The potential demand-side management in ATES systems

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Engineering the earth

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Abstract

The research described in this paper is focussed on the potential of marrying the concept of demand-side management with the Aquifer Thermal Energy Storage (ATES) system. The ATES system is a commercial heating and cooling technology that uses aquifers to store seasonal heat and cold for use in the opposite seasons. In order to operate this system flexibly based on the availability of electricity certain adaptations are required. This is done by adding a short-term thermal storage system in the form of a water tank to the system design called a buffer. A model was build based on measured data of existing ATES system to study the effects of adding a buffer to the ATES system.

The buffer allows the ATES system to generate heating and cooling during off-peak hours where it would otherwise be idle in most cases. The off-peak production runs on cheaper electricity and allows the ATES system to be reduced in its capacity. The result is that both the investment costs and the yearly energy costs can be reduced by 10% - 15%. The concept can be taken one step further by letting the system operation react to the prices on the imbalance market. In doing so, yearly energy costs can be reduced by as much as 35%

The new ATES system concept works only for end-users that have sufficient down-time in their thermal demand to charge the buffer. This rules out end-users like hospitals or airports. In choosing the dimensions of the buffer and ATES size there is a trade-off between CO_2 emission reduction and cost savings. Both a cost optimal solution and a CO_2 optimal solution can be achieved by the addition of a buffer. As a direct result of this research several pilot projects are starting to see how this concept will work in practise

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Introduction

Energy is one of the main driving forces behind our society's economic and social development. The application of fossil fuel based systems is for a large part responsible for the exponential growth of welfare in the developed countries since the industrial revolution (Kemp 2010). However, due to shrinking fossil fuel reserves and the increasing pressure their use puts on our environment, we are forced to look for renewable and sustainable alternatives to fuel our society. The urgency of this problem is reflected in the ambitious goals set by many of the world´s governing bodies with respect to energy saving, renewable energy targets and CO_2 emission reduction. The EU has set itself the goal of reducing carbon emissions by between 80% and 95% by 2050 compared with the 1990 level (ECN 2013). These goals have been translated to national targets and subsequently into national policy within each of the member states.

Every country within the EU has its own strategy towards achieving its targets. In general, electricity generation gets a lot of attention. As shown in Figure 1, for The Netherlands to achieve its target of 14% total share of sustainable energy in 2020, 35% of the country´s electricity is planned to be generated from renewable sources (G. Coenen et al. 2014).

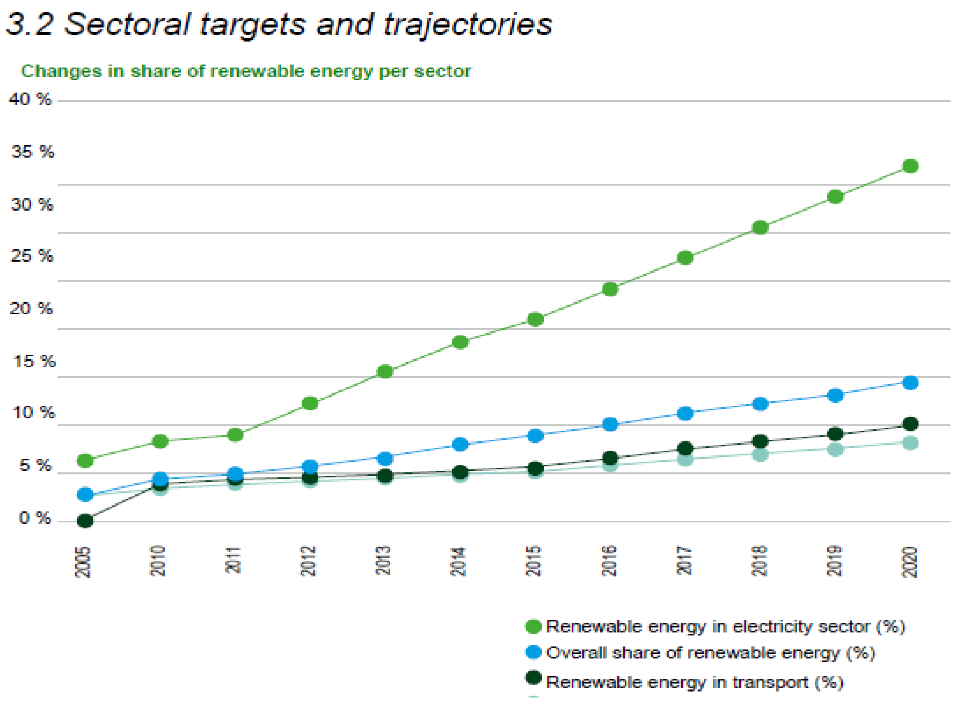


Figure 1: 2020 target of 14% share of RES within The Netherlands
Source: (G. Coenen et al. 2014)

Wind turbines are currently one of the most cost-effective means of renewable electricity generation, especially in the temperate climates found in northern Europe (Østergaard 2013). According to the National Renewable Energy Action Plans (NREAPs), the Renewable Energy Sources (RES) contribution to electricity generation within the EU27 will be about 33.9 % in 2020. Wind energy has the highest contribution in this renewable generation capacity of 41.3 % by 2020 (Márta et al. 2011). In figure 2 below, the trend of the increasing share of wind in Europe's renewable electricity generation from can be seen clearly.

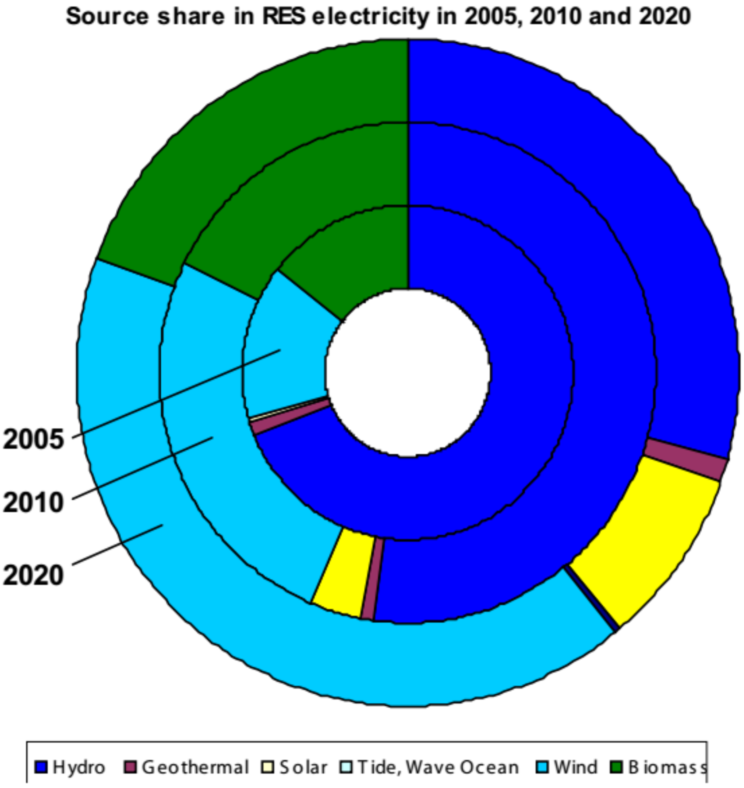


Figure 2: Source share in RES electricity in the EU27 countries. (Márta et al. 2011)

1.1 Problem definition

A common point of discussion around large scale wind power integration is the effect of intermittency on the operation and economics of our electrical grid. Identifying and quantifying the effects of increased intermittent renewable capacity on the electrical grid is a key element of current research on renewable energy. The impacts of additional renewable electricity production must first be fully understood before safe and effective changes can be made to the infrastructure and legislation. One of the key questions in this issue is how renewable production affects the electricity price and its volatility. Research by Jensen & Skytte (2002) suggested that renewable electricity production results in overall lower electricity prices. This idea was subsequently elaborated by research from Sensfuss et al. (2008) and Nicolosi and Fürsch (2009). The lower prices are caused by the fact that renewables bid into wholesale electricity markets at almost-zero prices. To understand how this lowers the overall energy price we have to look at how the electricity price is determined. The electricity markets are organized based on what is called a merit-order curve. This curve is generated by bids of the marginal costs of different dispatchable power producers. Based on the demand the lowest bidders are selected and all producers get the price of the highest bidder in the set. An example of a German merit order curve is shown in figure 3 below. Pay special attention to the order of energy sources and imagine the effect of adding more renewables on the left.

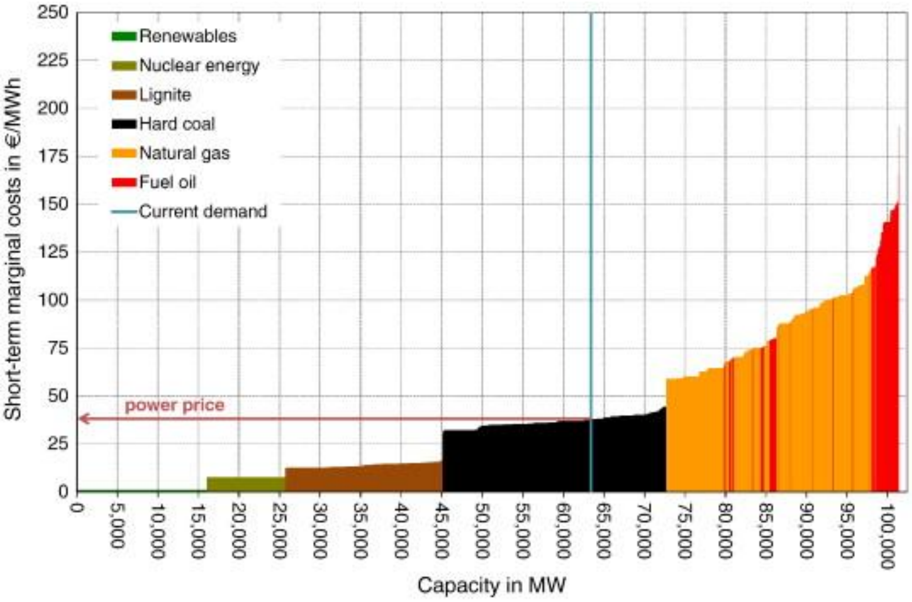
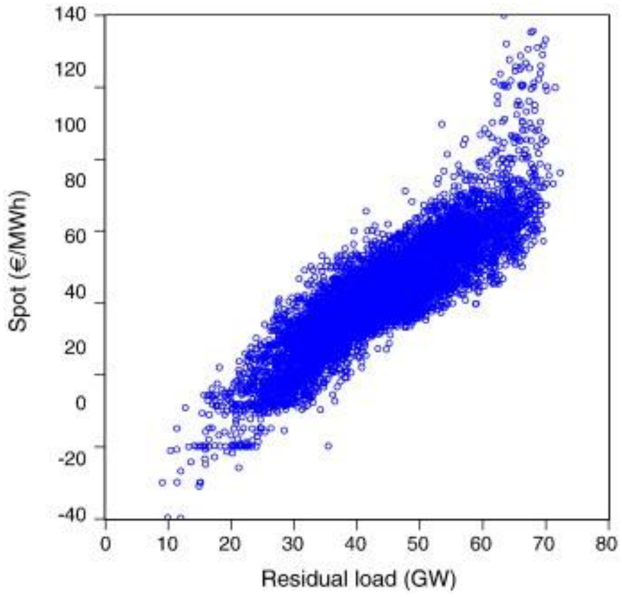


Figure 3: Example of a German merit order curve (Würzburg et al. 2013a)

Adding more renewables shifts the whole curve to the right. Given that electricity prices are set by the highest marginal cost power producer in the selected batch, and that the supply curve has a positive slope, the shift of the supply curve to the right results in a lower equilibrium price. This phenomenon is commonly known as the ‘merit-order effect’ (Würzburg et al. 2013a, Cludius et al. 2014). The strength of the merit order effect is directly related to the share of renewables in the grid mix at any one time. The strength of this effect is usually shown as the relation between the residual load and spot market prices. The residual load is defined as *Total load – renewables.* In other words, the residual load is the non-renewable part of the load.

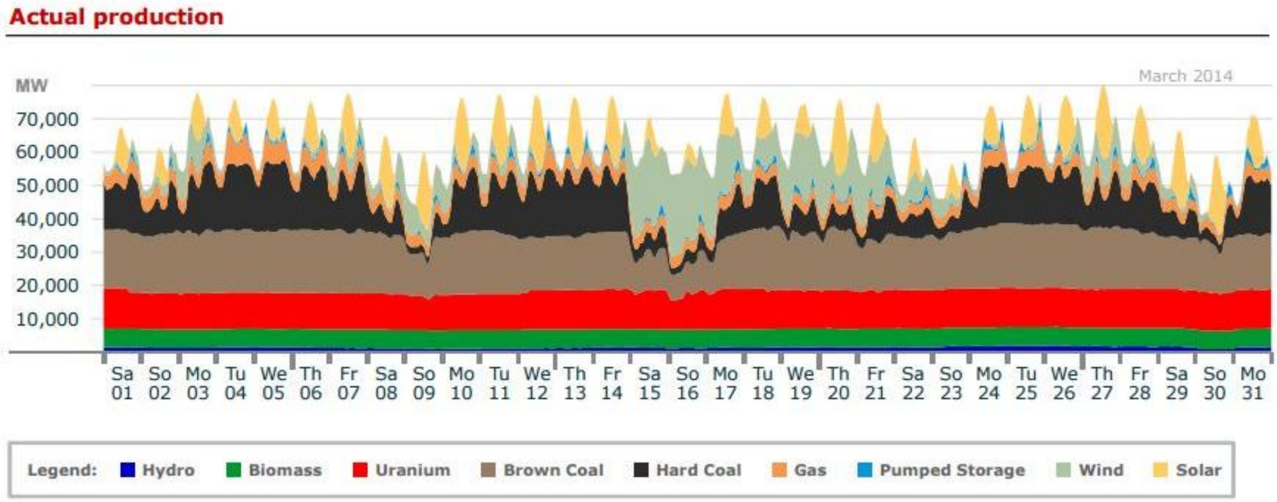
Figure 4 below shows the relation between spot prices and residual load in Germany in 2012. It shows that if more electricity is generated using non-renewable technologies, the spot price increases. At very low levels of non-renewable generation, the price of electricity can fall below €0. The negative prices stem from an interaction between renewable sources and traditional base load power plants. At low residual loads, below 40 GW in this case, renewables start to substitute base load power plants such as coal and nuclear. If low residual loads occur for a few hours only, the base load plants prefer not to shut down completely due to ramp rates and start-up costs. The tendency of base load plants to prefer running in partial load over shutting down causes negative prices to occur. The most extreme case in Germany in 2012 was on the 25th of December, where low demand coupled with a lot of wind, depressed the electricity price to below -200 €/MWh (Cludius et al. 2014).

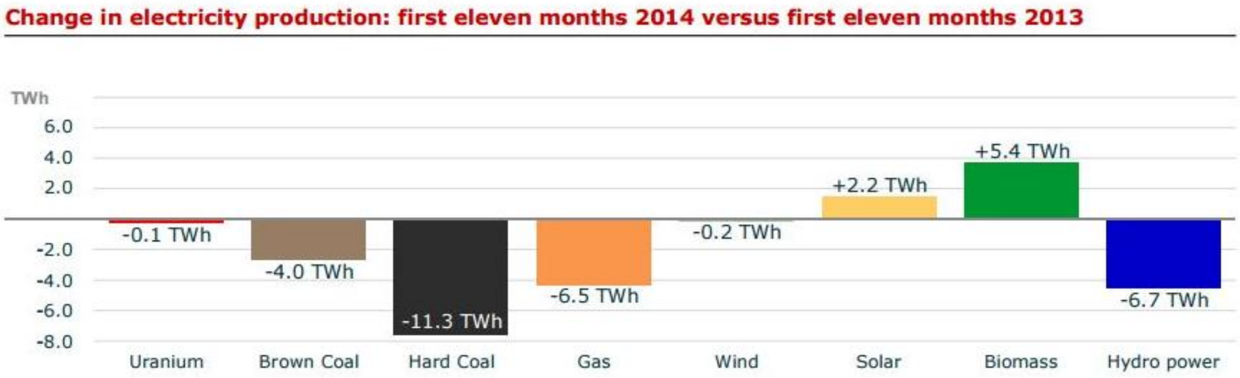
Figure 4: Merit-order effect as seen in Germany over 2012 (Cludius et al. 2014)



From all this we can conclude that, in general, increasing the share of renewables lowers the mean price of electricity. This could be considered a positive development and generally benefits the consumer. However, system operators are concerned by this trend because the most common way to compensate for the natural variations in wind turbine output is by reactive operation of conventional fossil fuel based power plants (Georgilakis 2008). The merit-order effect causes the price of electricity to drop and the dispatch of base load to become more irregular. Both these effects combined make it more difficult for traditional fossil fuel fire power plants to turn a profit. Countries that are experiencing a strong merit-order effect, like Germany, also see an accelerated rate of decommissioning of the existing fossil fuel plants and a reduction in the investment in new fossil fuel based capacity. The traditional fossil fuel base load plants like coal and lignite seem to suffer most from the reduced average price and more irregular dispatch (Cludius et al. 2014, Würzburg et al. 2013b). In figure 5, the effects and changes in the electricity system in Germany are clearly visible. Note how wind and solar eats into the dispatch of coal and gas fired plants (Burger 2014).

Figure 5: Developments in the German electricity market
Source: (Burger 2014)





From a sustainability point of view this might seem like a sign that renewable energy is beating the competition. However, regardless whether that is the case, the current developments also create some challenges. Sufficient back-up capacity still has to be kept in place for nights or cloudy days with little or no wind. As we have established in the previous paragraph; these fossil fuel plants become more costly to operate with the increasing share of intermittent renewables. The main implication of this is that capacity costs for each MW of peak load become much higher in systems with high wind and solar penetration (Mount et al. 2012). The costs of peak power combined with the natural fluctuation in wind turbine output leads ultimately to more volatile and unpredictable electricity markets in countries that have a high share of wind and solar (Haas et al. 2013, Nakamura et al. 2006).

At first glance this might not seem like a big issue as there are many volatile markets that have operated without problems regardless. But the electricity market has some unique properties that make a volatile electricity market problematic. One unique feature of the electricity market is that electrical demand always has to be met with supply, precisely and instantly, in order to maintain grid stability. This is a bigger problem due to the second unique feature of the electricity market; electricity cannot be stored easily. Guthrie and Videbeck (2007) go as far as treating electricity traded at different times as actually being distinctly different commodities. Yet, until cheap and sufficient storage capacity becomes available, this is not far from the truth. These properties of electricity markets force buyers to either buy the required power regardless of the price, or choose to not buy any electricity at all. And not buying electricity is not really an option in many cases.

The seemingly contradictory effect of rising shares of renewable electricity is that the average electricity price decreases while at the same time the risk of being forced to pay an extremely inflated price at times increases. This effect was analysed by Nakamura et al. (2006) who concluded that this risk would eventually become too large for firms with high electricity demand to continue business as usual. They advised that the best course of action is to either ensure that demand is flexible enough to react to these price changes, or in case that this is not feasible, to invest in privately held power production to become less dependent on the spot-market. This advice correlates with the conclusions of Mount et al. (2012) that an increasing share of renewables in the grid makes measures that reduce system peak load like controllable demand and/or electricity storage economically attractive and at some point even necessary.

1.2 Literature on the subject

So from the previous paragraph we can conclude that some form of electricity storage or flexible electric demand would be beneficial, both for the end-user as for the energy transition in general. Another conclusion is that the first to experience the effects of a volatile electricity market are the users with high peak demand. As this is one of the key challenges of the energy transition, much has been written about the problem and the two main avenues of approach towards its solution; cheap grid-scale electricity storage and Demand Side Management (DSM). In the paragraphs below the main conclusions of current research on these topics will be laid out and discussed.

