Paris system after the construction of the geothermal well.

Overall, the four assessed networks perform well on the developed 5gDHC KPIs. In Table 14, all the results, standardized by the decision trees, are shown. The average score of the KPIs of all the systems is 6.3. However, if only the complete systems (Brunssum CapCall and Paris after the geothermal well) are taken into account, the average of the KPIs is 7.1. The KPI that is scored the worst is KPI 5.2, which indicates the amount of electricity self-produced. Only Bochum, and Brunssum after the Capcall, are planning to install PV panels, in order to produce electricity. The electricity of Bochum is also partly produced by the CHP system, which is still questionable because of the use of gas. However, it is self-produced and therefore taken into account in this KPI.

Another KPI that scores not very high is the decentralized KPI. This means that there are not so many energy stations per end-consumers. So, self-exchange between the end-users is difficult, because the energy first needs to return to a station, to be used again. Ideally, you want a 1:1 ratio, so that every end-user has its own station, so the energy can be personalized per user.

Table 14. The standardized scores for all the KPIs for the 4 different case studies.

Scores	**Bochum**	**Brunssum**	**Brunssum CC**	**Paris before**	**Paris after**	**Genk**	**Average**	**Average finished systems**
KPI 1	6	5	10	0	8	10	**6.5**	**8.5**
KPI 2	5	9	8	1	5	7	**5.8**	**6.3**
KPI 3.1	6	5	5	10	10	9	**7.5**	**7.5**
KPI 3.2	10	2	2	1	2	10	**4.5**	**6.0**
KPI 4.1	9	0	9	8	8	8	**7.0**	**8.5**
KPI 4.2	8	8	8	7	7	9	**7.8**	**8.0**
KPI 5.1	8	10	10	2	8	10	**8.0**	**9.0**
KPI 5.2	7	0	4	0	0	0	**1.8**	**2.8**
Average	**7.4**	**4.9**	**7.0**	**3.6**	**6.0**	**7.9**	**6.3**	**7.1**

The 4 pilot sites score well on KPI 1, 4.1, 4.2, and 5.1. These are about the amount of thermal energy used internally or locally (KPI 1 and KPI 5.1), or the heating (KPI 4.1) and cooling capacity (KPI 4.2). Thermal energy is one of the main components in which 5gDHC distinguishes itself from older generations because the usage of biomass and gas for CHPs is penalized in some of the KPIs.

It is also understandable that the Capacity KPIs (4.1 and4.2) score well, as this data is from moslty designed systems, because there is no operational data for this yet. The system’s capacity is designed on the designed data, so it is convenient that the systems score well. However, it validates that this KPI gives a good indication of the principles.

Overall the case studies score good but varied. For example, on the one hand, Bochum does not score bad on any single KPI, but on most of them relatively average. On the other hand, Genk scores on all the KPIs very high, except for the 0% on KPI 5.2.

4.2 Cost-Benefit analysis

For the CBA, the environmental and economic impact of 5gDHC is assessed. First, the environmental costs are determined. Secondly, the financial indicators are calculated. Lastly, the environmental costs and the LCOE will be combined in order to see the total costs of the different energy solutions.

Environmental impact

First, the different air pollutants are calculated separately; the emissions as well as the environmental costs, for the low and the high scenario. Later, the total environmental costs will be determined for every system in total and per unit of supplied energy.

In Table 15, the results of the separate environmental impact of the different air pollutants are shown. Per pollutant, the amount of emissions is shown on the left side of the table and the environmental costs are shown on the right side of the table.

Table 15. The amount of emission per pollutant and the corresponding environmental costs for the lower and upper scenarios for all four alternatives. Between the brackets are the fuels that are used.

4gDHC (Biomass & electricity)

Pollutant	**Emissions [kg]**	**Costs lower scenario [€]**	**Costs upper scenario [€]**
CO2	48,657	€ 644.56	€ 2,578.20
As	0.00	€ 0.69	€ 1.20
Cd	0.06	€ 53.57	€ 122.92
CO	2666.6	€ 216.65	€ 447.43
Hg	0.00	€ 71.63	€ 155.10
NH3	173.09	€ 3,764.23	€ 9,324.60
Ni	0.01	€ 0.77	€ 2.32
NMVOC	1403.5	€ 2,494.34	€ 4,880.23
NOx	425.72	€ 11,325.75	€ 25,236.21
Pb	0.13	€ 553.14	€ 919.71
PM10	668.98	€ 23,483.98	€ 51,029.65
PM2.5	654.95	€ 41,066.24	€ 88,205.65
SOx	51.46	€ 1,005.48	€ 2,198.43
Total		**€ 84,681**	**€ 185,102**

Domestic gas boilers (Natural gas & electricity)

Pollutant	**Emissions [kg]**	**Costs lower scenario [€]**	**Costs upper scenario [€]**
CO2	245,385	€ 3,250.57	€ 13,002.27
Hg	0.00	€ 12.09	€ 26.18
NMVOC	7.96	€ 14.15	€ 27.68
PM10	0.88	€ 31.04	€ 67.46
NOx	185.71	€ 4,940.71	€ 11,008.96
As	0.00	€ 0.41	€ 0.72
CO	97.28	€ 7.90	€ 16.32
SOx	1.33	€ 25.92	€ 56.67
Pb	0.00	€ 0.03	€ 0.05
Cd	0.00	€ 0.00	€ 0.00
PM2.5	0.88	€ 55.45	€ 119.10
Total		**€ 8,338.27**	**€ 24,325.40**

5gDHC operational (Electricity)

Pollutant	**Emissions [kg]**	**Costs lower scenario [€]**	**Costs upper scenario [€]**
CO2	124,493	€ 1,649	€ 6,597
Total		**€ 1,649**	**€ 6,597**

5gDHC Designed (Electricity)

Pollutant	**Emissions [kg]**	**Costs lower scenario [€]**	**Costs upper scenario [€]**
CO2	76,040	€ 1,007	€ 4,029
Total		**€ 1,007**	**€ 4,029**

For the CO_2 emissions, the DGB alternative scores the worse, as it is using a non-renewable energy source. The 4gDHC alternative emits the least CO_2, this is because biomass has a low CO_2 emission factor and this alternative uses only a relatively small amount of electricity which is partly generated by PV panels. The 5gDHC operational emits the second most CO_2, followed by the 5gDHC designed. The operational system scores worse than the future designed systems, as PV panels will replace some of the electricity from the grid.

For the other pollutants, the electricity of the national grid does not count, as these pollutants have an impact on local health and the environment. The 5gDHC alternative only uses electricity from the grid or from PV panels, and clean geothermal energy, as a result, the two 5gDHC alternatives do not emit any other air pollutant.

The 4gDHC and the DGB alternative both do emit other air pollutants. Biomass emits more different, as well as higher quantities of, pollutants. For example, it emits a magnitude 2 more NO_X than the DGB alternative, for SO_2 a magnitude of almost 40 and $PM_{2.5}$ even a magnitude of 700.

In Figure 18 and Figure 19 the total costs of the different alternatives are shown for both scenarios. Due to their relatively high shadow costs, $PM_{2.5}$, PM_{10}, and NO_X have a large impact on the total environmental costs.

The 5gDHC designed system scores the lowest with only € 1,007 in the low scenario and € 4,029 in the high scenario. As second, the operating 5gDHC alternative has environmental costs of € 1,649 (lower scenario) and € 6,596 (higher scenario). The DGB alternative has environmental costs of € 8,338 (lower scenario) and € 24,325 (higher scenario). Lastly, the 4DHC alternative has substantially higher environmental costs of € 84,681 in the low scenario and € 185,102 in the high scenario. The biggest costs for the 4gDHC system are $PM_{2.5}$ and PM_{10}, followed by NO_X.

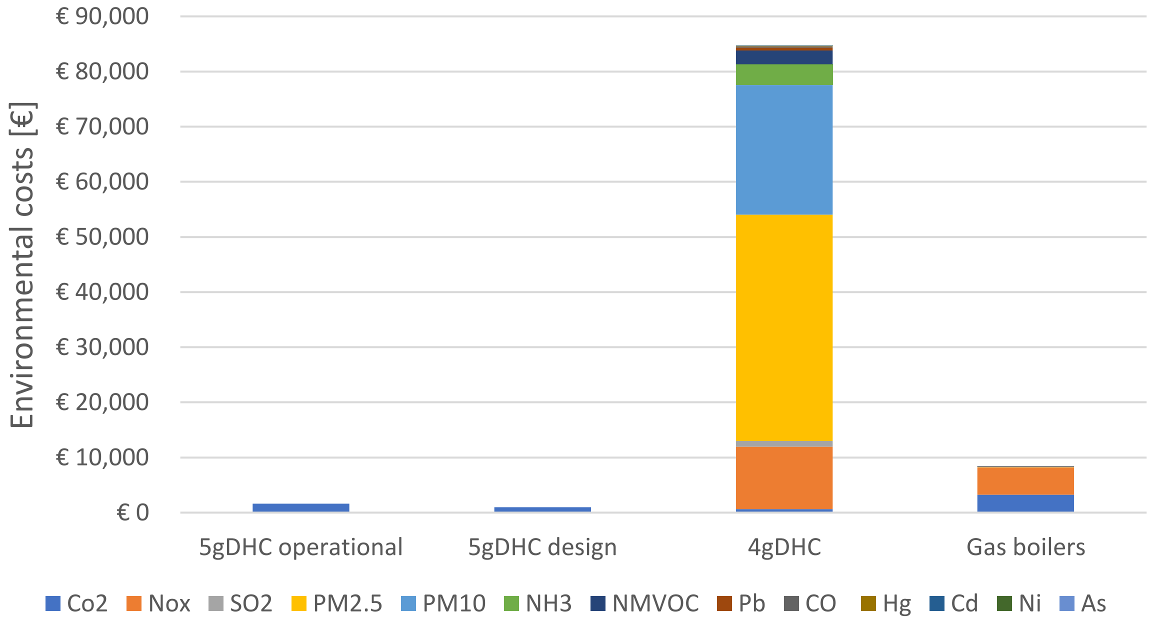

Figure 18. Environmental costs per technology for the low scenario per year.

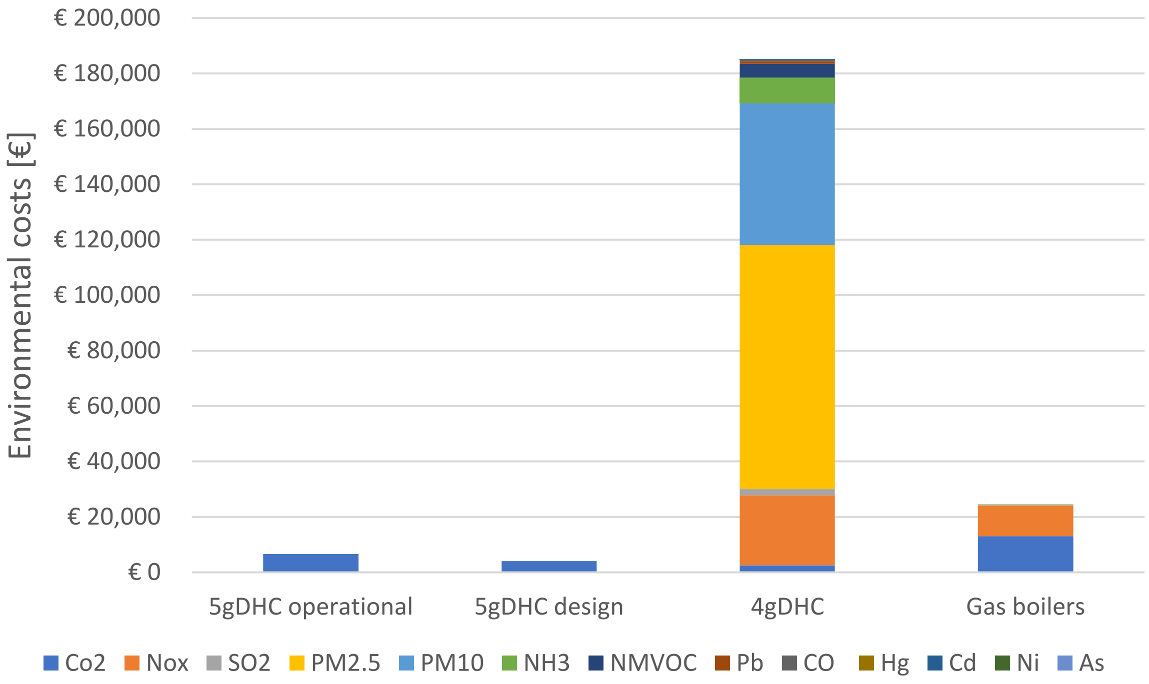

Figure 19. Environmental costs per technology for the high scenario per year.

