The potential role of high temperature aquifer thermal energy storage in the Dutch energy system

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Contents

Abstract

Heat accounts for almost half of global energy consumption and, as a result, is responsible for 40% of energy-related CO_2 emissions. Heat demand does not align well with sustainable energy supply, such as solar thermal or geothermal energy, which will produce heat in summer, when it is not needed. Seasonal thermal energy storage can help balance this discrepancy in demand and supply and reduce the required capacity for heat production.

This research focuses specifically on high temperature aquifer thermal energy storage (HT-ATES) to store heat at temperatures that can be directly supplied to district heating (50-100°C). HT-ATES technology is still in development and historically systems were usually shut down due to unforeseen losses of heat supply or demand. To investigate the impact that HT-ATES can have on an energy system, HT-ATES should be included in an energy system model that includes all energy sectors. In this research, this was done by implementing potential maximum energy production data for HT-ATES in the Netherlands to the PyPSA-Eur energy model.

HT-ATES was successfully added to the model and, as hypothesised, was able to reduce total system costs, depending on CO_2 limits and on the heat demand in the projected year. In the 2050 net-zero emission scenario, the maximum capacity of HT-ATES systems was installed and HT-ATES was able to reduce the system costs of the whole 5-country-network by 0.04%. Conservative technical and financial parameters were applied to the HT-ATES system, so this cost reduction has the potential to be even higher. HT-ATES stores mainly geothermal energy in summer and supplies heat to district heating in winter, contributing up to 6% of the district heating demand.

The model could be improved with even more detailed information on HT-ATES energy production, considering the possibilities of multiple well systems and additional heat pumps. For more realistic modelling, the potential location should become limited by proximity to a heat source and other systems present in the subsurface. If a potential HT-ATES map was created for Europe, this could be added to the PyPSA-Eur model and provide results on the impact HT-ATES can have on the whole European energy system. This research motivates further improvements of PyPSA-Eur and investigation of specific potential HT-ATES installation in the Netherlands.

Samenvatting

Warmte is verantwoordelijk voor de helft van wereldwijde energieconsumptie en is daardoor verantwoordelijk voor 40% van energie-gerelateerde CO_2 emissies. De warmtevraag komt niet overeen met duurzame warmteproductie zoals zonthermie of geothermie, die warmte produceren in de zomer, wanneer het niet gebruikt wordt. Seizoensgebonden warmteopslag kan helpen om dit verschil te balanceren en de benodigde warmteproductiecapaciteit te verlagen.

Dit onderzoek focust op "high temperature aquifer thermal energy storage" (HT-ATES) wat warmte opslaat bij temperaturen die overeenkomen met de benodigde temperaturen van stadswarmte (50-100°C). HT-ATES technologie is nog in ontwikkeling en historisch werden systeem vaak gesloten door onverwachte veranderingen in de warmtelevering of warmtevraag. Om de impact te onderzoeken die HT-ATES kan hebben op een energiesysteem, zou HT-ATES opgenomen moeten worden in een energiesysteemmodel dat alle energiesectoren omvat. Dat werd gedaan in dit onderzoek door potentiële maximum energieproductie data voor HT-ATES in Nederland te implementeren in het PyPSA-Eur energie model.

HT-ATES was succesvol toegevoegd aan het model en, zoals verwacht, was het in staat om de totale systeemkosten te reduceren, afhankelijk van de CO_2 limiet en de warmtevraag van het gekozen jaar. In een 2050 net-zero emissie scenario was the maximale capaciteit geïnstalleerd was HT-ATES in staat om de systeemkosten van het hele 5-landen-netwerk met 0.04% te reduceren. Conservatieve technische en financiële parameters waren geselecteerd voor dit model, dus deze kostenreductie zou nog hoger kunnen zijn. HT-ATES slaat vooral geothermische warmte op in de zomer en levert warmte aan stadswarmte in de winter, goed voor maximaal 6% van de vraag naar stadswarmte.

Het model zou kunnen worden verbeterd met nog gedetailleerdere informatie over de energieproductie via HT-ATES, rekening houdend met de mogelijkheden van meerdere putten en extra warmtepompen. Voor een realistischer model zou de potentiële locatie beperkt moeten worden door de nabijheid van een warmtebron en andere systemen in de ondergrond. Als er een potentiële HT-ATES kaart voor Europa zou worden gemaakt, zou deze kunnen worden toegevoegd aan het PyPSA-Eur model en resultaten opleveren over de impact die HT-ATES kan hebben op het gehele Europese energiesysteem. Dit onderzoek motiveert verdere verbeteringen van PyPSA-Eur en onderzoek naar specifieke potentiële HT-ATES installaties in Nederland.

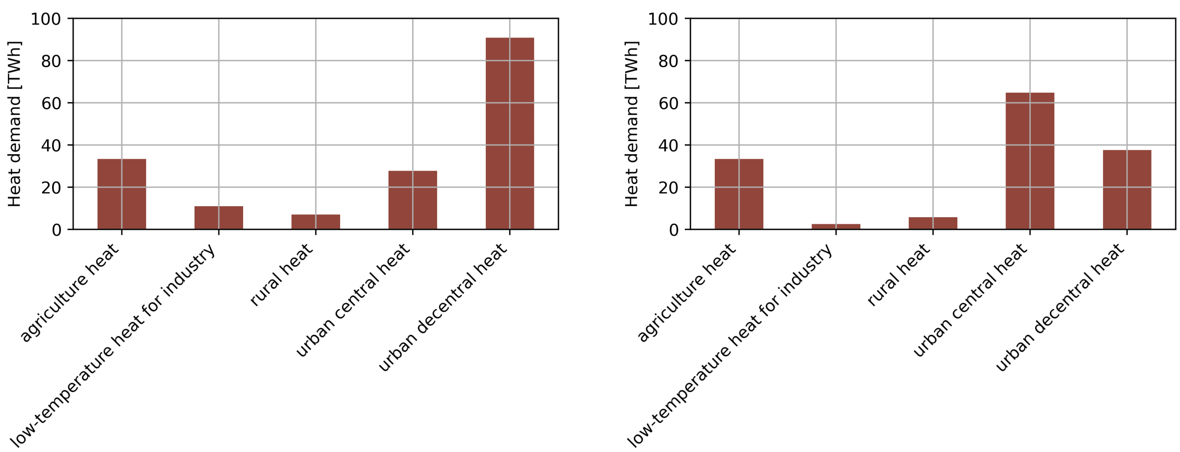
1 Introduction

1.1 Energy demand and supply

Heat accounted for almost half of the global final energy consumption in 2023, being responsible for almost 40% of energy-related CO_2 emissions. Despite advances in energy efficiency, global heat demand still increases. During 2017 and 2023, the annual heat demand increased by 7%. Only half of this heat demand was covered by renewable heat, and as a result, heat-related CO_2 emissions increased by 5% between 2017 and 2023, mainly in the industry sector [1].

Heat demand differs highly per consumer, in terms of the amount of energy, but also temperature. Figure 1 shows the projected heat demand in TWh for 2030 and 2050 in the Netherlands. The dominant heat sectors are central and decentral urban heat, which contains the demand for water and space heating of residential and service buildings [2]. The temperatures required for this type of heating are generally below 100 °C. Approximately 90% of Dutch homes still rely on natural gas to provide this heat [3]. With natural gas, heat can be produced whenever it is needed, which is ideal because heat demand differs greatly throughout the year. Figure 2 shows the projected heat demand in the Netherlands throughout the year 2050, with the highest peaks in January, February, and March, while the demand drops almost to zero during the summer.

Non-fossil heat is produced with less flexibility, which makes it more difficult to meet this varying heat demand. For example, the amount of available waste heat is determined by industry, not demand [4]. Geothermal plants ideally produce heat at a constant rate to avoid technical issues [5]. The production of solar thermal energy and power-to-heat from wind or solar depends on the weather [6]. All of this results in excess heat being produced in the summer, when the demand is close to zero.



(a) 2030 - Total demand: 170 TWh

(b) 2050 - Total demand: 144 TWh

Figure 1: Projected demand in TWh of heating subsectors in the Netherlands, excluding high-temperature heat for industry. Figures created by author, based on PyPSA-Eur data [2].

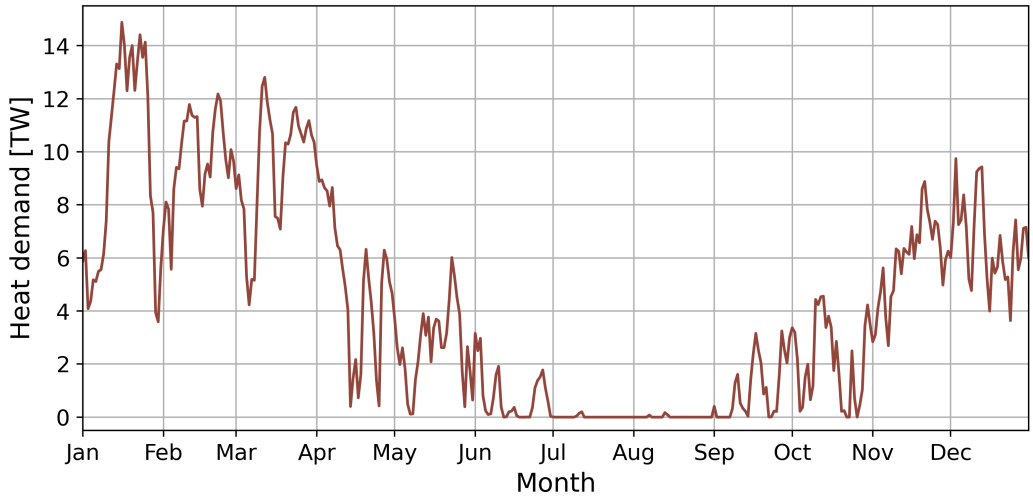


Figure 2: Projected heat demand for the Netherlands throughout the year 2050. Figure created by author, based on PyPSA-Eur data [2].

Even though non-fossil heat production is less flexible, efforts will still have to be made toward a more renewable heat sector to reduce greenhouse gas emissions. The stop of natural gas production in Groningen, as well as national and international climate agreements, require changes in the thermal energy supply of the Netherlands. Figure 1, together with several other studies, predicts an increase in urban central heating demand, which can be supplied by large heat sources instead of individual systems [4]. A large heat source could, for example, be thermal energy storage, which can be charged with excess heat in summer and supply heat to district heating in winter. By storing heat in summer, heat production in summer does not have to be stopped and lower overall heat production capacities are needed [7]. If power-to-heat is applied, excess electricity in summer could also be stored as heat, reducing the need for grid expansion. Electricity net congestion is an increasingly large issue, but grid enforcement takes time and has limited public support [2] [8]. This issue could be partially resolved with energy storage.

1.2 Thermal energy storage

The simplest category of thermal energy storage (TES) is sensible heat storage, where the temperature of a certain medium, such as water, is increased or decreased. It can be paired with heat sources such as solar thermal systems or heat pumps and is often used to heat or cool buildings. Sensible heat storage can be used both diurnally and seasonally, depending on the technology [9]. Being the most simple TES method, sensible heat storage is the most widely commercially available compared to latent heat or thermochemical storage [10]. Hence, the focus of this research will be sensible heat storage. The four main ways of sensible heat storage are pit TES (PTES), tank TES (TTES), borehole TES (BTES), and aquifer TES (ATES). PTES consists of an excavated pit, filled with water or a mixture of water and sand, covered by a floating lid made of insulated material. TTES consists of an insulated tank filled with water. The tanks can be deployed on a domestic scale or on a large scale, which can be both above and below ground. BTES consists of borehole pipes through which water can circulate to inject or retrieve heat from the ground. Lastly, there is ATES, which consists of wells to inject and retrieve water from an aquifer. This method can be done at low temperatures, where it can then also be used for cooling, or at high temperatures. PTES and TTES are the expensive options due to the insulation material, but for the same reason, they are also generally more efficient. BTES and ATES are cheaper and have a lower land footprint [11]. In this report, the focus is put on ATES, given its particular relevance in the Netherlands, as outlined below.

An aquifer is a geological layer of permeable rock (such as sandstone) that can hold groundwater. The aquifers selected for storage have an overlying clay layer, and sometimes an underlying one, to ensure the containment of the water and function as an insulation layer [12]. The thermal storage system consists of a hot and cold well, of which water can be pumped for cooling and heating purposes. This is a long-term storage option, where cool water can be pumped in summer to cool buildings through a heat exchanger. The warm water from the building is pumped into the warm well, which can be used again in winter, usually with the addition of a heat pump. This method is mainly used for the heating and cooling of buildings [13]. More than 90% of global low-temperature (LT) ATES systems are located in the Netherlands, including the largest ATES system on the university campus in Eindhoven [14]. One of the reasons for this is the large presence of highly productive porous aquifers in the Netherlands [15].

1.2.1 High temperature aquifer thermal energy storage (HT-ATES)

LT-ATES stores heat at temperatures below 25 °C in shallow aquifers. However, renewable sources such as biomass, geothermal, or solar produce heat at much higher temperatures. Therefore, high temperature (HT) ATES is introduced, which can store large energy volumes of 50-100 °C at greater depths. This higher temperature range does cause technical, financial, and legal difficulties, making the system much less common compared to LT-ATES. For example, high temperatures affect groundwater characteristics (density and viscosity) and well materials become more prone to scaling, clogging, and corrosion [16].

The aquifers used for HT-ATES are generally very large and isolated, allowing for large-scale and cost-effective storage [7]. There is also little risk of affecting critical drinking water aquifers, since they are located at much shallower depths [12]. An advantage of HT-ATES compared to LT-ATES is that stored heat can often be supplied directly to the heat sink without the need for a heat pump. Well-insulated buildings often require 40-60 °C heat, an ideal range for HT-ATES, as these relatively lower temperatures cause fewer technical problems [16]. In LT-ATES the heat source is simply the outgoing heat of the heat sink in summer, combined with a heat pump to supply high enough temperatures in winter. Meanwhile, HT-ATES is supplied with an independent heat source and often does not require a heat pump. Several options for both heat sources and heat sinks of HT-ATES are given in Figure 3.

