MASTER

Modelling the effects of different renovation scenarios of apartments on the configuration of the Ecovat energy storage system
finding the optimal economic combination of the Ecovat system and renovation

van den Bosch, R.T.M.

Award date:
2015

Link to publication

Disclaimer
This document contains a student thesis (bachelor's or master's), as authored by a student at Eindhoven University of Technology. Student theses are made available in the TU/e repository upon obtaining the required degree. The grade received is not published on the document as presented in the repository. The required complexity or quality of research of student theses may vary by program, and the required minimum study period may vary in duration.

General rights
Copyright and moral rights for the publications made accessible in the public portal are retained by the authors and/or other copyright owners and it is a condition of accessing publications that users recognise and abide by the legal requirements associated with these rights.

• Users may download and print one copy of any publication from the public portal for the purpose of private study or research.
• You may not further distribute the material or use it for any profit-making activity or commercial gain
Modelling the effects
of different renovation scenarios of apartments
on the configuration of the Ecovat energy storage system

Finding the optimal economic combination of renovation and the Ecovat system

R.T.M. (Ruud) van den Bosch
Modelling the effects
of different renovation scenarios of apartments
on the configuration of the Ecovat energy storage system

Finding the optimal economic combination of the Ecovat system and renovation

MASTER THESIS BY

R.T.M. (Ruud) van den Bosch

Graduation program
Construction Management and Engineering

Graduation committee
Prof.dr.ir. B. (Bauke) de Vries (TU/e)
MSc S. (Saleh) Mohammadi (TU/e)
Ing. A. (Aris) de Groot (Ecovat energy storage system)

Date of graduation
July 16th, 2015
Acknowledgements

Last six months have been the most educational ones of my study. Sometimes during this graduation period, it seemed like the more information I got and the more knowledge I gained, the less I understood. Fortunately, there were plenty of people who helped me through whom I would like to thank.

First of all, I would like to thank Aris de Groot who gave me the opportunity in January to perform this research for Ecovat. For his never-ending enthusiasm and his confidence in me. For the time he took to support me and provide me with the necessary information and contacts.

I would like to thank my first supervisor Bauke de Vries for his calm and clear guidance. His unambiguous decision making support has truly been a great help. Also, I would like to thank my second supervisor Saleh Mohammadi, for his critical questions and valuable advice.

I would like to thank my colleagues at Ecovat, Jan van den Boogaard, Eugène van Bouwdijk, and Fjo de Ridder from VITO for their continuous time and support and for the good mood at the office. Also I would like to thank all external advisors Martijn Bos, Davide Garufi, Munish Katiyar, Hein Enneking and Dyon Noy for all the different perspectives and practical guidance. Special thanks to Stijn and Tim for the final review.

Last but not least I would like to thank my parents who have supported me to study ever since I was little. Without their guidance, I would not have reached the point where I am today.

Ruud van den Bosch
Eindhoven, July 2015
Summary

Mother nature generates plenty of renewable energy every year. However, a major problem is that the supply of this renewable energy does not match its demand. Sun and wind are not always there when you need them the most and their predictability is limited. The result is that not 100% of the solar and wind energy can be used. Moreover, back-up facilities are needed for security of supply of electric energy. The share of renewable energy is expected to grow, therefore the imbalance will only become larger. Because of the introduction of renewable energy sources, the energy system has become more future proof but more pressure has come on the reliability and the affordability. The missing link is energy storage. Energy storage is an enabling technology that can stimulate the growth of renewable energy and therefore towards an energy neutral built environment. The ‘Ecovat energy storage system’ is the energy storage system that will be the core of this thesis.

The Ecovat energy storage system is built around a large-scale subterranean vessel for the storage of thermal energy. It is the first product that is able to store high temperatures (up to 90°C) efficiently over a longer period (> 6 months) with a loss of heat in this period less than 10%. The most important principle of the Ecovat innovation is that no water is pumped around in the vessel. Thus the water is stagnant and the heat is exchanged with the inside wall of the vessel. This makes the system highly efficient as a result of the natural layers of heat in the water. These layers, the so-called stratification of water, arise since water that has a higher temperature also has a lower density. The different layers will hardly mix, therefore the heat can be added from or extracted to each layer independently. This can be done with for example heat pumps and/or PVT panels.

This thesis focusses on the application of the Ecovat system on apartments. Applying the Ecovat system to apartments is most likely to occur in a situation when a housing corporation has the intention to renovate multiple apartments. The question that then arises for the housing corporations is: “What type of renovation would be the most favourable when the Ecovat system is applied?” This thesis tries to find an answer to this problem. A such the following research question is defined: “What is the most favourable renovation scenario for apartments in becoming energy neutral when the Ecovat system is applied?”

In order to find the answer to the research question, a system model of the Ecovat system is developed. For the setup of this model, several variables can be alternated. These variables are: the renovation scenario, the size of the vessel, the number of PVT panels and the power capacity for each of the installed devices. When these variables are set in a certain configuration then the system model is run. The system model is divided into seven parallel processes and each of these seven process can be triggered or not based on the data that is sent to the setup. This data consists of: the current state of the storage vessel, the power capacity of the installation, the current heat demand, the future heat demand and the variable energy price. The seven parallel processes are: the heat demand from the apartments, the heat supply from the air/water heat pump, improvement of the stratification of the layers with the high temperature...
water/water heat pump and the low temperature water/water heat pump, the heat supply from the resistor, the heat supply from the PVT panels and the energy losses.

The model is developed for an apartment building ‘portiek’ from the building period <1965. For the renovation scenarios, two criteria are determined that are important for the system model namely, the yearly heat demand and the heating temperature. From this, four renovation scenarios are determined, namely ‘Poor’, ‘Reasonable’, ‘Good’ and ‘Excellent’. Furthermore, for each renovation scenario two setups are determined with two different vessel sizes. Thus eight setups are determined that are run by the system model. Then, for each of the eight setups the optimal installation capacity for each device is determined. Finally, in order to decide which setup and thus which renovation scenario is the most favourable, eight TCOs are calculated and compared. In this thesis, the setup with the lowest cost is considered the most economically favourable setup.

As a result, the most economically favourable renovation scenario is renovation scenario ‘Poor’ in setup 1 with an Ecovat vessel size M. No improvements are made to decrease the energy consumption for space heating. This finding is relevant for Ecovat, since the Ecovat system would have high requirements for the housing corporation to improve their apartments if scenario 4 ‘excellent’ would have had the lowest TCO. In case of scenario 1 ‘Poor’, the housing corporation is less bothered with the implications on their apartments.

However, setup 1 with renovation scenario ‘Poor’ is also less robust than other setups and has a higher chance of an energy shortage. The value proposition of the Ecovat system is to provide a reliable and affordable energy supply system for a very long time, i.e. 25 to 50 years. Although little or no renovation resulted in the lowest TCO, these low cost renovation scenarios are also considered to have a higher chance of failing to deliver the demanded heat. These low cost renovation scenarios have high temperature heating and therefore the vessel can store less useable heat than when the same vessel is connected to low temperature heating. As a result the vessel can deplete in a very short time period; in setup 1 the vessel can have an energy shortage in less than nine days.

Another limitation of the results is the exclusion of other evaluation criteria in the scenarios than the TCO; the improvement of the energy performance of the apartments is often not the only motive to renovate apartments. Other aspects such as the comfort level, safety and aesthetics can be very important drivers for a housing corporation to renovate apartments. Moreover, the different scenarios are not evaluated in their sustainable performance.

To conclude, even though Ecovat would profit the most from selling large systems with ‘badly’ performing apartments, there should be a high emphasis on the robustness of the system. This robustness would make the system more reliable and future proof. It is suggested to perform a risk analysis on the probability of depletion and determine what the effect would be on the TCO.
Samenvatting

Ieder jaar genereert moeder natuur meer dan genoeg hernieuwbare energie. Echter, een groot probleem is dat het aanbod van deze energie niet overeenkomt met de vraag. Zon en wind zijn niet altijd aanwezig wanneer je ze het meest nodig hebt en hun voorspelbaarheid is beperkt. Daardoor wordt niet 100% van de zon- en windenergie gebruikt. Bovendien zijn back-up faciliteiten nodig voor de betrouwbaarheid van de energievoorziening. De verwachting is dat het aandeel hernieuwbare energie zal groeien, waardoor de onbalans alleen nog maar groter wordt. Door de introductie van hernieuwbare energie wordt de energievoorziening toekomstbestendiger, maar tegelijkertijd komt er meer druk op de betrouwbaarheid en betaalbaarheid. Energieopslag is hierin de missende schakel. Energieopslag is een bedienende technologie die de groei van hernieuwbare energie kan stimuleren en daarom een stap zet richting een energieneutrale bebouwde omgeving. Het energieopslagsysteem van ‘Ecovat energy storage system’ is het systeem dat de kern vormt voor deze thesis.

Het Ecovat energieopslagsysteem is opgezet rond een groot ondergronds vat voor thermische opslag. Het is het eerste product dat in staat is om hoge temperaturen (tot 90°C) op te slaan over een lange periode (> 6 maanden) met minder dan 10% verlies. Het belangrijkste principe van de innovatie is dat er geen water wordt rondgepompt in het vat. Het water staat stil en de warmte wordt uitgewisseld met de binnenste wand van het vat. Dit zorgt voor een hoge efficiëntie als gevolg van de natuurlijke lagen van warmte in het water. Deze lagen, ook wel de stratificatie van water genoemd, ontstaan omdat water met een hoge temperatuur een lagere dichtheid heeft. De verschillende lagen in het vat mengen nauwelijks en daarom kan aan iedere laag onafhankelijk van de andere lagen, energie toegevoegd of onttrokken worden. Dit kan bijvoorbeeld met het gebruik van warmtepompen en/of PVT panelen.

In deze thesis ligt de focus op de toepassing van het Ecovat systeem op appartementen. Dit systeem wordt het meest waarschijnlijk toegepast wanneer een woningbouwcorporatie besluit om meerdere appartementen te renoveren. De vraag die dan ontstaat voor de woningbouwcorporatie is: “Wat voor type renovatie is het meest gunstig wanneer het Ecovat systeem wordt toegepast?” In deze thesis wordt geprobeerd hier een antwoord op te vinden. Als zodanig is de volgende onderzoeksvraag opgesteld: "Wat is het meest gunstige renovatiescenario voor appartementen om energieneutraal te worden wanneer het Ecovat systeem wordt toegepast?"

Om hier een antwoord op te krijgen is een model gemaakt van het Ecovat systeem. Voor de opzet van dit model kunnen enkele variabelen aangepast worden. Deze variabelen zijn: het renovatiescenario, de grootte van het vat, het aantal PVT panelen en het geïnstalleerde vermogen voor ieder apparaat. Wanneer deze variabelen opgezet zijn in een configuratie kan het model gerund worden. Het model is opgedeeld in zeven parallele processen en ieder van die zeven processen kan geactiveerd worden op basis van de data die bij de setup is doorgegeven. Deze data bestaat uit: de huidige staat van het vat, het geïnstalleerde vermogen van ieder apparaat, de huidige energievraag, de toekomstige energievraag en de variabele energieprijs. De zeven parallele processen zijn: de warmtevraag van de appartementen, de warmtetoever
van de luchtwaterwarmtepomp, de verbetering van de gelaagdheid met de hoge en lage temperatuur waterwaterwarmtepomp, de warmtetoevoer van de weerstand, de warmtetoevoer van de PVT panelen en het energieverlies.

Het model is gemaakt voor portiekflats uit de bouwperiode <1965. Voor de renovatiescenario's zijn twee criteria bepaald die belangrijk zijn voor het model, namelijk de warmtevraag en de aanvoertemperatuur. Hieruit zijn vier renovatiescenario's opgesteld: ‘Slecht’, ‘Redelijk’, ‘Goed’ en ‘Uitstekend’. Vervolgens is voor ieder scenario twee verschillende maten vaten bepaald. In totaal zijn er dus acht setups die gerund worden door het model. Vervolgens is voor ieder van de acht setups het optimale vermogen van installatie bepaald. Tot slot zijn acht kostenberekeningen gemaakt en vergeleken om te bepalen welke setup, en dus welk renovatiescenario, het meest economisch gunstig is. In deze thesis is de setup met de laagste kosten beschouwd als de meest economisch gunstige setup.

Het resultaat is dat renovatiescenario ‘Slecht’ in setup 1 met vatgrootte M het meest economisch gunstige scenario is. In dit scenario wordt het verbruik voor ruimteverwarming niet gereduceerd en het verbruik voor warm tapwater met 25%. Deze bevinding is relevant voor Ecovat, omdat het Ecovat systeem hoge eisen zou stellen aan de woningbouwcorporatie als scenario 4 ‘Uitstekend’ de laagste kosten had gehad. In het geval van scenario 1 ‘Slecht’, is de woningbouwcorporatie minder gemoeid met de implicaties die het Ecovat systeem heeft op de apparementen.

Echter, setup 1 met renovatiescenario ‘Slecht’ is tegelijkertijd ook de minst robuuste setup en heeft een grotere kans op een tekort aan energie. De waardepropositie van het Ecovat systeem is het leveren van een betrouwbare en betaalbare hernieuwbare energievoorziening voor de lange termijn, namelijk 25 tot 50 jaar. Hoewel een slechte renovatie leidt tot een lagere prijs van het Ecovat systeem, hebben deze renovaties ook een grotere kans om niet aan de energievraag te kunnen voldoen. Die scenario’s hebben namelijk hoge temperatuur verwarming, waardoor het vat minder bruikbare warmte kan opslaan dan hetzelfde vat dat verbonden is met lage temperatuur verwarming. Als gevolg hiervan kan de warmte in het vat heel snel opraken; in setup 1 kan de bruikbare warmte in het vat in minder dan negen dagen op zijn.

Een andere beperking van het resultaat is het weglaten van andere evaluatiecriteria dan de totale kosten. Zo is de verbetering van de energieprestatie van de apparementen vaak niet de enige reden om apparamenten te renoveren. Andere aspecten zoals het comfortniveau, veiligheid en esthetica kunnen ook belangrijke beweegredenen zijn voor een woningbouwcorporatie om te renoveren. Daarnaast zijn de verschillende renovatiescenario’s niet vergeleken op hun duurzaamheidsprestatie.

De conclusie is dat, hoewel Ecovat het meeste profit heeft bij het verkopen van grote systemen met ‘slecht’ presterende apparamenten, toch een grote nadruk zou moeten liggen op de robuustheid van het systeem. Deze robuustheid zou het systeem betrouwbaarder en meer toekomstbestendig maken. Advies is om een risicoanalyse te maken van de kans dat de warmte in het vat opraat en wat het gevolg zou zijn voor de kosten.
List of Tables

Table 1 Different sizes of the Ecovat vessel and their capacity and cost.......................................................... 9
Table 2 Size of total housing stock per building type per building period (x1000) ................................................ 14
Table 3 Building types and building periods with the most potential for Ecovat.............................................. 15
Table 4 State of the insulation of the apartments................................................................................................. 22
Table 5 Heat demand and temperatures of the renovation scenarios in percentages ........................................... 23
Table 6 Heat demand and temperatures of the renovation scenarios in absolute values ........................................... 23
Table 7 Advantages and disadvantages of the different renovation scenarios ........................................................ 24
Table 8 Cost of renovation scenarios explicitly in the building ........................................................................ 26
Table 9 Charging cycles of the case per renovation scenario with Ecovat size S, M or L ........................................ 31
Table 10 Evaluation of the different energy sources .............................................................................................. 32
Table 11 Days of degrees per season ..................................................................................................................... 39
Table 12 Daily heat demand per season per renovation scenario (kWh) ........................................................... 39
Table 13 Different setups for the model ................................................................................................................ 57
Table 14 Hours each device is triggered in one year in the standard setup .......................................................... 63
Table 15 Installed power capacity for setup 1 - optimised .................................................................................... 64
Table 16 Hours each device is triggered in one year in setup 2 - standard .......................................................... 65
Table 17 Installed power capacity for setup 2 - optimised .................................................................................... 66
Table 18 Installed power capacity for setup 2 – final optimisation .................................................................... 67
Table 19 Hours each device is triggered in one year in setup 3 - standard .......................................................... 68
Table 20 Installed power capacity for setup 3 - optimised .................................................................................... 69
Table 21 Hours each device is triggered in one year in setup 4 - standard .......................................................... 70
Table 22 Installed power capacity for setup 4 - optimised .................................................................................... 71
Table 23 Hours each device is triggered in one year in setup 5 - optimised .......................................................... 73
Table 24 Installed power capacity for setup 5 – final optimisation ..................................................................... 74
Table 25 Hours each device is triggered in one year in setup 6 - standard .......................................................... 75
Table 26 Installed power capacity for setup 6 – final optimisation ..................................................................... 76
Table 27 Hours each device is triggered in one year in the setup 7 - standard ..................................................... 77
Table 28 Installed power capacity for setup 7 – optimised .................................................................................... 78
Table 29 Hours each device is triggered in one year in setup 8 - standard .......................................................... 79
Table 30 Installed power capacity for setup 8 – optimised .................................................................................... 80
Table 31 Power capacity and activity of all installed devices per setup .................................................................... 82
Table 32 Total cost of ownership for each setup for 25 years (€) ......................................................................... 83
Table 33 Configuration of the most favourable renovation scenario ..................................................................... 88
List of Figures

Figure 1 The conventional principle (left) compared to principle of the Ecovat vessel (right) .................. 8
Figure 2 3-D image of the Ecovat, size Small .......................................................................................... 8
Figure 3 The charging principle with PVT ................................................................................................. 10
Figure 4 The price on the imbalance market of the first week of January 2014. Source www.tennet.org
For the price of the whole year, see Appendix B .................................................................................. 17
Figure 5 The price on the day ahead market of the first week of January 2014. For the price of the whole
year, see Appendix C .............................................................................................................................. 18
Figure 6 Situation of the five apartment buildings .................................................................................... 21
Figure 7 Actual and theoretical gas consumption for each energy label. Source (D. Majcen, Itard, &
Visscher, 2013) ........................................................................................................................................ 25
Figure 8 Schema of the Ecovat system .................................................................................................... 29
Figure 9 Cashflow of 2 different vessel investments ................................................................................ 32
Figure 10 Flowchart of the system model in BPMN notation ................................................................ 35
Figure 11 Hourly energy demand for scenario 1 for four typical days. ...................................................... 40
Figure 12 Schema of the pvt panels and the Ecovat ............................................................................... 41
Figure 13 Ambient temperature in Eindhoven. Source KNMI ................................................................. 41
Figure 14 Global radiation in Eindhoven per hour. Source KNMI .......................................................... 42
Figure 15 Two different PVT technologies. Source (Tripanagnostopoulos, Souliotis, Battisti, & Corrado,
2003) ......................................................................................................................................................... 42
Figure 16 Solar irradiance factor F as a function of the irradiation. Source (Santbergen, 2008) ............ 43
Figure 17 Thermal and electric efficiency for $T_{m3}$. Source (Dupeyrat et al., 2014) ...................... 44
Figure 18 Output temperature of the PVT panel per hour ..................................................................... 46
Figure 19 Thermal and electric output of one PVT panel ...................................................................... 46
Figure 20 Schema of the air/water heat pump and the Ecovat ............................................................... 47
Figure 21 Schema of the low temperature water/water heat pump and the Ecovat ................................. 49
Figure 22 Schema of the high temperature water/water heat pump and the Ecovat ............................ 52
Figure 23 Schema of the resistor and the Ecovat .................................................................................. 54
Figure 24 Temperatures of the layers of setup 1 – standard .................................................................. 62
Figure 25 Temperatures of the layers of setup 1 – optimised ................................................................. 63
Figure 26 Temperatures of the layers of setup 2 – standard ................................................................. 65
Figure 27 Temperatures of the layers of setup 2 – optimised ................................................................. 66
Figure 28 Temperatures of the layers of setup 2 – final optimisation .................................................... 67
Figure 29 Temperatures of the layers of setup 3 – standard ................................................................. 68
Figure 30 Temperatures of the layers of setup 3 – optimised ................................................................. 69
Figure 31 Temperatures of the layers of setup 4 – standard .................................................................. 70
Figure 32 Temperatures of the layers of setup 4 – optimised ................................................................. 71
Figure 33 Temperatures of the layers of setup 5 – standard................................................................. 72
Figure 34 Temperatures of the layers of setup 5 – optimised.............................................................. 73
Figure 35 Temperatures of the layers of setup 5 – final optimisation.................................................. 74
Figure 36 Temperatures of the layers of setup 6 – standard............................................................... 75
Figure 37 Temperatures of the layers of setup 6 – optimised.............................................................. 76
Figure 38 Temperatures of the layers of setup 7 – standard............................................................... 77
Figure 39 Temperatures of the layers of setup 7 – optimised.............................................................. 78
Figure 40 Temperatures of the layers of setup 8 – standard............................................................... 79
Figure 41 Temperatures of the layers of setup 8 – optimised............................................................... 80
## Definitions and abbreviations

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Imbalance</td>
<td>When the electricity supply in the electricity grid does not match the booked and/or expected electricity demand.</td>
</tr>
<tr>
<td>Stratification</td>
<td>Naturally created different temperature layers as a result of stagnant water in the vessel.</td>
</tr>
<tr>
<td>Vessel</td>
<td>The large underground tank in the Ecovat system.</td>
</tr>
<tr>
<td>Volatility</td>
<td>The tendency of a value or price to fluctuate sharply and regularly.</td>
</tr>
<tr>
<td>ahwp</td>
<td>air/water heat pump</td>
</tr>
<tr>
<td>DAM</td>
<td>day ahead market</td>
</tr>
<tr>
<td>DSO</td>
<td>distribution system operator</td>
</tr>
<tr>
<td>hthp</td>
<td>high temperature water/water heat pump</td>
</tr>
<tr>
<td>imb</td>
<td>imbalance market</td>
</tr>
<tr>
<td>lthp</td>
<td>low temperature water/water heat pump</td>
</tr>
<tr>
<td>KNMI</td>
<td>Koninklijk Nederlands Meteorologisch Instituut (Royal Dutch Meteorological Institute)</td>
</tr>
<tr>
<td>PVT</td>
<td>photo-voltaic thermal panels</td>
</tr>
<tr>
<td>res</td>
<td>resistor</td>
</tr>
<tr>
<td>TCO</td>
<td>total cost of ownership</td>
</tr>
<tr>
<td>TSO</td>
<td>transmission system operator</td>
</tr>
<tr>
<td>EPC</td>
<td>energy performance coefficient</td>
</tr>
<tr>
<td>EPG</td>
<td>energy prestatie gebouw (energy performance building)</td>
</tr>
<tr>
<td>EMG</td>
<td>energieprestation norm voor maatregelen op gebiedsniveau (energy performance norm for measures on an area level)</td>
</tr>
</tbody>
</table>

---

XVII
1. Introduction.

