Business case

2021

Commercial use of HT-ATES systems

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Business case and sensitivity analysis for the commercial use of HT-ATES systems

Bachelor's thesis

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21 June 2021

Preface

In writing this thesis I conclude my bachelor Civil Engineering at the TU Delft and enthusiastically take my first step towards partaking in the master Geo-Engineering. With this thesis I have developed a business case for the commercial use of HT-ATES systems and assessed the business case sensitivity to the thermal energy demand.

This document can be used to gain insight on a business model for the commercial use of HT-ATES systems, with the corresponding sensitivity to the revenue elements.

I would like to thank my supervisors, Martin Bloemendal and Phil Vardon, for the valuable input and support throughout the process of writing this thesis. My supervisors where always able to steer me in the right direction and asked critical questions to fuel my curiosity, which I have highly appreciated during and after the period.

Den Haag, 21 June 2021
Sha'ief Dhauri

Abstract

Projections show that urban areas are growing at an increasing rate and produce 60% of the global greenhouse gas emissions (United Nations, n.d.). In Europe, the thermal energy sector consumes about half of the energy resources, of which 85% is produced by fossil fuel-based energy systems (Drijver, Bakema, & Oerlemans, 2019). As a result of this, district heating companies have set climate targets to lower the harmful emissions produced by the thermal energy sector. This can only be done by replacing fossil fuel-based energy systems by sustainable energy systems. One of the promising sustainable energy systems is the high temperature aquifer thermal energy storage (HT-ATES) system. HT-ATES is a buffer system used to store waste heat from industrial processes in a suitable aquifer and transfers this heat to buildings to heat them up in the winter and cool them down in the summer. However, this system is very complex in use and carries many risks. Due to the HT-ATES being a buffer system, complex in use and carrying many risks there are not many running projects incorporating this system. This makes the revenue model and possible exploitation for commercial use very unclear. Therefor, the goal of this thesis is to develop a business case for the commercial use of HT-ATES systems and to assess the business case sensitivity to the thermal energy demand. The research goal will be achieved by performing a literature study. Assessing the business case viability against other geothermal energy systems will not be in the scope of this thesis. This thesis is merely meant to gain insight on the business case of HT-ATES systems.

The findings of the research show that a project is solely profitable when the benefit outweighs the cost. The total business expenditure of a 30-year lifecycle HT-ATES project with 3,000 households will be fixed upfront expense of EUR 1,236,991 and an additional yearly expense of EUR 695,795. The benefit of the project is strongly dependent on the thermal energy demand. The revenue model of this project consists of a heating price model and government provided subsidy. This business model assumes a heat price of EUR 3.89 per kWh and a subsidy of EUR 2.73 per kWh thermal energy produced. Assuming the annual thermal energy demand is 12.66 kWh per household, the 30-year HT-ATES project with a district heating network of 3,000 households will have a payback time of 8.4 years. This means that the project will be profitable after 8.4 years. A sensitivity analysis on the thermal energy demand proved that a HT-ATES will be more profitable if the thermal energy demand is higher. This sensitivity analysis also shows that the project will need to have a minimum of 1,300 households in the network in order to be financially feasible, as the payback time of less households will not be within the project lifecycle. A district heating network with a 30-year lifecycle HT-ATES system will have a payback time of 22 year. When this same network where to incorporate 4,000 households the payback time will be reduced by a factor of 4.

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1 Introduction

Anthropogenic warming is the rise in the average temperature of the Earth's atmosphere as a result of the emissions produced by the agriculture and human industry. This is directly linked to the climate changes in the natural and human environment. In addition to a rise in average temperature, anthropogenic warming is the root cause of the change in precipitation and the rise in sea level (Intergovernmental Panel on Climate Change, 2007). These global warming, geopolitical and environmental concerns have fueled the interest in an evolution, wherein fossil fuel-based energy is aimed to be replaced by sustainable and renewable energy. In the past the use of sustainable energy for thermal energy systems, heating and cooling, has been neglected in these climate change mitigation strategies. Nowadays many scientists' plea for the decarbonization in the thermal energy sector (Fleuchaus, et al., 2020).

Projections show that by 2050 approximately 6.7 billion people will live in the urban areas around the world. These urban areas consume 78% of the world's energy sources and produce 60% of the greenhouse gas emissions (United Nations, n.d.). As the urban areas are increasingly growing and about half of the energy sources in Europe are consumed by the European thermal energy sector, of which 85% is produced by fossil fuel-based energy systems (Drijver, Bakema, & Oerlemans, 2019), district heating companies have set targets to lower the harmful emissions produced by thermal energy systems. The set target requires an alternative solution to produce sustainable and renewable thermal energy. One of these solutions is a *high temperature aquifer thermal energy storage* (HT-ATES) system. HT-ATES is a buffer system used to store waste heat from industrial processes in a suitable aquifer and transfer this heat to buildings to heat them up or cool them down.

However, currently there are not many active HT-ATES projects in the world, mainly because of its complex in use. Additionally, HT-ATES carry many site-specific risks such as the precipitation of minerals and the corrosion of components in the groundwater system (Snijder, 2000). Due to the current minimal use of HT-ATES, there are many obscurities within the revenue model of these systems and the exploitation for commercial use is unclear.

The aim of this thesis is to present a solution to the research goal: *"Develop a business case for the commercial use of HT-ATES systems and assess the business case sensitivity to the thermal energy demand"*. In developing this business case, the following five sub-questions will be answered:

1. What is a HT-ATES system?
2. How can a HT-ATES system be implemented for commercial use?
3. Who are the stakeholders involved?
4. What are the key costs for HT-ATES systems?
5. What is the business case sensitivity to the thermal energy demand?

The research goal and sub-questions in this thesis will be answered by performing a literature research on the technical and financial side of HT-ATES systems. During this literature research justified assumptions will be made where there is insufficient data.

Assessing the viability of this business case, compared to other sustainable geothermal energy systems, is not within the scope of this thesis. This thesis is merely a tool to gain insight, specifically, on the business case for the commercial use of HT-ATES systems.

The structure of this thesis will be as follows. Chapter 2 will describe what a HT-ATES system is, how it operates and what the limitations, boundaries are. Chapter 3 will discuss all the elements of the application of HT-ATES systems for commercial use. Thereafter, a business model will be made in chapter 4 wherein the key costs, revenue streams, ROI and business case sensitivity are assessed. Finally, in chapter 5 the solution to the research goal and sub-questions will be presented.

2 High Temperature Aquifer Thermal Energy Storage

The thermal energy sector in Europe consumes about half of the European energy sources, of which 85% is produced by fossil fuels (Drijver, Bakema, & Oerlemans, 2019). As the urban areas are growing and climate targets are set in which greenhouse gasses need to be reduced, it is of great importance to introduce sustainable energy systems in the thermal energy sector. A promising sustainable energy system for thermal energy use is the *high temperature aquifer thermal energy storage* (HT-ATES) system. In this chapter a clear description will be given on what a HT-ATES system is and how it operates. In addition, the site-specific risks involved in HT-ATES projects will be assessed.

2.1 Aquifer thermal energy storage systems

Aquifer thermal energy storage (ATES) systems are one of the most common underground thermal energy storage (UTES) systems. These ATES systems are open loop systems that use aquifers to store thermal energy. An aquifer is an underground soil layer with a high hydraulic conductivity, meaning that the soil layer is highly permeable. Because the soil layer is highly permeable, water can easily flow through it. Aquifers are classified as unconfined or confined (*figure 2.1*). In an unconfined aquifer the phreatic water table occurs within the aquifer layer itself. A confined aquifer is a fully saturated layer and has a confining layer above it. When a non-pumping well is installed in a confined aquifer, the water table will be higher than the top of the aquifer (Fitss, 2013).

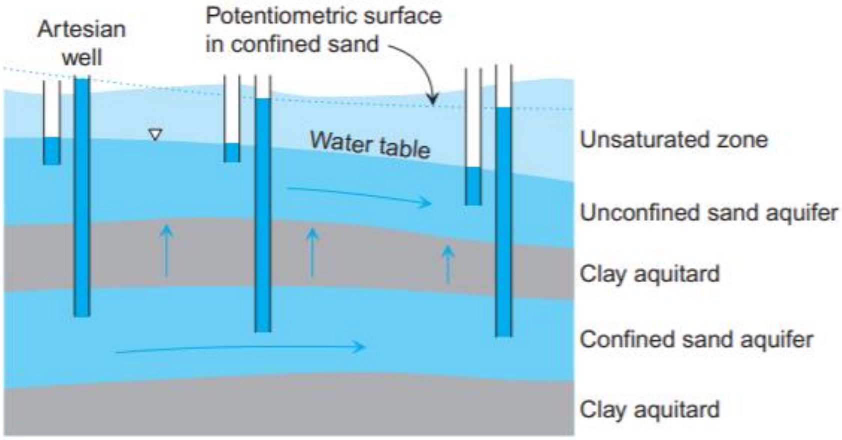

Figure 2.1: Confined and unconfined aquifers (Fitss, 2013)

In practice ATES systems have three applications: low temperature (LT-ATES), medium temperature (MT-ATES) and high temperature (HT-ATES). *Table 2.1* provides an overview of the key characteristics of these three applications.

Table 2.1: Characteristics ATES systems (Drijver, van Aarssen, & de Zwart, 2012)

	Temperature threshold	**Energy recovery efficiency***	**Utilization**
LT-ATES	5 – 30 °C	70 – 90%	Only applicable when combined with low temperature heating systems or heat pumps
MT-ATES	30 – 60 °C	60 – 80%	Direct usage or when necessary enhanced by heat pumps
HT-ATES	60 – 90 °C	40 – 70%	Direct usage

* ratio between the amount of recovered energy and the amount of stored energy, with equal amounts of injected and extracted water.

Compared to the other ATES systems, HT-ATES has the advantage of being directly usable for heating purposes and has the ability to satisfy other applications. One of the applications is the generation of electricity. Both LT-ATES and MT-ATES systems require heating pumps to meet a realistic energy demand. As HT-ATES can be directly used, energy savings can be significantly improved. Another advantage of HT-ATES is the ability to achieve larger temperature differences between infiltrated and extracted water, meaning more energy obtained per cubic meter of pumped water resulting in a reduced flow rate for an equal energy demand (Drijver, van Aarssen, & de Zwart, 2012). When climate targets and the growth of urban areas are taken into consideration, it is clear that HT-ATES is more favorable for commercial use. Therefor, only HT-ATES systems will be discussed in this thesis.