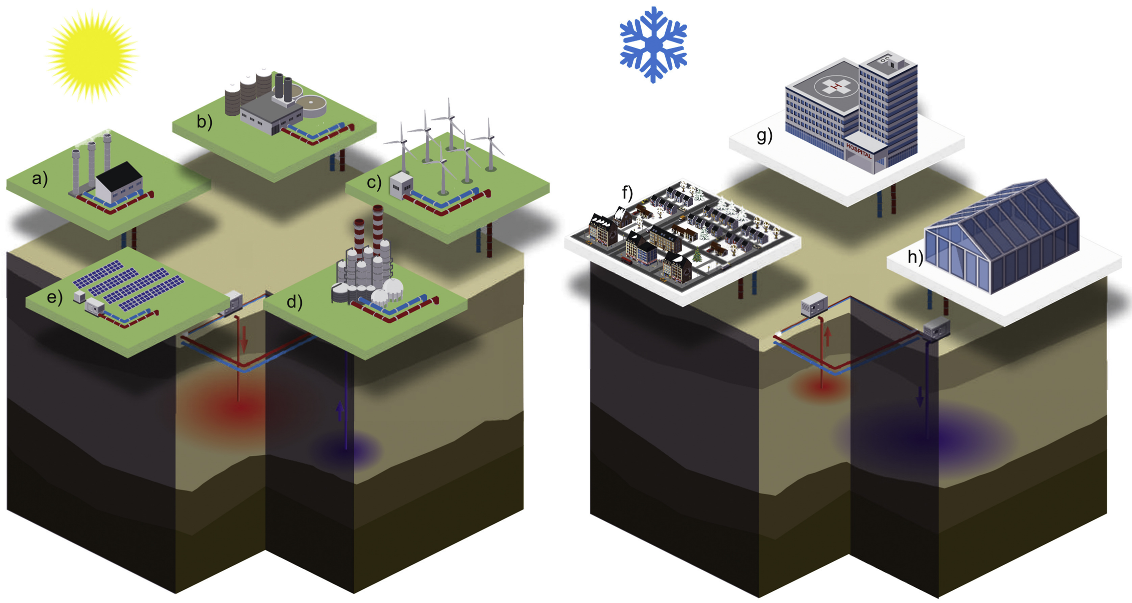


Figure 3: Charging and discharging options of HT-ATES. In summer, the aquifer is charged with heat from energy sources such as geothermal (a), biomass (b), power-to-heat (c), industrial heat waste (d) or solar (e). The stored heat is recovered in winter to supply district heating (f), large building complexes (g) or industrial applications such as greenhouses (h). Figure taken directly from [16].

The high temperature of HT-ATES not only affects the technical materials but also affects the efficiency of the system. The temperature of natural groundwater in aquifers generally ranges between 10 and 20 °C [7]. Therefore, the high temperatures of HT-ATES result in significant heat losses in the first few years of an operational system because the surrounding rock needs to heat up. Remmelts et al. (2021) concluded that it takes 5 years for HT-ATES to start supplying heat at steady temperatures [4]. After stabilising, the efficiency can range between 40% and 90% [17]. When running at full efficiency, a HT-ATES system can reduce CO_2 emissions by 50% to 85% compared to gas boilers, depending on the emissions of the heat source [12]. However, this can change in more specific cases. For example, a feasibility study was done for a HT-ATES system in Rotterdam that would be supplied by heat from a waste incinerator. They estimated a CO_2 emission reduction of just 17% compared to the original situation, which already used the waste incinerators as a direct heat source [18].

Despite not being widely deployed, there is a 50-year history in R&D on HT-ATES. Many projects have either been abandoned or are still in development. Most of them are located in Europe, specifically Germany, the Netherlands, and Switzerland. Before 2021 the only running HT-ATES system was in Rostock, Germany. This is a pilot plant built in 1999 and has a charging temperature of 50 °C [16]. The bottom of the aquifer lies just 30 m below the surface and the system consists of two wells. The temperature is kept low to prevent changes in groundwater chemistry [11]. The advantages of this system are the lower temperature, which has not caused technical issues, and no risk in losing the heat source (solar heat from the roof) and sink (a building-complex). It is interesting to note that such a system could not be built under current circumstances since it would not be able to obtain a license under the current legislation policy

[16]. In 2021 a new and much larger HT-ATES system started operating in Middenmeer, The Netherlands. The system consists of a doublet that stores geothermal energy at 85 °C to supply heat to greenhouses in the winter. The doublet is installed in a 25 m thick aquifer at 360 m below ground [19].

The most common reasons for an HT-ATES system to be shut down are overestimated heating demand or loss of heat source. To prevent this from happening in the future, research should focus not only on subsurface design but also on the whole energy system. Potential heat sources and sinks must be analysed, considering the long lifetime of HT-ATES of at least 30 years [16]. For this reason, this research will analyse the feasibility of HT-ATES in the current and future energy systems of the Netherlands.

1.2.2 HT-ATES potential in the Netherlands

As mentioned above, the Netherlands already has >90% of the global LT-ATES systems. With more than 30 years of experience with LT-ATES, there is a great interest and a good basis for the development of HT-ATES [7]. To investigate its potential, Dinkelman et al. (2020) created a regional potential map for HT-ATES in the Netherlands, shown in Figure 4. The map was created with a geological model consisting of eight different geological formations in the Dutch subsurface. The sandstone layers in these formations are analysed based on several criteria, including depth, thickness, and hydraulic conductivity. It was also analysed whether these aquifers overlapped with protected zones such as Natura2000 areas or groundwater protection zones. This resulted in three categories for potential; favourable, possible barrier, and one or more barrier. A possible barrier would mean that one of the criteria was unideal, but not automatically a real barrier. For example, a thickness <10 m would be a barrier, 10-15 m is a possible barrier, and >15 m is favourable [20].

Figure 4 shows that the most favourable areas for HT-ATES are in the west of the Netherlands, where there are more and thicker sand layers. A large part of the country is labelled with "possible barriers", which means that HT-ATES is possible there but requires more detailed investigation or changes in regulation. It should be emphasised that the maps are based on regional data, but the real potential of HT-ATES is highly location specific, so a detailed investigation will still be required when planning to install such a system [21].

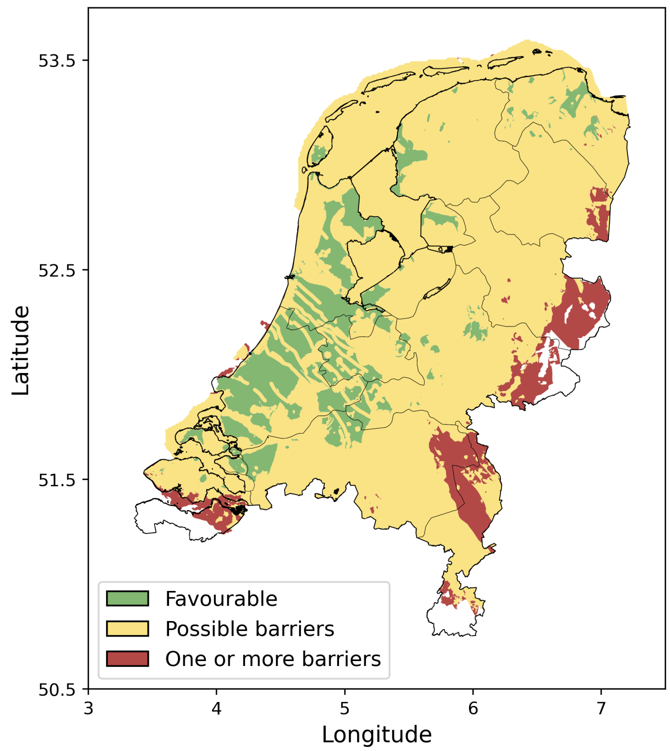


Figure 4: This map shows the potential for HT-ATES in the Netherlands based on subsurface criteria. The data for this image were provided by Dorien Dinkelman [20]

1.2.3 ThermoGIS-HT-ATES

An application called ThermoGIS-HT-ATES is currently being developed to provide information on subsurface and economic parameters regarding HT-ATES in the Netherlands. The application is an extension of the existing ThermoGIS workflow for geothermal potential [22]. At the moment the application includes data on maximum flow rate, expected power, and energy production for three formations; Maassluis, Oosterhout, and Brussels Zand. The Maassluis and Oosterhout formations are shallower than the Brussels Zand and could therefore not be applied to the official ThermoGIS workflow. Input from REGIS II v2.2 is used instead, which is better suited for subsurface modelling down to 100 m depth [22]. As a result, the produced maps are put on the ThermoGIS New developments page [23].

The expected power is calculated from the maximum achievable flow rate and specified temperature levels. ThermoGIS-HT-ATES applied an injection temperature of 80 °C and a return temperature of 40 °C. It is important to note that these values depend on the heating network and the heat sources and can therefore differ per specific installation [23]. There is no standard method for calculating the flow rate, so four different methods were applied and the most restrictive value was selected for each grid cell. The median power values of the last simulated year, when efficiency has stabilised, can provide an indication of the amount of energy that can be produced during the discharge of HT-ATES in winter [22]. The resulting energy production maps for each formation are shown in Figure 5. The Maassluis formation consists of three separate layers, which are all modelled separately.

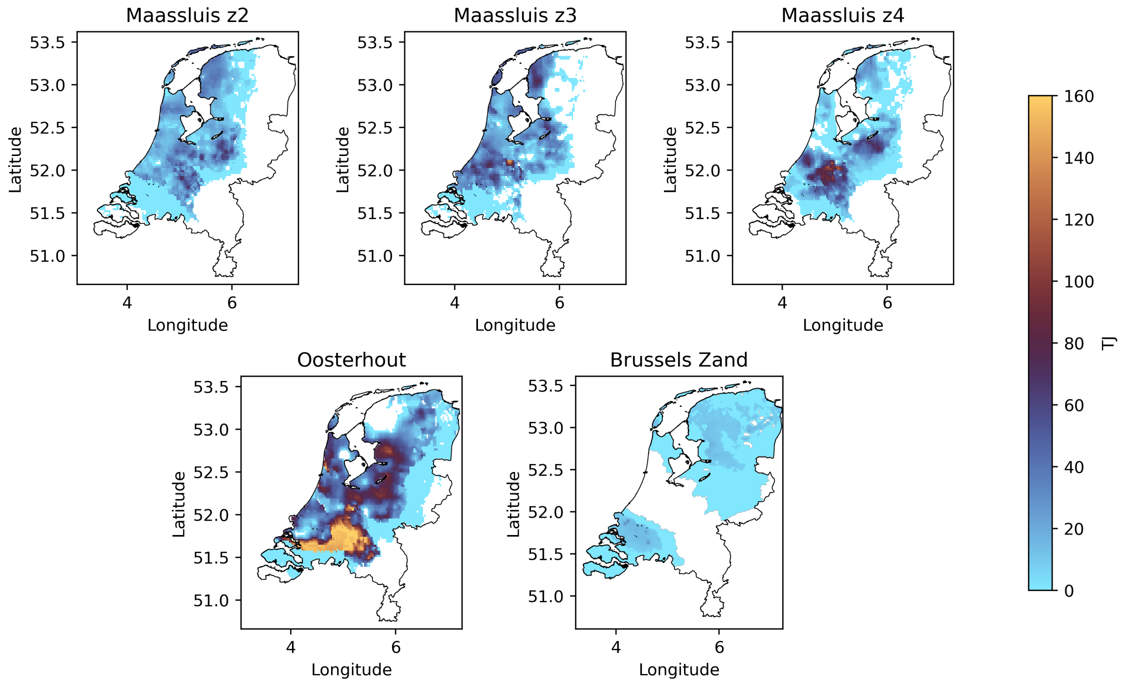


Figure 5: These maps show the HT-ATES median energy production in the Netherlands for the three formations considered in ThermoGIS-HT-ATES. The data for this image were provided by [24] and [25].

1.3 District heating

As previously mentioned, HT-ATES can directly supply heat to district heating due to the high temperature range. District heating will play an increasingly important role in future heat demand, as demonstrated in Figure 1. Therefore, district heating will be discussed in more detail in this section.

District heating (DH) networks supply hot water through pipes to residential, commercial, or industrial consumers for space heating, domestic hot water heating, and process heating [6]. DH can be supplied by many different heat sources, traditionally this has mostly been gas and coal. However, by 2050 renewable energy sources are expected to provide 77% of heat for DH. These renewable sources include geothermal heat, solar heat, bioenergy and heat from waste incineration or industrial processes [6]. The main advantages of district heating are the potentially low environmental impact and the low operating costs. However, the costs of DH increase when the heat demand is less concentrated, like in rural areas [26].

District heating can supply heat at different temperatures, usually separated into high temperature (>75 °C), medium temperature (55-75 °C), low temperature (30-55 °C) and ultra low temperature (<30 °C). Lower temperature DH reduces heat losses and allows for integration of other sustainable sources. However, the existing DH systems in the Netherlands supply high temperature heat of 70 to 90 °C [3] [4] [12] [27]. Existing dwellings that are not yet connected to district heating networks also typically require heat of around 70 °C for space heating and hot water, usually supplied by in-house boiler systems. Therefore, considering the current built environment, high temperature district heating networks have a better economic performance, because it does not require changes in the infrastructure or end-user investments [4]. A 70 °C network is also what is implemented in the ThermoGIS-HT-ATES studies, as it is seen as most realistic for the upcoming years [22].