Due to a significant increase of the world population and the world economy, energy consumption is increasing as well. More specifically, the non-OECD\(^1\) countries are expected to have a large energy consumption growth in the next decades (EIA, 2014). The supply of fossil fuels is decreasing and the dependency on these fossil fuels is increasing. The limited supply of these fuels are a risk for future demand and energy prices. Moreover, for these fossil fuels there is a high dependency on unstable conflict regions. As a result of the increasing energy consumption, CO\(_2\) levels are affected and thus the climate clock is ticking: concentrations of greenhouse gases in the atmosphere have reached 400 parts per million, the highest in three million years (UNEP & Frankfurt school, 2013).

The scenario described above has resulted in an increased necessity and awareness to make an energy transition towards a society based on sustainable energy ever since the global think tank the Club of Rome published *The Limits to Growth* (Meadows, Meadows, Randers, & Behrens, 1972). The European Union has therefore set up ambitious targets for 2020, 2030 and 2050 for all of its members. The goal for 2020 is to have a CO\(_2\) reduction of 20%, a 20% increase in energy efficiency and furthermore a 20% share in renewable energy generation. In the Netherlands, the share of renewable energy is growing every year but is still relatively low compared to other European countries (Netbeheer Nederland, 2014) and is behind on schedule for the European 2020 goals.

The worldwide industry of renewable energy is growing fast, with global investments in 2013 in renewable energy of 214 $billion, but is still nowhere near the size of the fossil fuels industry. Major investors worldwide are looking for alternatives to divest 5 $trillion from fossil fuels but the clean energy industry does not have the scale of other multi-trillion dollar sectors; its equities are liquid but volatile and its yield instruments are still very small (Bullard, 2014). The biggest barriers worldwide for the development of clean energy systems are: conversion cost, location selection, distribution network and others (Wee, Yang, Chou, & Padilan, 2012).

Mother nature generates plenty of sustainable energy every year. However, one major problem is that the supply of this sustainable energy does not match the demand. Sustainable energy production often needs direct consumption, but sun and wind are not always there when you need them the most and their predictability is limited. The result is that not 100% of the solar and wind energy can be used. Moreover, back-up facilities are needed for security of supply of electrical energy. On top of that, the frequent imbalances in high voltage grids and remnant heat are often leading to negative economic effects. The share of renewables, such as wind and solar power, is expected to grow, therefore the imbalance will only become larger.

---

\(^1\) Organisation for Economic Co-operation and Development, is an international organisation of 34 (developed) countries.
To summarise, the missing link is energy storage. So far, there are many energy storage solutions but they are not suitable enough for the major part of the built environment. Ecovat has a solution to the energy storage problem in the built environment. This solution will be the core of this thesis. Energy storage however, is not a goal in its own. Because of the introduction of renewable energy sources, the energy system has become more future proof, but more pressure has come on the reliability and the affordability of the system. Energy storage is a means to secure this reliability and affordability. As such, energy storage is an enabling technology.

This paper is structured as following. First, in chapter one the problem is introduced, identified and defined. Chapter two is the contextual orientation. In this chapter the Ecovat system is explained, and then the context for this thesis of the housing stock, energy neutrality and the electricity market is elaborated. The third chapter introduces the case which is used for the system model. The fourth chapter explains the design of the system model for this thesis. The fifth chapter extensively illustrates the results that are produced with the system model. Finally, chapter six contains the conclusions, discussion and recommendations.

1.1. Problem identification

In this subchapter the problem for this thesis is further narrowed down and elaborated. In subchapter 1.2, the problem definition is stated.

In the current European energy sector, three parallel trends can be identified. First the trend of decentralisation, in which growing amounts of decentralised (sustainable) energy are delivered by new players on the energy market with new ways of collaborations and with the involvement of the end users. Secondly, the trend of the ‘Europeanisation’ of energy, with several acquisitions of energy giants, great distances between energy plants and the large consumption centre and energy crossing the borders. Thirdly, the strong increase of installed sustainable energy. These three trends form the basis of the energy transition (DNV-GL, Berenschot, Topsector Energie, & TU Delft, 2015). In order to facilitate these trends, extra flexibility in supply and demand of energy is needed. This can help to improve the reliability and affordability of the energy system. This flexibility can be realised with a cost effective combination of four options: adjustable power plants, reinforcing the electricity grid, demand response and energy storage (DNV-GL et al., 2015). The Ecovat energy storage system is a possible energy storage solution and a demand response solution that has the potential to realise a future that is more sustainable, reliable and affordable.

Large scale, long term energy storage is a solution to many problems but most importantly to the imbalance between supply and demand of renewable energy. Energy storage is not a goal in itself but an enabling technology that can stimulate the growth of renewable energy and therefore towards an energy neutral built environment. The energy storage system that will be used in this thesis is the one of Ecovat® energy storage system. The Ecovat is a solution for the energy system on one side and a supplier
of renewable energy on the other side. The demand side in this thesis will focus on apartment buildings of a social housing corporation.

Of the total housing stock of 7.5 million houses only the houses in the social housing stock will be considered. The housing corporations have a large market potential for Ecovat since many buildings need to be renovated or made energy neutral for the next 35 years. In the Netherlands, 33% of all dwellings (stable at 2.4 million for years now) are owned by social housing associations (Aedes, 2013), and 86% (CBS, 2013)² of them do not yet conform to the European 2009/28/EC, which states that all the existing houses have to reach at least energy label B in 2020 (as stated by (Garufi, 2015)). In the last years, the renovation rate for these dwellings is rising at a very low speed, and if this trend will not significantly increase, the Dutch social housing corporations will not comply with the European Commission requirements (Garufi, 2015).

The Ecovat system is a solution that can help to make the current social housing stock energy neutral. Applying the Ecovat system to social housing is likely to occur in a situation when the housing corporation has the intention to renovate multiple apartments. The question that then arises for the housing corporations is: “What type of renovation would be the best option if the Ecovat system is applied?” The housing corporations would like to be advised on this. This thesis tries to find an answer to this problem.

1.2. Problem definition

From the problem analyses above we can derive the following problem definition:

“It is not clear how different renovation scenarios for apartments will influence the configuration (size of the energy storage vessel and power capacity of the installation) of the thermal energy storage system. It is important to know what will be the most cost effective scenario for making the apartments energy neutral. A higher investment in the energy performance of the apartments is likely to result in lower investment costs of the Ecovat system and vice versa.”

² This source on CBS.nl only states data until 2011, and only 1.8 ml out of 2.4 ml houses have been given an energy label.
1.3. Research question

RQ: “What is the most favourable renovation scenario for apartments, in becoming energy neutral, when the Ecovat system is applied?”

In order to answer the research question, the following sub questions need to be answered in sequential order.

Sub-question 1: “Which apartment type of the housing corporation’s stock has the most potential and should therefore be used for the model?”

Sub-question 2: “What is the energy performance of the chosen case and what should be the different renovation scenarios?”

Sub-question 3: “What is the most optimal configuration of the Ecovat system for each renovation scenario?”
2.
2. Contextual orientation

2.1. Sustainable Thermal Energy Storage System

The Ecovat energy storage system is built around a large-scale subterranean vessel for storage of thermal energy and provides a solution to make Europe’s energy supply in the built environment sustainable. It is the first product that is able to store high temperature heat (up to 90°C) over a longer period (> 6 months) with a loss of heat in this period less than 10%. Ecovat can be applied to long term storage (across the seasons), short-term storage (day/night) or for economic storage (store when energy is cheap and sell when it is more profitable). The Ecovat system is a solution to several problems. First, it stores thermal energy that would otherwise be lost. Secondly, it secures the sustainable energy supply. Thirdly, it prevents imbalance on the high-voltage grid. Finally, it provides cost savings and preservation in the greenhouse cultivation as well as built environment. As stated in the problem analysis, the Ecovat system is a solution for both demand response and energy storage. However, in this thesis electric storage is excluded and since heat is not delivered back to the grid, the system is considered as demand response.

2.1.1. The Ecovat vessel

The central element of this system is a large, underground thermal water storage vessel. The most important principle of the Ecovat innovation is that no water is pumped around in the vessel. This makes the system more efficient. This efficiency is a result of the natural layers of heat in the water. These layers, the so-called stratification of water, arise since the water that has a higher temperature has a lower density and therefore rises. The different temperature layers will not mixture. The division between a cold water layer and a hot one is called thermocline. This thermocline does not only increase the thermal efficiency of the system but also reduces the heat loss and increases the exergetic efficiency of the system.

Current systems for thermal heat storage pump the water (and thus its heat) in and out of the vessel. This disrupts the stratification and mixes the different temperature layers into one uniform average temperature in the vessel. Also, this stratification creates the opportunity to apply a cooling basement in the bottom of the vessel for applications that have a cooling demand. This can be done at the same time that heat is stored in the upper layers, thus temperature levels can range from under 0°C up to 90°C and above (see Figure 1).
Figure 1 The conventional principle (left) compared to principle of the Ecovat vessel (right)

So the water stays in one place and the heat is exchanged with the inside wall of the vessel. This is possible because of the ‘vessel in a vessel’ principle. A constructive outer vessel is made and within that vessel another insulated vessel is placed which functions as one large heat exchanger. Figure 2 shows the cross section. It shows the different inner vessel sections, which can all be activated separately. The inner vessel consists of prefabricated wall parts and because of the tubes in these wall parts, each layer can be turned ‘on and off’ independently from each other. Because of this the natural stratification is not being disturbed and more than 40% extra energy quality is preserved (Figure 1).

Figure 2 3-D image of the Ecovat, size Small
The vessel is designed in five different sizes: S, M, L, XL, XLL (Table 1). The L sized barrel can provide heat year round for 200 to 400 houses. Note that the difference in volume of the different sizes are large. Naturally, the price per m³ will decrease when the size of the barrel increases. Different sizes in between these fixed sizes are not possible.

Table 1 Different sizes of the Ecovat vessel and their capacity and cost.

<table>
<thead>
<tr>
<th>Ecovat Size</th>
<th>Volume (m³)</th>
<th>Diameter (m)</th>
<th>kWh (th) (∆T = 50 K)</th>
<th>Natural gas equivalent (m³)</th>
<th>Cost price per m³ (€)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>1.500</td>
<td>11</td>
<td>87.208</td>
<td>9.910</td>
<td>226</td>
</tr>
<tr>
<td>Medium</td>
<td>5.000</td>
<td>20</td>
<td>290.694</td>
<td>33.033</td>
<td>137</td>
</tr>
<tr>
<td>Large</td>
<td>19.000</td>
<td>39</td>
<td>1.104.639</td>
<td>125.527</td>
<td>59</td>
</tr>
<tr>
<td>Extra Large</td>
<td>43.000</td>
<td>58</td>
<td>2.499.972</td>
<td>284.088</td>
<td>44</td>
</tr>
<tr>
<td>Extra Large Large³</td>
<td>60.000</td>
<td>58</td>
<td>3.488.333</td>
<td>396.402</td>
<td>39</td>
</tr>
</tbody>
</table>

2.1.2. The system

The building system basically consists of a heat buffer (Figure 3), a modular integration of various wall sections and a system for energy exchange. The heat can be generated with PVT modules, with heat pumps and with a heat resistor. The heat pumps and resistor will be controlled in such a way that they serve as an electricity grid stabiliser, either directly using excess PVT electricity in summer time or centrally generated electricity at low power demand periods. The heat pump then can be used to move heat from a relatively low temperature segment to a higher temperature segment in the Ecovat storage, thus increasing the quality of the stored heat while stabilising the grid and being cost-effective.

By cooling the PVT panels with the temperature of the water from the bottom of the barrel (5 °C) this water is heated. With the help of an air/water heat pump, driven by the electricity of the PVT panels, the temperature is raised further and then with a water/water heat pump up to 85 °C. The PVT panels and the heat pumps do not need to be in sequential order like in Figure 3 The charging principle with PVT but they can also be in parallel order with the Ecovat. The water/water heat pump takes a layer from the Ecovat as a source and creates cold which can be delivered to the buildings or PVT panels.

³ The term Extra Large Large is choosen on purpose instead of the term Extra Extra Large since the diameter is the same as the Ecovat Extra Large but only the height is higher.
2.1.3. Charging the Ecovat system
Which sources the Ecovat system uses to charge the Ecovat vessel are dependent on the location and situation. For example, if there is enough space for PVT panels then they could charge the vessel. Also waste heat if available can be readily used. But most probable and suitable for the business case is the level playing field of the imbalances on the energy market. For dump prices the vessel can be charged rapidly. A more extensive description on charging strategies in subchapter 4.1.

2.1.4. Applications of the Ecovat system
The Ecovat can be used for three general applications. First, long term storage over the seasons. Secondly, short term storage over day and night. And lastly, economical storage where energy is stored when the price is low and sold or used when the price is high. All of these three applications can work simultaneously if necessary. These three applications can result in the following solutions:

- A sustainable energy supply in the build environment.
  By storing the sustainably generated energy over the seasons in heat in the Ecovat, it becomes possible to match the strongly volatile offer of sustainable energy with the demand. This could be applied to residential areas, business premises etc.
- Storage of thermal energy.
  Ecovat as a buffer in heat grids with waste heat from power plant and incineration of waste. By adding an Ecovat the heat can be stored at moments of high production or low demand and being used at other moments of low production.
- Creating a security of supply.
  Heating grids need back-up installations for moments of low heat production or even total shut down because of maintenance or failure.
- Preventing an imbalance on the electricity grid.
  The balance on the electricity grid gets disturbed by fluctuations in the generation of sustainable energy (wind and sun). The Ecovat can store the surplus by means of power-to-heat.
In this thesis the focus will be on the application in the built environment and social housing in particular. This does not mean that the other applications are not relevant for this thesis. For the business case it is very interesting to combine the application for the built environment with the application to prevent imbalance on the electricity grid.

2.2. Building energy neutral

An energy neutral built environment is one step closer to a sustainable world. However, energy neutral is just a term, and therefore a mean to a sustainable future. Thus it is important to describe what an energy neutral building or built environment actually is in order to reach it. There are several interpretations of the term energy neutral. A policy maker, technician or a user can hold other definitions and indicators for energy neutrality (Haytink & Valk, 2013).

What most of the interpretations on energy neutral have in common is that the amount of energy consumed is equal to the amount of energy that is sustainably generated on a yearly basis. But then the interpretations start to vary since there are different ways to define what constitutes as the consumed energy and also different ways to define what constitutes as sustainably generated energy. Should the energy to charge your car be included? What about the energy to produce and transport the building materials? And what about the energy for your computer and dishwasher? And does a wind turbine 5 km further away account for your sustainably generated energy?

In the following definition of PeGO, the project boundaries include all buildings and installations that are under the direct influence of the project owner. The system boundaries can be wider and the project owner defines the location of these boundaries: “A project is energy neutral when there is no net import necessary of fossil or nuclear fuels on an yearly basis from outside the system boundaries to build the building, use it and break it down. This means that the energy consumption within the project boundaries is equal to the amount of sustainable generated energy within the project boundaries or can be acknowledged to the project on the basis of external measures. The energy consumption that comes from the establishment and demolishing of the building is divided to an annual contribution based on the life expectancy of the building.” (PeGO, 2009)

Besides the theoretical definitions defined in literature, there are three directions in practice for energy neutrality, namely (Haytink & Valk, 2013):

- Demand = supply (average resident – connected to the grid). Assumed here is an average resident that is connected to the grid and annually as much energy is produced as is used. Also known as ‘zero on the meter’.
- Indicator. Energy neutrality can be expressed in a value or numerical indicator such as: kWh, MJ, €. The energy performance coefficient (EPC) of a building can be determined on the basis of the
energy performance of a building (EPG)\(^4\) as well as with the energy performance norm for measures on an area level (EMG)\(^5\).

- Area, building, user. The degree of energy neutrality can be linked to the area, the building or the user. This means that on a larger scale the exchange of energy can take place and opportunities arise to compensate energy streams.

Next to the term energy neutral, there are several other terms that can be used to cover slightly different meaning on the subject, namely:

- CO\(_2\)-neutral. Buildings are CO\(_2\)-neutral when annually there is no net emission of CO\(_2\) to use the building (and depending on the definition also to create and demolish the building).
- Climate neutral. Climate neutral is almost the same as CO\(_2\)-neutral but it also considers other greenhouse gasses. However, it is not very relevant to make this distinction since there are hardly any other greenhouse gas emissions in the built environment.
- Autarkic. Energy neutral, CO\(_2\)-neutral and Climate neutral all look at the net result per year and this means that buildings still need to be connected to the energy grid and is therefore still partially dependent on energy from fossil fuels. An autarkic house or built environment on the other hand, is completely disconnected from the energy grid and can sustain itself all year round.

The biggest barrier in making autarkic buildings is the lack of an energy storage solution.

The energy demand does not need to be sustainably generated within the area in order to classify as energy neutral. There are other ways. For example when sustainably generated energy is linked to the electricity grid it is no longer traceable. Therefore the electricity has become anonymous. In order to distinguish green from grey energy production it is possible to certify the origin with a so called guarantee of origin (Dutch: garantie van oorsprong). In this case the green energy stays green and consumers have control over the origin of their energy. This thesis assumes a context that takes this one step further. In chapter 2.4 the opportunities of the energy market for charging the Ecovat will be addressed. The charging strategy will take the opportunities on the energy market to charge the Ecovat when the price is low or even below €0,-/MWh. These price fluctuations, as will be explained in subchapter 2.4, are a result of the volatility of the renewable energy sources such as wind and solar energy. In other words, the prices are low when there is a high supply of renewable energy. Therefore, although there is no legal justification (yet) for this basis, the energy taken from the electricity grid at low costs is considered renewable.

