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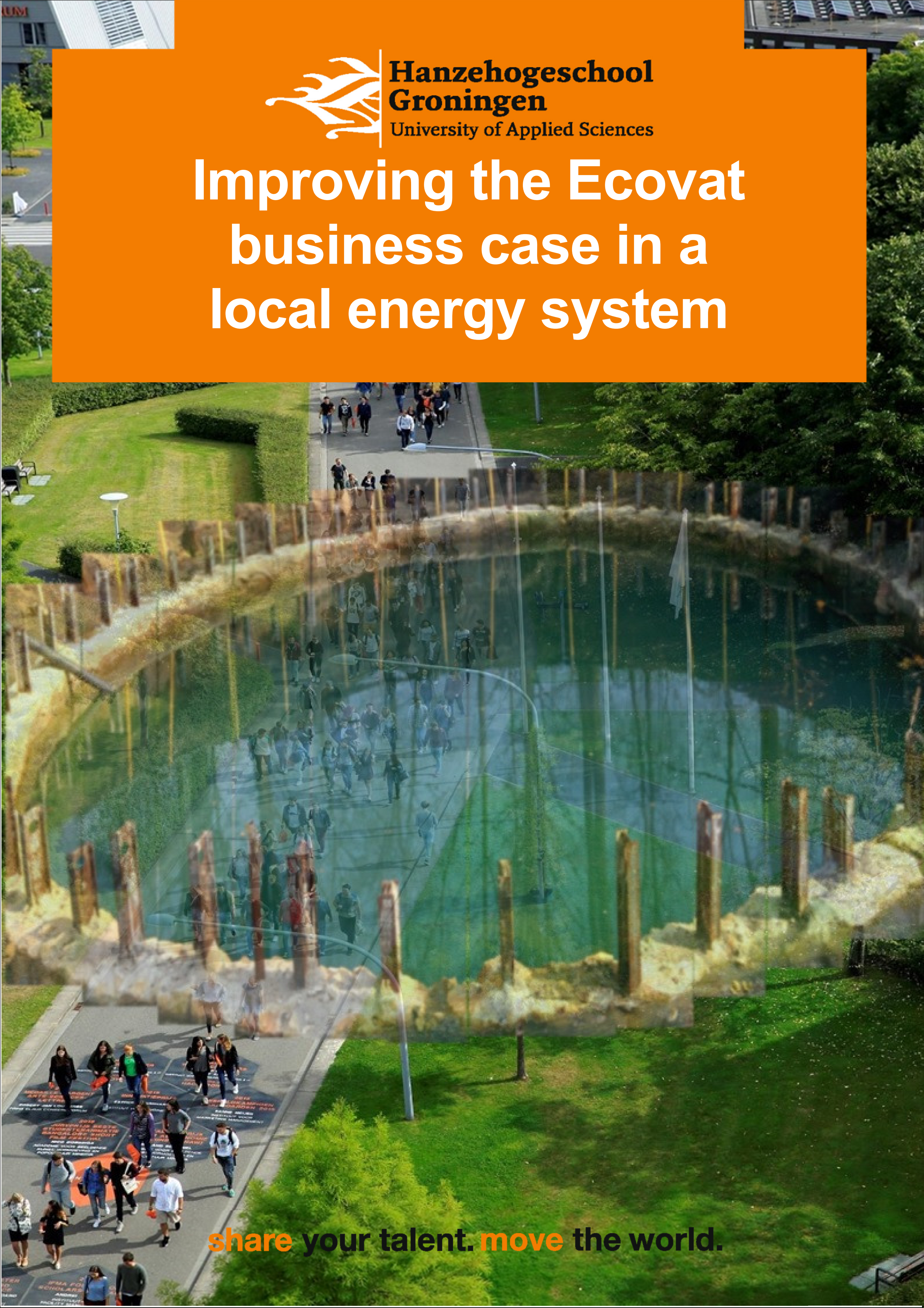
# Improving the Ecovat business case in a local energy system



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# Colofon

Groningen, December 2020

Dr ir Dirk Kurstjens
Hanze University of Applied Sciences, Groningen

Scott van Leeuwen BSc
Nextheat BV

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Please use the following reference:
Kurstjens DAG, Leeuwen S van, 2020. Improving the Ecovat business case in a local energy system.
Hanze University of Applied Sciences, Groningen,
The Netherlands

# Improving the Ecovat business case in a local energy system

22 December 2020

# Table of contents

1. **Introduction ........ 7**

2. **Selecting and justifying neighbourhood-specific heating solutions and heat storage ........ 9**

2.1. Introduction ........ 9

2.2. Model-based multi-criterion comparison of strategies ........ 11

2.2.1. Municipalities and the heat transition of neighbourhoods ........ 11

2.2.2. Regional Energy Strategy and the energy infrastructure ........ 13

2.3. Business case ........ 15

2.3.1. Situation-specific design and performance ........ 15

2.3.2. Quantify system benefits and costs to society ........ 15

2.3.3. Flexibility and reduced risk through stepwise implementation ........ 17

2.3.4. Challenge commonly accepted perspectives ........ 18

2.4. Pilot and demonstration project ........ 18

2.5. Interim conclusions and discussion ........ 19

3. **Decision processes of local energy collectives ........ 20**

3.1. The role of energy collectives ........ 20

3.2. Observations and reflections ........ 20

3.2.1. Creating plans ........ 21

3.2.2. Taking decisions ........ 21

3.2.3. Convincing people and realising plans ........ 23

3.3. Interim conclusion ........ 23

4. **Heat transition approach ........ 24**

4.1. Introduction and problem identification ........ 24

4.1.1. Participation means seduction to join the plan ........ 24

4.1.2. Lack of transparent, participative integral system design methodology ........ 25

4.1.3. Limited up-front regard for exergy efficiency and dynamic system behaviour ........ 25

4.2. Suggested phasing and participation approach ........ 26

4.2.1. Optimise and monitor a cluster before developing the larger infrastructure ........ 27

4.2.2. Consequences for various stakeholders – roles and benefits ........ 29

4.2.3. Balancing home improvement cost and heat generation cost ........ 31

4.3. Proposed technical innovations ........ 33

4.3.1. Heat storage at home and cluster level ........ 33

4.3.2. System efficiency in cluster installations ........ 35

4.4. Conclusion ........ 37

**5. Simulation study – Combining ecovat and aquifer heat storage to reduce heat storage cost ......... 38**
5.1. Introduction ........ 38
5.2. Case 1 – Charging the Ecovat using high temperature heat ........ 39
5.3. Case 2 – All heat generated via the electricity grid with heat pumps ........ 43
5.3.1. Method ........ 43
5.3.2. Results ........ 44
5.4. Impact on the business case ........ 45
5.5. Conclusions ........ 46
5.6. Discussion and recommendations for further research ........ 47
**6. Summary of conclusions and recommendations ........ 48**
**7. Appendix ........ 50**
7.1. Starting parameters ........ 50
7.2. Loading logic ecovat ........ 51
7.3. Loading SAS ........ 53
7.4. Unloading the SAS ........ 53
7.5. Thermal losses Ecovat ........ 54
7.6. Thermal losses SAS ........ 55
7.7. Selected model outputs ........ 55
7.8. Case 2 specifics ........ 57
7.9. Parameter settings ........ 57

# Preface

This research is part of the Community Responsible Innovation towards Sustainable Energy (CO - RISE) project [176] and is funded through the socially responsible innovation program of The Netherlands Organization for Scientific Research, the Netherlands. Grant number: (NWO-MVI 2016 [313-99-304]).

In the last four years the authors have been involved with several local energy collectives, advising on technical and energy efficiency aspects. All projects were in early stages of development, with a large variety of issues coming to the table. We are both grateful to be given this learning opportunity.

This report aims to support Ecovat B.V. in their ambition to establish projects with local governments and energy collectives. We hope the insights and ideas presented in this report will be helpful and open new perspectives.

In the process of writing this report we found that our initial setup could not be fully realised. Chapters 2 and 4 contain several claims that need further argumentation and substantiation by references. We also omitted the chapter reporting the discussions with several experts and stakeholders on the material presented in chapters 2-5 and on the question what Ecovat B.V. could do to support the decision-making process of municipalities and energy collectives.

Groningen, 22 December 2020

Dirk Kurstjens
Senior lecturer Mechanical Engineering
School of Engineering, Hanze University of Applied Sciences

Scott van Leeuwen
Director Nextheat

# 1. Introduction

This research is part of the MVI-CO-RISE[1] project, which contributes to the exploration of socio- technical configurations of local community-based sustainable energy systems. In the Netherlands, over 500 local energy collectives are initiated by citizens to produce their own sustainable energy, e.g. by establishing solar fields or sharing investments in wind turbines. More recently, collectives have realised that their heat consumption [in kWh/year] is far greater than their electricity consumption and have started supporting neighbours in improving home insulation. Some collectives therefore aim to develop collective generation, distribution and storage of heat. Such initiatives help municipalities in taking steps, for example by supporting pilot projects.

Although the need for seasonal heat storage is recognised, it is technically, financially and organizationally too complex to handle for municipalities and energy collectives. Therefore, enterprises are involved in the further development. This report explores how Ecovat B.V. could support energy collectives and municipalities in selecting appropriate sustainable heating solutions and developing district heating system (DHS) with seasonal heat storage.

The company Ecovat B.V. developed the ecovat[2]: a large underground high-temperature seasonal heat storage vessel made of concrete and filled with water. The ecovat, when connected to a district heating system (DHS) and various renewable electricity and heat sources, could eliminate both the direct and indirect use of fossil fuels for heating buildings, and provide many benefits to the energy system beyond the project's boundaries. Model studies[3] indicate that implementing an ecovat seasonal heat storage system (32,750 $m^3$, serving 17 GJ/year total heat demand) could save 97-167 k€/year on peaker plants and electricity grid reinforcements.

However, the initial investments for the complete DHS + ecovat system are substantial. The investments, efficiency and avoided grid reinforcements strongly depend on the local situation. Although the anticipated long technical service life of the system counterbalances the high initial investment, fixing oneself to such a long-term decision is difficult when technology develops rapidly. Laws, policies, prices, financial options and other factors that determine the assumption business case may change over time. So, given these complexities and uncertainties, how can we answer the main question of this report:

"In which situation(s) is an ecovat a favourable option (as compared to alternatives),
with a feasible business case?"

Answering this question is not only relevant for Ecovat B.V., but also concerns potential customers such as municipalities, energy collectives and district heating companies. They need to justify their decisions concerning neighbourhood energy systems to citizens and clients. The authors think that justification should go beyond comparing business cases, as those only deal with the financial aspect, and because the numbers are inherently approximate and uncertain. Therefore, justification should (also) follow from sound assumptions, argumentation,

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[1] This abbreviation stands for *Maatschappelijk Verantwoord Innoveren* - Responsible Innovation towards Sustainable Energy. MVI is a research agenda of the Dutch Topsector Energy.

[2] Throughout the report "Ecovat B.V." refers to the company and "ecovat" refers to the storage technology.

[3] Warnaars J, Kooiman A, Ouden B den, 2018. System consequences of Ecovat. Quantification of costs for grid reinforcement and peaker plants. Berenschot report 59593. https://www.ecovat.eu/wp-content/uploads/2018/10/Ecovat-System-costs-avoided.pdf

methods and design principles[4]. Apart from the final solution, the transparency and thoughtfulness of the selection & design process are important, maybe even critical.

“Technology providers” like Ecovat B.V., energy collectives, and governments each have different selection & design processes and ways of justification:

1. Model-based multi-criterion comparison of strategies to heat homes without natural gas
2. Business case
3. Pilot and demonstration project

Chapter 2 discusses these methods and their weaknesses with respect to selecting neighbourhood-specific heating solutions, particularly considering energy storage and energy system integration. How do (and could) these methods identify the value of seasonal heat storage? What kind of information or analysis could improve the quality of decisions made? How could Ecovat B.V. contribute to, or be involved in, the selection & design processes of potential customers?

Chapter 3 reflects on the decision process of local groups of citizens who attempt to establish a pilot project including energy storage in their village. The authors have supported several groups with technical expertise and have witnessed how they discarded seasonal heat storage for the time being, whereas it was a key part in their initial vision. The authors reflect on the decision process and on the tensions that arise when ambitions and ideals are confronted with various complications, such as developing a business case and applying for subsidies.

Chapter 4 proposes a stepwise transition approach that reduces uncertainty in business cases. This approach reduces the complexity of design and dimensioning decisions, as large investments in infrastructure (piping and storage) are postponed to the moment that source and demand profiles (power and temperature as function of time) are known in detail. It includes thermal storage at various locations, suited for various timescales and volumes. This approach could elucidate the specific additional value of a large high-temperature seasonal heat storage such as an ecovat.

The proposed approach also clarifies the mutual consequences of decisions on various levels (homeowner, street/block, village)[5]. This could facilitate the participation of citizens and help municipalities develop their heat transition vision and apply heat storage and demand-side management.

Chapter 5 presents a simulation of a DHS with Ecovat, where the DHS supply temperature adapts to the hourly heat demand. It explores to which extent the initial investment cost per home could be decreased by supplying (the low temperature) part of the heat demand through a central heat pump that uses aquifer storage as a source. The simulation study determines the feasible expansion of the DHS by aquifer storage + heat pumps, depending on heat/electricity price ratios and supply temperature levels. The effect of 3 heat pump capacities on heat cost and potential DHS expansion is evaluated, assuming optimal use of variable electricity prices. These simulations aim to identify the specific added value of high temperature seasonal heat storage (ecovat) in a smart DHS.

Each chapter has a separate introduction and conclusion. Chapter 6 summarizes the overall conclusions and recommendations.

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[4] For example, a capital-intensive infrastructure should have a very long technical and economical service life. Therefore, it should be adaptable, able to integrate future technologies, resilient to various economic scenarios, etc. Implementing this principle would be at odds with outsourced commercial exploitation with 15-year concession periods. Chapter 3 and 4 elaborate this further.

[5] For example: Decisions of homeowners concerning insulation and heat delivery system adaptation affect the supply and return temperature of the generation and distribution system. These affect the potential sources and generation technologies and ultimately the annual heat cost. Local heat storage and clustering affects the load profile, layout and dimensioning of the DHS. These costs need to be balanced with each other, and to (direct and indirect) fossil fuel consumption, electricity grid investments and sensitivity to prices and policies.