The total environmental costs can be converted to the environmental costs per energy unit. With this measurement, it is better comparable with other cost parameters. Figure 20 shows the results of this conversion. For the gas alternative, it results in € 0.0074 per kWh (low scenario) and € 0.0215 per kWh (high scenario), for the 4gDHC € 0.0643 and € 0.1405 per kWh, for the 5gDHC operating € 0.0014 and € 0.0055 per kWh, and the designed 5gDHC € 0.0008 and € 0.0034 per kWh.

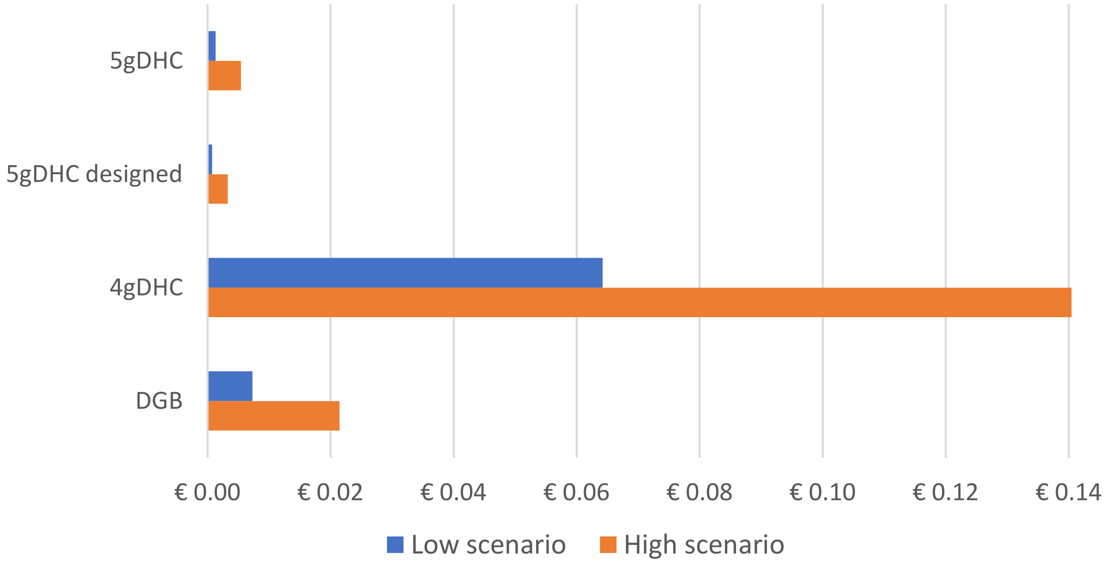

Figure 20. The total environmental costs of the different alternatives.

Economic impact

For the financial impact, three measurements are calculated to determine the economic performance of the different alternatives. Firstly, the CAPEX assesses the investment costs of the different systems. Secondly, the OPEX indicate the costs of the systems during operations. Lastly, the LCOE determines the levelized costs of the energy output per energy unit.

CAPEX & OPEX

Table 16 displays the CAPEX and the OPEX for the 4 alternatives.

Table 16. The CAPEX and the OPEX of the different alternatives.

	Capex [€/kW]	CAPEX based on Brunssum [€]	OPEXvar [€/kWh]	OPEXfix [€/kW]	OPEX based on Brunssum [€]
5gDHC	€ XXXXX[2]	€ XXXXXX[2]	NA	€ XXXXX[2]	€ XXXXX[2]
5gDHC designed	€ XXXXX[2]	€ XXXXXX[2]	NA	€ XXXXX[2]	€ XXXXX[2]
4gDHC	€ 1,422	€ 1,039,841	€ 0.03	€ 97.72	€ 103,309
DGB	€ 83.03	€ 95,150	€ 0.05	€ 1.66	€ 63,316

The CAPEX of the DGB alternative is significantly lower than the other systems (magnitude 10). This is mainly because the other solutions are district energy systems, which require a pipe network. These networks have high upfront costs as it needs to be newly constructed. It is assumed that for the gas alternative no new infrastructure needs to be created.

The CAPEX of the 5gDHC is also substantially higher than the 4gDHC, this is probably due to the fact that 5gDHC is a new concept, which is not commercially available. Features such as the large ATES system and the booster HPs at the customers of the 5gDHC are all costly investments.

The OPEX for the district heating systems is, on the other hand, relatively similar. However, this is again higher than the DGB alternative. Operating an energy network also requires electricity for the transport pumps and the IT of the systems. Furthermore, newer technologies need most of the time higher maintenance costs. The 5gDHC does not have variable OPEX, as the only fuel they use is electricity, and these costs are directly charged from the customers.

Levelized costs of energy

The LCOE calculates the total levelized costs of the total system during its entire lifetime.
It takes into account the CAPEX, OPEX, discount rate, and expected lifetime of a system.
For the discount rate, 3% is taken. For the lifespan, the district heating is set to 30 years and for the DGB, it is 20 years. In Table 17, the LCOE of the different alternatives is shown.

Table 17. The calculated LCOE of the different alternatives

	LCOE [€/kWh]
5gDHC	€ 0.282
5gDHC design	€ 0.360
4gDHC	€ 0.117
DGB	€ 0.062

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[2] Known by the author, you can contact jibbebertholet@gmail.com for inquiries.

The two 5gDHC are the most expensive solutions. This is a result of the extremely high CAPEX. The 4gDHC is the third most expensive. The DGB alternative has an LCOE of almost half the LCOE of the 4gDHC. This shows that based, solely on the LCOE, 5gDHC seems not very promising.

Total costs

The environmental and levelized financial costs of the systems are combined in Figure 21 and Figure 22.

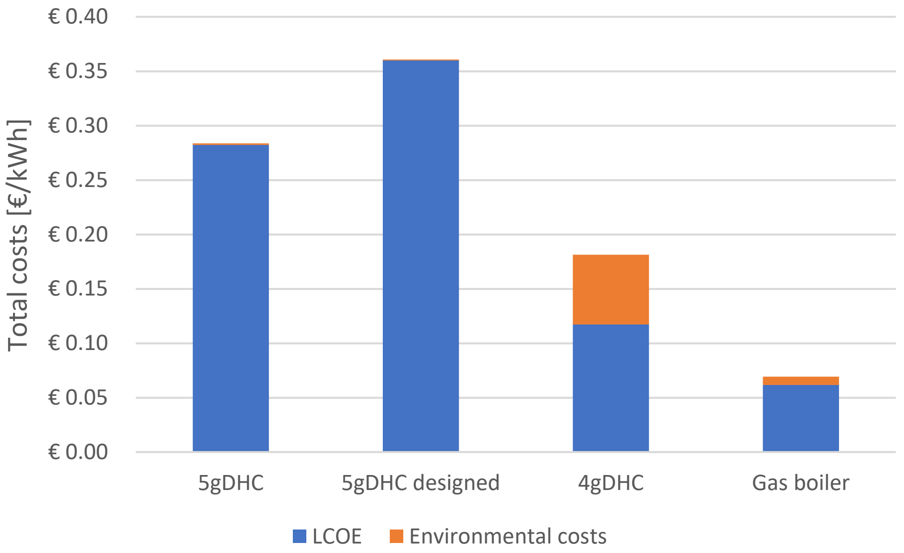

Figure 21. The LCOE combined with the environmental costs of the low scenario in €/kWh.

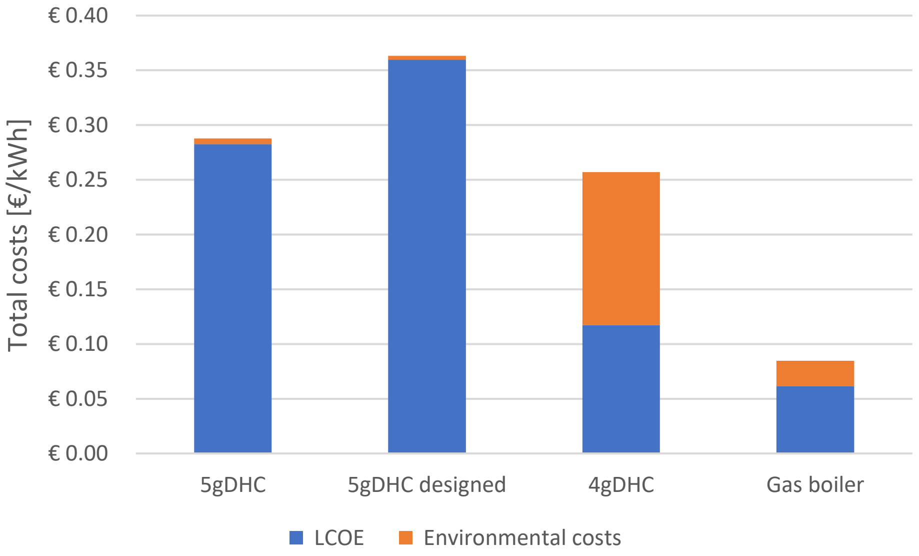

Figure 22. The LCOE combined with the environmental costs of the upper scenario in €/kWh.

In both scenarios, the order from cheap to most expensive stays the same, namely, DGB, 4gDHC, 5gDHC operational, and 5gDHC designed. However, in the high scenario, the difference between the 5gDHC and 4gDHC decreased by more than half. The environmental costs are, in the low scenario, 55% of the total costs of the 4gDHC, so has a substantial impact. Also, the DGB alternative increases by 12%, because of these costs. For the 5gDHC alternatives, the environmental costs are less than 1% of the total costs. For the higher scenario, the environmental costs are 119% of the LCOE for the 4gDHC, 37% for the gas alternative, 2% for the 5gDHC operating, and 1% for the 5gDHC designed.

So, although the environmental costs do compensate for a large share the financial costs of the 5gDHC alternatives, it is not enough to make it less expensive if we combine it with the LCOE.

Sensitivity Analysis

In the economic part of the CBA, there is some uncertainty. For example, the discount rate is something that is a large discussion in the literature. But also the gas prices and the CAPEX of the 5gDHC are variables that can change in the (near) future.

Because of this uncertainty, a sensitivity analysis is conducted. First, the change of the LCOE of the four alternatives is assessed if the discount rate changes. After, also other parameters are changed in order to calculate possibilities for future LCOEs.

For the calculations of the first analysis, only the discount rate changes, the other variables used are the same as the LCOE calculation of the economic impact chapter are used. The results are shown in Figure 23.

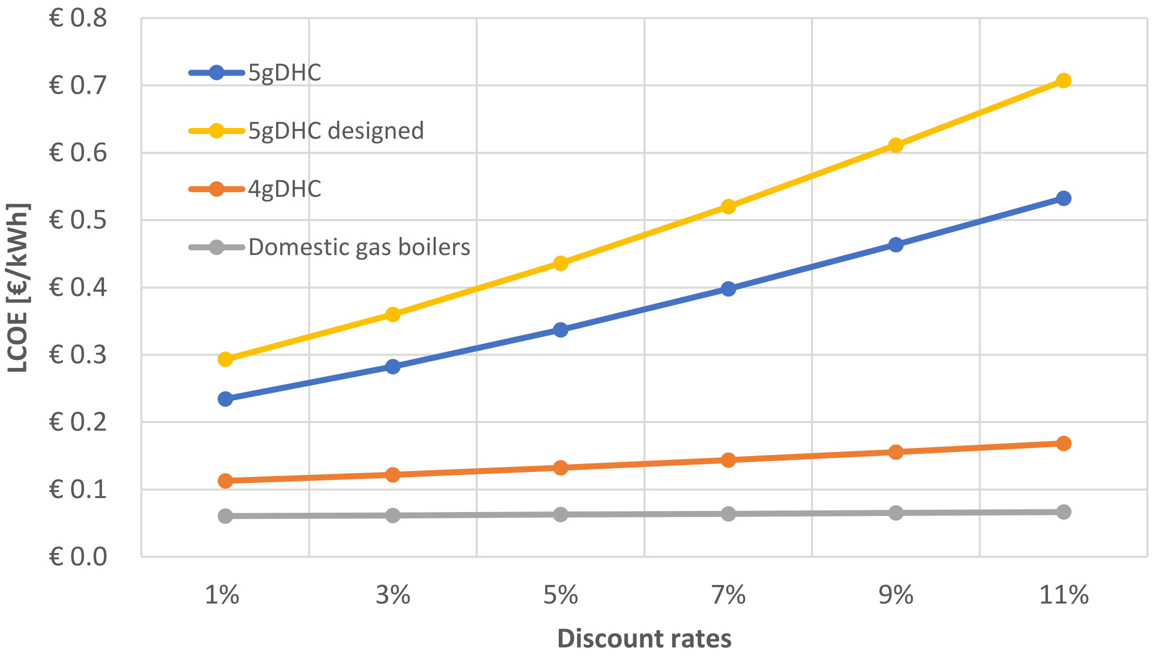

Figure 23. The change in LCOE with different discount rates for all the alternatives.

The change in the discount rate is more important for systems with relatively high CAPEX compared to OPEX. This is especially the case for the 5gDHC alternative. The gas alternative has a very low CAPEX, which results in an almost flat line. This means that it does not matter what discount rate is used for this alternative.