The temperature demand can be reduced by improving the insulation of a building. Besides insulation, temperatures of 30-50 °C also require installation of low-temperature heat distributors. Newly constructed dwellings are already built to have higher energy efficiency and can be supplied with lower temperatures for space heating without need for further investments [3] [27]. Considering that HT-ATES can supply heat at 50-100 °C, it is well suited to supply older residential buildings without the need for insulation measures.

Manz et al. (2024) identified future district heating areas in the EU-27 countries based on heat demand, gross floor area, a distribution cost ceiling and a DH market share within DH areas. They assumed a large decrease in heat demand from 3129 TWh in 2020 to 1900 TWh in 2050 for residential and service buildings in the EU. However, with more connections to a district heating network, DH demand is still expected to increase. This is what we also observe in Figure 1, where urban central heat more than doubles in demand when going from 2030 to 2050. The resulting DH areas identified by Manz et al. (2024) for the Netherlands are shown in Figure 6. Most of the DH areas are located in the west of the country, which overlaps nicely with the favourable HT-ATES areas of Figure 4.

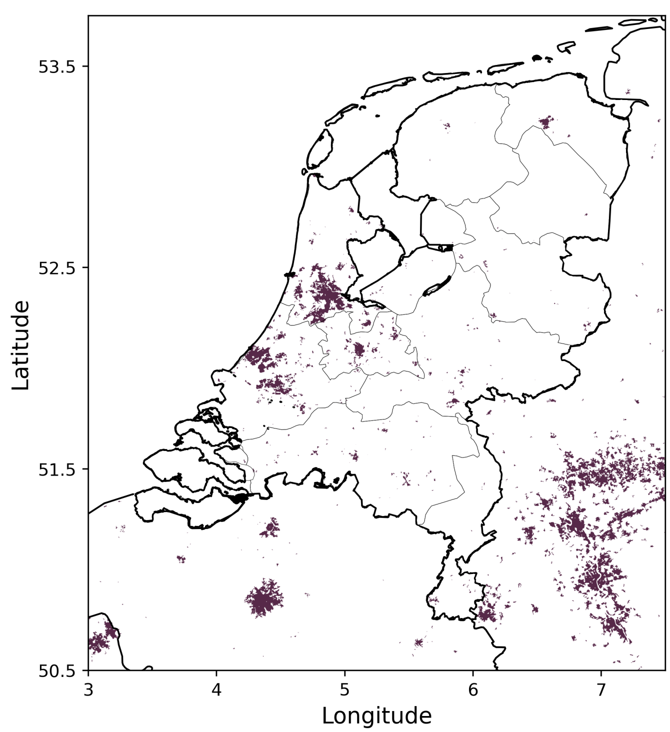


Figure 6: This map shows the expected district heating areas for the Netherlands in 2050 [28].

Seasonal thermal energy storage systems are often large in volume, so they work well with district heating. Discharging of TES can be dynamically turned on and off depending on the demand, even just throughout the day [6]. Interestingly, Remmelts et al. (2021) concluded that

HT-ATES is the most suitable form of TES for large district heating networks in the Netherlands, due to its large size and small surface area [4]. There are several examples in Germany, Canada, Denmark and Sweden of solar district heating systems being combined with borehole or pit thermal energy storage. However, these systems often still include a gas or electric boiler, as the installed capacity of solar energy and heat storage is often not sufficient to match the total heat demand [6].

1.4 Research aim

Due to the importance of heat in energy-related CO_2 emissions and the mismatch of heat demand with sustainable energy supply, it is important to investigate the potential advantages of high temperature aquifer thermal energy storage. According to Lyden et al. (2022), there is limited research in detailed ATES models in co-simulation with an energy system that includes both the electricity and heat sector. Such a model could enable analysis of the smart application of ATES in a large energy system [11]. Therefore, the focus of this research will be to combine detailed HT-ATES potential data with an energy system model. HT-ATES will be added as a new technology to an existing model, considering the HT-ATES potential energy data from ThermoGIS-HT-ATES. Scenarios of the near-future and future energy system are modelled with and without HT-ATES. The aim is to observe any changes in system costs and the overall deployment of HT-ATES in district heating in the Netherlands.

With HT-ATES having the lowest investment costs of the different TES systems and the increase in district heating capacity, it is expected that HT-ATES can have the potential to decrease the Dutch energy system costs.

2 Methods

To investigate the potential economical benefits and deployment of HT-ATES in the Dutch energy system, the open-source energy model PyPSA-Eur (v2025.04.0) is used. PyPSA-Eur stands for Python for Power System Analysis Europe and is a Python model that optimises an energy system based on raw data [2]. The model can be filtered to focus specifically on the Netherlands and different planning horizons. PyPSA-Eur does not yet include HT-ATES as an option to store energy, so this method will describe how it will be added. The focus will be put specifically on how HT-ATES can supply heat to district heating, called "urban central heat" in PyPSA.

A simple schematic of the method is provided in Figure 7, showing the different aspects relevant to the addition of HT-ATES. HT-ATES is added to PyPSA-Eur with estimated performance parameters for capacity, lifetime, storage time, and costs. Furthermore, the possible locations for HT-ATES, shown earlier in Figure 4, should be used to restrict where the systems are installed. This is similar to how, for example, the PyPSA model accounts for land use when considering possible locations for wind and solar production. In this research, HT-ATES will be added to the model specifically to supply heat for district heating. Hence, the location should also be limited to a proximity to expected district heating areas. The possible capacity of HT-ATES depends on the aquifer's properties, so the potential aquifers and their capacities need to be detailed as well. After the addition of this new type of storage, the results can be analysed for how much HT-ATES is deployed and how that affects overall system costs.

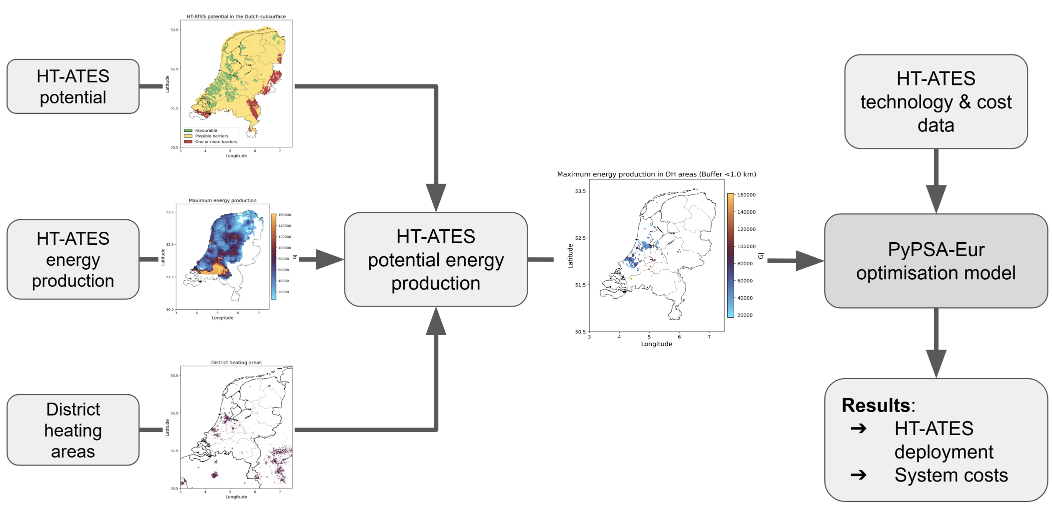


Figure 7: Schematic of the method where HT-ATES potential, HT-ATES energy production and district heating areas are combined to create a potential of HT-ATES energy production, used as input for the PyPSA-Eur model. HT-ATES technology and cost data are also used as input. The PyPSA-Eur model provides results on HT-ATES deployment and overall system costs.

2.1 PyPSA-Eur

PyPSA-Eur is a sector-coupled energy system model with the main objective of minimising investment and operational costs, using linear optimisation [2] [29]. The objective function is also constrained by a few other parameters, such as a CO_2 limit and technical and physical constraints. The mathematical formulation for the objective function and constraints can be found in Neumann et al. (2023) [2]. The system is modelled for an overnight scenario assuming perfect competition and foresight for a certain reference year, without pathway dependencies. This means that most existing assets are ignored, except for electricity and gas transmission infrastructure and large power plants. To optimise the network, the commercial solver Gurobi is used.

Generally, the energy system is modelled for a full year, to account for seasonal changes in energy production and demand. Seasonal changes in production are based on historical weather data from the year 2013 [2]. Energy use data is taken from a Eurostat report for the year 2019 [30]. PyPSA-Eur builds its own electricity demand based on hourly data from Open Power System Data, which includes electricity prices and electricity consumption [31] [32]. Based on data from JRC-IDEES, the model builds its own hourly heat demand for both water and space heating, accounting for ambient temperature, retrofitting measures, and differences between weekdays and weekends. The heat demand of the building sector is divided into several sectors based on population density. For decentral and rural demand, heat can be supplied individually, for example, with ground-sourced heat pumps or gas boilers. Urban central heat is supplied with large-scale district heating systems, which can be supplied with geothermal heat, waste heat or large-scale heat pumps for example. In PyPSA-Eur, cooling demand is only supplied with electricity and is not part of the heat sector [2]. Importantly for this research, heat demand can also be met by thermal energy storage, which will be discussed further in the next section.

2.2 Thermal energy storage in PyPSA-Eur

PyPSA already includes several thermal energy storage technologies, namely pit thermal energy storage (PTES) and large- and small-scale hot water tanks. Small-scale tanks are used for decentral heat supply, with a discharging time of 3 days, whereas large tanks and PTES are used for seasonal (180 days) central heat supply [30]. Each technology has its own technology details specified in the technology catalogue, this includes costs, lifetime, and the capacity of one unit for several prospective years [33]. Recently, LT-ATES was added to a newer PyPSA-Eur model (v2025.07.0) to supply heat for district heating. The release notes on this addition mention that "Some parameters (CAPEX, standing losses) might require tuning by the user. Eligibility computation is relatively basic. Turned off by default." [34]. Therefore, LT-ATES remains turned off in this research, but can be used as inspiration for adding HT-ATES to the model.

Tank thermal energy storage stores heat in water within a tank that is fully insulated. The full insulation means that water can be stored at temperatures up to 100 °C. Large-scale tanks can be used for district heating and can be located above ground, partially underground, or fully underground. Placing the tank underground does increase investment costs, but decreases heat losses and land footprint [11]. Pit thermal energy storage uses an excavated site filled with a storage medium, either water or a mixture of water and gravel, to store heat at temperatures of up to 80 °C. PTES is lower in costs compared to tank storage, because the side and bottom are typically not insulated, they are only covered with a watertight liner. The storage is located at 5-15 m underground [11] [35] [36].

One of the disadvantages of PTES is that according to Bolton et al. (2023) "available and affordable land is key" [37]. This is also the reason PTES is often not deployed in urban areas, as there is a lack of space. Another requirement for PTES is that there preferably should be no groundwater at the depth where PTES is to be located. The presence of groundwater can cause challenges to excavation and increase investment costs. When the PTES system is located near groundwater, heat can transfer from the pit, through the side and bottom walls, to the groundwater. This causes heat losses for PTES and increases groundwater temperatures, which may reduce its quality. To avoid such heat losses, the side and bottom walls can be insulated, but this increases the cost of a PTES system [38]. Increasing PTES investment costs affects the economic feasibility of this technology. Groundwater near PTES can increase heat losses by 14% when the water is static, or by up to 60% when it is moving. Heat losses caused by groundwater can be avoided if the groundwater table is at least 13 m below the bottom of the pit [36].

Most models neglect the effect of groundwater on PTES systems, because it requires more complex modelling [38]. Indeed, groundwater levels are not taken into account in the PyPSA-Eur model. However, a large part of the Netherlands has groundwater levels that at their highest point in the year reach within 2 m of the surface [39]. Furthermore, the Netherlands is a very densely populated country, with 541.4 people per km^2 in 2024 [40]. In addition, about half of the land in the Netherlands is used for agriculture, with agricultural land prices being one of the highest in Europe [41] [42]. Therefore, it can be concluded that available and affordable land is difficult to find. Taking this into account, together with the groundwater table, the implementation of many PTES installations in the Dutch energy system is likely to be unrealistic.

This conclusion was also drawn by De Groot (2020), who stated that low groundwater levels mean that PTES construction is either "impossible or at least very troublesome in almost all areas of the country" and that the land use of PTES is another "insurmountable barrier in densely populated Netherlands" [43]. CE Delft (2020) and Rovers et al. (2022) agree that maximum groundwater levels are a limiting factor for PTES in the Netherlands [44] [45]. Rovers et al. (2022) also mention that studies are still being done on the possibility of PTES with high groundwater levels [45]. Hence, in analysing the added HT-ATES to the PyPSA-Eur model, all simulations will be performed without PTES installations in the Netherlands.

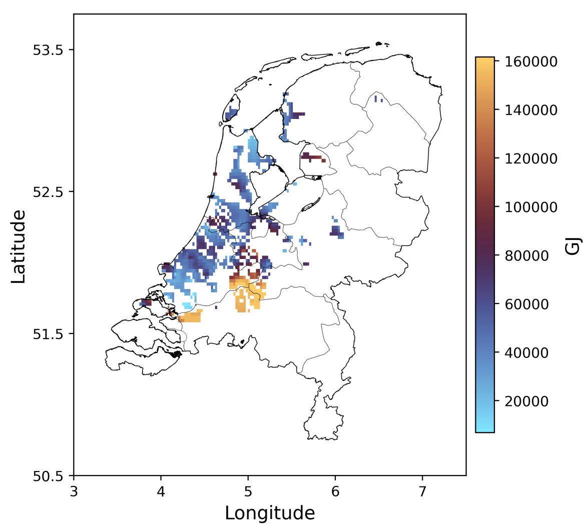
In the addition of HT-ATES to PyPSA-Eur, the effects of groundwater flow are accounted for, as a low groundwater flow velocity of $<$ 20-30 m/y is one of the criteria used to create the HT-ATES potential map for the Netherlands. The low velocity is a criterion as it prevents the stored hot water from flowing away. Another criterion for this map is also to avoid groundwater protection zones, water extraction areas, drilling-free zones, and Natura2000 zones for legal purposes [12] [21]. Contrary to PTES, HT-ATES has a very low land use, so other than the protected zones, this is not considered in the model [4] [11].