# 2. Selecting and justifying neighbourhood-specific heating solutions and heat storage

**Although Ecovat BV knows how to justify an investment in their product, their potential clients have a different perspective. Most municipalities are in the process of finding suitable pathways to realise the heat transition in their neighbourhoods. For them, a district heating system (DHS) is just one of the options, wherein an ecovat is an optional component.**

**As municipalities use models, business cases and pilot projects to guide their decisions, it is worth examining whether these methods adequately appraise the potential of DHS and (seasonal) heat storage. That analysis should reveal how Ecovat BV could help improve the quality and justification of decisions.**

## 2.1. Introduction

Most people involved in energy transition are aware of the necessity of energy storage as part of the future energy system. The logic follows from the intermittent and seasonal nature of solar and wind energy production, and the limited space available for these installations[6]. Nevertheless, storage technologies are far less eagerly adopted than solar panels, wind turbines and individual heat pumps. Why?

Storage does not generate green electricity or replace fossil fuels directly, so its contribution to the energy transition is less tangible. Storage facilitates the integration of other technologies, which is also indirect. It could therefore be perceived as a technical matter, only to be considered during implementation, as a mitigation option for grid problems.

This popular view is in stark contrast to realisation that appraising the value of storage requires a system perspective. The significance of a system perspective lies in adverse foreseeable and irreversible boomerang effects of decisions taken with narrow scope. For example, disconnecting homes from natural gas by installing a

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[6] MacKay DJC, 2009. Sustainable energy – without the hot air. https://www.withouthotair.com/. This study shows that the available land and sea area of the UK is by far insufficient to generate the nations required energy through renewable sources.

heat pump and solar panels, necessitates investments in the electricity grid, battery storage and peak power. This will increase electricity cost, thus corrupting the assumptions on which the initial decision was based. Whereas the initial scope of that decision was limited to a single home, the effective result (in case of broader simultaneous implementation) is an indirect effect of the system beyond that scope.

Most actors who are to decide on the implementation of storage, so far have not taken a system perspective when deciding on installations and appliances in their homes. In conventional fossil fuel- based systems, the responsibility for reliable and efficient supply has been outsourced to other parties like Tennet, Gasunie, network operators and commercial energy producers. They have so far emphasised on conversion and distribution because the fossil fuel itself essentially fulfilled the storage function.
One may conclude that we find ourselves in a world in which no one has had to make sound decisions on energy storage. Therefore, the authors think we still need to learn how to make those decisions (developing appropriate methods) wisely, and how to organise the associated responsibilities (who is entitled to make decisions, and who carries the consequences).

How is a heat storage system supplier like Ecovat B.V. to operate in a world where their potential customers[7] have essentially outsourced decisions on energy storage? The ecovat solution is well-known, but it is still difficult for potential customers to decide on and financially justify such an investment. Ecovat B.V. has provided extensive case studies[8] that account for many aspects including economics, finance and the system benefits of storage (see Box 1). Although system benefits appeal to visionary clients, they have not materialised in business cases and pilot projects. Therefore, we explore where the system perspective is considered, and how this is done. The parties involved in preparing regional energy strategies (RES) might offer some additional opportunities for Ecovat B.V. Not so much directly (selling ecovat systems), but indirectly through quantifying the system benefits of seasonal heat storage, identifying situations with best opportunities, and through informing stakeholders (i.e. network companies) that influence or negotiate with potential customers.

This chapter explores three current methods potential customers use to select and justify neighbourhood-specific heating solutions: model-based multi-criterion analysis, business cases, and pilot projects. How do (and could) these methods identify the value of seasonal heat storage? What kind of information or analysis could improve the quality of decisions made? How could Ecovat B.V. contribute to or be involved in the selection & design processes of potential customers?

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[7] In this report the term "customers" refers to governments, semi-governmental bodies and institutions, energy collectives and companies that affect or take decisions on the adoption of seasonal heat storage. They either own the system, set requirements, provide subsidies, or devise and implement policies. Although terms like actors, stakeholders or influencers might be more appropriate than "customers", the latter term was chosen because the authors think Ecovat B.V. is looking for customers who will buy what Ecovat B.V. has on offer. From a commercial point of view a customer is someone who decides whether money will come your way. Actors, stakeholders and influencers do influence but don't always make critical decisions.

[8] Bosch R van den, Verbeeten M, Bouwdijk E van, 2016. Een 100% duurzame warmte/koude voorziening voor de "Trekvlietzone" in Den Haag. De toepassing van een Ecovat energiesysteem. https://projecten.topsectorenergie.nl/storage/app/uploads/public/5c0/513/20e/5c051320e2d1d720475773.pdf

## Box 1 – System benefits of energy storage

1. Better / more effective use of the generated sustainable energy, resulting in:
    a. Less generation power is required to achieve a certain $CO_2$ reduction target. This reduces the associated sacrifice of landscape quality, and the natural and financial resources to be invested in generation installations.
    b. Further ultimate reduction of fossil fuel dependency. In western Europe, the available area limits the generation capacity that can be installed[6]. So, apart from reducing energy demand, storage and demand management determine the ultimately achievable fossil fuel reduction.
    c. Sustained low-risk investments in further expansion of generation capacity, because storage sets a bottom in the energy prices (i.e. also peak production remains valuable).
    d. Less investment in backup generation capacity.
2. More freedom in selecting the type of renewable resource:
    a. If wind power is not acceptable (noise, landscape quality), storage allows a greater proportion of solar power to be installed, despite the unfavourable seasonal pattern as compared to wind.
    b. Thermal heat sources (surface water, ambient air, residual heat) can be stored when available, for later use. Temperature levels can be elevated by heat pumps.
3. Less investment in the distribution system through more efficient utilisation.
    a. Storage can absorb production peaks and provide peak demands and causes a more equal load. However, the required transport capacity is only reduced if the storage is close to the source of the variability.
    b. Load variability particularly affects the efficiency and cost of heat networks. Peak flow determines pipe diameter, which affects pumping energy and cost per metre. Low flow causes heat losses and decreases generation efficiency by high return temperatures. Different demands (flow, temperature) at various locations in the network also add to losses.
    c. Storage, peak power and transportation capacity are complementary infrastructural investments, that require situation-specific matching. Storage is beneficial if the ratio kWh transported/ € invested for the network is low.
4. More efficient utilisation of power plants, CHP's and heat pumps because of:
    a. Less on/off switching increases lifetime and reduces maintenance cost.
    b. Optimal operating point / part load, and less idle/standby operation.
    c. Valorisation of excess by-product (i.e. residual heat of CHP or electrolyser).
    d. Operating preferably at times when input energy is abundant, and prices are low.

The magnitude of all benefits of storage depend on the mismatch in generation and demand patterns and their variability in time. Particularly benefits 3 and 4 can reduce energy cost, whereas benefits 1 and 2 increase acceptance and the ultimate fossil fuel dependency.

## 2.2. Model-based multi-criterion comparison of strategies

### 2.2.1. Municipalities and the heat transition of neighbourhoods

Municipalities (and their advisors) are in the process of gathering data and making decisions on the way homes and neighbourhoods are to be disconnected from natural gas. By the end of 2021 each municipality should present its TVW (*Transitie Visie Warmte*). For each neighbourhood, this document identifies the strategy to replace natural gas, and when it will be implemented. The process of developing the TVW is well-structured and supported by advisory agencies ECW (*Expertise Centrum Warmte*) and PBL (*Planbureau voor de Leefomgeving*). For example, ECW proposes 5 candidate strategies[9]:

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[9] ECW, 30-10-2019. Handreiking voor de lokale analyse. Verrijking Startanalyse ten behoeve van de transitievisie warmte, page 6.
https://expertisecentrumwarmte.nl/themas/de+leidraad/handreiking+voor+lokale+analyse/default.aspx

1. Individual electric heat pump: Extensive insulation, low-temperature heat delivery system, air-source or ground-source heat pump with buffer
2. District heating system (DHS) with high- and medium-temperature (>70℃) sources
3. District heating system (DHS) with low-temperature sources and heat pump(s)
4. Green gas and air-source heat pump
5. Hydrogen and air-source heat pump.

The strategy selection is based on several criteria, and quantification of costs and avoided $CO_2$ emissions, as projected by the Vesta MAIS model[10]. This advanced open source model inventories potential heat sources, estimates energy demand and insulation costs for individual homes, and uses geographical information on various aspects, so the strategies can be compared with respect to $CO_2$ emissions, spatial impact and cost.

One could question the validity of the model outcomes for specific situations, as many input values are generalized averages. Particularly with DHS, situation-specific choices on home measures, sources and network design have a large effect on costs and efficiency. However, including a high level of detail would make the model unworkable and unfit for its purpose. After all, the TVW is a first step in the planning, selection, communication and development process.
At this stage, it seems more relevant to examine whether the approach currently taken would miss opportunities for DHS and heat storages or would result in unfavourable choices that cannot be repaired later. These insights could then be communicated to relevant parties, whilst presenting feasible alternatives.

In what situations would misappraisal of DHS including heat storage be likely to occur? District heating systems are generally considered in densely built urban environments, where home insulation measures to current standards would be too expensive, and where heat sources are close and available. Most considered heat sources (industrial waste heat, waste incineration plants, biomass, deep geothermal source) provide high- or medium-temperature heat continuously, also in wintertime. In such DHS, heat storage would only add value where there is limited heat power available in winter, combined with a heat surplus in summer. In this case, seasonal heat storage would allow more homes to be connected to the same heat source. However, if homes require a year-round high supply temperature from the DHS, the required storage volume would be very large, whereas the temperature degradation during the storage period should be very low. Therefore, an ecovat is not compatible to a high- and mid-temperature DHS (strategy 2).

The feasibility of a common seasonal heat storage such as an ecovat would improve where:

1) The DHS supply temperature would vary during the season, matching the requirement for space heating. In this case additional home installations are needed to supply domestic hot water. Homes requiring a relatively high supply temperature for space heating could be equipped with a booster heat pump.
2) The return temperature would be reduced through various ways of heat cascading, either within or between homes. For example, by adding floor or wall heating in series to existing radiators, or through local booster heat pumps. DHS with larger delta T (supply – return temperature) allow for smaller pipe diameters, improved heat storage utilisation and reduced heat loss.

The above implies that opportunities for low-temperature DHS (strategy 3) should not be missed, particularly if heat storage could make them more feasible.

The Vesta MAIS model focuses on energy generation and demand on annual basis, so the role of energy storage is not being considered. Moreover, the Vesta model considers supply temperature requirements indirectly and very roughly. Therefore, the authors expect that opportunities will be missed particularly in the following situations:

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[10] Wijngaard R van den, Polen S van, Bemmel, B van, 2017. Het Vesta MAIS ruimtelijk energiemodel voor de gebouwde omgeving. Algemene beschrijving, achtergrondstudie. Planbureau voor de Leefomgeving (PBL). https://www.pbl.nl/publicaties/het-vesta-mais-ruimtelijk-energiemodel-voor-de-gebouwde-omgeving-algemene-beschrijving

1) Neighbourhoods with no present nearby heat sources, and with large available areas for solar PV or solar collectors on roofs or nearby open spaces. The Vesta MAIS model does not consider such heat sources for a DHS. However, excess solar electricity in summer could be used to power heat pumps or electrolysers, whilst storing heat for winter use. Heat produced by solar collectors could be used or stored directly.
2) Regions where heat storage and smart control of heat pumps and CHP's would considerably reduce investments in electric infrastructure. More precisely, the annual heat infrastructure cost (CAPEX + OPEX) minus gains from providing grid flexibility should be less than the annual cost of grid reinforcements and indirect costs due to losses and installed peak power. Models supporting the development of TVW's and RES (regional energy strategy) use extensive GIS data, so it should be possible to implement a method to estimate those costs components. Unfortunately, the authors haven't been able to look deeper into this relevant issue.
3) Neighbourhoods with few homes per kilometre of network length, where insulation to label B would be very costly or intrusive. If homes will not be rebuilt to new isolation standards in the foreseeable future, heat generation and the energy infrastructure should be very efficient to attain 2050 $CO_2$ emission targets. Although hybrid systems and high-temperature heat pumps could generate the required high temperature for space heating, the indirect use of fossil fuels and the load on the electricity grid will remain substantial. Supplying the heat pump with low-temperature heat stored during summer would reduce investments in the electricity grid and peak power plants. Section 4.3.2 presents technical options that would reduce heat losses and lead to optimised DHS investments for such situations.
4) Neighbourhoods with terraced houses or multi-apartment buildings, where a common installation (heat pump, local short-time heat storage, smart control system) could provide heating and cooling through an indoor electricity and heating grid. As compared to individual home installations, this would reduce investment costs and facilitate optimisation and service[11,12]. Once the energy profile of each block is known and once additional heat sources become available, common installations could be connected to a well-dimensioned DHS with seasonal heat storage.

These categories partly overlap and would probably yield strategy 4 or 5 (green gas or hydrogen plus individual heat pump) as the recommended strategy. They mostly apply to rural villages, where DHS is usually not considered as an option. What combination of local storage and demand management would provide a more cost-effective alternative in the end (including cost of adapting gas networks and establishing storage and production of biogas or hydrogen)?

This question is urgent in areas where hybrid strategies (4 and 5) are viewed as the most economically and technically viable option in neighbourhoods that start transitioning before 2030. If network operators then plan grid reinforcements to facilitate heat pumps and solar PV on roofs, it would not be plausible to add a DHS afterwards. Therefore, the authors advise Ecovat B.V. to reach out to network operators and make them aware of alternatives. Together they could also select cities, towns and large villages where an ecovat could most effectively provide grid services or avoid grid investments.

### 2.2.2. Regional Energy Strategy and the energy infrastructure

The Netherlands has established 30 energy regions that each deliver a regional energy strategy (RES)[13] to the national programme. Each energy region coordinates plans of municipalities (TVW's, implementation plans), grid operators, semi-governmental bodies and other stakeholders within that region, to provide shared insight in:

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[11] Roestenberg B, 2020. Futuristisch project in Berlijn is showcase totaalsysteem voor energie en verwarming. https://www.vakbladwarmtepompen.nl/projecten/artikel/2020/07/futuristisch-project-in-berlijn-is-showcase-totaalsysteem-voor-energie-en-verwarming-1016184 .

[12] Mooi, R, 2020. Mini-warmtenet als alternatief voor buitenunit warmtepompen https://www.vakbladwarmtepompen.nl/bronnen/artikel/2020/01/mini-warmtenet-als-alternatief-voor-buitenunit-warmtepompen-1015488 .