To conclude, there is no consensus yet on the definition for energy neutrality. For each project it is important to have a definition that can be checked and juridical justified. However, juridical certification often lags behind to new technologies and concepts. In the scope of this research, the Ecovat system is

---

\(^4\) This is documented in the NEN 7120 norm.
\(^5\) This is documented in the NVN 7125 norm.
considered to provide 100% renewable energy\(^6\), therefore making the housing connected to the system energy neutral. A share of the renewable energy can be generated from solar energy with PVT. The largest share however will be from the electricity grid. If a housing corporation wishes the project to become an autarkic system with the Ecovat, then this is possible but this will not be considered in this thesis for two economic reasons. First, because the cost per kW installed power capacity is much higher with solar energy than with heat pumps and heat resistors that are connected to the grid. Secondly, only solar energy means a charging cycle of less than 2 (as will be elaborated in chapter 4) and therefore a much larger vessel is required.

2.3. The social housing stock.

The current housing stock consists of over 7.200.000 dwellings and has not grown much in recent years (CBS, 2014). From 2020, all new built houses are energy neutral (they are obligated to be so). For the rest of the all the houses in the Netherlands, the renovation rate should be increased significantly to make them all energy neutral by 2050. The model in this thesis will be made for one apartment type. This subchapter will explain which apartment type has the most potential and will therefore be used for the model on the basis of the following criteria: collective heating, ownership, building period and size of stock. A database of the stock of all the housing corporations is used, namely Shaere. This the database of Aedes, a union of housing corporations. It contains the data of over 1.7 million out of the 2.4 million dwellings in the social housing stock.

Out of all housing types, only apartments are considered in this thesis for two important reasons. First, collective heating is highly desirable and 92% of the social housing stock connected to collective heating are apartments. Secondly, because housing other than apartments have a low density of houses. Transport and distribution of heat is expensive. This means that the costs for the heat tubing will be high. The presence of collective heating is important for two reasons: a social one and economic one. First socially, it means that all the tenants are already familiar with collective heating and there is not going to be a major change. Changing from individual boilers to collective heating often creates a lot of resistance from the tenants. Second economically, the heat distribution system is already in place and is thus a financial advantage. If there is no collective heating yet, it depends on the housing type whether it is easy to install it. In the social housing stock, 16% of the housing has collective heating. Apartments of the type ‘galerieij’ cover 67% of all social housing connected to collective heating, and apartments of the type ‘portiek’ 23%.

As already stated multiple times in this report before, only apartments of social housing corporations are considered in this thesis and the reason is very simple. Namely, a group of apartments within an area can belong to only one owner. The Ecovat vessel is a one-time construction that can last for a hundred years.

\(^6\)To be clear, in reality this is not correct and the customer should define its own goals about what the energy sources should be. Whether they want more sustainably generated energy within the area (with PVT) or be more dependent on the electricity grid.
technically. Therefore the size of the vessel should be of adequate proportion. Building this vessel for private owned apartments is too risky since there is no guarantee about the number of households that will join the project or stay connected in the future. Also, the initial number of connected apartments is likely to be the highest with housing corporations. To reach this with privately owned housing is nearly impossible. Social housing corporations too, have to have 70% of the tenants approval for the project but once this is reached, there is more certainty about the number of apartments in the project now and in the future. In the Netherlands the housing stock is divided as following, in terms of tenures 60% owner occupation, 33% social renting which is the highest share in the EU and 7% private renting (Pittini, 2015).

The energy index is very different per building period. The housing type however, does not strongly influence the energy index. Therefore, the most improvement can be made on apartments from earlier building periods. Since the housing corporations often use an exploitation time of 50 years, it can be expected to have an increase in renovation in the houses of those earlier building periods.

Table 2 shows that terraced housing is the largest share of the social housing stock. In regards to the potential for the application of the Ecovat system, only at the largest market shares might be interesting, such as terraced housing. However, as discussed in the previous paragraphs, those are unsuitable for the low density (and therefore high costs in the heat distribution grid) and are often not connected to heating grids or collective heating.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Terraced house in between</td>
<td></td>
<td>163</td>
<td>121</td>
<td>81</td>
<td>43</td>
<td>23</td>
<td>60</td>
<td>492</td>
</tr>
<tr>
<td>Terraced house corner</td>
<td></td>
<td>85</td>
<td>62</td>
<td>42</td>
<td>21</td>
<td>11</td>
<td>23</td>
<td>244</td>
</tr>
<tr>
<td>Detached house</td>
<td></td>
<td>2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Apartment building ‘galerij’</td>
<td></td>
<td>33</td>
<td>139</td>
<td>53</td>
<td>50</td>
<td>33</td>
<td>159</td>
<td>468</td>
</tr>
<tr>
<td>Apartment building ‘portick’</td>
<td></td>
<td>190</td>
<td>49</td>
<td>50</td>
<td>59</td>
<td>27</td>
<td>49</td>
<td>425</td>
</tr>
<tr>
<td>Apartment building ‘maisonette’</td>
<td></td>
<td>13</td>
<td>4</td>
<td>10</td>
<td>6</td>
<td>2</td>
<td>5</td>
<td>41</td>
</tr>
<tr>
<td>Apartment building ‘other’</td>
<td></td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>1</td>
<td>6</td>
<td>15</td>
</tr>
<tr>
<td>Semi detached</td>
<td></td>
<td>26</td>
<td>10</td>
<td>6</td>
<td>3</td>
<td>2</td>
<td>5</td>
<td>52</td>
</tr>
<tr>
<td>Building with non-independent living space</td>
<td></td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td>517</td>
<td>387</td>
<td>247</td>
<td>186</td>
<td>100</td>
<td>309</td>
<td>1.746</td>
</tr>
</tbody>
</table>

To conclude, on the basis of the following criteria: collective heating, ownership, building period and size of stock, two building types and two building periods have the most potential for the Ecovat system (Table 3). The model in chapter 4 is made for the apartment building ‘portiek’ from the building period <1965.
Table 3 Building types and building periods with the most potential for Ecovat

<table>
<thead>
<tr>
<th>Building type</th>
<th>Building period</th>
<th>Heating</th>
<th># Houses</th>
<th>Gas consumption (m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Apartment building 'galerij'</td>
<td>&lt;1965</td>
<td>Collective</td>
<td>8.318</td>
<td>786.46</td>
</tr>
<tr>
<td>Apartment building 'galerij'</td>
<td>1965-1975</td>
<td>Collective</td>
<td>95.452</td>
<td>886.38</td>
</tr>
<tr>
<td>Apartment building 'portiek'</td>
<td>&lt;1965</td>
<td>Collective</td>
<td>8.931</td>
<td>1.034.35</td>
</tr>
<tr>
<td>Apartment building 'portiek'</td>
<td>1965-1975</td>
<td>Collective</td>
<td>24.973</td>
<td>775.83</td>
</tr>
</tbody>
</table>

2.4. The electricity market system

The business case of the Ecovat system is for a large part dependent on the price fluctuations on the energy market. First, this subchapter will give some contextual information on the electricity grid. Then this part explores the possibilities and future scenarios of the energy market. Finally, will be explained how Ecovat will make use of these opportunities.

To create a free market system in the electricity sector, the functions of generation and retail are separated from the functions of transmission and distribution. In the European Union (EU), each country has a transmission system operator (TSO). The TSO has two tasks. First, own and operate the transmission grid (i.e., the high-voltage grid). Secondly, maintain a balance between supply and demand. Hence, the TSO is responsible for the security of supply. The TSO is also responsible for cross country bulk transfer of electricity. These international connections are used to solve national surplus or shortages. The Dutch transmission system operator is TenneT. The TSO delivers the electricity from central generation facilities to several regional network operators, the distribution system operators (DSO) such as Liander and Stedin who deliver the electricity to the consumers.

Wind power is associated with fluctuations that can be different between day and night, or seasonal, or in fact from minute to minute. Fluctuations lead to grid imbalances which then leads to issues on the reliability and availability. Given the drivers at European Union and Dutch level to increase the share of renewable energy sources, and wind being the most important renewable energy source in the Netherlands, large investments in wind-energy in the near future to meet 2020 targets are inevitable. Utilities or grid operators have to find ways to deal with the fluctuations accompanying wind. There should be a system in place where the peaks and troughs of wind can be managed. Statistics give insight in the long-term average production of wind energy, but not in the actual moment of production. The unpredictability of wind and energy production may result in more short-term trades and thus in a more volatile spot price with lower minima and higher maxima. Countries with high volatility such as Germany and Denmark can be taken as an example how the volatility in Netherlands could be in the future. The increase in photovoltaic capacities in Germany had since 2011 on some days already significant impacts on spot market prices at the German electricity exchange. The variability of the generation of renewables will further increase if much higher quantities of wind and PV are fed into the grid. The effects of these developments on the prices in electricity markets will be (Haas, Lettner, Auer, & Duic, 2013):
• Much higher price volatility from hour-to-hour and day-to-day;
• Higher prices for electricity from fossil capacities and storage technologies for balancing the intermittent renewable generation;
• Growth of balancing markets and intensified competition at the level of decentralized balancing organizations.

Increasing wind and solar power generation above a 30% share in annual electricity consumption will dramatically increase flexibility requirements. Especially large PV contributions of more than 20-30% in the wind/PV mix will foster this trend. The future flexibility requirements in power systems in Europe will depend on three major parameters: the share of variable renewables, their mix and the balancing area size (Huber, Dimkova, & Hamacher, 2014). This study showed that balancing larger, well-interconnected power systems can reduce ramp requirements substantially. For example, it showed that at 50% variable generation penetration, the most extreme hourly net load ramp drops from 30% of peak load at the regional level to 22% for a large country and 11% for an interconnected Europe.

The imbalance in supply and demand of electricity is a major driver for the business case of the charging strategy of the Ecovat. As stated by (Haas et al., 2013) storage technologies can charge high prices for balancing the volatile renewable generation. Given a large deployment of wind and solar capacities, there are two major impacts on electricity systems: First, the electricity system must be flexible enough to cope with the volatile renewable energy source generation, i.e., ramp up supply or ramp down demand on short notice. Secondly, sufficient back-up capacities are needed during times with low feed-in from wind and solar capacities (Bertsch, Growitsch, Lorenzczik, & Nagl, 2014). The Ecovat system can be used as back-up capacity with battery packages parallel to the thermal storage vessel. However, in the scope of this thesis only thermal storage will be taken into account. Therefore delivering energy back to the grid will not be considered and only demand side flexibility will be the core for the business case. The future flexibility requirements of the electricity grid will also create opportunities for other technologies than the Ecovat system and the competition can intensify. Examples here are power to production, power to steam and an domestic demand response. Whether this competition will be a serious threat to the business case for the Ecovat charging strategy, does not lie within the scope of this thesis. The pricing of the day-ahead market and the real-time pricing forecast in this thesis will be based on the pricing of recent years. No assumptions or predictions will be made about the increase of the need for flexibility and the possible competitors in this level playing field.

In this thesis, two level playing fields will be used. First the spot market, also known as the APX or as the Day Ahead Market (DAM). This is a market for purchase and sale of electricity per hour per day. It offers the opportunity of a higher return by responding to current events. You may trade up till a day ahead, where you buy a certain amount of energy for the next day. Therefore this market will hereon be referred to as the day ahead market. Secondly, the imbalance market which is a mechanism to alter imbalances between supply and consumption on the national grid. When an excess of electricity occurs, you can seize
the opportunity consume energy at a low price. This price varies every minute and the highest (or lowest) price of every fifteen minutes determines the price for that entire fifteen minutes. This is not a market on which you can trade energy, it is a market on which it is possible to respond on the energy price. Figure 4 shows the price per MWh on the imbalance market in the Netherlands of the first week of January 2014. The price dropped below €0,- 80 times in that week. This gives plenty of opportunities to charge the vessel if the power capacity of the heat pumps and power to heat resisters is sufficient.

Figure 4 The price on the imbalance market of the first week of January 2014. Source www.tennet.org For the price of the whole year, see Appendix B
The day ahead price is a price per hour and isn’t as volatile as the imbalance price as shown in Figure 5. The day ahead price hardly ever goes under €0.7/MWh, thus the imbalance market seems far more lucrative than the day ahead market. However, when there have not been any opportunities on the imbalance market for a while and the storage reserve is running low, the day ahead market becomes more interesting to bid on. The lesser useful energy is stored in the Evacov, the higher the price level will be on which the installation will be triggered. All installations, both heat resistors, as heat pumps will use their maximum capacity when the price on the imbalance market is below €0.7/MWh, and the vessel is not yet fully charged.

![Figure 5 The price on the day ahead market of the first week of January 2014. For the price of the whole year, see Appendix C.](image-url)
3.
3. Case description and scenario development

As discussed in 2.3, the apartment types ‘galerij’ and ‘portiek’ from building period <1965 and 1965-1975 have the most potential for the Ecovat system. The model in chapter 5 is made for an apartment building ‘portiek’ from the building period <1965. The case is a project in Eindhoven and it consists of 78 dwellings divided over 5 apartment buildings. The building year is 1958 and therefore fits with the requirements of the conclusion of 2.3. However, some limitations of this should be stated here. First, each apartment building has only 15 or 18 houses which make the project rather small scale for the Ecovat system. Secondly, the façade is authentic which means no insulation can be applied on the outside of the façade. Finally and most importantly, the apartment buildings are relatively far apart which means high costs for the heat distribution (Figure 6). In its defence, these sub optimal factors will not influence the system model, only the investment costs.

3.1. Current state

All five apartment buildings have their own collective heating system to which all the houses are connected to. So there are five kettle houses with each their own natural gas heated kettles. Each kettle house has three kettles connected in cascade. The tap water is heated individually with a boiler in every apartment. These boilers have a very low COP estimated at 0.5. Since the early 70’s, the housing corporations have actively been renovating their social housing stock step by step. However, as depicted in Table 4, the current level of insulation still offers much potential for improvement.

Figure 6 Situation of the five apartment buildings
Table 4 State of the insulation of the apartments

<table>
<thead>
<tr>
<th>Building component</th>
<th>Insulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brick façade</td>
<td>Unknown (most likely no insulation)</td>
</tr>
<tr>
<td>Panel façade</td>
<td>No (2m² per apartment)</td>
</tr>
<tr>
<td>Roof</td>
<td>Yes (marginally)</td>
</tr>
<tr>
<td>Floor</td>
<td>No</td>
</tr>
<tr>
<td>Glazing</td>
<td>Double glass (18m² to 22m² per apartment)</td>
</tr>
<tr>
<td>Window frame</td>
<td>Separated thermally</td>
</tr>
<tr>
<td>Door</td>
<td>No (1,8m² to 4m² per apartment)</td>
</tr>
</tbody>
</table>

3.2. Renovation Scenarios

Renovation of the existing housing stock of a particular building is necessary over time, not only to improve the energy performance but also to improve the comfort level and raise the value of the building. However, in this thesis only the improvement of the energy performance will be taken into account in the final results. Housing corporations often just renovate or replace what is necessary at a certain point, step by step. Renovation in one big leap is rare, although this strategy is increasing. With the Ecovat system, a renovation in one leap is proposed for all scenarios.

Ecovat will deliver the energy to the point where the collective heating installation starts, namely the kettle/installation room of each apartment building. The housing corporation takes it over from there and is thus responsible for the distribution from this point to the individual apartments. The Ecovat system is responsible of the energy supply up to this point. All that is required from the system is that it delivers the required amount of energy at the right temperature that is needed for heating the dwellings and tap water. How the Ecovat system will store or generate it's energy is of little interest to the housing corporation. Since their expertise with technologies such as the Ecovat system is limited, they would rather not be troubled with the possible implications of the Ecovat system.

A top-down approach is used to set up the scenarios. Namely, the output of each scenario is relevant for the system model and not the specific details of these renovation scenarios. This output consists of two aspects about the renovation that are relevant for the system model. First, the yearly heat demand for each renovation scenario. Secondly, the input temperature $T_{in}$ and output temperature $T_{out}$. Each scenario will also have a cost price but this is not relevant for the system model, only for the cost calculation. Thus, the yearly heat demand and the $T_{in}$ and $T_{out}$ are determined for each scenario.

As will be explained in more detail in subchapter 4.3, the distribution of the space heating demand is different over time than the distribution of the tap water heating demand. The space heating demand is highly dependent on the season whereas the tap water heating demand is roughly the same ever day of the year. As a result, these two heat demands have a different impact on the configuration of the Ecovat system. Therefore, these two different heat demands are separated in the scenarios. In Table 5 and Table
6 the four scenarios for the case are depicted. The current heat demand in Table 6 is not a theoretically calculated heat demand but the actual heat demand. The consumption data on 2014 was collected and then calibrated for the days of degrees of that year, as will be explained in detail in subchapter 4.3.

The tap water heating system is assumed to be improved in all scenarios since the boilers are very inefficient currently with a COP of 0.5. There are three possibilities for the improvement of the tap water heating system. First, the boilers are replaced by boilers with a higher COP of 0.9. This will not be considered as a possibility since this still makes the apartments very dependent on gas and decreases the necessity of the Ecovat system. Secondly, if the Ecovat system is made to supply heat for a 70/50 heating system then no extra heating will be necessary in the dwellings for the tap water heating (since this needs to be above 65°C). So in that case the whole system always has to deliver 70°C even in the summers. Thirdly, if the 40/30 heating system is applied, then the apartments will need to have their own individual heat pumps for the tap water. The second and third possibility are used for scenario 1, 2 and scenario 3, 4 respectively.

| Table 5 Heat demand and temperatures of the renovation scenarios in percentages |
|-----------------------------------------------|----------------|----------------|----------------|----------------|----------------|
| Space heating % | 100% | 100% | -25% | -25% | -50% |
| Tap water heating % | 100% | -25% | -25% | -25% | -50% |
| T_{in} °C | 90 | 70 | 70 | 40 | 40 |
| T_{out} °C | 70 | 50 | 50 | 30 | 30 |

| Table 6 Heat demand and temperatures of the renovation scenarios in absolute values |
|-----------------------------------------------|----------------|----------------|----------------|----------------|----------------|
| Space heating GJ | 1635,8 | 1635,8 | 1226,8 | 1226,8 | 817,9 |
| Tap water heating GJ | 1048,8 | 786,6 | 786,6 | 786,6 | 524,4 |
| T_{in} °C | 90 | 70 | 70 | 40 | 40 |
| T_{out} °C | 70 | 50 | 50 | 30 | 30 |

Each of the different scenarios is described individually. The reductions of the heat demand are not elaborated with solutions. Again, this is done so on purpose since there are numerous solutions to reach for example a space heating demand reduction of 25%. The focus in this thesis is not on the most effective solutions in heat demand reductions. All that is necessary for the system model is the output of the different renovation scenarios.

**3.2.1. Scenario 1 - Poor**
This scenario is the least ambitious scenario of these four scenarios. The space heating demand stays the same. In other words, no improvements are made to decrease the energy consumption for space heating. The input temperature T_{in} will be lowered to 70°C, and the output temperature of the system T_{out} will then be 50°C. With these temperatures the system can provide both space heating and tap water heating,
without extra installations in the dwellings. The removal of the inefficient boilers is expected to reduce
the heat demand for tap water by 25%.

3.2.2. Scenario 2 - Reasonable
Compared to scenario 1, only the demand for space heating is decreased by 25%. The tap water demand
is the same as in scenario 1, namely 25% less than currently. $T_{in}$ will be 70°C and $T_{out}$ will be 50°C.

3.2.3. Scenario 3 - Good
The energy demand is the same as in scenario 2, thus a 25% decrease for both space heating and tap
water heating. $T_{in}$ and $T_{out}$ will be 40°C and 30°C respectively. This means that the space heating system
will be outlined for maximum 40°C. For the tap water, individual electric heaters will be placed in the
dwellings to bring the tap water to 65°C.