2.3 Adding HT-ATES to PyPSA-Eur

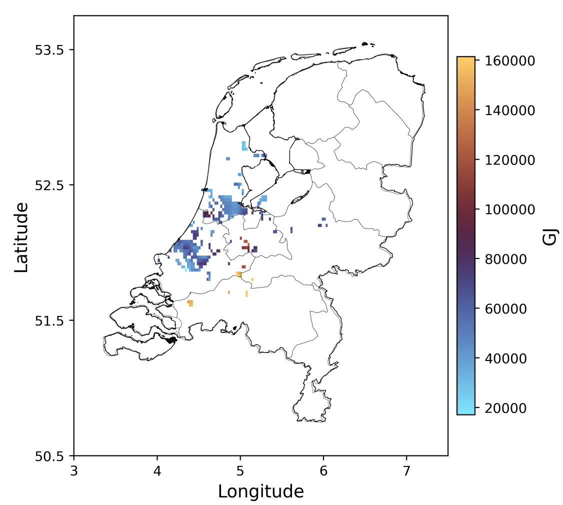
HT-ATES will be added only to supply urban central heating, because it is a large technology and is not intended for decentral individual use [17]. HT-ATES could also be used to supply greenhouses, however, as these are not a specific category in PyPSA, this research will not focus on it. The method created to find the HT-ATES potential within the PyPSA-Eur model is similar to the method of building LT-ATES potential, which can already be found in the model. In that method, the potential for LT-ATES in MWh is calculated for each cluster region. It calculates the potential of LT-ATES in MWh/m^2 based on standard aquifer parameters and a district heating temperature profile. Then it intersects areas of highly productive porous aquifers with future district heating areas. By multiplying the MWh/m^2 value with the potential areas, the energy storage potential can be calculated for each cluster [46].

Similarly to LT-ATES, Python code is written to generate energy storage potential for each cluster in the PyPSA network. As discussed in Section 1.2.2, Dinkelman et al. (2020) developed maps to determine suitable areas for HT-ATES in the Netherlands. By analysing these maps for each of the eight input formations, it can be found that the formations with the highest amount of suitable areas are the Oosterhout Formation and Maassluis Formation [20]. Thus, these two formations are the most representative of the Dutch HT-ATES potential. They are also two of the three formations for which energy production data is available from ThermoGIS-HT-ATES. This provides us with four datasets, three separate layers of the Maasluis formation and one for the Oosterhout formation. Important to note is that the energy production was calculated for a HT-ATES doublet system without heat pumps, hence, this is also what will be used in PyPSA-Eur [22]. For the PyPSA-Eur model, these energy production maps are separately filtered for favourable HT-ATES areas. After filtering, the four maps are compared and, for each overlapping grid cell, the grid cell with the highest energy production is selected, creating a map of maximum energy production (Figure 8a). From this map, the total energy production and total production area can be found to create a $\mathrm{MWh/m^2}$ value.

To avoid high heat losses from transport, HT-ATES will only be installed in areas close to future district heating networks. Data from Figure 6 are taken, and a 1 km buffer is placed around these predicted district heat (DH) areas. The DH buffer of 1 km was also used for LT-ATES to slightly loosen the restriction of the proximity to DH areas. Then, the energy production area of Figure 8a is overlain with the buffered district heating areas to create Figure 8b. This area is then multiplied again with the $\mathrm{MWh/m^2}$ value to find the maximum amount of energy that can be produced in each clustered region in the Netherlands.



(a) Filtered for favourable regions.



(b) Filtered for favourable regions and district heating regions with a <1 km buffer.

Figure 8: These maps show the maximum energy production from HT-ATES in the Netherlands, from the Maassluis and Oosterhout formations. The maps are filtered for favourable regions and DH areas and are to be used as input data for the PyPSA-Eur model. The data used to create these images were provided by [24], [20], and [28].

The actual HT-ATES system is added in the "prepare_sector_network.py" script, using two links and a store component. A maximum nominal energy is set for each cluster based on the maximum potential energy production calculated with the previous script. The link and store components are also assigned values of parameters such as lifetime, standing loss, and marginal cost. These parameters will be described in detail in Section 2.4. The store and links have extendable energy and power to ensure that new installations can be built. Because HT-ATES is a type of seasonal storage, the store is set to be cyclic so that the model understands that energy can flow over into other years.

2.4 HT-ATES technical and financial parameters

Similar to PTES and water tanks, several technical parameters need to be defined when adding HT-ATES to PyPSA-Eur. These parameters include the lifetime of one system, the storage capacity, the discharging time, the investment costs, marginal costs, and the fixed operational and maintenance costs.

The technical lifetime of a HT-ATES system is reported by several sources. Collignon et al. (2020) report that the lifetime of ATES systems ranges from 25 to 50 years [47]. Fleuchaus et al. (2020) report that the lifetime of HT-ATES is at least 30 years [16]. This same value of 30 years is also reported by Topsector Energy [17], CE Delft [44], and IF Technology [48] and used by ThermoGIS-HT-ATES [49]. Hence, this slightly conservative lifetime of 30 years is chosen for the PyPSA-Eur model.

The thermal output (in MW) of a HT-ATES system depends on the possible flow rate, the well injection temperature, and the cut-off temperature. The cut-off temperature refers to the temperature at which the HT-ATES system stops discharging, in the ThermoGIS-HT-ATES model this is set at 45 °C. A larger difference between the temperatures of the hot well and lukewarm well will increase the thermal output [22]. These temperatures depend on the heat source and the district heating network, and can therefore differ from system to system [23]. The ThermoGIS-HT-ATES model calculates thermal output dependent on a varying flow rate, an injection temperature of 80 °C, and a return temperature of 40 °C, resulting in a power range of 1-10 MW. More generally, the maximum thermal output of a HT-ATES system is estimated to range from 1-15 MW [17]. The HT-ATES system in Middenmeer, The Netherlands is reported to have a capacity of 10 MW when charging and 2-8 MW when discharging [19].

Similarly to thermal output, the energy storage capacity is site-specific, ranging from 0.6 - 40 GWh/yr per seasonal storage cycle [17] [48]. Fleuchaus et al. (2020) report a theoretical potential for a planned HT-ATES storage system of >10 GWh/yr in Lüneburg, Germany. A case study of the Greater Geneva Basin provides potential capacity ranges between 10 TJ and 75 TJ (2.8-20.8 GWh), depending on the amount of wells and the aquifer, or, more specifically, the permeability [47]. The target storage capacity of the planned HT-ATES system in Delft, The Netherlands is 25-50 TJ (7-14 GWh) [50]. The HT-ATES doublet in Middenmeer stores 28 GWh of geothermal heat in summer and discharges 20 GWh of heat in winter [19]. In Rostock, Germany the storage capacity is much lower, just 0.295 GWh/yr. This is most likely because the well is at a much shallower depth of 13-27 m and a lower temperature of 50 °C, while the Middenmeer wells are at 360-383 m and heat is stored at 85 °C [51] [19].

The thermal output and energy storage capacity are used to calculate an energy-to-power ratio (etpr), which is needed to ensure that nominal energy and nominal power capacity remain linked and are not optimised separately. For each thermal energy storage unit we apply $Store\_e_{nom} - etpr * Link\_p_{nom} = 0$. The storage capacity of a HT-ATES system depends on flow rate, temperature, and size, resulting in quite a broad range, as demonstrated above. Considering this information, an average energy storage capacity of 20 GWh and an output capacity of 7 MW are selected for this study. This results in etpr of approximately 2880 hours, which corresponds to a discharging time of 120 days (120*24=2880). The energy storage capacity of 20 GWh matches the most recently installed HT-ATES system, the one in Middenmeer, and is therefore also used to calculate the amount of system installed by the PyPSA model.

During storage, thermal energy decays over time, depending on the production period. This is implemented in the model as a "standing loss" and is calculated as follows:

$$\text{Standing loss} = 1 - e^{(-1/24\tau)} \tag{1}$$

where the time constant τ is the amount of discharging time, which can be a maximum of 180 days, to ensure enough time for recharging [4] [30]. Instead, a time constant of 120 days is chosen, as this is the production period used by ThermoGIS-HT-ATES to calculate the HT-ATES energy potential maps [23]. This results in a standing loss of 0.035 %/hour, which is used to calculate the nominal energy of the storage system.

The investment cost required to install a HT-ATES system depends on the depth, size, and flow rate of the aquifer [19]. It also depends on the temperature of the injected heat and the water treatment because both affect the required piping material [17]. Another investment expense comes from consultancy and permits that are needed for installation [19]. As a result of all these parameters, the reported investment cost estimates differ significantly per source. Arntz et al. (2020) stated that investment estimations can easily differ by ±25% from the real costs [52]. Table 1 provides an overview of the different values of investment costs found in the literature. For many cost values, the capacity of the HT-ATES system was not reported, so the capacities that were decided on in this study (7 MW and 20 GWh) were used to calculate the value in €/KWh. Based on all the different estimations, a relatively conservative value of 0.2 €/kWh is chosen for the PyPSA-Eur model, similar to the costs of the Middenmeer installation. For a 20 GWh system, this value is equivalent to €4 mln. A conservative value is chosen because for some of the estimates it is unclear if they include the investment costs of well drilling and pump installation.

In addition to investment costs, the model also requires a value for fixed operational and maintenance costs, or FOM, as a percentage of investment costs. Again, estimations for its value differ by source. Topsector Energy estimates a FOM of 1% to 3% of investment for an HT-ATES system that operates at temperatures of 60 °C to 90 °C [17]. The exploration study on the Rotterdam Nesselande HT-ATES system found FOM costs of 2% to 4% of investment costs [52]. Wesselink et al. (2018) and Pluymaekers et al. (2013) take a FOM of 1% of total HT-ATES investment costs per year [53] [54]. The feasibility study on combining geothermal energy with HT-ATES by Van 't Westende & Dinkelman (2023) considered a fixed OPEX of 12 k€/MW/yr, which for a system of 7 MW and investment costs of €4 mln would result in 2.1%/yr [55].

Table 1: Overview of different estimations regarding the investment costs of a HT-ATES system. When no specific capacity was provided, 7 MW / 20 GWh was used as this is what is applied in this research.

Investment cost	**HT-ATES capacity**	**Investment cost in [€/KWh]**	**Source**
14 €/GJ	7 MW / 20 GWh	0.05	Remmelts et al. (2021) [4]
1.1 M€ & 25 €/kW	7 MW / 20 GWh	0.064	ThermoGIS-HT-ATES [49]
1.85 M€	7 MW	0.09	Pluymaekers et al. (2013) [54]
0.33 M€/MW	7 MW / 20 GWh	0.12	Van 't Westende & Dinkelman (2023) [55]
1.48 M€	3.15 MW	0.16	Wesselink et al. (2018) [53]
2.5-3.4 M€	7 MW / 20 GWh	0.125-0.17	Oerlemans et al. (2022) [7]
2.5-4 M€	7 MW / 20 GWh	0.125-0.2	IF Technology [48]
0.4-0.8 M€/MW	7 MW / 20 GWh	0.2	HT-ATES in Middenmeer [7]
2.1-2.6 M€	1.8-4.2 MW	0.29	HT-ATES in Rotterdam [22]
0.1-1 €/KWh	60-90 °C	0.1-1	Topsector Energy [17]

Again, a relatively high value is chosen for the FOM costs; 3%/yr of investment costs. High values are chosen to observe the deployment of HT-ATES in the energy model for a more conservative scenario. If HT-ATES is still deployed in a conservative scenario, a stronger conclusion can be drawn regarding its benefits.

A source of marginal costs that was comparable to other marginal costs in PyPSA-Eur could not be found for HT-ATES, so instead the same value was chosen as was used for LT-ATES in PyPSA-Eur, which is 0.035 €/MWh. This value is higher than the marginal costs for tank and pit storage, which are 0.03 €/MWh and 0.025 €/MWh respectively [56]. Table 2 provides all the parameters discussed in this section with their selected values. These are the values that will be used in the base scenarios of the model. The technical and financial assumptions for all other technologies are taken from [33] (v0.12.0), archived on Zenodo [57].

Table 2: Base case technical and financial parameters for HT-ATES in PyPSA-Eur.

Parameter	**Value**	**Unit**
DH area buffer	1000	m
Lifetime	30	years
Energy-to-power ratio	2880	hours
Time constant	120	days
Investment	0.2	€/kWhCapacity
Fixed O&M	3	%/year
Marginal costs	0.035	€/MWh

2.5 PyPSA-Eur configuration and scenarios

Generally, the default configuration is used for the energy models, which is described in detail on the PyPSA-Eur website, including all the parameter values [30]. This includes using the year 2013 for the snapshot, as it is a representative year with respect to the weather. Like Neumann et al. (2023), a time resolution of 3 hours is applied [2]. Of course an hourly resolution would be more realistic and is possible with most input data, however, it also significantly increases computation time. Besides, Neumann et al. (2023) found that a 3-hourly resolution still captures dominant intraday, daily, and seasonal patterns [2].

The energy network is modelled for the Netherlands, as well as Belgium, Germany, Denmark, and Norway. Other countries are included because the objective function for a network with just the Netherlands and a net-zero CO_2 emission scenario is unsolvable. These specific countries are selected because they all have a high-voltage connection to the Netherlands, so trading electricity with these countries is already possible [58]. Including these other countries also makes the model more realistic because it is unlikely that the Dutch energy system will remove all its connections to other countries in the future. Only a select few countries are chosen instead of the entire European network to limit computation time. The network is clustered using k-means with a focus weight on the Netherlands, so that most nodes are placed there, as this is the country of interest in this research. This results in the network shown in Figure 9, with eleven nodes in the Netherlands to be able to show clear differences in the location of installed HT-ATES. The other countries are modelled with just one node each, to simplify the model. With the exception of Denmark, which has two nodes instead of one, because it has two asynchronous subnetworks [59].