2.2 How does it operate?

ATES systems are open loop systems that use groundwater from aquifers to heat up or cool down buildings. The groundwater in the aquifer is at constant temperature which is correlated to the mean annual temperature at location. During the summer, the cold groundwater from the cold side of the aquifer is pumped up to the building to lower the room temperature. When the temperature is transferred to the building, the now hot water is pumped to the warm side of the aquifer. During the winter, this process is reversed. The groundwater from the warm side of the aquifer is pumped up to the building, resulting in a rise in room temperature of the building. The now cold water is pumped to the cold side of the aquifer. The heat or cold from the groundwater is transferred to the building by using a heat exchanger. In *figure 2.2* an illustration of this process is given.

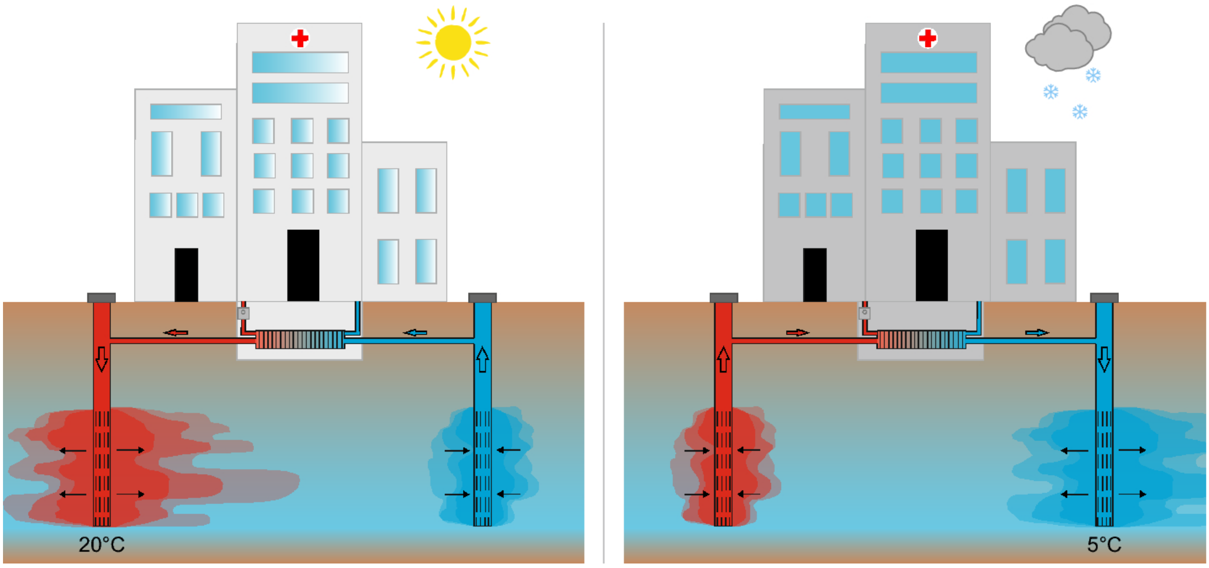

Figure 2.2: ATES system (Schuppler, Fleuchaus, & Blum, 2019)

In order to overcome higher temperature differences due to harsher climate conditions the temperature of the warm side of the aquifer needs to be much higher, if direct usage of the ATES systems is desired. This is where HT-ATES applications hold significant value. Power plants and industrial processes both produce waste heat, which can vary from 100 °C up to 500 °C (Papapetrou, Kosmadakis, Cipollina, La Commare, & Micale, 2018). This waste heat can be stored in the warm side of the aquifer, allowing the HT-ATES system to overcome greater temperature differences during the winter without the use of a heat pump.

2.4 Risks involved

The storage of heat in groundwater contains many complex risks, especially when temperatures rise above 50 °C. Therefor, comprehensive risk management should be top priority in any HT-ATES project in order to develop site-specific risk mitigation strategies. *Table 2.*2 provides an overview of the most common risks involved in HT-ATES projects. For each categorized risk, the effect is given and in which stage during the project it will occur.

Table 2.2: Common risks in HT-ATES projects (Fleuchaus, et al., 2020)

				Stage	**Effect**
#	**Risk item**	**Category**	**Sub-category**	**P-C-O**	**CAPEX/OPEX - T - E**
1.	Decreasing heat demand	Financing	Marketing	○ ○ ●	● ○ ○
2.	Competing technologies			● ○ ●	● ○ ○
3.	Loss of heat source	Technical	Operation	● ● ●	● ● ○
4.	Heat losses			○ ● ●	● ○ ○
5.	Clogging & scaling		Geochemical and geological	○ ● ●	● ● ●
6.	Corrosion			○ ● ●	● ● ●

* P = planning, C = construction, O = operation, CAPEX = capital expenditure, OPEX = operational expenditure, T = time, E = environment, ● = Applies, ○ = Does not apply

The financing of a HT-ATES project faces two commonly occurring risks, namely a decreasing heat demand and competing technologies. Both risks have a huge impact (effect) on the capital and operational expenditure of the project and usually occur during the operation stage. Loss of heat source in the aquifer, heat losses during pumping, clogging & scaling of reservoirs and corrosion of components are the most common technical risks and usually occur during either the construction stage or the operational stage. These four technical risks can have an impact on the costs and schedule of a project and can even cause harm to the environment. An in-depth risk assessment with the corresponding risk certainty and severity can be found in *Appendix I*.

3 Commercial Use

Rather than applying a HT-ATES system to solely one building, this thesis considers the financial feasibility of implementing a HT-ATES system on district heating. The aim of district heating is to use local heat resources to satisfy the thermal energy demand of local customers, by using a distribution network of pipes. The primary advantage of district heating is the ability to lower the cost of heating and lower the impact on the environment and climate (Werner, 2017). However, most district heating systems still use fossil fuel-based energy systems. Even though the climate impact is lower by satisfying multiple building with one heat source, climate targets will not be met if the use of fossil fuel-based energy systems will continue. As urban areas are growing at an increasing rate and produce 60% of the greenhouse gas emissions, it is of great importance to introduce sustainable energy systems in district heating. In this chapter the commercial use, or the implementation on district heating, of HT-ATES systems will be discussed.

3.1 Energy demand in the thermal sector

HT-ATES systems have an extremely efficient way of bridging the seasonal thermal energy demand gap. During the winter the thermal energy, from the waste heat, in the warm side of the aquifer is pumped up and used to heat up the building. During the summer, the cold water from the cold side of the aquifer is pumped up and used to cool down the building. As the system is a High temperature-ATES system, it is able to overcome higher temperature differences and able to cope with higher seasonal temperature differences. Thus, this system will only be technically and financially feasible in temperate continental climates.

In a temperate continental climate, the thermal energy demand is variable, with the highest peak in the winter and the lowest trough in the summer (*figure 3.1*). HT-ATES systems can prove to fit these climates perfectly, as cold is produced in the summer and heat in the winter. During the summer, the waste heat will not be used by the HT-ATES system. However, the waste heat will inevitably be produced. This excess waste heat can be stored in the aquifer over the summer, to be used in the winter. This is called the storage potential. The storage potential will result in a lower mean annual waste heat demand.

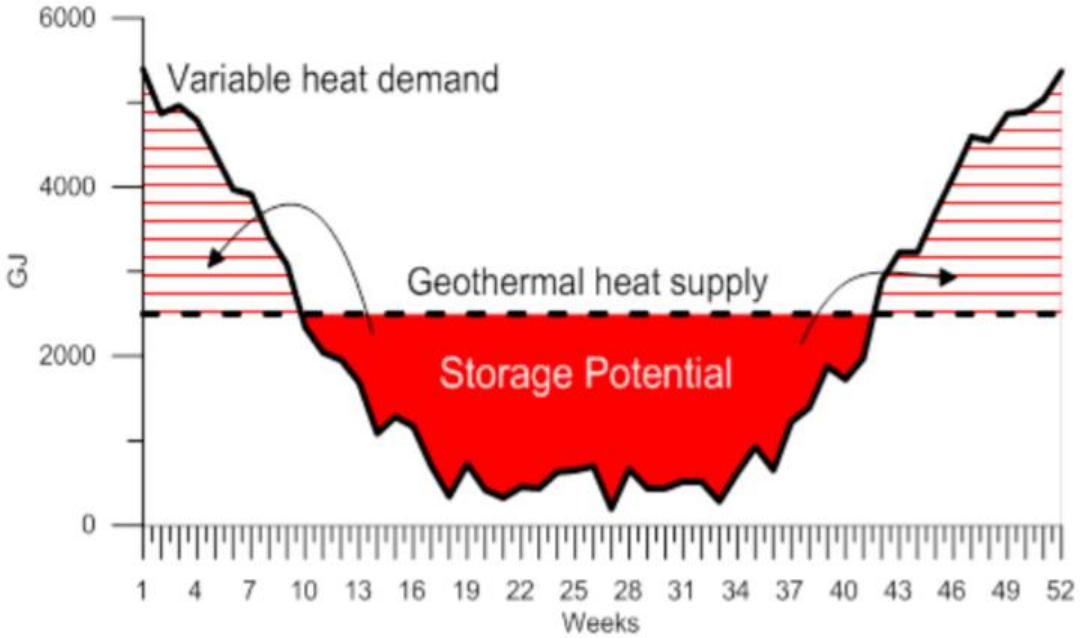

Figure 3.1: The variable thermal heat demand in temperate continental climates (Rocchi, 2020)

Table 3.1 provides an overview of the natural gas consumption for heating and cooling per household in the Netherlands in 2019. The natural gas consumption varies based on the house characteristics, which influence the effect that the weather conditions have on the room temperature in the house. A corner house will be more exposed to the weather conditions, in comparison to an apartment, which will result in an increase in natural gas consumption for heating. This factor is significantly increased in a detached house.

Table 3.1: Natural gas consumption for heating and cooling per household in the Netherlands in the year 2019 (CBS, 2020)

House characteristics	**Average consumption of natural gas (m^3)**
Apartment	770
Terraced house	1100
Corner house	1320
Semi-detached house	1540
Detached house	2040

The assumption will be made that the annual natural gas consumption for heating and cooling per household will be 1,200 m^3. As 1 m^3 natural gas equals 0.011 MWh, the amount of energy annually used per household for heating and cooling will be 12.66 MWh. In the business model it will be assumed that this annual amount of energy per household used for heating and cooling will be equal for a HT-ATES system.