[13] Handreiking regionale energiestrategie 1.1, oktober 2019. https://www.regionale-energiestrategie.nl/ondersteuning/handreiking/default.aspx

- possibilities for regional energy generation (wind, solar, biomass) and energy savings,
- possibilities translated into choices for specific places, projects and planning,
- coordination concerning the use of heat sources by the various municipalities,
- the implications for energy infrastructure, and
- realised projects and plans.

In October 2020 all energy regions have delivered a concept RES document. After national evaluation and further elaboration, RES 1.0 is to be delivered the 1st of July 2021, followed by RES 2.0 in March 2023. Until 2030 RES and TVW's will be updated every two years, thus integrating plans at various levels (municipality, energy region, national), involving all stakeholders (governments, network operators, companies and civil society).

More than TVW's of municipalities, RES pays specific attention to necessary adaptations of the energy infrastructure, the associated cost and the resulting system efficiency. A suite of models[14] is available to evaluate plans in different stages of development. Several models include hourly energy use and production profiles, network layouts and storages of heat and electricity. Available energy infrastructure studies[15] give insight in the potential of using models and expert groups. Such studies impact decisions made within the RES process through providing a factual basis for considerations by multiple stakeholders.

Having the ecovat implemented in selected models[16] could be an avenue for Ecovat B.V. to elucidate the benefits of heat storage to various parties in a neutral and balanced way, while avoiding perceived bias associated to commercial interest. Such models could also help Ecovat B.V. to identify promising business cases or adapt the configuration to improve the proposed business case or mitigate downsides. Therefore, the authors think that cooperating with consultants[17] contracted by RES teams could be advantageous to Ecovat B.V.

If Ecovat B.V. would take this avenue, the authors advise also to include other storage methods (at home and block/cluster level, see chapter 4), methods to optimise DHS design (e.g. https://comsof.com/heat/), and help provide situation specific datasets to be applied in business case templates (cost and efficiency parameters).

Although models may offer opportunities, it is not clear how they will be used in which stage of the process, and to what extent decisions can be influenced. For example, network operators are to indicate the consequences of proposed plans for the gas and electricity infrastructure: the lead time, cost and space occupation of the required other patients. They consider options for conversion, storage, grid reinforcements and flexibility (demand and supply management), but they don't have a decisive say.

Ecovat B.V. probably cannot play a role in shaping plans at the regional level, as producing energy and providing flexibility are legally assigned to market parties. Nevertheless, RES documents should provide a view of how "the market" could and would participate in the realisation of the regional heat infrastructure (RSW[18]): What (governmental) means would be required to that end, and which parties (a.o. technology suppliers) could have relevant input to develop the business case of the energy system.

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[14] www.energierekenmodellen.nl links to a Netbeheer Nederland website, which provides links to a graphical overview of models and their application areas ("grafische keuzehulp") and an online model selection tool (https://etrm.nl).

[15] See for example https://www.ce.nl/publicaties/2323/rapportage-systeemstudie-energie-infrastructuur-noord-holland-2020-2050 and https://www.ce.nl/publicaties/2390/systeemstudie-energie-infrastructuur-groningen-drenthe .

[16] the first models to look at would be CHESS, ETM (energietransitiemodel) and MOTER, followed by LEAP, ES-IT, warmtevraagprofielen and Powerfys. See https://etrm.nl for more information. See also Box 3 in chapter 4 concerning the recent initiative of TNO and partners to develop a method and toolkit for planning future-resilient DHS (https://www.warmingup.info/project/13/1c-systeem-re-design-toolkit).

[17] See for example https://overmorgen.nl/nieuws/energiemodellering-onmisbaar-voor-res-1-0/

[18] Dutch: regionale structuur warmte. This concerns the shared use of heat sources in multiple municipalities (including industry, utility buildings, horticulture and agriculture) and the infrastructural implications.

## 2.3. Business case

Many ideals, visions and ambitions stumble when put to the test of a business case. This reality checking method answers questions such as:

1. Can the loan plus interest be paid back within an acceptable time period?
2. What are the risks to be taken by each participant? How well are those backed up by securities?
3. How robust is the proposition in the light of future developments in markets, technology, policies etc.?
4. How good is the proposition as compared to alternatives (including doing nothing, postponing or spreading out the proposed plan over time)?

Although business cases tend to emphasise on quantifying financial parameters such as payback time, net present value or total cost of ownership for specific stakeholders, such numbers would not answer the above questions satisfactorily. This section aims to address issues that could help strengthen the business case for DHS including seasonal heat storage.

### 2.3.1. Situation-specific design and performance

Ecovat B.V. presented a business case for a project in The Hague[19], including arguments that could convince the municipality and financers. The report compares an ecovat with aquifer thermal storage (ATS, at max 25℃) as a heat source for a central heat pump. Although ecovat excelled on many criteria, the outcomes depend on many assumptions and parameter estimates. Site-specific optimisation, basic engineering and simulation studies would require much effort which will not likely be paid for.

As the cost and performance of a DHS are very situation-dependent, it would be helpful to
1) have configuration software (e.g. https://comsof.com/heat/, footnote 16),
2) elaborate typical examples linked to pilot projects, or
3) develop situation-specific parameter sets for models used in RES studies (see 2.2.2) and
4) include ecovat in reference business case templates[20].

In addition, elaboration of typical examples could be fruitful in the short-term, because DHS has recently received renewed attention, whereas DHS are generally still perceived to be only applicable in densely built towns with nearby heat sources. Publicity on atypical applications could help tilt this perception.

### 2.3.2. Quantify system benefits and costs to society

System benefits of storage (see Box 1) are not yet being rewarded financially to the investors. So, investments in storage facilities could only be repaid by the price difference between selling and buying energy at different times. The business case for an electricity storage facility could be based on statistics and projections of price volatility on various markets. However, a business case for heat storage is more difficult to assess accurately (see Box 2). For example, a recent feasibility study on the business case of small-scale heat storage technologies[21], did not

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[19] Bosch R van den, Verbeeten M, Bouwdijk E van, 2016. Een 100% duurzame warmte/koude voorziening voor de “Trekvlietzone” in Den Haag. De toepassing van een Ecovat energiesysteem. https://projecten.topsectorenergie.nl/storage/app/uploads/public/5c0/513/20e/5c051320e2d1d720475773.pdf

[20] https://expertisecentrumwarmte.nl/kennis/template+businesscase+warmtenetten/default.aspx This DHS business case template gives a first impression of the costs and the impact of factors and cost components. Greenvis developed the F1F9 method: https://greenvis.nl/diensten/engineering/greenvis-warmtetool/

[21] Slot D van ‘t, 2020. Businesscase kleinschalige warmteopslag. Reductie aansluitvermogen door kleinschalige warmteopslag. DWA 18470, TKI Urban Energy. https://www.dwa.nl/actueel/onderzoek-naar-kleinschalige-warmteopslag/

## Box 2 – Why heat storage business cases are difficult to assess

The issues below particularly apply to medium- and large-scale seasonal heat storages, which are connected to a delivery network that serves multiple homes.

1. A heat storage facility is linked to a specific area for a long period of time. Future reduction in heat demand reduces revenues or necessitates further investments to expand the distribution network. This could result in a lock-in condition.
2. Seasonal and daily variations in total supply or demand vary in their amplitude, so that installed capacity is not fully utilised (and paid for). Balancing investments between peak demand facilities and storage volume is difficult without adequate information on supply and demand patterns.
3. Storage and distribution network efficiency depends on many system design parameters in interaction with demand patterns. Heat losses decrease the delivery temperature, whereas this should meet requirements of the homes and buildings. The associated costs for heat pumps or peak generation facilities are difficult to predict.
4. The heat generation costs depend on the source (generation pattern, investment cost), the temperature delivered to the storage, and temperature to be delivered to the network. Both temperatures vary over time, as do the electricity costs for upgrading the delivered heat to the required temperature.
5. The selling price of heat is constant over time, and legally maximised. The allowed heat tariff is presently related to the price of natural gas and independent of temperature.
6. The investment costs depend on many situation-dependent factors. Quantification requires extensive pre-engineering studies. Situation- and configuration-specific cost parameters are either not available or not very accurate (e.g. piping network costs).

The likely future financial reward for benefits to the national energy system is highly uncertain, as it depends on and affects decisions of several stakeholders.

include the avoided cost of grid reinforcements because of their location dependency. Another study[22] indicated that implementing an ecovat seasonal heat storage system (32,750 m$^3$) could save 97-167 k€/year on peaker plants and electricity grid reinforcements.

Although quantifying system benefits in financial terms is difficult and does not affect the costs and income of current projects, there are several ways in which it could strengthen the business case in more general terms. Firstly, business cases are often developed when the project is not profitable on itself (or: not financially attractive according to market standards). If subsidies or arrangements are required, the project's contribution to the common good and to governmental policies needs substantiation. In recent studies on energy infrastructure scenarios[23] and solar PV on different locations[24], societal costs benefit analysis provided a very different perspective than the business case. Providing such information to RES partners and municipalities could strengthen the case for a large long-term investment in seasonal heat storage. After all, decisions are largely political.

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[22] Warnaars J, Kooiman A, Ouden B den, 2018. System consequences of Ecovat. Quantification of costs for grid reinforcement and peaker plants. Berenschot report 59593. https://www.ecovat.eu/wp-content/uploads/2018/10/Ecovat-System-costs-avoided.pdf

[23] Den Ouden B den, Kerkhoven J, Warnaars J, Terwel R, Coenen M, Verboon T, Tiihonen T, Koot A, 2020. Klimaatneutrale scenario's 2050. Scenariostudie ten behoeve van de integrale infrastructuurverkenning 2030-2050. Berenschot 61689, Kalavasta. https://www.berenschot.nl/actueel/2020/april/nederland-klimaatneutraal-2050/

[24] Schellekens J, Terwel R, Tiihonen T, Coenen M, Kerkhoven J, 2020. Maatschappelijke kosten-batenanalyse naar toekomstige inpassing van drie alternatieven voor opwek van zonne-energie. Berenschot 63354, Kalavasta. https://www.enpuls.nl/persberichten/kosten-batenanalyse-zonnepanelen-op-bedrijfsdaken-zijn-beter-dan-op-landbouwgrond-in-2020/

Secondly, some effects that are external to the project indirectly affect its business case in the long term. Grid reinforcements are eventually paid by citizens through electricity bills, whilst subsidies are paid through taxes in the end. If $CO_2$ emission targets are not met, future policies (taxes and tariffs) might create a new reality with which a project then has to cope. Proving the resilience of the business case to such risks could make a difference for investors. Providing potential customers with studies that quantify these effects[25,26] could be an easy way to raise awareness. These indirect effects may also be incorporated in sensitivity analysis and tariff scenarios.

An ecovat is part of a DHS which can have several configurations. Strategies without ecovat and even without DHS could also provide part of the system benefits that ecovat offers, at lower initial investment (see chapter 4). For instance, through smart control of heat pumps combined with heat buffers in individual homes (Hydrobag, Solar Freezer, Viessmann ice buffer, Flamco Flexterm Eco, water tank). Heat buffers in or near individual homes would reduce peak flow in the DHS as well. Therefore, the system benefits of an ecovat would be identified more clearly when combined with a “smart DHS” that implements decentral storage in (cluster of) homes.

### 2.3.3. Flexibility and reduced risk through stepwise implementation

Planning and realising a total system solution (like ecovat + DHS + sustainable sources) upfront is attractive because it reduces many uncertainties and dependencies (cost, tariffs, financial markets, policies) for decades. The business case then involves all major decisions and their financial impact in the total project timespan. However, limited upfront information and coarse assumptions make the business case less reliable.
For example, excluding home measures from the business case scope and assuming a year-round supply temperature of 70℃ for both domestic hot water (DHW) and space heating could lead to over-investment, excessive generation and network losses, and risk of reduced income over time when home owners improve home insulation. Including optimized home measures in the scope would reduce these risks. On the other hand, this would make the business case development process complicated, costly and time consuming.

Instead of overviewing the whole transition project in one upfront business case, one could develop a staged business case. The first project stage then would contain safe investments that are complementary or synergetic, and robust for various future scenarios. Subsequent project stages then could use monitoring data from the first project stage to optimise selection and dimensioning of additional installations such as DHS and storages. The decision on including a central seasonal heat storage (and on its design, location and dimensions) can then be based on better information on citizens acceptance, local flows and required supply temperatures. The transition process can start small and in short term, build confidence and sense of progress and cooperation, and test the real willingness of citizens to participate. This information and preceding implementation success would make the subsequent business case stages more accurate and reliable. This staged transition strategy will be elaborated in chapter 4.
However, such an “open-end” business case is uncommon and unlikely to be accepted by subsidy providers that want their goals (e.g. disconnect from natural gas) and conditions (equal or lower cost for citizens) to be secured upfront. This is one issue that requires a change of perspective (see also 2.3.4).

Flexibility implies that system components could be exchanged or added later, without decreasing the value of existing investments. After all, maximising the technical and economic life of an asset is a way to decrease capital cost. For example, charging a seasonal storage first through heat pumps, which could later be replaced by electrolysers once the heat pump technical lifetime ends, the hydrogen infrastructure is available, and the hydrogen market is sufficiently attractive.

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[25] Melle T van, Ramaekers L, Terlouw W, 2014. Waarde van slimme netten. Welke waarde creëren slimme oplossingen in het distributienetwerk? Ecofys INTNL15184. https://quintel.com/publications/ecofys

[26] Blom MJ, Bles M, Leguijt C, Rooijers F, Gerwen R van, Hameren D van, Verheij F, 2012. Maatschappelijke kosten en baten van intelligente netten. CE Delft, Kema. https://www.mkba-informatie.nl/index.php/download_file/force/156/325/

How could such options be processed in business cases? The authors think that good business case avoid blocking future opportunities, postpone uncertain investments and find a merit order for situation-dependent subsequent investments. The desire or custom to have a business case with everything fixed upfront seems at odds with the essence, timescale, complexities and uncertainties of a transition process.