In the second analysis, a random probability generator is used to create a set of multiple results. A normal distribution is created with a mean and standard deviation. Table 18 shows the variables that are varying during the sensitivity analysis, together with their mean, standard deviation, and the possible range of the probability. Because the investing costs of the 5gDHC are likely to decline in the future, a larger standard deviation is taken and only the probability of 0 to 0.5, so it can only decrease compared to the mean. Furthermore, because of the increasing gas prices, the OPEX of the DGB alternative also has a larger standard deviation, and only the probability range is from 0.5 to 1, so it only increases compared to the mean. Furthermore, for the other variables, a 10% change compared to the mean is taken into account, except for the DGB CAPEX, as it is a mature technology, so it is probably not going to change enormously in the future.

Table 18. The changing input variables of the sensitivity analysis.

	Variable	**Mean**	**Standard deviation**	**probability**
5gDHC	CAPEX	€ XXXXXX[3]	33% of mean	0 - 0.5
	OPEX	€ XXXXXX[3]	10% of mean	0 - 1
5gDHC designed	CAPEX	€ XXXXXX[3]	33% of mean	0 - 0.5
	OPEX	€ XXXXXX[3]	10% of mean	0 - 1
4gDHC	CAPEX	€ 999,828	10% of mean	0 - 1
	OPEX	€ 103,309	10% of mean	0 - 1
DGB	CAPEX	€ 95,150	5% of mean	0 - 1
	OPEX	€ 63,316	33% of mean	0.5 - 1

In figures Figure 24 to Figure 27, the results of the sensitivity analysis are shown. For every discount rate scenario, 500 simulations have run. The line in the middle of the box is the median, and the outer lines of the box are the 1st and 3rd quartiles. the two extremities of the lines outside the box show the minimum and maximum LCOE from the distribution model. Isolated dots outside these lines are outliers.

The results show that for the scenarios of 5gDHCs, the boxplots are very skewed to lower prices, which is logic, as we set that only the probabilities for lower prices are possible. The LCOE is € 0.11/kWh (discount rate: 1%) to € 0.55/kWh (discount rate: 11%) for the operating 5gDHC and the designed 5gDHC shows a range from € 0.12/kWh to € 0.75/kWh.

For the gas alternative, it is the other way round, as we only set possible probabilities for higher gas prices. The range of LCOE for this alternative is from around € 0.06/kWh (discount rate: 1%) to approximately € 0.11/kWh (discount rate: 11%).

The 4gDHC has an LCOE that shifts from around € 0.08/kWh (discount rate: 1%) to almost € 0.20/kWh (discount rate: 11%).

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[3] Known by the author, you can contact jibbebertholet@gmail.com for inquiries.

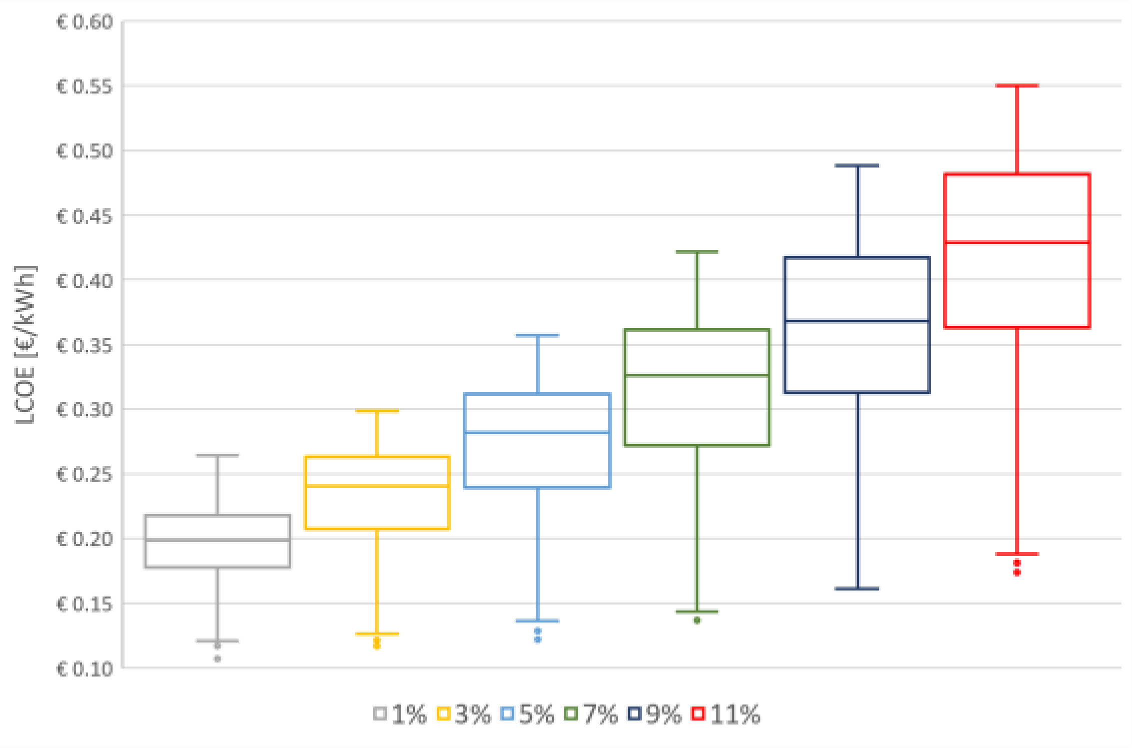

Figure 24. Results of the second sensitivity analysis for the 5gDHC alternative with different discount rates.

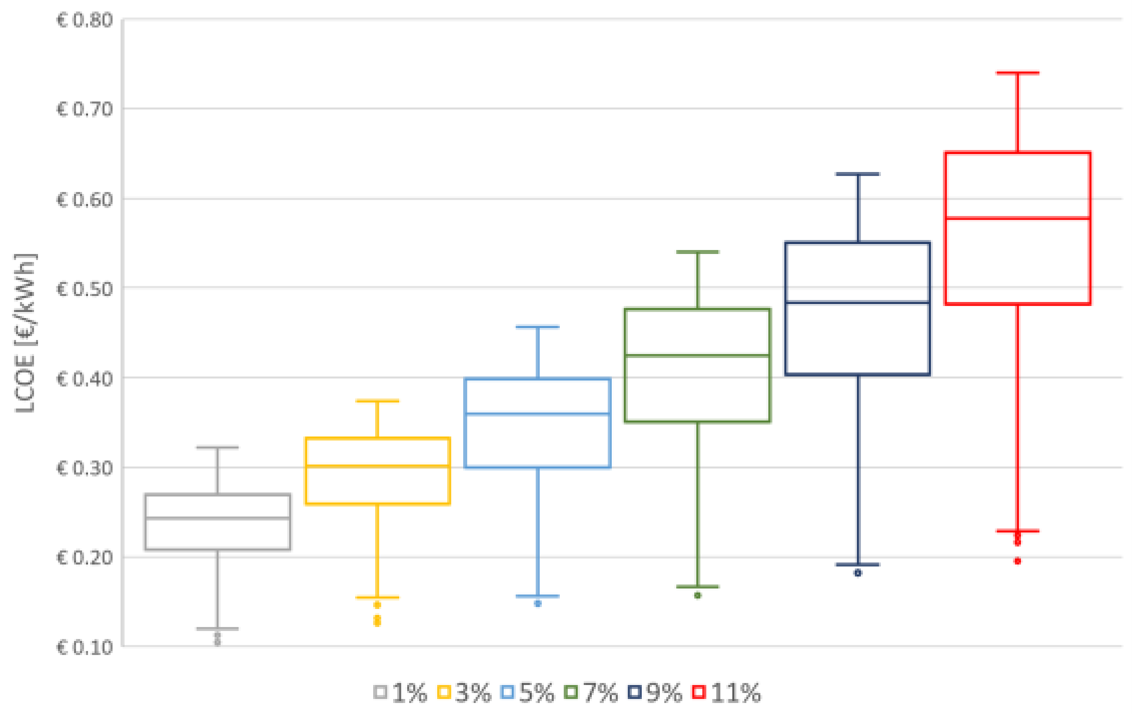

Figure 25. Results of the second sensitivity analysis for the 5gDHC designed alternative with different discount rates.

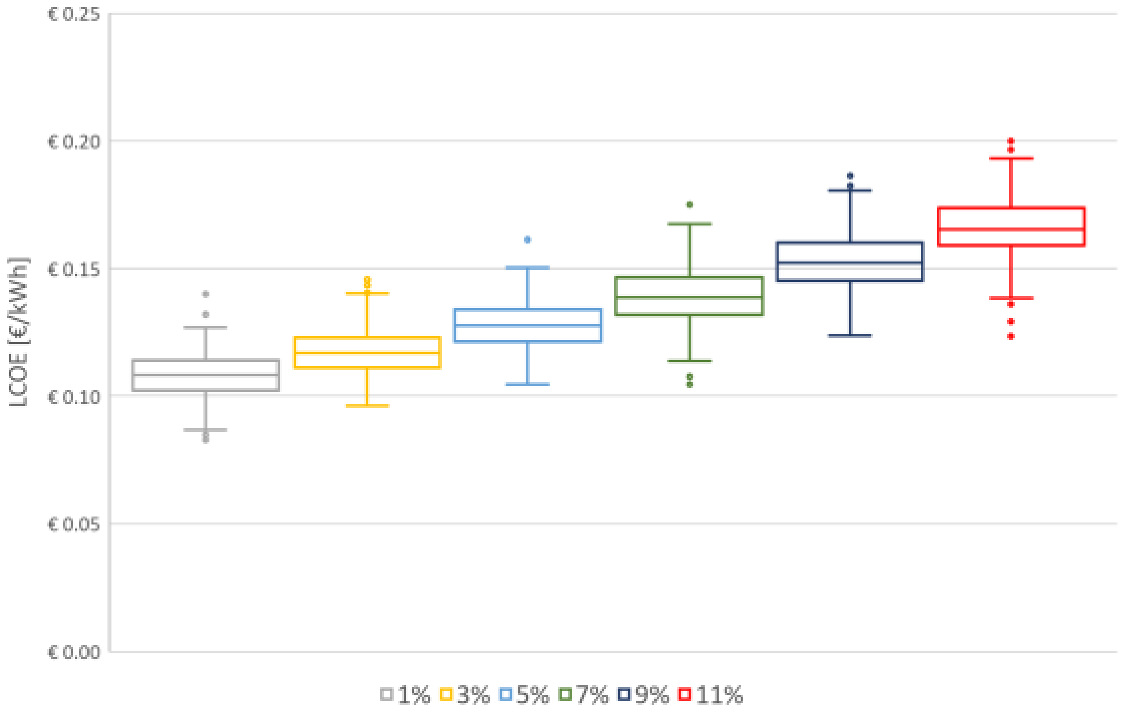

Figure 26. Results of the second sensitivity Carlo analysis for the 4gDHC alternative with different discount rates.

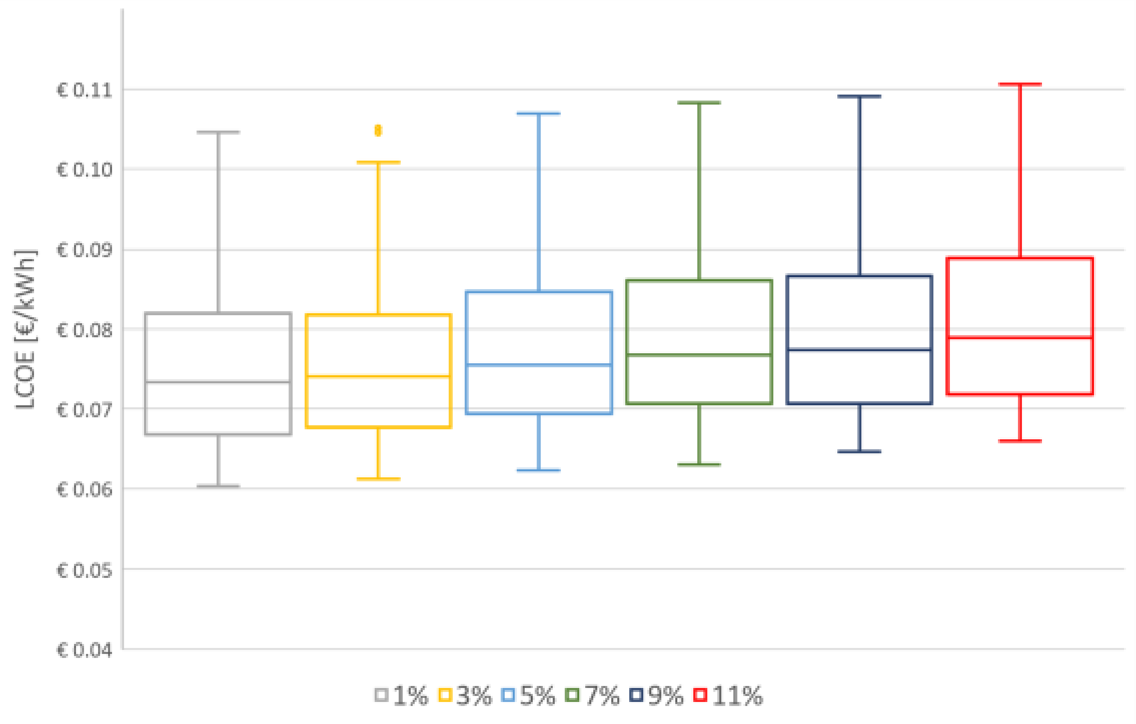

Figure 27. Results of the second sensitivity analysis for the DGB alternative with different discount rates.