3.2 Implementation on district heating

In *figure 3.2* the implementation of a MT-ATES on a district heating network in Riehen, Switzerland, is illustrated. This district heating network uses heat from the production well and transfers this to the network. However, the heat produced in the production well is not of sufficient temperature to meet the consumer's demand. To get the heat up to standard, this system makes use of heat pumps and boilers. The implementation of HT-ATES will be similar, apart from the heat pumps and boilers. Instead, a waste heat source, power plants or other industrial processes, will be added to the network.

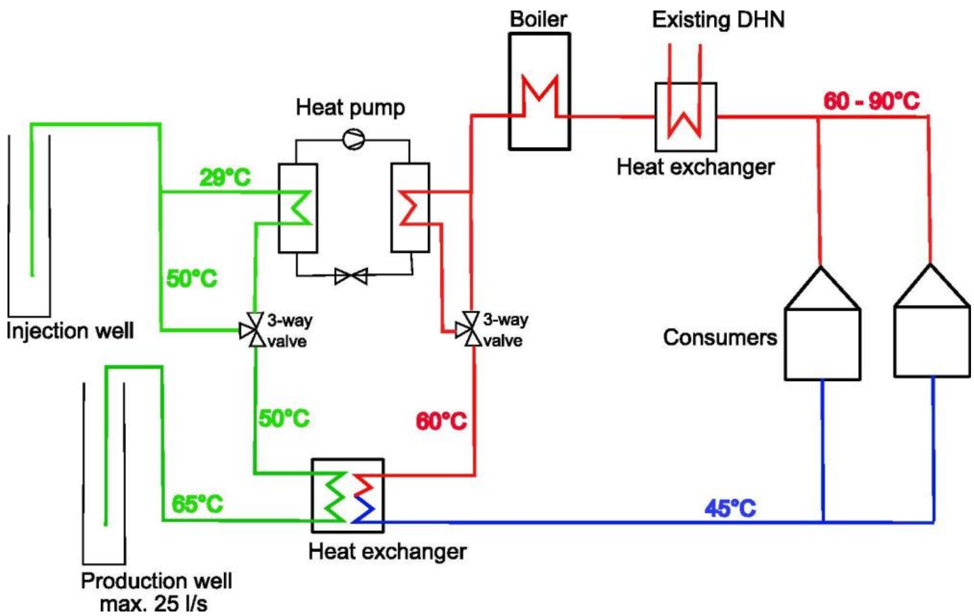

Figure 3.2: Geothermal district heating system in Riehen, Switzerland (Unternahrer, Moret, Joost, & Marechal, 2017)

4 Business Model

There are not many running HT-ATES projects due to its complexity in use and the many site-specific risks involved. Another hurdle is that HT-ATES systems act as a buffer, as it is not a heat source. HT-ATES systems merely store and transfer (waste) heat to structures. This creates many obscurities in the revenue model and the possible exploitation for commercial use. In this chapter the aim is to create clarity on this matter and map out a business model for the commercial use of HT-ATES systems. In order to support the business model a business model canvas will be discussed, wherein the way HT-ATES systems create, deliver and capture value for commercial use will be visualized. The key costs and the return on investment will be discussed in the following paragraphs and finally a sensitivity analysis will be performed.

4.1 Business Model Canvas

A *Business Model Canvas* (BMC) is a visual modelling tool which captures how a business model creates and delivers value to the customer. The BMC defines the nine building blocks in any business model (*figure 4.1*) and for every business model the same methodology is used. The first step in using a BMC is to define the core building block in every business model, which is *customer segments*. For the customer segments the business model has specific products and services that create and deliver value for the customers, which is described in *value propositions*. The *channels* describe which touchpoints with the customers are necessary in order to deliver value. The type of relationship established with the customers will be described in the *customer relationships*. The *revenue streams* elaborate on how and through which pricing models the business model captures value. The infrastructure of the business model will be described in the *key resources*, *key activities*, and *key partners*. Once these eight building blocks have been defined, the most important and significant building block in any business model can be described: *cost structure* (Strategyzer AG, 2020).

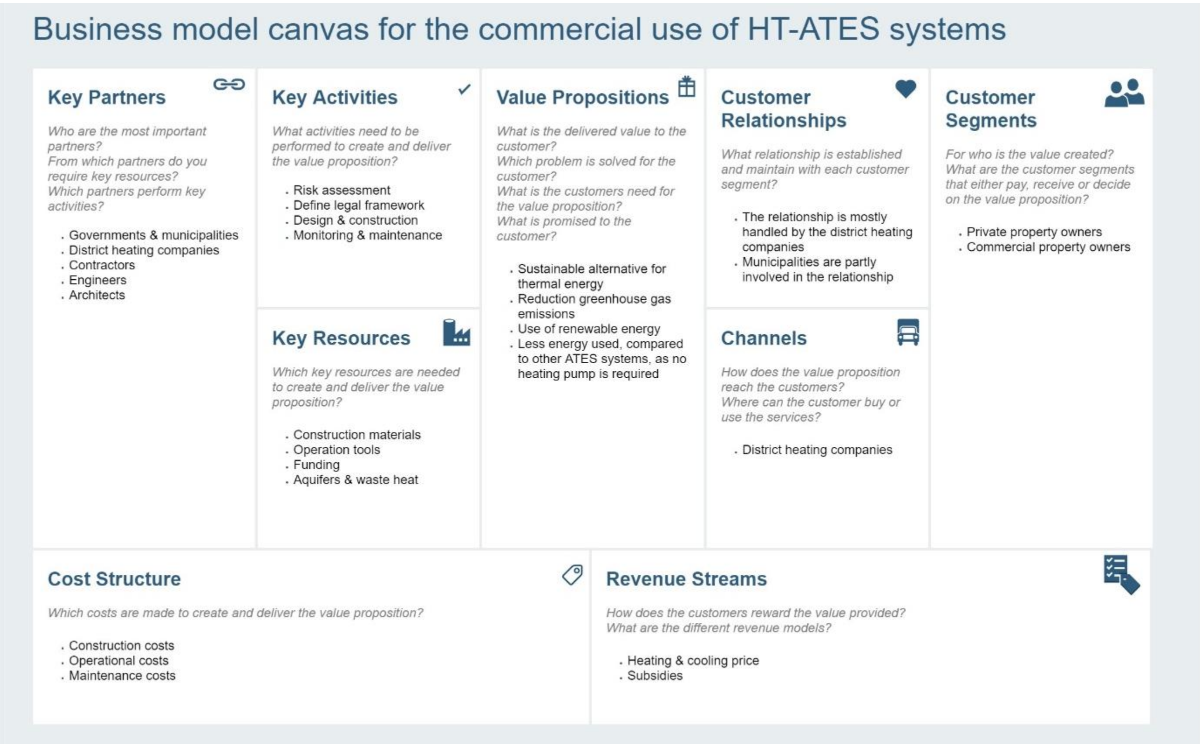

Figure 4.1: Business model canvas for the commercial use of HT-ATES systems

Customer segments
As HT-ATES is an alternative for the renewable generation of sustainable thermal energy in order to heat up and cool down buildings, the customers will be property owners. The property owners can either be private property owners or commercial property owners (apartment building owner, office building owner, medical building owners, industrial plaza owners, etc.).

Value proposition
The main delivered value of HT-ATES systems is that it is a sustainable alternative for the generation of thermal energy. As this business model will use HT-ATES systems for commercial use (district heating), multiple fossil-fueled thermal energy systems can be replaced resulting in a significant reduction in greenhouse gas emissions. An additional value is that HT-ATES systems use less energy compared to other ATES systems, as there is no need for a heating pump (*section 2.1*).

Channels
The value of the business model, sustainable and renewable thermal energy, will reach the customers through district heating companies. The district heating companies are responsible for the heat network, which is used to distribute the thermal energy for commercial use.

Customer relationships
The relationship with the customers will be mainly maintained by the district heating companies, as they are in direct contact with the customers. The district heating companies directly distribute the value to the customer, meaning that the customer will hold the district heating companies accountable. The quality of the relationship with the customer and the customer satisfaction will be ensured by the district heating companies. Municipalities will be partly involved in the relationship with the customers, as the municipality will notify and inform the customers of construction in the area.

Revenue streams
The customers will reward the delivered value through the heating and cooling price model. In order to make use of thermal energy, the customer will have to pay for their usage of this thermal energy. Another important element of the revenue model is the subsidy (*section 4.3*).

Key resources
The most important resource for this business model is the acquired waste heat, from power plants or other industrial processes, which will be stored in a suitable aquifer in order to satisfy the high temperature energy demand. The second most important resource is the suitable aquifer itself. Other key resources are construction materials, operation tools and funding.

Key activities
Time and costs can be saved by defining the legal framework upfront, as many urban areas do not allow the storage of heat above 25 °C in groundwater. Another significantly important activity is a comprehensive risk assessment because HT-ATES are very complex in use and risks differ per site (*section 2.4*). Other key activities are design, construction, monitoring, operation, and maintenance.

Key partners
As mentioned before, district heating companies will play an essential role because they deliver the value of the business model to the customer. Therefor, district heating companies will be a key partner in this business model. Other key partners will be governments and municipalities, as most of the construction will be done in urban areas. Additional key partners are contractors, engineers and architects who will design and construct the HT-ATES system for commercial use.

Cost structure

The key costs made in this business model in order to create and deliver value to the customer are construction, operation and maintenance costs. The cost structure of the business model will be further discussed in *section 4.2*.

4.2 Key costs

This paragraph will provide a clear overview of the key costs for the commercial use of HT-ATES systems. The key costs comprise of the *capital expenditure* (CAPEX) and the *operational expenditure* (OPEX). CAPEX defines the financial means to acquire, maintain or upgrade a physical asset such as a building, equipment, or technology. OPEX is the expense made in order to keep a project operational (Fernando, 2021). In combination, these two parameters define the financial scope of a project and create opportunity to increase economic benefit. *Figure 4.2* illustrate where the CAPEX and OPEX are positioned in the cost structure.