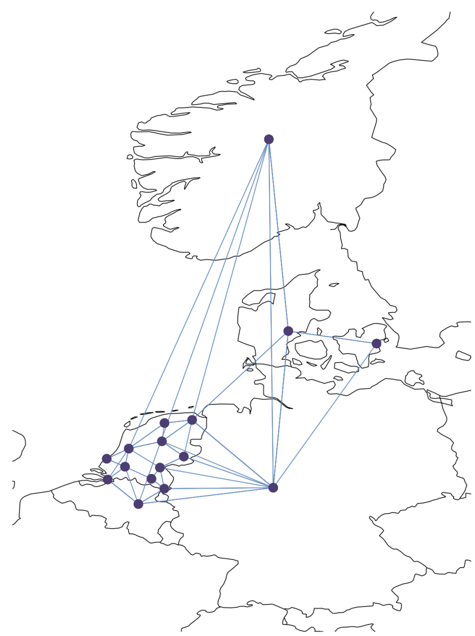


Figure 9: Visual representation of the network with 16 nodes.

By default, residential and service heat buses are clustered together to save memory. This means that "urban central heat", or district heat, consists of both residential and service heat demand. The model has set a potential for a maximum of 60% of urban demand that can be supplied by district heating. The model also provides numbers for the progress to reach this potential; in 2030 only 30% of this potential is achieved, but by 2050 100% of the potential is achieved [30] [2].

CO_2 limits are set depending on the planning horizon in accordance with European climate law. This means that CO_2 emissions are reduced by 55% in 2030 relative to 1990 emissions. By 2050, a 100% reduction is modelled, which is in line with the goal of being climate neutral by 2050 [30]. To investigate the dependence of the model results on this CO_2 limit, scenarios are run for both 2030 and 2050. Important to note is that for both horizons, technology cost assumptions are for the year 2030, as was also done in Neumann et al. (2023) [2]. By taking 2030 assumptions, near-term cost reductions can be accounted for with reliable projections. Besides, to reach net-zero emissions in 2050, infrastructure must be gradually built before 2050, so taking predicted cost reductions for 2050 would be too optimistic [2] [60]. Furthermore, no cost predictions for HT-ATES in 2050 could be found.

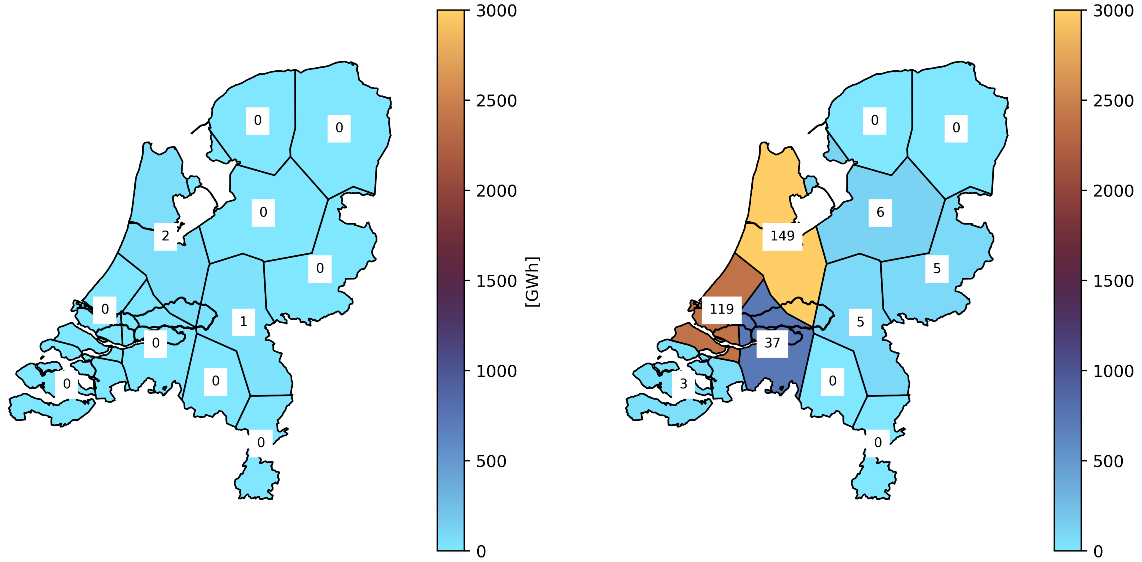
Two main changes were made regarding the energy supply because two bugs were found. First of all, the nuclear power plant in Borssele is seen by the model as a coal plant. Hence, this power plant is removed and a custom nuclear power plant is added to create more realistic results. Secondly, geothermal energy was not included in the model by default. The main reason for this was that geothermal was not considered a viable input for heat pumps. However, both direct geothermal heat supply and supply with an additional heat pump would only be modelled if geothermal energy *can* be a heat pump source, hence this was changed. It is also good to note that the geothermal data was only provided for EU-27 countries, which excludes Norway.

A summary of all changes made to the default configuration, as described above, can be found in Table 4 in the Appendix. For the main analysis of the addition of HT-ATES to the PyPSA-Eur model, four scenarios are run with the above configuration. These scenarios are for 2030 and 2050 and both include and exclude HT-ATES. Then, the deployment of HT-ATES in these different scenarios is investigated, as well as the resulting system costs. To analyse the system's sensitivity to the estimations made regarding all HT-ATES-related parameters, a sensitivity analysis is performed.

3 Results

3.1 Deployment of HT-ATES in the Dutch energy system

Firstly, scenarios for 2030 and 2050 are run with the base parameters of Table 2. The amount of HT-ATES systems installed for each of these scenarios is shown in Figure 10, assuming that one system has a capacity of 20 GWh, just like the HT-ATES doublet in Middenmeer. In 2030 just 79 GWh of capacity is installed, whereas in 2050 this increases to 6466 GWh, which is also the maximum amount that can be installed considering the input data. This tells us that with the lower demand of urban central heating and the CO_2 limit of 2030, HT-ATES is not yet economically viable. This changes completely for 2050 where the maximum amount of capacity is installed, amounting to around 324 systems. As expected, most of those systems are installed in the west of the country, where district heating and favourable HT-ATES areas overlap.



(a) 2030 - 79 GWh installed

(b) 2050 - 6466 GWh installed

Figure 10: These maps show the amount of HT-ATES systems that were installed in each cluster, assuming that one system has a capacity of 20 GWh.

To observe seasonality, the state of charge of all HT-ATES systems combined is plotted in Figure 11. It shows that the system consistently charges with heat from May to November and then discharges from November to April. It also shows that it does not charge to the full maximum capacity of 6.5 TWh. Figure 12 depicts the heat balance throughout 2050 in GW, with the positive y-axis showing the heat supply and the negative y-axis showing the heat demand. HT-ATES discharges in the months with the highest heat demand and charges in the months with low demand from the built environment, as expected. It can also be observed that in the HT-ATES charging months (May-Nov), the dominant source of urban central heat is direct utilisation of geothermal heat, so this is most likely the main source of heat for HT-ATES.

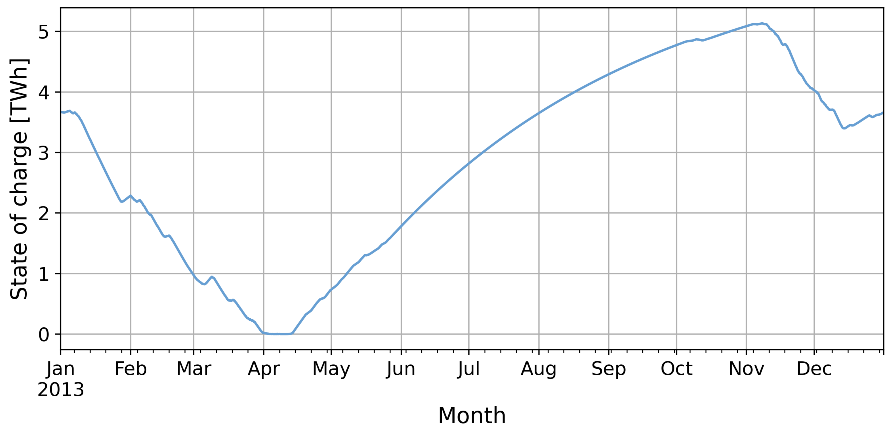


Figure 11: The state of charge in TWh of all HT-ATES systems combined, for the 2050 base scenario.

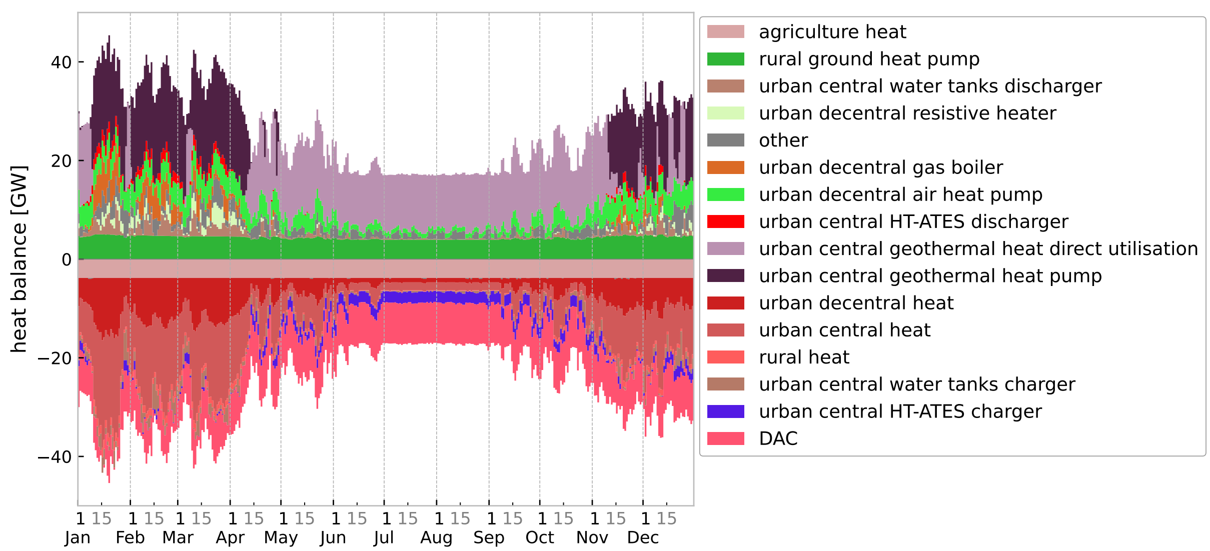


Figure 12: Heat balance of the Netherlands in 2050, with HT-ATES.

Figure 13 shows how much HT-ATES contributes to district heating supply in 2050. It is good to note that because of the internal structure of PyPSA-Eur, HT-ATES supplies heat to "urban central heat", however, only 42% of urban central heat actually goes to district heating. The rest of the heat goes to direct air capture (DAC) (43%), charging HT-ATES (8%), charging water tanks (5%), and low temperature industry (2%). In Figure 13 2.6% of the district heating demand is supplied with discharged heat from HT-ATES. The same percentage applies to the whole "urban central heat" load, because the heat is evenly divided over the different urban central heat components. If all HT-ATES heat was directed just to district heating, it would supply 6% of the demand.

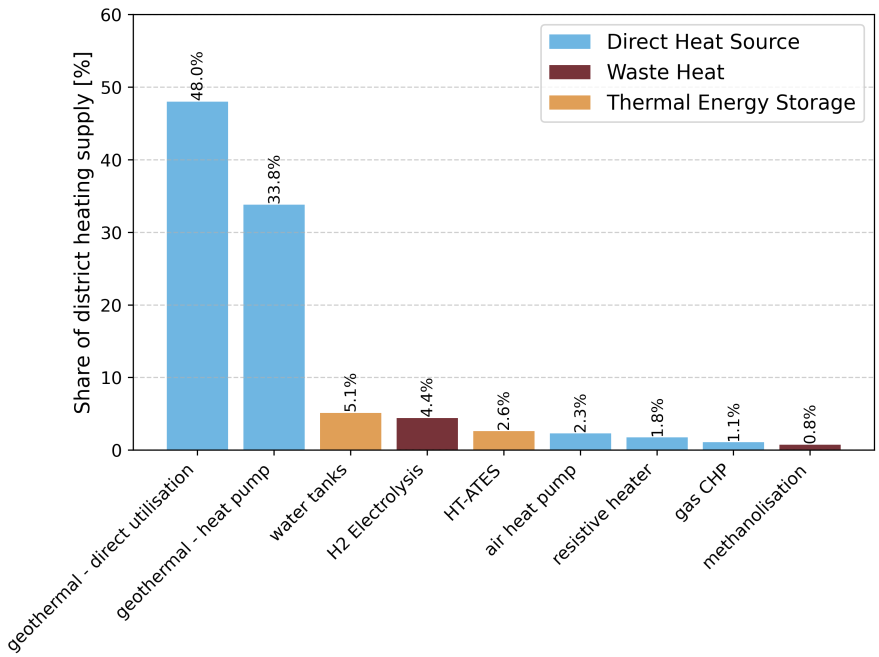


Figure 13: District heating supply by source, split up into direct heat sources, waste heat and thermal energy storage. This graph shows the results for 2050 with HT-ATES, where HT-ATES contributes 2.6% to total district heating energy supply (29 TWh).