The CBA assesses 4 different heating and cooling solutions on two impacts; the environmental and economic.

The environmental impact is based on the emissions factor of the energy sources used and the associated shadow costs of these emissions. These two together estimate the total environmental costs of a system. For the shadow costs, there are the low scenario and the high scenario. In this assessment, the 4gDHC with the centralized biomass boilers scores, the worst with € 0.036/kWh in the low and € 0.080/kWh in the high scenario. The DGB alternative scores € 0.007/kWh (low scenario) and € 0.021/kWh (high scenario). The 5gDHC scores significantly lower than the alternative solutions with a total environmental cost of € 0.001/kWh (Low scenario) and € 0.005/kWh (high scenario) for the operational system and even lower for the designed system.

The economic impact is mainly assessed by the LCOE. The 5gDHC has the highest LCOE with € 0.394/kWh with for the designed system and € 0.278/kWh for the operational system. The 4gDHC has an LCOE of € 0.117/kWh, and the DGB alternative € 0.036/kWh. The large differences in the LCOE are mainly due to the high CAPEX of the 5gDHC, with € 5.1 million for the operational system and even € 7.1 million for the system after the CapCall. The 4gDHC has a CAPEX of € 1.0 million and the DGB only € 95.1 thousand. The OPEX lies for the different alternatives closer to each other. Although the DGB cost only € 63.3 thousand annually, the 4gDHC and the 5gDHC cost € 103 thousand.

Table 19. The total costs for the alternatives with a discount rate of 3%, for the lower and upper scenario in €/kWh.

	5gDHC	**5gDHC designed**	**4gDHC**	**DGB**
Lower scenario	€ 0.28	€ 0.36	€ 0.18	€ 0.07
Upper scenario	€ 0.29	€ 0.36	€ 0.26	€ 0.08

If the environmental and LCOE are combined, the total costs per kWh for the energy supplier are determined. The total costs for both scenarios are shown in Table 19. For the lower scenario, the impact of the environmental costs is substantially lower than in the higher scenario. In the higher scenario, the 5gDHC alternative is only € 0.03/kWh lower than the 4gDHC. However for both scenarios, is the sequence the same, with gas significantly lower than the rest, followed by the 4gDHC.

Lastly, the sensitivity analysis shows the different results, when variables are changed within the LCOE. The first analysis showed that a lower discount rate results better for the alternatives with higher CAPEX, which are the two 5gDHC alternatives. Furthermore, doing the sensitivity analysis for several variables, shows that some changes can have a large impact on the outcome of the LCOE. Especially for the 5gDCH scenario, where it is assumed that the CAPEX will decrease due to the learning and experience curve. And for the gas alternative where the OPEX will probably increase in the future because of increasing gas prices.

4.3 Multi-criteria analysis

The MCA compares the social impact of 5gDHC to three alternative heating and cooling systems. Firstly, the different indicators are all elaborated on how and why they score the alternatives. Secondly, the scores are standardized and weight factors are given to the different alternatives. Lastly, with these scores and weight factors, a final score is calculated.

Indicators

Urban heat island effect

Energy usage in the city increases the temperature in the urban environment, for example, cars, but also AC. With AC it works in a vicious circle (Ouali, El Harrouni, Abidi, & Diab, 2018) It starts with high temperatures, which causes more ACs to be used, which will emit more heat to the urban environment, which causes even hotter urban temperatures, resulting in more AC to be used. Especially during nighttime, when cities already tend to cool down slowly, the AC effect seems to be higher (de Munck, et al., 2013; Salamanca, Georgescu, Mahalov, Moustaoui, & Wang, 2014). Furthermore, also the heat that is produced during the combustion of fuel can contribute to heating the urban area (Emilsson, 2021). On the other hand, DHC networks that operate at lower temperatures can absorb heat, and therefore have a positive effect on the UHI. A study on the impact of geothermal energy on the UHI shows that urban aquifers can have a positive influence on the UHI (Zhu, et al., 2010). The aquifers can be heated up to 5ºC due to the UHI. This heat can later be used for space heating with a DHC. It not only reduces the heat in the city but also uses it for heating later.

In this study, it is assumed that in the alternatives DGB and the 4th gen district heating without cooling, the cooling demand is fulfilled with individual residential AC units. That is why these alternatives do score negative on this criteria. The individual boiler scores - - as it only emits its heat and cooling to the outside. The 4gDH scores one – as the heating system also has a return flow that returns cooled water back to the system after it has delivered its heat. Also, it operates at a relatively cooler temperature. The 4gDHC scores + as it does not uses AC units but cools with the district energy systems, so it also takes back the heat to the geothermal well. Its only drawback is that there is still combustion from the biomass boiler and it operates at a higher temperature than the 5gDHC. The 5gDHC does not have this combustion, so scores + +.

Noise

Noise pollution from energy systems is mainly caused by moving air, such as air HPs or AC. The average HP has a sound pollution of around 50 decibel (dB) (Zhang, Hu, Geng, Hu, & Wang, 2020), AC units have noise pollution between 45 and 50 dB (Iannace, Ciaburro, & Trematerra, 2018), and DGB have noise pollution lower than 40 dB (Chevret, Coulon, Bessac, & Parizet, 2008). It is assumed that a centralized biomass boiler will be placed on a strategic spot, far enough from the residential area, so it will not cause much noise pollution.

5gDHC has booster HPs at all end-users and several more HPs on a cluster level, for heating purposes. For cooling, it does not use AC, but passive cooling from the cooling grid, which emits no noise. So in total, it scores medium with 0. The 4gDHC scores relatively good with +, because it uses less HPs than the 5gDHC and also cools with the district heating system. For the 4gDH and the DGB, it is assumed that the cooling demand is covered by AC units. They both score relatively bad for the cooling aspect of the system. The 4gDH also uses a few HPs, so it scores low on this indicator with -. Residential gas boilers are relatively quiet devices compared to HPs so for this the gas alternative scores better. In total, with the AC, it scores a +.

Land use

Land use of an energy system includes the heating devices, infrastructure, and also the surface that is needed to extract the fuel (e.g. gas and biomass). In addition, urban areas are more costly to use than rural areas, as there is in general less space available. Hoogwijk et al. (2005) state that mostly the former USSR, East Asia, and South America have a high biomass potential. Europe has a relatively low potential and this is most likely not increasing the next decades.

For the 5gDHC, the main land uses are the control centers and energy centers with heat and transportation pumps. These buildings are close to the end-users, so in the urban area. Moreover, the geothermal well also uses some land, but it mostly uses the land vertically and has no large surface (U.S. office of Energy Efficiency & Renewable Energy, N.D.). Furthermore, within the households, an extra booster HP with a buffer vessel needs to be installed within the customer's building. In total, the 5gDHC scores a – on land use. The 4gDHC and the 4gDH both use, in addition to the geothermal well, the biomass boiler as a heating system. Biomass requires, cultivating the crops, which also uses space. Therefore both 4g alternatives score - -. The DGB only has a boiler unit in the customer's building. It is assumed that the gas is not from a well near the system so does not have a local impact. That is why the gas alternative scores very high with + +.

Local employment

Energy systems can create working opportunities. These opportunities can be temporary and permanent jobs. Temporary jobs are the installation and construction jobs that are needed to deploy the system. Permanent jobs are the jobs that are needed for controlling the operations of the system and to do the billing of the energy delivered.

For the 5gDHC, the construction of the system is relatively complex, with many pipe systems, a geothermal well, energy centers, and the connections of the customers. Furthermore, during the operations, also maintenance and billing are jobs for the grid operator, which is why 5gDHC scores + +. For 4gDHC, it is almost the same and also scores + +. For 4gDH, there is no cooling by the system but by AC units, so it is not the task of the local grid operator but temporary jobs, so it will score a less than the DHCs, with 0. Regarding the gas alternative, for the cooling and the heating, the jobs are mainly temporary, as after the installation there is no real local operational job attached to it. That is why it scores - -.

Import shares

The parts of an energy system that mostly are imported are the electric devices and the fuel. Heavy materials such as pipes are most of the time made relatively locally, as it is not efficient to transport products which such weight. ACs are mostly produced in Asia and the US (Fortune Business Insights, N.D.). For HPs, there are also large manufacturers in Europe and it is expected that Europe will expand at a compound annual growth rate of 8.6% in the coming decade (Grand View Research, 2021). Furthermore, Fuels are also most of the time not cultivated locally. Gas in the Netherlands is 54.2% imported from other countries and 45.8% from its own gas mining, in 2019 (Wolting, 2020). However, the Dutch governance wants to stop gas extraction from its land as soon as possible, as it causes micro-earthquakes in the mining areas (Government of the Netherlands, 2019; Meijer, 2019). As biomass needs large amounts of land to cultivate the fuel, it is not convenient that this is close to the energy systems. Next to this, a study showed that biomass is most suitable and sustainable if some parts are imported so that not too much land will be used and depleted (Chary, Aubin, Guindé, Sierra, & Blazy, 2018).

In the MCA, 5gDHC scores + +, on the import shares indicator. This is because it uses the geothermal well as thermal energy source, which is local. Also, the HPs used by the case study 5gDHC Brunssum are all from EU manufacturers, which is relatively local for such devices. Besides geothermal energy, only electricity is used. It does not score the full amount, because the electricity is from the grid. 4gDHC scores 0, because of the use of biomass for heating. They cool without AC units, which has a positive effect on this score. 4gDH does use AC, so it scores worse with -. the DGB alternative scores the lowest with - -. Although some of the gas is from the Netherlands it scores the minimum score because the Dutch government has said that they want to get rid of the national gas mining it is assumed that in the near future this will be cancelled out. Also, the use of AC for cooling makes this alternative score bad.

Volatile prices

The prices that are most likely to fluctuate over time for an energy system are the costs of electricity and fuels. In the past, electricity and gas prices have mutated almost simultaneously (CBS, N.D.). However, it is expected that in the (near) future, gas prices will increase faster (van Polen, 2020). This is mainly because, nowadays, renewable electricity production is stimulated and becoming popular. Gas on the other hand is slowly cancelled out of the Netherlands. Prices of biomass are being relatively stable over the last years (Bang, Vitina, Gregg, & Lindboe, 2013). In the future, they are predicted to increase, but not as volatile as gas and electricity prices. However, shadow costs for air pollution are foreseen to increase in the future (CE Delft, 2018). The results of the environmental impact showed that biomass emits the most hazardous air pollutants of the alternatives, so that is why biomass prices can still rise higher in the future.

Because 5gDHC, only uses electricity, but electricity still has an unpredictable cost, it only scores +. 4gDHC and 4gDH, use mostly biomass and some electricity. Because biomass has probably high emission costs in the future it scores -. The Gas alternative scores - -, because the gas price is most likely to increase the most and is the most uncertain fuel because it will be cancelled out in the Netherlands.

Air quality

As the CBA showed, heating and cooling systems can emit large amounts of air pollutants and GHGs. Some of those air pollutants can have a very hazardous impact on human health. As the CBA already calculated the emissions (Figure 18 and Figure 19), those scores are translated into the scores in this analysis.

So, 5gDHC scores + +, as it does not emit any air pollutants locally. 4gDHC and 4gDH score both - -. In the results of the CBA, it is shown that the 4gDHC alternative emits many different pollutants in also relatively large amounts. The DGB alternative scores -, as it emits some pollutants, but substantially less than the 4gDH(C).

Scoring

In Table 20, an overview is shown of all the scores given to the four alternatives on the different social impact indicators.

Table 20. The scores of the social impact indicators on the different alternatives.

Social Impact	Unit	5gDHC	4gDHC	4gDH	DGB
UHI	--/ ++	++	+	-	- -
Noise	--/ ++	0	+	-	-
Local Employment	--/ ++	++	++	0	--
Land use	--/ ++	-	--	--	++
Import Shares	--/ ++	++	0	-	--
Volatile Prices	--/ ++	+	-	-	--
Air Quality	--/ ++	++	--	--	-

After the scoring, the scoring system needs to be standardized to make the different indicators better comparable. The standardizing scores are shown in Table 21.