### 2.3.4. Challenge commonly accepted perspectives

Beyond financial parameters, comparisons and arguments can put business cases in perspective and add essence to the justification of an investment. Here are some examples:

- Many investments don't consider the business case. Who calculates the payback time of a new kitchen?
- What is the purpose of an investment? "Rejecting a green investment whose net present value is zero, means that sustainability has no value to you."
- Why do professional investors put their money in obligations that offer zero interest? How then about the risks associated to conventional energy systems as compared to (for example) solar + seasonal storage + DHS, in the next 50-70 years?
- Fossil fuels have fulfilled the storage function in the energy system. We have taken that for granted. Therefore, we don't have a real sense of its value. However, in times of crisis we quickly learn to value stocks of essential goods we never cared about before (e.g. mouth masks during Covid-19 pandemic).
- The value of energy storage has been included in the OPEX of fossil fuels and this value has been underrated. Converting the value of energy storage to CAPEX requires a different economic logic, centred on maximising the economic and technical lifetime of assets. This calls for long-term decision-making and other criteria than e.g. payback time.
- The government will at some moment (be forced to) find mechanisms to transfer the financial burden of energy transition from the government's budget to companies and citizens, through taxing energy use or grid connection fees. In that perspective there is value in systems that can avoid this burden. How would a future-proof energy infrastructure that reduces policy-dependencies and risks affect the value of the connected real estate and assets?
- Current heating options are often compared to the present cost of using natural gas. This reference is not realistic for DHS and energy storage if the government has decided to phase out this option in the long-term. So, comparing the future-proof ecovat option to natural gas is not fair. Only when this realisation has landed, we can we examine the remaining options and their implications on the cost of the energy infrastructure in a long-term perspective. This would be fairer because both ecovat and infrastructural investments have a technical life of 50 years or more.

To be effective, these bullet points need further elaboration into appealing stories and metaphors.

## 2.4. Pilot and demonstration project

Seeing installations in real life, hearing experiences of various people involved, and learning directly about the real performance is often more convincing than a pile of reports. Showing that something can be done and works well creates enthusiasm and trust. Nevertheless, the question remains: "Can this work in our village?". How could Ecovat BV respond better to that question and make more of the investment in pilot projects?

To transfer a clear picture of reality, it is important to record the real costs and time expenditure as compared to the budget and planning, and note (causes for) troubles, delays or budget overruns. This would enable a more realistic cost estimation in future projects (provided that lessons learned are being applied). In addition, detailed monitoring of the installation performance and the impact of improvements is crucial for checking the assumptions made in the design and engineering process. Ideally, a monitoring programme were implemented that would allow for developing digital twins. If such digital twins would become easily configurable to local situations, the cost and performance could be estimated with greater accuracy, ease and speed. The outcomes might even be more credible than the direct results of physical pilot projects from which the data were derived.

The authors are aware these are still projections. However, companies such as PowerSpex[27] have progressed to a level that may be of great interest to Ecovat BV. Further research into this emerging market could be a fruitful avenue, particularly if not many pilot projects can be realised in due time. Participation in TNO's WarmingUp project (see Box 4) could also be fruitful. Moreover, data collection in pilot projects should cover several years, to cover a variety of (extreme) situations and yield representative results.

Pilot projects can be difficult to realise according to the initial intentions, because of the many complications with stakeholders, finances, uncertainty etc. This will be further elaborated in Chapter 3.

## 2.5. Interim conclusions and discussion

After TVW's are submitted by the end of 2021, it would be worthwhile to find municipalities which indicate low-temperature DHS (strategy 3) as a candidate energy infrastructure. Those municipalities could be interested in developing a business case including seasonal heat storage. Moreover, their participation in RES could be a vehicle to put system benefits of seasonal storage more prominently on the RES agenda.

It is not clear how municipalities will proceed after having selected preferable energy infrastructures. After this selection at the conceptual level, many issues need to be resolved before situation-specific measures and installations are adequately specified to develop a business case, let alone a pilot project. This "gap" involves many decisions that have consequences for citizens, network operators and others. If transition plans are to succeed[28], these actors should have influence on the decisions and be enabled to know and weigh alternatives and consequences. All three methods for selecting and justifying neighbourhood energy systems discussed in this chapter, don't deal with this "gap". Chapter 4 explores an alternative.

What are the options for Ecovat B.V.? In addition to a project-based commercial approach (offering propositions, developing business case and set up financing, establish pilot projects), the authors think the above-mentioned "gap" offers additional opportunities. For example, by participating in the development of a configuration tool which can be operated by a local team of neighbourhood inhabitants, a technical expert, a financial expert and a process manager of the municipality.

Simulation models play a key role in all three methods for selecting and justifying investments in seasonal heat storage. Their most important feature is to account for situation-specific designs, costs and efficiency (related to required supply temperatures). Detailed mechanistic models (digital twins) could be a means to optimise hydraulic designs and system control. They could be at the core of the above-mentioned configuration tool.

After developing some examples of promising designs that show markedly reduced costs to society, reaching out to network operators or even PBL could be a next step. In parallel, improved data of cost components should be gathered to improve DHS business case templates, including various types of storage and adaptations of home installations (particularly for preparing domestic hot water).

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[27] https://www.powerspex.nl/ . To get an impression of Powerbrix process simulations, see https://www.youtube.com/watch?time_continue=3&v=Ph4LiraKA_Q&feature=emb_logo

[28] In the Dutch societal context, citizens and companies are expected to take part in realising the energy transition and carry part of the cost directly. This in addition to democratic support of policies and acceptance of measures that affect their finances and environment.

# 3. Decision processes of local energy collectives

**This chapter shares observations and reflections on the decision processes of energy collectives the authors have been involved in. What is the role that fits the nature of energy collectives in developing DHS? How could Ecovat B.V. facilitate energy collectives that consider implementing seasonal heat storage?**

## 3.1. The role of energy collectives

Although groups of engaged citizens are not direct customers to Ecovat B.V., they play an important role through establishing energy collectives and through zealous initiatives that get municipalities, fellow citizens and companies involved. They initiate projects and organise financial support for the early adoption of sustainable energy technologies. They can facilitate citizen participation in ways governments cannot. Where governments follow time consuming procedures in developing TVW's and RES and have experts writing piles of documents, energy collectives are more action minded and work with the here and now. These are reasons why energy collectives play an important role in the energy transition of the built environment.

On the other hand, there are questions to be asked about how energy collectives can/do fulfil their role in reality. Are their processes and methods truly participative? For whom are they speaking and what is (the basis of) their mandate? How are different views of citizens and members dealt with? Can they make decisions that finally will be executed? How about the knowledge and skills available within the team concerning technical, legal, financial, and organisational issues? Answering such questions would help delineate and focusing their role in concordance with their competence and position.

Although this chapter will not answer these questions, it shares reflections on the dynamics of decision processes observed in meetings. The intention is to find ways to facilitate energy collectives in fulfilling their role, particularly regarding the development of collective heating solutions such as DHS and ecovat.

## 3.2. Observations and reflections

People at the core of energy collectives are generally passionate and highly motivated to either achieve a specific goal or contribute to a grand ideal. They are willing to spend energy and time to investigate things, and take initiatives towards municipal governments, enterprises, universities and fellow citizens. To motivate municipal governments and fellow citizens, they also need a clear plan and an attractive offer for citizens that have different motivations and concerns. This is where the problems usually start.

This section deals with four phases: Creating plans, taking decisions, convincing people and realising plans.

### 3.2.1. Creating plans

Citizens prime concern is their own home and then their surroundings/landscape, so making plans could start at either side of that spectrum. A regional energy transition approach[29] explores spatial, social, economic, and livelihood aspects in sessions with citizens. Design sessions and the We Energy Game are used to raise awareness of opportunities, limitations, trade-offs, attitudes and preferences of various citizens in the region (i.e. one or a few villages). Based on an energy profile, citizens explore options and locations for sustainable energy generation. This approach collects, shares and documents ideas, connects people and generates engagement that could lead to further initiatives. Although there is no plan at the end of this process, this approach supports municipalities where citizen initiatives still need stimulation.

The weakness of this approach lies in the organisation and facilitation of the follow-up. The ownership is not clear, particularly when the process is facilitated (and initiated) by an external party that is involved on project basis. The methods used are very open to citizen input, and the process is intended to be “by the citizens”. Nevertheless, the project was still “for the citizens” because they did not initiate, organise and own the process by themselves. Therefore, activities intended as facilitation could have the opposite effect. Although ambitions and visions were shared and further developed, steps towards design and implementation were not. Furthermore, it is not clear how and to what extent citizen input will be considered in further decision making by the municipality. Workshop participants do not (officially) represent (groups of) citizens. Although such sessions may bring the need for seasonal storage on the table, the authors think it will not be worthwhile for Ecovat B.V. to participate in such initiatives.

Ownership is also an issue when planning starts at the other side of the spectrum: People’s homes. Whereas the region and landscape are shared ownership, homes are essentially individual. The shared needs are information, support and finances. Energy collectives like Paddepoel Energiek started out facilitating neighbours through personal home improvement advise and deals with selected suppliers. Thus, such activities contributed by convincing people and helping to realising plans (i.e. subsection 3.2.3).
As the team would like to take further steps towards making their neighbourhood energy neutral, other options to disconnect from natural gas were explored. When extensive home insulation proved to be too expensive to implement the all-electric strategy, a DHS supplied by a central heat pump (extracting heat from a canal or aquifer, delivering 70℃ year-round, no significant home improvements) was one of the options coming to the table. After Hanze University assisted in evaluating the options[30], the preferred plan was selected and presented to the neighbourhood.

### 3.2.2. Taking decisions

The previous paragraph describes a typical example of how the ambitions of a small team drive an informal process of inquiry and selection of preferable options. This process is messy and sensitive to external influences and personal preferences. Whereas it is very difficult to make transparent and consensus-based decisions within a team[31], it seems impossible to involve many more fellow citizens in this process. So, the team decides on the plan that will be presented to the neighbourhood.

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[29] For example: K.J. Noorman, 2019. Contouren van een energieneutraal Middag Humsterland. https://research.hanze.nl/nl/activities/contouren-van-een-energieneutraal-middag-humsterland

[30] Model study by Bouw K, 2019. Onderzoeksverslag Buurtwarmte: ‘Wijkscenario’s Aardgasvrij Paddepoel’. Hanzehogeschool Groningen, Entrance – Centre of Expertise Energy. https://research.hanze.nl/en/publications/onderzoeksverslag-buurtwarmte-wijkscenarios-aardgasvrij-paddepoel

[31] Intentions are more easily agreed on than necessary compromises. Decision-making can be very difficult if team members hold firm to personal views, or when changes in team composition cause loss of collective memory. Decisions are then sometimes disputed again later, revised or diluted. Sometimes it is difficult to decide rationally by having all arguments clearly on the table for everyone. Many teams need support and guidance by independent external experts to select appropriate solutions.

If collective heating solutions are required to realise sustainability ambitions, there is a need for shared ownership, decision making and planning. However, if people with less idealistic motives are to be involved, the function and type of planning changes from “sharing and implementing vision/ideals by exploring options” into “proving and convincing others of option X”. If participative decision making is an important team value, they now face a dilemma. The benefit of collective solutions should be proven and quantified before fellow citizens can convince themselves and commit to participate. Without proof and clear view of the consequences and proposed final situation, many people might sympathise with the initiative but keep waiting. If waiting takes too long, people might lose interest or confidence, or start making other plans.

The point here is that the energy collective is forced to play a role that requires some form of mandate. If there is no mandate, the collective needs to get people along with their plan. Although their plan might receive more support than plans issued by governments or companies, the authors think a supporting role would fit better to the nature of energy collectives than taking decisions.

Before “proving and convincing others of option X” starts, alternatives and many aspects need to be elaborated, considered and decided. This requires expert knowledge from various disciplines and takes a lot of time. At this point there are two avenues to make progress:

1) The collective involves third parties to elaborate and engineer the concept. After giving feedback, the collective then helps to gain support with fellow citizens, municipality and might involve other parties to realise further steps. Remarks:
    - This requires financial resources (when outsourcing to professional parties) or collaboration with universities.
    - Third parties may have their own agenda (i.e. establishing a pilot project with their favoured technology) or make decisions that favour the interest of the future owner more than the citizens, or just follow conventions (to avoid risks and execute the project within budget).
    - The involvement of citizens in the decision-making is limited to details (e.g. where to place components). Alternative options and their consequences are often not (clearly) communicated.
    - If there is not enough expertise in the collective’s team, they cannot oversee the limitations and consequences of their order, its scope and the set of requirements (which the third parties take as a starting point and guideline for their decisions during the elaboration).
2) The collective elaborates plans by themselves in order to acquire subsidies. In that case, a small team elaborates the plan and takes decisions that meet the requirements of the subsidy provider. Remarks:
    - To gain subsidy for realising a cluster DHS, the project should meet several criteria. The business case should show the project is feasible within the maximum subsidy budget. Not meeting the criteria is not an option, as most plans cannot be realised without subsidies. Thus, financial pressure, time pressure and subsidy requirements force the team to think of alternatives and compromises to the initial plan.
      For example, the PAW[32] requirement to ultimately disconnect from natural gas could have urged the team in Katwijk[33] to select an electric peak boiler instead of a gas-fired peak boiler. Even when using green electricity, this choice is less sustainable and has higher societal costs, because electricity during peak demand will always have to be generated by fossil fuel powered plants, also after far more wind power is installed. Moreover, if electric peak boilers would be widely adopted, this would require high investments in grid reinforcements and battery storage or peak power plants.
    - Compromising is difficult if the plan has been formally or informally communicated to fellow citizens beforehand. The urge or need to make tangible progress may also lead to limited consideration of alternatives and inferior plans/solutions being selected.

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[32] Dutch: *Programma Aardgasvrije Wijken* supports the establishment of pilot projects and knowledge exchange (https://www.aardgasvrijewijken.nl/).

[33] The system in Katwijk Hoornes uses surface water heat, aquifer storage and a heat pump to provide 70°C DHS supply temperature year-round. The system and its development is described on the PAW website (https://www.aardgasvrijewijken.nl/proeftuinen/proeftuin+smartpolder/default.aspx ) and explained and discussed in a webinar (https://www.topsectorenergie.nl/tki-urban-energy/uptempo/proeftuin-aardgasvrije-wijken-meets-innovatie).

- These pressures may even force the team to compromise on principles such as participative decision-making and being there to serve fellow citizens in reaching their sustainability objectives.

In both cases, decisions are not taken by (or involving) private homeowners. Therefore, it would not be fair to force them to take on the investments and carry the consequences. In that case, participation is degraded to deciding on whether to accept the proposed offer. To make this decision, the consequences and risks should be made crisp and clear beforehand. This essentially puts citizens in the individual client role (see section 4.1.1). Involving homeowners in a transition journey requires a different approach, like proposed in section 4.2).