3.2 System costs

Total system costs are calculated by summing all capital and operational costs for each node in the network. Therefore, we can analyse the systems costs from just the Dutch nodes or for the whole network. It is important to note that by default, random noise is added to the marginal costs of generators and to the capital costs of lines and links to help the solver find a solution. As a result, the system costs for one specific scenario will differ when it is optimised multiple times. To account for this, the 2030 and 2050 scenarios with and without HT-ATES are optimised three times so that a mean can be taken with a standard deviation.

The results of the system costs are provided in Table 3, for the whole network and after filtering for only the Dutch nodes. Looking at just the Dutch network, the differences for 2030 with and without HT-ATES fall within their standard deviation, aligning with the previous very low result of installed HT-ATES systems. In 2050 much more systems were installed and this results in a larger difference between the costs; when HT-ATES is added to the model, system costs decrease by 0.52 bln €/yr, or 1.1%. This decrease is almost ten times larger than the standard deviation in the system costs, so it is not a result of random noise. However, the difference in costs is smaller when the whole network is considered, with system costs decreasing only 0.1 bln €/yr, or 0.04%, when HT-ATES is added to the model. The differences between the 2030 scenarios are larger for the total network, however, this result is neglected due to the high standard deviation compared to the standard deviations in the 2050 scenarios.

Table 3: The system costs (capital and operational) for the main four scenarios.

	Netherlands [bln €/yr]	Total network [bln €/yr]
2030	21.6 ± 0.2	225.2 ± 0.1
2030 with HT-ATES	21.5 ± 0.2	225.03 ± 0.05
2050	46.10 ± 0.07	250.7995 ± 0.0001
2050 with HT-ATES	45.58 ± 0.07	250.7027 ± 0.0001

In addition to a decrease in total system costs, a reduction in the price of urban central heat was also observed when HT-ATES is added to the 2050 energy system. This price was calculated as the load-weighted marginal price, reflecting the average cost of supplying urban central heat, weighted by hourly demand at each node. It is approximate to the price consumers would pay under marginal-cost pricing, assuming perfect competition and foresight. Without HT-ATES, the load-weighted marginal price of urban central heat in the Netherlands is 33 ± 10 €/MWh,. With HT-ATES it drops to 30 ± 8 €/MWh, a decrease of approximately 7%. When the total network is considered, both prices increase slightly to 33 ± 10 €/MWh without HT-ATES and 32 ± 9 €/MWh with HT-ATES, corresponding to a decrease of around 4.7%.

3.3 Sensitivity analysis

To analyse the effect that estimations for HT-ATES-related parameters have on the deployment of HT-ATES, a sensitivity analysis is performed. Each parameter is increased and decreased by 25%, and then the optimisation model is run again. This is only done for the 2050 scenario with HT-ATES, as the capacity installed in the base 2030 scenario is already very low. The results can be found in Figure 14, showing the difference in system costs compared to the base scenario, of which the costs were 250.7027 ± 0.0001 bln €/yr. Due to time limitations, each variation could not be run three times, so the standard deviation of the base case is applied to all scenarios. However, the standard deviation for the total network was only ± 0.0001 bln €/yr, and is therefore too small to appear in the figure.

The parameters with the highest impacts are the energy-to-power ratio and the investment cost, resulting in a maximum change in system costs of almost 0.019% when the energy-to-power ratio is decreased by 25%. This cost difference is still significantly smaller than the difference between a model with and without HT-ATES, which was 0.04%. The energy-to-power ratio ensures that the power and energy capacities of a HT-ATES system are always constrained by that ratio. The model selects the power capacity based on what the energy system requires, and the corresponding energy capacity is determined by the fixed ratio. Since HT-ATES capital costs are only applied to the energy capacity, a lower energy-to-power ratio results in lower total capital cost for the same power capacity, and therefore lower total system costs. Reducing the investment cost and fixed operational and maintenance (FOM) cost also decreases total system costs, as expected. In contrast, a shorter lifetime increases system costs, as the time frame for recovering the investment costs becomes shorter. A smaller DH area buffer limits the potential area for HT-ATES installations, thereby reducing the technology's contribution to overall system cost reduction. Interestingly, a change in marginal costs hardly affects total system costs, with the bars barely visible in Figure 14. This is good to know, since sources for marginal costs were difficult to find and its value was selected only by comparison to other TES systems. If all parameters in Table 2 are lowered by 25% in the same model, the total system costs decrease by 0.024%.

Besides the parameters from Table 2, the figure also shows what happens when the areas of "possible barriers" are included in the filtering of potential HT-ATES areas. With this increased potential area, system costs are decreased by around 0.012%, because more systems could be installed. This value might seem low considering how large the area of "possible areas" is, however, this area does not overlap as much with district heating zones, reducing the positive effect of including it.

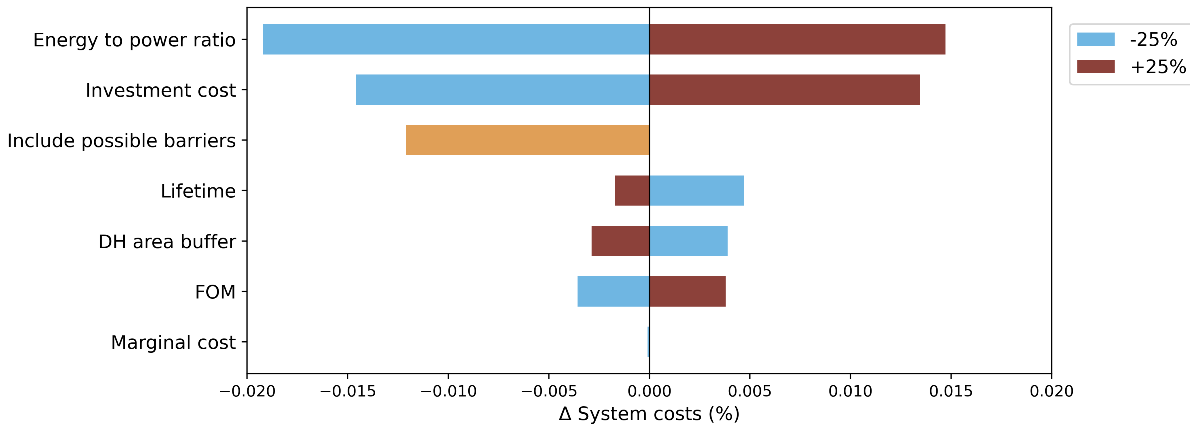


Figure 14: Difference in total system cost compared to the base scenario as a result of changing HT-ATES-related parameters. This sensitivity analysis was done for the 2050 scenario with HT-ATES, including all five countries in the network.

The number of clusters that were selected for the network also greatly affects system costs. When the total number of clusters was increased from 16 to 20, the system costs decreased by 0.22%, which is much higher than the difference between a model with and without HT-ATES, which was 0.04%. However, the difference in costs for a 20 cluster model with and without HT-ATES is still around 0.04%. Therefore, even though the number of clusters affects the value of system costs, it does not greatly affect the results concerning HT-ATES, where the difference in costs is more important.

As explained in Section 2.5, cost predictions for the year 2030 were used for both 2030 and 2050 scenarios. However, PyPSA-Eur does also estimate technology costs for 2050 [33]. Some main changes include a 25% reduction in solar photovoltaics costs, a 33% reduction for DAC costs, and 45-60% reduction of battery and electrolyser costs [2]. To test the sensitivity of the model to 2050 cost assumptions, two 2050 scenarios were run with and without HT-ATES. It should be noted that the HT-ATES cost and technology assumptions remain the same in both cases, because no 2050 assumptions could be found. The total system costs are reduced by around 13% when 2050 cost assumptions are applied. This reduction is similar to what Neumann et al. (2023) found in their research, where total costs were reduced by 15-18% for a full European network [2]. The difference between a scenario with and without HT-ATES decreases from 0.04% to 0.02%, when going from 2030 to 2050 assumptions. This can be explained by the fact that a lower HT-ATES capacity is installed; 5.6 TWh instead of 6.5 TWh with 2030 cost assumptions. HT-ATES is now also relatively more expensive than other heat sources, so even though it is still used because of low CO_2 emissions, it will not decrease system costs as much.

4 Discussion

The purpose of this research was to investigate the impact HT-ATES can have on the Dutch energy system. This was done by adding HT-ATES to the PyPSA-Eur energy system model, accounting for the energy production potential of Dutch aquifers. In this section, the results of the model will be discussed, as well as the limitations and possible improvements of the method.

Comparing the 2030 and 2050 scenarios, we can see that the installed capacity of HT-ATES systems goes from 79 to 6466 GWh. This can be explained by the CO_2 limit becoming stricter, but also by a difference in urban central heating demand, which increases from 27.7 to 64.9 TWh (see Figure 1). In 2050, the need for district heat sources increases, as well as the need for heat sources without CO_2 emissions, resulting in the maximum amount of HT-ATES systems installed and HT-ATES supplying 2.6% of the district heating demand. However, in addition to district heating, this also includes supplying heat to, for example, direct air capture. If HT-ATES would only supply heat to district heating, the share it has in district heating supply would increase to 6%. In 2050, geothermal heat has become the main source of heat, either directly or with an additional heat pump, it supplies around 80% of urban central heating. It can be expected that a similar percentage would be found regarding the sources of heat that charge the HT-ATES systems. The only HT-ATES system that is already installed in the Netherlands and one of the few planned HT-ATES systems, are also (going to be) supplied by geothermal heat [19] [50]. Therefore, it is not surprising that the model also invests largely in geothermal heat and applies it to HT-ATES. A reason for the large share of geothermal heat is its low cost compared to other heat sources with low CO_2 emissions, such as solar thermal energy or power-to-heat with heat pumps [57].

The total system costs show a statistically significant decrease when HT-ATES is added to the model in 2050. The total network costs decrease by 0.1 bln€/yr, or 0.04%. This percentage might seem low, but the network includes five countries and HT-ATES is added to only one of them. If we filter for the Dutch nodes, the decrease becomes 0.52 bln€/yr, or 1.1%. Of course, this simply means costs in other countries are increased, but it does show a significant effect caused by the HT-ATES addition. This effect can also be found in the change in the marginal price of urban central heat in the Netherlands, which is lowered by 7% when HT-ATES is added. The parameters chosen for the base model were often selected to be conservative, the sensitivity analysis in Figure 14 shows that a change of just 25% in their values can affect total network costs up to 0.019%, depending on the parameter. If all the technology and cost parameters of Table 2 are reduced by 25%, a system with HT-ATES would cost 0.063% less than a system without HT-ATES. An increase in the number of clusters in the Netherlands does not affect the cost difference between a scenario with and without HT-ATES. Applying 2050 cost assumptions instead of 2030 cost assumptions reduces the impact of HT-ATES, with a cost difference of just 0.02%. However, as explained in Section 2.5, 2050 cost assumptions are less realistic and more prone to change and therefore not considered in the conclusion.

PyPSA-Eur, as any model, has its limitations, so some of the limitations most relevant for this research will be discussed here. For example, the distribution of energy demand is based on the distribution of the population and GDP in each country. This might not reflect the real circumstances, especially when considering very local demands. For example, an area of low population could still have a town suitable for district heating even though it would not be considered "urban central". Furthermore, due to a lack of data, information on existing renewable capacities for technologies such as wind, solar, or geothermal are excluded. Therefore, the installed renewable capacity, especially in near-future scenarios such as 2030, could potentially overestimate capacity if certain locations are already used with potentially less efficient technologies, because these would be older than what the model installs. Besides, there is incomplete information on other existing technologies as well due to missing data on, for example, existing space and water heating supply [61].

To limit computation time, a network of just five countries was used in this research, however, in reality these countries also trade energy with other countries, but this is not considered by the model. Even if all countries in PyPSA-Eur were used, international interactions would still be limited to the countries in the ENTSO-E area, excluding, for example, Russia, Turkey, Morocco, and Ukraine [61].

In Section 2.2 it was decided that pit thermal energy storage would be excluded from the Netherlands in the PyPSA-Eur model, because it was thought to be unlikely to be installed in reality. This analysis was only performed for the Netherlands and not for the other countries in the network where PTES was still installed. A further improvement to the PyPSA-Eur model would be to consider groundwater levels and land use as a limitation for PTES installations. Tank thermal energy storage was still allowed for the whole network, however, the costs of TTES depend heavily on if it is installed above or below ground. PyPSA-Eur does not distinguish between these when it comes to investment costs for example, which was determined based on "references from various projects in Danish district heating systems" [33]. Therefore, it is possible that PyPSA-Eur underestimates the costs of TTES when installed in areas where the tank needs to be underground.

As was seen in the sensitivity analysis, the model is rather sensitive to small changes in costs. Despite that, the default configuration of the model uses cost predictions for 2030 for all scenarios, including 2050 scenarios. This causes an overestimation of total system costs, as Neumann et al. (2023) described in their own sensitivity analysis [2]. This was also shown with a sensitivity analysis in this study, where 2050 cost assumptions decreased total system costs by 13%. With the learning-by-doing principle, it can be expected that especially newer technologies will decrease in costs in the future. This, of course, also applies to HT-ATES. However, because costs predictions for 25 years away are difficult to make, this is not accounted for in the default model.

PyPSA-Eur is also constantly in development, hence the results of this research are likely to change with newer editions. For example, four new versions of the technology and cost assumptions have already been published since the HT-ATES model of this research was created [33].

In addition to the limitations of PyPSA-Eur itself, there are also limitations in the addition of HT-ATES. Starting with the locations for HT-ATES, we limit them to being in close proximity to district heating areas, however, there is no limit set to the proximity of heat supply, mostly geothermal heat in this case. If heat production does not take place in close proximity to HT-ATES, a lot of heat could be lost during transport. On the topic of heat loss, in the first few years of an HT-ATES system, much of the heat is lost due to the surrounding rock heating up. These losses are not accounted for in the model. In adding the HT-ATES components to PyPSA-Eur, a similar approach was taken as for tank storage, PTES and LT-ATES, which all do not include specific efficiencies. Therefore, no efficiency was provided for HT-ATES either. This is partially resolved by the standing losses that the model takes into account, but further investigation of the use of standing loss and efficiency values is needed. If a real efficiency value could be given to the model, it could be simply averaged throughout the lifetime of the system, accounting for the low efficiency in the first few years.