Besides the scores, also weight factors are assigned to all the different indicators. As Noise, prices and air quality have a direct impact on the health of the people living in the area and on their finances, these have the highest weights. As second heaviest, the UHI, land use and local employment, are ranked. This because they all have no direct impact on the people and are not that harmful. The lowest weight is assigned to the import shares, as it not directly impact the local habitants, but it shows that the money paid for products of the system stays within the area. The weight factors are shown in Table 22. These weights together with the standardized scores result in a total social impact score of the different energy solutions. These scores are shown in Table 23.

Table 21. The standardized scores of the social impact indicators on the different alternatives.

Social Impact	Unit	5gDHC	4gDHC	4gDH	DGB
UHI	0 - 1	1	0.75	0.25	0
Noise	0 - 1	0.5	0.75	0.25	0.75
Local Employment	0 - 1	1	1	0.5	0
Land use	0 - 1	0.25	0	0	1
Import Shares	0 - 1	1	0.5	0.25	0
Volatile Prices	0 - 1	0.75	0.25	0.25	0
Air Quality	0 - 1	1	0	0	0.25

Table 22. The weights of the different indicators.

Indicator	Rank order	Weight
Noise	1	0.251
Volatile prices	1	0.251
Air quality	1	0.251
UHI	2	0.091
Land use	2	0.091
Local Employment	3	0.032
Import shares	3	0.032

Table 23. The total social impact of the different alternatives.

Alternative	Social Impact
5gDHC	0.74
4gDHC	0.37
DGB	0.34
4gDH	0.17

In the social impact assessment, the 5gDHC is compared with a 4gDHC, a 4gDH, and a DGB alternative. Based on the seven indicators with their corresponding weight factors, the 5gDHC scores the highest, with a score of 74%, which is double the score of the 4gDHC which is number two, with 37%. The DGB scores 34%, and the 4gDH scores the worst with 17%.

5 Discussion

The assessments of the 5gDHC system show some interesting results, some in favor of the new technology, and others show some drawbacks, compared to alternative solutions. However, there are several points of discussion that can be thought of that influence these results. In this section, the limitations and implications of this study will be discussed, as well as the contribution to previous literature and recommendations for future research.

5.1 Limitations of the methodology and data

An important limitation of this study is the usage of a limited amount of case studies and alternatives. For the KPI analysis, only four case studies were examined. These pilot sites are chosen because of their participation in the EU project D2Grids. These case studies were assessed because of the easy access to their data, via the D2Grids project.

For the CBA and MCA, also only a few alternatives are assessed. For the CBA only a 5gDHC, a 4gDHC, and a DGB alternative were taken into consideration. For the MCA almost the same alternatives were used, in addition, a 4gDH was used as the fourth alternative.

For the three analyses, more possible alternatives could be assessed, for example, a full electric heating alternative, or DHCs with different configurations. However, due to time reasons and data availability, this has not been done.

Secondly, another uncertainty for the KPI analysis is the data used. Firstly, because all the systems are in the design phase or not (fully) operating yet. So all data is from estimations and simulations. Most of these estimations are based on estimated annual averages, for example the energy demand and supply data. However, in real-life this data will fluctuate every year. Especially with climate change, higher and more extreme temperatures are expected in the coming decades. This can result for example, in less heat demand, but higher cooling demand. That is why a more convenient manner to assess systems is to calculate the KPIs for several years in a row, based on operational data, and take the average of these results. However, a system needs to be fully operational for those years already, in order to do such analysis.

Thirdly, the energy usage habits of the customers could also change over time. For example, climate change is a motive for people to try to reduce their energy consumption. A more extreme incentive is the War in Ukraine. The Dutch government has started a national campaign for reducing residential energy usage. An example of this campaign is reducing the room temperature to 19ºC (Dutch Government, N.D.). The Dutch government states that dwellings can reduce their energy usage by 36%.

The data used for the CBA also has some uncertainties.

The shadow costs used are from 2015. These are the most recently published shadow costs from the CE Delft (2018). They state that these values still can be used for a CBA if there is a correction for inflation. This study uses this method. However, the CE Delft (2018) also shows alternative solutions;

for example, an additional increase of 1% or 3.5% per year. Using these options would have resulted in even higher environmental costs for the 4gDHC and DGB alternatives.

Furthermore, the CBA inflation has been taken into account, however, the inflation rate between 2015 and the average of 2021 is used. With the War in Ukraine (March 2022), this inflation has almost doubled compared to the average value used in 2021 (CBS, 2022b). This study assumes that this is an incidental situation, which therefore is not used, because of its uncertainty. However, if the inflation rate of march 2022 was used, the results of the environmental impact would have been also more extreme.

For the economic impact, also several notes can be taken. First of all, the economic data of the 4gDHC and gas alternative are from several years ago. This means that these can be changed during this period. Due to inflation, this can be increased, but as a result of the learning and experience curve, it could also have declined. Due to this uncertainty in both ways, there is no correction for both done in this study.

Furthermore, the economic data used for the 5gDHC is based on only a few months based of operations and some assumptions. This also entails a certain amount of uncertainty. Because every different season brings other heating and cooling demands, so also different costs. This research has tried to correct for this. However, data used from a complete year will entail less uncertainty.

For the social impact, the MCA has likewise several implications which can be thought of. To begin with, an MCA is by definition an assessment that is partly considered subjective. This is because the weight factors used for the indicators are assigned subjectively. These weight factors are important factors for the results. However, if the weight factors of every indicator should have been the same, 5gDHC would have scored also substantially higher than the other alternatives.

Secondly, the indicators used in the MCA are also limited. These are impacts are seen as important by the author. Numerous other indicators potentially could be used, but due to the limited time span of this study and the lack of importance, these are not considered in this research.

For the indicators that are assessed in this study, mostly qualitative arguments are used to score the different alternatives on the indicators. These arguments are based on articles, websites, and sometimes rational thinking. However, quantitative arguments would have been better to get to more objects and concrete results. But for most of the indicators, this is very hard because the social impact is mostly a very hard quantifiable metric since it varies per person. In addition, for example, the UHI effect is an indicator that is already hard to measure on its own, not to mention, only the fraction caused by heating and cooling systems.

5.2 Limitations and interpretations of the results

The KPI analysis' main uncertainty is that it is explorative research. The KPIs are still in the design phase and this study is the first time that these are tested on real cases. So, some of them could change somehow in the future. In order to conclude them, they need to be tested on multiple other systems, to see if they are telling what the principles mean.

For the CBA, there are also some limitations to this study. In the environmental impact assessment, only a selection of emissions has been taken into account. This selection is based on the report of shadow costs of the CE Delft (2018), so probably the most important ones have been taken into account. However, maybe some other emissions could also be relevant for this study and would change the outcome. Moreover, other environmental impacts could have been assessed. For example soil pollution. Especially with the geothermal well of the 5gDHC alternative, this could be an impact that also is interesting for the future.

Besides, the DHC of Brunssum was taken as the 5gDHC alternative. However, if for example the Paris or Bochum pilot would have been taken as the 5gDHC pilot, it would have scored probably worse, as those two pilots still use some gas for their heating demand.

In the economic impact assessment, also several things can be thought of that can influence the outcome of the study. The 5gDHC alternative is based on the Brunssum pilot site of the D2Grids project. This system is only serving less than 200 buildings at the moment, which is a relatively small network. Sandvall, Ahlgren, & Ekvall (2017) state that large heat networks have significantly lower costs than small networks. This is due to the economy of scale effect. If a DHC is larger, the investments of parts that are not connection specific can be divided by more consumers, for example, the HPs and the geothermal well. In the CBA it is tried to correct for the scale, by comparing the costs of the 4gDHC and gas alternatives if they were as large as the Brunssum site. However, this entails a large uncertainty.

Secondly, the 5gDHC is overall a new technology, that is used in only a few places, mostly in pilot projects. New technologies have most of the time much higher overall costs than conventional technologies. This is due to the learning curve and the experience curve. The Learning curve decreases the labor costs over time, as people and companies learn from every system they construct. For example, they will learn from a mistake, which will ensure this will not happen again with a future project. The experience curve is the decrease of overall costs as the volume of the production of technologies increases, so if a company has planned to construct several 5gDHC networks, they can increase the volume of materials, which will result in declining costs. For energy supply technologies an average learning rate of 18 ± 9% is found by scholars (Weiss, Junginger, Patel, & Blok, 2010). This means that on average, 18% of the costs decline if the cumulative production of a certain technology has doubled.

Furthermore, for the LCOE analysis, the discount rate is an important factor in the results. The discount rate is always uncertain and should be determined with some assumptions (Fischedick, et al., 2011). In this study, we used a discount rate of 3% because other scholars also use this as it also takes some social costs into account and the funding with subsidies (Nuclear Energy Agency, 2018). However, higher discount rates would have resulted in a worse performance of the 5gDHC relative to the other alternatives, because of its high CAPEX. Because of the uncertainty of the discount ratio, this study conducted an uncertainty analysis on the discount rate to show its importance.

5.3 Contribution to literature

This study contributes to the existing literature in multiple ways.

Firstly, the KPI analysis shows a new way of assessing the performance of DHCs and measuring whether they are 5th generation or not. As the existing literature states that there is still no consensus on what a 5gDHC exactly is. These KPIs can be a starting point to finding a manner to benchmark and make a clear definition of this new concept.

Secondly, some scholars already have assessed the environmental and economic impact. However, for the environmental impact, most of the time only CO2 emissions are taken into account, and the environmental costs are not been combined with LCOE. This study shows that if this combination is made, more environmentally friendly solutions can score better even if their economic costs are higher. Also, taking more emissions into account make the result more complete.

Lastly, no previous study directly addressed the social impact of 5gDHC. This study contributes to the literature by touching upon this topic. With the MCA, the 5gDHC performance on several social impact indicators is qualitatively compared with different heating and cooling alternatives.

5.4 Future research

After this study, several new fields of further research can be thought of.

Because of the limited amount of these experimental, not fully operational, sites, an important new study can be testing the developed KPIs on a larger set of different energy systems. With this, the KPIs will be validated if they are scoring the systems, the way they are intended to. With this research, also a benchmark for 5gDHC could be made. Such a benchmark could entail the possibility to label systems 5th generation. In addition, also weight factors can be assigned to the different KPIs if it is assumed that they have different levels of importance. This could also be necessary in order to set the benchmark for 5gDHC. For this benchmark also the consideration must be made whether a DHC is 5g as it scores above a certain average of all the KPIs or if all the KPIs score not below a certain minimum score.

Another important field for further research could be including a life cycle assessment in environmental analysis. In this study, only the emissions during the operations are taken into account. But it could be interesting to also include the environmental impact during the construction of the systems. Or also more environmental impact, for example, soil pollution.

Further research could also be done for a more in-depth social impact assessment, with interviews of consumers of different energy systems. Also, a study can try to quantify the social indicators, however, for most of these, this is still very hard to measure.

6 Conclusion

5gDHC is the new generation of DHC, which is still in its development phase. Several companies have claimed to be, and some scholars have labelled some networks, already 5th generation. However, there is no broad understanding of the performance of this new heating and cooling technology. That is why this study tries to find an answer to the research question: "What are the technical, environmental, economic and social performances of 5gDHC systems in different energy system contexts?". To get a complete answer to this question, three different assessments are conducted to determine one or more performances of 5gDHC.

In order to determine the technical performance, a KPI analysis has been conducted. This assessment showed that the evaluated case studies score relatively well on the developed KPIs. One of the main focus points is now the renewable thermal energy, rather than the electrical energy used.

To assess the environmental and economic impact of 5gDHC, a CBA has been done. This analysis shows that the environmental impact of 5gDHC is substantially lower than a 4gDHC or DGB alternative. However, on the economical aspect, the LCOE of 5gDHC is much higher than these of the alternatives. If the environmental costs are combined with the LCOE the 5gDHC comes closer to the other alternatives but is still higher.

An MCA showed the social impact of 5gDHC compared to alternative solutions. It shows that the social impact is significantly lower for this new technology than for the alternatives assessed. However, more (quantitative) research on this performance is needed to get a more complete answer.

The 5gDHC shows some real potential for the (near) future. Compared with alternatives, it scores better on the environmental and social impact. However the economic impact scores at the moment substantial worse than the alternatives. This makes the technology probably, without subsidies or funding, not an economically viable solution for energy suppliers. However, 5gDHC is a new technology and costs potentially can decrease with the learning and experience curve. With this in mind, as well as the increasing demand for renewable solutions for heating and cooling systems, because of climate change and the rising gas prices, 5gDHC has a large potential for being one of those solutions.