Avenue 2 could result in a subsidised project that involves homeowners, if financers don't demand a detailed design and fixed business case upfront. This implies homeowners decide on the investments and risks they take on, and that the financer contributes a smaller part. The collective then could support the decision making process of citizens through information, providing contacts to advisors and other groups of homeowners, or supporting the process. Ecovat B.V. and DHS operators only would come into play much later, if homeowners have optimised their homes, can provide reliable data and consider connecting to a DHS collectively. Ecovat B.V. and the DHS operator then could negotiate in a more professional way with a representative instead of trying to get individual homeowners on board.

In avenue 1, decisions are probably least transparent. This is not problematic if decisions are taken by the party that takes on the investment and associated consequences. If the energy collective remains independent, it could fulfil a role in convincing people and helping to realise the plan.

### 3.2.3. Convincing people and realising plans

The signatories of the Dutch climate agreement agreed that the energy transition should be realised at lowest cost to society. The NMDA[34] principle maximises DHS heat delivery cost to the level of using natural gas. This principle seriously impedes the development of DHS[35]. The PBL report[36] showing that making homes more energy efficient does not pay off financially, exposed the reality behind the low willingness of citizens to invest. How to convince people that rather spend money on a new kitchen or car than on a heat pump and home insulation? Do energy collectives have a role to play?

Although energy collectives try to get people to participate, they realise many people don't share their passion and priorities, or don't have the means and knowledge. The key contribution of energy collectives is to help fellow citizens recognise attractive/realistic opportunities and make it easier for them to take steps towards realisation. Unburdening (Dutch: *ontzorgen*) is the key word. At present, local energy collectives and governments don't seem to have the tools to fulfil this role.

## 3.3. Interim conclusion

In the initiation and development of sustainable collective heating solutions, the role that fits energy collectives best is taking initiatives, coordination and organisation of support in various ways (depending on interests and competences of team members). To assist collectives in their supporting role and relieve them of roles that don't match their competences, adequate tools and methods should be developed. The next chapter will be devoted to that challenge.

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[34] Dutch: *Niet Meer Dan Anders*. This implies sustainable heat should not be more expensive than using natural gas. This principle is transferred into yearly maximum tariffs for heating delivery and connection cost.

[35] For example: NOS, 16-10-2020. Proef in Purmerend met gasvrij maken van wijk ligt stil. https://nos.nl/artikel/2352510-proef-in-purmerend-met-gasvrij-maken-van-woonwijk-ligt-stil.html

[36] https://www.pbl.nl/nieuws/2020/verduurzamen-eigen-woning-financieel-onaantrekkelijk

# 4. Heat transition approach

**The approach, methods and technologies presented in this chapter aim to support bottom-up development of heat transition in cooperative structures that could be supported by municipalities and energy collectives. Connecting homes to a DHS and/or seasonal storage is postponed until the cluster energy systems are optimized. Designs and business cases can then be elaborated from detailed and reliable data.**

## 4.1. Introduction and problem identification

Chapter 2 concluded there is still a “gap” after municipalities select the preferred energy strategies for their neighbourhoods. How to further elaborate and implement these concepts, in a way that citizens and companies can affect decisions and take their part of the required investments? Chapter 3 shows that also bottom-up initiatives such as local energy collectives find it difficult to develop plans in a truly participative and transparent way.

Several organisations and companies have developed approaches to improve individual homes[37] or neighbourhoods[38], including process steps which municipalities and energy corporations could adopt. Ecovat B.V. also has a clear vision on the techno-economic conditions that would provide opportunity for applying DHS + ecovat[39]. Ecovat B.V. has conceived an implementation plan as well, but the stakeholder process needs further elaboration.

Before we describe our suggested heat transition approach, we mention three remarkable observations to which our approach seeks to respond.

### 4.1.1. Participation means seduction to join the plan

Although the need for citizen participation in the heat transition is widely recognised, the end goal (disconnect from natural gas) and the method (gas, electric or heat infrastructure) are set by governments, without participation or adequate local democratic process. As homeowners are entitled to take decisions concerning their property, governments either should seduce owners by offers that are both attractive and secure, or by forcing owners through laws, taxes and regulations.

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[37] For example: https://www.thuisbaas.nl/energie-besparen-2/

[38] For example: Enpuls, 2020. Slimme wijken. Aanpak voor gemeenten en bewoners. https://www.enpuls.nl/slimme-wijken/

[39] Personal communication Ecovat BV, October 2020: >670 homes renovated to B-label, adaptive DHS delivery temperature of 35-55°C, heat tariffs comply to equivalent cost of natural gas (Dutch: *Niet meer dan anders*).

Governments have not taken up the roles and responsibilities required to realise DHS yet[40]. Recalling the unsteadiness of government policies in the past, it would be rational for citizens to 1) wait for sufficiently attractive provisions and use subsidies as long as they are available, and 2) focus on no-regret measures that are helpful in various future scenarios. This implies that citizens and governments approach energy transition differently:

1) (municipal) government: planning approach, starting from formulating ideals and goals, translating them to specific targets, then determine strategies, followed by implementation.
2) (majority of) citizens: opportunistic approach: available means, options and circumstances determine (mainly responsive) actions.

Among the five strategies mentioned in 2.2.1, DHS requires a planning approach most, because the heat demand from homes should match the heat source(s). However, in 5th generation DHS, and with homes producing heat and or electricity, a more stepwise, small scale approach might work as well, particularly in neighbourhoods where many citizens are willing to improve their homes and are open to collective solutions. This would also allow governments some time to find their role and take their part in adequate ways to support the development and operation of DHS and the inclusion of storage and demand management.

### 4.1.2. Lack of transparent, participative integral system design methodology

After a municipality or energy collective has defined what it wants and hands over the design and engineering to specialist companies or organisations, will it get what it expected? There are several causes for mismatch between expectations and outcomes:

- The client doesn't realise the consequences of critical requirements and choices.
- The assignment, task or problem is ill formulated or conceived, or puts options and aspects out of scope without due consideration.
- Criteria, conditions or requirements are added or changed during the process.
- The specialist decides on trade-offs based on experience or convention, without involving the client. Involving the client is difficult and time-consuming, particularly if the client lacks knowledge and oversight, decides without properly balancing pros and cons, and represents or is a group of diverse individuals. Participation does not lead to better outcomes per se, and time is money.
- When many parties and subcontractors are involved, things tend to "get lost in translation" or "fall between the ship and the shore". It makes the above-mentioned complications more difficult to deal with, particularly if parties have little intrinsic involvement or direct interest in what is in the client's best interest (i.e. focus on defined task, compliance to minimum requirement, squeezing costs). Another cause is the change of persons involved during the process, which causes loss of shared perception and memory.

Although this list is not exhaustive, all issues concerning the design process and its organisation and methods. How to better structure decisions in time and make them more transparent and open for client participation?

### 4.1.3. Limited up-front regard for exergy efficiency and dynamic system behaviour

The current system design practice generally resembles more to "technology/concept selection" than to implementing design principles. For example, replacing the natural gas-fired boiler by a hydrogen boiler is advocated for its simplicity, because insulation measures, low-temperature radiators or floor heating are not required. From an energy chain efficiency point of view however, this would not be wise. Also with DHS, the focus has been on replacing the heat source[41]. This is because adapting home installations and insulation is outside the sphere of influence of the heat supplier.

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[40] Enpuls, 2020. Vaart maken met warmtenetten. Whitepaper visielijn Enpuls – 'Collectieve warmtesystemen' https://www.enpuls.nl/downloads/whitepaper-vaart-maken-met-warmtenetten/

[41] Enpuls, 2020. Vaart maken met warmtenetten. Whitepaper visielijn Enpuls – 'Collectieve warmtesystemen' https://www.enpuls.nl/downloads/whitepaper-vaart-maken-met-warmtenetten/

Home renovation packages[42] combine insulation measures with installing an air-source heat pump and solar panels. Although homes can be disconnected from natural gas, the indirect use of fossil fuels in winter results in only moderate $CO_2$ emission reduction[43]. Thus, the target (disconnect from natural gas) is reached, but the goal is not. In addition, the combination of investments is not optimised for individual homes. This is a lost opportunity because in conventional DHS designs, the home requiring the highest supply temperature sets the supply temperature of the entire DHS. Control systems to manage lower supply temperatures in parts of the grid have only been developed recently[44].

These examples show there has been little consideration of 2nd law thermodynamic principles (i.e. minimise loss of energy quality through minimising conversions and "temperature drops") and dealing with variable supply and demand temperatures over time. How can these issues be better incorporated while keeping things accessible and easy to implement?

## 4.2. Suggested phasing and participation approach

The approach suggested here has been developed in cooperation with J. Christiaansen and A. Simons (energy collective Durabel) and A. Das (municipality Het Hogeland), when preparing an application for subsidies to develop a cluster-DHS in the village of Zuidwolde (Groningen). A cluster is a group of homes connected to a common heat/cold supply system, which could also include generation and storage. After realising and optimising cluster installations, they could later be connected to a DHS through a single connection. Clusters could be a multi-apartment block owned by a single owner or by multiple residents, one or more adjacent rows of terraced houses, or a group of (semi-)detached houses at close distance. Having similarity in construction, layout and insulation levels is convenient but not a precondition. The approach will be further elaborated and tested once subsidies are granted, and technically resembles a 5th generation district heating and cooling system[45]. The system integration structure resembles the recently proposed holarchy[46].

This section will highlight differences as compared to conventional approaches. The most important one is the addition of and the focus on the cluster level, which is between the individual homeowner and the level of the village, city, municipality or region. Planning approaches like RES, TVW and DHS projects usually start at these higher levels (see Box 3) but require information on the energy demand pattern of homes. This information is aggregated (e.g. monthly consumption per postal code), based on averages linked to house types and year of construction and subject to change over time (e.g. if insulation measures are undertaken during or after the project). This leads to uncertainty margins in the design and engineering phase of a DHS.

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[42] For example https://www.thuisbaas.nl/energie-besparen-2/

[43] According to a model scenario study with terraced houses built in the early 1970's, isolated from label D to label A, equipped with air-source heat pump and low-temperature radiators, CO2 emission reduction was 33%. When solar panels were added that generated 45% of the annual consumption, CO2 reduction was 62%. Source: Model study by Bouw K, 2019. Onderzoeksverslag Buurtwarmte: 'Wijkscenario's Aardgasvrij Paddepoel'. Hanzehogeschool Groningen, Entrance – Centre of Expertise Energy. https://research.hanze.nl/en/publications/onderzoeksverslag-buurtwarmte-wijkscenarios-aardgasvrij-paddepoel

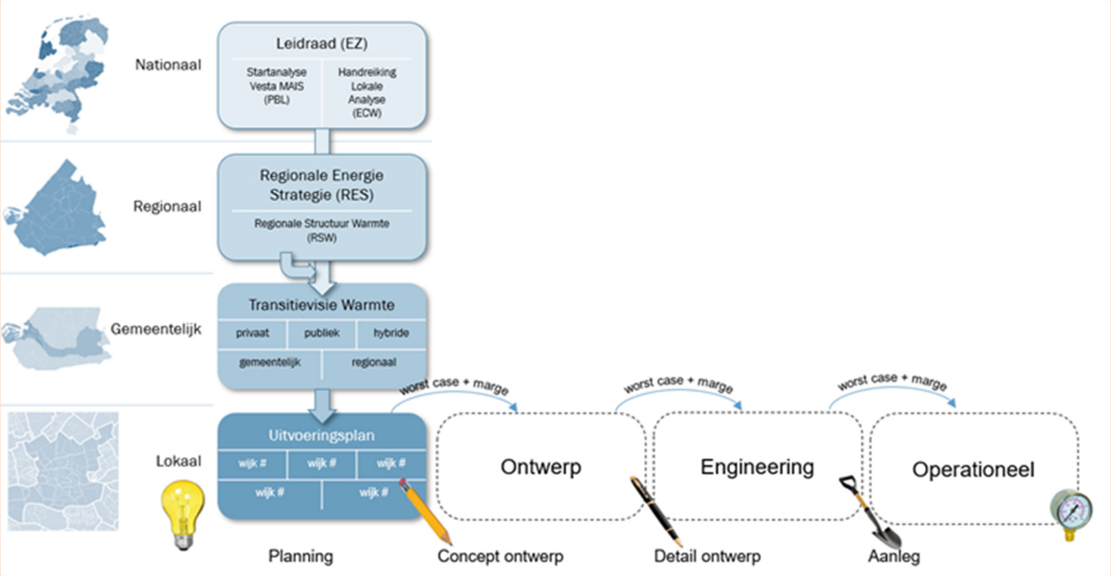
[44] For example Grundfos iGRID, see Østergård Pedersen C, 2020. How to reduce carbon emissions with low temperature zones in district heating. https://www.openaccessgovernment.org/how-to-reduce-carbon-emissions/82205/

[45] Video "Zo ziet de volgende generatie stadsverwarming eruit!" https://youtu.be/JakFLCJfSjg . See also the D2Grids project: https://www.nweurope.eu/projects/project-search/d2grids-increasing-the-share-of-renewable-energy-by-accelerating-the-roll-out-of-demand-driven-smart-grids-delivering-low-temperature-heating-and-cooling-to-nwe-cities/ .

[46] Webinar Werkconferentie Topsector Energie, session "Systeem integratie", passages 1:36-6:26 and 15:32-29:35. https://www.topsectorenergie.nl/agenda/werkconferentie-topsector-energie.

## Box 3 – TNO design method and design toolkit

The method and toolkit (https://www.warmingup.info/project/13/1c-systeem-re-design-toolkit) being developed by TNO and partners provide a uniform approach for planning future-resilient DHS. Source: https://www.tno.nl/nl/aandachtsgebieden/energietransitie/roadmaps/naar-een-energie-producerende-gebouwde-omgeving/versnelde-verduurzaming-lokale-warmtevoorziening/toekomstbestendige-warmtenetten-een-nieuw-ontwerp/



A second important difference is the order of the development process. Most approaches known to the authors start with planning, followed by concept design, detailed engineering and finally the construction and operational phase (see Box 3). This order makes resident participation difficult, as they are primarily concerned with the specific adaptations, costs and options regarding their own house, and secondarily with the liveability of their near surroundings. In early project stages this information cannot be given as specifically as needed for residents to take part in decision-making. Nevertheless, these decisions have great impact and will not be revised later. In the meantime, residents want to take steps by themselves (e.g. installing a heat pump) or are left waiting with many open questions. This is not helpful in building trust and support.