Another inaccuracy can be found in the calculation of maximum energy potential. An average MWh/m^2 value is used to find the maximum amount of energy that can be stored in each clustered region. This was done to have a more general idea of the heat that can be stored, especially since only two geological formations are considered in this study. However, it would have been more precise to take the exact values of energy production for each grid cell that is still present after filtering for district heating areas. Because this was not done, it is possible that the current model overestimates or underestimates the potential energy production of HT-ATES.

The potential energy could also be underestimated because the model assumes only doublets for HT-ATES, which limits the capacity of the storage system. The contributors to the ThermoGIS-HT-ATES model state that adding an option for multiple-well systems could allow higher energy production [22]. However, since this has not yet been implemented in their model, it also could not be implemented in PyPSA-Eur. The system is also created in such a way that HT-ATES supplies district heating directly, without a heat pump in between, although this could also increase the total power of the system. A heat pump could also provide a more stable temperature supply, which is important for district heating. However, it would also increase the costs of the heat due to the high investment costs of a heat pump and lower allowed flow rate in the system [22]. Vrijlandt et al. (2023) did create some examples of the power that could be achieved from the Maassluis formation when a heat pump is added to the system, however, this was not yet implemented in the ThermoGIS-HT-ATES data [22]. ThermoGIS-HT-ATES also used the most restrictive flow rate values in calculating the energy production, potentially underestimating the amount of energy that can be stored in the aquifer formations.

As expected of an energy model, it does not always account for resistance towards new technology installations. For example, the benefits of HT-ATES rely on the installation of more district heat networks, however, this has its own problems. In the Netherlands, the installation of new district heating has stalled; from 2019 to now, the percentage of heat delivered by district heating remains largely unchanged, stuck at 6-7%. This is partially caused by struggles in governmental organisations, but also because the installation of individual heat pumps has increased rapidly in the last few years. When many individual heat pumps are installed in an area suitable for district heating, it makes less sense to remove them again and install a heating network [62]. Furthermore, even though the operating costs of district heating with seasonal heat storage would be low, the initial investment costs are high with long payback periods [6].

The presence of barriers for a HT-ATES system are highly location-specific, meaning that there is a possibility that in a "favourable" area, there could still be a barrier for HT-ATES [21]. This is not accounted for with the regional potential maps used in this research. The maps also do not account for barriers that could be caused by other installations in the subsurface, such as LT-ATES and BTES systems, of which there are many in the Netherlands [20].

Duscher et al. (2015) developed a hydrogeological map of Europe, depicting the locations of productive and non-productive aquifers in porous and fissured rocks [15]. This map is used in the LT-ATES scripts of PyPSA-Eur, where they filter for only "Highly productive porous aquifers" as possible aquifers for LT-ATES [46]. The map shows that the Netherlands has large areas of highly productive porous aquifers. However, other countries have such large productive porous aquifer areas as well, for example; Germany, Belarus, Hungary, and Romania. Therefore, it would be interesting to investigate the potential for HT-ATES in these other countries. This could be a future improvement to the model, to include all other ENTSO-E countries in the HT-ATES addition. However, data on the HT-ATES energy potential throughout Europe is currently not available. Dinkelman and Van Bergen (2022) already suggested the idea of recreating the HT-ATES possibility map for the whole of Europe. It would require an assessment of all sedimentary basins in Europe, most likely with lower resolution maps, as not all geological databases are as extensive as the ones for the Netherlands. Still, they already suggested some potential resources and enough data is available on the heat supply and demand for HT-ATES [21]. If such a EU potential map is made, the addition of HT-ATES to PyPSA-Eur could be extended to the whole of Europe.

The model makes it so that HT-ATES is mainly charged with geothermal heat. Currently, we already experience moments, in summer for example, with an excess of electricity, which could of course be stored in batteries or as hydrogen, however, with power-to-heat it could also be stored in HT-ATES. It would be interesting to either adapt the model or use a different model, where we can control the source of heat and observe how that affects the overall system. Similarly, it would be interesting to adapt the model so that HT-ATES would really only supply district heating and no other urban central heat demand, such as DAC. Especially because HT-ATES locations are limited by proximity to DH areas, but only 42% of HT-ATES actually goes to DH networks.

Despite the limitations, one can still conclude that HT-ATES installations in the Netherlands can lower system costs in a network that includes the Netherlands, Belgium, Germany, Denmark, and Norway. This research provides motivation for the installation and further research of HT-ATES in the Netherlands. The outcome was the most sensitive to the capacity of the system and the investment costs of HT-ATES, so these parameters might need further investigation for more realistic results. However, this could be difficult because these parameters, as well as the precise favourable HT-ATES locations, are very case-specific.

5 Conclusions

The aim of this research was to evaluate the impact high temperature aquifer thermal energy storage can have on the Dutch energy system with the PyPSA-Eur energy model. HT-ATES was successfully added to the model and, as hypothesised, was able to reduce total system costs. However, this reduction depends on the CO_2 limit of the model and on the heat demand in a certain year, because hardly any systems were installed in 2030. In 2050 however, the maximum capacity was installed, and as a result HT-ATES was able to reduce the costs of the whole 5-country-network by 0.04%. Conservative technical and financial parameters were applied to the HT-ATES system, so this cost reduction has the potential to be even higher. For example, if the values of all parameters are reduced by 25%, the cost reduction would become 0.06%. HT-ATES stores mainly geothermal energy in summer and supplies heat to district heating in winter, with the possibility to contribute to up to 6% of district heating demand.

However, the PyPSA-Eur model is constantly in development to make it more realistic, so the results of this research are subject to change with newer model versions. For example, the other TES technologies do not yet have land use limitations and cost assumptions change often.

The data used to calculate the potential maximum energy production of HT-ATES in the Netherlands limits energy production by only applying doublet systems without heat pumps. Multiple well systems and heat pumps allow for higher power, so the maximum potential could be significantly higher if these additions were considered. On the other hand, the model does not account for potential local limitations for HT-ATES installations, such as other systems already being present in the subsurface or heat sources being too far from the storage system. Accounting for these limitations would result in a more accurate model and potentially reduce the impact of HT-ATES. Another improvement to the model would be to apply this HT-ATES addition to all European countries, however a HT-ATES potential map based on geological and energy data would first need to be made for Europe.

Adding HT-ATES to the Netherlands in a PyPSA-Eur model successfully reduced system costs. As a result, this research provides motivation for further improvements in the addition of HT-ATES and other TES technologies in PyPSA-Eur. This research might also inspire further investigation of specific HT-ATES locations and the corresponding technical and financial parameters.

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A Configuration

Table 4: This table shows the custom configuration parameters used for the 2050 scenario with HT-ATES.

scenario	
clusters	16
sector_opts	3H
planning_horizons	2050
countries	['NL', 'BE', 'DE', 'NO', 'DK']
snapshots	
start	"2013-01-01"
end	"2014-01-01"
electricity	
powerplants_filter	and not (Name.str.contains("Borssele") and Fueltype == "Hard Coal")
custom_powerplants	true
sector	
district_heating	
dh_area_buffer	1000
limited_heat_sources	
geothermal	
constant_temperature_celsius	65
ignore_missing_regions	true
tes	true
ht_ates	true
gas_network	true
heat_pump_sources	
urban central	air and geothermal
enable	
retrieve_cost_data	false
costs	
marginal_cost	
central HTATES charger	0.035
clustering	
focus_weights	NL: 0.75

B Extra figures

This section includes some extra figures to potentially clarify questions the reader might have. Figure 15 shows how the DH areas overlap with the favourable HT-ATES areas. Figure 16 shows the maximum energy that can be produced, where the Maassluis and Oosterhout formations are compared and the grid cell with the highest energy production is taken. Figure 17 shows the favourable areas separately for the Maassluis and Oosterhout formation, which were used for filtering energy production maps.

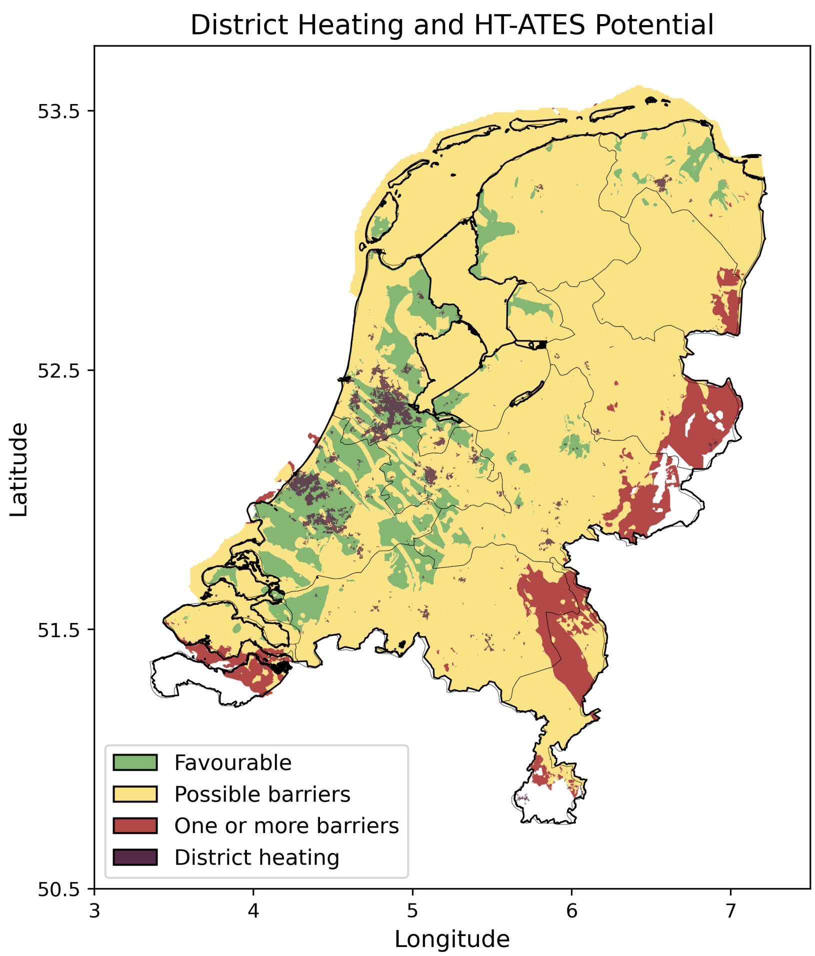

Figure 15: This map how the DH areas overlap with the HT-ATES potential areas. The data for this image were provided by [20] and [28].

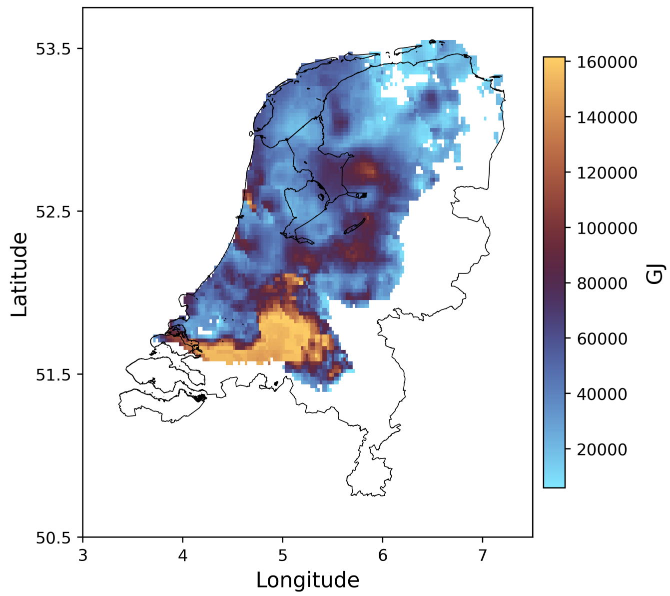

Figure 16: This map shows the maximum energy production from HT-ATES in the Netherlands, from the Maassluis and Oosterhout formations combined. The data for this image were provided by [24].

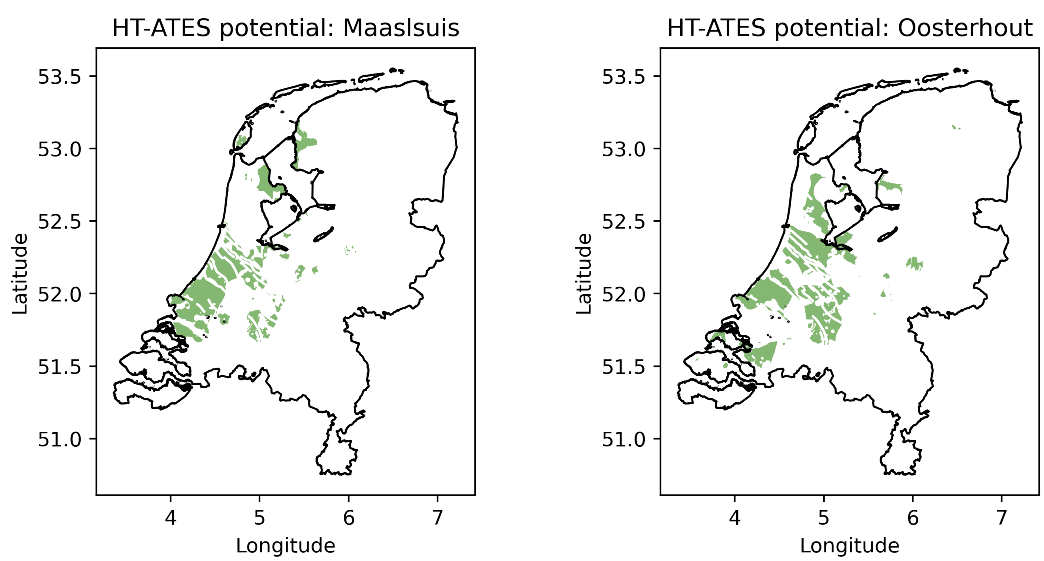

Figure 17: These maps show the favourable HT-ATES potential in the Netherlands for the separate Maassluis and Oosterhout formations. The data for this image were provided by [20].