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Appendices

A KPI analysis

A.1 Decision trees for the KPIs

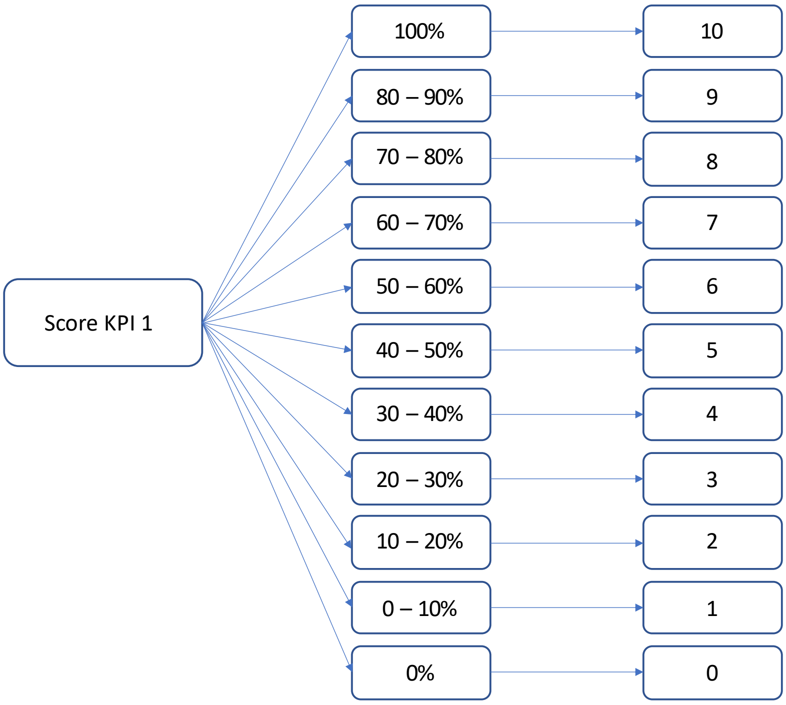

Figure A. 1. Decision tree for KPI 1.

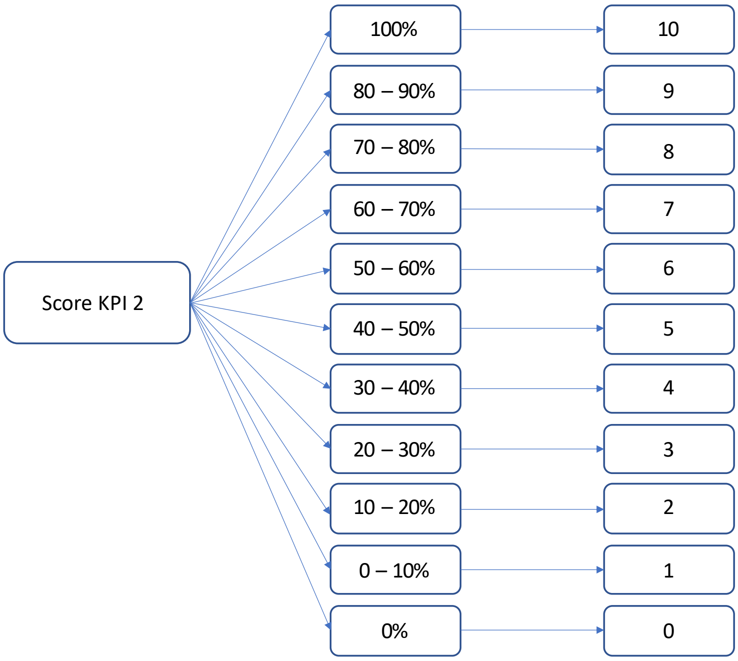

Figure A. 2. Decision tree for KPI 2.

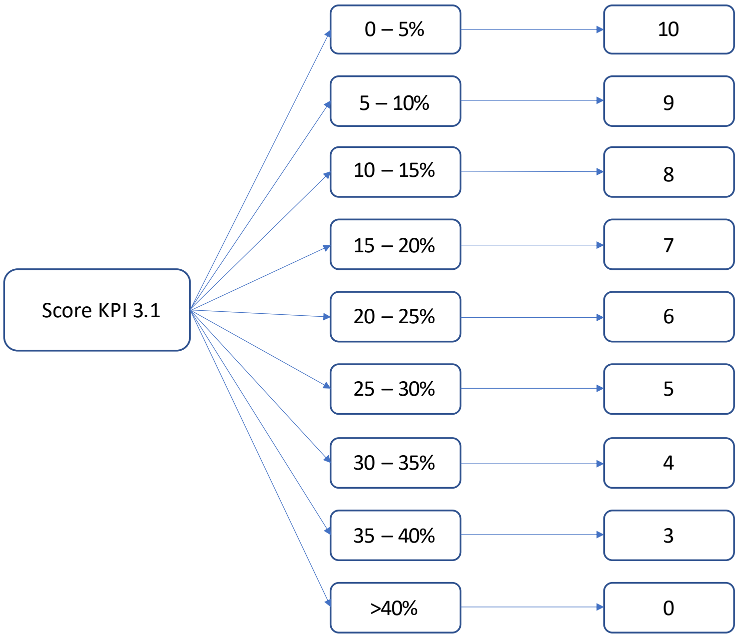

Figure A. 3. Decision tree for KPI 3.1.

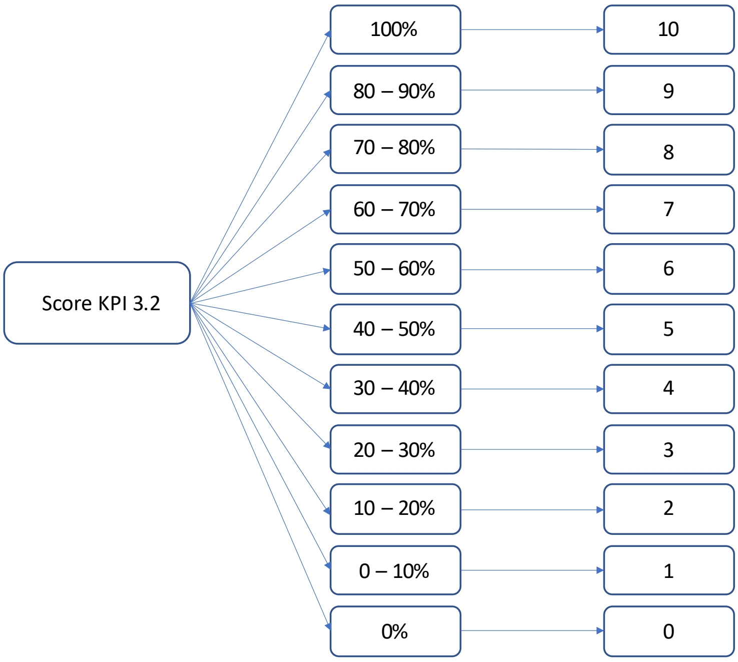

Figure A. 4. Decision tree for KPI 3.2.

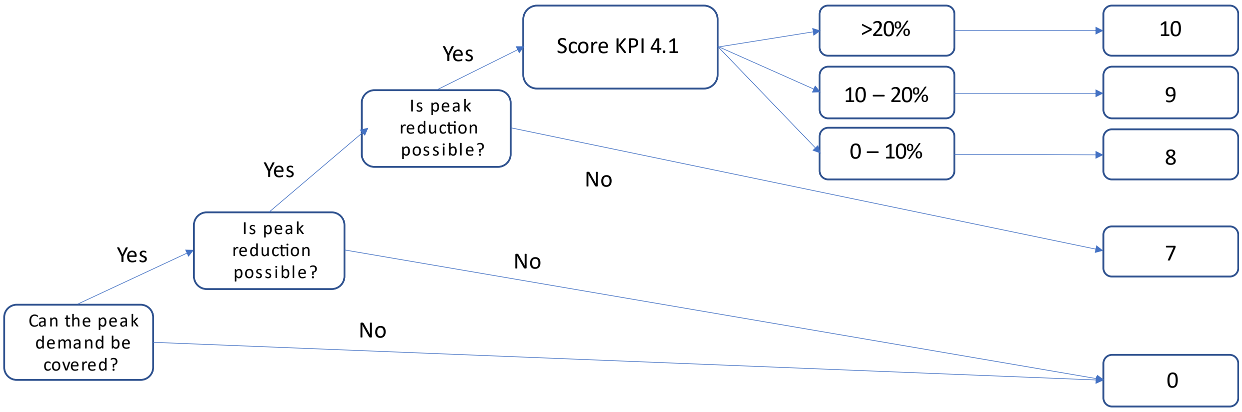

Figure A. 5. Decision tree for KPI 4.1.

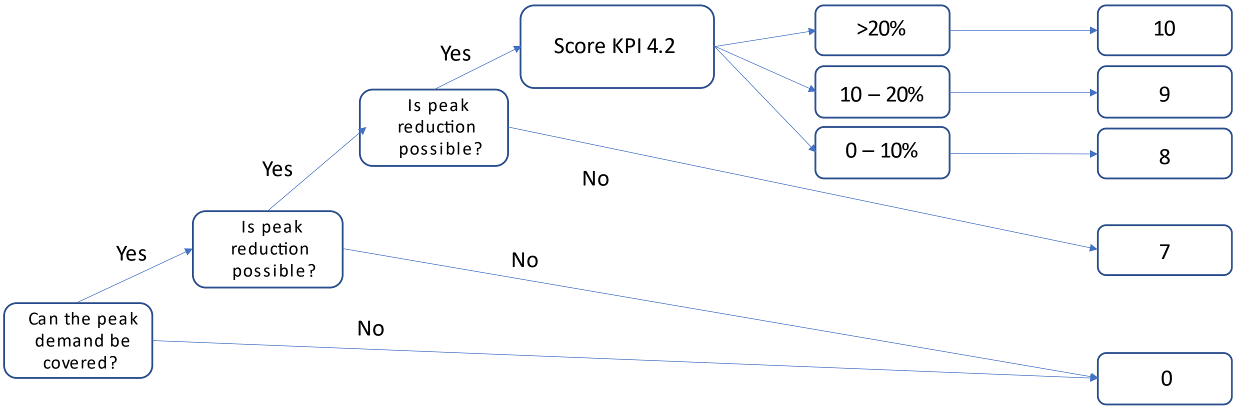

Figure A. 6. Decision tree for KPI 4.2.

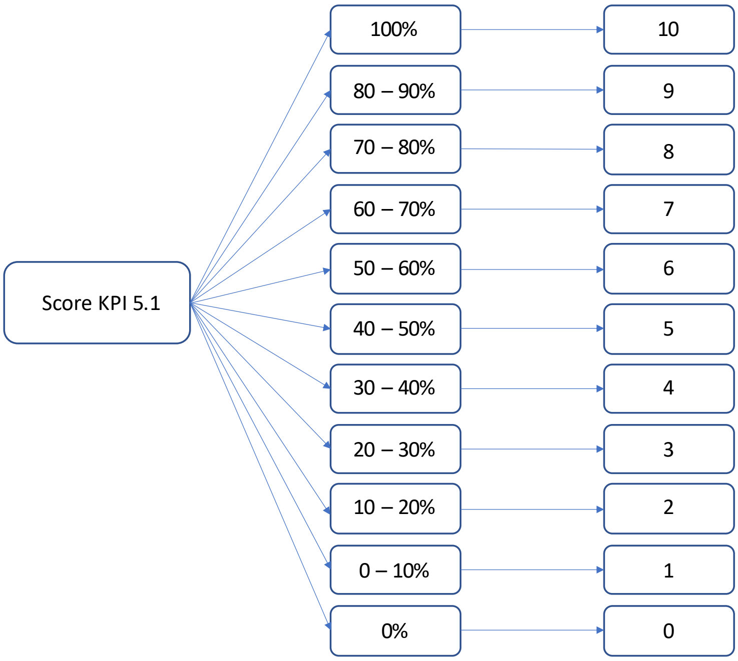

Figure A. 7. Decision tree for KPI 5.1.

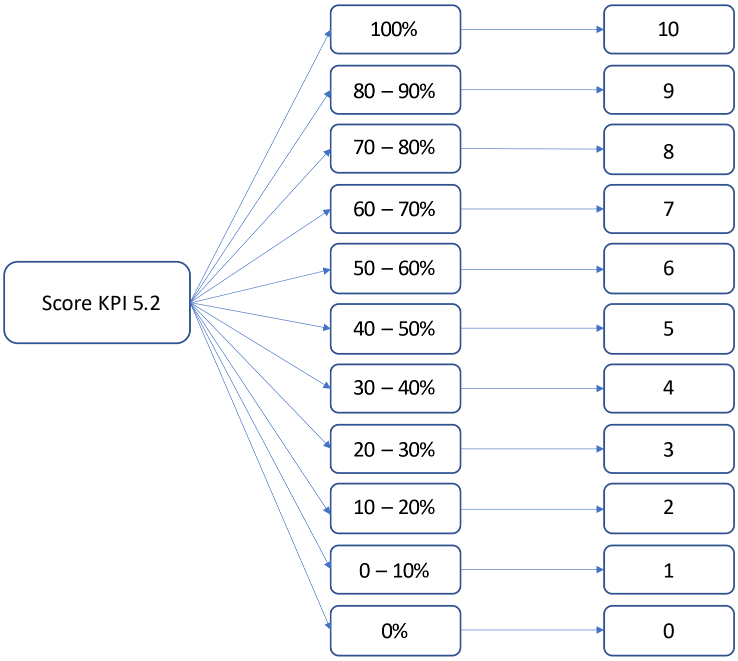

Figure A. 8. Decision tree for KPI 5.2.