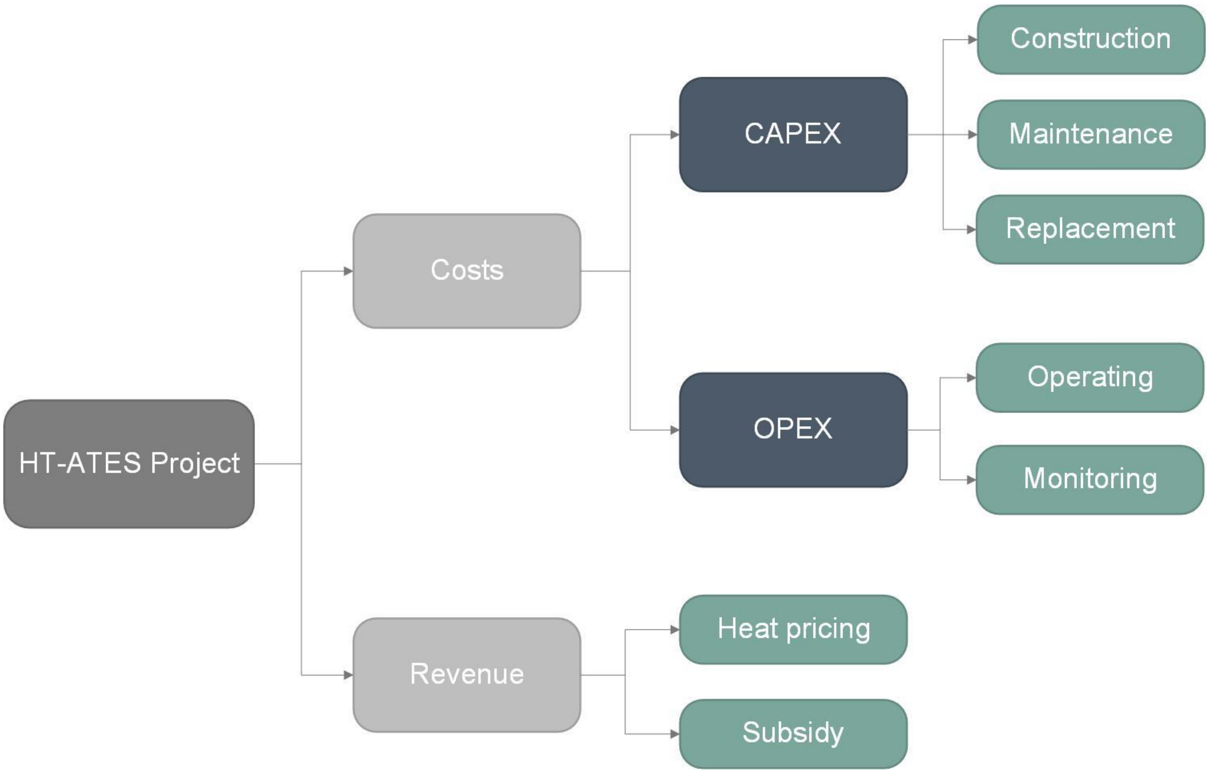

Figure 4.2: Flowchart of the cost structure and revenue streams for a HT-ATES project

A clear overview of the cost structure and the revenue streams is provided in *figure 4.2*. The figure illustrates that the CAPEX in a HT-ATES project mainly consists of costs for construction, maintenance, and replacement of components. The OPEX mainly consist of cost for operating and monitoring. The benefit of a HT-ATES project is defined by the heat pricing and most importantly the provided subsidy (*section 4.3*).

Similar to the risks involved in HT-ATES projects, the costs are also very site specific. The CAPEX for HT-ATES systems will vary per project, region, and site. The construction CAPEX for a HT-ATES project with a lifecycle of 30 years is presented in *table 4.1*. The variation of the construction CAPEX is incorporated by defining the minimum, mode, and maximum of each component in every category in the project. The construction CAPEX of a HT-ATES project with a 30-year lifecycle will typically be EUR 1,236,991 with a deviation of ± 50%.

Table 4.1: Construction CAPEX for a 30-year lifecycle HT-ATES project (Schuppler, Fleuchaus, & Blum, 2019)

Category	**Component**	**Minimum (EUR)**	**Mode (EUR)**	**Maximum (EUR)**
Pre-investigation/Feasibility	Site inspection	50	1,216	2,382
	Construction schedule	5	846	1,687
	Feasibility study	3,939	22,488	41,037
	Design planning	6,200	47,706	89,212
Preparation	Site equipment	1,738	7,319	12,900
	Transport & movement site equipment	1,991	21,765	41,540
	Bore log & drilling profile	539	803	1,066
	Washing & pumping tests	57,930	72,026	86,120
Drilling	Well drilling	24,780	90,825	156,870
Well piping & well installation	Pipe installation	49,482	79,838	110,194
	Well equipment installation	42,733	67,552	92,370
	Filters & seals	3,541	84,834	166,127
	Pumps	40,770	52,408	64,046
	Well connections	1,204	52,298	103,392
Controlling & monitoring	Pump control system	4,885	108,437	211,986
	Site equipment monitoring well	2,100	11,550	21,000
	Drilling monitoring wells	2,219	31,654	61,087
	Control line	15,000	20,000	25,000
	Electricity connection	35,000	55,000	75,000
Piping	Horizontal piping	189,815	331,988	474,161
	Pressure washing	7,161	8,638	10,115
Building integration	Heat exchanger	65,600	67,800	70,000
	Total construction CAPEX:	**556,682**	**1,236,991**	**1,917,292**

This model will continue with the assumption that the construction CAPEX of a 30-year lifecycle HT-ATES project will be EUR 1,236,991. The 50% deviation of the CAPEX will not be further assessed in this model. The additional CAPEX for a 30-year lifecycle HT-ATES project are for maintenance of the system and replacement of broken or defective parts. This additional CAPEX for this project is given in *table 4.2*. The total CAPEX will be a fixed upfront expense of EUR 1,236,991 with an additional yearly expense of EUR 58,500.

Table 4.2: Additional CAPEX for the 30-year lifecycle HT-ATES project (Schuppler, Fleuchaus, & Blum, 2019)

Category	**Value**	**Unit**
Maintenance	50,000	EUR/year
Replacement of parts	8,500	EUR/year

The OPEX describe which costs need to be made in order to monitor a project and keep it operational. For HT-ATES projects the OPEX comprise of a fixed value of 5% of the construction CAPEX for the project, electricity to keep equipment operational and the waste heat retrieved from power plants or other industrial processes. The different parameters and their value with the corresponding unit are presented in *table 4.3*.

Table 4.3: Parameters for the annual OPEX of a HT-ATES project

Parameter	Value	Unit	Source
Fixed OPEX	5% of CAPEX	EUR	(van Wees, et al., 2014)
Electricity price	0.165	EUR/kWh	(Schuppler, Fleuchaus, & Blum, 2019)
Waste heat	0.014	EUR/kWh	(Gudmundsson, Thorsen, & Zhang, 2013)

The 5% fixed OPEX will be taken from the mode of the construction CAPEX. The waste heat stored in the aquifer is assumed to be equal to the thermal energy demand. Thus, this model will consider an annual waste heat demand of 12.66 MWh per household in the district heating network. Based on Schuppler, Fleuchaus, & Blum (2019), the electricity used by components in the HT-ATES system are assumed to have a value of 265 MWh per year. The annual OPEX for a HT-ATES project, with 3,000 households, in EUR per year is given in *table 4.4*.

Table 4.4: Annual OPEX for a HT-ATES project with a 30-year lifecycle and 3,000 households

Parameter	Value (EUR/year)
Fixed OPEX	61,850
Electricity price	43,725
Waste heat	531,720

In *figure 4.3* the total business expenditure is illustrated. As illustrated in *figure 4.2* the total business expenditure comprises of the CAPEX and the OPEX. The total CAPEX for a HT-ATES project with a 30-year lifecycle and 3,000 households will be EUR 1,236,991 with an additional yearly expense of EUR 58,500. In *figure 4.3* it can be observed that the CAPEX line is increasing over time. This is because of the additional yearly expense of EUR 58,500. On top of the total CAPEX the yearly OPEX is added, resulting in the "*total expenditure*". The OPEX adds a yearly expense of EUR 637,295 (*table 4.4*).

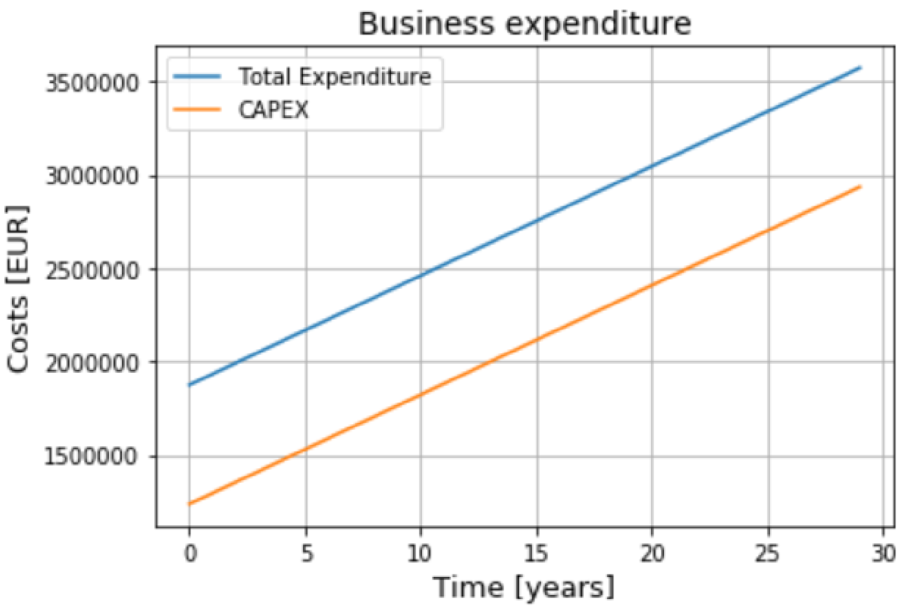

Figure 4.3: Total business expenditure of the HT-ATES project over the 30-year lifecycle

4.3 Return on investment

A project is solely attractive if and only if it is profitable. The profitability of a project is defined by the *return on investment* (ROI). The ROI is a tool used to measure the financial performance of a project and to assess the benefit, or return, of the investment. The deliverable of a ROI is the tradeoff between the benefits and the costs of a project. This paragraph will clarify the ROI and determine the payback time of a 30-year lifecycle HT-ATES project with 3,000 households.