Figure 18 shows the heat balance for the whole network in 2050. The charging and discharging of HT-ATES becomes difficult to see. It does show that geothermal energy is less prevalent in other countries compared to the Netherlands, when we compare this figure to Figure 12. Therefore, if HT-ATES was to be installed in other countries, its supply might also come from air heat pumps.

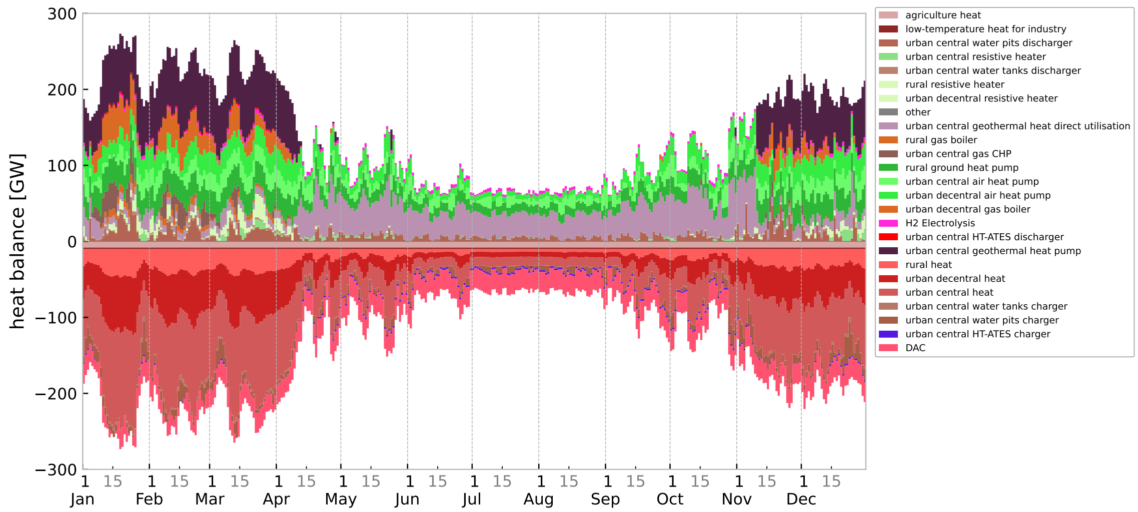

Figure 18: Heat balance of the whole network in 2050, with HT-ATES.

Figures 19, 20, 21, and 13 display the share different sources of heat have in district heating supply. Results are provided for all four scenarios; 2030 and 2050 with and without HT-ATES.

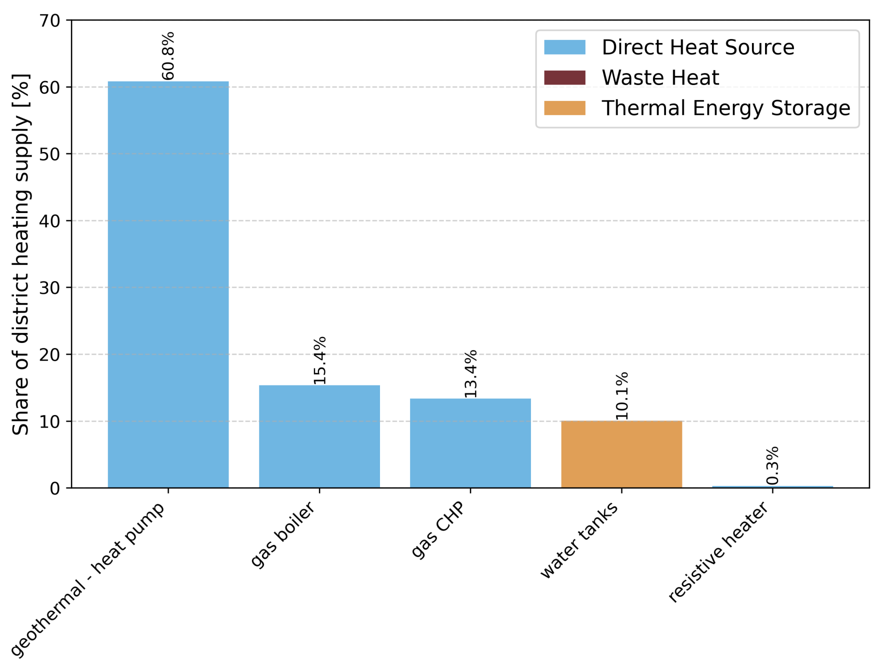

Figure 19: District heating supply by source, split up into direct heat sources, waste heat and thermal energy storage. This graph shows the results for 2030 without HT-ATES, the district heating energy supply is 25 TWh.

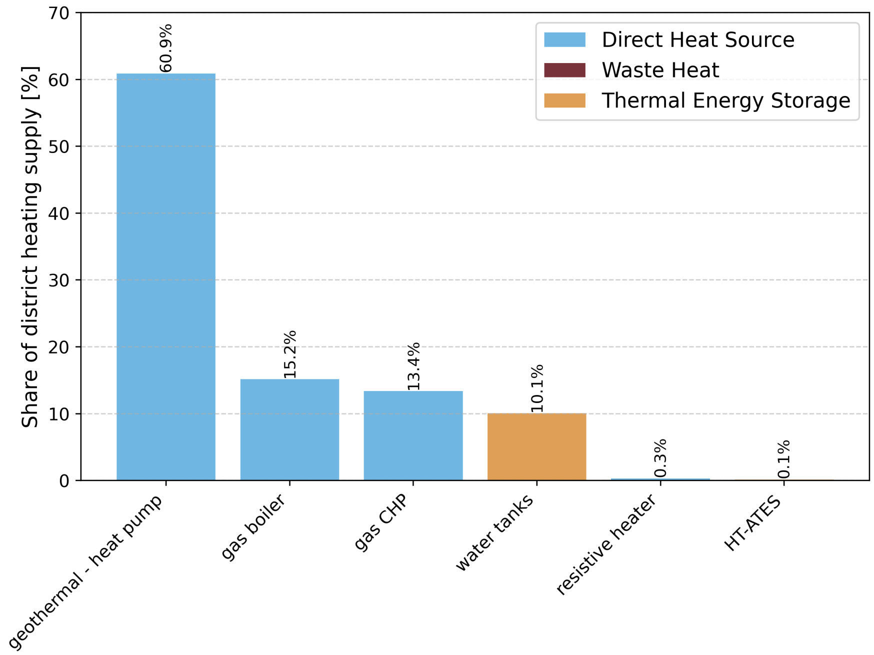

Figure 20: District heating supply by source, split up into direct heat sources, waste heat and thermal energy storage. This graph shows the results for 2030 with HT-ATES, where HT-ATES contributes 0.1% to district heating energy supply (25 TWh).

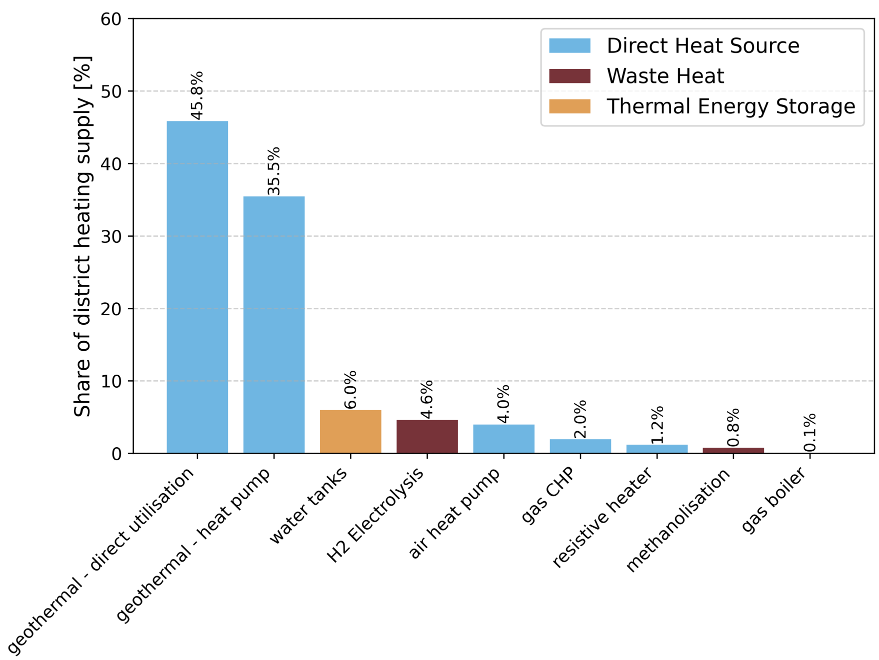

Figure 21: District heating supply by source, split up into direct heat sources, waste heat and thermal energy storage. This graph shows the result for 2050 without HT-ATES, the district heating energy supply is 28 TWh.

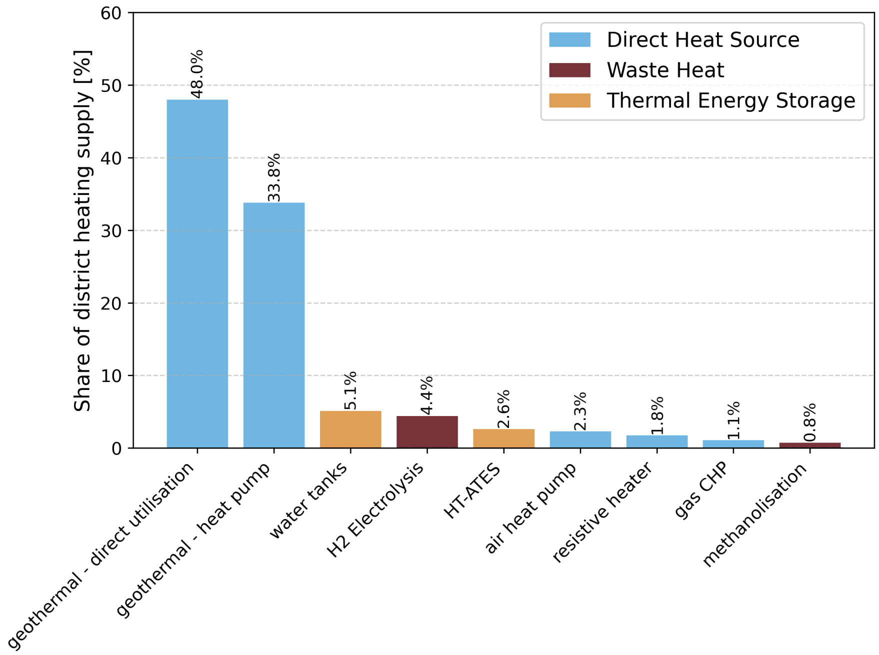

Figure 22: District heating supply by source, split up into direct heat sources, waste heat and thermal energy storage. This graph shows the result for 2050 with HT-ATES, where HT-ATES contributes 2.6% to district heating energy supply (28 TWh).

C Research Data Management Plan

C.1 Data Collection

C.1.1 Type of data

PyPSA-Eur uses many different types of data, both observational and derived from simulations. The data I specifically added for my model, the HT-ATES potential and energy production, were created with models. My results are data output from the PyPSA-Eur model simulations.

C.1.2 Format

The HT-ATES potential files are SHP files, accompanied by DBF and SHX files. The HT-ATES energy production files are ASC files, accompanied by a PRJ file. The resulting networks of the different scenarios are NC files. The costs corresponding to these networks are stored in CSV files.

C.2 Data Storage and Back-up

C.2.1 Data documentation

All input data used in this thesis are added to the Data folder within the PyPSA-Eur model. The HT-ATES potential and energy production data have descriptive file names. The model scripts and configurations are documented with descriptive comments, and a README file is included in the GitHub repository to explain the purpose and content of each dataset.

The datasets of the results are stored in a network folder, a nodal cost folder, and a new nodal cost folder. The new nodal cost folder was made because in the initial nodal cost files, geothermal energy was not assigned to different nodes.

C.2.2 Primary and intermediary data information

Primary data includes the HT-ATES potential and energy production data obtained from Dorien Dinkelman, as well as publicly available datasets integrated into PyPSA-Eur. There is no intermediary data.

C.2.3 Name and location of the data

My whole model, including the relevant input data, is on a GitHub repository: https://github.com/mareenjp/pypsa-eur-htates/. The HT-ATES potential and energy production data is located within the TNO-HT-ATES folder within the Data folder in my PyPSA-Eur model. My PyPSA-Eur model, including this data, is uploaded to a GitHub repository. The data of my results can be found in a Google Drive folder I shared with my supervisor.

C.2.4 Back-up strategy

My whole PyPSA-Eur model, including the results, remain stored on the Geo-Energy computer. The model is also uploaded to GitHub and the results to Google Drive.

C.2.5 Data deposition

Was the data deposited to the Y-drive with a READ ME file before handing in the thesis? Yes/**No**

C.3 Data Access and Ownership

C.3.1 Privacy and security

PyPSA-Eur is an open source and open data model. The HT-ATES potential and energy production were provided by Dorien Dinkelman via personal correspondence. Maps that were created with that data can be found on the ThermoGIS-HT-ATES website [23] and in Dinkelman et al. (2020) [20]. Dorien did not object to uploading the data to my GitHub page.

C.3.2 Accessibility

The data I used to create the model can be found on my GitHub repository, which is public. The results were too large to upload and are therefore uploaded to Google Drive instead, which can only be accessed by me and my supervisor.