3.2.4. Scenario 4 - Excellent
This is the most ambitious scenario of these four scenarios. The tap water demand is reduced compared
to scenario 3, namely 50% less than currently. The space heating demand will be 50% less than currently.
The $T_{in}$ and $T_{out}$ will be the same as in scenario 3, namely 40°C and 30°C respectively.

3.2.5. Comparison
Before the model shows any results, some advantages and disadvantages on all four scenarios can already
be stated. Note that the housing corporation wants to exploit the apartments for at least another 25 years.
This means that the advantages and disadvantages need to be put in a perspective of 25 years (or even
more preferably).

Table 7 Advantages and disadvantages of the different renovation scenarios

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1</td>
<td>-Minimum changes to the building, which means the least hazards with the current inhabitants. It is plug and play. -No over investments in the building if the Ecovat can always deliver the heat for a reasonably fixed price.</td>
<td>-A fully charged Ecovat can use less energy, namely only heat from 70°C to 90°C (a low ΔT). -Solar energy is less useful for charging the Ecovat since the PVT panels have relatively low output temperatures. -A low quality building with a high quality energy system (the Ecovat system).</td>
</tr>
<tr>
<td>Scenario 2</td>
<td>-Renovating the building improves the quality and life expectancy. -The reduction of the energy demand will have an effect for the whole life cycle of the building.</td>
<td>-A fully charged Ecovat can use less energy, namely only heat from 70°C to 90°C. -Solar energy is less useful for charging the Ecovat since the PVT panels have relatively low output temperatures.</td>
</tr>
<tr>
<td>Scenario 3</td>
<td>-High comfort level (low temp. heating). -Renovating the building improves the quality and life expectancy.</td>
<td>-Installing low temperature heating can lead to more hazards for the current inhabitants at construction time.</td>
</tr>
</tbody>
</table>
- Price for heat could become dependent on the input temperature in the future (currently the quality of the heat is not considered in the NMDA-principle	extsuperscript{7}, only the quantity of heat).

Scenario 4

- Will probably need the smallest and cheapest Ecovat system because of low heat demand and a high usable $\Delta T$ in the Ecovat vessel.
- High comfort level (low temp. heating).
- The quality of the apartments will be very high.
- The life expectancy of the apartments is highest.
- High costs to reach a reduction of the energy demand of 50%.
- 50% energy reduction might be hard to accomplish since the façade is authentic and cannot be covered or removed.
- Installing low temperature heating can lead to more hazards for the current inhabitants at construction time.

Agentschap NL (2011) calculated the costs for every housing type, building period, and divided it into sub-types within an apartment building, e.g. a corner-roof apartment and an in-between first floor apartment. These calculated costs for primary energy consumption are based on a theoretical energy label calculation method. The theoretical energy label calculation method is often not comparable to the actual consumption due to user behaviour changes, system losses and other (Daša Majcen, Itard, & Visscher, 2013). Therefore, this data is calibrated to make it suitable for this thesis. There is less variation in the actual consumption than in the theoretical consumption. The theoretical consumption of a house with label C is comparable to the actual consumption. However, the actual consumption of a house with label A is higher than the theoretical consumption. Moreover, the actual consumption of a house with label G is far less than the theoretical consumption as depicted in Figure 7.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure7.png}
\caption{Actual and theoretical gas consumption for each energy label. Source (D. Majcen, Itard, & Visscher, 2013)}
\end{figure}

\textsuperscript{7} The not more than else (dutch: niet meer dan anders) principle means that the price the consumer pays for heat cannot be higher than the average price for heat in a comparable situation with a natural gas boiler.
The next step is calculating the average cost for the apartments. The costs for the roof apartments (1/3 of all the apartment in this project) are much higher than for the ground floor apartments. The total is calculated bottom-up based on 6 different sub-types, namely corner roof, corner middle, corner ground, in-between roof, in-between middle and in-between ground. Then the total costs is divided over 78 apartments, giving an average cost per apartment in this case (Table 8).

*Table 8 Cost of renovation scenarios explicitly in the building.*

<table>
<thead>
<tr>
<th>Renovation scenario</th>
<th>Renovation costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1</td>
<td>€ 4,000</td>
</tr>
<tr>
<td>Scenario 2</td>
<td>€ 8,000</td>
</tr>
<tr>
<td>Scenario 3</td>
<td>€ 12,000</td>
</tr>
<tr>
<td>Scenario 4</td>
<td>€ 20,000</td>
</tr>
</tbody>
</table>
4.
4. System modelling

This chapter explains the system model step by step. First, to understand the system model, the configuration of the physical system is explained in subchapter 4.1. Then in subchapter 4.2 the set-up of the system model is explained along with the assumptions that lie underneath. Note that when the term system is used, this means the physical system configuration and when the term model or system model is used, this means the system model that is developed in this thesis about the system. Then in the following subchapters, each part of the system model is elaborated individually. Finally subchapter 4.10, explains how the model is used to find optimal configurations.

4.1. System design

Figure 8 shows a simplified schema of the Ecovat system. In the middle, the thermal storage vessel is displayed as five separate boxes, but of course in reality these layers are not separated and just form one vessel. The Ecovat energy storage system is a hybrid system that stores both electricity (in batteries) and thermal energy (in the underground vessel). However, only thermal storage will be modelled, therefore all energy will be converted to thermal energy and no energy is stored in batteries. The right part of Figure 8 shows the heat demand of the apartments and the heat loss of the storage. The left side shows the different installation devices that can add energy or improve the energy quality. The purpose and setup for each part on the left and right of the thermal storage vessel is elaborated in the following subchapters. A brief explanation will be given here.

There are five types of devices in the model that can deliver energy to the vessel (or improve the energy quality in the vessel). These are PVT panels, a low temperature water/water heat pump (lthp), a high temperature water/water heat pump (hthp), an air/water heat pump (awhp), and a power to heat resistor (res). Each device has its own function.
• The PVT panels can be left out of the system if desired. Depending on the desires of the housing corporation, they can be implemented. Including PVT panels in the system has a major consequence for the other devices in the system. Namely, the temperature that comes from the PVT panels is much too low to use for residential heating. Therefore this temperature needs to be raised with the lthp and hthp.
• The lthp and hthp do not actually add energy to the vessel. They bring one layer to a lower temperature and another layer to a higher temperature at the same time. These water heat pumps do not have a range from 0 to 85°C, therefore this is split into two pumps with each their own range.
• The lthp is used for two main purposes. First, the temperature of layer 5 needs to be at 5°C for the cooling of the PVT panels. Therefore, all the energy that is delivered to the layer 5 from the PVT panels, should be moved to the upper layers. The temperature of layer 5 will then remain at 5°C. Secondly, whenever the temperature in layer 5 is lower than 5°C, then the heat pump can be put to use to bring energy from layers other layers to upper layers. The range of the lthp is 0 to 55°C.
• The hthp has a range of 49 to 85°C. Just as the lthp, this pump raises the temperature of an upper layer and at the same time lowers the temperature of another layer.
• The awhp has a range of 0 to 65°C and is used to add energy to layers with a temperature lower than 59.
• Finally, the power to heat resistor is necessary to charge the vessel rapidly when the imbalance price is low. This is the most important device in the system, with the highest installed power capacity.

The setup as it is displayed in Figure 8 is not the only possible set-up of the system but it will be the setup for this thesis. In other setups for example, the PVT part or the resistor, or even some heat pumps could have been left out. However, every part of the system is there for a reason. What the setup looks like is dependent on the charging strategy and the preferences of the customer. Namely, the preference of a customer could be a large share of PVT panels or perhaps the customer does not even care how the energy is generated and what thus the setup of the system looks like.

The charging strategy for the Ecovat can be made very complex. Therefore, some assumption are made to simplify the strategy. The charging strategy can be explained with the concept of ‘charging cycles’. One charging cycle is the amount of useful energy in a fully loaded vessel, thus the useful capacity of the vessel. The number of charging cycles is thus determined by dividing the total annual energy demand by the useful capacity of a fully loaded vessel. Table 9 shows the number of charging cycles for the case per renovations scenario and per size of the Ecovat vessel. The amount of energy that we can sell is the same with every charging strategy, namely the total heat demand of all the apartments in one year. A vessel with only one charging cycle per year, is big and has thus a high investment cost. A vessel with for example 6
charging cycles per year, can be 6 times smaller than with only one charging cycle. A vessel 6 times smaller is considerably cheaper (see Table 1 in subchapter Table 12.1). We can notice big differences between the first two scenarios and the last two scenarios in Table 9, namely in the heat capacity and charging cycles. In case of 70/50 heating the vessel has a very small ΔT of useful energy namely 90 – 70 = 20°C. In the case of 40/30 heating the ΔT is 90 – 40 = 50°C. Also the heat demand is lower in the 40/30 scenarios which contributes to an even lower number of charging cycles. Thus the renovation scenarios have a significant influence on the number of charging cycles.

Table 9 Charging cycles of the case per renovation scenario with Ecovat size S, M or L

<table>
<thead>
<tr>
<th>Size</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
<th>Scenario 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual heat demand (kWh)</td>
<td>672.878</td>
<td>559.282</td>
<td>559.282</td>
<td>372.854</td>
</tr>
<tr>
<td>Tin (°C)</td>
<td>70</td>
<td>70</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Tout (°C)</td>
<td>50</td>
<td>50</td>
<td>30</td>
<td>30</td>
</tr>
<tr>
<td>Heat capacity (kWh)</td>
<td>S 8.442</td>
<td>S 8.442</td>
<td>M 163.799</td>
<td>M 163.799</td>
</tr>
<tr>
<td>Charging cycles</td>
<td>S 79.7</td>
<td>M 27.909</td>
<td>M 24.1</td>
<td>M 20.0</td>
</tr>
<tr>
<td>Heat capacity (kWh)</td>
<td>M 49.549</td>
<td>M 11.3</td>
<td>L 622.847</td>
<td>L 3.4</td>
</tr>
<tr>
<td>Charging cycles</td>
<td>S 11.3</td>
<td>S 7.5</td>
<td>L 0.9</td>
<td>L 0.6</td>
</tr>
<tr>
<td>Heat capacity (kWh)</td>
<td>L 106.123</td>
<td>L 106.123</td>
<td>L 622.847</td>
<td>L 2.3</td>
</tr>
<tr>
<td>Charging cycles</td>
<td>L 6.3</td>
<td>L 5.3</td>
<td>L 0.9</td>
<td>L 0.6</td>
</tr>
</tbody>
</table>

Figure 9 shows an example of the effect of the number of loading cycles on the investment costs and the breakeven point. We can see a comparison of three vessels, size S, M and L, for renovation scenario 1. The number of charging cycles is 79.7, 24.1 and 6.3 respectively. The payback time is 8.5 years and 22 years for size S and M resp. This means that more loading cycles results in a shorter payback time. This does not necessarily mean that more charging cycles is better. More charging cycles also means that the vessel can deplete in a very short time in the winter. If there are no or little opportunities on the energy market in that particular time, the costs for charging the vessel can be very high. For example, a vessel with 24 charging cycles only has enough energy to supply the apartments for 2 weeks, and even less in the coldest period of the year. In scenario 1, vessel S would have 79.7 charging cycles. This means that a fully charged vessel would only contain enough energy for four winter days. This is far too little, since the risk of depletion is high. On the other side, scenario 4 with vessel size L would result in 0.6 charging cycles. In this case the vessel would be unnecessarily big. Therefore, for the results in chapter 5, only two sizes will be investigated for each renovation scenario. Namely, size M and L for scenario 1 and 2, and size S and M for scenario 3 and 4.

---

8This ΔT is even lower for the bottom layers since the temperature limit for layer 1, 2, 3, 4 and 5 is 90°C, 75°C, 50°C, 30°C and 5°C respectively, as will be explained in subchapter 4.2.
Not: For this comparison, only the capital costs of the vessel and the income on the sale of energy are taken into account here. The costs for the installation (heat pumps, power to heat, etc.) are higher with more loading cycles since the power capacity should be higher.

In addition, Table 10 shows the advantages and disadvantages of the different installation devices. These should be kept in mind for the next subchapters in order to understand the strategies that are developed for the system model.

<table>
<thead>
<tr>
<th>Energy Source</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>PVT</td>
<td>- Predictable long term generation</td>
<td>- No high temperature output</td>
</tr>
<tr>
<td></td>
<td>- High reliability</td>
<td>- High investment costs (€250,-/panel)</td>
</tr>
<tr>
<td></td>
<td>- Sustainable energy generated within the area</td>
<td>- Little output when the demand is high and vice versa</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Roof space required</td>
</tr>
<tr>
<td>Resistor</td>
<td>- Cheap to charge Ecovat vessel rapidly</td>
<td>- Dependency on energy market, less predictable in long term</td>
</tr>
<tr>
<td></td>
<td>- High output temperatures</td>
<td>- Low COP of 1</td>
</tr>
<tr>
<td></td>
<td>- High power capacity</td>
<td>- Restricted by flow capacity of vessel walls</td>
</tr>
<tr>
<td></td>
<td>- Low investment costs (€30,-/kW)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Opportunities all year round</td>
<td></td>
</tr>
<tr>
<td>Heat pumps</td>
<td>- Improve stratification in Ecovat</td>
<td>- Dependent on energy market, less predictable in long term</td>
</tr>
<tr>
<td></td>
<td>- Bring PVT output to higher temperature</td>
<td>- Opportunities all year round</td>
</tr>
<tr>
<td></td>
<td>- High COP</td>
<td>- High investment costs (€600,-/kW)</td>
</tr>
</tbody>
</table>

### 4.2. Model design

Figure 10 shows a schematic view of the system model. The model starts with a setup. More on the different possible setups in subchapter 4.10. From the setup the data is loaded, namely the current data of
the vessel and three external sources of data namely the power capacity of the installation, the heat demand and the energy price. After that, on the basis of this loaded data, the model will run seven parallel processes. Each of these seven process can decide whether to take action or not based on the data that was sent to the setup. Each of these seven processes will be elaborated in the subchapters that are under the headers in Figure 10. When one hour has passed, the data of the vessel will be updated. The setup will load this new data of the vessel and the energy price and heat demand of this new hour. The power capacity of the installation will stay the same. This process is repeated until t=8760 is reached which is the end of one year.

The heat storage vessel is divided into five layers that can be charged and discharged independently. From a study on the thermal stratification it is assumed there is no de-stratification. For a conductivity range below 1 W/m·K no important de-stratification effects have been observed, although for higher values relevant changes in both the exergy performance (up to 4% lower for Ecovat S) and in stratification level have been detected (UPC, 2014). Therefore each layer will be regarded as an independent storage vessel.

The goal of the model is to calculate the total cost that is needed on a yearly basis to keep the state of each layer in the vessel at a sufficient state (e.g. temperature). For each layer will be defined what is sufficient and more. The state of each layer is determined as following.

\[
T_{t+1} = T_t + \frac{Q_{in} - Q_{out} - Q_{loss}}{m \cdot C_p \cdot 3600}
\]  

(4.1)

Where:

- \( T_{t+1} \) : temperature of the layer at time \( t+1 \) (°C)
- \( T_t \) : temperature of the layer at time \( t \) (°C)
- \( Q_{in} \) : total heat input to the layer (kWh)
- \( Q_{out} \) : total heat output from the layer (kWh)
- \( Q_{loss} \) : storage loss per hour (kWh)
- \( m \) : mass of the layer (kg)
- \( C_p \) : specific heat capacity = 4,186 (kJ/(kg·K))
- \( t(0) \) : January 1, 2014
- \( T_{in} \) : 70 or 40 (°C) for scenario 1 or 2 and 3 or 4 respectively
- \( T_{out} \) : 50 or 30 (°C) for scenario 1 or 2 and 3 or 4 respectively

In other words, the state of each layer at a certain hour is the net flow of energies in and out of the previous hour plus the temperature of the previous hour. The energy output is the sum of all the energy flows going out of a layer as following.

\[
Q_{out} = Q_{out\, lhp} + Q_{out\, lhp} + Q_{demand}
\]  

(4.2)

Where:

- \( Q_{out\, lhp} \) : energy that is extracted from a layer by the low temperature heat pump (kWh)
\( Q_{\text{out htp}} \)  
energy that is extracted from a layer by the high temperature heat pump (kWh)

\( Q_{\text{demand}} \)  
energy that is extracted from a layer and pumped to the apartments (kWh)

The energy input is the sum of all the energy flows going into a layer as following.

\[
Q_{\text{in}} = Q_{\text{in ltp}} + Q_{\text{in htp}} + Q_{\text{in awhp}} + Q_{\text{in pvt}} + Q_{\text{in res}}
\]  
(4.3)

Where:

\( Q_{\text{in ltp}} \)  
energy that is added to a layer by the low temperature heat pump (kWh)

\( Q_{\text{in htp}} \)  
energy that is added to a layer by the high temperature heat pump (kWh)

\( Q_{\text{in awhp}} \)  
energy that is added to a layer by the air/water temperature heat pump (kWh)

\( Q_{\text{in pvt}} \)  
energy that is added to a layer by the PVT panels (kWh)

\( Q_{\text{in res}} \)  
energy that is added to a layer by the power to heat resistor (kWh)
Figure 10 Flowchart of the system model in BPMN notation
Furthermore, the following assumptions are defined:

1. The model starts at $t(0) = \text{January 1, 2014}$
2. The state of the vessel starts at an arbitrary but sufficient temperature at $t(0)$, namely $T_{t(0)} = 90 \degree C, 75 \degree C, 50 \degree C, 30 \degree C, 5 \degree C$ in layer 1, 2, 3, 4, 5 respectively.
3. The height of the layers in the vessel is 3,3m for layer 1, 2 and 3 and the height is 2,9m for layer 4 and 5. This is the same for all vessel sizes. Only the diameter is different.
4. The energy used to pump the water in and out of the devices and to the apartments not taken into account.
5. The density of the water in the vessel and in the tubes is considered to be at a constant 1.000 (kg/m³) at all times.
6. The maximum flow capacity of the vessel $q_{\text{max}}$ is $6,5 \text{ m}^3/\text{h}$ per layer for size S, $13 \text{ m}^3/\text{h}$ for size M and $26 \text{ m}^3/\text{h}$ for size L.
7. All devices in the system model are either on or off. So the devices always use their full power capacity. Except the pvt panels, their production is dependent on the ambient temperature and the global radiation.
8. $\Delta T_{\text{hp}}$ of all 3 different heat pumps is 6°C. This means that these pumps raise (and lower) their input temperatures by 6°C. A high $\Delta T_{\text{hp}}$ results in a low COP and a very low $\Delta T_{\text{hp}}$ means high energy consumption for the pumping of the water compared to the delivered energy. The balance between these two effects is estimated to be at 6°C.
9. $\Delta T_{\text{rs}}$ = the temperature difference between the water flowing in and out of the power to heat resistor, is 13,3°C. This is the maximum temperature difference related to the maximum flow rate of the layer and the heat transmission capacity. The temperature difference is not relevant for the efficiency of the resistor. Namely, the COP is always 1, thus the electric energy going into the resistor is equal to the energy flowing out.
10. The temperature flow out of a layer is assumed to be the same temperature as the temperature of that particular layer.
11. The maximum temperature for each layer is 90, 90, 79, 49, 5°C for layer 1, 2, 3, 4, 5 respectively. The reason is the following; First, layer 5 is used for the cooling of the pvt panels which is stated at 5°C. Therefore the installation will act to bring it back to 5°C whenever this temperature is higher than 5°C. Secondly, the energy that is extracted from layer 5 to bring it back to 5°C must be delivered to another layer. This is done with the lthp which has a max output of 55°C. Since $\Delta T_{\text{hp}} = 6\degree C$, the lthp can only deliver energy to a layer when the temperature of that layer is lower than $55 - 6 = 49\degree C$. If this temperature would be higher than 49°C then the lthp cannot keep layer 5 at 5°C. Therefore one layer, layer 4 needs to stay under 49°C. Thirdly and consequently, in order to keep the temperature in layer 4 under 49°C, the hthp needs to take energy from layer 4 and bring it to upper layers. The maximum delivery temperature of hthp is 85°C and since $\Delta T_{\text{hp}} = 6\degree C$, the hthp can only deliver energy to a layer if it is below $85 - 6 = 79\degree C$. Therefore, to keep
layer 2 under 49°C, layer 3 needs to stay under 79°C. When the temperature of layer 3 goes above 79°C, no energy will be added to this layer until the heat demand of the apartments has brought it back under 79°C. Fourthly, the temperature of layer 4 can be as high as possible. The resistor can deliver temperatures far above 100°C, but the temperature in the vessel cannot be higher than 90°C since boiling the water would result in too much pressure on the top of the vessel. The same accounts for layer 5.