The ROI and payback time of the project will be determined with the defined parameters for the CAPEX and OPEX in *section 4.2*. In addition to the business expenditure, the revenue generated by the project needs to be determined in order to calculate the ROI and payback time. In *table 4.5* the parameters needed to calculate the generated revenue are given. HT-ATES system are applicable for government provided subsidies, which have a huge impact on the revenue model. Every country has its own subsidy regulations. The subsidy regulation that will be approached in this model is the SDE++ of the Rijksdienst voor Ondernemend Nederland in the Netherlands. The SDE++ regulation has the following requirements for geothermal energy systems using waste heat and no additional heat pumps or boilers (Rijksdienst voor Ondernemend Nederland, 2020):

- The system has a thermal capacity of at least 5MWth
- A minimum of 0.3833 kilometers of new transmission pipelines must be installed per MWth output

Assuming all the requirements will be met, this subsidy regulation will add an additional 70% of the heat price to the revenue model. With a heat price of EUR 3.89 per kWh, the subsidy regulation will add EUR 2.73 per kWh to the revenue model.

Table 4.5: Parameters for the revenue model of a HT-ATES project

Parameter	Value (EUR/kWh)	Source
Heat price	3.89	(CBS, 2021)
Subsidy	2.73	(Rijksdienst voor Ondernemend Nederland, 2021)

In *figure 4.4* the payback time of a 30-year lifecycle HT-ATES project with 3,000 households is illustrated. The project will have a payback time of 8.4 years. At this point in time the project will reach a financial breakeven point, wherein the revenue and costs are even. Only after this period in time the project will be profitable. At the end of the 30-year lifecycle the total generated revenue will be EUR 7,547,234. The total costs of the project, CAPEX and OPEX, after 30 years will be EUR 3,570,521. These values are calculated with a python model, which can be found in *Appendix II*.

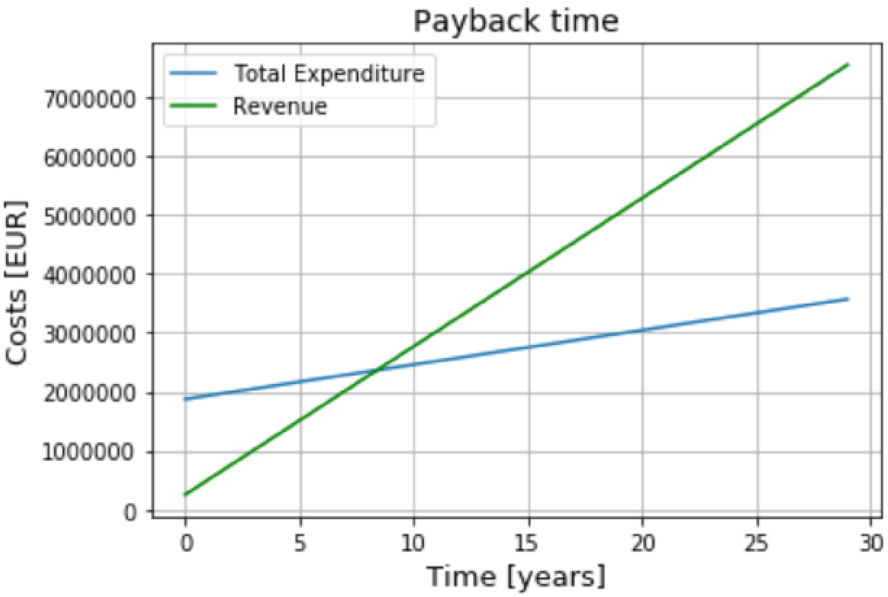

Figure 4.4: Payback time of a 30-year lifecycle HT-ATES project with 3,000 households

4.4 Sensitivity analysis

Performing a sensitivity analysis is to calibrate and validate. Calibration is done by adjusting a set of parameters in order to maximize the model agreement with respect to experimental data. Validation is to quantify the predictive capability of the model (Trucano, Swiler, Igusa, Oberkampf, & Pilch, 2006). The set of parameters that will be adjusted in this sensitivity analysis are the number of households incorporated in the district heating network and the annual thermal energy demand per household.

Table 4.6: Sensitivity of the model through varying the number of households

Number of households	Payback time (years)	Total revenue (EUR)	Total cost (EUR)
1,000	NaN	2,515,745	3,216,041
1,500	22.0	3,773,617	3,304,661
2,000	14.0	5,031,489	3,393,281
2,500	10.4	6,289,361	3,481,901
3,000	8.4	7,547,234	3,570,521
3,500	7.1	8,805,106	3,659,141
4,000	6.2	10,062,978	3,747,761
4,500	5.5	11,320,851	3,836,381
5,000	5.0	12,578,723	3,925,001

In *table 4.6* the output of the sensitivity analysis through varying the number of households is documented. If a 30-year lifecycle HT-ATES project where to satisfy 1,000 households, the payback time of this project would surpass the project lifecycle. When the payback time of a project surpasses the project lifecycle, the project is not financially feasible as the project will not be profitable during its lifetime. It can be observed that if more households are satisfied by a HT-ATES system the business model will reach the financial breakeven point faster, meaning the project will become profitable earlier in the project lifecycle. If the district heating network incorporates 4,000 households, the payback time is significantly decreased (*figure 4.5*). This is due to a significant revenue growth when the total annual thermal energy demand is higher as a result of more households in the district heating network.

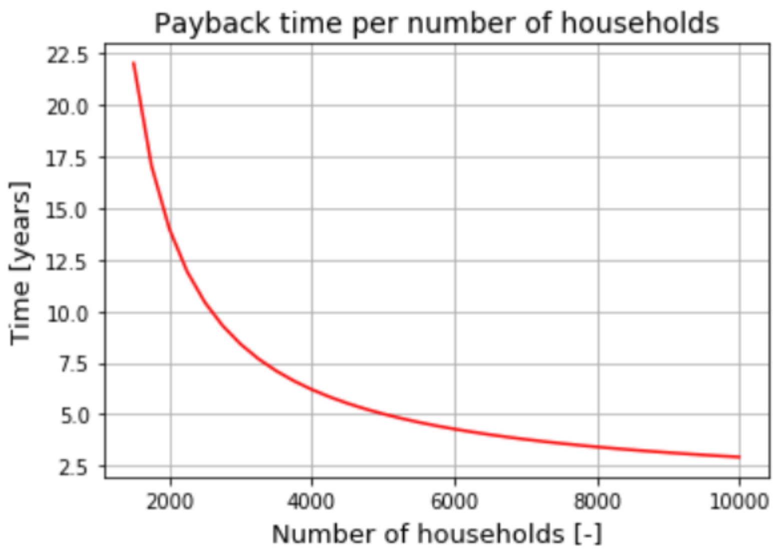

Figure 4.5: Plot of the payback time of a district heating HT-ATES project per number of households

By performing a sensitivity analysis through varying the annual thermal energy usage per household, the statement that a higher thermal energy demand will generate more revenue is validated. This sensitivity analysis is presented in *table 4.7*. When the annual thermal energy demand per household is increased the total generated revenue will correspondingly increase, even if the number of households in the district heating network is kept constant.

Table 4.7: Sensitivity of the model through varying the annual thermal energy demand per household

Annual thermal energy demand (MWh)	Payback time (years)	Total revenue (EUR)	Total cost (EUR)
9	12.8	5,365,332	3,46,801
11	9.9	6,557,628	3,500,801
12.66	8.4	7,547,234	3,570,521
14	7.5	8,346,072	3,626,901
16	6.5	9,538,368	3,710,801

Due to the higher total annual thermal energy demand of the network, when more households are incorporated or an increase in energy demand, the total generated revenue of the business model will increase. It makes sense that the total cost also increases when more households are incorporated in the district heating network, however this increase is of smaller gradient. Thus, a HT-ATES project for commercial use will be more profitable when the district heating network incorporates more households. This relation is illustrated in *figure 4.6*.

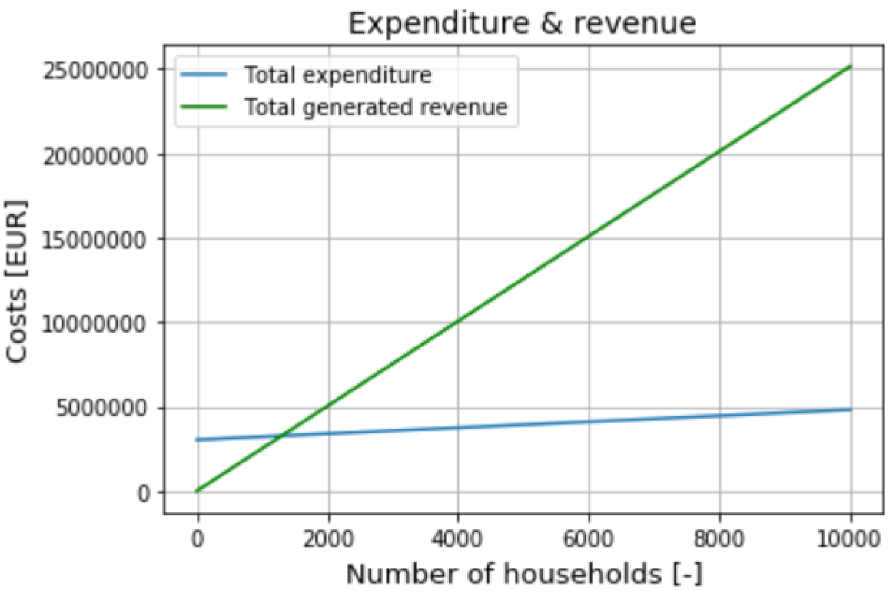

Figure 4.6: Plot of the total business expenditure and generated revenue of a HT-ATES project with the corresponding number of households

Figure 4.6 illustrates that the business expenditure of a district heating network will increase when the number of households incorporated increases. If the district heating network where to satisfy 1,300 households, it will not be profitable within the project lifecycle. This means that a district heating project with an HT-ATES system with less than 1,300 households will not be financially feasible.

6 Conclusion and recommendation

As urban areas are growing at an increasing rate and produce over half of the global greenhouse gas emissions, district heating companies set climate targets to contribute to lowering the harmful emissions produce by the thermal sector. This can only be done if the fossil fuel-based energy systems are replaced by sustainable energy systems. One of the promising sustainable energy systems in the thermal energy sector is the HT-ATES system. However, due to it being a buffer system, complex in use and carrying many risks there are not many thermal energy projects incorporating this system. Thus, the revenue model and possible exploitation of the commercial use of HT-ATES system is unclear. Therefor, the goal of this thesis is to develop a business case for the commercial use of HT-ATES systems and assess the business case sensitivity to the thermal energy demand. This goal will be achieved by a literature research on the technical and financial side of HT-ATES systems.