Section 4.2.1 presents an alternative approach, whilst further subsections highlight its key features.

### 4.2.1. Optimise and monitor a cluster before developing the larger infrastructure

Starting at the cluster level instead of at higher scale is expected to be particularly useful with older existing buildings which are diverse and where it is difficult or expensive to apply high levels of insulation. In that case, all-electric is not feasible, but the preferable alternative energy structure is not obvious. In that case, optimising a cluster means reducing natural gas consumption as far as possible within the capacity of the existing grid. Depending on the result of the optimisation process, infrastructural investments can be postponed, reduced (avoiding over-dimensioning) or left behind (if additional $CO_2$ emission reductions would not justify the extra investments).

This implies that storage and demand management will be applied on the cluster or individual home level, to reduce peak loads on/from the grid. Insulation measures and HVAC installation adaptations are optimised for total cost through a method described in 4.2.3 and implemented together with sensors in each home. The sensor system not only records energy consumption patterns but also provides information for improving control and adjustment of the HVAC system and advising residents on behavioural options to reduce energy consumption without sacrificing comfort.

After completing this feedback cycle on behaviour and installation performance, a second phase of monitoring should record representative energy consumption patterns, building skin thermal performance parameters and installation performance parameters. Technical specialists and homeowners in the cluster will then use this information to investigate further steps towards their goals (e.g. reduce energy costs, disconnect from natural gas, use opportunities). In this stage, several alternatives are on the table, with their technical, economical and spatial implications well-quantified, based on models fed by patterns and parameters from monitoring data:

- add or extend own generation capacity (solar PV, solar collectors, heat pumps) and storages in homes or at the cluster level,
- targeted additional insulation and heat delivery units (radiators, air heater, underfloor heating) in homes that require the highest supply temperature within the cluster,
- reinforced electricity grid connection to disconnect from natural gas or deliver grid services,
- joint connection to a DHS to access additional heat sources and/or (seasonal) storages[47].

If a joint connection to a DHS is considered, the municipality, DHS operators and companies like Ecovat B.V. start to be involved, for a planning process at a higher integration level. Before subsection 4.2.2 outlines the advantages of this approach for all involved parties, the preceding phases will be explained further.

## Box 4 – Suggested phasing at the cluster level

| Phase | Activities |
|---|---|
| **0** | Preparation by energy collective and municipality (village or neighbourhood level)<br>• Prepare project organisation, finances, municipality support<br>• Identify provisional cluster structure, communicate initiative and process to residents<br>• Assess willingness to participate → go/no go per cluster |
| **1** | Design and implementation of safe & sure measures by homeowners in cluster<br>• Organise cluster meetings and assess resources to form cluster team and organisation<br>• Inventory available energy consumption data and current conditions of homes: installations, insulation, usage patterns, resident's plans and preferences<br>• Trade-off investments in home improvements versus energy costs (4.2.3) and evaluate design options for individual and common installations<br>• Decide on measures at the home and cluster level, and organise financing and implementation, including monitoring and control system |
| **2** | Monitoring and optimisation by technical specialist<br>• Feedback on energy-comfort trade-off to residents<br>• Improving installation performance through control system settings |
| **3** | Monitoring to prepare evaluation and explore next step(s) by technical specialist<br>• Develop representative consumption patterns and system parameters to feed models<br>• Report to residents, energy collective and municipality on energy performance, costs, challenges and opportunities (newsletter)<br>• Prepare and select options to be explored into more depth in phase 4, in cooperation with cluster team, energy collective and municipality |
| **4** | Homeowners, energy collective and municipality investigate and decide on further steps |

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[47] This option can only be quantified once the DHS operator has data from the whole area covered by the DHS, data concerning the heat sources and once the concept design has been elaborated.

This 4-phase approach (Box 4) implies that not all technical measures are necessarily implemented at once. In phase 1, homeowners can match the measures taken to their individual situation, ambition and risk-perceptions regarding costs, comfort and reliability. Of course, measures that are more efficiently applied in combination (for logistic, cost or constructional reasons), should preferably be carried out simultaneously to avoid unnecessary costs and nuisance.

When gas-fired boilers remain operational as backup and for delivering peak demands in phase 1, detailed data on energy consumption, solar gain and skin thermal performance are not critical. Although a hybrid installation (gas-fired boilers and heat pump) avoids risks and over-investment in phase 1, the heat pump might need replacement to meet goals set in phase 4. In that case, installing water-water booster heat pumps which are fed by a common low-temperature heat source cluster-DHS could be a good alternative to individual air-water heat pumps. If phase 4 would then aim to disconnect homes from natural gas, this could for example be achieved through adding common equipment (heat storage, solar collectors, central heat pump) that raises DHS supply temperature when needed. Therefore, in phase 1, residents are made aware of the advantages of having common installations (see Box 5) and are informed about the different installation configurations and trade-offs between investments in insulation, heat delivery systems and other installations (see 4.2.3).

An important principle of the suggested approach is that it does not work from predefined goals or aims to meet certain standards (e.g. label A, energy neutrality). In contrast, it starts by taking safe steps, based on what participants want to do. Instead of analysing baseline energy use and developing master plans and business cases, experts emphasise on supporting the decision-making process. Only after people have experienced what working together this way can bring, they could choose to set goals in phase 4. However, the process could also stop there, depending on the merit of further home and installation improvements. Thus, cluster residents set goals and priorities and find fitting ways to realise them. Isn't this what participation ought to look like?

### Box 5 – Advantages of having common installations at the cluster level

- More options for installation placement (space for buffers and solar collectors).
- Increased efficiency through more advanced heat pumps, buffers and controls; better equipment and more complex installations (more valves) pay off more easily.
- Cheaper installations, because
  1. investment cost per kW decreases with increasing capacity, and
  2. required capacity is lower because peak demands don't coincide.
- Possibly cheaper electricity tariffs (depending on cluster size)
- Common backup facilities and redundant equipment increase reliability.
- Exchange of locally produced energy "behind the meter" reduces operational expenses.
- Easier connection (of installations in the cluster's central technical room) to a DHS for access to external heat sources, seasonal storages and conversion installations (CHP, electrolyser).
- Easier monitoring and service by a third party, through remote control and supervision.
- Easier replacement and extension of equipment (e.g. heat pump, buffer, battery) placed outside homes.
- Less organisational burdens and better negotiating and information position through cooperation with neighbours and trusted third parties, e.g. through a legal entity and ownership structure in which participants have a voice. For example, if equipment is replaced before its technical life ends, it could be exchanged within or between clusters, or leased from the legal entity or third party.

### 4.2.2. Consequences for various stakeholders – roles and benefits

The national government acknowledges that homeowners differ greatly regarding their willingness and ability to make their homes more sustainable. At the national level, various financial facilities are being developed, whereas municipal governments should direct the process in their region to ensure a smooth customer journey for all homeowners. Unburdening (Dutch: *ontzorging*) is the key word. This means that homeowners are provided with clear information and good advice so that wise choices can be made at all steps. Although the approach presented in this report fits these purposes well, the Letter to Parliament[48] reflects a different vision on the following issues.

- The homeowner is approached as an individual decision-maker
- Homeowners are supported through a digital platform and a municipal energy booth (Dutch: *energieloket*). The national government sets quality standards for those energy booths.
- Where the TVW does not specify a solution, standardised insulation levels are being developed for typical houses to prevent measures that are unfavourable or insufficient.
- Reliance on enterprises (“the market”) to develop and offer “unburdening integrated concepts”. The national government considers a quality mark and a standardised calculation tool to guard that companies will provide clear and reliable information.

In the authors’ opinion, this bureaucratic neoliberal approach ignores the potential of citizens’ collectives. Here, informal relationships based on personal trust and a shared interest provide stimulus and support in ways that transactional relationships cannot. Although citizens initiatives have flaws, the authors think they are the missing link between individual homeowners and other stakeholders. If citizens initiatives play their role well, other stakeholders don’t have their roles stretched. The next few paragraphs will elaborate the benefits of several stakeholders.

### *4.2.2.1. DHS operators*

Connecting to clusters instead of to individual homes reduces the number of DHS connections, reduces cost and complexity of construction and operation and simplifies customer relationships. The cluster operator (e.g. service company or a volunteering homeowner with technical skills) guards the proper functioning of the system behind the DHS connection. This allows grid and DHS operators to maintain their focus on the network and security of heat supply, at the scale at which they presently operate. As demand management is already implemented in clusters, this offers operational flexibility on both the heat and electricity grid.

Grid dimensioning will be based on better data on energy demand patterns and on the behaviour and adaptive range of the control systems. As the cluster is optimised regarding insulation, heat pumps, storage, hydronics and system control, the heat demand will remain similar for many years, thus providing a stable business case.

As the timing of cluster connection to a DHS is less critical, this allows for flexibility in planning the construction of the piping system. However, spreading the cluster connections over time and the risk of clusters not connecting could cause financial burdens (limited initial cash flow). Such risks can be avoided by postponing decisions on trajectory and construction until all clusters have reached phase 4. Without DHS, clusters can still reduce fossil fuel consumption considerably.

### *4.2.2.2. Ecovat B.V.*

All the advantages for DHS operators would also apply to Ecovat B.V. Particularly the demand management and storage in clusters, combined with performance data would considerably reduce the uncertainty in business cases. This eases the acquisition process and is an advantage to municipal governments and citizens as well. In addition, heat storage and generation within clusters and could increase the number of homes connected to one ecovat, thus decreasing the investment per house. This is because heat in mild conditions (spring, summer, autumn) will be produced within clusters, so the ecovat will deliver mostly high-temperature heat in cold and dark periods. Exploiting this distinguishing feature might help to position ecovat towards other storage alternatives on the market. This avenue will is explored further in Chapter 5.

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[48] Ministerie van Binnenlandse Zaken en Koninkrijksrelaties, 17-12-2019. Kamerbrief over financiering en ontzorging van woningeigenaren. https://www.rijksoverheid.nl/documenten/kamerstukken/2019/12/17/kamerbrief-financiering-en-ontzorging-woningeigenaren

With only one loading cycle per year, cluster+DHS design and control should help increase the value of the storage volume. Increasing the value of the delivered heat and decreasing the cost of stored heat (by charging in midsummer) are designated strategies to make ecovat more attractive (besides cheaper and less intrusive construction and extending lifetime). Model studies like the one in chapter 5 should help quantify the value of high-temperature seasonal heat storage relative to other storage technologies at lower temperature and for shorter periods of time.

#### *4.2.2.3. Municipal governments*

The cluster approach makes life easier for municipal governments, while improving participation. Through supporting energy collectives and cluster teams, municipalities support many citizens indirectly. This enables municipalities to focus on higher-level planning and on adjusting these plans and policies (TVW, implementation plans, infrastructural projects) to the progress of energy collectives. Performance data from clusters will allow better decisions, which can be justified far better than based on present models (see 2.2.1).

Energy corporations could take care of the neighbourhood-specific communication. However, guarding the democratic process and carrying out procedures remain a key municipal responsibility.

#### *4.2.2.4. Citizens*

If people work together to negotiate and implement a transition plan, this could have many advantages as compared to an individual approach:

- better access to neutral expertise, government subsidies and information, through various contacts, resources and skills of group members,
- cost savings through less preparation/overhead cost, more efficient work logistics, and a better negotiation position,
- options for other financing, ownership and organisational structures, that help keep margins in own pockets,
- direct influence on plans that affect the near surroundings,
- advantages related to common installations as mentioned in Box 5.

#### *4.2.2.5. Enterprises*

Before builders, installers and equipment dealers can do their thing, they spend a lot of time informing potential customers and giving quotations. Valuable time spent by experts is often not followed by an order, whereas informing with several enterprises does not improve the quality of decisions made by the nonexpert homeowner. This wasteful but seemingly inevitable market practice could be replaced by long-term mutual commitments between the community of owners and enterprises that takes responsibility for the whole process of design, engineering, building, commissioning, monitoring and servicing of the installations. All with reasonable and transparent profit margins and properly sharing of project risks.

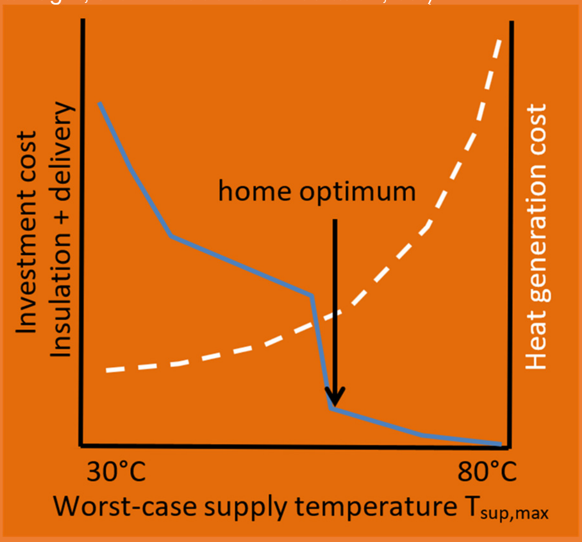
Larger projects would allow for the involvement of independent advisory companies. This and the information exchange between energy corporations regarding the quality of service would foster reliability, stable profits and work satisfaction more than thin and fleeting seller-buyer relationships. The presence of well-advised energy collectives in the marketplace could help improve the culture and practices in the sector, where brokering and subcontracting tend to inflate margins and undermine responsible behaviour and delivering quality.

### 4.2.3. Balancing home improvement cost and heat generation cost

In phase 1, several decisions are made. Two types of decisions are 1) selecting between discrete options and 2) trading-off between mutually interacting options. A decision of the latter type is choosing the optimum combination of insulation measures and expanding the heat delivery system on one hand, and installation investments and annual heating cost on the other hand. Although best practice guidelines for various housing types and construction years are available, those are far too general with respect to investment cost, applicability and heat cost savings (e.g. targeting at label B). Therefore, Nextheat BV developed easy-to-use software to assess the optimum allocation of investments. This subsection describes the method and explains the underlying vision of having decisions structured and made transparent, supported by specific tools that energy collectives and advisers could use, sitting at the kitchen table together with homeowners of a cluster.

## Box 6 – Optimum insulation

Graph to assist in finding the optimum trade-off between investments in insulation and heat delivery devices (blue line) and heat generation cost (red line). Lines are fictional. Blue line is staggered because of the discrete nature of insulation measures (e.g. first air-tight, then include wall insulation, etc).