12. The energy price at every 15 minutes is the lowest price available at that time on the day ahead market or the imbalance market. Most of the times this is the price on the imbalance market.

\[ P = \min (P_{\text{dam}}, P_{\text{imb}}) \]  

(4.4)

Where:

\( P \)  
energy price (€/MWh)

13. The energy price was below 0 €/MWh 5% of the time in 2014. All the devices will turn on when the price is below 0 €/MWh but when the vessel is running low on energy, the heat pumps will turn on when the price is higher to prevent the vessel from running out of useful energy. This is done with the following two statements.

If \( Q_{\text{storage}} \leq Q_{\text{demand, 2weeks}} \)  
\[ \rightarrow 15\% \text{ of the time} \rightarrow P_{\text{mt, 2weeks}} \]

If \( Q_{\text{storage}} < Q_{\text{demand, 2days}} \)  
\[ \rightarrow 90\% \text{ of the time} \rightarrow P_{\text{mt, 2days}} \]

Where:

\[ Q_{\text{storage}} = \frac{C_p}{3600} \sum_{L=1}^{4} m\text{layer}_L \cdot (T_{\text{layer}_L} - T_{\text{in}}) \]  

(4.5)

Where:

\( Q_{\text{storage}} \)  
currently stored useful heat in the whole vessel (kWh)

\( C_p \)  
4,186 kJ/(kg·K)

\( m \)  
mass of layer L (kg)

\( T_{\text{layer}_L} \)  
temperature of layer L, where if \( T_{\text{layer}_L} < T_{\text{in}} \rightarrow T_{\text{layer}_L} = T_{\text{in}} \) (°C)

\( T_{\text{in}} \)  
input temperature to the apartments 70 or 40°C

\( P_{\text{mt, 2weeks}} \)  
price margin tipping point = 21 (€/MWh)

\( P_{\text{mt, 2days}} \)  
price margin tipping point = 49 (€/MWh)

And:

\[ Q_{\text{demand, 2 weeks}} = \sum_{t} Q_{\text{demand}} (t) \]  

(4.6)

\( ^9 \) It is possible to raise the boiling temperature in the vessel with, for example, glycol. This possibility with the Ecovat system is still under development though.
And:

\[ Q_{\text{demand, 2 days}} = \sum_{i=1}^{t+48} Q_{\text{demand}}(t) \]  

(4.7)

Where:

- \( Q_{\text{demand}} \): the energy demand (kWh)
- 336: 24 hours times 14 days

### 4.3. Heat Demand

For the model, the hourly heat demand is calculated. The annual energy consumption of the dwellings is given by the housing corporation, which makes it possible to make a very accurate and realistic heat demand calculation. If these figures are not (yet) known, then the annual heat demand will be determined by the model based on the average of all the houses of that specific archetype, building period and type of heating. This amount can be found in the database of *Shaare*. The real consumption is preferred over the average consumption of the *Shaare* database, since the real consumption can be very different as a result of the influences of the location, the user behaviour, the user profiles, the building characteristics, etc.

Then the annual heat demand is distributed over four seasons. The total heat consumption of a household is often divided into three functions, namely space heating, tap water heating and cooking. Cooking will be neglected in this thesis since its demand is relatively small. Before we can distribute the heat demand over four seasons, we need to separate the tap water heating from the space heating. Namely, the heat for tap water does not have the same distribution over the year as the heat for space heating does. Since the space heating in the case is currently provided with collective heating and the tap water heating is provided with individual heating, there are two different meters that record the heat consumption. One for the space heating and one for the tap water heating. So in this case, luckily, it is possible to accurately calculate how these two heat demands are divided.

The real consumption of the tap water heating is not the same as the heat demand for tap water. Namely, the real consumption is dependent on the COP of the tap water heating system. Currently this system is very inefficient, with a COP of 0,5. Multiplying the tap water heat consumption by this COP will return the tap water heat demand if the COP would be 1. The tap water heating is independent of the weather, so the tap water demand will be the same for every day of the year.

The space heating consumption will then naturally be as following.

\[ Q_{\text{space}} = Q_{\text{total}} - Q_{\text{tapwater}} \]  

(4.8)

The space heating consumption is, in contrast with the tap water heating, dependent on the weather. For example, January usually requires the most energy and July usually the least. Also, not every year has the same total heat demand as other years. So the heat consumption as given by the housing corporation
needs to be calibrated to an average year. The ‘coldness’ of a year is determined with the so called ‘days of degrees’ (dutch: graaddagen). These days of degrees are determined with the average temperature of each day on multiple locations in the Netherlands by the KNMI. The days of degrees of one day (24 hours) is.

\[
days\ of\ degrees = heating\ limit - average\ day\ temperature
\]  

(4.9)

When the average day temperature is less than the heating limit then the number of days of degrees is 0. The heating limit in the Netherlands is set at 18°C. Also, the winter months are weighted more (because of the change in caloric value of one m3 natural gas) than the summer months. November, December, January and February are multiplied with 1,1. March and October with 1,0. April, May, June, July, August and September with 0,8. For example, 2011 had 2665 days of degrees and 2013 had 3094 days of degrees. From a 10 year period (2005-2014) the average number of days of degrees is calculated as 2815. Depending on the year the heat consumption measurements, the heat consumption can be calculated for an average year.

\[
Q_{space\ (weighted)} = \frac{2815}{days\ of\ degrees\ (year)} \cdot Q_{space}
\]  

(4.10)

When the heat consumption is calibrated, the heat consumption is spread over 4 seasons. The number of days of degrees for each season is calculated as a percentage per year as shown in Table 11.

<table>
<thead>
<tr>
<th>Season</th>
<th># days of degrees</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Winter</td>
<td>1436,4</td>
<td>51,0%</td>
</tr>
<tr>
<td>Spring</td>
<td>642,1</td>
<td>22,8%</td>
</tr>
<tr>
<td>Summer</td>
<td>107,8</td>
<td>3,8%</td>
</tr>
<tr>
<td>Autumn</td>
<td>629,2</td>
<td>22,3%</td>
</tr>
</tbody>
</table>

The heat demand for each day of the year is now known (Table 12) for a typical day of every season. It shows that the daily heat demand for tap water heating is independent of the season. Thus the heat demand is still significant because of the tap water heat demand.

<table>
<thead>
<tr>
<th>Daily demand (kWh)</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
<th>Scenario 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Space heating Winter</td>
<td>2.575</td>
<td>1.931</td>
<td>1.931</td>
<td>1.287</td>
</tr>
<tr>
<td>Space heating Spring</td>
<td>1.126</td>
<td>845</td>
<td>845</td>
<td>563</td>
</tr>
<tr>
<td>Space heating Summer</td>
<td>232</td>
<td>174</td>
<td>174</td>
<td>116</td>
</tr>
<tr>
<td>Space heating Autumn</td>
<td>1.113</td>
<td>835</td>
<td>835</td>
<td>557</td>
</tr>
<tr>
<td>Tap water heating</td>
<td>599</td>
<td>599</td>
<td>599</td>
<td>399</td>
</tr>
</tbody>
</table>
So the daily heat demand is known and from RvO (RvO, 2013) the hourly heat demand is determined. In Figure 11 we can see the distribution of the daily space heating demand for scenario 1 for four typical days (one for each season) and the tap water heating demand for each day of the year. The distribution of a typical day in spring is almost the same as a typical day in autumn. Appendix A shows the full total heat demand of one year.

For every hour the model will extract the heat from the most optimal layer to the apartments. This is the layer that has the lowest temperature but still about $T_{in}$. As stated before and depicted in Table 9, $T_{in}$ is dependent on the chosen renovation scenario.

![Figure 11 Hourly energy demand for scenario 1 for four typical days.](image)

4.4. Solar energy

Capturing solar energy can be realized with the following devices: photo voltaic panels (PV), solar thermal collectors and photo voltaic thermal panels (PVT). Only photo voltaic thermal panels are considered in this thesis. PVT panels are co-generation components that convert solar energy into both electricity and heat and represent in principle one of the most efficient ways to use solar energy (Dupeyrat, Ménézo, & Fortuin, 2014). Figure 12 shows the setup of the PVT panels in the system. As stated in 4.2 the temperature in layer 5 is sustained at 5°C and the PVT panels will always use this layer 5 to add its energy to. Thus $T_{in}$ is considered to be 5°C at all times. The electric output is used for all other devices.
For the PVT panels, two data sources are required about the location of the case. Namely, the ambient temperature of every hour of one year and the global radiation of every hour of one year. All other parts of the system do not have an influence on the output of the PVT panels. Figure 13 and Figure 14 show the ambient temperature and global radiation of Eindhoven. The data is extracted from the data of the KNMI and is calibrated from 2005-2011 to an average year. This data is used for all the calculations further on. The total global annual radiation is 991 kWh/m².
In Figure 15 we can see 2 different PVT principles namely PVT unglazed and PVT glazed. The hybrid PVT systems consisting of PV modules without thermal protection of their illuminated surface to the ambient, have high top thermal losses and therefore the achieved operating temperature is not high. To increase the system operating temperature, an additional glazing cover is necessary. Therefore glazed PVT panels are used in this model.

\[ E_{el} = L \cdot A \cdot \alpha \cdot \sum_{hour1}^{8760} G \cdot F \cdot \eta_{el} \]  

(4.11)

Where:

- \( E_{el} \) = electric output (kWh)
- \( L \) = system losses = 0.95 (-)
- \( A \) = surface of the panel = 1.8 (m²)
- \( \alpha \) = efficiency factor for the inclination and orientation at angle 0° = 0.87 (-)
G  global radiation in (W/m²)  
F  solar irradiance factor (-)  
η_{el}  electric efficiency (-)  

For the electrical output of the PVT panels some assumptions are made. The system losses, such as transport losses, dirt losses are assumed to be 5%. An inclination of the panels in the Netherlands of around 33° gives a 100% inclination efficiency. At an inclination of 0°, this efficiency factor \( \alpha = 0.87 \). This inclination thus results in a minor efficiency loss but this is chosen for two reasons. First, one advantage is that the orientation is not relevant at that inclination. Secondly, there is limited roof space in the case and with an inclination of 0°, more panels fit on this limited roof space. The solar irradiance factor is dependent on the radiation at that time as depicted in Figure 16 (Santbergen, 2008). Especially at low irradiance, for example in the winter, this factor is very low.

The electric efficiency of glazed (covered) is assumed as a linear equation derived from Figure 17 (Dupeyrat et al., 2014) as following.

\[
\eta_{el} = \eta_0 - a_1 \cdot T_{\text{red}} 
\]  
\( (4.12) \)  

And:

\[
T_{\text{red}} = \frac{T_{\text{in}} + T_{\text{out}} - T_a}{2} 
\]  
\( (4.13) \)

Where:

\( T_{\text{red}} \)  reduced temperature (m²·K/W)  
\( \eta_0 \)  maximum electric efficiency = 0.1 (-)  
\( a_1 \)  electric loss coefficient glazed collector = 0.44 (-)  
\( T_{\text{in}} \)  input temperature to the panel (°C) = 5

Figure 16 Solar irradiance factor F as a function of the irradiation. Source (Santbergen, 2008)
The output temperature $T_{out}$ of the PVT is determined as following:

If $G = 0$  \rightarrow \#N/A

If $T_{out} < 5$  \rightarrow 5

otherwise

$$T_{out} = \frac{2 \cdot \eta_0 \cdot G + a_1 \cdot T_{in} - 2 \cdot a_1 \cdot T_a + 2 \cdot m \cdot C_p \cdot T_{in} - a_1 + 2 \cdot m \cdot C_p}{-a_1 + 2 \cdot m \cdot C_p}$$ (4.14)

Where:

$\#N/A$ if there is no sun or not enough to heat the water, no water is pumped through the PVT panels

$\eta_0$ maximum thermal efficiency = 0.73 (-)

$a_1$ thermal loss coefficient glazed collector = 7.25 (W/(K·m²))

$m$ mass flow = 0.018 (kg/s)

$C_p$ specific heat capacity = 4186 (J/(kg·K))

$T_{in}$ input temperature to the panel (°C) = 5

$T_{out}$ output temperature from the panel (°C)

$T_a$ ambient temperature (°C)

$G$ global radiation (W/m²)

The thermal output per panel for each month is calculated as following.
If $G = 0 \quad \Rightarrow E_{\text{th}} = 0$
If $T_{\text{out}} < 5 \quad \Rightarrow E_{\text{th}} = 0$
otherwise

\[
E_{\text{th}} = L \cdot A \cdot \alpha \cdot \sum_{\text{hour}1}^{8760} G \cdot F \cdot \eta_{\text{th}}
\] (4.15)

And:

\[
\eta_{\text{th}} = \eta_0 - a_1 \cdot T_{\text{red}}
\] (4.16)

Where:

- $L$: system losses $= 0,95$ (-)
- $A$: surface of the panel $= 1,8$ (m$^2$)
- $\alpha$: efficiency factor for the inclination and orientation at angle $0^\circ = 0,87$ (-)
- $G$: global radiation in (W/m$^2$)
- $F$: solar irradiance factor (-)
- $\eta_{\text{th}}$: thermal efficiency (-)
- $\eta_0$: $0,73$ (-)
- $a_1$: $7,25$ (-)

The thermal efficiency of glazed (covered) PVT panels is assumed as a linear equation derived from Figure 17 (Dupeyrat et al., 2014). The thermal and electric output of one PVT panel is depicted in Figure 19. Figure 18 shows the output temperature of one PVT panel. With an input temperature of $5^\circ C$ the output temperature varies from $5^\circ C$ to $18^\circ C$. Only when the output temperature is above $5^\circ C$, the flow in the panels will be turned on. When the output temperature is below $5^\circ C$, there will only be an electric output. An output temperature of $6^\circ C$ might seem too low to generate some reasonable output, but reducing the panel temperature also improves the electricity output, therefore the water is always running through the PVT panels when the output temperature is above $5^\circ C$. 
4.5. **Air/water heat pump**

The heat pumps can use both the electricity both from the PVT panels and from the electricity grid. The system uses three types of heat pumps. First, an air-water heat pump that uses the outside air as a heat source and adds energy to the vessel. Secondly, a low temperature water/water heat pump that uses the water inside the vessel as a heat source and can raise the temperature of the water up to 55°C. This heat pump will not actually add heat to the vessel but will only bring the temperature in the lower layer down and the temperature in the upper layer up. Thirdly, a high temperature water/water heat pump that uses the water inside the vessel as a heat source and can raise the temperature of the water up to 85°C.
The heat source for the awhp is the ambient air outside. The drive energy is the energy from the PVT panels and/or from the electricity grid. Figure 20 shows the setup of the awhp in the system. The air/water heat pump will only charge layer 1 to layer 4. The heat production is calculated as following.

In order to determine the amount of heat that this heat pump can add under certain conditions, some statements on the input and output temperatures are made. The temperatures of the flows depicted in Figure 20 are stated as following.

\[ T_2 = T_{\text{layer L}} \]  
\[ (4.17) \]

And:

\[ T_4 = T_a \]  
\[ (4.18) \]

And:

\[ T_1 = T_2 + \Delta T_{hp} = T_{layer L} + \Delta T_{hp} \]  
\[ (4.19) \]

And:

\[ T_3 = T_4 - \Delta T_{hp} = T_a - \Delta T_{hp} \]  
\[ (4.20) \]

Where:

- \( T_1, T_2, T_3, T_4 \) temperature (K)
- \( T_{t_{\text{max}}} \) 65°C
- \( \Delta T_{hp} \) 6°C
- \( T_a \) temperature outside (K)

The temperature input to a layer is thus always exactly 6 degrees higher than the current temperature of that layer. As stated in the assumptions in 4.2, this is assumed to be a good temperature difference to be
as efficient as possible. This also means that this heat pump is not able to add any energy to a layer when the temperature is higher than the max output of the heat pump minus 6.

The thermal output is calculated as following.

\[ Q_{\text{layer L}} = E + Q_a \]  
(4.21)

And:

\[ \text{COP}_w = \frac{Q_w}{E} = \eta_{\text{carnot}} \cdot \frac{T_1}{T_1 - T_3} \]  
(4.22)

Where:

- \( Q_{\text{layer L}} \): heat added to layer L (kWh)
- \( Q_a \): heat extracted from the air outside (kWh)
- \( E \): electric input (kWh)
- \( \eta_{\text{carnot}} \): 0.4 (-)

The purpose of the carnot factor \( \eta \) is to calibrate the theoretical performance of heat pumps to a realistic performance. Namely, the real COP of heat pumps is usually between a 50 to 70% lower than the theoretical COP.

The triggering strategy goes as following.

If \( T_{\text{layer 4}} < 45 \) and \( (T_{\text{layer 3}} < 59 \) or \( T_{\text{layer 4}} < 59 \) or \( T_{\text{layer 5}} < 59 \) then

- If \( P < 0 \) \( \rightarrow \) HP\(_{aw} \) = on
- Else if \( Q_{\text{storage}} < Q_{\text{demand, 2 weeks}} \) and \( P < P_{\text{mt, 2weeks}} \) \( \rightarrow \) HP\(_{aw} \) = on
- Else if \( Q_{\text{storage}} < Q_{\text{demand, 2 days}} \) and \( P < P_{\text{mt, 2days}} \) \( \rightarrow \) HP\(_{aw} \) = on

Else \( \rightarrow \) HP\(_{aw} \) = off

When HP\(_{aw} \) = on, the layer choosing strategy goes as following.

If \( T_{\text{layer 1}} < 59 \) °C \( \rightarrow \) Layer L = Layer 1
Else if \( T_{\text{layer 2}} < 59 \) °C \( \rightarrow \) Layer L = Layer 2
Else if \( T_{\text{layer 3}} < 59 \) °C \( \rightarrow \) Layer L = Layer 3
Else \( \rightarrow \) Layer L = Layer 4

Where:

- \( P \): electricity price (€/MWh)
- HP\(_{aw} \): air water heat pump
- \( Q_{\text{storage}} \): useful stored energy in the whole vessel (kWh)
- \( Q_{\text{demand, 2 weeks}} \): total heat demand of the upcoming 2 weeks (kWh)
\( P_{\text{mt}, \text{2weeks}} \) margin tipping point of price = 21 (€/MWh)
\( P_{\text{mt}, \text{2days}} \) margin tipping point of price = 49 (€/MWh)

In other words the air water heat pump turns on when it can deliver energy to a layer and the price is below €0,-/MWh. If the price > €0,-/MWh then the air water heat pump can still turn on when 2 conditions are met. First the current useful stored energy should be less than what is needed for the following 2 weeks. Secondly, the price should be lower than the margin tipping point price of \( P_{\text{mt}, \text{2weeks}} \). When these conditions are not met the pump can still turn on when the state of the vessel becomes critique, namely when the vessel has less energy stored than the demand for the following 2 days. In that case the price is allowed to be high and otherwise this pump will not turn on. When the heat pump is on then it will chose the most optimal layer to charge, namely the highest layer possible. This is the best option energetically.

### 4.6. Low temperature water/water heat pump

The calculations are quite similar to those of the air-water heat pump. The biggest difference is that it uses the water from the Ecovat as a heat source. The main purpose of this low temperature water/water heat pump is to keep the temperature of layer 5 at 5°C since this layer will be the input temperature for the pvt panels. The energy from layer 5 is brought to the upper layers. Figure 21 shows the setup of the heat pump.