6.1 Conclusion

The commercial use of HT-ATES systems will only be attractive if and only if the benefit outweighs the costs, meaning the project should be profitable. The costs of the HT-ATES project consist of capital expenditure (CAPEX) and operational expenditure (OPEX). The total CAPEX can be categorized in costs for construction, maintenance, and replacement of parts. For a 30-year lifecycle HT-ATES project with a district heating network satisfying 3,000 households will be a fixed upfront expense of EUR 1,236,991 with an additional yearly expense of EUR 58,500. The OPEX of a HT-ATES project can be categorized in costs for operation and maintenance. For the same 30-year lifecycle HT-ATES project with a district heating network satisfying 3,000 households will be a yearly expense of EUR 637,295. Thus, the total business expenditure of this HT-ATES project will be a fixed upfront expense of EUR 1,236,991 and an additional yearly expense of EUR 695,795. The benefit of the project is defined by the generated revenue, which is strongly dependent on the thermal energy demand. The HT-ATES project generates revenue through the heat pricing model and the government provided subsidy. In this business model it is assumed that the heat price equals EUR 3.89 per kWh and the subsidy equals EUR 2.73 per kWh thermal energy produced. Assuming that the annual thermal energy demand per household equals 12.66 kWh, a HT-ATES project with a district heating network of 3,000 households will have a payback time of 8.4 years.

As the generated revenue by the HT-ATES project is strongly dependent on the thermal energy demand, a sensitivity analysis on the thermal energy demand is performed and the corresponding business model response is assessed. The sensitivity analysis is performed by varying the number of households in the district heating network or varying the thermal energy demand itself, and estimating the payback time of the project through the cost structure and revenue model. The result of the sensitivity analysis shows that the payback time of a HT-ATES project will be significantly decreased when the thermal energy demand is increased. When 4,000 households are incorporated in the district heating network, the payback time is reduced by a factor of 4. This can be explained by the generated revenue, which will significantly increase when the thermal energy demand is higher. It makes sense that the costs of the project will increase when the thermal energy demand is higher, as more households are incorporated in the district heating network. However, this increase is of smaller gradient the costs for waste heat and construction, for the additional households, will be less than the generated revenue through the heat pricing model.

6.2 Recommendation

In order to successfully implement a HT-ATES system for commercial use, a comprehensive site investigation should be top priority. As risks and some elements in the CAPEX are very sit specific. Other points of attention should be the thermal energy demand and the government provided subsidy. These elements have a huge impact on the revenue model of a district heating HT-ATES project. Misinterpreting these elements can have significant influence on the project success. Additionally, the number of households should be defined upfront, as these will provide insight on the project profitability and feasibility. If a HT-ATES project for commercial use would desire maximum profitability, the number of households incorporated in the district heating network should be as many as feasible. When more households are incorporated in the network, the project will have a shorter payback time and will generate more revenue.

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Appendix I: Risk Assessment

Table I.1: Identified risks of HT-ATES categorized by type, source, and time of occurrence (Fleuchaus, et al., 2020)

Cause of risk				Effect on		
Category	Sub-category	Risk item	Stage* P-C-O	CAPEX/ OPEX	Time	Environment
Financial	Financing	Liquidity / creditability	●●○	●	◑	○
		Loss of investor	●●○	●	●	○
		Interest rate	●●○	●	●	○
		Insurances	●●●	●	●	○
	Market	Decreasing heating demand	○○●	●	○	○
		Competing technologies	◑○●	●	○	○
		Contracting	●◑●	●	◑	○
	Costs	Electricity price	○○●	●	○	○
		Material costs	●●○	●	◑	○
		Labor costs	○◑●	●	◑	◑
Technical	Site-investigation	Exploration risk	●●○	●	●	◑
		Improper test-drilling	●●○	●	●	●
	Construction (technical)	Improper drilling	●●○	●	●	●
		Poor building integration	◑●●	●	●	◑
		Insufficient components	◑●●	●	●	◑
		Barring (existing) infrastructure	●●○	●	●	◑
		Ground(water) pollution	●●●	◑	◑	●
	Construction (geological)	Induced seismicity	◑●◑	●	●	◑
		Subsidences & swellable formations	◑●◑	●	●	◑
	Operation (technical)	(HVAC / DH)	○○●	●	●	◑
		Well integrity	●●◑	●	●	○
		Loss of heat source	●●◑	●	●	○
		Groundwater pollution	○○●	◑	○	●
		Heat losses	○◑●	●	○	○
	Geochemical and geological risks	Clogging & scaling	○◑●	●	◑	◑
		Corrosion (wells, pipes, EHX)	○◑●	●	◑	◑
		(Changing) quality of formation water	●●◑	●	●	○
		Induced seismicity (M <3)	●●◑	●	●	○
		Induced seismicity (M >3)	●●◑	●	●	○
		Subsidences & swellable formations	●●◑	●	●	○
Organizational		Time management	●◑●	●	◑	○
		Cooperation of all involved parties	●◑◑	●	●	○
Political		Varying subsidy programs	●◑●	●	◑	○
		Taxation regime	●◑●	●	○	○
		Decision-making structure	●◑◑	●	●	○
Legal		Changing legal framework	●●●	●	●	●
		Complex/uncertain permit procedure	●●◑	●	●	○
		Safety/monitoring requirements	●●◑	●	●	○
Social		Public perception	●●●	●	●	○
		Grid connection	●○○	●	●	○

* P = Planning, C= Construction, O= Operation, ● = Applies, ◑ = Partly applies, ○ = Not applies

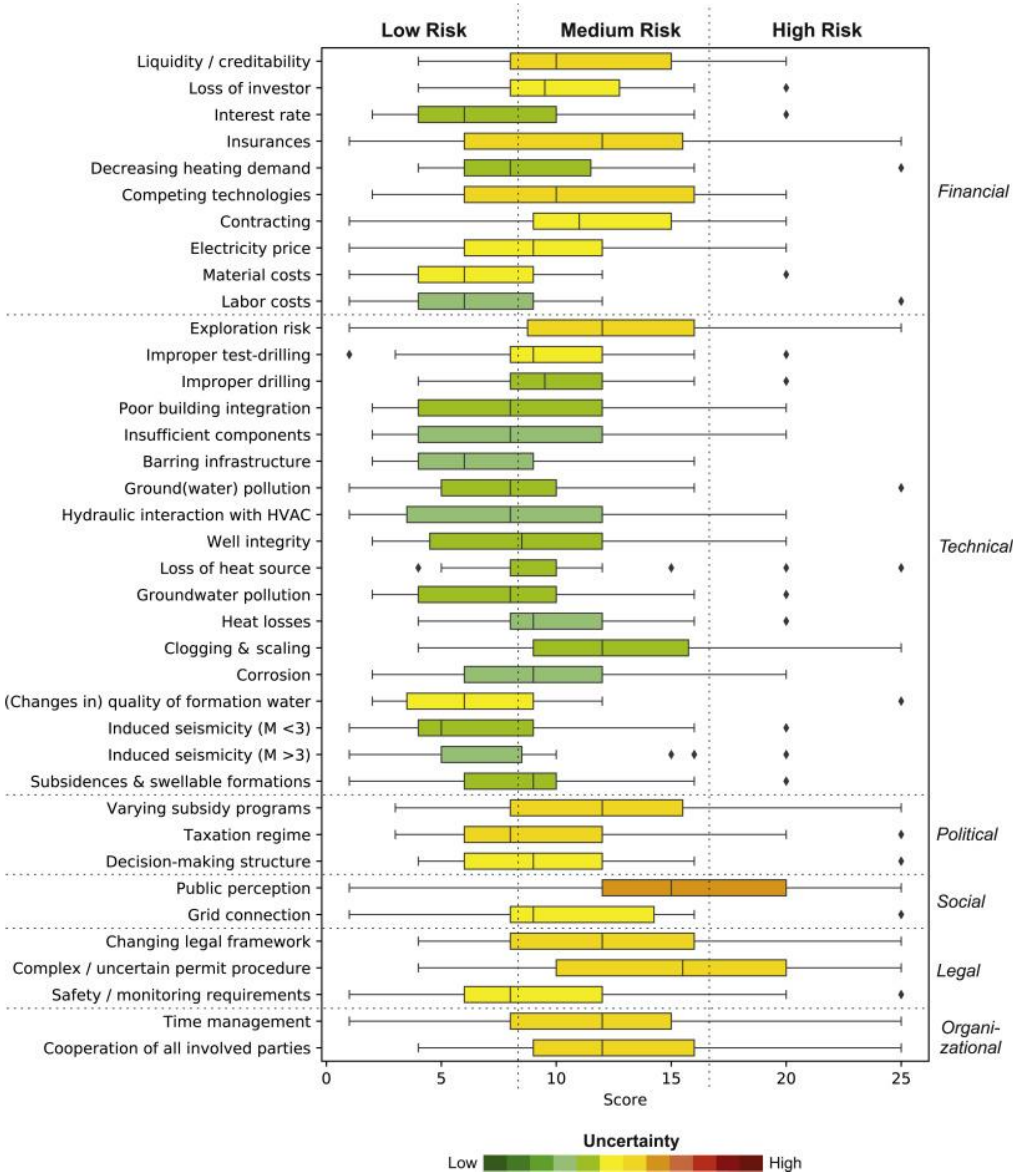


Figure I.1: Risk rating calculated by certainty and severity (Fleuchaus, et al., 2020)