Grid-scale electricity storage

Looking at literature on grid-scale electricity storage we find there is currently much debate in the scientific community about the merits of different technologies and their adoption in the future. When looking at the different models that authors use to predict the technological trajectories of these technologies, both the assumptions and the predictions vary widely among even a small sample of the vast library of literature on the subject. This conclusion is also supported by a comparative literature study done by (Castillo and Gayme (2014). Surprisingly though, most authors can agree on the barriers to adopting grid-scale electricity storage technologies in their current state. The reasons most commonly noted are: insufficient technological maturity, cycle efficiency, as well as capital, operating and maintenance costs. (Luo et al. 2015, van der Linden 2006, Castillo, Gayme 2014, Ibrahim et al. 2008, Hadjipaschalis et al. 2009, Tuohy et al. 2012, Beaudin et al. 2010). The problem is further enhanced by the sheer amount of electricity that would have to be stored. An overview of relation between the current potential of different technologies and scope of the challenges in the UK can be seen in figure 6 below. Note the order of magnitude difference between wind power variability and the potential of the largest storage capacity in the UK, Pumped Hydro Storage (PHS).

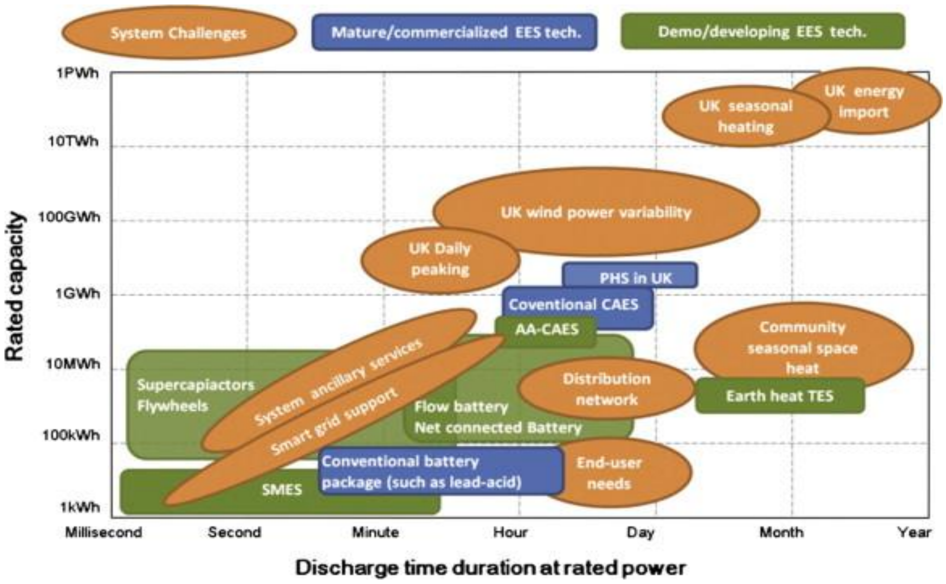


Figure 6: Comparison between storage Technologies and system challenges (Luo et al. 2015)

It is also useful to point out that it is mentioned by several authors that even when electric storage reaches a level the level of maturity required for compensating the variation in renewable generation, it is not an all-encompassing solution for addressing the myriad of challenges associated with renewable energy integration. Many authors agree that the final design of a renewable energy system should contain a wide array of generation, storage and end-user technologies all working together (Castillo, Gayme 2014, Beaudin et al. 2010, Ibrahim et al. 2008).

Demand side management

Where grid-scale electricity storage attempts to solve the mismatch between supply and demand from the supply side, DSM attempts to do this from the demand side. Take note that these two technologies are complementary to each other and one does not exclude implementation of the other. If we look at the amount of literature on DSM, we find it to be as extensive as the library of research on electricity storage. However, more than the previous topic, research on DSM seems to zoom in more on specific concepts like;

- *charging and discharging electric cars* (López et al. 2015, Masuta et al. 2014, Di Giorgio et al. 2014, Druitt, Früh 2012),
- *flexible operation of household appliances* (Kobus et al. 2015, Nistor et al. 2015, Gottwalt et al. 2011, Adika, Wang 2014)
- *building thermal demand variation/storage*. (Favre, Peuportier 2014, Arteconi et al. 2013, Ellerbrok 2014, Ferrari et al. 2014, Ruddell et al. 2014, Arteconi et al. 2012).

Results vary per concept, and occasionally per author within a single concept, but some general conclusions can be drawn looking at the different studies. One conclusion that seems to fit all concepts is that bigger is better. In other words, a single application with a large power demand benefits more from DSM than several smaller applications. This is due to the fact that costs are more or less fixed and mainly related to investments in infrastructure and ICT. The benefits, both financially and structurally are related to the amount of electricity use that is shifted from peak to off-peak moments. This relationship between costs and benefits favours large power capacity applications. A second conclusion that can be drawn from the literature is that applications that aim for the consumer market and interfere in day-to-day life more directly seem to be met with more social apprehension and resistance than applications aimed at the commercial sector. The reason behind the public apprehension was well described by Balta-Ozkan et al. (2013) who concluded that the public's main concerns are related to: feeling a loss of control, privacy and data security, costs and trust. Of those barriers mentioned it is especially concerns about privacy, data security and overall trust in energy companies that are hard to overcome from a technological approach. Due to this it is the wider societal debate on privacy, digitalization and the ownership of data that is a key pacing factor in the consumer branch of DSM applications.

Looking at the lessons learned from the different studies we can conclude that DSM currently has the most potential in high power applications, specifically for commercial/professional end-users. This synchronizes well with the earlier conclusion on market effects and the risks of a volatile market to specifically the end-users with high peaks in electricity demand.

Demand side management of heating and cooling systems

One such high power application that almost all commercial end-users have is electrical heating and/or cooling equipment. The use of heating and cooling equipment in a DSM context gets positive results in the studied literature, especially those used on the commercial/industrial scale. There are several reasons for this; firstly, the installed capacity of an electric heat pump or compression cooler is relatively high (most commonly ranging from +/-100kWe up to several MWe). Secondly, the generation of heating and cooling has some inherent flexibility as slight temperature variations within a building or process are usually quite acceptable. Note that this level of inherent flexibility is quite rare in electrical applications. On top of that, the flexibility of heating and cooling systems can be increased further with the addition of a thermal storage system. The idea of using heating and cooling systems with thermal storage in a DSM framework has also been researched extensively both from an energy system perspective (Favre, Peuportier 2014, Arteconi et al. 2013, Ellerbrok 2014, Ferrari et al. 2014, Ruddell et al. 2014, Østergaard 2013) and from the building/end-user perspective. (Hessami, Bowly 2011, Benli 2011, Hewitt 2012, Rismanchi et al. 2013, Asadi et al. 2014, Reynders et al. 2013, Arteconi et al. 2012). All of these studies come to the conclusion that that DSM using heating and cooling systems can be very beneficial given the right circumstances. Some of these circumstances mentioned are: A volatile electricity market, Centralized and high capacity thermal equipment like heat pumps and end-users that have a strong fluctuating thermal demand that peaks during electrical peak hours (during the day on weekdays). Typical end-users that fit this bill are most office buildings, universities, public amenities etc.

1.3 ATES systems

A system commonly used in The Netherlands for specifically the aforementioned office buildings, universities and public amenities is the Aquifer Thermal Energy Storage (ATES) system. An ATES system uses underground aquifers to store the seasonal warmth of summer and cold of winter for use as respective heating and cooling in the opposite seasons. The ATES system is becoming increasingly more common in The Netherlands and is now the most used system for renewable heating and cooling of commercial buildings in the country, totalling up to 4% of the total renewable energy used in The Netherlands. (CBS 2014). This research aims to conceptualize and model what would happen if we would apply the principles of DSM and short-term thermal storage to the ATES system.

An ATES system uses an underground aquifer to store thermal energy over the seasons. By injecting cold water during winter, this cold can be used in summer for cooling. By cooling a building the water heats up, which can be injected a few 100 meters further for use in winter. The ATES system is more expensive to construct than conventional heating and cooling system because of these wells. But by storing energy for use in the opposite seasons, the energy costs of an ATES system are much lower than traditional systems. Most of the energy costs of an ATES system go towards the heatpump needed to upgrade the heat extracted from the groundwater at around 18°C to the temperature of the heating system (30-60°C).

1.4 Research questions

The general goal of this research is to find out:

Can the performance of an ATES system be improved in terms of costs and CO_2 *emission by addition of a demand-side management strategy in combination with a short-term thermal energy storage system?*

As there are many different forms of demand-side management and a wide variety of ATES systems, some more focus is needed. The scope is narrowed by dividing this goal into two more specific sub-questions. The first sub-question is related changes that would have to be made to the conventional ATES system in order to allow for DSM. The design and operation of an ATES system has to be altered in order to create the necessary flexibility to regulate operation based on the availability of electricity. This research attempts to achieve this by adding a short-term thermal storage system that will allow operation and demand to be decoupled up to a certain extent. Because this thermal storage then changes the design and operation of the system, the effects of this have to be estimated. Therefore, the first sub-question that needs to be answered is:

What are the optimal conditions, design parameters and operating strategies to incorporate short-term thermal storage into conventional ATES systems and how does this affect the costs and CO_2 *emission of the end-user?*

This should give us an idea of what this new ATES system should look like. Next, it is important to figure out how to best operate these systems in relation to the electricity market. Therefore, the second sub-question is:

What is the best strategy to operate ATES systems that have short-term thermal storage in response to variations in the price and availability of electricity and how does this affect the costs and CO_2 *emissions of the end-user?*

In order to answer these questions, a model will be build based on the measured thermal demand and system operation of several existing cases using conventional ATES systems. The input data will be used to simulate an existing system and estimate the effects of the proposed changes. By making iterative changes to input parameters like storage size and operating strategies it is possible to propose new system design and operating parameters. The Net Present Value (NPV) will be used to determine whether a change has improved the concept economically. Yearly CO_2 emission will serve as a proxy for the climate impact of the system. Details about the approach, assumptions and design behind the model will be further explained in the methodology chapter. The end results of the model will be the Net Present Value and change in yearly CO_2 emissions that result directly from the proposed changes in design and operating regime. Something that is not part of this research is the effects of the proposed changes on the electricity markets and energy system as a whole. It is assumed, based on the studied literature, that demand side management has a positive effect on the integration of intermittent renewables. The motivation behind this study is to conceptualize and model a new idea and see if this could be a competitive concept under current market conditions. The resulting effects leading from significant adoption rates of this new concept could be an interesting topic for further research.

2

Relevance of this research

2.1 Scientific relevance

The direct scientific relevance of this research is the addition of ATES systems to the body of literature on DSM applications. This paper could be considered as an explorative effort, attempting to show the potential of DSM in this context. Significant research has been done on DSM and ATES systems separately. However, after looking through multiple search queues, no research has been found that combined the addition of thermal storage to demand side management in the context of ATES systems. If the results turn out positive, further research could be justified into this topic leading to an extension of the body of knowledge in this field.

In terms of methodology, this paper takes an empirical and data-driven modelling approach to ATES system design and operation within a DSM context. The reasoning behind this approach is the fact that the thermal dynamics of a building are very complex and hard to model accurately in the hour by hour level of detail required in this case. The chosen method of empirical data based modelling is not new in itself but its application could be considered innovative, or at least uncommon, in this context. Other papers that apply modelling in a DSM context do already apply a broad range of modelling techniques, some common methods are:

- system/technology based modelling
- agent based modelling
- neural network based modelling
- scenario based modelling

Even though these modelling approaches are unique and have very different applications, they are all based on detailed knowledge or assumptions on the states and interactions between the different system elements. The data-driven approach is different in the sense that empirical data substitutes the need for a complete understanding of the interactions and system states. This approach is commonly used in situations where complexity or lack of knowledge favours a more empirical approach. The thermal dynamics and the effects of energy efficiency measures see common use of this approach for the aforementioned reasons of complex system dynamics. The difficulty with a data-driven approach is in acquiring accurate data on the time intervals required to run a model on. Even though most building operators measure their heating and cooling demand, very rarely is this done on hourly intervals for long periods of time (Hong et al. 2014). Even if the data is being monitored, most building owners would not want this privacy sensitive data published. The way around this issue is usually to do experiments. (Artač et al. 2013) resorted to building two complete office spaces solely to collect data for their study on energy saving measures.

However, ATES systems in The Netherlands have one distinct feature that greatly increases the amount of data that is gathered on their operation. Dutch owners of ATES systems have a legal obligation to monitor and report the subsurface operations on a detailed level to the provincial government. This legal obligation makes for much more detailed measuring data to be available, opening up a new avenue of research. Furthermore, this study is being done in collaboration with engineering and consulting company IF Technology. This collaboration allows access to a wide variety of ATES systems and their monitoring data. These factors combined make it possible for this study to take a unique approach and therefore also add a new methodology to the existing the body of literature on the topic

2.2 Societal relevance

This research attempts to redesign ATES systems in order to increase the performance and thereby reducing costs and CO2 emissions of the end-user. There are two distinct societal benefits that would result from this redesign. The first is related to the reduction in CO_2 emissions resulting from heating and cooling of buildings. The second results from demand-side management and the counteracting variations in the electricity markets.

The reduction of CO_2 emissions caused by this new ATES system comes from a direct and an indirect effect. The direct effect results from the changes that an increase in ATES performance has on the CO_2 emission of the end-user. For instance, if more energy could be extracted from an existing ATES system, the peak-demand boiler would have to be used less, thus resulting directly in less natural gas use and lower CO_2 emissions. Next to this direct reduction, there is also a potential indirect reduction in CO_2 emission. The indirect effect is related to the fact that increasing performance and reducing costs makes the ATES system a more competitive technology. If the redesign causes at least one end-user to adopt the more efficient ATES system over the less efficient conventional technologies, CO_2 emission is indirectly reduced. However, the extent and impact of this indirect effect is not studied in this paper.

The second societal benefit is related to DSM and grid-stability. As mentioned in the previous chapter, a volatile electricity market has negative effects on society. Therefore, a technology or idea that negates this effect while still allowing for the adoption of intermittent renewable has significant societal relevance.

3

Methodology

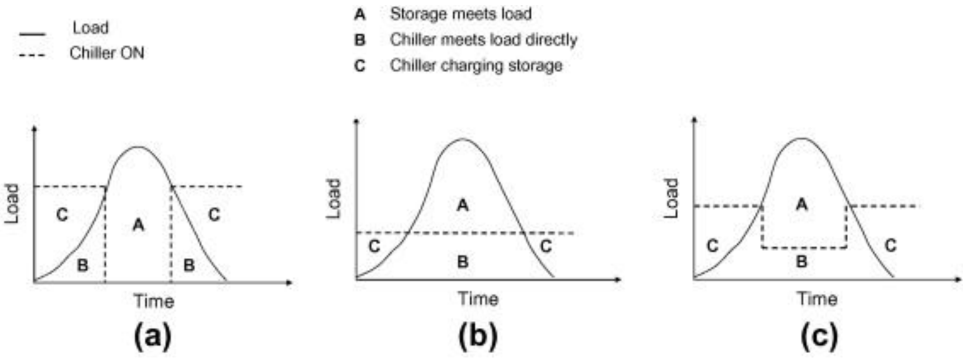
3.1 Research objectives and design

The primary goal of this study is to conceptualize and optimize a new ATES concept that is more beneficial for the end-user. The secondary goal is to achieve the primary goal while at the same time lowering electrical peak-load and reducing grid imbalance The approach to achieving these goals consists of two parts: The first part aims at creating flexibility in the operation of ATES systems by adding a short-term thermal energy storage and redesigning the system accordingly. The second part aims at developing strategies to make use of this flexibility and react to price changes in the electricity market. These two parts have their own sub-objectives explained further in separate paragraphs below.

3.1.1 Short term thermal energy storage

The first part of this research aims to find out how best to incorporate short-term thermal storage into the ATES concept. To do so, several important questions need to be answered. Firstly, there are different mediums available that could store this thermal energy like water, concrete or phase change materials. Based on the parameters set by the ATES system, the end-user and contextual factors, a decision has to be made on which to go for in this context. Secondly, there are different strategies in implementing a storage system which affect the system dimensions and operating range. The effects of different storage strategies have to be tested for different end-users. Figure 7 below shows an example of three different storage strategies in a cold storage system. Note that the whole range of intermediate steps in-between these strategies are also possible.

Figure 7: Schematic of different storage strategies in a cold storage system source:



And the thirdly there are important interactions and secondary effects that need to be identified and quantified. For instance; Different users have different thermal demand profiles. The shape of this profile directly affects the potential of this concept. i.e. if there is hardly any peak in the electrical load there is also less potential for peak-load reduction. This means that certain types of end-users will benefit more from this concept than others, these have to be identified. Another important interaction is related to the fact that most system components have the highest efficiency in full-load. Depending on the strategy, the system will run more hours in full-load, thereby changing the overall system efficiency. For the purpose of this research it is important to identify these and other important effects and attempt to quantify these as far as possible. Where these turn out to be too complex, assumptions will have to be made and further research will be recommended.

The overall objective of this part is to find the best way to implement short-term thermal storage into the ATES design. This comes down to finding an optimal balance in all the above mentioned parameters and strategies. The end-result of this optimization would be an estimation of what the system should look like in a best-case scenario for different end-users. This would look something like: The system has most potential if you: use this storage medium, apply this storage strategy, for these end-users, under these secondary conditions etc… In doing so these changes would cause the following effects: of x% change in investment, x% change in yearly energy costs and x% change in yearly CO_2 emissions.

3.1.2 Demand-side management

The interaction of the ATES system with the electricity market could be seen as an element of the system optimization mentioned above, and to a degree it is. However, it is by far the most complex interaction and also requires a different approach. In order to limit the complexity of the optimization, the interaction of the ATES system with the electricity markets is treated separately. Within the interaction between an ATES system and the electricity markets there are two distinctly different sets of challenges. The first is related to the technical changes that are required for this concept to work. In other words, how do we need to adapt the system to be able to interact with this market? For instance: Benefitting from price changes on the electricity markets requires very fast and precise reactions in demand, ideally under a minute. A heat pump, especially the screw compressor type used in ATES systems, needs several minutes to ramp up and down without damaging itself. These and other technical challenges require adaptations or put limitations on the applicability of this concept.

The second, and perhaps largest, challenge is the organizational challenge. The electricity markets are heavily regulated and trading on them is not without risk. Since the primary function of an ATES system is to provide heating and cooling, large risks and organizational burden could form a barrier to implementation. To illustrate this, without going into too much detail; One of the main organizational challenges is related to the imbalance regulatory system. All suppliers and buyers on the electricity markets are legally obliged to withdraw or supply the exact amount they respectively bought or sold. If this is not the case, imbalance is caused in the electricity grid and a fine is incurred by the actor that caused it. The height of this fine is directly related the imbalance-price necessary to compensate the imbalance. These prices commonly go up to €400/MWh, a lot if you consider the spot market prices commonly range between €30 - €70/MWh. (TenneT 2005) Figure 8 below shows a month of imbalance market prices in The Netherlands during July 2014. Also note the negative prices that occur quite regularly, meaning money can be earned by withdrawing additional electricity.

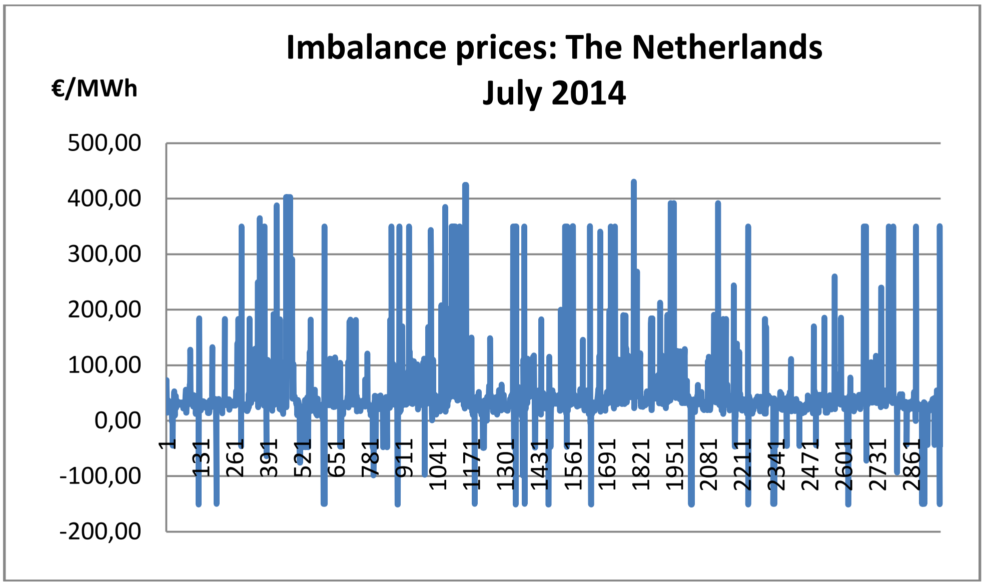


Figure 8: Imbalance prices Netherlands July 2014. Source:(TenneT 2015)

The direct effect of this system is that compensating grid-imbalance with an ATES system can have significant financial benefits. Either power bought for spot market prices (€30 - €70/MWh) can be sold for imbalance market prices (up to €400/MWh), or additional power can be bought for negative prices. However, there are risks attached to this as well. Causing imbalance at the wrong times can lead to paying a lot more for the same electricity. Because the electricity has to be bought in advance on the spot market, this indirectly means that the heating and cooling loads now have to be predicted. The short term thermal storage system is important in this context for two reasons. Firstly, a storage system allows the ATES system to be switched on or off when the imbalance market is at its extremes while avoiding over- or under heating a building. But more importantly, it can compensate for the inaccuracy in the thermal demand predictions, thus, reducing the risk of causing fines. However, doing so requires the storage system to be neither empty nor full most of the time to make sure surplus and deficit are acceptable. This in turn means redefining the dimensions and operating strategies once again. With every step the complexity in the design and operation of this already complex system increases.