Insulation measures affect dimensioning and efficiency of heat generation through 1) reducing heating power ($Q_{heat}$ [kW]), 2) reducing the required supply temperature ($T_{sup}$ [°C]) to radiators and other heat delivery devices, and 3) increasing the effective thermal mass of wall parts within the insulation envelope. As $T_{sup}$ decreases, the efficiency of heat pumps and utilisation of low temperature heat sources (e.g. solar collectors charging heat buffer in winter) increases. Besides improving insulation, $T_{sup}$ can be reduced by replacing radiators (larger units with more plates, more fins and/or ventilator-assisted airflow), adding floor or wall heating and/or full delivering heat or cooling through the ventilation system.

A graph like the one in Box 6 clarifies the consequences of this technical and physical complexity to homeowners. The horizontal axis represents $T_{sup}$ in design conditions (worst-case, winter): $T_{sup,max}$. A thermal building model could predict $Q_{heat}$ and $T_{sup}$ on hourly basis, for given temperature setpoints and occupational patterns, skin thermal properties and heat delivery system properties. From those values $T_{sup,max}$, generation efficiencies and annual heat costs can be derived and plotted in a graph. Several energy cost curves could be plotted, including individual and common installations. Different $T_{sup.max}$ values could correspond to different configurations of the installations and result in a more staggered red curve in Box 6. For example at $T_{sup,max} = 30$ °C, infrared electric heating panels and/or air source heat pump plus floor heating might be optimal, whereas at 80 °C booster heat pumps supplied by a cluster DHS at 40 ° might be more efficient (than a high-temperature air source heat pump).

The issue of selecting the optimum installation configuration as related to $T_{sup,max}$, available heat sources and other factors requires further work and is an essential part of filling the “gap” mentioned in section 4.1. Developing tools like Vesta MAIS to select between standardised configurations at the cluster level would offer opportunities to municipalities and energy collectives to support the heat solution selection in transition phase 1 (of Box 4). After selection, engineering tools can be used for designing, dimensioning, visualisation and detailed cost calculation.

The tool developed by Nextheat BV uses a simplified approach, based on an automated input form to be filled in by homeowners. Required data are a.o. monthly gas consumption, ground floor dimensions, window areas, insulation measures taken, and type and area of radiators. Based on this input, the tool searches for the cheapest combination of radiator replacements and insulation measures that can attain a particular $T_{sup,max}$. This optimisation is performed for a range of $T_{sup,max}$ temperatures and results in the blue line in the graph of Box 6.

The automatically produced graphs allow home homeowners to find the optimum trade-off for their house. Data can be combined for a cluster consisting of difference houses, to match installation measures for individual houses to a common installation. The calculation of heating costs for specific installations has not yet been implemented, and the cost database could be expanded. Nevertheless, this example shows how our approach could clarify the interaction between decisions of individual homeowners and the consequences for energy generation cost at the cluster level. Sitting around the kitchen table, these consequences can be weighed in, as they are charged back to homeowners in the end.

Conventional DHS projects usually don't investigate this interaction between insulation, delivery system adaptation and generation and distribution systems cost. As a result, DHS operators tend to supply excessively high temperatures, to ensure proper functioning of installations they can't access. If an individual homeowner would improve insulation, this would not reduce the generation costs and heat tariff. Therefore, the presented approach gives homeowners tools and influence on their heat generation cost, and more incentive for insulation measures. Perhaps this approach could also be used to clarify interactions on higher levels as well.

## 4.3. Proposed technical innovations

Although the cluster approach simplifies DHS and heat storage decisions, we seem to have moved several technical complexities to be solved at the cluster level. This section clarifies the kind of installations the authors have in mind and describes how cluster installations could work more efficiently than conventional installations.

### 4.3.1. Heat storage at home and cluster level

Homes have been designed with little space for HVAC equipment because gas boilers are compact and don't require buffer tanks for domestic hot water (DHW). As people got used to this, claiming more space for installations often meets resistance, even if installations are placed in the garden, in a shed, on the attic or in other storage spaces within the house. Partly people resist because of having to clean up such spaces, whereas they often have no complaints afterwards. The following technical reasons highlight the need for heat storage in or very close to homes when using heat pumps:

- Pipe diameters, heat losses and costs of the heat-delivering piping system can be reduced if pipes feed a buffer instead of delivering (peak) demand directly.[49]
- Buffers absorb locally produced heat by solar collectors, heat pump or CHP, which can later be used at the same place. Buffers thus reduce/avoid unnecessary transport and losses.
- Heat pumps can be dimensioned smaller and will run more efficiently (avoid low part load) with increased lifetime (less on/off switching than with conventional tanks).
- Buffers allow demand management. This means operating the heat pump when producing own electricity, when electricity from the grid is cheap, or to limit grid load. If these periods coincide with the warmest hours in a day, air-source heat pumps run more efficiently and might defrost less frequently.
- Increased reliability through allowing time for repairs and grid outages.

The present function of buffers is providing DHW comfort (quick delivery of required temperature, enough flow) and reducing on/off switching of heat pumps. The above advantages require larger temperature-stratified buffer tanks that accommodate demand generation fluctuations within 1-3 days. Calculations based on unpublished own monitoring data show that annual electricity consumption of a 12 kW air-source heat pump could be reduced 9,3% by generating the required heat of each day during the warmest hours, when combined with a 4,13 m$^3$ buffer tank (Box 7). The potential reduction of installed power to 7,7 kW indicates the impact of variable demand.

This impact also applies to flows in a piping system (and their required diameter) when applying home buffers.

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[49] For example, as demonstrated by a case study using Comsof Heat DHS design software: Jebamalay JM, Marlein K, Laverge J, 2020. Influence of centralized and distributed thermal energy storage on district heating network design. Energy 202. https://doi.org/10.1016/j.energy.2020.117689

As apartments and terraced houses don’t have enough space, part of the buffer volume could be centralized per cluster, and placed below a parking space, lawn or park. This cluster buffer could be connected to home buffers through a piping system with relatively small diameters, connecting attics or crawl spaces (avoiding digging and disturbing gardens and pavements). Box 8 compares characteristics of buffers at the level of home, cluster or DHS.

Recently, thermal storage bags have been developed that can be placed in the crawl space or below terraces (Hydrobag, Solar Freezer). Such bags and large thanks operate at ambient pressure, whereas the water contains solved gases. Therefore, they are connected to the heat distribution grid via heat exchangers. This requires additional pumps and controls to minimise temperature drop. Buffers operating at distribution system pressure can balance flow between generation and delivery circuit, thereby facilitating demand-independent operation of the heat pump (Box 9).

## Box 7 – Air-source heat pump performance optimization using a 24-hour buffer.

Based on 389 days of unpublished monitoring data (time interval 5 minutes) of a 12 kW air-water heat pump, the effect of generating each day’s heat demand during the warmest hours of the day was calculated. Relative electricity savings are based on manufacturer’s COP data at various ambient temperatures. The assumed temperature drop of the water-filled buffer tank was set at 15 Kelvin. The required buffer volume was calculated for each day; the table shows the maximum value for each power value. Without buffer, the heat pump ran for 3379 hours, starting 1793 times on 270 days with heat demand. During the 389 days of monitoring 23.353 kWh heat was delivered at an average COP of 3,27. A 7,7 kW heat pump would need to run for 24 hours to fulfil the maximum daily heat demand.

| Heat power [$kW_{th}$] | Uptime [hours] | Electricity savings | Buffer volume [$m^3$] |
|---|---|---|---|
| 7,7 | 3034 | 6,8% | 2,65 |
| 9 | 2595 | 7,8% | 3,10 |
| 12 | 1946 | 9,3% | 4,13 |
| 17 | 1374 | 10,5% | 5,80 |

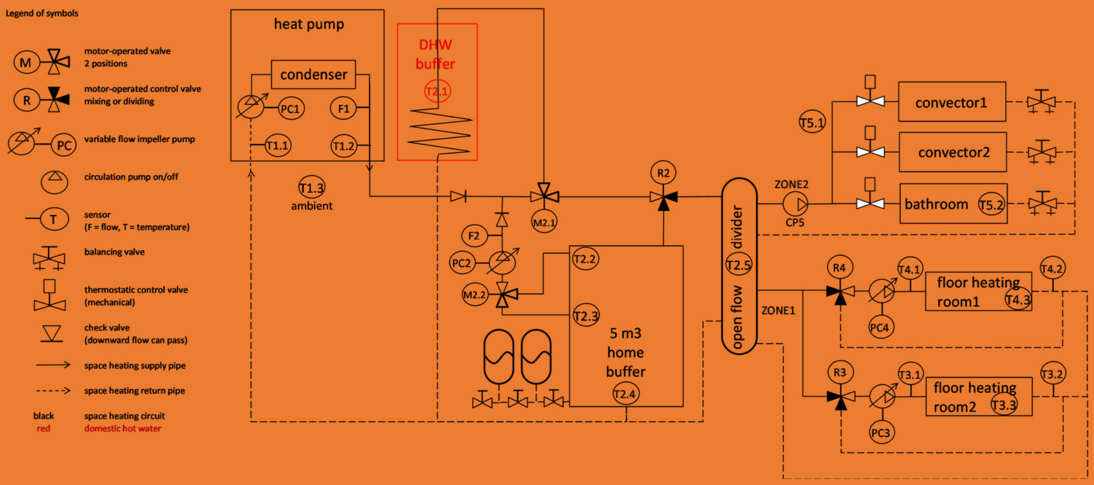
Additional investments in buffers close to the source of variability should be justified by reduced investments in piping network, investments in upstream equipment, system efficiency and other (anticipated) advantages (e.g. additional income from flexibility services to the electricity grid). It should be mentioned that the required buffer size and investment is related to buffer pressure and the difference between supply and return temperature.

## Box 8– Characteristics of three levels of thermal storage

| Characteristic | Home | Cluster | Neighbourhood/village |
|---|---|---|---|
| Storage timespan | 1-2 days | 2-20 days | 2 days - seasonal |
| # homes | 1 | 3-40 | >200 |
| Pressure | Central heating system | Atmospheric | Atmospheric |
| Temperature level (variable in time) | ≥ heating system | ≥ heating system | Ground storage 8-25 °C<br>High temperature: 20-80 °C |
| Heat sources | Home heatpipes<br>(Booster) heat pump<br>Other home buffer<br>Cluster buffer | Home buffers<br>Cluster heatpump<br>Cluster heatpipes<br>Village DHS | Village DHS<br>Central heatpump<br>Central heatpipes<br>CHP, electrolyser<br>Other heat sources |
| Transition phase (see Box 4) | 1 | 1 or 4 | 4 or later |

### Box 9 – Example of home buffer and heat pump supplying DHW and cascaded space heating system.

The home buffer is charged by solar collectors (not shown) or by the heat pump. Control valve R2 controls the return temperature (T1.1) and manages the heat pump duty.



Cascading delivery systems is the key to achieving low return temperatures. Box 9 shows an example, applying a vertical open flow divider that puts radiators and floor heating in series. Although such examples are provided in manufacturer documentation[50], many installers yet don't apply them and don't master the implementation of the required controls. The authors think this is because many installers and advisers are not acquainted with the concept of exergy as a basis for understanding system efficiency.

## 4.3.2. System efficiency in cluster installations

System efficiency includes heat source and buffer utilisation, heat losses, optimised heat pump operation and minimizing other types of exergy losses (e.g. by mixing cold and warm water, temperature drops in heat exchangers). This subsection elaborates several tactics that can be applied in centrally controlled cluster installations.

- In-house buffers allow the cluster distribution system to be shut down after buffers have been charged. Slowly flushing the piping system with cold water to collect the warm water remaining in the supply pipe and store it in the cluster buffer would virtually eliminate heat losses, even in long pipes. This would alleviate a major disadvantage of applying DHS with low heat demand per metre of pipe length.
- In-house buffers combined with solar collectors could also transport surplus heat in summer to the cluster buffer, and eventually via the DHS to central storages like ecovat. Like described above, simultaneously discharging the surplus from all home buffers within a limited time could reduce heat losses.
- If a distribution network connects house buffers and the cluster buffer, it is possible to deliver heat collected in one house buffer to another house buffer directly. Consequently, a large solar collector system (perhaps even covering several adjacent houses) could be connected to one home buffer. Citizens who are able and willing to invest in solar collectors can then sell surplus heat to neighbours or store it in the cluster buffer. The same principle could be applied between clusters within the DHS. Because of the buffers, a two-pipe

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[50] For example: Panasonic, 2020. Handleiding hydraulische ontwerpen Aquarea, Bi-Bloc oplossingen. http://panasonicwarmtepompen.nl/wp-content/uploads/2018/10/2016-Aquarea-hydraulische-ontwerpen-versie-20161128.pdf

distribution system is enough to facilitate this bidirectional heat transport.

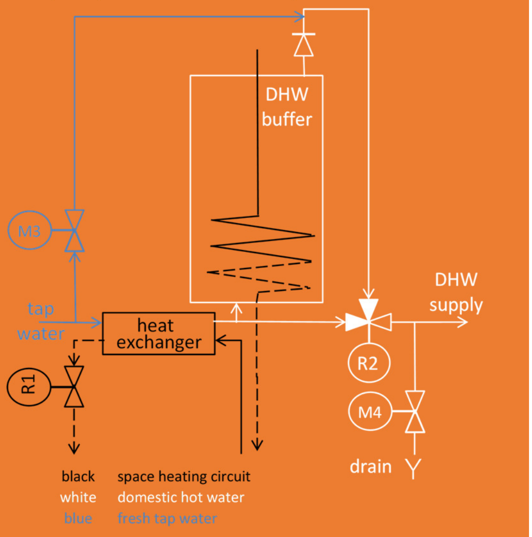
- Minimising piping system length is an important tactic to improve efficiency, which could also reduce costs. Much depends on the willingness of homeowners and municipality to consider unconventional alternatives to the standard routing for public infrastructure[51]. For example, an indoor piping system connecting attics of terraced houses[52] or a drilled pipe connecting crawl spaces via the shortest path through private gardens. Shortening the branches and using smaller pipe diameters reduce the volume water stored between buffers and may avoid the need for flushing procedures mentioned above.

- To avoid exergy losses, the temperature delivered by the heat pump should not exceed the temperature required by the delivery system for transferring the required heat power Q. A heating curve (delivery temperature setpoint as related to ambient temperature) is a helpful but coarse method. Not only because settings are determined by trial and error, but also because of the interaction with flow control, thermostat behaviour and on/off switching. Ideally, the flow to the delivery system be constant, thus spreading the daily required heat output over maximum time. Reducing heat power decreases required supply temperature and return temperature (except if this effect is overcompensated by reduced heat transfer through laminar flow).