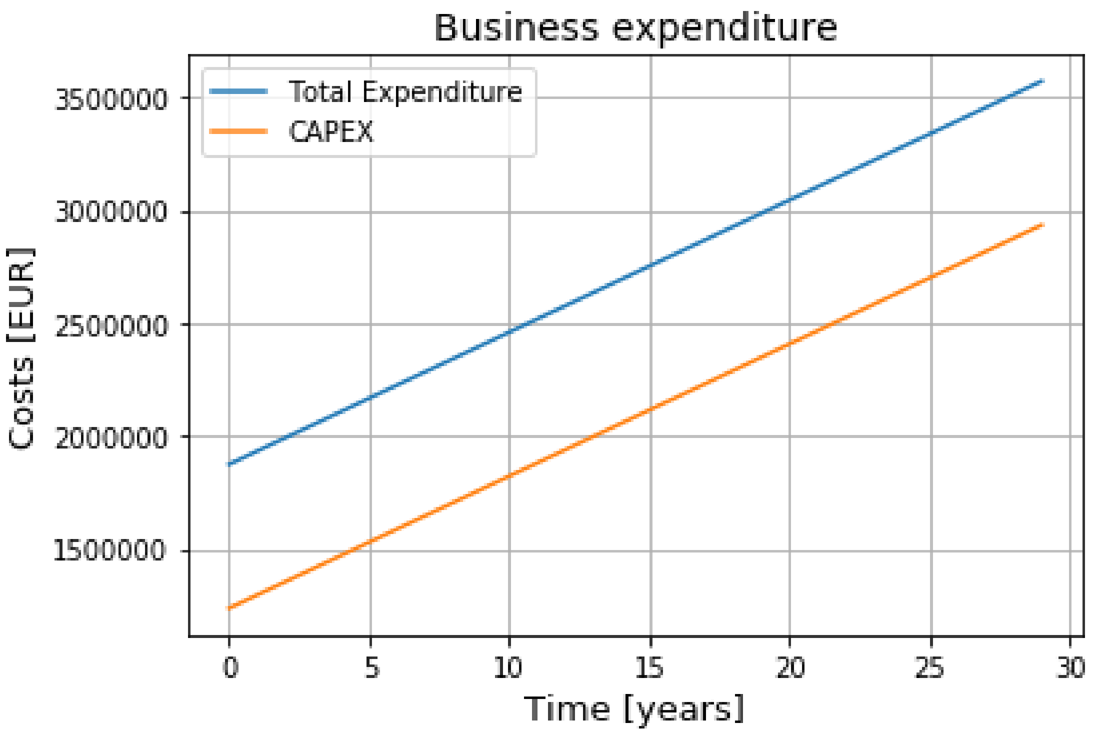
Table I.2: Problems occurring at HT-ATES sites and risks expected (Fleuchaus, et al., 2020)

	Experiences from abandoned and running projects											Expected risk	
Source of risk	Colombier	Mobile	St. Paul	Lausanne	Hørsholm	Plaisir	Utrecht	Zwammerdam	Berlin	Rostock	Neubrandenburg	Hamburg - shallow	Hamburg - deep
Liquidity / creditability	○	○	○	○	○	○	🟢	🟢	🟢	🟢	🟢	🟢	🟢
Loss of investor	○	○	○	○	○	○	🟢	🟢	🟢	🟢	🟢	🟢	🟢
Interest rate	○	○	○	○	○	○	🟢	🟢	🟢	🟢	🟢	🟢	🟢
Insurances	○	○	○	○	○	○	-	-	○	○	○	🟡	🔴
Decreasing heating demand	○	○	○	○	○	○	🔴	-	🔴	🟢	🟢	🟢	🟢
Competing technologies	○	○	○	○	○	○	🔴	🔴	🟡	🟢	🔴	🔴	🔴
Contracting	○	○	○	○	○	○	🟢	🟢	🟢	🟢	🟢	🟢	🟢
Electricity price	○	○	○	○	○	○	🟢	🟢	🟢	🟢	🟢	🔴	🟢
Material costs	○	○	○	○	○	○	🟢	🟢	🟢	🟢	🟢	🟡	🟡
Labor costs	○	○	○	○	○	○	🟢	🟢	🟢	🟢	🟢	🟢	🟢
Exploration risk	🟡	○	○	○	○	○	🟢	🟢	🟢	🟢	🟢	🟢	🔴
Improper test-drilling	○	○	○	○	○	○	○	○	🟢	🟢	○	🟢	🔴
Improper drilling	○	🔴	🟢	○	○	○	🟢	🟢	🟢	🟢	○	🟢	🟢
Poor building integration	○	○	○	○	○	○	🟡	-	🟡	🟢	○	🟢	🟢
Insufficient components	○	○	○	○	🔴	○	🟡	🟢	🟢	🟢	🟡	🟢	🟡
Barring infrastructure	○	○	○	○	○	○	○	○	🟡	🟢	🟢	🟡	🟡
Hydraulic interaction	○	○	○	○	○	○	○	○	🟢	🟢	🟢	🟢	🟢
Well integrity	-	-	-	-	-	-	🔴	🟢	🟢	🟢	🟡	🟢	🟢
Loss of heat source	○	○	○	○	🟢	○	🔴	🔴	🔴	🟢	🔴	🟡	🟢
Groundwater pollution	-	-	-	-	-	-	🟢	🟢	🟢	🟢	🟢	🟢	🟢
Heat losses	🔴	🔴	🟢	🟡	🟡	-	🟡	🟡	🟢	🟢	🟢	🟢	🟢
Clogging & scaling	-	🔴	🔴	🔴	🔴	🔴	🟡	🟢	🟡	🟢	🟡	🔴	🔴
Corrosion	-	-	🟡	🔴	🔴	-	🟢	🟡	🟡	🟢	🟡	🟢	🟡
(Changing) quality of form. water	-	-	-	🟡	-	🔴	-	-	🟢	🟢	🟡	🟡	🟢
Induced seismicity	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟡
Induced seismicity (M >3)	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢
Subsidences & swellable formations	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢
Varying subsidy programs	○	○	○	○	○	○	○	○	🟢	🟢	🟢	🟢	🟢
Taxation regime	○	○	○	○	○	○	○	○	🟢	🟢	🟢	🟢	🟢
Decision-making structure	○	○	○	○	○	○	○	○	🟢	🟢	🟢	🔴	🔴
Public perception	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢
Grid connection	○	○	○	○	○	○	🟢	🟢	○	○	🟢	🟢	🟢
Changing legal framework	○	○	○	○	○	○	-	-	🟢	🟢	🟡	🟢	🟢
Complex permit procedure	○	○	🟡	-	-	-	-	🟡	🟢	🟢	🟢	🔴	🟢
Safety/monitoring requirements	-	-	🟡	-	-	-	-	🟡	🟢	🟢	🟡	🔴	🟢
Time management	-	○	○	○	○	○	-	-	🟢	🟢	🟢	🟢	🟢
Cooperation of all involved parties	○	○	○	○	○	○	-	-	🟢	🟢	🟢	🟡	🟡

* - = No information, ○ = Not relevant, 🟢 = Not encountered (low), 🟡 encountered (medium), 🔴 = Crucial (high)

Appendix II: Python script business model

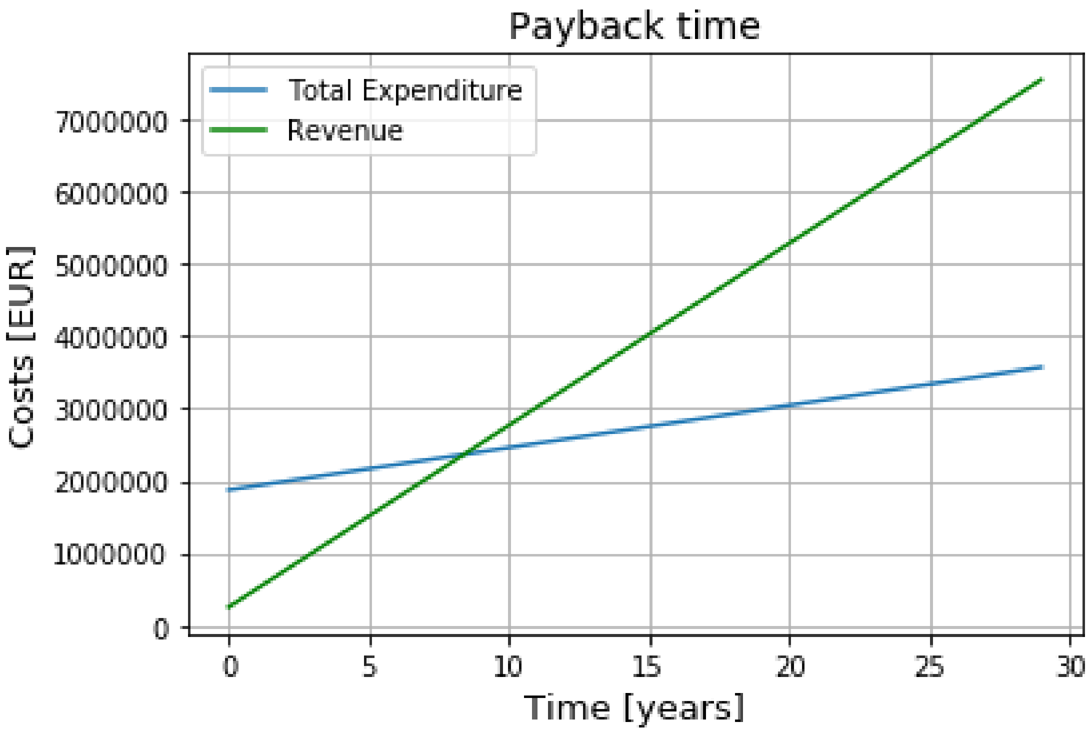
```
%matplotlib inline
import numpy as np
import matplotlib.pyplot as plt

CAPEX = np.zeros(30)
#construction CAPEX
CC = 1236991 #initial upfront costs
CAPEX[0] = CC
#maintenance and replacement CAPEX
MC = 50000 #annual maintenace costs
RC = 8500 #annual costs for the replacment of parts
#total CAPEX
for i in range(len(CAPEX)-1):
    CAPEX[i+1] = CAPEX[i] + MC + RC
# print(CAPEX)
#parameters OPEX
households = 3000 #number of households in the district heating network
consmpt = households * 12660 #annual energy consumption for heating and coo
ling [kWh]
electrcty = 265000 #annual electricity consumption bythe components of the
HT-ATES system [kWh]
#total expenditure (CAPEX + OPEX)
TEX = np.zeros(30)
for j in range(len(TEX)):
    TEX[j] = CAPEX[j] + (0.05*CC) + (consmpt*0.014) + (electrcty*0.164)
#plotting the figures
plt.figure()
plt.plot(np.arange(0,30),TEX,label='Total Expenditure')
plt.plot(np.arange(0,30),CAPEX,label='CAPEX')
plt.title('Business expenditure',fontsize=14)
plt.xlabel('Time [years]',fontsize=13)
plt.ylabel('Costs [EUR]',fontsize=13)
plt.legend()
plt.grid()
```




```
revenue = np.zeros(30)
revenue[0] = ((3.89+2.73)/1000)*consmpt #[EUR]
for k in range(len(revenue)-1):
    revenue[k+1] = revenue[k] + ((3.894+2.73)/1000)*consmpt
# print(revenue)
def line_intersection(line1, line2):
    xdiff = (line1[0][0] - line1[1][0], line2[0][0] - line2[1][0])
    ydiff = (line1[0][1] - line1[1][1], line2[0][1] - line2[1][1])
    def det(a, b):
        return a[0] * b[1] - a[1] * b[0]
    div = det(xdiff, ydiff)
    if div == 0:
        x = 0
        y = 0
    d = (det(*line1), det(*line2))
    x = det(d, xdiff) / div
    y = det(d, ydiff) / div
    return x, y
#line TEX
A = (0,TEX[0])
B = (29,TEX[29])
#line Revenue
C = (0,revenue[0])
D = (29,revenue[29])
#intersection (payback time)
x, y = line_intersection((A, B), (C, D))
# print(x,y)
```

```
print('The payback time for this commercial use HT-ATES project with', hous
eholds, 'households will be', x, 'years')
print('The revenue generated after 30 years will be', revenue[29], 'EUR')
print('The total costs after 30 years will be', TEX[29], 'EUR')
#plotting the figures
plt.figure()
plt.plot(np.arange(0,30),TEX,label='Total Expenditure')
plt.plot(np.arange(0,30),revenue,label='Revenue',color='green')
# plt.plot(x,y,'ro')
plt.title('Payback time',fontsize=14)
plt.xlabel('Time [years]',fontsize=13)
plt.ylabel('Costs [EUR]',fontsize=13)
plt.legend()
plt.grid()
```

```
The payback time for this commercial use HT-ATES project with 3000 househol
ds will be 8.403754836349302 years
The revenue generated after 30 years will be 7547233.679999994 EUR
The total costs after 30 years will be 3570520.55 EUR
```