The reason why the benefits for the end-user play such a central role in this research can be better understood now. For if there is no significant gain for the end-user, convincing owners of adopting such a complex alteration of their heating and cooling systems will be a tall order. It is the goal in this second part to give an indication of these benefits in order to assess whether this concept has a chance of success. The first step is to conceptualize what such a system might look like based on the technical adaptations required. Based on that concept an estimation can be made of the potential costs, benefits and CO_2 emissions of this new system. If positive, these results can then be used to warrant further research and/or pilot projects.

3.2 Theoretical framework

Due to the nature and complexity of this topic a very broad theoretical basis is needed as a backbone for the model. However, the part of theoretical framework that supports the model loses its meaning when presented separate from the actual model. In order to keep the context of the information intact, that part of theoretical framework is incorporated in chapter 4 explaining the structure of the model. The theoretical framework behind the modelling approach itself as well as some other essential concepts taken from literature are presented in the paragraph below.

3.2.1 Data-driven modelling

A study done by Solomatine and Ostfeld (2008) into data-driven models used in hydrology described Data-driven modelling (DDM) as:

“Data-driven modelling (DDM) is based on the analysis of the data characterizing the system under study. A model can then be defined on the basis of connections between the system state variables (input, internal and output variables) with only a limited number of assumptions about the “physical” behaviour of the system.” (Solomatine and Ostfeld, 2008)

The characteristic of using empirical data as the basis of the model is where the commonality between data-driven models ends. The applications of DDM are broad and range from signal analysis in health monitoring (Cortial et al. 2001), to tracking the path of wildfires (Douglas et al. December 2006) to gas-turbine behaviour (Wu et al. 2014). The closest relation to this study found in literature is a study done by (Zhang et al. 2015) looking into minimizing pump operating and maintenance cost using a data-driven approach. The commonality is that both studies aim to improve the cost-effectiveness of energy-intensive equipment. The difference is that the complexity in the study of (Zhang et al. 2015) stems from hydraulic effects in a multiple-pump system and in this study from the thermal effects in a building. However, the idea to use iterative application of algorithms to solve the multiple variable equations as used by (Zhang et al. 2015) is innovative and seems to work well. The same approach will be used to solve the similar cost-optimisation challenge in this study

3.2.2 Thermal storage technology

An important theoretical consideration is the choice of thermal storage system. To avoid adding an additional layer of complexity to the proposed model, the choice of storage technology is made based on a literature review. Several comparative studies have been consulted in order to substantiate the choice. Of most assistance in this aspect of the study was the book by (Dincer, Rosen 2010) comparing all aspects of different technologies and storage mediums in great detail. The authors of the book argued that when designing a centralized thermal energy storage system, sensible heat storage using water is commonly the cheapest and safest option. They recommend considering other systems when the requirements exceed the operating range of sensible heat storage in water. There are several reasons given for this.

- Water is stable, cheap, non-toxic and readily available.
- The technology of storing and transporting water is mature, common and cheap technology.
- Water has one of the highest thermal capacities of all common substances

In addition to this there are several benefits of using water storage specifically in the context of this research derived from technology descriptions given by (Dincer, Rosen 2010)

- Water as opposed to phase change materials can store both cold and heat in the same system. A benefit in ATES systems as those are generally designed to provide both heating and cooling
- Using the most mature thermal storage technology avoids implementing multiple innovative concepts at once

The recommendation of adopting sensible heat storage in water was not so clearly stated by other authors. However, Kalaiselvam et al. (2014) also stated in their book on the same topic that sensible heat storage in water was by far the most used technology, adding that they expected this not to change in the near future.

Another important aspect retrieved from literature are the costs of thermal storage systems. A study done by (Mangold, Schmidt 2007) compared the actual costs of TES systems of varying size in Germany. This data is used directly to assess the costs of a

TES system per M^3. A graph of this relation can be seen in figure 9 below. This graph is used as an input in the modelling process.

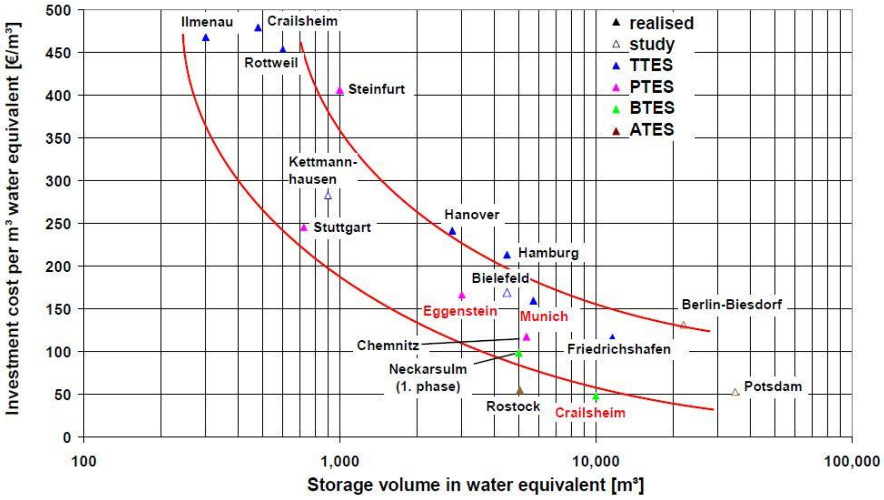


Figure 9: Investment costs of TES systems of varying size source: (Mangold, Schmidt 2007)

3.2.3 Heat pumps, thermal storage and predictive control

A descriptive problem occurs when looking for literature combining ATES systems with short-term thermal storage. This is partly because ATES (Aquifer Thermal Energy Storage) already has the words thermal, energy and storage in the acronym. Searching for short-term storage in this context just returns papers referring to papers that have the acronym ATES written out. However, a lot of studies have been done, and found, that combine a heat pump with short-term thermal storage. Even though the ATES system is more than just a heat pump, lessons can be learned from studies combining heat pumps and thermal storage nonetheless.

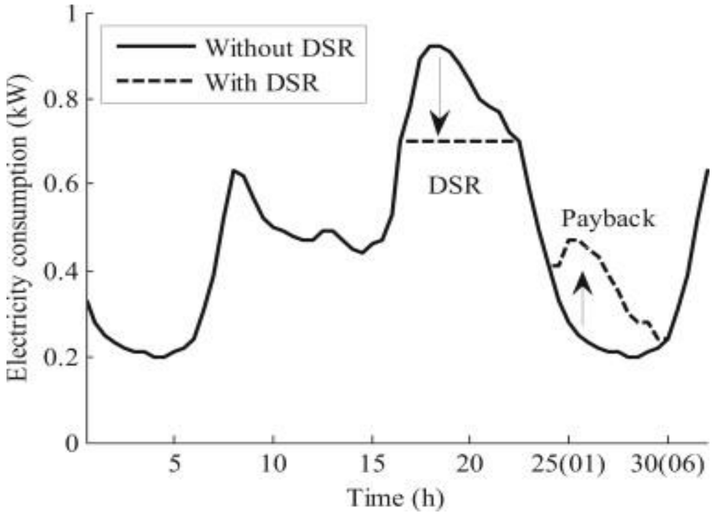
Studies into both domestic (Arteconi et al. 2013, Kobus et al. 2015, Reynders et al. 2013) and commercial (Benli 2011, Hewitt 2012, Ellerbrok 2014) applications of heat pumps combined with thermal storage found substantial benefits in combining the two. Some of the most prominently mentioned were the reduced on/off cycling, lower peak-demand and use of cheaper off-peak electricity. Hewitt (2012) looked into this topic from a broader DSM approach and concluded there was great potential in compensating the variation of intermittent renewables. However, he also mentioned the relatively slow reaction times of heat pumps cause difficulty when attempting to react to the quick price changes that occur on current markets. His solution was a more predictive approach where the heat pump load is strategically predicted based on what is called model predictive control. Model predictive control is a data-driven approach to controlling a process. The recommendation of using such a system state control scheme will be taken into account in the development of the model.

3.2.4 DSM and risk

Another relevant topic that has significant theoretical background in literature is modelling of demand-side management. More specifically relevant for the purpose of building this model is the literature on key processes identified in real-world applications of DSM.

A study done by Eduardo et al. (2015) specifically mentions the challenges embedded in the interaction between imbalance markets and DSM. Especially the risk of creating imbalance on the wrong moment is highlighted. One effect, called the payback effect by Eduardo et al. (2015), is specifically linked to the type of thermal systems under study in this paper. The payback effect occurs for applications that can be curtailed but require that energy to be paid back at a later time, usually soon after the curtailment has occurred. This is true for most thermal applications of DSM as well as variable charging of electric cars and household appliances like washing machines. The process is shown in figure 10 below (DSR stands for Demand-Side Response)

Figure 10: The payback effect source: (Eduardo et al. 2015)



Eduardo et al. (2015) concluded the payback effect can become an issue in the case of active curtailment. Active curtailment is real-time and unplanned reaction of systems to imbalance on the electricity markets. The problem is that if the curtailment is unscheduled, the electricity required for the payback is also unscheduled. This means that the imbalance resolved during curtailment is created again sometime later. This exposes the end-user to the risk of paying more for the imbalance caused by the payback then was earned during the curtailment. However, this is a general and purely theoretical argumentation on the effects of payback effect. In a thermal energy system with short-term storage, the level of flexibility in the payback effect is directly related to the size of the storage. A more relevant question is how the costs of the additional storage relate to the benefits of reducing the acute need for energy payback. The proposed model will simulate this interaction to see if a positive end result can be achieved.

3.3 Input data

A key element in the methodology of this study is the availability and quality of the input data. As mentioned earlier the subsurface effects of ATES systems are very strictly monitored, logged and reported. This data consists of m^3 of water extracted and injected and the temperatures of those flows. These two combined can be used to calculate the energy delivered to the building by the ATES system at any one time. However, what we need is the total thermal demand of the building. In many cases there are also Gas Fired Boilers (GFB) or Compression Coolers (CC) installed. The problem is that, since these are not part of the obligated reporting of an ATES system, these are in many cases not monitored as actively as the subsurface components. This limits the suitable systems from which data can be acquired to the more limited set of end-users that do apply complete monitoring schemes. Additionally, the suitable monitoring data should span a period of at least a year to ensure seasonal variations are accounted for. From the 100+ systems in the monitoring database of IF Technology, 5 were found to have monitoring data of all thermal systems, measured in intervals of one hour or shorter in complete sets of at least a year. Due to privacy concerns the actual names and locations of these buildings have been redacted for the purpose of this study. The buildings will be referred to by their type and size. The following buildings have been selected for use in the study:

- Small office – 9.000 m^2
- Medium office – 60.000 m^2
- Large office – 120.000 m^2
- Small hospital – (sq m unknown)
- Large trainstation (sq m unknown)

The selected buildings and related ATES systems constitute a good cross-section of the commercial end-user ATES systems. The only obvious missing group are the residential buildings. These end-users were part of the database but the monitoring of those systems was found to be less extensive then their commercial counterparts. Therefore it was not possible to include this user group in this study. An example of a section of data exported from the monitoring database can be seen in figure 11 below

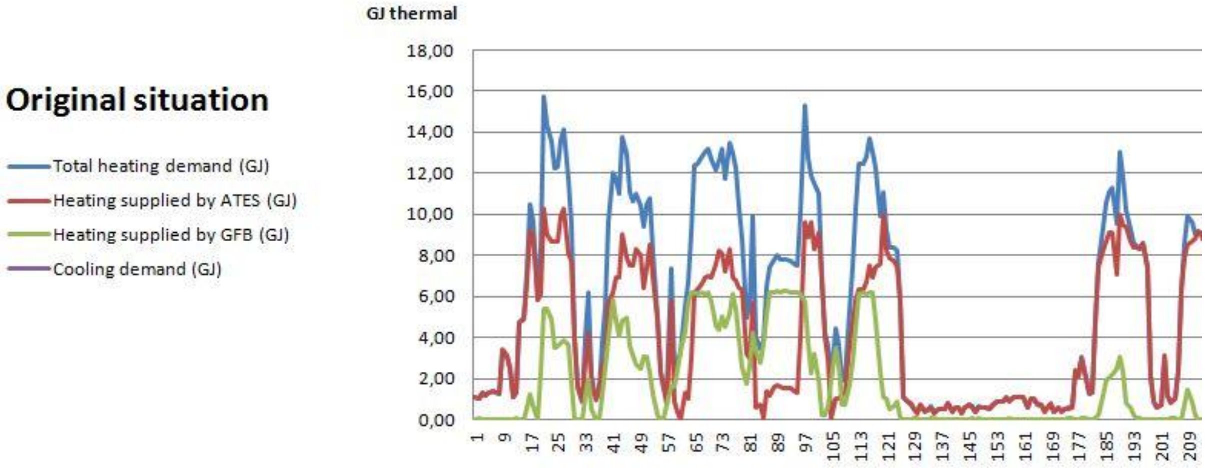


Figure 11: One week of thermal data for the Medium office in January

3.4 Assumptions

Not all the required information in this research can be obtained from literature or monitoring data within the scope of this research. Several assumptions are required to turn the limited information into a working model. The most important assumptions are listed directly below. Assumptions behind specific choices made in the modeling process are described in the next chapter with the rest of the model.

3.4.1 Data accuracy

The first assumption made is that the information gained from the monitoring program is accurate and complete. Because this data comes from a third party, no guarantees can be given as to accuracy of the data. To at least partly mitigate this issue some checks have been built into the data selection process. The first check was done by a visual scan for obvious errors like negative measurements and large gaps in the data. To catch less obvious errors, several additional checks were performed on the data itself. For example: The heating supplied by the GFB and the ATES have to add up to the total heating demand and the total number of data points have add up to 8760 in a year (if its hourly data). And as a final check the gas and electricity use were put alongside the data to see if the system operates within expected efficiency parameters. This was done to make sure the model was run on a healthy ATES system. This selection process narrowed the database down to 5 cases that seemed most accurate and met all the requirements. From this point on it is assumed that the data is an accurate representation of the operation of that specific system.

3.4.2 Flexibility of demand

The second assumption made is that the heating and cooling demand is not flexible. In reality, temperatures can vary within a certain band, making the thermal energy supply also somewhat flexible. But, because the relationship between the thermal energy supplied and the change in inside temperature is unknown, the thermal demand is assumed to be fixed. It is worthwhile to mention that this means the model underestimates the capabilities of the system in this respect.

3.4.3 Storage system dynamics

The third assumption is related to the thermal storage system. As mentioned earlier, the choice was made to focus on a sensible thermal storage system using water as a medium. These systems use a thermo-cline gradient to separate the hot and cold part of the storage system. The thermal energy losses that occur over the boundary layer inside this storage system are not modeled as accurately as they could be. Some literature was found on models focused specifically on this process (Furbo, Cabeza 2015, Votyakov, Bonanos 2014), but those were deemed too complex for the purpose of this study. The process was approximated by modeling the part of the buffer that actually stores the relevant thermal energy, i.e. the hot part if heating is stored, as a fictitious homogenous storage tank that changes in size as more or less energy is stored. In reality, convection, mixing and the higher thermal conductivity of the boundary layer compared to the outside wall means the losses are underestimated in this model. The degree to which this underestimation affects the result of this study is hard to predict. In the current model, thermal losses have little impact on the final result due to very low loss rates. Only if the internal losses are several times higher than the external losses can we expect it to significantly affect the feasibility of the concept. In order to avoid confusion with the word ‘storage’ that is both in Aquifer Thermal Energy Storage (ATES) and the Short-term thermal energy storage, the latter will from now on be called the buffer.

3.4.4 Predictive control

And finally, more of a challenge than an assumption; this research uses historical data to generate control strategies. A real-life application of this concept would need to make predictions of those variables into the future. Most notably, the thermal demand of the building will have to be estimated for at least 24 hours in advance. This can be done using weather predictions and historical data of the building in question. However, this will add another layer of complexity to the whole concept and the challenge of doing this in real-time should not be underestimated. Studying these kinds of system-control challenges are best done in conjunction with pilot projects or test-setups. It is assumed for the purpose of this study that it is possible to do so. How to do it exactly is an interesting topic for further research.

4

Model design

4.1 Model overview

The model used in this research is an iterative model where the control variables are manually altered by the user. The goal is to optimize the resulting Net Present Value using these control variables. An overview of the sub models, input variables and the relations between them can be seen in figure 12 below. In this paragraph an overview of the sub models and the interactions between them will be explained. The details of the inner workings of each sub model will be explained separately in the following paragraphs.

4.1.1 Reading guide

In order to read the schematics a reading guide is added. The sub models are shown as green blocks that have grey inputs and outputs. Within the sub models the different elements are coded by color.

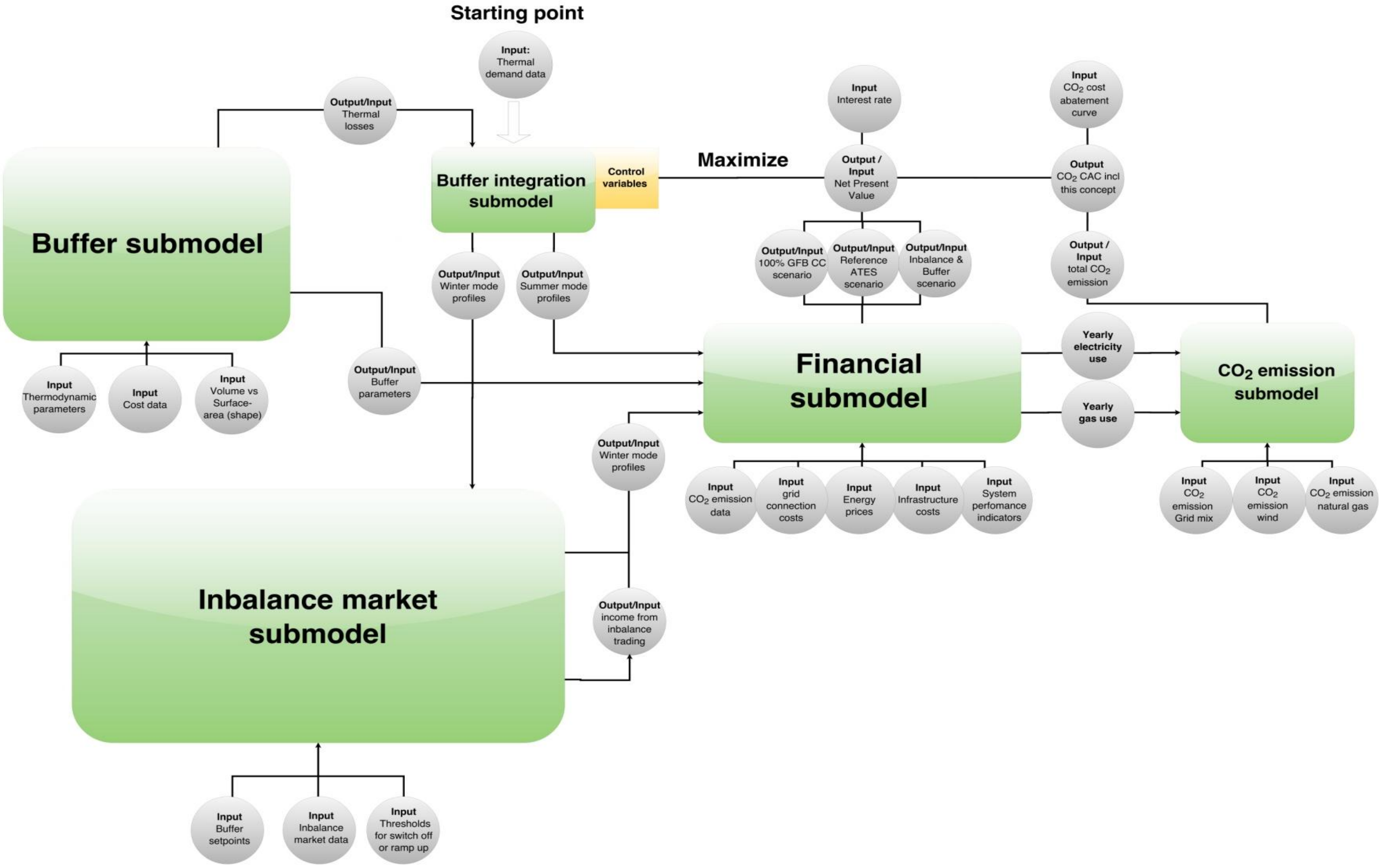
- The yellow bricks are inputs
- The grey bricks are internal system states
- The red bricks are outputs

As each sub model has several parallel processes, the best way to read the schematics is from the yellow blocks, through the grey blocks, towards the red blocks.