A.2 Data of Case studies

	Datapoint
General Information	Name of the system/company
	City and Country
	Amount of end-users *[#]*
	Surface served *[m²]*
	Building(s) type: dwellings, public space, industrial or mix
	Building(s) maturity: new, old or mix
Energy demand	Total cold demand *[kWh/a]*
	Total heat demand *[kWh/a]*
	Total domestic hot water demand *[kWh/a]*
	Electricity used for heating and cooling *[kWh/a]*
Energy supply	External supply by cooling tower *[kWh/a]*
	External supply by gas *[kWh/a]*
	Energy supply by geothermal well (or ATES*) **BALANCED**** part *[kWh/a]*
	Energy supply by geothermal well (or ATES*) **UNBALANCED**** part *[kWh/a]*
System specifications	Length of Ambient loop *[m]*
	Average temperature of water in the Ambient loop *[°C]*
	Length of Hot pipes *[m]*
	Length of cold pipes *[m]*
	Temperature of heating pipes *[°C]*
	Temperature of cooling pipes *[°C]*
	Average temperature of soil *[°C]*
	Amount of substations *[#]*
Capacity of the system	Maximum heat capacity *[kW]*
	Maximum cooling capacity *[kW]*
Origin of thermal energy sources	Local (**<10km** (also all internal sources)) *[kWh]*
	Region (**<50km**) *[kWh]*
	National (**>50km** and within **national borders**) *[kWh]*
	International* (**>50km** and **not** within **national borders**) *[kWh]*
Source of electrical energy	Electricity from the grid *[kWh]*
	Electricity self produced *[kWh]*

Table A. 1. The data retrieved from the different pilot sites of the European Interreg project D2Grids.[4]

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[4] For this data you can contact jibbebertholet@gmail.com.

B Cost-Benefit analysis

B.1 environmental data

Biomass Commercial boiler	emission factor	Unit
CO2e*	0.10	g/kWh
As	0.19	mg/GJ
Cd	13	mg/GJ
CO	570	g/GJ
Hg	0.56	mg/GJ
NH3	37	g/GJ
Ni	2	mg/GJ
NMVOC	300	g/GJ
NOx	91	g/GJ
Pb	27	mg/GJ
PM10	143	g/GJ
PM2.5	140	g/GJ
SOx	11	g/GJ

*Table B. 1. Emission factors of primary energy of biomass (European Environment Agency, 2021). * per unit of delivered energy (Ivančić , Romaní, Salom, & Cambronero, 2021).*

Natural gas Residential boilers	emission factor	Unit
CO2e*	56.4	kg/GJ
Hg	0.1	mg/GJ
NMVOC	1.8	g/GJ
PM10	0.2	g/GJ
NOx	42	g/GJ
As	0.12	mg/GJ
CO	22	g/GJ
SOx	0.3	g/GJ
Pb	0.0015	mg/GJ
Cd	0.00025	mg/GJ
PM2.5	0.2	g/GJ

Table B. 2. Emission factors of primary energy of natural gas (European Environment Agency, 2021). (Zijlema, 2020)*

Dutch Electricity Grid	emission factor	Unit
CO2e	0.373	kg/kWh

Table B. 3. The emission factor of primary energy of the Dutch national grid (Ortiz, et al., 2020).

B.2 Economic data

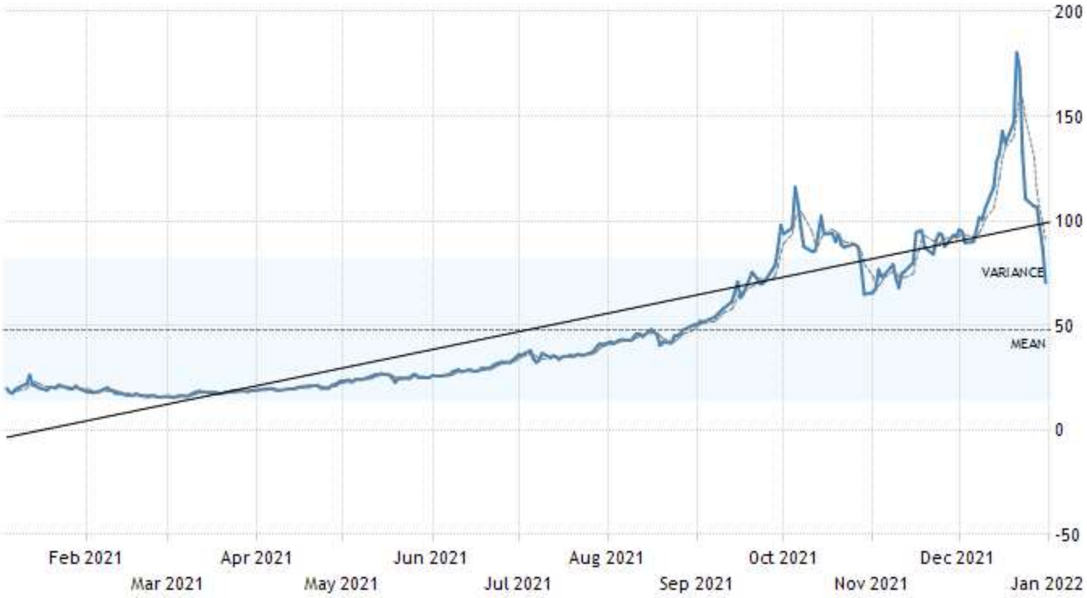

Figure B. 1. The European gas price in 2021 (Trading Economics, n.d.).

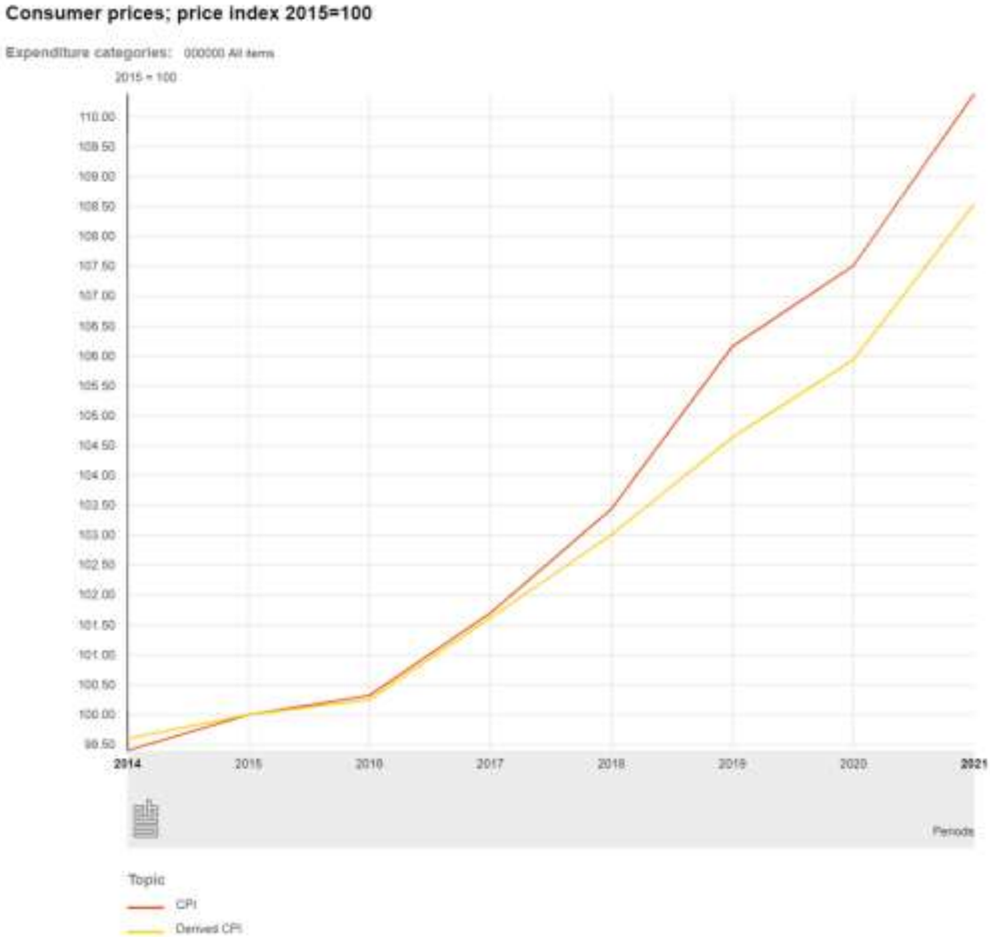

Figure B. 2. The Dutch Consumer price index (2015= 100) (CBS, 2022).

	Brunssum (D2Grids pilot)	**unit**
Capacity heating DHC	435	kW
Capacity heating individual boilers	1,146	kW
Capacity cooling	268	kW
kWh heating	748,333	kWh/a
kWh DHW	381,667	kWh/a
Total heating	1,130,000	kWh/a
kWh Cooling	187,083	kWh/a
Total	1,317,083	kWh/a

Table B. 4. The basic characteristics used during the CBA for all the alternatives.

Parameter		**Units**	**Total H&C**	**Heating Only**	**Common H&C**	**Cooling Only**
CAPEX	Direct costs	€	1.023.441	269.411	641.921	85.109
	Other costs	€	43.400	-	43.400	-
	Total	€	1.066.841	296.411	685.321	85.109
OPEX	Fix	€/kW	-	11.523	89.458	2.553
	Decommissioning	€/kWh	-	9.181	13.669	496
	Residual value	€	-	41.349	96.629	27.556
	Variable	€/kWh	-	48.918 *	-	2.439 **

*Table B. 5. The economic data of the 4gDHC system * Biomass cost. ** Electricity cost. (Ivančić , Romaní, Salom, & Cambronero, 2021) .*

# C	Multi-Criteria Analysis

## C.1	Standardization Graphs

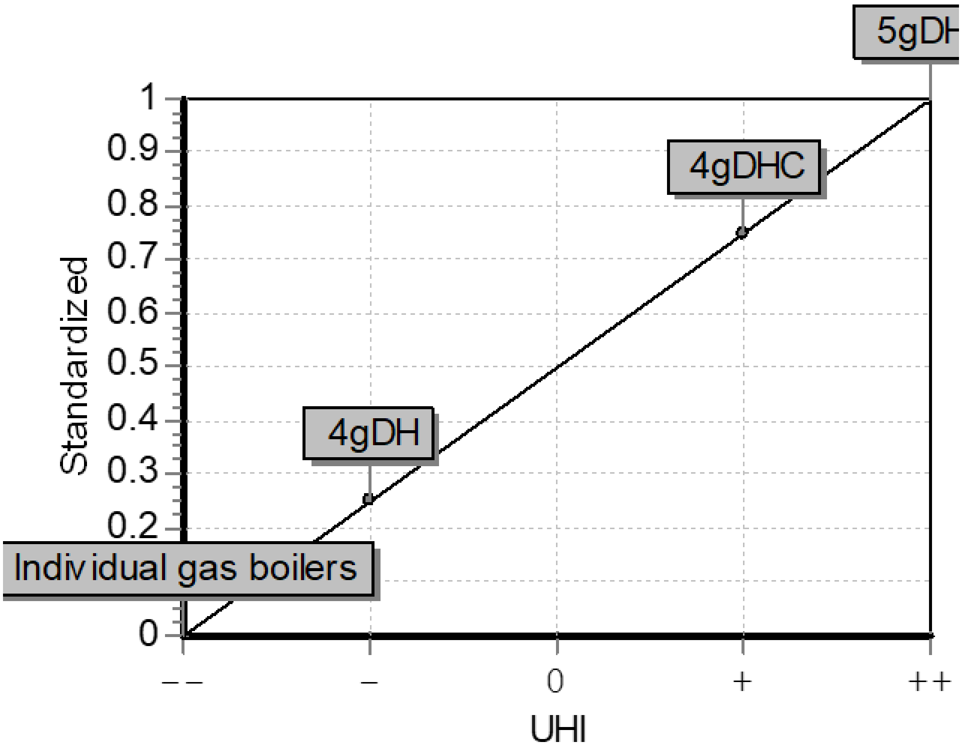

Figure C. 1. Standardization for UHI for the MCA.