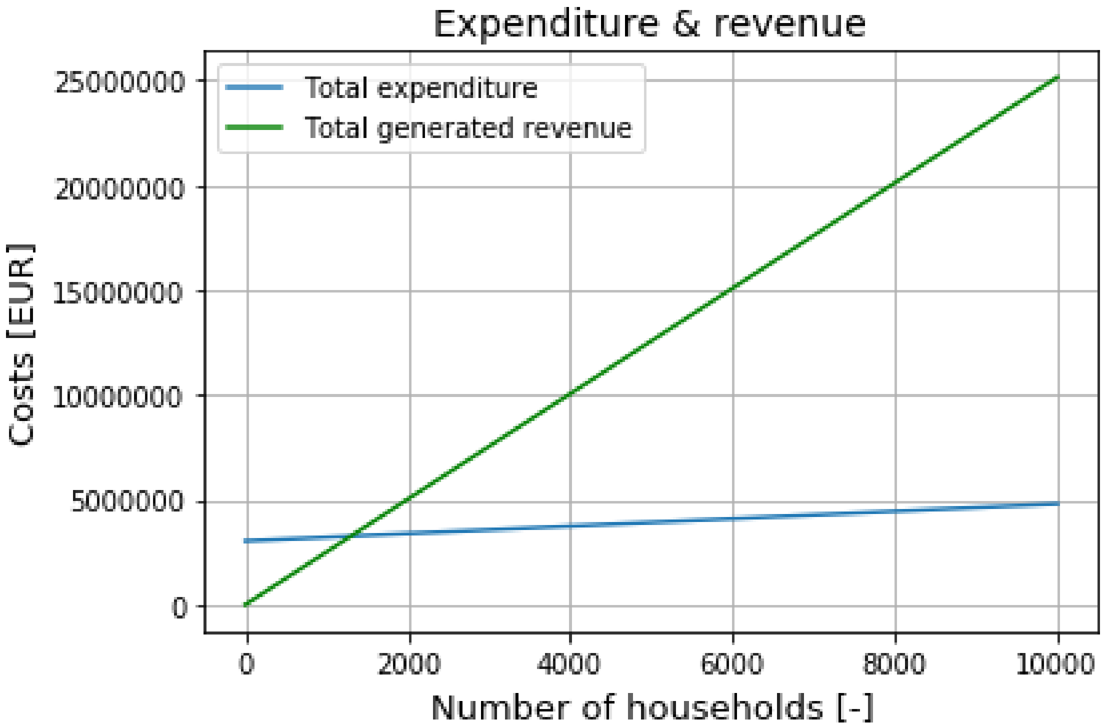



```
#sensitivity analysis
def CAP(hsh): #function for the CAPEX per household
    #hsh equals the number of households in the district heating network
    #to determine the CAPEX for 3000 households
    CE = np.zeros(30)
    #construction CAPEX
    CCOST = 1236991 #initial upfront costs
    CE[0] = CCOST
    #maintenance and replacement CAPEX
    MCOST = 50000 #annual maintenace costs
```

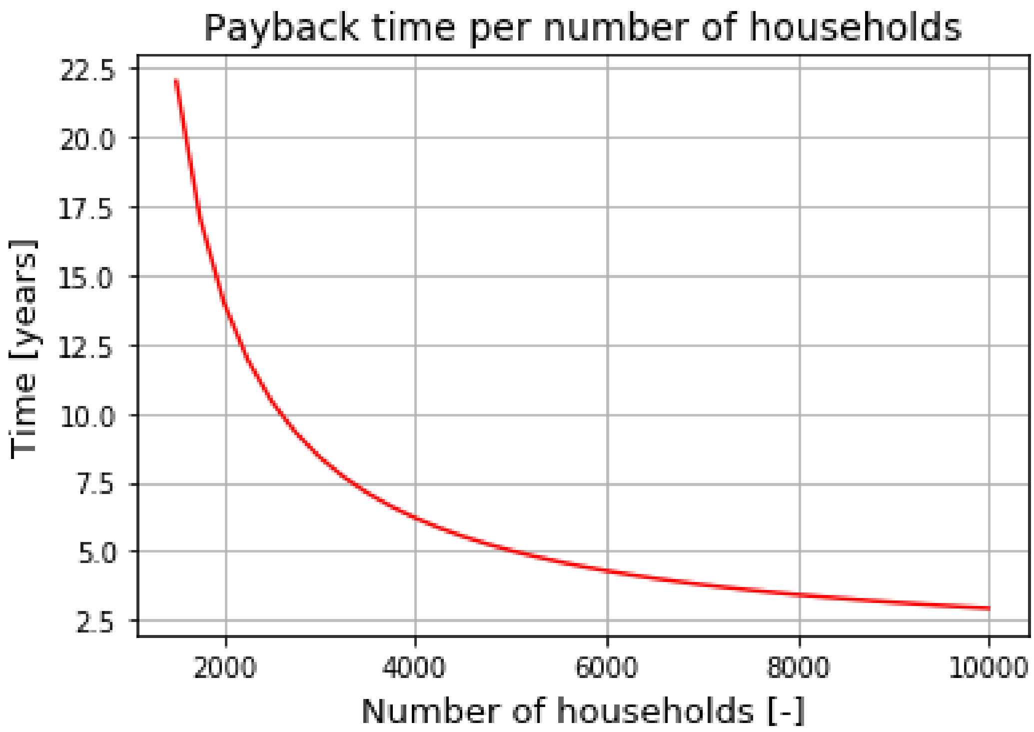
```
    RCOST = 8500 #annual costs for the replacment of parts
    #total CAPEX
    for l in range(len(CE)-1):
        CE[l+1] = CE[l] + MCOST + RCOST
    return CE
def TOTEXP(hsh): #function for the total expenditure per household
    #hsh equals the number of households in the district heating network
    CONS = hsh * 12660 #annual energy consumption for heating and cooling [
kWh]
    ELC = 265000 #annual electricity consumption bythe components of the HT
-ATES system [kWh]
    #total expenditure (CAPEX + OPEX)
    TE = np.zeros(30)
    for m in range(len(TE)):
        TE[m] = CAP(hsh)[m] + (0.05*CC) + (CONS*0.014) + (ELC*0.164)
    return TE
def REV(hsh): # function for the generated revenue per household
    CONS = hsh * 12660 #annual energy consumption for heating and cooling [
kWh]
    rev = np.zeros(30)
    rev[0] = ((3.89+2.73)/1000)*CONS
    for n in range(len(rev)-1):
        rev[n+1] = rev[n] + ((3.894+2.73)/1000)*CONS
    return rev

hsh = np.arange(0,10250,250) #number of households
expenditure = [] #total business expenditure of the project [EUR]
revenue = [] #total generated revenue [EUR]
for o in range(len(hsh)):
    expenditure.append(TOTEXP(hsh[o])[29])
    revenue.append(REV(hsh[o])[29])
#plotting the figures
plt.figure()
plt.title('Expenditure & revenue',fontsize=14)
plt.plot(hsh,expenditure,label='Total expenditure')
plt.plot(hsh,revenue,label='Total generated revenue',color='green')
plt.xlabel('Number of households [-]',fontsize=13)
plt.ylabel('Costs [EUR]',fontsize=13)
plt.yticks(np.arange(0,3*10**7,0.5*10**7),['0','5000000','10000000','150000
00','20000000','25000000'])
plt.legend()
plt.grid()
#line expenditure
E = (0,expenditure[0])
F = (hsh[40],expenditure[40])
#line revenue
G = (0,revenue[0])
H = (hsh[40],revenue[40])
```

```
#intersection (profitability)
x, y = line_intersection((E, F), (G, H))
# print(x,y)
print('A district heating network with less than', x, 'households not be pr
ofitable')
# plt.plot(x,y,'ro')
```

```
A district heating network with less than 1299.463170599933 households not
be profitable
```




```
#payback time assessment
PB = np.zeros(len(hsh)) #payback time of the project
for q in range(len(hsh)):
    L = (0,TOTEXP(hsh[q])[0])
    M = (29,TOTEXP(hsh[q])[29])
    N = (0,REV(hsh[q])[0])
    O = (29,REV(hsh[q])[29])
    xx, yy = line_intersection((L,M), (N,O))
    if 0 < xx < 30:
        PB[q] = xx
    else:
        PB[q] = np.nan
# print(PB)
#plotting the figures
plt.figure()
plt.title('Payback time per number of households',fontsize=14)
plt.plot(hsh,PB,color='red')
plt.xlabel('Number of households [-]',fontsize=13)
plt.ylabel('Time [years]',fontsize=13)
plt.grid()
```


Payback time per number of households
Time [years]
22.5
20.0
17.5
15.0
12.5
10.0
7.5
5.0
2.5
2000
4000
6000
8000
10000
Number of households [-]