4.1.2 Model overview

Figure 12 below shows the complete schematic overview of the model. It is not meant to be understood as such but should serve as a reference to place the different sub models into context. Scan over it but do not spend too much time trying to understand it by itself.

Figure 12: Model overview



4.2 Sub models

4.2.1 Thermal demand profiles input

This element is not an actual sub model but since it is of particular importance it is treated separately. The thermal demand input can be found just under the starting point in the model overview schematic. The thermal demand profile input is the starting point of the model. The previously mentioned data-driven approach is based primarily on this data being available in the right format. Before the model can process the data, it has to meet the following requirements.

- Separate heating and cooling demand of the whole building in GJ
- Coverage of at least one year

- Measured in hourly or smaller intervals
- Split according to production methods if there are more than one
- Preferred but non-crucial information: Overall electricity use, working temperature of heating or cooling system, current energy prices, plans for renovation/expansion

After inputting the data in the correct format, the input section of the model performs some additional tasks on the dataset. The first step is to cut the dataset up in 24-hour sections, each starting at 23:00 each day. The reason for starting at 23:00 each day is that after this time, electricity prices drop off steeply in The Netherlands. Charging the thermal storage system for the next day is best started after 23:00, hence the sections run from 23:00 till 23:00 each day.

The next step is to determine when the system has to switch from ‘winter mode’ to ‘summer mode’ or vice versa. Because this entails switching the storage system from between heat and cold storage, only two switches per year are allowed to minimize thermal short-circuits. The process of determining when to do so is done by hand as the boundaries between warm and cool seasons are not clearly defined. As a rule of thumb in this selection the following strategy is used: Periods where heating and cooling dominant days are alternating are defined as heating dominant periods. This is because heating requires much more electricity and is therefore best done in off-peak hours as long as possible.

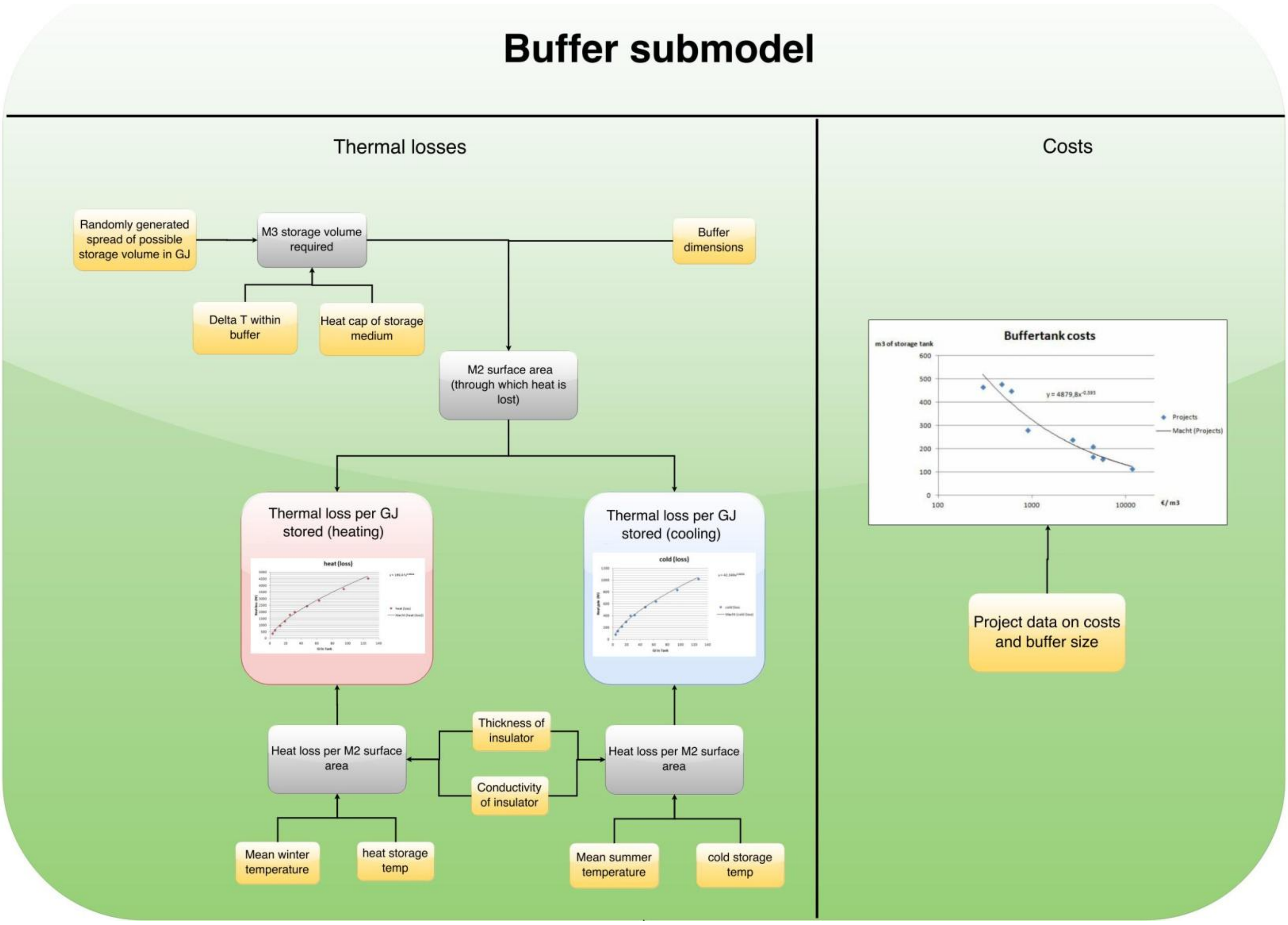
The end-result of the data-input process is a whole year worth of 24-hour sections of thermal demand in GJ starting at 23:00 each day separated in ‘winter-’ and ‘summer mode’. An example of such a 24-hour section is shown in figure 13 below. These 24-hour sections serve as an input to the buffer integration sub-model.

Figure 13: Example of a 24-hour section of thermal demand data.

4.2.2 Buffer sub-model

There are two key characteristics of the buffer system that are incorporated in the model: Thermal loss per GJ stored and the investment costs per m^3 of buffer tank. The thermal loss per GJ stored is estimated based on mean temperatures, average insulator values and the surface area of the tank. By calculating the thermal losses for several storage sizes, the relation between GJ stored and thermal loss was determined. The investment costs per m^3 of storage tank are estimated based on reported project costs of existing buffer tanks. Figure 14 below shows the interactions and the resulting outputs.

Figure 14: Buffer sub-model



By applying a regression analysis on the results, relationships between the parameters in question can be estimated. This resulted in the following relationship between thermal loss for and the amount of thermal energy stored:

Thermal loss
Phl = *Heat loss (W)*
Pcl = *Cold loss (W)*
Qh = *Heat stored (GJ)*
Qc = *Cold stored (GJ)*

$$Phl = 189{,}47 * Qh^{0{,}6644}$$
$$Pcl = 42{,}349 * Qc^{0{,}6636}$$

And the relation between storage tank size and its investment costs:

Investment cost
Ci = *Investment cost (€)*
Vst = *Storage tank size* (m^3)

$$Ci = 4879{,}8 * Vst^{-0{,}393}$$

4.2.3 Buffer integration sub-model

General description

The buffer integration sub-model is where the buffer is integrated into the input data from an existing ATES system. There are several control variables in this part of the process that have an important role in determining the overall system behaviour and performance. The first control variable set in the model is the installed capacity of the ATES system. This can be reduced because the buffer can supply part of the peak demand that would otherwise have to be supplied by the ATES system. However, there is a trade-off. At some point the system becomes too small to supply sufficient thermal energy over 24 hours. This forces peak load systems like the GFB and CC to compensate. Since these peak load systems have higher marginal costs, this also increases the yearly energy costs of operating the system. The goal is to find the optimal point in this dynamic. The second control variable is the size of the buffer itself. Increasing the size of the buffer system means more of the operation can be shifted to off-peak hours. The benefits of this shift are counteracted by the fact that the costs of the buffer also increase with size. The interaction between the benefits of shifting demand and the costs of the buffer system also has an optimal point. It is important to note that these two optimisation parameters also affect each other. For instance, if the ATES system becomes smaller, less energy can be stored during off-peak hours; thus, a smaller buffer is required to store that energy. The third control variable is the max power of the CC. The CC is not a standard part of the ATES system concept. It is added in the model to supply peak-cooling, much in the same way the GFB is used. The reason for its addition was that a few peaks in cooling demand determined the dimensions of the whole system. Adding the CC allowed a more optimal system balance. The trade-off is that a CC is cheaper per kW to install, however it also uses about 10 times more electricity than an ATES system (COP of 4 vs a COP of 40).

The sub-model runs differently for the winter and summer mode segments. The main reason behind this is the very high COP of the cooling cycle of an ATES system. A high COP means the system uses relatively little electricity. Hence, switching cooling operations from peak to off-peak hours also has relatively little effect on the overall electricity costs. The two processes are linked because cooling and heating is stored in the same buffer, but at different times in the year. This means that the same system limitations exist for both operations in terms of m^3 storage capacity. The difference between heat and cold storage is the seasonal and storage temperatures. This is where the parameters calculated in the earlier buffer sub-module come in.

Winter mode

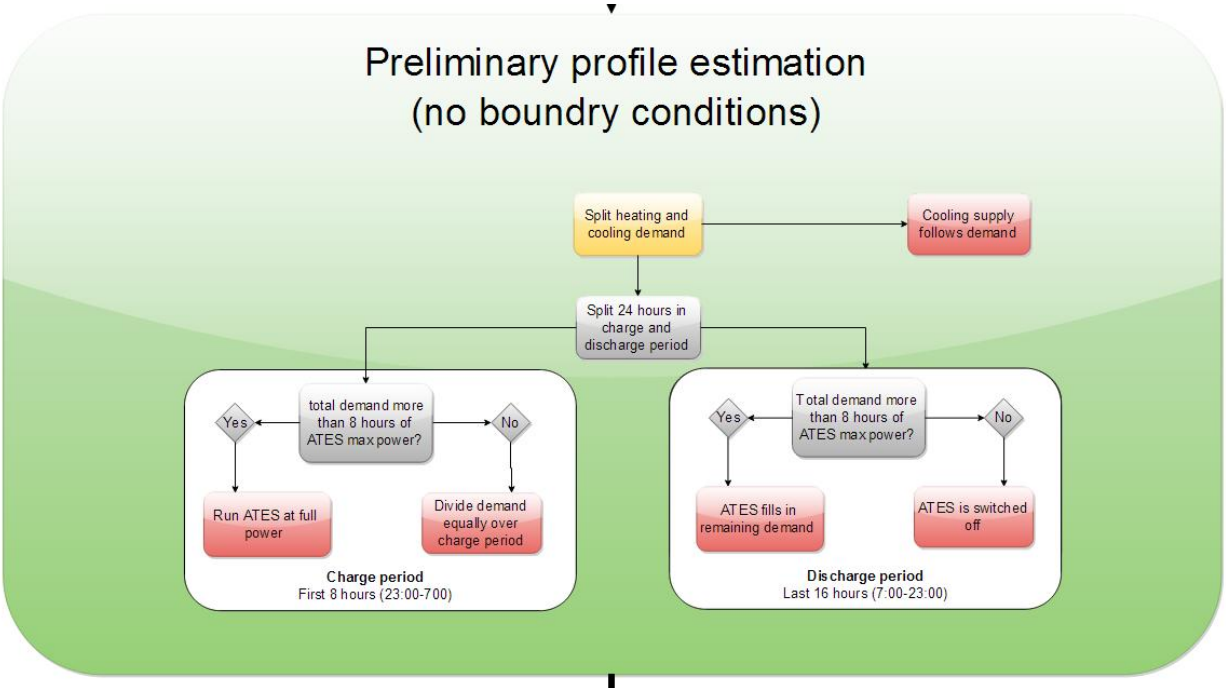
Winter mode is where the buffer stores heat. This part of the model only applies to the segments of thermal demand data that have been designated as operating in winter mode. The winter mode section works in two separate steps. The first step is a preliminary estimation of the new system without taking the boundary conditions of the buffer into account. This step serves as a framework upon which later alterations can be made.

Winter mode – preliminary profile estimation

When the 24 hour segments enter this part of the model, the heating demand is separated from the cooling demand. As there is no possibility to store cooling during this period, the system has to deliver the cooling demand as it occurs. The heating demand over the 24 hours is further divided in a charge period and a discharge period. The charge period lasts 8 hours from 23:00 to 7:00 each day corresponding with the off-peak electricity period. The discharge period consists of the remaining 16 hours, lasting from 7:00-23:00.

The charge period is where the model attempts to charge the complete demand of the 24 hour segment into the buffer. If that is possible it charges the buffer until the amount of the discharge period is loaded in the buffer. If the demand is too large then the ATES system runs at full power during the charge period, loading as much as possible into the buffer. During the discharge period, the ATES system fills in the remaining demand if there is any, and up to the limits of its capacity. The different steps involved in this process are visible in figure 15 below.

Figure 15:
Preliminary profile estimation



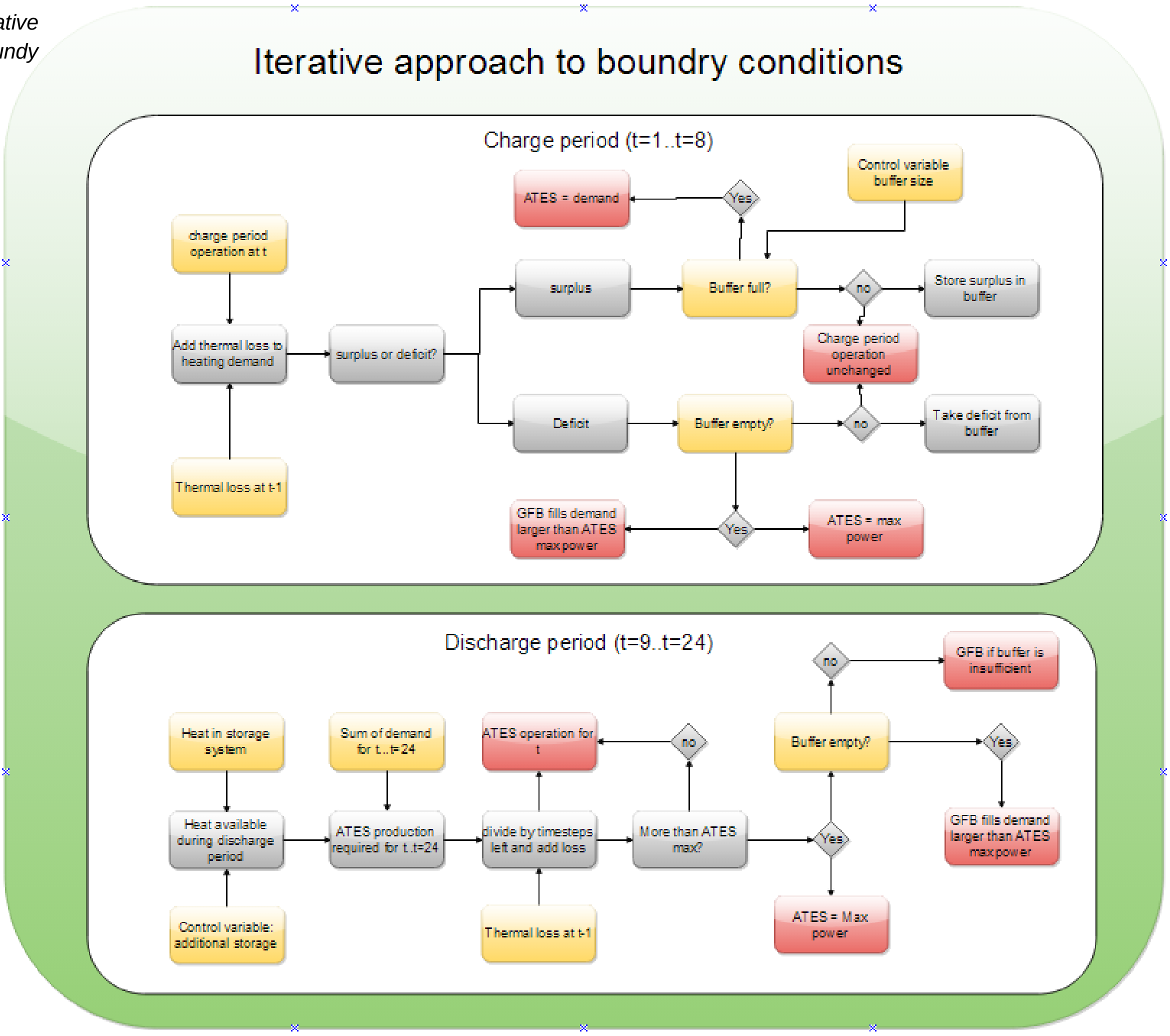
These profiles are called preliminary because there are boundary conditions that are not taken into account. The most obvious one is that the storage capacity of the buffer is limited. Meaning that at some point it's full and the system has to stop charging and compensate elsewhere. Another boundary condition is that the storage amount can't be negative. This happens when the overall demand is higher than what can be supplied over 24 hours. But also when there is a strong negative slope in the demand curve during the discharge period. The negative slope causes a deficit to occur before a surplus, pushing the storage into the negative and charging it back to 0 in the final few hours. This can be compensated by the GFB but that is inefficient when the ATES system is not running at full power. To avoid these inefficiencies caused by averaging demand, an iterative optimisation was added that uses the preliminary profile as a basis.

Winter mode – boundary conditions

The iterative section looks at each time-step separately in order to optimise the system within the boundary conditions. Charge- and discharge periods are treated separately because they have different goals and therefore have to be optimised differently. The charge period starts out with the preliminary profile. For each time step the thermal loss that occurred in the buffer in the previous time step is added. After that the model checks whether there is a surplus or a deficit in thermal energy production versus demand. If there is surplus while the buffer is full, the operation is altered from the preliminary profile and production for that time step is made equal to demand. Similarly, if there is a deficit while buffer is empty, the ATES is set to max power (if it wasn't already) and the GFB is set to make up the difference. If neither is the case, the preliminary profile is followed for that time step.