![Figure 21 Schema of the low temperature water/water heat pump and the Ecovat.](image)

The temperatures of the flows are stated as following.

\[
T_2 = T_{\text{layer } w}
\]  
(4.23)

And:

\[
T_4 = T_{\text{layer } c}
\]  
(4.24)
And:

\[ T_1 = T_2 + \Delta T_{hp} = T_{layer\ w} + \Delta T_{hp} \]  

(4.25)

And:

\[ T_3 = T_4 - \Delta T_{hp} = T_{layer\ c} - \Delta T_{hp} \]  

(4.26)

Where:

- \( T_1, T_2, T_3 \) and \( T_4 \) temperature (K)
- \( T_{max} \) 55°C
- \( T_{layer\ w} \) layer with the highest temperature but under 49°C (K)
- \( T_{layer\ c} \) \( T_{layer} \ 5, 4 \) or 3 (K)
- \( \Delta T_{hp} \) 6°C

The thermal output is calculated as following.

\[ Q_w = E + Q_c \]  

(4.27)

And:

\[ COP_w = \frac{Q_w}{E} = \eta_{carnot} \cdot \frac{T_1}{T_1-T_3} \]  

(4.28)

And:

\[ COP_c = \frac{Q_c}{E} = \eta_{carnot} \cdot \frac{T_3}{T_3-T_1} \]  

(4.29)

Where:

- \( E \) electric input (kWh)
- \( Q_w \) heat added to the warmer layer (kWh)
- \( Q_c \) heat extracted from the colder layer (kWh)
- \( \eta_{carnot} \) 0,4

The triggering strategy goes as following:

If \( T_{layer\ 5} > 5 \) \( \rightarrow \) \( HP_h = \) on

Else if \( T_{layer\ 3} < 49 \) or \( T_{layer\ 2} < 49 \) then

If \( Q_{storage} < Q_{demand, 2 \ weeks} \) and \( P < P_{mt, 2\ weeks} \) \( \rightarrow \) \( HP_h = \) on

Else if \( Q_{storage} < Q_{demand, 2\ days} \) and \( P < P_{mt, 2\ days} \) \( \rightarrow \) \( HP_h = \) on

Else \( \rightarrow \) \( HP_h = \) off

When \( HP_h = \) on, the layer choosing strategy goes as following.

If \( T_{layer\ 5} > 5 \) \( \rightarrow \) Layer c = Layer 5

Else if \( T_{layer\ 4} > 5 \) \( \rightarrow \) Layer c = Layer 4

50
Else if \( T_{\text{layer 3}} > 5 \) \( \rightarrow \) Layer \( c = \text{Layer 3} \)
Else \( T_{\text{layer 2}} > 5 \) \( \rightarrow \) Layer \( c = \text{Layer 2} \)
If \( T_{\text{layer 1}} < 49 \) \( \rightarrow \) Layer \( w = \text{Layer 1} \)
Else if \( T_{\text{layer 2}} < 49 \) \( \rightarrow \) Layer \( w = \text{Layer 2} \)
Else if \( T_{\text{layer 3}} < 49 \) \( \rightarrow \) Layer \( w = \text{Layer 3} \)
Else \( \rightarrow \) Layer \( w = \text{Layer 4} \)

Where:

- \( P \) electricity price (€/MWh)
- \( HP_h \) air water heat pump
- \( Q_{\text{storage}} \) useful stored energy in the whole vessel (kWh)
- \( Q_{\text{demand, 2 weeks}} \) the total heat demand of the upcoming 2 weeks (kWh)
- \( P_{\text{mt, 2weeks}} \) margin tipping point of price = 21 (€/MWh)
- \( P_{\text{mt, 2days}} \) margin tipping point of price = 49 (€/MWh)

In other words the low temperature water/water heat pump can only turn on if it is required from the layers. Either the temperature in layer 5 is higher than 5°C or the temperature in layer 2 or 3 can be raised with this pump. When the temperature in layer 5 is higher than 5°C, this heat pump will always turn on. When the temperature in layer 5 is lower than 5°C and the temperatures in layer 2 or 3 are low enough for this pump too be able to raise it, then it will turn on when the price is lower than €0,-/MWh. The pump can still turn on if the price is higher than €0,-/MWh but some extra conditions need to be met. First the current useful stored energy should be less than what is needed for the following 2 weeks. Secondly, the price should be lower than the margin tipping point price of \( P_{\text{mt, 2weeks}} \). When these conditions are not met, the pump can still turn on when the state of the vessel becomes critique, namely when the vessel has stored less energy than the energy demand for the following 2 days. Then the price is allowed to be high. Otherwise it will not turn on. When the heat pump is on then it will extract energy from the lowest layer possible and add the energy to the highest layer possible.

**4.7. High temperature water/water heat pump**

The calculations are quite similar to those of the low temperature water/water heat pump. The function of this heat pump is to keep enough useable heat in the vessel, thus at a higher temperature than \( T_{\text{in}} \). The calculations here will use the terms warm layer and cold layer as in 4.6. The cold layer in this paragraph here will be minimally 47°C which is not particularly cold. However this will be the layer that the heat pump will extract the heat from and therefore it will be the ‘cold’ layer compared to the warm layer.
The temperatures of the flows are stated as following.

\[ T_2 = T_{\text{layer } w} \]  

(4.30)

And:

\[ T_4 = T_{\text{layer } c} \]  

(4.31)

And:

\[ T_1 = T_2 + \Delta T_{hp} = T_{\text{layer } w} + \Delta T_{hp} \]  

(4.32)

And:

\[ T_3 = T_4 - \Delta T_{hp} = T_{\text{layer } c} - \Delta T_{hp} \]  

(4.33)

Where:

- \( T_1, T_2, T_3 \) and \( T_4 \) temperature (K)
- \( T_{\text{layer } w} \) layer with the highest temperature but under 78 °C (K)
- \( T_{\text{layer } c} \) layer with lowest temperature but above 47 °C (K)
- \( \Delta T_{hp} \) 6 °C

The thermal output is calculated as following.

\[ Q_w = E + Q_c \]  

(4.34)

And:

\[ \text{COP}_w = \frac{Q_w}{E} = \eta_{\text{carnot}} \cdot \frac{T_1}{T_1 - T_3} \]  

(4.35)

And:

\[ \text{COP}_c = \frac{Q_c}{E} = \eta_{\text{carnot}} \cdot \frac{T_3}{T_3 - T_1} \]  

(4.36)
Where:

- $E$: electric input (kWh)
- $Q_w$: heat added to the warmer layer (kWh)
- $Q_c$: heat extracted from the colder layer (kWh)
- $\eta_{\text{carnot}}$: 0.4

The triggering strategy goes as following.

If

\[
(T_{\text{layer 4}} > 49 \quad \text{and} \quad T_{\text{layer 3}} < 79) \quad \text{or} \quad (T_{\text{layer 3}} > 49 \quad \text{and} \quad T_{\text{layer 2}} < 79) 
\quad \text{or} 
\quad (T_{\text{layer 2}} > 49 \quad \text{and} \quad T_{\text{layer 1}} < 79)
\]

then

If $P_{\text{imb}} < 0$ \rightarrow $\text{HP}_{ht} = \text{on}$

Else if $T_{\text{layer 4}} > 50$ and $P < P_{mt, 2\text{weeks}}$ \rightarrow $\text{HP}_{ht} = \text{on}$

Else if $T_{\text{layer 4}} > 51$ and $P < P_{mt, 2\text{days}}$ \rightarrow $\text{HP}_{ht} = \text{on}$

Else if $Q_{\text{storage}} < Q_{\text{demand, 2 weeks}}$ and $P < P_{mt, 2\text{weeks}}$ \rightarrow $\text{HP}_{ht} = \text{on}$

Else if $Q_{\text{storage}} < Q_{\text{demand, 2 days}}$ and $P < P_{mt, 2\text{days}}$ \rightarrow $\text{HP}_{ht} = \text{on}$

Else \rightarrow $\text{HP}_{ht} = \text{off}$

When $\text{HP}_{ht} = \text{on}$, the layer choosing strategy goes as following.

If $T_{\text{layer 4}} > 49$ \rightarrow $\text{Layer c = Layer 4}$

Else if $T_{\text{layer 3}} > 49$ \rightarrow $\text{Layer c = Layer 3}$

Else \rightarrow $\text{Layer c = Layer 2}$

If $T_{\text{layer 1}} < 79$ \rightarrow $\text{Layer w = Layer 1}$

Else if $T_{\text{layer 2}} < 79$ \rightarrow $\text{Layer w = Layer 2}$

Else \rightarrow $\text{Layer w = Layer 3}$

Where:

- $P$: electricity price (€/MWh)
- $\text{HP}_{ht}$: high temperature water/water heat pump
- $Q_{\text{storage}}$: useful stored energy in the whole vessel (kWh)
- $Q_{\text{demand, 2 weeks}}$: total heat demand of the upcoming 2 weeks (kWh)
- $Q_{\text{demand, 2 days}}$: total heat demand of the upcoming 2 weeks (kWh)
- $P_{mt, 2\text{weeks}}$: margin tipping point of price = 21 (€/MWh)
- $P_{mt, 2\text{days}}$: margin tipping point of price = 49 (€/MWh)

In other words, the high temperature water/water heat pump can turn on if the temperature of layer 4 and 3 have a desired state. In that case the pump will turn on if the price $< 60.000$ /MWh. The pump can turn on if the price is higher than $60.000$ /MWh but some conditions need to be met. First the current useful stored energy should be less than what is needed for the following 2 weeks. Secondly, the price should be
lower than the margin tipping point price of $P_{\text{mt,2weeks}}$. When these conditions are not met the pump can still turn on when the state of the vessel becomes critique, namely when is has less energy than the demand for 2 days. Then the price is allowed to be high. Otherwise it will not turn on. When the heat pump is on then it will extract energy from the lowest layer possible and add the energy to the highest layer possible.

4.8. Resistor

The function of the resistor (power to heat pipes) is to bring high temperature heat into the vessel as fast as possible. The resistor will only be triggered when the price on the imbalance market is below €0,-/MWh since the COP is only 1. The capital costs per installed MW is low compared to the other charging source. Thus a large capacity can be installed for only few opportunities on the imbalance market when the price goes below €0,-/MWh, namely 5% of the time. The maximum power capacity of the resistor is restricted by $\Delta T_{\text{res}} = 13.3^\circ\text{C}$ and the maximum flow capacity of the vessel walls $q_{\text{max}}$. For example, this would result in a maximum power capacity of 201 kW per layer for Ecovat size M. In the model however, it is assumed that an unlimited amount of power capacity can be installed. In reality the energy could also still be transferred by activating more layers at the same time and/or increasing $\Delta T_{\text{res}}$, but this is not considered in the setup of the model.

![Figure 23 Schema of the resistor and the Ecovat.](image)

The temperatures of the flows are stated as following.

\[
T_2 = T_{\text{layer } L}
\]  
(4.37)

And:

\[
T_1 = T_2 + \Delta T_{\text{res}} = T_{\text{layer } L} + \Delta T_{\text{res}}
\]  
(4.38)
Where:
\( T_{\text{layer } L} \quad \text{layer with the highest temperature but under 90°C (K)} \)
\( \Delta T_{\text{res}} \quad 13.3 \quad ({^\circ}\text{C}) \)

The thermal output is calculated as following.

\[
Q_w = E
\]

Where:
\( Q_w \quad \text{heat output to the warmer layer (kWh)} \)
\( E \quad \text{electric input (kWh)} \)

The triggering strategy goes as following:

If \( T_{\text{layer } 4} < 45 \) or \( T_{\text{layer } 3} < 78 \) or \( T_{\text{layer } 4} < 90 \) or \( T_{\text{layer } 5} < 90 \) then

If \( P < 0 \) \( \Rightarrow \) Res = on

Else \( \Rightarrow \) Res = off

When Res = on, the layer choosing strategy goes as following:

If \( T_{\text{layer } 5} < 90 \) \( \Rightarrow \) Layer L = Layer 5

Else if \( T_{\text{layer } 4} < 90 \) \( \Rightarrow \) Layer L = Layer 4

Else if \( T_{\text{layer } 3} < 78 \) \( \Rightarrow \) Layer L = Layer 3

Else \( \Rightarrow \) Layer L = Layer 2

Where:
\( P \quad \text{electricity price (€/MWh)} \)
\( \text{Resistor} \)

In other words, the resistor can turn on when the state of the layers is appropriate, namely when the layers are not yet at their maximum temperature. Then it will turn on if the price is below €0.5/MWh. When the resistor is on it will choose the most optimal layer to charge, namely the highest layer possible.

4.9. Energy loss

The energy loss from a layer to the ground per 6 months is estimated at 10%, 8% and 5% for Ecovat size S, M and L respectively. The energy loss is thus lower for larger vessels, since their volume is larger compared to their surface. The energy loss per hour is calculated as following.

\[
Q_{\text{loss}} = (1 - (1 - \beta) \frac{1}{4380}) \cdot (T_{\text{layer } L} - T_{\text{ground}}) \cdot m_{\text{layer } L} \cdot \frac{C_p}{3600}
\]

If \( (T_{\text{layer } L} - T_{\text{ground}}) < 0 \) \( \Rightarrow Q_{\text{loss}} = 0 \)
Where:

\( \beta \)  
heat loss per 6 months:  
\( 0,10 \) for Ecovat size S  
\( 0,08 \) for Ecovat size M  
\( 0,05 \) for Ecovat size L

\( 4380 \)  
\( 182,5 \text{ days} \cdot 24 \text{ hours} \)

\( T_{\text{layer L}} \)  
temperature in the particular layer (°C), where \( L = 1, 2, 3, 4 \) or 5.

\( T_{\text{ground}} \)  
15 (°C)

\( m_{\text{layer L}} \)  
mass of layer L (kg)

\( C_p \)  
specific heat capacity = 4,186 (kJ/(kg·K))

### 4.10. Implementation of the model

Essentially, all the values, parameters and assumptions can be altered when desired. However, only a few parameters are changed to find the results that are required for this thesis. These changeable parameters can form different setups. These setups will influence the outcomes when the model is run, but the processes will stay the same. The parameters are: four different renovation scenarios, three vessel sizes, the number of PVT panels, power capacity of the heat pumps and the power capacity of the resistor. This results in eight different setups and these setups are presented in Table 8. As discussed in subchapter 4.1, for the results in chapter 5, only two sizes will be investigated for each renovation scenario. Namely, size M and L for scenario 1 and 2, and size S and M for scenario 3 and 4. The number of PVT panels is set at 100 for renovation scenario 1 and is proportional to the total annual heat demand, which results in 83, 83 and 55 panels for scenario 2, 3 and 4 respectively. For all setups, the power capacity is as following: for \( l_{\text{hp}} = 9\text{kW}, h_{\text{hp}} = 9\text{kW}, a_{\text{awhp}} = 9\text{kW} \) and resistor = 864kW. This assumption is an estimated required capacity based on the first Ecovat, which is currently being built. The model will generate two outcomes that are used to optimize each of the eight different setups. First, the model will produce a graph that shows the temperature of each of the five layers for each hour of the year. Secondly, the model will produce a table that shows the number of hours that each device was triggered in that year. The information in these two outcomes is used to modify the power capacity of each device for each of the eight setups. The result will be eight different optimized setups.
Table 13 Different setups for the model

<table>
<thead>
<tr>
<th>Setup</th>
<th>Renovation scenario</th>
<th>Size</th>
<th>PVT panels</th>
<th>Plthp (kW)</th>
<th>Phthp (kW)</th>
<th>Pawhp (kW)</th>
<th>Pres (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>M</td>
<td>100</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>864</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>L</td>
<td>100</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>864</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>M</td>
<td>83</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>864</td>
</tr>
<tr>
<td>4</td>
<td>2</td>
<td>L</td>
<td>83</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>864</td>
</tr>
<tr>
<td>5</td>
<td>3</td>
<td>S</td>
<td>83</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>864</td>
</tr>
<tr>
<td>6</td>
<td>3</td>
<td>M</td>
<td>83</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>864</td>
</tr>
<tr>
<td>7</td>
<td>4</td>
<td>S</td>
<td>55</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>864</td>
</tr>
<tr>
<td>8</td>
<td>4</td>
<td>M</td>
<td>55</td>
<td>9</td>
<td>9</td>
<td>9</td>
<td>864</td>
</tr>
</tbody>
</table>
5.
5. Results

As explained in subchapter 4.10, eight different setup configurations of the model (Table 13) are optimised and the results of these eight different setups are explained and compared with each other. This chapter elaborates each of these eight setup configurations one by one. For the optimisation of each setup, the model produced two outputs that are used to optimize each of the eight different setups. First, the model produces a graph that shows the temperature of each of the five layers for each hour of the year. Moreover, the model will produce a table that shows the number of hours that each device is triggered in one year. The information of these two outcomes is used to modify the power capacity of each device for each of the eight setups. The result is eight different optimized setups. After the analysis of these eight optimised setups, their Total Cost of Ownership (TCO) is presented. With these TCO’s, all eight optimised setups are compared with each other. Keep in mind that the term ‘scenario’ refers to the renovation scenario and the term ‘setup’ or ‘setup configuration’ refers to the eight different setups as depicted in Table 13.

The optimisation procedure is conducted as following. Two outputs are used: the temperature graph and the table with the number of triggered hours for each device. The graph with the temperatures of the layers provides information about the lack and surplus of installed power capacity. Four requirements of this graph are defined that need to be met. When one of these requirements is not met, the power capacity of the installation needs to be adjusted and the system model is run again with the new setup. The first requirement would like the temperature in layer 5 to stay, ideally, at 5°C. However, temperatures up until 10°C are still considered to be acceptable. Therefore, to create some flexibility in the vessel, the temperature of layer 5 has a maximum temperature limit of 10°C. Secondly, at all times, the vessel should contain some energy at a useful temperature, i.e. higher than the input temperature to the apartments $T_{in}$.

Whenever this is not the case, the system fails to deliver the required heat. Thirdly, the temperatures of all 5 layers at hour $t(8760)$ (the last hour of the year) should be almost equal to the temperatures of $t(1)$. Finally, the overall graph should look valid at all points in time, i.e. no temperatures getting out of bound or mixing between layers. As stated in subchapter 4.2, the state of the vessel starts at an arbitrary but sufficient temperature at $t(0)$, namely $T_{(0)} = 90°C, 75°C, 50°C, 30°C, 5°C$ in layer 1, 2, 3, 4, 5 respectively. Note that a month has around 730 hours, thus each vertical grid line is around two weeks in the following graphs. Next to a graph, the system model also returns a table for each setup. This table shows the number of triggered hours per device in one year. This will help to determine whether all the devices are triggered often enough or not. In Appendix D all graphs are depicted together in an overview.

5.1. Setup 1

The standard configuration for this setup: renovation scenario 1, vessel size M, 100 PVT panels, 9kWh lthp, 9kWh hthp, 9kWh awhp and 864kWh res. Figure 24 shows the graph of the temperatures of the layers for the standard configuration of this setup. Two requirements with this setup are not met namely, the temperature of layer 5 is not kept under 10°C and the temperature in layer 1 does not stay above $T_{in}$.
which is 70°C in scenario 1. In a little more than 2 weeks around t(400), the vessel is empty. As a result of these issues, the different lines show undesired effects later in the year. The solution to these two issues is addressed as following. First, the issue with layer 5 is solved and then the issue with the energy shortage if this is still necessary after the adjustments for the first issue. The reasoning behind this choice goes as following: the only way to bring the temperature of layer 5 under 10°C is to increase the power capacity of the lthp and this could bring the temperature of the upper layers up as well. The other way around, on the contrary, adding power capacity to the high temperature devices will not bring the temperature in layer 5 down. As a result of the increase in power capacity of the lthp, the power capacity of the hthp needs to be raised as well. Namely, when the power capacity of the hthp is (much) lower than the power capacity of the lthp, then the hthp will not be able to extract enough heat from lower layers that the lthp is adding to those layers.