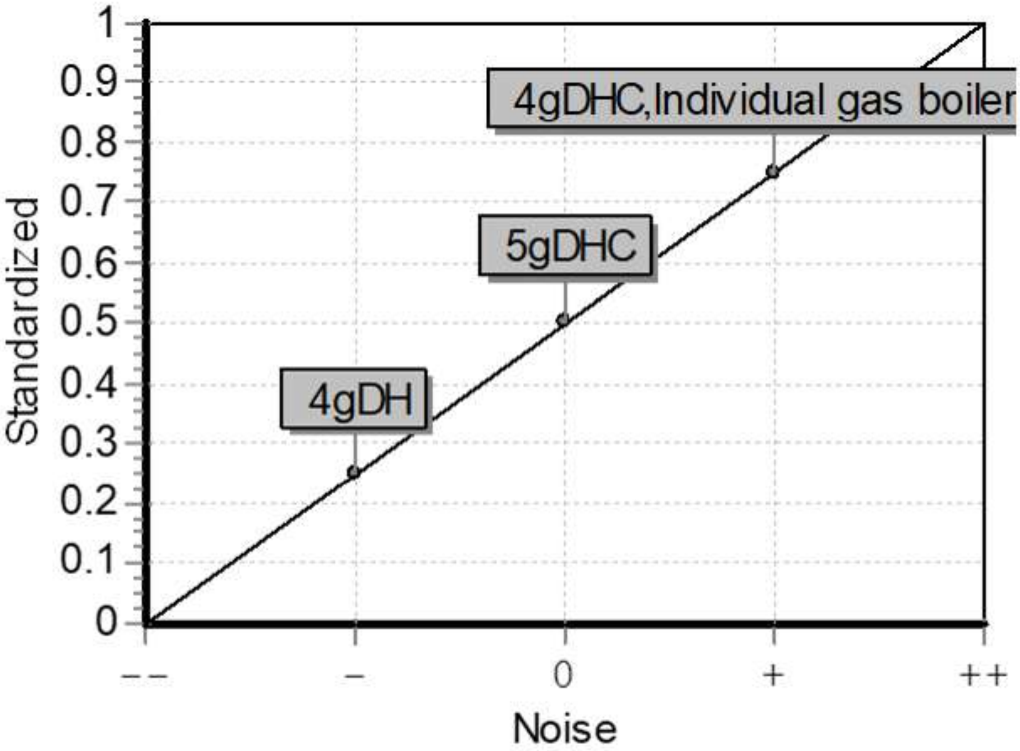

Figure C. 2. Standardization for Noise for the MCA.

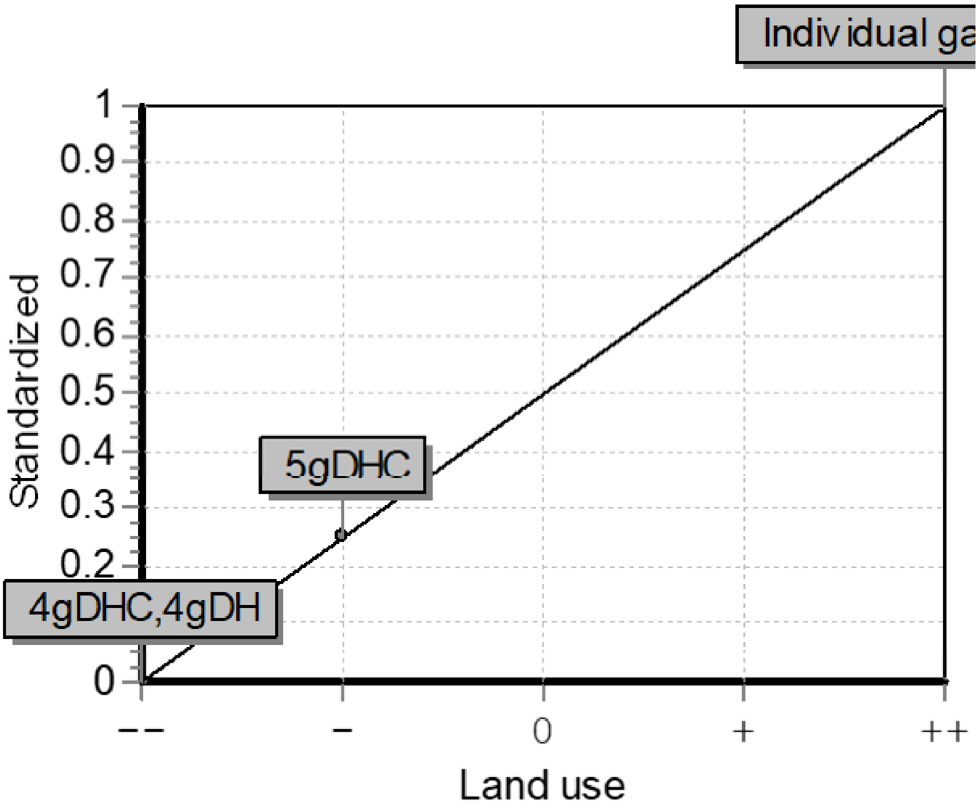

Figure C. 3. Standardization for Land use for the MCA.

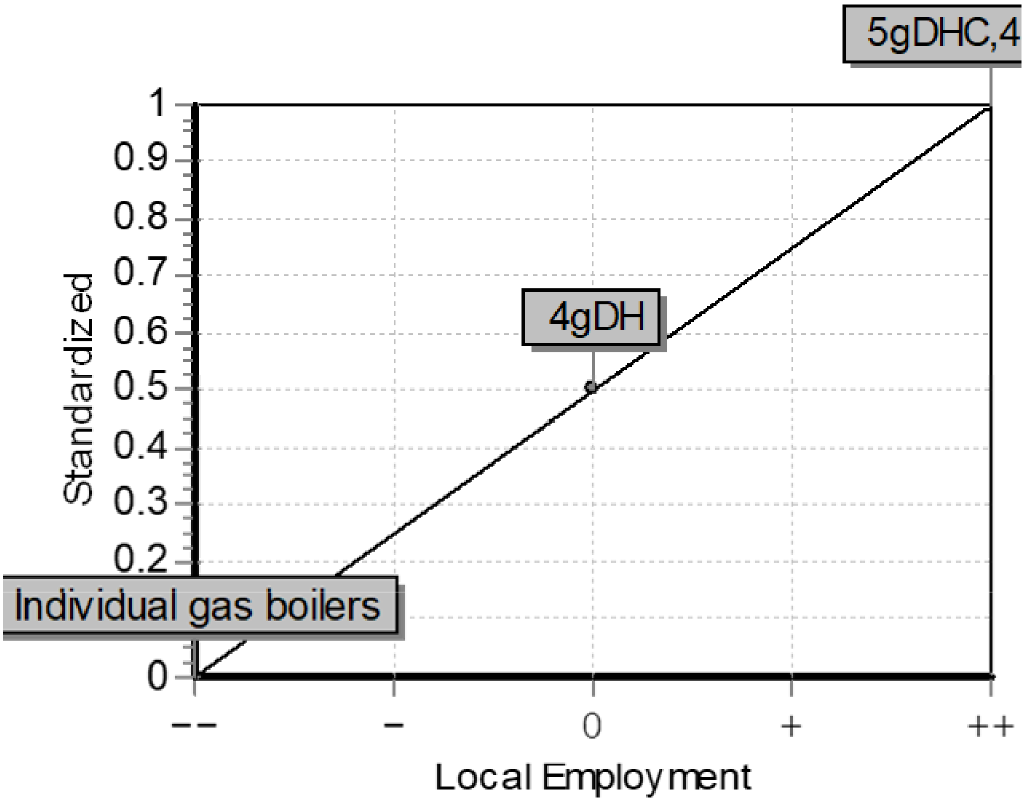

Figure C. 4. Standardization for Local Employment for the MCA.

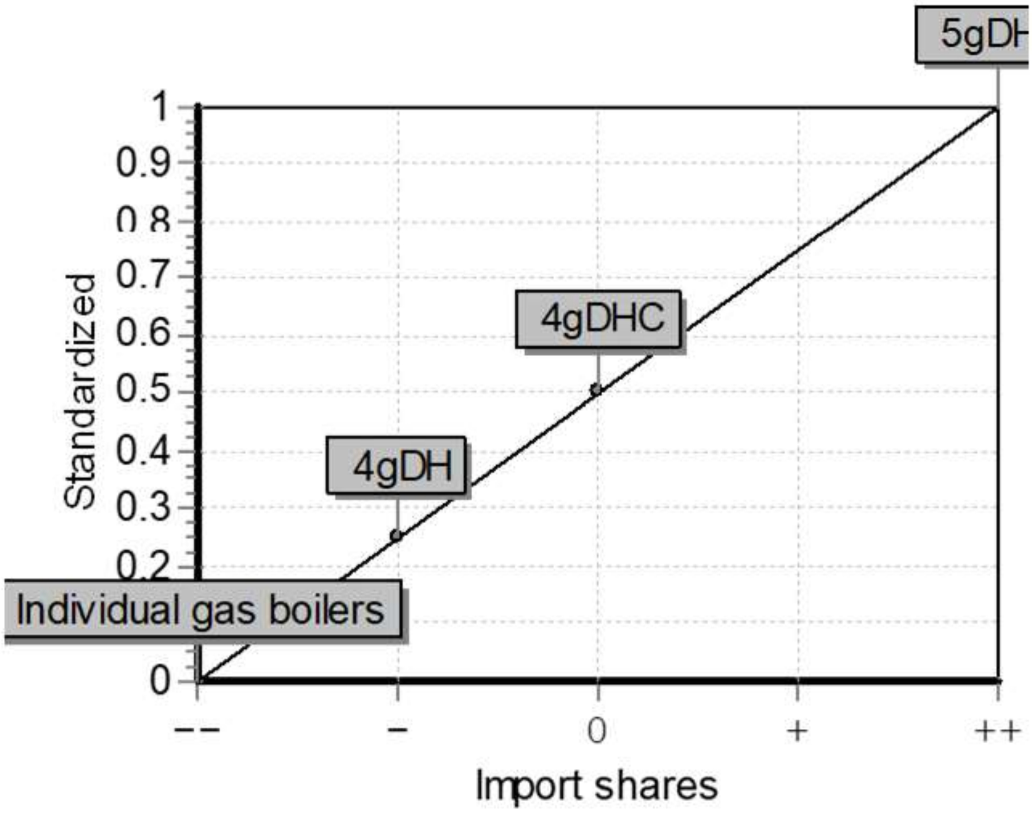

Figure C. 5. Standardization for Import shares for the MCA.

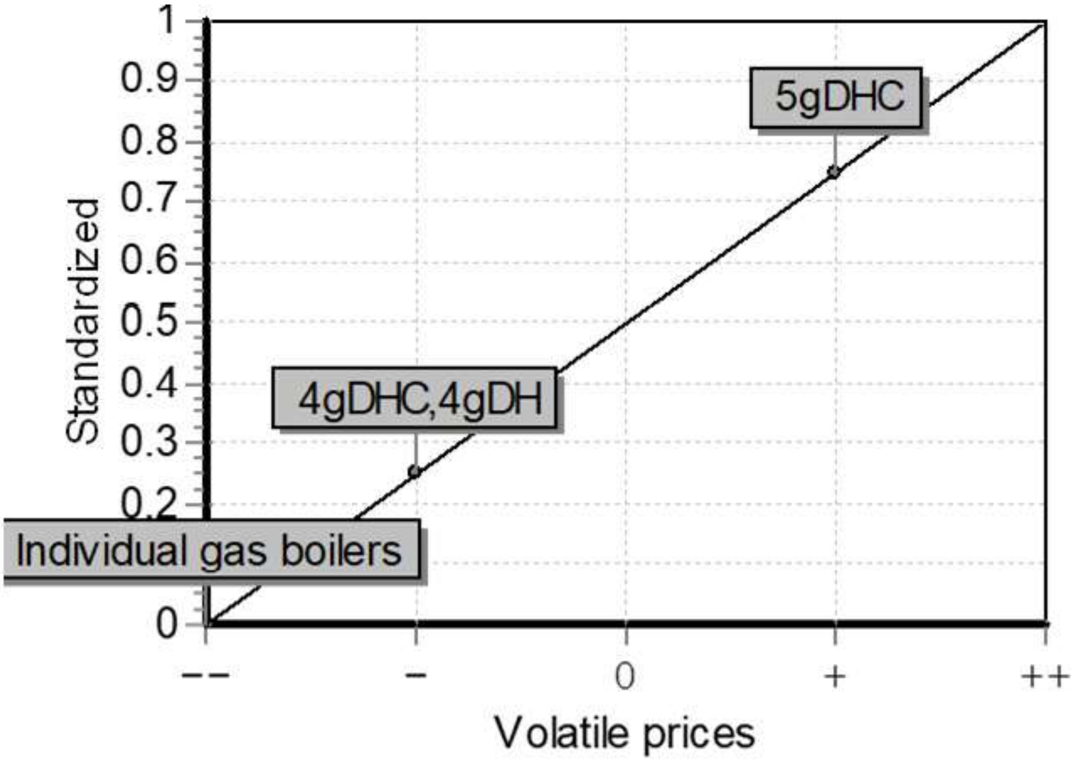

Figure C. 6. Standardization for Volatile prices for the MCA.