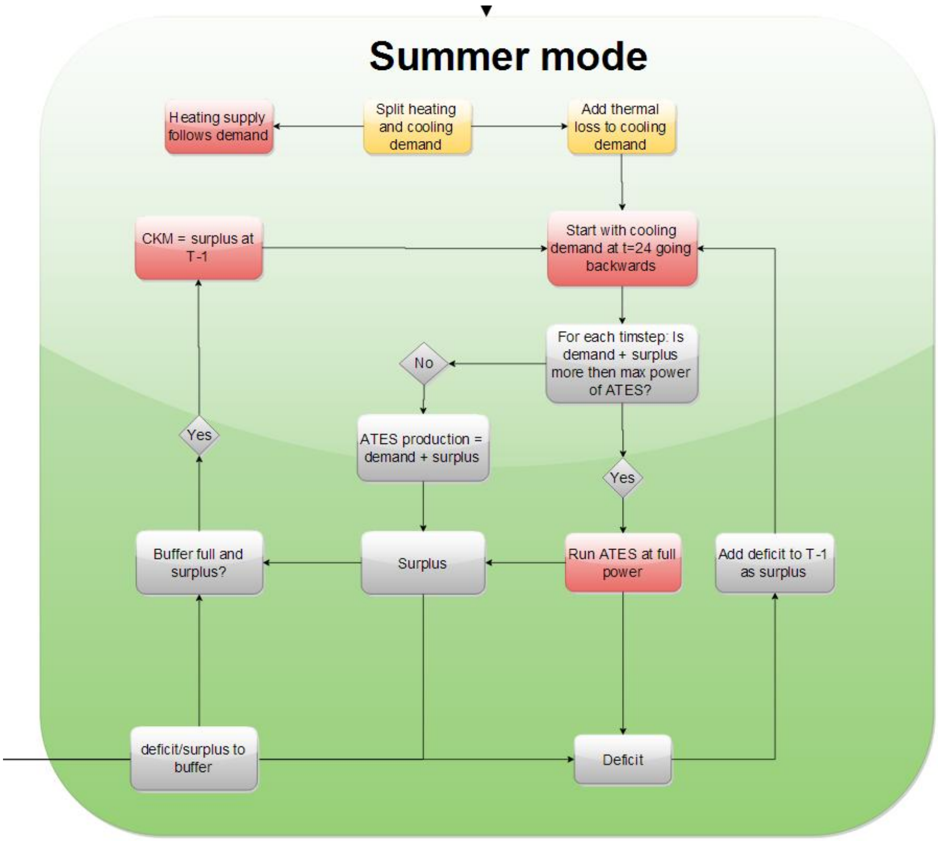
The discharge period is different because the aim is not to charge as much as possible but to use the charged amount as well as possible. Instead of averaging the use of the stored energy over the whole period it is now assessed per time step how much the ATES system should do and how much should be drawn from the storage. In order to create some additional space in the system, an additional control variable has been added. Instead of ending the 24 hour section with no energy left in the buffer, the goal is now to end with some spare energy in the storage. This aim-point is set in the control variable 'additional storage'. This strategy proved effective for several reasons; the first is that the additional storage reduces the 'negative slope effect' mentioned earlier by essentially setting a higher zero-line that can be crossed if necessary. The second reason this strategy is beneficial has to do with the imbalance market trading. The additional storage makes reacting to shortage on the electricity market easier. Thirdly, from a modelling perspective it's beneficial to avoid problems that occur when an absolute 0 is the target of an iterative process. An overview of this iterative part of the sub-model can be seen in figure 16 below.

Figure 16: Iterative approach to boundy conditions



Summer mode

The summer mode operation differs from winter mode in the sense that storing thermal energy is only done if necessary. Because storage has to happen before it is needed the 24-hour segments are run backwards. For each step the model checks if the demand can be supplied directly by the ATES system. If this is not the case, the model runs the ATES system at full power and adds a ‘deficit’ to the time step before. This deficit is an additional demand that is added to that time step’s demand. If this is again too much for that time-step, the deficit is carried backwards. The deficit is then generated as surplus and added to the buffer. Only when the buffer is full is the CC used



4.2.4 Imbalance sub-model

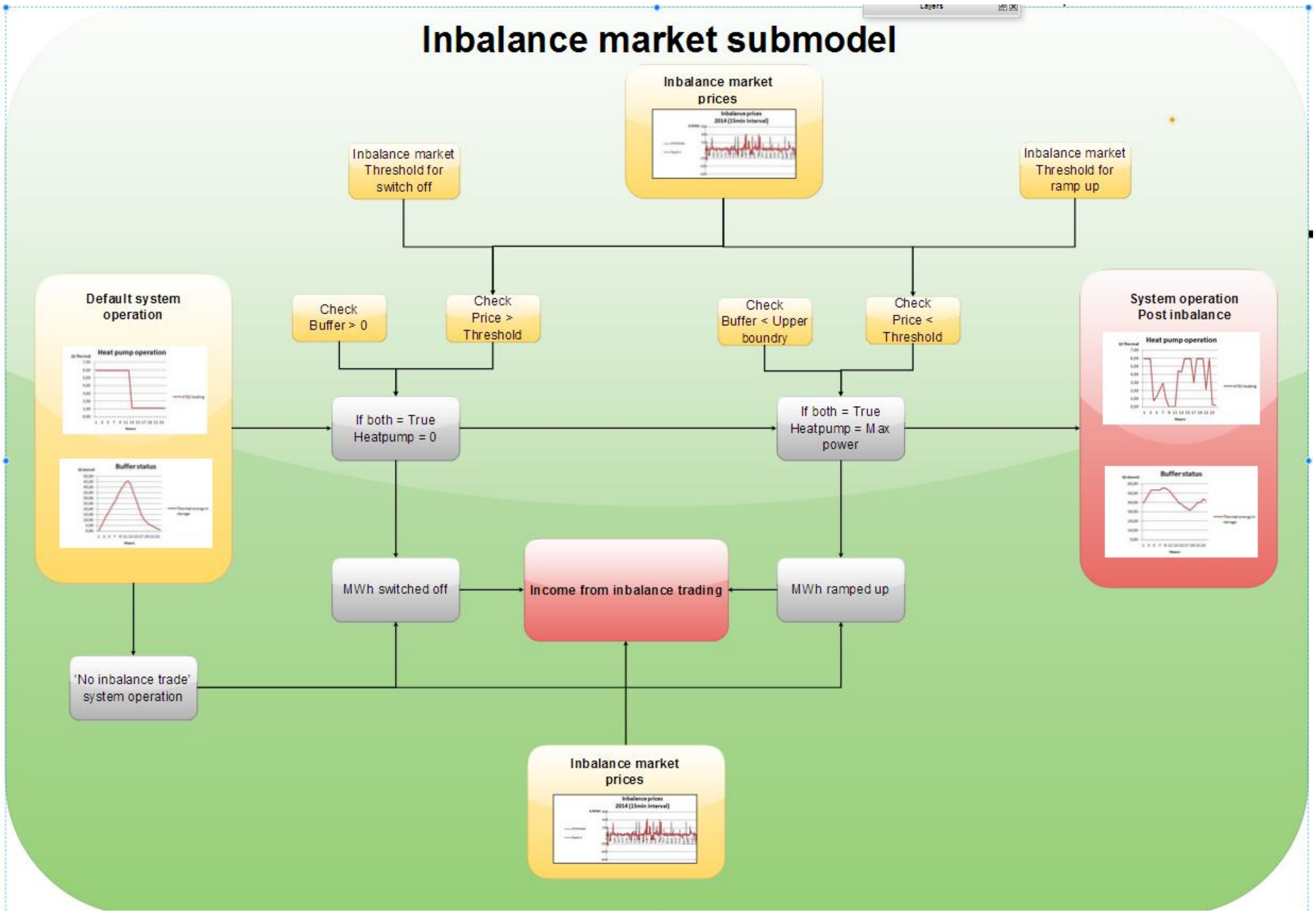
The imbalance market is the electricity market where TSOs offer real time prices for balancing out a deficit or surplus of electricity in the grid. These prices are sent out by the TSO every minute. However, the prices are averaged out and charged over 15 minutes, meaning price fluctuation occur in 15-minute blocks. Because the model is built on hourly time intervals this section’s first step is to break down the model in 15 minute time steps. In the end these will be added back up to hourly data values.

There are two important control variables in this part of the model. They are called ramp-up threshold and switch-off threshold. What these do is determine thresholds in the imbalance price above which the ATES system reacts. Lowering these thresholds causes the system the react more often and increases the earnings. The trade-off is that it also pushes the system out of balance, increasing inefficiency. In order to avoid reacting during inconvenient times a secondary check on the buffer state is added. This means that the system will only turn off when there is some energy in the buffer and only ramp up if the buffer is not full. A case can be made that switching to the GFB is acceptable as there are not many electrical applications that can switch to fossil fuel so easily. The effects of this can be simulated by setting the minimum buffer status check to 0. Doing this, in general, decreases costs while increasing the direct CO_2 emissions. Where this variable balances out is subjective and an interesting topic of debate. This interaction will come back in the discussion chapter

Figure 17 below shows a schematic of the decision tree used to operate the system in relation to the imbalance market. There is one important mechanism in this sub-model that is not directly visible in this schematic however. One of the key challenges facing DSM in heating and cooling applications is the 'payback effect' mentioned earlier. This concept entails that compensating after a demand-side response has to be done with care to avoid unnecessary costs. There are two distinct ways this can be done: The best way to compensate for a response is on the spot-market for the next day. This way the imbalance market is avoided altogether. However waiting this long is not always possible and switching to the GFB should be avoided if possible. However, the real question is; at what costs should this be avoided? To find out, this interaction was added to the model by setting a price-threshold at which the system attempts to restore balance.

The main indicator of 'system balance' is the amount of energy in the buffer. Whenever the amount of energy goes below the 'additional storage' parameter at any point or ends above the additional storage parameter after a 24h section, the system is considered out of balance. The price threshold is set as the control variable 'balancing threshold'. This interacts with the earlier mentioned 'additional storage' control variable. In doing so, the model attempts to restore the buffer to the additional storage capacity value if the imbalance market allows it to do so at a reasonable price.

Figure 17: Schematic of the imbalance market sub model



4.2.5 Financial sub-model

The financial sub-model calculates the financial effects of the changes made in the previous sub-models. The calculations are considered self-explanatory, so less focus is put on explaining the workings of the sub-model. Instead this section is focussed on the assumptions that a particularly large impact on the outcome of the model.

The model is build up of two cost calculations: The investment costs and the yearly energy costs, treated separately below. The financial sub-model runs three separate scenarios; a 100% GFB/CC scenario, the ATES system with buffer and the ATES system that includes a buffer and participates in active imbalance market trading. The end result is aggregated in an overview of the cost parameters for each scenario for the current setting of the control variables.

Investment costs

The investment costs are mainly based on the installed capacities of the different system components. The cost dynamic of a sensible heat storage tank for water was deducted from literature as explained in sections 3.2.2 and 4.2.2. Determining the investment costs of an ATES system per kW installed capacity is more difficult. These systems are custom build based on location specific factors like, subsurface topography, legislative restrictions, thermal demand profiles etc. Since literature proved unable to give an indication, the consultants at IF technology were asked to give their working model for estimating prices. General costs for the other system components could be taken from literature. The following list of cost parameters are used in the model.

System component	**Investment costs**	**Source**
ATES	€70.000 + €600/kW.	IF technology consultants
Gas fired Boiler	€100/kW	x
CC	€200/kW	x
Buffer	$€4879{,}8 * (\mathrm{Vst}^{-0{,}393})$	
Battery	€700/kWh	x

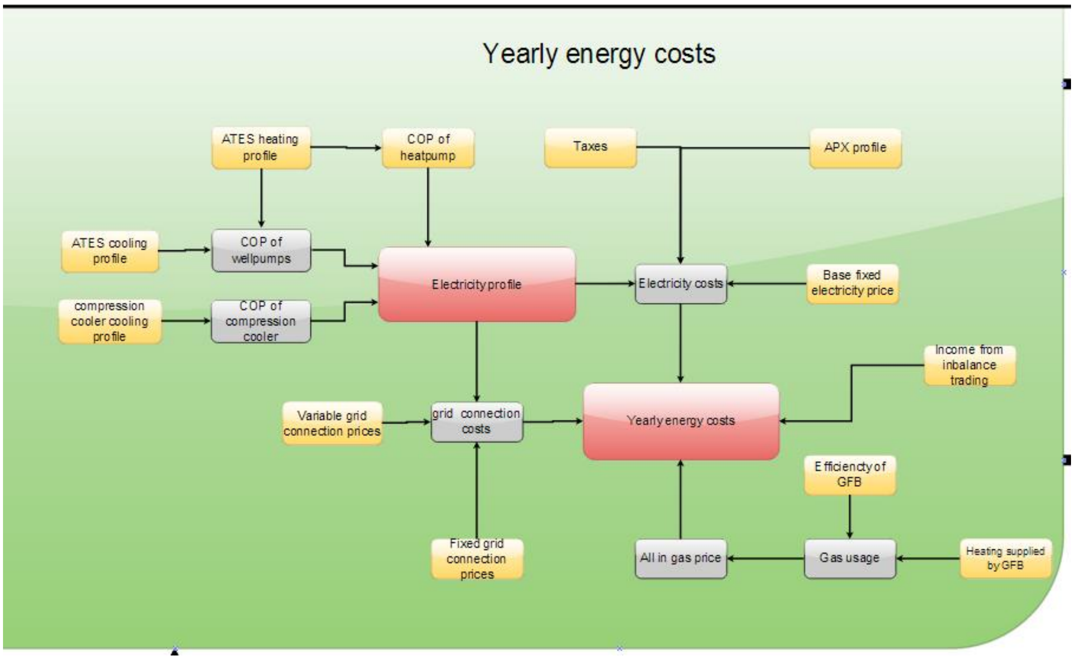
One system component not mentioned earlier is the Battery. In talks with representatives of heat pump producer Carrier, the technological barriers of this new concept were discussed. Their main concerns were related to the on/off switching that would occur in the interactions with the imbalance market. The heat pumps used in the ATES systems are mostly of the screw-compressor variety. Carrier stated these types of heat pumps need at least 5 minutes to ramp up or down to avoid damage to the compressor. To allow the heat pump to run these ramping periods, a battery was added to the system. This battery allows the power to be cut instantaneous, therefore maximizing the DSM potential. An additional benefit is that the battery also protects the heat pump from damage trough power outage. The storage capacity of the battery is calculated as covering 1/12 of the electricity the heat pump uses in one hour on full power. As going from full power to stop and back linearly over 10 minutes uses the same amount of electricity of to running at full power for 5 minutes.

Some aspects of investment costs dynamics have been purposely omitted from the investment cost calculations. Most notable are the costs related to building specific adaptations required to use an ATES system. As an ATES system produces low-temperature heating, conventional radiators are not adequate for space heating. Air-treatment in conjunction with floor heating is a common way of distributing the heating into the building. The costs of these adaptations over conventional radiators are not incorporated in this study. However, since the main thesis of this paper is adapting conventional ATES systems to incorporate this new concept, these costs are part of both scenarios making their omission less of a problem. This same reasoning goes for many other omitted costs like monitoring equipment, permit costs etc.

Yearly costs - electricity

The yearly energy costs calculations have more complex interactions than the investment costs. These interactions can be seen in figure 18 below.

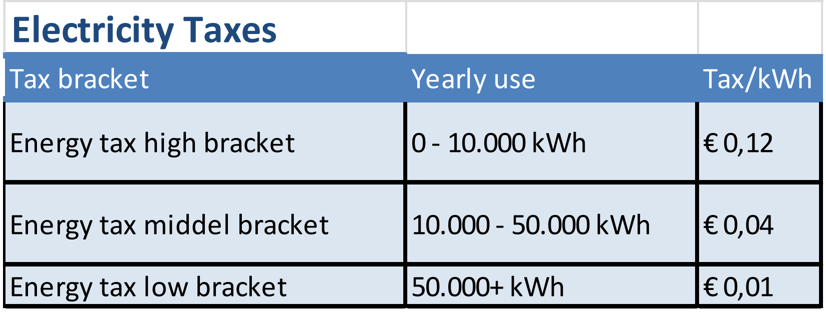
Figure 18: Schematic overview of the yearly energy costs calculations



The electricity profile of the ATES system of each of the three scenarios can be extracted from the thermal demand data. Calculating the price the end-user would have to pay for each profile is somewhat obscure. This because ATES systems are commercially operated systems (even in domestic applications), meaning that the price of electricity is not fixed as it is in the consumer market. Because the consumer market for electricity is much more heterogeneous and predictable, a set price can be determined that averages out over the client base of an energy company. This is not the case for commercial end-users, especially those with large demands. In this market the electricity price is set in a negotiation with the energy company. A big factor in this negotiation is the electricity demand profile of the buying party. This also means that an end-user that alters his demand profile to more favourable spot-market prices can renegotiate the contracted electricity prices. For the purpose of this study, we calculate the cost-savings that can be achieved on the spot-market but make no attempt to speculate how these should be divided over the different parties involved.

On top of the spot-market prices the energy taxes also have to be taken into account. The Dutch energy taxes on electricity make use of a bracketed system. The brackets and prices can be seen in table 1 below.

Table 1: Electricity taxes
Source: (Tennet, 2015)



Electricity Taxes

Tax bracket	Yearly use	Tax/kWh
Energy tax high bracket	0 - 10.000 kWh	€ 0,12
Energy tax middel bracket	10.000 - 50.000 kWh	€ 0,04
Energy tax low bracket	50.000+ kWh	€ 0,01

Next to the spot-market prices and the taxes, the yearly electricity costs also consist of grid-connection costs. The grid-connection costs are based on several surcharges; there are the connection costs that increase stepwise with contracted max power and there is a transport charge per kW contracted max power. The savings in connection costs are hard to estimate due to the fact that the ATES system is usually part of the general grid-connection of the respective building. If the adaptation doesn't allow the building to go to a smaller connection bracket there are no savings on grid-connection costs. On the other hand, if the ATES system does allow a smaller connection, the savings are disproportional to reduction in capacity. Due to this contextual sensitivity, the grid-connection costs are not counted as savings in the model. The transport charge per kW also varies with the size, voltage and connection type of the system. But since it is a direct charge per kW, there will always be some savings and it is incorporated in the model. The system used to calculate the transport charge is based on the cost structure published by Stedin, of the larger TSOs in The Netherlands. (Stedin, 2015)

Yearly costs – total

The combined spot-market costs, taxes and grid connection costs make up the electrical side of the yearly energy costs. These are completed by the gas costs, which comprise of the costs per m^3 and the actual m^3 used. Since the GFB also serves as a back-up, its installed capacity and grid connection costs don't change in the different models. The final addition to the yearly energy costs are the benefits obtained from the imbalance market trading. These are summed up as yearly income and subtracted from the yearly costs in the imbalance trading scenario.

5

Results

The first section of this chapter is reserved for an example of the outputs produced by the model. This is to illustrate the kinds of changes made to the ATES system and how those changes affect key system parameters. After the example section, the comparisons and in depth analysis of the results will be done. The final part consist of an overview of the results of all the different datasets combined,

5.1 Buffer integration

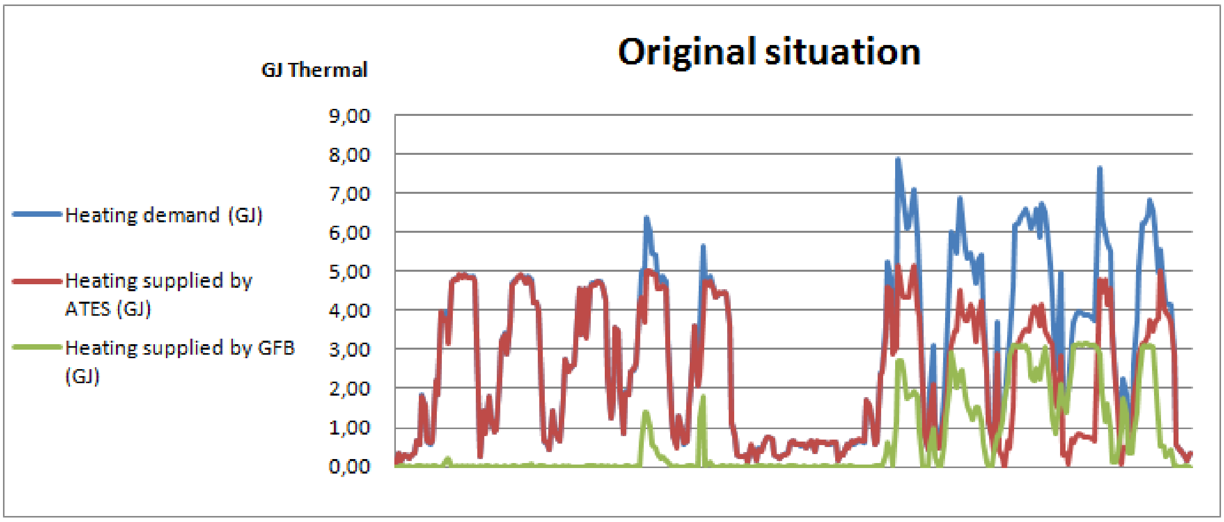
This is a detailed example of the output of the model made for the medium office dataset. This section is an example of how the buffer system is integrated into the ATES design. The first paragraph illustrates the changes in system operation when a buffer is introduced. In the second paragraph the economic and CO_2 emission effects of these changes are shown.