![Figure 24 Temperatures of the layers of setup 1 – standard](image)

Table 14, shows the number of hours each device is triggered. This can give extra feedback on the effect of an increase in capacity. In this case, in the standard configuration, both water/water heat pumps are triggered very often. Increasing the capacity of these pumps will result in less triggered hours, since these pumps will not turn on anymore when the electricity price is too high.
The power capacity of the lthp and hthp is increased with 3 kW, each time the model is run, until the temperature of layer 5 goes under 10°C. Then the second issue is solved by subsequently adding more power to the resistor and the awhp and to observe the response to each power increase. The result of the optimisation of setup 1 is illustrated in Figure 25. Eventually, all four requirements for the graph are met. Namely, the temperature of a least one layer stays above $T_{\text{in}}$ at all times, the temperature of layer 5 does not go above 10°C, the end state at t(8760) is similar to the state of t(1) and the temperature lines of the layers do not show any undesired behaviour. One remark should be made though. The temperature of layer 4 seems to go over the temperature of layer 3. However, this difference is small and is not considered to have a significant influence on the annual performance of the total system.

![](image)

**Figure 25 Temperatures of the layers of setup 1 - optimised**

A few other trends are noticed in the temperature lines, that show how the system model works and how it responds to the state of the vessel. First, the temperature of layer 2 starts to increase around t(1461). This can be explained as a result of spring season setting in and thus the increase in the output of the PVT panels. The lthp starts taking the heat from layer 5 to layer 4 from this t(1461). As a result, the
temperature of layer 2 starts to increase since the hthp is extracting the heat from layer 4 and is adding it to layer 2. Layer 3 seems to be left out in this process which is a sensible response since this is more efficient energetically than transferring the energy over an extra station (layer 3). Secondly, the vessel almost seems to be running out of useable energy after three weeks. Namely, the temperature of layer 5 goes down very rapidly. This means that the state of the system becomes very critique. The resistor will not act upon this critique state since the resistor is triggered only when the energy price goes below €0,-/MWh. As a result the heat pumps accept a higher energy price and are thus triggered more often. The power capacity of these heat pumps is just high enough to prevent a the system from running out of useable energy. Thirdly, the PVT output produces far more smooth temperature lines than the other devices do. We can clearly see the difference between layer 4 and layer 2 in Figure 25. Finally, the output of the PVT panels starts to have a significant impact on the system somewhere around t(4000), which is, the where the summer season starts. Hereon, the temperatures from layer 4 and 5 stay at the maximum temperature of 90°C and layer 3 is used as a heat source for the apartments. Somewhere in autumn, around t(7301), the vessel starts to deplete again and the heat pumps will need to be triggered more often again for higher energy prices.

The optimisation results in a new power capacity as depicted in Table 15. From this table, a few observations are made. All devices that have a higher capacity now than in the standard configuration have less triggered hours than in the standard configuration. This means that the heat pumps will be triggered less on the moments with expensive energy prices on the market than in the standard configuration. The number of triggered hours of the lthp is still high, but the costs of this heat pump are reduced, since the electric output of the PVT panels is used for this heat pump.

<table>
<thead>
<tr>
<th>device</th>
<th>power capacity (kW)</th>
<th>triggered hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>awhp</td>
<td>9</td>
<td>999</td>
</tr>
<tr>
<td>lthp</td>
<td>18</td>
<td>5266</td>
</tr>
<tr>
<td>hthp</td>
<td>21</td>
<td>2976</td>
</tr>
<tr>
<td>res</td>
<td>1200</td>
<td>385</td>
</tr>
</tbody>
</table>

**5.2. Setup 2**

The standard configuration for this setup: renovation scenario 1, size L, 100 PVT panels, 9kWh lthp, 9kWh hthp, 9kWh awhp and 864kWh res. Figure 26 shows the graph of the temperatures of the layers for the standard configuration. Like in setup 1, two requirements with this setup are not met namely, the temperature of layer 5 is not kept under 10°C and the temperature in layer 1 does not stay above T_in which is 70°C in scenario 1. In this setup however, compared to setup 1, problems are less significant. After two months at t(1461) the vessel is almost empty and at t(2921), the vessel is empty. Like in setup 1,
the solution to these two issues is addressed as following. First, the issue with layer 5 is solved and then the issue with the energy shortage.

![setup 2 - standard](image)

**Figure 26 Temperatures of the layers of setup 2 - standard**

Table 16, shows the number of hours each device is triggered. In this case, in the standard configuration, the lthp is triggered very often. Increasing the capacity of this pump will result in less triggered hours, namely this pump will not turn on anymore when the electricity price is too high.

<table>
<thead>
<tr>
<th>device</th>
<th>power capacity (kW)</th>
<th>triggered hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>awhp</td>
<td>9</td>
<td>1537</td>
</tr>
<tr>
<td>lthp</td>
<td>9</td>
<td>7921</td>
</tr>
<tr>
<td>hthp</td>
<td>9</td>
<td>4418</td>
</tr>
<tr>
<td>res</td>
<td>864</td>
<td>413</td>
</tr>
</tbody>
</table>

The power capacity of the lthp and hthp is increased with 3 kW, each time the model is run, until the temperature of layer 5 goes under 10°C. Then the second issue is solved by subsequently adding more power to the resistor and the awhp and to observe the response to each power increase. The result of the optimisation of setup 2 is illustrated in Figure 27. All four requirements for the graph are met. Namely, the temperature of a least one layer stays above $T_{in}$ at all times, the temperature of layer 5 does not go above 10°C, the end state at $t(8760)$ is similar to the state of $t(1)$ and the temperature lines of the layers do not show any undesired behaviour. Like in setup 1, the temperature of layer 4 seems to go over the
temperature of layer 3. Again, this difference is small and is not considered to have a significant influence on the annual performance of the total system.

In setup 1, some trends were noticed in the temperature lines that show how the system model works and how it responds to the state of the vessel. Some of those trends are noticed here in setup 2 as well, but one addition is needed. Compared to setup 1, as a result of the impact of the larger vessel size, the temperatures in this setup are much less volatile. It takes more time for the fully charged vessel to deplete than a fully charged vessel does in setup 1.

![setup 2 - optimised](image)

**Figure 27 Temperatures of the layers of setup 2 – optimised**

Some observations made in setup 1, apply here in setup 2 as well, as depicted in Table 17. One important observation was made though, which resulted in another run of the model after some modifications. Namely, the awhp is triggered only 196 times. Since the installed power capacity of the awhp is not particularly high, it is assumed that the conditions of the system were not suitable for the awhp to turn on more often. The system model was run again with no awhp and, as expected, only very little modifications were noticed. Therefore the awhp was not installed.

<table>
<thead>
<tr>
<th>device</th>
<th>power capacity (kW)</th>
<th>triggered hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>awhp</td>
<td>9</td>
<td>196</td>
</tr>
<tr>
<td>lthp</td>
<td>15</td>
<td>5689</td>
</tr>
<tr>
<td>hthp</td>
<td>15</td>
<td>1913</td>
</tr>
<tr>
<td>res</td>
<td>1300</td>
<td>413</td>
</tr>
</tbody>
</table>

Table 17 Installed power capacity for setup 2 - optimised
The final optimisation of setup 2 is depicted in Figure 28, with hardly any change compared to Figure 27.

As a result of the final optimisation the power capacity and number of triggered hours is revised and depicted in Table 18.

Table 18 Installed power capacity for setup 2 – final optimisation

<table>
<thead>
<tr>
<th>device</th>
<th>power capacity (kW)</th>
<th>triggered hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>awhp</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>lthp</td>
<td>15</td>
<td>5691</td>
</tr>
<tr>
<td>hthp</td>
<td>15</td>
<td>1858</td>
</tr>
<tr>
<td>res</td>
<td>1300</td>
<td>413</td>
</tr>
</tbody>
</table>

5.3. Setup 3

The standard configuration for this setup: renovation scenario 2, vessel size M, 83 PVT panels, 9kWh lthp, 9kWh hthp, 9kWh awhp and 864kWh res. Figure 29 shows the graph of the temperatures of the layers for the standard configuration. Like in setup 1 and setup 2, two requirements with this setup are not met namely, the temperature of layer 5 is not kept under 10°C and the temperature in layer 1 does not stay above $T_a$ which is 70°C in scenario 2. After one month at $t(731)$ the vessel is empty. Like in setup 1 and setup 2, the solution to these two issues is addressed as following. First, the issue with layer 5 is solved and then the issue with the energy shortage if this is still necessary after the adjustments for the first issue. The power capacity of the lthp and hthp is increased with 3 kW, each time the model is run, until the temperature of layer 5 goes under 10°C.
Table 19, shows the number of hours each device is triggered. In this case, in the standard configuration, the lthp is triggered very often. Increasing the capacity of this pump will result in less triggered hours, namely this pump will not turn on anymore when the electricity price is too high.

Table 19 Hours each device is triggered in one year in setup 3 - standard

<table>
<thead>
<tr>
<th>device</th>
<th>power capacity (kW)</th>
<th>triggered hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>awhp</td>
<td>9</td>
<td>1367</td>
</tr>
<tr>
<td>lthp</td>
<td>9</td>
<td>6787</td>
</tr>
<tr>
<td>hthp</td>
<td>9</td>
<td>5145</td>
</tr>
<tr>
<td>res</td>
<td>864</td>
<td>413</td>
</tr>
</tbody>
</table>

The power capacity of the lthp and hthp is increased with 3 kW, each time the model is run, until the temperature of layer 5 goes under 10°C. Then the second issue is solved by subsequently adding more power to the resistor and the awhp and to observe the response to each power increase. The result of the optimisation of setup 3 is illustrated in Figure 30. All four requirements for the graph are now met.
Some observations are made on the number of triggered hours. This time, in contrast with setup 2, the awhp was triggered a significant number of hours. The reduced energy demand, as a result of better renovation scenarios, compared to setup 1 and 2 is reflected in a lower required power capacity of the lthp, the hthp and the resistor.

### Table 20 Installed power capacity for setup 3 - optimised

<table>
<thead>
<tr>
<th>device</th>
<th>power capacity (kW)</th>
<th>triggered hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>awhp</td>
<td>9</td>
<td>842</td>
</tr>
<tr>
<td>lthp</td>
<td>15</td>
<td>5199</td>
</tr>
<tr>
<td>hthp</td>
<td>15</td>
<td>3043</td>
</tr>
<tr>
<td>res</td>
<td>1000</td>
<td>407</td>
</tr>
</tbody>
</table>

### 5.4. Setup 4

The standard configuration for this setup: renovation scenario 2, vessel size L, 83 PVT panels, 9kWh lthp, 9kWh hthp, 9kWh awhp and 864kWh res. Figure 31 shows the graph of the temperatures of the layers for the standard configuration. Two requirements with this setup are not met namely, the temperature of layer 5 is not kept under 10°C and the temperature in layer 1 does not stay above $T_a$, which is 70°C in scenario 2. However, unlike setup 1, 2 and 3, this setup almost suffices for all requirements. Only just before the end of the year the vessel gets empty. In addition, the temperature of layer 5 hardly gets under 10°C.
Table 21, shows the number of hours each device is triggered. In this case, in the standard configuration, the lthp is triggered very often. Increasing the capacity of this pump will result in less triggered hours, namely this pump will not turn on anymore when the electricity price is too high. The resistor is triggered the maximum number of hours, namely all hours that the price on the electricity market is below €0,-/MWh.

Table 21 Hours each device is triggered in one year in setup 4 - standard

<table>
<thead>
<tr>
<th>device</th>
<th>power capacity (kW)</th>
<th>triggered hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>awhp</td>
<td>9</td>
<td>559</td>
</tr>
<tr>
<td>lthp</td>
<td>9</td>
<td>7124</td>
</tr>
<tr>
<td>hthp</td>
<td>9</td>
<td>2577</td>
</tr>
<tr>
<td>res</td>
<td>864</td>
<td>413</td>
</tr>
</tbody>
</table>

The power capacity of the lthp and hthp is increased with 3 kW, each time the model is run, until the temperature of layer 5 goes under 10°C. In this case, lthp = 12 kW was sufficient already. Also, since the hthp seemed to have somewhat little number of triggered hours, this capacity was reduced. When the lthp capacity was raised to 12kW the number of triggered hours of the awhp became very low, so the awhp was set at 0kWh. This hardly showed any results in the graph (Figure 32). Just as setup 2 compare to 1, this setup is far less volatile compared to setup 3 and it also does not need the awhp. This is a direct result of the large vessel size.
Table 22 shows that the power capacity of the awhp is set to 0kW and the hthp was reduced to 6kW.

Table 22: Installed power capacity for setup 4 - optimised

<table>
<thead>
<tr>
<th>device</th>
<th>power capacity (kW)</th>
<th>triggered hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>awhp</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>lthp</td>
<td>12</td>
<td>5801</td>
</tr>
<tr>
<td>hthp</td>
<td>6</td>
<td>2778</td>
</tr>
<tr>
<td>res</td>
<td>1100</td>
<td>413</td>
</tr>
</tbody>
</table>

5.5. Setup 5

The standard configuration for this setup: renovation scenario 3, vessel size S, 83 PVT panels, 9kWh lthp, 9kWh hthp, 9kWh awhp and 864kWh res. Figure 33 shows the graph of the temperatures of the layers for the standard configuration. The temperature of layer 5 goes completely out of bound. This is most likely the result of too little capacity power for the lthp. Namely, this renovations scenario has $T_{in}$ to the apartments at 40°C. Therefore this pump is not only necessary to cool layer 5, but it can also add heat at a sufficient temperature to become usable heat. Therefore this capacity power is increased.
In this case it is not yet relevant to show the table with the number of triggered hours per device, since the system model has gone out of bound. Therefore first a new graph is made with a higher capacity power of the lthp (Figure 34). The new graph shows that this setup is highly volatile and completely different compared to setup 1, 2, 3 and 4 as a result of the low temperature heating in the apartments. A few observations are made. First, the temperatures of each layer seem to stay in place in relation to the other layers, i.e. no lower layer has a higher temperature than an upper layer. Except for one small time step in layer 5 around t(4381). Secondly, the temperature of layer 1 seems to be above $T_{in}$ at all times, thus the system is able to supply useable heat year round. Because of this low $T_{in}$, this setup offers far more flexibility than the setups with high $T_{in}$. Also, the temperatures going out of the PVT panels and the lthp are more useful. Therefore the lines of layer 4 and 5 are less smooth than in the previous setups with high temp. heating.
Table 23 shows the triggered hours of the optimised setup. For the first time in all setups it shows a very low number of triggered hours for the hthp and a relatively high number of triggered hours for the awhp. This can be explained as following: the hthp turns on when the price is below €0,-/MWh and will only accept a higher price when the state of the vessel becomes a little critique. This does not happen since all energy above 40°C is useable, thus the state in the vessel hardly becomes critique.

Table 23 Hours each device is triggered in one year in setup 5 - optimised

<table>
<thead>
<tr>
<th>Device</th>
<th>Power Capacity (kW)</th>
<th>Triggered Hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>awhp</td>
<td>9</td>
<td>1222</td>
</tr>
<tr>
<td>lthp</td>
<td>15</td>
<td>4879</td>
</tr>
<tr>
<td>hthp</td>
<td>9</td>
<td>4</td>
</tr>
<tr>
<td>res</td>
<td>864</td>
<td>413</td>
</tr>
</tbody>
</table>

The final graph of the optimization with a decrease of power capacity of the hthp and an increase of the power capacity for the resistor is depicted in Figure 35.
The installed capacity power for the optimisation of setup 5 is depicted in Table 24.

**Table 24 Installed power capacity for setup 5 – final optimisation**

<table>
<thead>
<tr>
<th>device</th>
<th>power capacity (kW)</th>
<th>triggered hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>awhp</td>
<td>9</td>
<td>774</td>
</tr>
<tr>
<td>lthp</td>
<td>15</td>
<td>4753</td>
</tr>
<tr>
<td>hthp</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>res</td>
<td>1100</td>
<td>364</td>
</tr>
</tbody>
</table>

### 5.6. Setup 6

The standard configuration for this setup: renovation scenario 3, vessel size M, 83 PVT panels, 9kWh lthp, 9kWh hthp, 9kWh awhp and 864kWh res. Figure 36 shows the graph of the temperatures of the layers for the standard configuration. Only one requirement of this setup is not met. Namely, only the temperature of layer 5 goes over 10°C. Most likely, the power capacity of some devices can be decreased.
Like in setup 5, the hthp is hardly used so this pump is set to 0kW for the optimization. Furthermore, the awhp is triggered only 413 hours so the model is run a few times to study the effects when the power capacity of this pump is decreased. Also, the awhp is only triggered here since the electricity price is below €0,-/MWh. The state of the vessel is not nearly in a critique state yet for the awhp to turn on.

Table 25 Hours each device is triggered in one year in setup 6 - standard

<table>
<thead>
<tr>
<th>device</th>
<th>power capacity (kW)</th>
<th>triggered hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>awhp</td>
<td>9</td>
<td>413</td>
</tr>
<tr>
<td>lthp</td>
<td>9</td>
<td>6032</td>
</tr>
<tr>
<td>hthp</td>
<td>9</td>
<td>4</td>
</tr>
<tr>
<td>res</td>
<td>864</td>
<td>413</td>
</tr>
</tbody>
</table>

Figure 37 shows the optimized configuration.
In setup 6, both the awhp and the lthp appeared to be redundant as a result of the low temperature heating, and are set to 0kW.

Table 26 Installed power capacity for setup 6 – final optimisation

<table>
<thead>
<tr>
<th>device</th>
<th>power capacity (kW)</th>
<th>triggered hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>awhp</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>lthp</td>
<td>13</td>
<td>4803</td>
</tr>
<tr>
<td>hthp</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>res</td>
<td>1000</td>
<td>413</td>
</tr>
</tbody>
</table>
5.7. Setup 7

The standard configuration for this setup: renovation scenario 4, vessel size S, 55 PVT panels, 9kWh lthp, 9kWh hthp, 9kWh awhp and 864kWh res. Figure 38 shows the graph of the temperatures of the layers for the standard configuration. Only one requirement of this setup is not met. Namely, only the temperature of layer 5 goes over 10°C.

![Figure 38 Temperatures of the layers of setup 7 – standard](image)

Like in setup 5, the hthp is hardly used so this pump is set to 0kW for the optimization. Furthermore, the awhp is triggered only 434 hours so the model is run a few times to study the effects when the power capacity of this pump is decreased.

<table>
<thead>
<tr>
<th>device</th>
<th>power capacity (kW)</th>
<th>triggered hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>awhp</td>
<td>9</td>
<td>434</td>
</tr>
<tr>
<td>lthp</td>
<td>9</td>
<td>4834</td>
</tr>
<tr>
<td>hthp</td>
<td>9</td>
<td>25</td>
</tr>
<tr>
<td>res</td>
<td>864</td>
<td>352</td>
</tr>
</tbody>
</table>

Figure 39 shows the optimized configuration.
Both the awhp and the hthp appeared to be redundant in this setup as a result of the low temperature heating, and is set to 0kW.

**Table 28 Installed power capacity for setup 7 – optimised**

<table>
<thead>
<tr>
<th>device</th>
<th>power capacity (kW)</th>
<th>triggered hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>awhp</td>
<td>6</td>
<td>573</td>
</tr>
<tr>
<td>lthp</td>
<td>10</td>
<td>4518</td>
</tr>
<tr>
<td>hthp</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>res</td>
<td>700</td>
<td>372</td>
</tr>
</tbody>
</table>
5.8. Setup 8

The standard configuration for this setup: renovation scenario 4, size M, 55 PVT panels, 9kWh lthp, 9kWh hthp, 9kWh awhp and 864kWh res. Figure 40 shows the graph of the temperatures of the layers for the standard configuration if setup 8. This setup is already sufficient for all four defined requirements. In this case, the capacity power of the installation is decreased gradually until the setup just meets the requirements.

![setup 8 - standard](image)

**Figure 40 Temperatures of the layers of setup 8 – standard**

From Table 29 is noticed that, like in setup 7, the hthp is hardly used so this pump is set to 0kW for the optimization. Furthermore, the awhp is triggered only 413 hours so the model is run a few times to study the effects when the power capacity of this pump is decreased.