5.1.1 New system operation

Heating – Original situation

Figure 19 below shows the standard operation of an ATES system as retrieved from the monitoring database. This is a section of this data covering about 12 days picked for demonstration purposes. The peak in operation during the 5 weekdays can be clearly distinguished in the data. This is a section in January covering some of the coldest days. The inefficiency in the system can be seen clearly in the sense that the GFB is needed during peaks in demand during the day while during the night the ATES system is almost switched off. The goal is to make use of this downtime by adding a buffer and using this downtime to supply part of the peak-demand during the day.

Figure 19: Example of original ATES heating profile for the medium office building (January 2014)



Heating – Strategy without GFB

In the redesign of the system, two distinct strategies can be identified. The first strategy is to design a buffer large enough to replace the need for a GFB. Figure 20 below shows the new operation over the same 12 day period mentioned in the previous paragraph. The second week in this graph has the highest peak-demand in the year wide dataset. The system is designed to supply the heat required during the coldest day over a 24-hour period. The buffer is sized to cover the mismatch between supply and demand in this period. This strategy has the lowest CO_2 emission that is reasonably achievable with these systems. In this scenario the financially optimal situation is to reduce the installed capacity of the ATES system, only slightly, from about 5,5 GJ/hour (1550 kWth) to around 4.5GJ/hour (1250 kWth). To do so under these conditions requires a buffer of around 28 GJ (450m^3) to cover the demand without a GFB. The economic and CO_2 effects of this strategy will be shown and discussed in section 5.3 below. Note how the ATES system charges as much of the demand during off-peak hours as system boundaries will allow.

Figure 20: Example profile of strategy without GFB

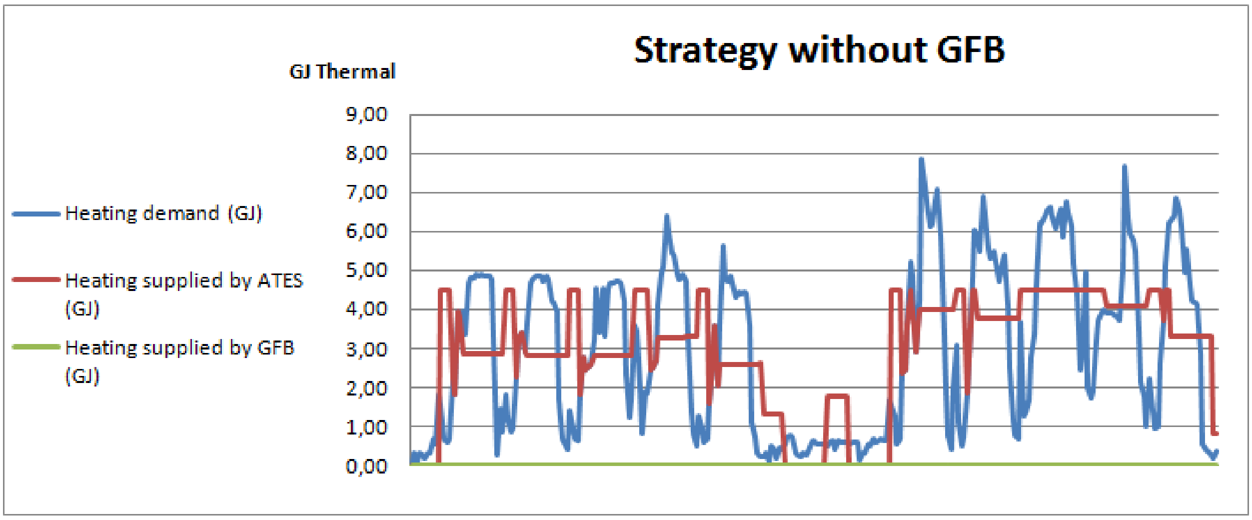
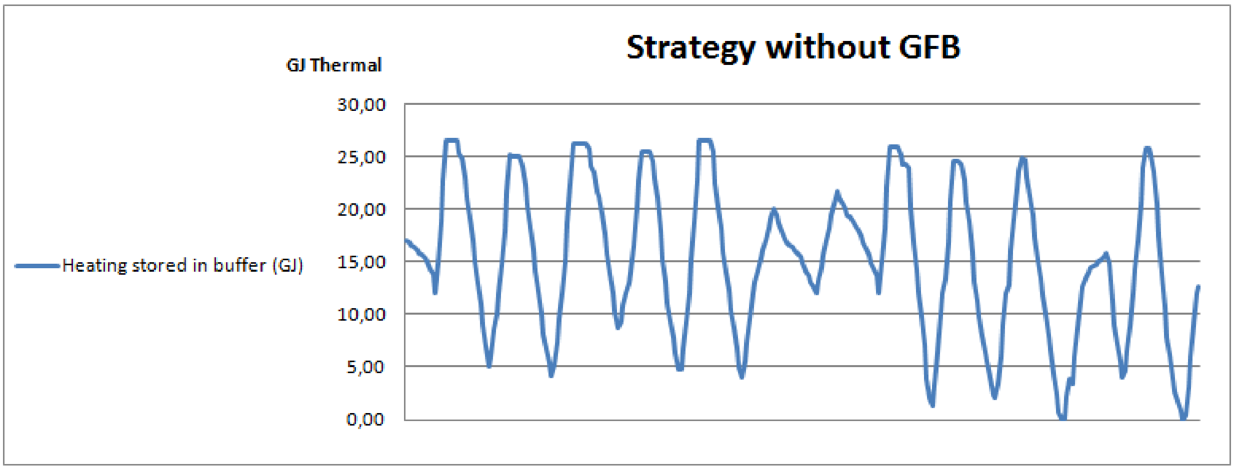


Figure 21: Example profile of thermal energy in storage

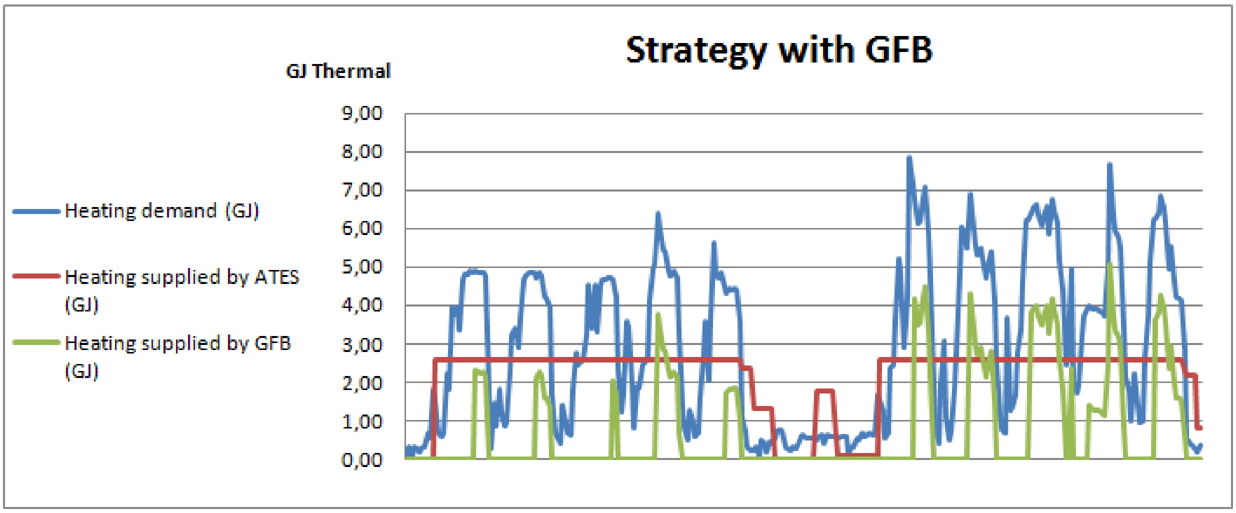


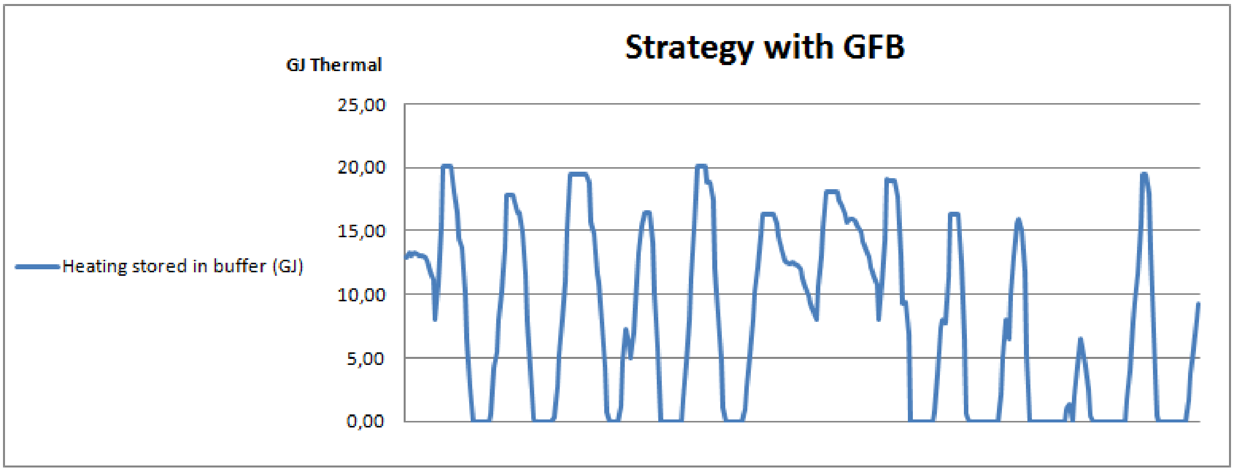
Heating – Strategy with GFB

Another option is to keep using the GFB and reduce the size of the ATES system even further. In doing so, we find that the most economical system, generally, also leads to higher CO_2 emission than the conventional ATES system. From a modelling perspective it is hard to define if, and to what degree, this is acceptable. To avoid this issue, the strategy with the GFB uses the CO_2 emission of the conventional ATES system as a boundary condition and aims to design the most economically beneficial system within that framework. Figure 22 and 23 below shows the new system operation under these conditions. Note that it might seem that this new system has a higher amount of natural gas use just from this section alone. However, even though gas use increases during the very cold days as can be seen in figure 22, this is compensated by less natural gas use in the intermediate seasons. This is important as higher natural gas use is the main contributor to higher CO_2 emissions in the confines of this concept.

In this new strategy, keeping the GFB but sticking to the natural gas use boundary condition allows the heating power of the ATES system to be reduced to 2.6GJ/hour (720 kWth) and the buffer required has a capacity of around 17GJ (275m^3). The downside is that the CO_2 emissions are not reduced below that of the conventional ATES system. Note how the ATES system runs at max capacity for the whole week, needing the GFB to fill in the remaining demand when the buffer is empty.

Figure 22 & 23: Example profile of ATES operation and thermal energy in storage





5.1.2 New system operation for cooling

The conventional ATES system usually supplies 100% of the cooling demand. Because we have reduced the size of the ATES system, we have to use that same reduced system to supply the cooling as well. As it is now ‘underpowered’, cooling storage is also required to meet peaks in demand. As mentioned earlier, cooling is only stored when it is necessary to meet the demand. The model shifts the part of the peak-demand that tops the maximum cooling power of the ATES system to the hours before the peak. This process can be seen in figure 24 below. The overproduction precedes and matches the deficit of each peak in demand. However, if no CC is used, the cold storage would require a larger storage system than that required for the heating demand (with GFB strategy). The main reason is that the temperature differential over a cooling system is generally lower (~10°C as opposed to ~15°C for heating) causing one GJ of cold storage to require a larger volume of water. This means that the 18 GJ of cold storage required in the situation without a CC would require almost 430m^3 of storage capacity. The result is that the 'with GFB strategy' for heating designed with a buffer of 275 m^3 would not be able to store sufficient cooling. Testing different solutions determined that a CC is the most cost-effective way of bridging this gap. The effects of incorporating the CC can be seen in figure 25 below. The addition of the CC allows the storage requirement to be reduced from 18GJ to 11GJ. A cold storage of 11GJ requires around 265 m^3 of storage capacity, making it more or less equal to the size of the heating storage and thus creating a more economically balanced system. Note that only small bursts of cooling by the CC are needed to greatly reduce the amount of cold storage needed. The overall cooling produced by the CC in this scenario is only 70 GJ over the year, a small amount compared to the just over 3500 GJ of cooling produced by the ATES system during the same period.

Figure 24: Example of ATES cooling profile without CC

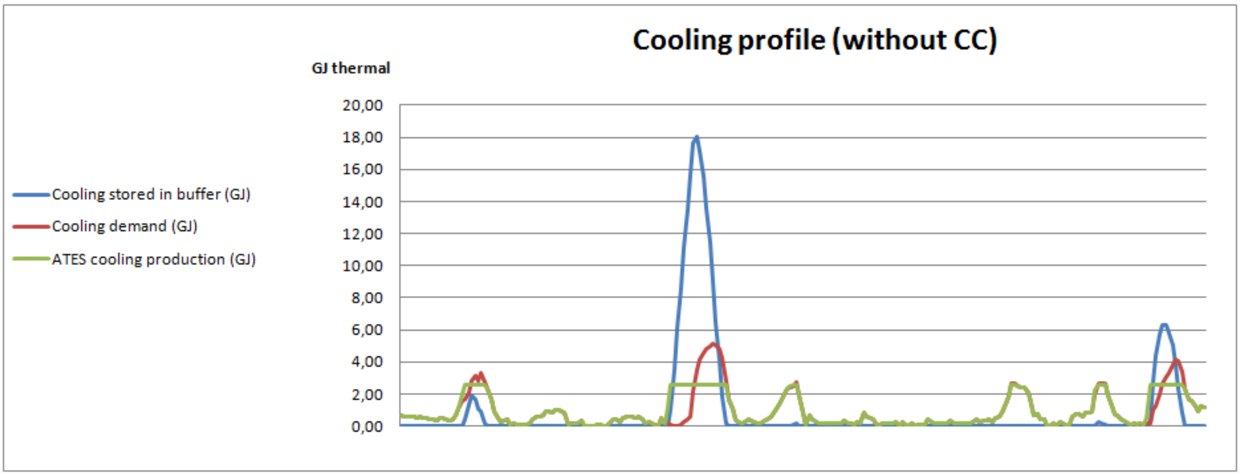
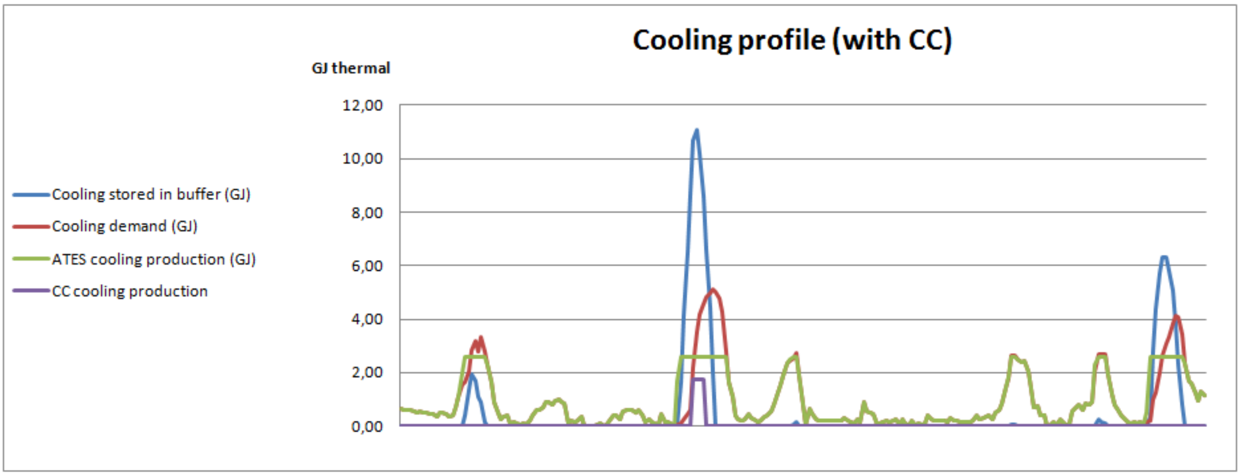


Figure 25: Example of ATES cooling profile with CC



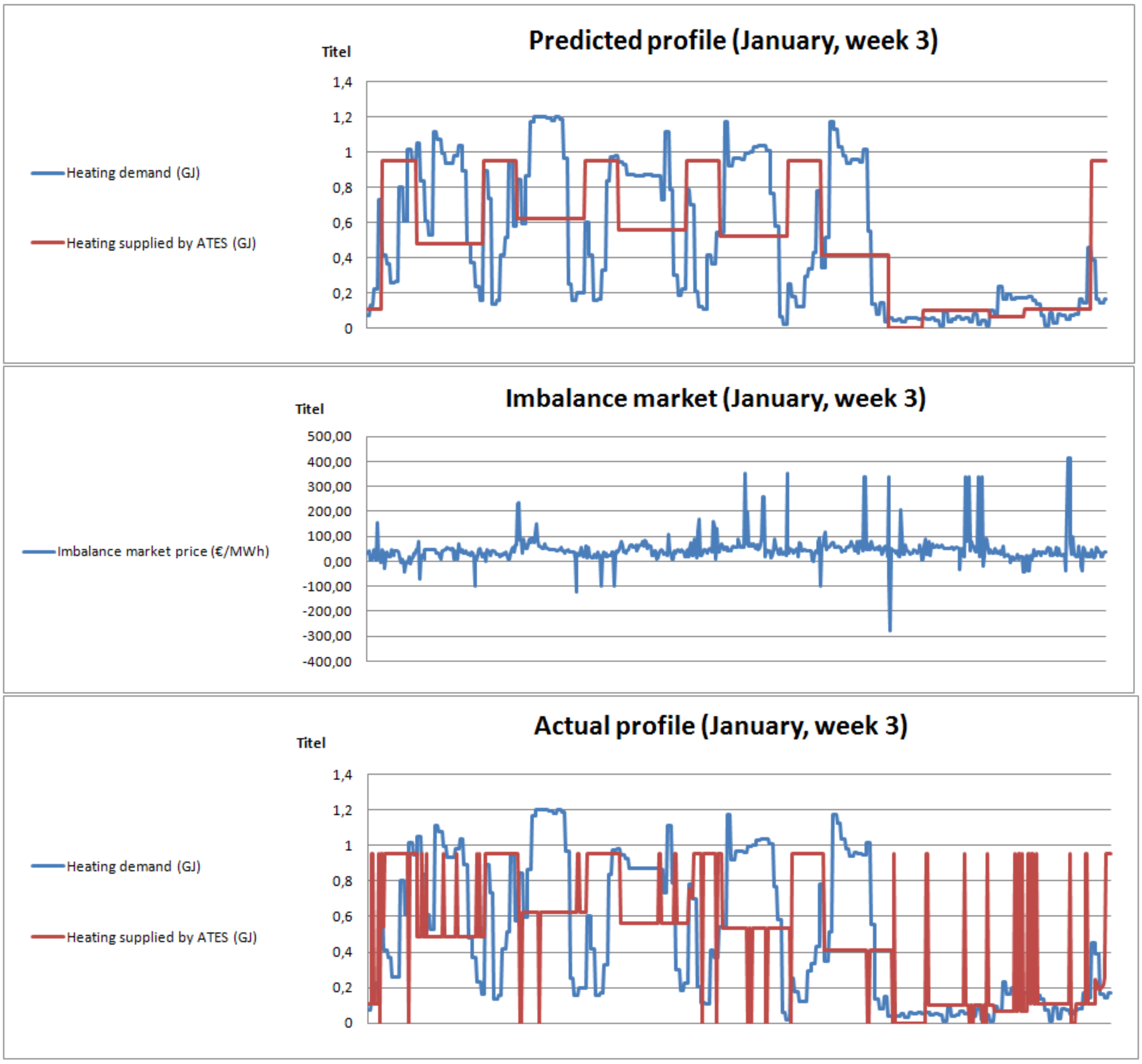
5.2 Imbalance trading

The second element of this research looks into the interaction between the redesigned ATES system and the imbalance market. The input of the imbalance trading mechanism is the prediction of the system operation as generated by the buffer integration model, explained in the previous paragraph. As mentioned earlier, imbalance trading is only done with the heat pump and therefore only applies to the heat production. This part of the model splits up the hourly intervals into 15 minute intervals. This explains why the values displayed in graphs xx to xx below are 4 times lower than what they were in the graphs preceding this section.

5.2.1 New system operation

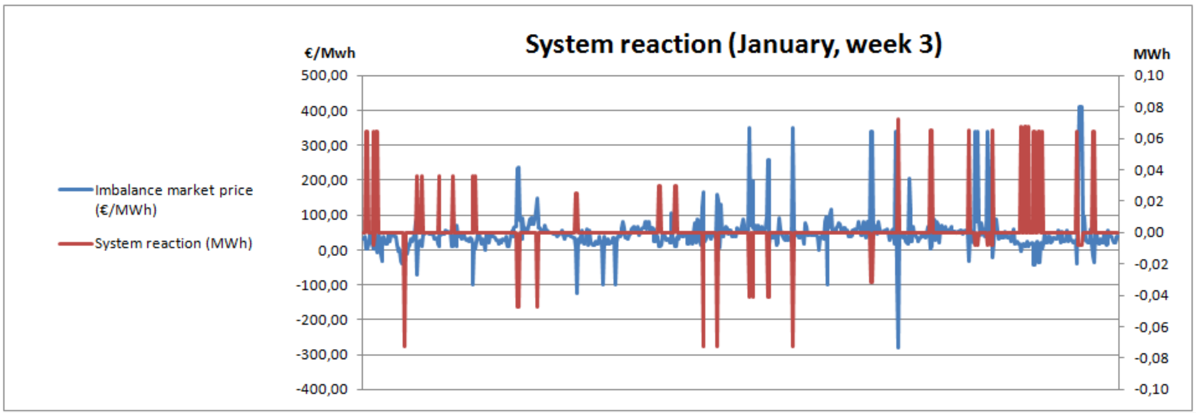
The interaction between the ATES system and the imbalance market happens as follows: Graph 26 shows the prediction of the system operation as produced in from the earlier buffer integration sub-model. In a real world application, this represents the electricity bought on the spot-market for the next day based on predicted thermal load for that day. In real-time operation, the imbalance prices (graph 27) are monitored and when a certain threshold is reached the ATES system deviates from its predicted path. This leads to the actual operation of the ATES system shown in Graph 28. For short periods, usually either 15- or 30 minutes, the ATES system ramps up or down depending on the state of the imbalance market. These deviations are called ‘system reaction’ in the model.

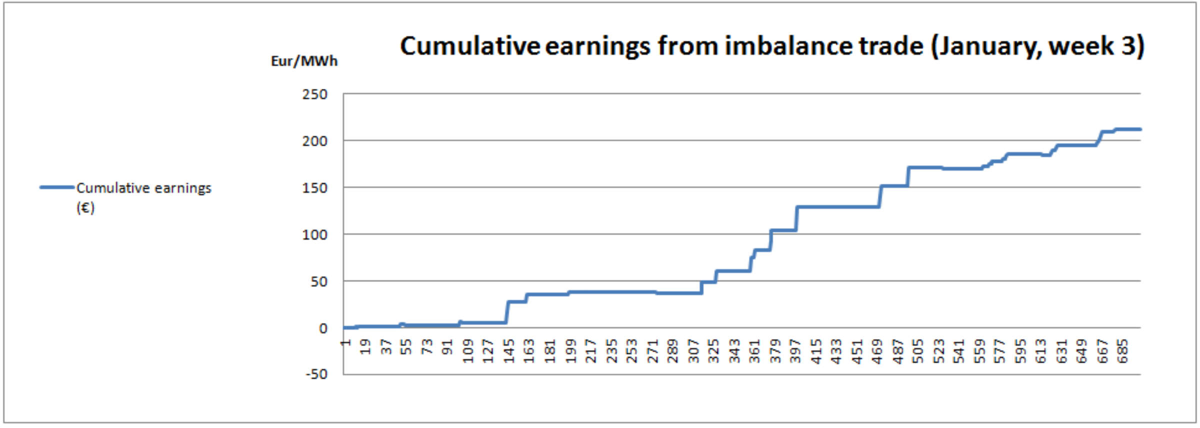
Figure 26, 27, 28: Example of imbalance market trading



To show the interaction between system reaction and the imbalance market more clearly the two are overlaid in graph 29 below. Note how the system does not always react when the imbalance market breaches the threshold. This is because if a system reaction causes the ATES system to go too far out of balance, the reaction is prevented. The cumulative earnings from these system reactions are shown in graph 30. However, the cumulative earnings do not paint the complete picture of the benefits of imbalance trading. In the case of negative or near-zero prices, the ATES system can withdraw additional power and get receive an income for doing so. This income is reflected in graph 30. On top of that, the additional electricity received would otherwise have to be bought from the spot market for the next day. The savings generated indirectly from receiving ‘free electricity’ are not represented in the cumulative earnings.

Figure 29, 30: Example of system reaction and cumulative earnings





5.3 Comparison

5.3.1 System dimensions

Tables 2 and 3 below show the alterations to the key system components ATES system, GFB, CC and buffer. Note how under the strategy without GFB there is no need for a CC either. The complete heating and cooling demand can be supplied with the ATES system and the buffer. The strategy with GFB allows for a much smaller ATES system but requires an increase in the power of the GFB as there is a bigger gap between the maximum ATES system production and the peak demand to fill when the buffer is empty

Table 2: Changes in installed capacities

installed capacities	Without GFB	With GFB	Imbalance trade	
ATES conventional	1.549	1.549	1.549	kWth
GFB conventional	883	883	883	kWth
ATES new system	1.250	722	861	kWth
GFB new system	0	1.405	1.710	kWth
CC new system	0	484	345	kWth
Change in ATES capacity	-299	-826	-688	kWth
percentage	-19 %	-53%	-44%	

5.3.2 Storage requirements

The storage system requirements within the two strategies are different in the sense that the strategy without the GFB has only limited need for cold storage. The issue with insufficient cold storage is further reduced by the fact that without a GFB, the heat storage capacity is larger, making cold storage easily possible within the design parameters set by the heat storage. However, in the case where the GFB is kept the CC is used to lower m^3 of cold storage until more or less equal to the heat storage requirement.

Table 3: Required buffer size for heating and cooling

	Without GFB	With GFB	Imbalance trade
Max heat storage	28,16 GJ	17,21 GJ	14,25 GJ
Size required	448 m^3	273 m^3	226m^3
Max cold storage	2,33 GJ	11,09 GJ	9,14 GJ
Size required	56 m^3	264 m^3	218m^3

5.3.1 Investment costs

These new system dimensions lead to changes in the investment costs related to the system. Table 4 below compares investment costs of the proposed changes to conventional ATES system

Table 4: Changes to investment costs

Investment costs	Conv. ATES	Without GFB	With GFB	Imbalance trade
ATES system	€ 1.004.167	€ 825.045	€ 508.459	€ 591.667
GFB	€ 88.250	€ 0	€ 140.514	€ 82.722
CC	€ 0	€ 0	€ 96.806	€ 69.028
buffer	€ 0	€ 198.499	€ 147.218	€ 131.254
Battery	-	-	-	€ 6.279
Total installation costs	€ 1.092.417	€ 1.023.544	€ 892.997	€ 749.696
Change from conv. ATES	-	-€ 68.873	-€ 199.420	-€ 211.467
Percentage	-	- 6%	-18%	-19%

5.4 Yearly energy costs

An overview of the yearly energy costs can be seen in table 5 below. As a reference, the model also calculates the yearly energy costs that would occur if the demand profile were to be generated for 100% with a GFB and a CC. This data is only shown to provide some context to the results. We can see that a conventional ATES system reduces the use for natural gas by over 90% while only slightly more than doubling the electricity use compared to the 100% GFB/CC scenario. This is due to the efficiency increase when switching from a GFB to a heat pump and changing a CC for direct cooling with groundwater

Another interesting observation is that the 'without GFB' strategy uses more electricity than the conventional ATES system but has lower yearly electricity costs. This can be explained by the fact that the new system conducts more of its operation on cheaper electricity during off-peak hours. The 'with GFB' strategy has higher energy costs than the scenario without GFB, as was expected due to the use of natural gas. Here we can also verify that the overall gas use of this scenario is not higher than that of the conventional ATES system. A less obvious benefit of keeping the GFB is that it also lowers grid connection costs due to the substantial reduction (over 50%) in the electrical capacity of the ATES system.

Table 5: Changes to yearly energy costs

Yearly energy costs	GFB / CC	Conv. ATES	Without GFB	With GFB	Imb. trading	
Total electricity use	246.390	528.750	574.943	533.967	529.291	kWh
Heating supply GFB	203.265	16.630	0	14.926	15.111	m3
Grid connection	€ 8.626	€ 9.758	€ 8.530	€ 6.222	€ 9.653	/year
Electricity costs (APX)	€ 17.229	€ 38.203	€ 37.749	€ 35.740	€ 37.390	/year
Gas costs	€ 101.633	€ 8.315	€ 0	€ 7.463	7.556	/year
Income from trading	-	-	-	-	-€ 10.702	/year
Net yearly costs	€ 127.487	€ 56.275	€ 46.279	€ 49.424	€ 37.809	/year

5.4.1 Net Present Value

Because we are dealing with upfront costs and periodical costs/savings we use the NPV to distil this into a single parameter representing the economic value of the proposed changes. A discount rate of 10% was used over a 30 year period. Because we propose these new systems as an alternative to a conventional ATES system, the NPV is calculated using the economics of a conventional ATES system as the baseline. From a purely economic standpoint we can see from table 6 below that that imbalance trading has the economic advantage over the other changes.

Table 6: Changes to yearly energy costs

Cost overview	Without GFB	With GFB	Imbalance trading
Change in investment costs	-€ 68.873	-€ 199.420	-€ 211.467
Percentage	-6.3%	-18.3%	-19,4%
Change in yearly energy costs	-€ 9.996	-€ 6.851	-€ 12.379
percentage	-17.8%	-12.2%	-22,0%
NPV (30 year/10% interest)	€ 147.759	€ 239.646	€ 297.685

5.4.2 CO_2 emissions

The CO_2 emissions differ greatly depending on whether 'grey' or 'green' electricity is used. The CO_2 emissions for 'grey' electricity are equated to the average CO_2 emissions of the grid-mix in The Netherlands for the purpose of this study. The CO_2 emissions of 'green' electricity are equated to that of wind power. If we look at the results in table 7, it is surprising to see that all the proposed changes matter very little from a CO_2 emission perspective when the Dutch grid-mix (grey electricity) is used. The only explanation for the lack of differentiation when using grey electricity is that, apparently, heating with either a GFB or a heat pump on grid-mix electricity emits similar amounts of CO_2 per GJ of heat production. This would also explain why the differences are larger, especially percentage wise, when using green electricity.

Table 7: Changes to CO_2 emissions

CO2 emissions	Grey Elec.	Green Elec.	
CO2 emission / kWh	0,565	0,015	kg/kwh
CO2 emission of natural gas	1,785	1,785	kg/m3
100% GFB / CC	502.039	366.524	Kg CO2 / year
Conventional ATES	328.428	37.616	Kg CO2 / year
Buffer int. without GFB	324.843	8.624	Kg CO2 / year
Buffer int with GFB	328.335	34.653	Kg CO2 / year
ATES system with imbalance trade	326.023	34.913	kg CO2 / year

5.4.1 Checks

This section is used to check whether the errors made by the model are acceptable. The reason why the model is not 100% accurate is because the model uses numerical approximations of non-linear processes. However, if these errors stay within a few percent of the values taken from the measured data this is deemed acceptable for the purpose of this study. This check become increasingly more important when the model is pushed to extreme boundary conditions or when it's used for something it's not specifically designed for.

Table 8: Checks to see if the model is working correctly

Buffer integration

Heating demand	7149	GJ
ATES heat production	6708	GJ
GFB	456	GJ
Thermal losses	26	GJ
left in buffer	10	GJ
missing	21	GJ
error percentage	0,30%	

Cooling demand	3548	GJ
ATES cooling production	3478	GJ
CC	70	GJ
Thermal losses	26	GJ
left in buffer	0	GJ
missing	26	GJ
error percentage	0,74%	

Imbalance trading

Heating demand	**7092**	**GJ**
ATES heat production	6920	GJ
GFB	188	GJ
Thermal losses	14	GJ
left in buffer	6	GJ
missing	5	GJ
error percentage	0,07%	

Cooling demand	**3547**	**GJ**
ATES cooling production	3544	GJ
CC	70	GJ
Thermal losses	29	GJ
left in buffer	0	GJ
missing	-39	GJ
error percentage	1,09%	

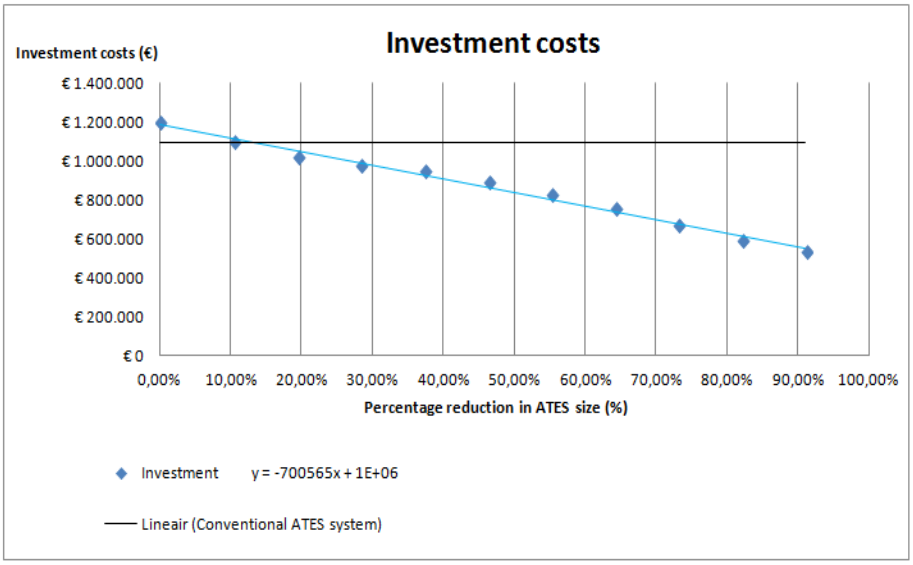
5.5 ATES size reduction sensitivity analysis

The key process in this model is the reduction of the ATES system capacity. All other variables compensate this variable to ensure the thermal demand of the building can still be met. By reducing the size reduction in steps, some interesting system dynamics can be distilled from the data. The variables show similar trends in all three variants of the concept discussed so far, with exception of the buffer size variable. For simplicity reasons, where the trends are similar, the results are shown for the imbalance trade variant only. Where relevant, the graphs show the level of that particular variable as it is for the conventional ATES system as a thin black line in the graph. The relationships between the studied variables and the ATES size reduction are approximated by regression analysis and shown next to the corresponding variable in the legend of the graphs.

5.5.1 Investment costs

The biggest contributor to the investment costs variable is the investment required for the ATES system itself. Since the investment required to construct an ATES system is directly related to its size, it makes sense that the investment costs of the whole system decrease more or less linear with the reduction in the size of the ATES system. The investment costs start out higher than the conventional ATES system due to the additional investment required for the buffer system. From figure 31 below we can see that a reduction of 10-15% in the ATES system can compensate for the investment of the buffer in this case. Further reduction in the ATES system leads to lower investment costs compared to the conventional ATES system.

Figure 31 Relation between investment costs and ATES size reduction



5.5.2 Buffer size – buffer integration

The relationship between optimal buffer size and the size of the ATES system is unique for each of the three variants of the concept and is therefore treated separately. Figure 32 below shows the required buffer size in relation to the reduction in ATES system capacity without imbalance trading (concepts with and without GFB). We can see that if the ATES system is reduced beyond 20% of the original capacity, the size of the buffer starts to increase rapidly if the GFB is kept out of the design. This does not happen in the variant with the GFB as it is the GFB that takes over when the buffer is empty. This means the buffer can be sized to be as economically effective as possible while relying on the GFB to ensure demand can always be met.

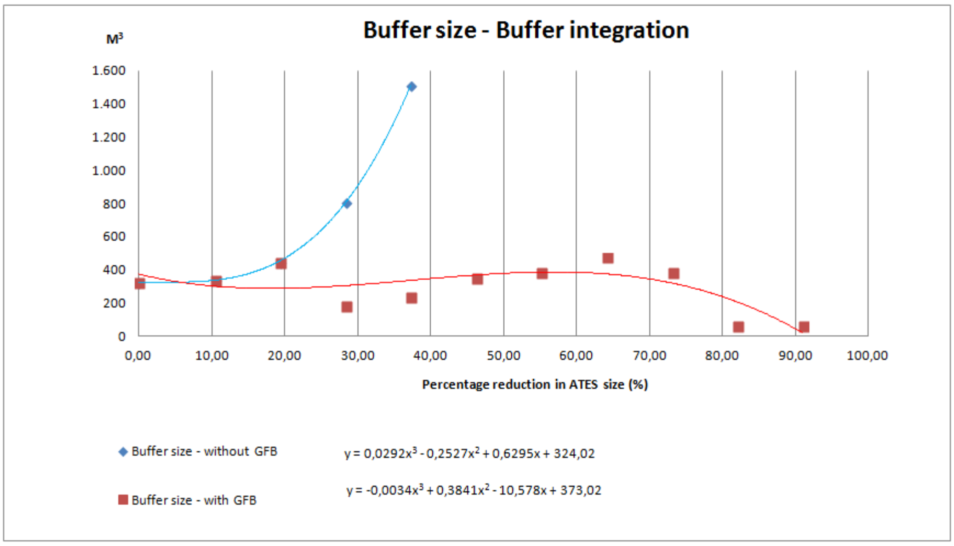
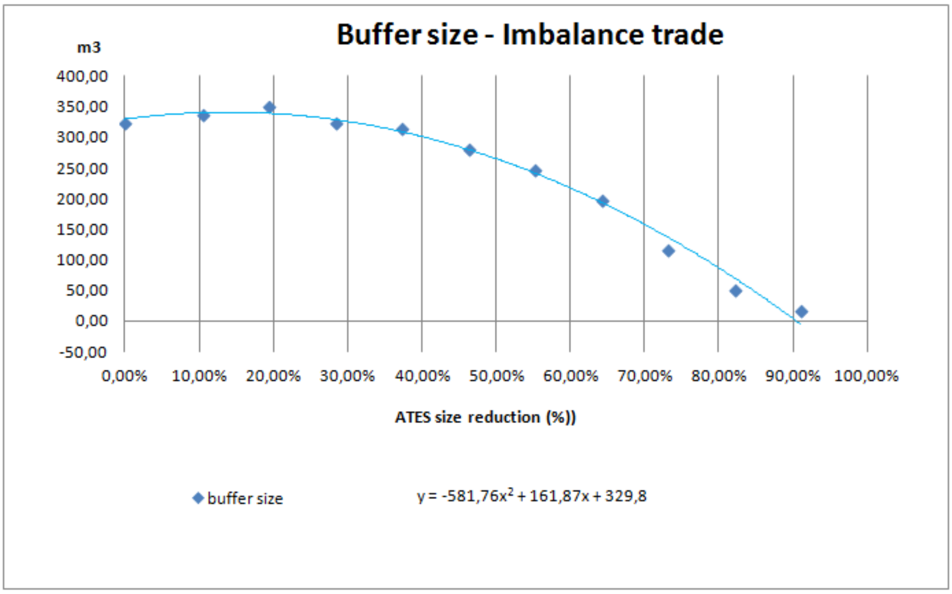