<table>
<thead>
<tr>
<th>device</th>
<th>power capacity (kW)</th>
<th>triggered hours</th>
</tr>
</thead>
<tbody>
<tr>
<td>awhp</td>
<td>9</td>
<td>413</td>
</tr>
<tr>
<td>lthp</td>
<td>9</td>
<td>4756</td>
</tr>
<tr>
<td>hthp</td>
<td>9</td>
<td>5</td>
</tr>
<tr>
<td>res</td>
<td>864</td>
<td>413</td>
</tr>
</tbody>
</table>

*Table 29 Hours each device is triggered in one year in setup 8 - standard*

Figure 41 shows the optimized configuration.
Both the awhp and the hthp appeared to be redundant. And the power capacity of the lthp and the resistor was decreased significantly.

\[ \text{Setup 8 - optimised} \]

\[ \begin{array}{c|c|c}
\text{device} & \text{power capacity (kW)} & \text{triggered hours} \\
\hline
\text{awhp} & 0 & 0 \\
\text{lthp} & 8 & 5178 \\
\text{hthp} & 0 & 0 \\
\text{res} & 700 & 413 \\
\end{array} \]

### Table 30 Installed power capacity for setup 8 – optimised

5.9. **Final result**

In the previous subchapters, eight setups are optimised. In this subchapter here, these setups are compared with each other. First, the physical setups and their activity are compared. Then the TCO is analysed. Table 31 shows the power capacity of each device and the number of triggered hours. Note that setup 1 and 2 represent renovation scenario 1, setup 3 and 4 represent renovation scenario 2 etc. Therefore every renovation scenario has thus two setups, two with a different vessel size. The following six observations are made.

First, the required installed power capacity shows a steady decrease from setup 1 to 8 for the lthp, the hthp and the resistor. This is most likely to be the result of both the decrease of the heat demand from the apartments as well as the decrease of installed PVT panels.
Secondly, both the different renovation scenarios as well as the different vessel sizes seem have an effect on the required power capacity. Moreover, as shown in the temperature graphs of the different setups, the different vessel sizes also result in a large difference in their robustness. The largest vessel size of a renovation scenario (for scenario 1 and 2, this is size L, for scenario 3 and 4 this is size M) does not deplete or does not get in a critique state as fast as the small vessel does.

Thirdly, the awhp was often found to be redundant. This can be explained as following. The awhp was often ‘overruled’ by the power resistor or by the water/water heat pumps. Meaning that the other devices acted earlier upon a (critique) situation, which means that the state of the system was sufficient again before the awhp was triggered. The awhp was redundant in the setups with the highest vessel size of one renovation scenario. These were setup 2, 4, 6 and 8. These setups were thus less often in a critique state, since their stored potential was much higher.

Fourthly, the resistor has a steady number of triggered hours in all setups. Apparently, 413 hours is the maximum number of hours, namely all hours in 2014 where the electricity price was below €0,-/MWh. The required capacity of the resistor showed a small decrease though in the setups with a lower heat demand.

Fifthly, the lthp was triggered most often in all setups. Since the main purpose of the pump was to bring the heat of the PVT output to higher layers, it makes sense that this pump is triggered the same number of hours in all setups. Namely, when this pump was triggered a lot more or a lot less, then this usually meant that too much or too little lthp capacity was installed. This high number of triggered hours does not necessarily mean that electricity bill for this pump is high. Since, the electric output from the PVT panels was used for the lthp, the number of hours that the lthp used electricity from the grid is substantially smaller in most setups.

Finally, the hthp was completely redundant in the setups with low temperature heating in the apartments (setup 5, 6, 7 and 8). Since the hthp can already suffice the vessel with useable heat in those setups, there is no incentive for the hthp to be triggered. Namely, the hthp will only get triggered when the price is below €0,-/MWh or when the demand for the next 2 weeks is higher than the currently stored energy.
So far, all the results that are analysed only addressed the physical performance of the system and have not yet analysed the economic performance. The economic performance in this thesis is analysed with a TCO calculation, depicted in Table 32. The TCO is divided into three parts. First, the investment cost includes: the renovation cost, the heat tubing cost, the installation cost and the vessel cost. Secondly, the DSO cost, which is the total cost that has to be paid to the local DSO\textsuperscript{10}. This consists of the one-time connection to the electricity grid, the annual connection cost for each kW and transportation cost for each kWh. Finally, the energy bill is the cost for the energy that has to be paid to the energy company. However, in all cases this energy bill is negative since most energy is used when the price is below €0,-/MWh. The following observations are made.

First, the TCO does not vary much amongst the different setups. The lowest TCO is 1.7mln and the highest is 2.6mln. A steady increase is observed from setup 1 to 4 and from setup 5 to 8. This indicates two things. To begin with, improving the renovation by only reducing the heat demand and/or increasing the vessel size results in a higher TCO. In addition, improving the renovation by changing to low temperature heating has a much higher savings effect than the reducing the heat demand does. Namely, the heat demand between renovation scenario 2 (setup 3 and 4) and 3 (setup 5 and 6) is the same. The two differences are the heating temperature and the vessel size.

Secondly, a paradoxical issue is at hand here. Naturally, a higher energy demand results in higher DSO costs and a larger vessel. But it also results in more income through the resistor. Since this resistor actually generates income instead of costs, it becomes more lucrative to install a higher resistor capacity power and to have a higher heat demand. Therefore the energy reducing measures only have a positive effect on the DSO costs, and not on the energy bill.

\textsuperscript{10} In Eindhoven the DSO is Endinet
Thirdly, when comparing the two different vessel sizes of one scenario, the setup with the smallest vessel is always the one with the lowest cost. Thus scenario 1, 3, 5 and 7 have a lower cost than 2, 4, 6 and 8.

Finally, renovation scenario 4 (setup 7 and 8) has a big savings impact on the DSO costs, as a direct result of the big power capacity reduction of the resistor compared to the other setups.

<table>
<thead>
<tr>
<th>Setup</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Investment</td>
<td>1.392.000</td>
<td>1.822.000</td>
<td>1.689.750</td>
<td>2.118.250</td>
<td>1.492.250</td>
<td>1.832.750</td>
<td>2.048.950</td>
<td>2.390.950</td>
</tr>
<tr>
<td>DSO costs</td>
<td>1.132.513</td>
<td>1.198.253</td>
<td>957.664</td>
<td>1.016.924</td>
<td>925.757</td>
<td>924.747</td>
<td>667.899</td>
<td>666.634</td>
</tr>
<tr>
<td>TCO</td>
<td>1.731.149</td>
<td>2.163.114</td>
<td>2.022.685</td>
<td>2.417.097</td>
<td>1.838.040</td>
<td>2.090.313</td>
<td>2.291.154</td>
<td>2.589.139</td>
</tr>
</tbody>
</table>

Note 1: All costs displayed are the total costs for 25 years
Note 2: The full TCO can be found in Appendix E
6.
6. Conclusion, Discussion and Recommendations

6.1. Conclusion

This chapter presents the conclusions based on the findings in the contextual orientation and the results of this thesis. With these extensive results the research question is answered. As stated in subchapter 1.3, in order to answer the research question, the sub questions need to be answered first, in sequential order. The first two sub questions are answered with the findings in the contextual orientation. The third sub question is answered with the results presented in subchapter 5.1 until 5.8. Finally, the research question is answered with the findings presented in 5.9.

Sub-question 1: "Which apartment type of the housing corporation’s stock has the most potential and should therefore be used for the model?"

Two building types and two building periods are identified to have the most potential for the Ecovat system based on the following requirements: the presence of collective heating, ownership by a housing corporation, building period <1975 and the size of particular housing stock. These two types are the apartment building types ‘portiek’ and ‘galerij’ and the building periods are <1965 and 1965-1975. The company has a lead for a renovations project that suits these requirements well. Namely, an apartment building ‘portiek’ from the building period <1965.

Sub-question 2: “What is the energy performance of the chosen case and what should be the different renovation scenarios?”

The apartment buildings have a collective heating system to which all the houses are connected to. The current level of insulation still offers much potential for improvement. Four renovation scenarios are determined, namely ‘Poor’, ‘Reasonable’, ‘Good’ and ‘Excellent’. A top down approach is used to set up the scenarios as following. The output of each scenario is relevant for the system model and not the specific details of these renovation scenarios. This output consists of two aspects about the renovation scenario that are relevant for the system model. First, the yearly heat demand for each renovation scenario. Secondly, the input temperature $T_{in}$ and output temperature $T_{out}$. Each scenario also has a cost price but this is not relevant for the system model, only for the cost calculation. Thus, the yearly heat demand and the $T_{in}$ and $T_{out}$ are determined for each scenario. With those four renovation scenarios the effect of each of these two aspects can be analysed.

Sub-question 3: “What is the most optimal configuration of the Ecovat system for each renovation scenario?”

The results presented in subchapter 5.1 until 5.8 show an optimisation for each of the eight setup configurations. Each renovation scenario has thus two different setups. For each of these eight setups, the most optimal required power capacity for each device is determined, as depicted in Table 31. For each renovations scenario, the setup with the smaller vessel size is the most profitable one, i.e. setup 1 for renovation scenario 1, setup 3 for renovations scenario 2, setup 5 for renovation scenario 3 and setup 7.
for renovation scenario 4. However, this smaller vessel size is also less robust and has a higher chance of an energy shortage. These risks will be discussed in subchapter 6.2.

**RQ: “What is the most favourable renovation scenario for apartments, in becoming energy neutral, when the Ecovat system is applied?”**

A system model is designed in which two setups for each of the four renovation scenarios is optimised, i.e. eight setups were optimised. In order to decide which setup is the most favourable, eight TCOs are calculated and compared. The setup with the lowest cost is then considered the most favourable setup in this thesis.

A steady increase in the TCO is observed from setup 1 to 4 and from setup 5 to 8. This indicates that the higher investment costs of those better renovation scenarios do not result in a cost saving of the Ecovat system of the same amount. As a result, the most favourable renovation scenario is the renovation in setup 1. This is renovation scenario ‘Poor’ and is stated as the least ambitious scenario of all four renovation scenarios. No improvements are applied to decrease the energy consumption for space heating, thus the space heating demand stays the same. The input temperature to the apartments $T_{in}$ is 70°C, and the output temperature from the apartments $T_{out}$ is 50°C. With these temperatures the system can provide both space heating and tap water heating, without extra installations in the dwellings. The inefficient boilers are removed, resulting in a reduction of the tap water demand of 25%. The most optimal configuration of this setup has an Ecovat storage vessel of size M and an installed capacity power as depicted in Table 33.

<table>
<thead>
<tr>
<th>Table 33 Configuration of the most favourable renovation scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>Device</td>
</tr>
<tr>
<td>--------------------------------</td>
</tr>
<tr>
<td>Air water heat pump</td>
</tr>
<tr>
<td>Low temperature water/water heat pump</td>
</tr>
<tr>
<td>High temperature water/water heat pump</td>
</tr>
<tr>
<td>Resistor</td>
</tr>
<tr>
<td>PVT panels</td>
</tr>
</tbody>
</table>

### 6.2. Discussion

This subchapter first discusses the limitations of the system model and this thesis in general. Then the external validity is discussed. Finally, the importance and relevance of the findings is discussed.

The first and most important limitation in this thesis is the exclusion of other evaluation criteria in the scenarios than the TCO; the improvement of the energy performance of the apartments is often not the only motive to renovate apartments. Other aspects such as the comfort level, safety and aesthetics can be very important drivers for a housing corporation to renovate apartments. Moreover, the different scenarios are not evaluated in their sustainable performance.
The second limitation concerns the setup of the system. For this thesis a system is proposed with PVT panels, several heat pumps and a resistor. However, another system could have very different results on the renovation scenarios. For example, a system with only a resistor and heat pumps. There would be no need for cooling (of the PVT) and thus all layers could be heated up to 90°C. Then the useable storage capacity of the Ecovat vessel would be much higher. Namely the storage capacity would be increased with 100% in setup 1, 2, 3 and 4 and with 70% in setup 5, 6, 7 and 8.

The final limitation concerns the exclusion of electric energy storage in the system model. The combination with electric energy storage in batteries is not implemented. As a result, the system occasionally needs to buy its electricity at a high price on the electricity market when the state of the vessel becomes critique. Moreover, no surplus energy can be sold back to the grid on the imbalance market. This market can be very lucrative and has a high economic potential for the business case.

The generalizability of the conclusions is very limited. A common discussion in the renovation sector is whether the focus should be on improving the energy performance of the building or on sustainable energy supply. The results of this thesis show that the focus should be on sustainable energy supply, in the application of the Ecovat system, and not on the energy performance of the building. It is important to note here that the result of this thesis is not an answer to this discussion in general but for the application of the Ecovat system only. The external validity, on the contrary, for other renovation projects with the application of this Ecovat system is high. Namely, other apartment configurations are expected to show results that coincide with the case study in this thesis. The only significant differences with other apartment configurations would be on the renovation costs. The system model however is expected to show similar results.

To conclude, the findings are very relevant for Ecovat. Most importantly, if scenario 4 ‘excellent’ would have the lowest TCO. Then the Ecovat system would have high requirements for the housing corporation to improve their apartments. In case of scenario 1, the housing corporation is less bothered with the implications of the requirements on their apartments.

### 6.3. Recommendations

The value proposition of the Ecovat system is to provide a reliable and affordable energy supply system for a long time, i.e. 25 to 50 years. Although little or no renovation resulted in the lowest TCO, these low cost renovation scenarios are also considered to have a higher risk of failing of the Ecovat system to deliver the demanded heat. Namely, the low cost renovation scenarios have high temperature heating and therefore the vessel can store less useable heat than when the same vessel is connected to low temperature heating. As a result the vessel can deplete in a very short time period; in setup 1 the vessel can have an energy shortage in less than nine days when no or little heat is delivered. This failing could be caused by one of the following situations. To start with, the heat demand could be higher when the winter is colder than the average winter or when the winter lasts longer. Moreover, the electricity price
could be less volatile for some weeks or even longer. Even worse, the ‘worst’ renovation scenarios have a higher dependency on the electricity market compared to the better renovation scenarios. Perhaps, in five or ten years, the developments on the electricity market could result in little or no negative prices on this market. In that case, the apartments and the Ecovat system would be better off with a good renovation.

As a result of the risks described above, it is suggested to make a risk analysis on the probabilities that each of the above stated situations could occur and determine what the effect would be on the TCO. Most of those situations can be implemented and the model can be run again. However, some assumptions require more emphasis and should be studied in more detail, like the risks of the dependency on the low energy prices.

To conclude, even though Ecovat would profit the most from selling large Ecovat systems with ‘badly’ performing apartments, there should be a high emphasis on the robustness of the system. This robustness would make the system more reliable and future proof.
References

Aedes. (2013). Dutch social housing in a nutshell.


UPC. (2014). Assessment report corresponding to SUB UPC 2014 V0.1 ENG subcontracting from VITO to UPC.

Appendix A Total annual heat demand of the case
Appendix B Imbalance price 2014
Appendix C Day ahead market price 2014
Appendix D Overview of all temperature graphs

setup 1 - standard

T (°C)

Tlayr1  Tlayr2  Tlayr3
Tlayr4  Tlayr5

setup 1 - optimised

T (°C)

Tlayr1  Tlayr2  Tlayr3
Tlayr4  Tlayr5

setup 2 - standard

T (°C)

Tlayr1  Tlayr2  Tlayr3
Tlayr4  Tlayr5

setup 2 - optimised

T (°C)

Tlayr1  Tlayr2  Tlayr3
Tlayr4  Tlayr5
setup 5 - standard

setup 5 - final optimisation

setup 6 - standard

setup 6 - optimised
## Appendix E  Full TCO

<table>
<thead>
<tr>
<th>Setup</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Investment costs:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cost vessel</td>
<td>685,000</td>
<td>1,121,000</td>
<td>685,000</td>
<td>1,121,000</td>
<td>339,000</td>
<td>685,000</td>
<td>339,000</td>
<td>685,000</td>
</tr>
<tr>
<td>Renovation</td>
<td>312,000</td>
<td>312,000</td>
<td>624,000</td>
<td>624,000</td>
<td>780,000</td>
<td>780,000</td>
<td>1,357,200</td>
<td>1,357,200</td>
</tr>
<tr>
<td>awhp kW</td>
<td>4,500</td>
<td>-</td>
<td>4,500</td>
<td>-</td>
<td>4,500</td>
<td>-</td>
<td>3,000</td>
<td>-</td>
</tr>
<tr>
<td>lthp kW</td>
<td>9,000</td>
<td>7,500</td>
<td>7,500</td>
<td>6,000</td>
<td>7,500</td>
<td>6,500</td>
<td>5,000</td>
<td>4,000</td>
</tr>
<tr>
<td>hthp kW</td>
<td>10,500</td>
<td>7,500</td>
<td>7,500</td>
<td>3,000</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>res kW</td>
<td>36,000</td>
<td>39,000</td>
<td>30,000</td>
<td>33,000</td>
<td>30,000</td>
<td>30,000</td>
<td>21,000</td>
<td>21,000</td>
</tr>
<tr>
<td>pvt panels</td>
<td>25,000</td>
<td>25,000</td>
<td>21,250</td>
<td>21,250</td>
<td>21,250</td>
<td>21,250</td>
<td>13,750</td>
<td>13,750</td>
</tr>
<tr>
<td>Tubing (m)</td>
<td>310,000</td>
<td>310,000</td>
<td>310,000</td>
<td>310,000</td>
<td>310,000</td>
<td>310,000</td>
<td>310,000</td>
<td>310,000</td>
</tr>
<tr>
<td>Total 25 years</td>
<td>1,392,000</td>
<td>1,822,000</td>
<td>1,689,750</td>
<td>2,118,250</td>
<td>1,492,250</td>
<td>1,832,750</td>
<td>2,048,950</td>
<td>2,390,950</td>
</tr>
<tr>
<td>DSO costs (endnet):</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>On time connection cost</td>
<td>42.600</td>
<td>42.600</td>
<td>42.600</td>
<td>42.600</td>
<td>42.600</td>
<td>42.600</td>
<td>42.600</td>
<td>42.600</td>
</tr>
<tr>
<td>Fixed annual cost</td>
<td>1.046</td>
<td>1.046</td>
<td>1.046</td>
<td>1.046</td>
<td>1.046</td>
<td>1.046</td>
<td>1.046</td>
<td>1.046</td>
</tr>
<tr>
<td>Annual transport cost</td>
<td>5.461</td>
<td>5.653</td>
<td>4.678</td>
<td>4.701</td>
<td>3.848</td>
<td>4.134</td>
<td>2.687</td>
<td>2.874</td>
</tr>
<tr>
<td>Total 25 years</td>
<td>1,132,513</td>
<td>1,198,253</td>
<td>957,664</td>
<td>1,016,924</td>
<td>925,757</td>
<td>924,747</td>
<td>667,899</td>
<td>666,634</td>
</tr>
<tr>
<td>Energy bill:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>awhp</td>
<td>-</td>
<td>127</td>
<td>-</td>
<td>72</td>
<td>-</td>
<td>-45</td>
<td>-</td>
<td>-66</td>
</tr>
<tr>
<td>lthp</td>
<td>1,296</td>
<td>1,989</td>
<td>1,746</td>
<td>1,623</td>
<td>1,632</td>
<td>1,510</td>
<td>1,037</td>
<td>1,000</td>
</tr>
<tr>
<td>hthp</td>
<td>368</td>
<td>378</td>
<td>817</td>
<td>668</td>
<td>310</td>
<td>-3</td>
<td>-8</td>
<td>-2</td>
</tr>
<tr>
<td>resistor</td>
<td>-33,525</td>
<td>-36,653</td>
<td>-27,625</td>
<td>-31,014</td>
<td>-25,096</td>
<td>-28,194</td>
<td>-17,991</td>
<td>-19,736</td>
</tr>
<tr>
<td>TCO</td>
<td>1,731,149</td>
<td>2,163,114</td>
<td>2,022,685</td>
<td>2,417,097</td>
<td>1,838,040</td>
<td>2,090,313</td>
<td>2,291,154</td>
<td>2,589,139</td>
</tr>
</tbody>
</table>