Figure 31 Relation between buffer size and ATES size reduction (1)

5.5.1 Buffer size – Imbalance trade

The Imbalance trade variant is different in the sense that a GFB is always required. This is because the system is switched off from time to time, making the backup capacity of the GFB essential. This means there is only one buffer size that is optimal for a particular sized ATES system. The required size of the buffer decreases with decreasing capacity of the ATES system. This is due to the fact that a smaller ATES system can generate less heating during the off-peak period, therefore, requiring less storage capacity. This relation can be seen in figure 32 below

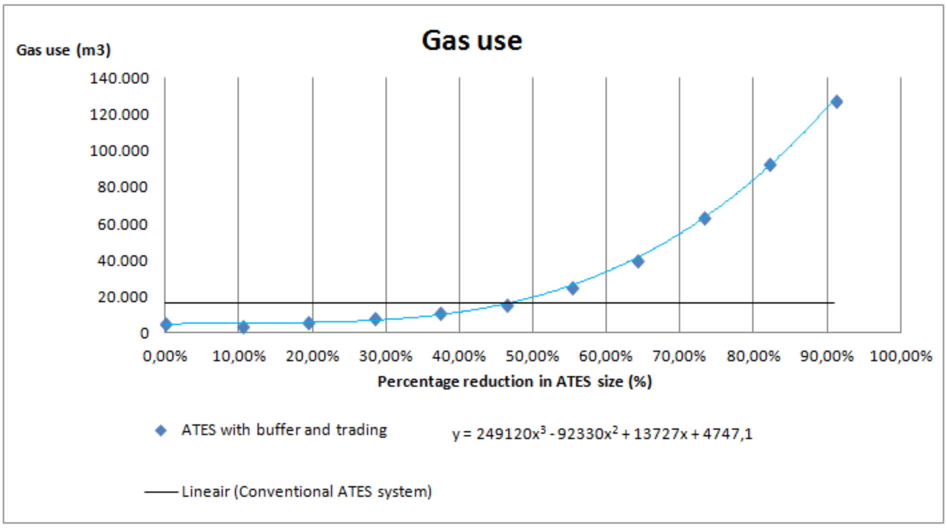
Figure 32 Relation between buffer size and ATES size reduction (2)



5.5.2 Gas use

Figure 33 below shows that gas use is still lower as with the conventional ATES system up until a reduction of around 45%. This is because, up to this point, the buffer can still supply peaks in the heat demand previously supplied with the GFB. If the self-imposed boundary condition of no higher CO_2 emission is kept in place then, in this case, for this variant, we cannot reduce the ATES system more than 45% of the original capacity. Note that this percentage will be different for each case and each variant. The important lessons to take away from this graph is that the

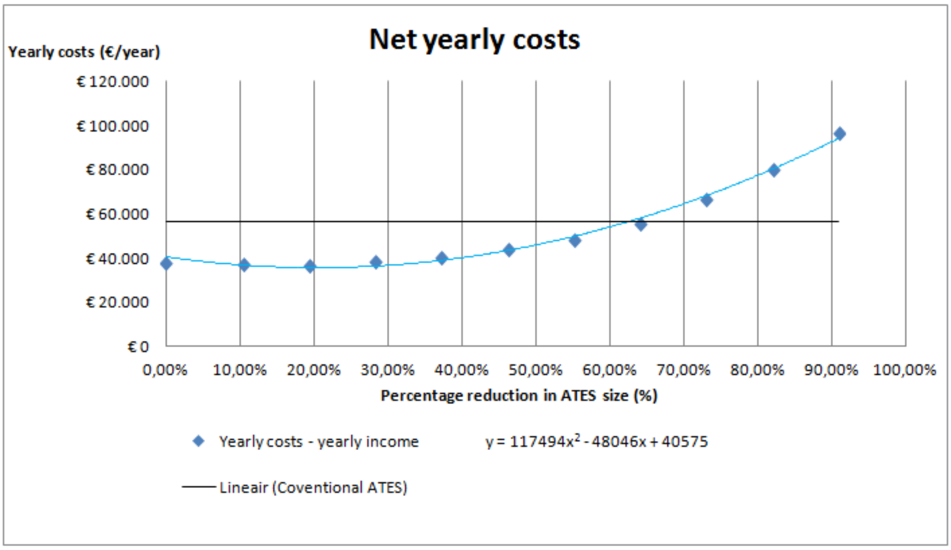
Figure 33: Relation between gas use and ATES size reduction



5.5.3 Net yearly energy costs.

The biggest differentiation in energy costs when varying ATES size is related to natural gas use. This is why we see a similar curve in figure 33 and 34. The yearly costs are further lowered by the fact that electricity is bought cheaper and imbalance trading earns additional income. This is why the yearly costs break the yearly costs of the conventional system at a greater reduction percentage as would be expected if only the gas use was taken into account. The relevance of this is discussed in the next section on NPV

Figure 34: Relation between gas use and ATES size reduction



5.5.4 Net present value and CO_2 emission

The NPV variable is the key decision-making variable put forward by this model. The relation between NPV and the ATES size reduction can be seen in graph xx below. The optimal dimensions are found around a 65% reduction in ATES size. The problem is that this level of ATES size reduction also leads to a higher CO_2 emission, especially when using green electricity. For reference check figure 36 and 37 to see the CO_2 emissions using either grey or green electricity at 65% ATES size reduction. This means that the highest NPV achievable, while adhering to the CO_2 emission boundary condition, is found at the intersection of the CO_2 emission for new system and the conventional ATES system seen in figure 36 and 37. In this case this is around 45% ATES size reduction.

Figure 35: Relation between NPV and ATES size reduction

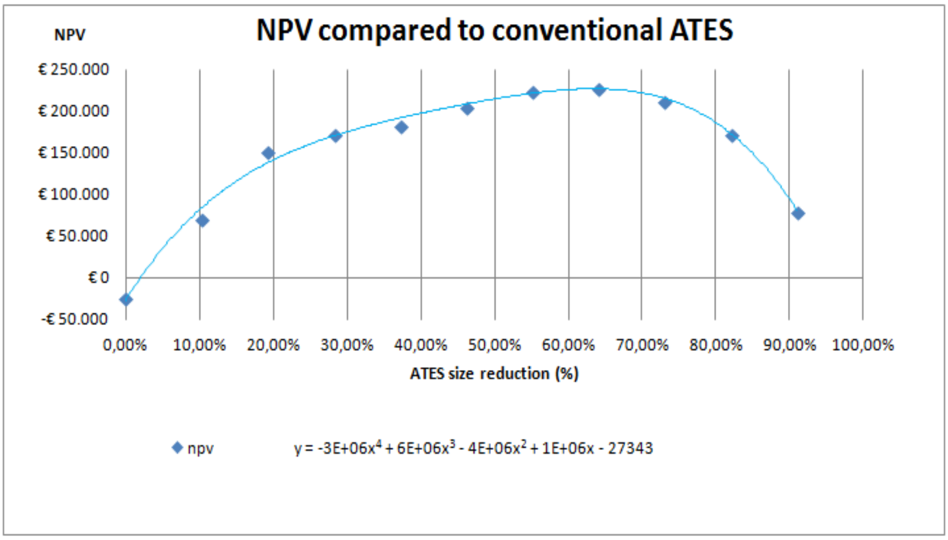


Figure 36: Relation between CO_2 emission (grey) ATES size reduction

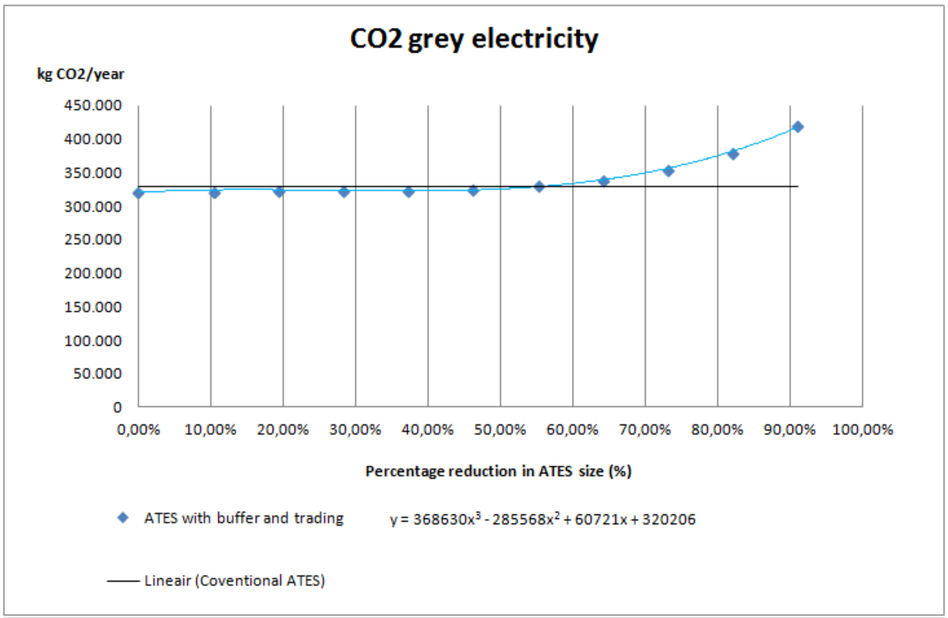
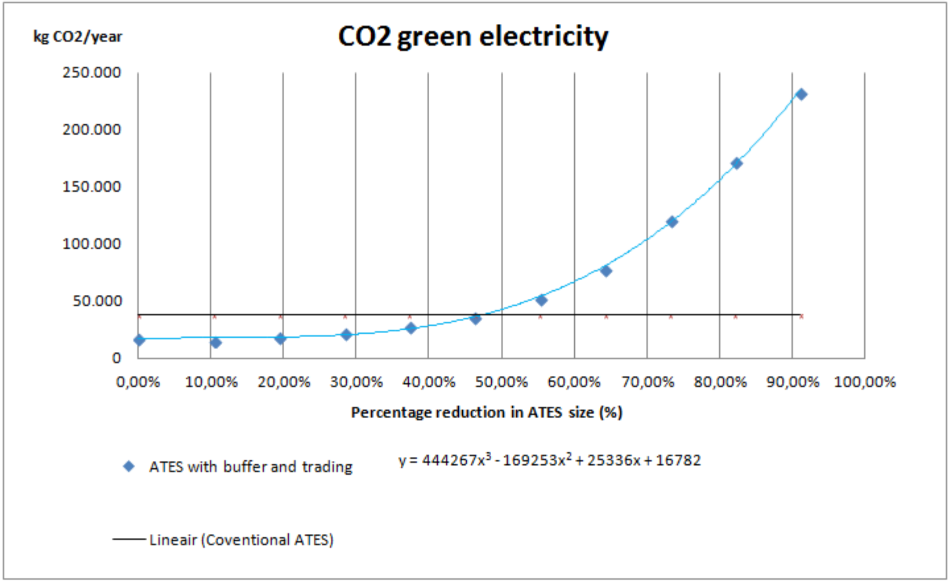


Figure 37: Relation between CO_2 emission (green) ATES size reduction



5.6 Results from other cases

The model was run for several other cases as well. For these cases the NPV of the most optimal situation is presented. Looking at the different cases we see that the office buildings are most suitable for implementation of this concept. The least suitable is the hospital and the train station. The reason these last two are less suitable is because these buildings have longer opening hours compared to the office buildings. This means there is little downtime in the thermal demand, making it more difficult to charge thermal energy in the buffer. This is especially true for the hospital which is open 24 hours per day 7 days a week. In order to make the concept work in a hospital, the ATES system has to be expanded in order to create enough room in the system to charge heating or cooling in the buffer. These extra costs are not earned back by the reduction in yearly energy costs leading to a negative NPV.

Table 9: Results from other cases

Large office

Cost overview	Conv ATES	buffer int.	Imbalance trading
Investment costs	€ 2.220.863	€ 2.016.493	€ 1.674.601
Percentage		-9,2%	-24,6%
Yearly energy costs	€ 204.551	€ 171.257	€ 128.595
Percentage		-16,3%	-37,1%
NPV (30 year/10% interest)		€ 469.382	€ 1.143.582

Small office

Cost overview	Conv ATES	buffer int.	Imbalance trading
Investment costs	€ 351.842	€ 280.352	€ 268.699
Percentage		-20,3%	-23,6%
Yearly energy costs	€ 15.930	€ 13.760	€ 14.571
Percentage		-13,6%	-8,5%
NPV (30 year/10% interest)		€ 83.472	€ 87.154

Small hospital

Cost overview	Conv ATES	buffer int.	Imbalance trading
Investment costs	€ 379.903	€ 659.065	€ 640.862

Percentage		73,5%	68,7%
Yearly energy costs	€ 64.288	€ 45.663	€ 41.557
Percentage		-29,0%	-35,4%
NPV (30 year/10% interest)		-€ 95.144	-€ 43.615

Large trainstation

Cost overview	Conv ATES	buffer int.	Imbalance trading
Investment costs	€ 806.314	€ 753.249	€ 784.264
Percentage		-6,6%	-2,7%
Yearly energy costs	€ 60.624	€ 58.173	€ 50.230
Percentage		-4,0%	-17,1%
NPV (30 year/10% interest)		€ 69.122	€ 108.585

6

Conclusion

Looking back at the main research question we can conclude that the addition of short-term thermal energy storage can indeed improve the performance of an ATES system in terms of costs and CO_2 emissions. The modelling showed that in the new system design there is a trade-off between cost savings and reducing CO_2 emissions. The model further showed that the amount of improvement achievable by application of short-term thermal energy storage depends heavily on the thermal demand curve of the end-user. More specifically, end-users that have a higher amount of down-time in their daily thermal demand curve benefit more from short-term thermal storage. This also means that buildings that operate around the clock, like hospitals, have little to gain from this concept.

In terms of optimal design parameters when incorporating short-term thermal storage into the ATES system the following could be concluded: The addition of thermal storage allows for a reduction in the ATES system installed capacity, which in turns saves on investment costs. However, at some point the CO_2 emissions start increasing due to an increasing need for the GFB to supply peak-demand. The most optimal point in this equation from a cost perspective is at the point where yearly costs increase more than a further reduction in capacity yields in savings. However, it is possible that this point also causes higher CO_2 emissions compared to the conventional system, it depends on the system designer whether this is acceptable. In order to have the optimal system from a CO_2 emission perspective, the best strategy is to replace the GFB completely by the thermal storage system. Next to these general conclusions, some more specific lessons learned can be summed up:

- Water-tank storage is the safest and most mature technology for thermal energy storage in this context
- accurate predictions of the thermal load for the next day are important to run the system optimally
- An additional storage strategy, leaving some spare thermal energy in the buffer at the end of the day, improves performance
- Switching from heat to cold storage should be done only when the cooling supply becomes insufficient to meet demand. Switching from cold to heat storage should be done as soon as cooling demand allows for it.
- Because of decreasing costs of the buffer (per/m^3) with increasing size, bigger projects see larger benefits
- End-users that have significant down-time or high peaks in their 24-hour heating and/or cooling demand benefit more from short-term thermal storage. On the

contrary, End-users that have a very flat thermal demand curve benefit less to not at all short-term thermal energy storage.

The second part of the research aimed to define the best strategy of interacting with the electricity market, more specifically the imbalance market. From attempting to optimize this interaction, the following conclusions can be drawn: The first lesson learned is that the heat production cycle of an ATES system is the only suitable candidate for trading on the imbalance market because of the heat pump. In addition to the heat pump, the thermal storage is essential to allow system reactions to occur while still supplying the thermal demand of the building. To know when to react to the imbalance market, a decision matrix is required to ensure the system reaction doesn’t push the system out of balance. By experimenting with different decision matrices we found that the percentage to which the storage system is filled proved to be the best indicator of whether a system reaction should be undertaken. In other words, ramping up while the storage is full or switching off when the storage is empty should be prevented. in the cases under study, the best strategy proved is to ramp up if imbalance prices fall below €10/MWh and to ramp down if prices exceed €150/MWh. Next to these general conclusions, some more specific lessons learned are summed up below.

- Imbalance trading always requires a GFB as backup for when the system reactions deplete the energy storage in the buffer faster than expected.
- A battery is required to ensure quick reaction times to imbalance prices while preventing damage to the heat pump due to rapid on/off cycling
- Imbalance trading sees direct earnings from buying low and selling high, as well as indirect earnings by receiving cheaper of ‘free’ electricity which does not need to be bought later for market price.
- Imbalance trading involves some financial risks to the end-user which have to be managed properly to avoid unnecessary costs.
- Imbalance trading could, if done properly, save up 40% of the annual energy costs of an ATES system without increasing its CO_2 emission.

If we zoom out a bit and look at these results form a societal perspective we could conclude two things: Firstly, all variants researched in this paper show potential to improve the competitiveness of the ATES system in specific markets. Since the ATES system is considered a more renewable alternative to traditional GFB and CC systems, this is a worthwhile endeavour in and of itself. The second conclusion we can draw is that demand-side management with ATES systems will also have a positive impact on the integration of intermittent renewables as it can, at least partly, counteract the price fluctuations caused by intermittent production.

7

Discussion

There are many elements of this research that warrant further discussion. One obvious point of discussion is the shortcomings of modelling and the assumptions that lie at the basis of it. We could discuss different details that might have been overlooked or over-simplified but all those discussions would return to the same point; This research is a first step in a process that should include more sophisticated models, test setups and pilot projects. The point of this research was to estimate the potential of this concept, not outline the finished product. And in that context, it would be more relevant to discuss the merits of the concept from a broader perspective.

One such issue not yet discussed is related to complexity. If we look at the ATES systems currently in operation we find that many don't operate as intended due to the inherent complexity of the system and the issues that arise when implementing a complex system in a real-world environment. The concept presented in this paper only adds to the complexity by adding additional components. Especially when imbalance market trading comes into the picture, mistakes now can cost a lot of money. It is therefore essential that we discuss whether current issues that exist around ATES systems should be resolved first or how to otherwise tackle those. An article written by Geelen & Braber (2013) looked into the difference in satisfaction between greenhouse owners and utility owners of ATES systems. It found that over 90% of the greenhouse systems worked without problem as opposed to slightly more than 50% in utilities. The reason given by the authors is that in a greenhouse there is one person in charge, the farmer. As opposed to utilities where there is the architect, real estate investor, contractor, building operator and renting party. The problem is that there is not one person in charge of designing, building and operating the system. This makes it easy for mistakes to occur.

But the concept laid out in this paper could be part of the solution, especially regarding imbalance market trading. Because imbalance market trading is a very specialist activity, this has to be done by experts. And there are clear benefits of doing this over several systems at once. The reason to do this is to spread costs, but more importantly to lower risks. Now this is where we could propose a new business case, one where the ATES system is no longer owned by the owner of the building. A business case where there is one party responsible for designing, building and operating the system. This party could operate several systems at once, making imbalance market trading even more profitable and complexity less of an issue. The renting party would, instead of buying gas and electricity, buy heating and cooling per GJ without the hassle of operating a complex ATES system.

Another interesting topic of debate is the trade-offs that occur when redesigning the ATES system. The main trade-off we find is that the most optimal design from a cost perspective also emits more CO_2 and the design with the lowest CO_2 emission lacks the reduction in investment costs we see in the cost-optimal design. A possible solution to this problem would be to attach an economic value to CO_2 emissions in order to find one optimal design. This was considered during the modelling process but finding a fair price for CO_2 emissions proved a difficult task. In the end it seems putting a price on carbon emissions is not the best way to solve this problem as choosing a price is just as subjective as simply choosing one variant over the other. In the end maybe it’s a problem that does not need solving if we accept that there is not an optimal design from an objective point of view. It is the preference of the end-user that determines the optimal design. I personally believe that any change to the conventional ATES system should not emit more CO_2 but even that is debatable. An argument could be made that higher CO_2 emissions are acceptable as it is still a lot less than the reference scenario of using a GFB and CC. It could even be true that the higher emissions but better competitiveness reduce overall CO_2 emissions even further if it causes more buildings to adopt the ATES system over the GFB and CC.

8

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