  In reality, the required heat power is not constant during the day because of occupation pattern, varying ambient temperature, solar gain and comfort limits. Artificial intelligence could help determine patterns of Q and $T_{sup}$ that would meet time-dependent comfort requirements. Based on those patterns, the buffer could be charged to a temperature that covers the total heat demand of the day, whilst the buffer volume passes through the delivery system just once in 24 hours. The delta T realised by the delivery system determines the buffer volume. Too small a buffer would result in a charging temperature greater than the highest required delivery temperature of that day.

## Box 10 - Example DHW system.

DHW is preheated in a heat exchanger supplied by the space heating buffer. R2 controls DHW supply at a user-specific temperature. Shortly after heat delivery, M3 and M4 open to flush cold water through DHW piping system to prevent legionella infection. The DHW buffer is periodically charged by a heat pump to achieve a temperature > 60 ℃.



  Although this description only deals with the basics, to many installers it will sound overly complex. The challenge is therefore to develop control systems that deal with this complexity while remaining transparent and straightforward in its settings, so that ill-functioning can be diagnosed and fixed using practical common sense.

- A high delta T improves buffer utilisation but compromises the efficiency of heat pumps (perhaps except those using $CO_2$ as refrigerant). If a buffer should be heated from 25 ℃ to 40 ℃ in one pass, all heat would be delivered at the maximum refrigerant condensation temperature (e.g. 45 ℃). As the optimum delta T of water passing to a condenser is 5-7 ℃, the buffer volume could be cycled through the heat pump multiple times (e.g. heat from 25 to 30° in cycle 1, to 35° in cycle 2 and to 40°

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[51] Network main piping in public area (street, pavement), with each house having its own branch, entering the house near the front door.

[52] For example: Froukemaheerd, Groningen city. https://kennisbank.isso.nl/publicatie/energievademecum-energiebewust-ontwerpen-van-nieuwbouwwoningen/2015/7 , and
Boumans A, 1988. Evaluatie warmteopslag Beijum, afstudeerverslag TU Delft Sectie Geotechniek nr 298. https://repository.tudelft.nl/islandora/object/uuid%3A58100721-903f-49b2-b903-2088ef2df54b

in cycle 3). If a central heat pump charges home buffers, charging could start and stop at different temperatures to allow for different buffer status and temperature requirements of different homes. If heat should be delivered during charging, a system like Box 9 could be applied, or the 2 buffer vessels could be used (one charging while the other delivers heat).

- Heat pumps and buffers can be used for both space heating and cooling. Cold be supplied from the DHS cold aquifer source (8℃) to cool passively. Alternatively, cold could be generated by home or cluster heat pumps, using locally produced electricity. The heat could be stored in home or cluster buffers and supplemented by solar collectors to produce DHW.
  Surplus heat could be delivered to the DHS to charge the aquifer storage or high temperature storage. Heat pumps could use surplus solar electricity in summer to collect and store heat from walls, streets, surface water or ambient air, thus increasing heat pump COP in winter[53].

- Finally, there are several ways to make DHW systems more efficient without compromising health risks related to legionella infection. Space heating buffers could preheat cold tap water before it enters the DHW buffer and is delivered to the DHW mixing valve (Box 10). The mixing temperature could be adjusted to the user (e.g. shower 45℃). This would reduce the DHW buffer volume and save electricity for after heating and periodical disinfection.

## 4.4. Conclusion

Connecting clusters of houses once their internal energy system is fully optimised and known would reduce the uncertainty in business cases and simplify the development process in several ways. Ecovat B.V could advocate the proposed phasing to potential customers, as this is an advantage to both.

The proposed approach provides opportunities for municipalities and energy collectives to assist groups of homeowners in developing heat solutions that match their preference. Although citizens might choose different goals than governments, our approach may offer better participation opportunities for groups of homeowners desiring to start making steps in heat transition. However, this still requires an active attitude, perseverance and willingness to really cooperate with neighbours. Taking a good approach is just one of the several keys to success.

Another key are the proposed technical innovations regarding control strategies and exergy efficiency. Applying buffers at various places might reduce heat demand and reduce the need for implementing DHS and ecovat. On the other hand, increasing the value of the heat stored in the ecovat and increasing the number of houses connected would improve the business case.

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[53] NRGTEQ and HoCoSto developed the PHAC concept (passive heating active cooling): https://www.vakbladwarmtepompen.nl/techniek/artikel/2019/08/koelende-warmtepomp-vult-ondergrondse-buffer-1015084

# 5. Simulation study – Combining ecovat and aquifer heat storage to reduce heat storage cost

**The high initial investment of an ecovat has caused potential clients to quickly label it as being too expensive. A possible solution explored in this chapter is to divide the investment over more homes through the addition of a seasonal aquifer storage with lower cost per kWh of stored heat.**

## 5.1. Introduction

Combining a seasonal high temperature storage (ecovat) and a seasonal aquifer storage (SAS) would allow a division of heat supply based on the required temperature of the heat demand. This means a DHS can combine the strengths of both storage systems; high-temperature heat from an ecovat at low ambient temperatures, and cheaper low temperature heat from a SAS at mild ambient temperatures.

In this study, the ecovat stores heat from two sources. In case 1, solar collectors deliver high- temperature heat (90℃) to charge each of the 8 layers to its maximum temperature (specified Appendix Table 1). In case 2, an air-source heat pump charges the ecovat when electricity prices are low. The heat pump will deliver heat at 5℃ higher than the to be charged layer, running at maximum power (1.500 kW thermal). The ecovat delivers heat directly to the DHS without heat pumping. Heat is extracted from the layer that best matches the required DHS supply temperature at each specific hour. The model does not assume specific DHS return temperatures and flows, thus resembling a situation with low delta T (high return temperature).

In both case 1 and 2, the SAS stores heat generated by an air-source heat pump. In case 1, the SAS stores heat when day-ahead electricity prices are ≤ 45 €/MWh. In case 1 the COP while loading the SAS is calculated from the ambient temperature. To reduce computing time in case 2, the SAS stores heat at a fixed electricity price (45 €/MWh) and COP (10). These values correspond to the averages found in case 1.

When the SAS delivers heat, the heat pump uses the SAS as a source to supply the DHS with heat at the desired temperature of that specific hour. The heat pump uses electricity at grid prices of that moment, assuming historic price data. All temperatures, energy flows, heat pump operation and storages being charged or depleted (depending on required DHS temperature and temperature availability in the ecovat) are simulated with a time resolution of 1 hour. The model, its methods and assumptions are further described in the Appendix.

The idea is that the SAS + heat pump combination generates low-temperature heat with a high COP. The simulation model finds the optimal division of heat supplied by ecovat and SAS, as influenced by heat cost of solar collectors, day-ahead electricity prices and the space heating demand pattern of homes.

The ecovat was sized after the Arnhem case[54]. The SAS capacity depends on the number of homes connected to the DHS. When homes require a lower DHS temperature, more homes can be connected to one ecovat, with the SAS delivering a larger part of the heat. This would reduce the cost of storage per house, whereas high-temperature heat is still available for short periods of time. This would allow a lower installed heat pump capacity and would reduce peak loads on the electricity grid.

## 5.2. Case 1 – Charging the Ecovat using high temperature heat

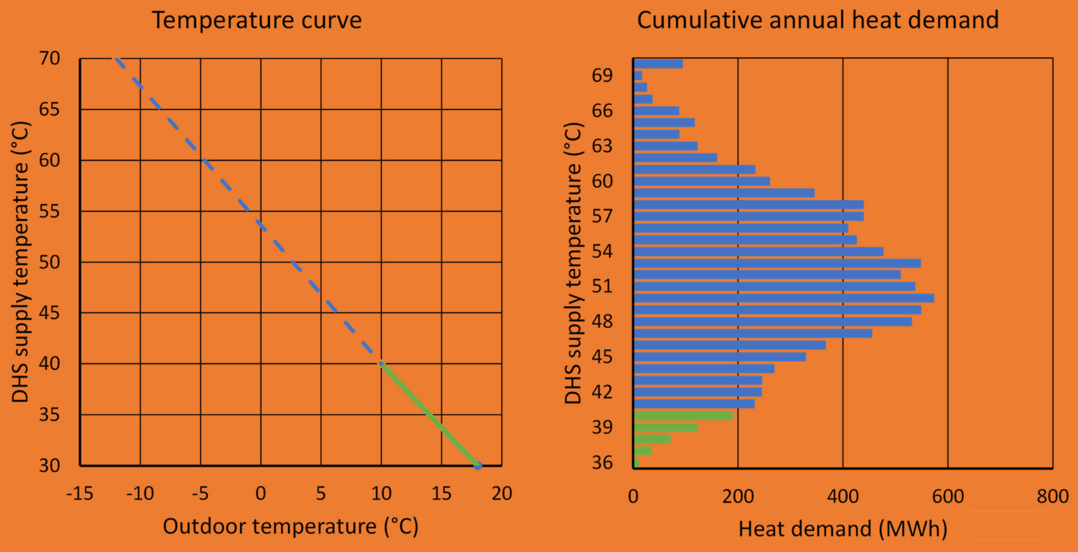
Since the SAS efficiency drops when supplying higher temperatures, the SAS only delivers heat when below a certain temperature, $T_{SAS}$. This threshold temperature also depends on the cost of the high-temperature heat supplied by the ecovat. This cost trade-off and the temperature requirement of homes determine the amount of heat the SAS delivers, and how many homes can be connected to the DHS.

The heat demand and required temperature of the DHS are determined with a static temperature curve (Box 11). Each DHS temperature is also associated with a cumulative annual heat requirement. Connecting both graphs in Box 11 represents the division of heat between SAS and ecovat.

The histogram in Box 11 reveals that increasing $T_{SAS}$ by 1 °C would have a relatively large impact on the heat demand to be delivered by the SAS. Increasing $T_{SAS}$ reduces heat pump efficiency, whereas decreasing $T_{SAS}$ reduces the number of homes connected to one ecovat. If the ecovat would deliver heat at higher temperatures than required by the DHS, this would cause exergy losses, whereas more homes could have been connected.

### Box 11 – Temperature curve and cumulative annual heat demand

Assuming a 70-30 °C DHS temperature regime and $T_{SAS}$=40 °C. Green represents the heat demand supplied by the SAS, while blue represents the heat demand supplied by the ecovat. All heat demand below the maximum SAS temperature ($T_{SAS}$) will be supplied from the SAS.



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[54] As specified in Bosch R van den, 2018. Thermal efficiency Ecovat. Validation of the thermal efficiency based on the demonstration Ecovat Uden. Ecovat Werk BV, Veghel.

To divide heat supply between ecovat and SAS profitably, equation 1 was developed.

$$\frac{Sp_{cost}}{Sc_{cost}} = \frac{COP_{min}}{1+\frac{1}{COP_{av\_load}}} = COP_{min,corr} \quad \text{(equation 1)}$$

With
$Sp_{cost}$ = the average cost 1 kWh of electricity, over one year
$Sc_{cost}$ = the cost of producing 1 kWh of heat with solar collectors
$COP_{min}$ = the lowest COP of SAS delivered heat, over one year
$COP_{av\_load}$ = the annual average COP when charging the SAS
$COP_{min,corr}$ = the lowest COP of SAS delivered heat, over one year, corrected with the loading COP

This example illustrates the principle:
*Assume the heat price is 20 €/MWh and the average electricity price is 60 €/MWh. This would make the fraction 3. After running the model several times, the COP when loading the SAS was often 10. Using this COP, the following equation remains:* $3 = \frac{COP_{min}}{1+\frac{1}{10}}$.
*Solving this, we get a* $COP_{min}$ *of 3,3. Thus, if high DHS temperatures cause the heat pump's COP to dip below 3,3 it would be cheaper to buy the heat and deliver it from the ecovat. If the heat pump achieves COP greater than 3,3, it is cheaper to buy electricity and deliver heat from the SAS.*

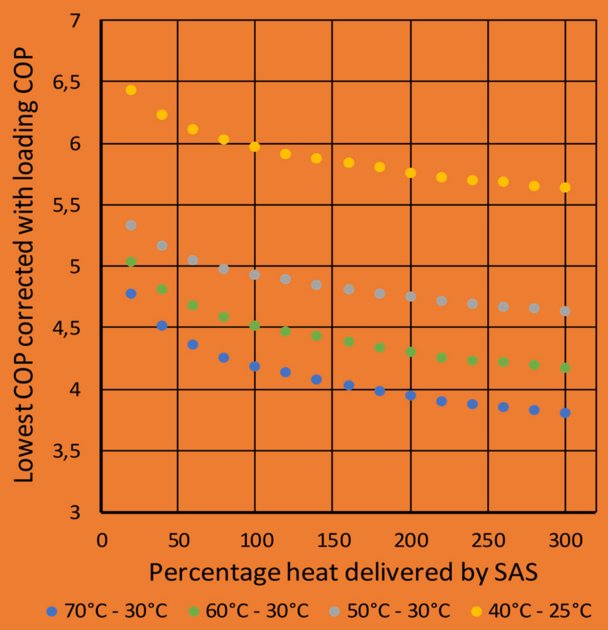
So, $COP_{min}$ is linked to the maximum temperature at which the SAS delivers heat to the DHS ($T_{SAS}$, see Box 11). Consequently, increasing the share of heat demand supplied by the SAS would increase $T_{SAS}$, thus decreasing $COP_{min,corr}$ (see Box 12). Delivering that percentage of heat by SAS is only beneficial if the average electricity/heat price ratio is lower than $COP_{min,corr}$.

Assuming 2019 prices of natural gas and grid electricity as a reference, the electricity/heat price ratio would be 2,96 for the largest industrial consumers and 2,17 for average households[55]. These values are well below the values plotted in Box 12, even at the 70℃-30℃ temperature curve. This means adding a SAS reduces the heat generation cost and divides the investment cost of an ecovat over potentially double, triple or even quadruple the amount of buildings it was initially designed for.

The results in Box 12 were generated by simulating a total of 60 scenarios,

## Box 12 – $COP_{min,corr}$ as related to the percentage heat delivered by SAS

The lowest $COP_{min}$, corrected with loading COP, at which the SAS delivers heat to the DHS, assuming 4 DHS temperature curves.



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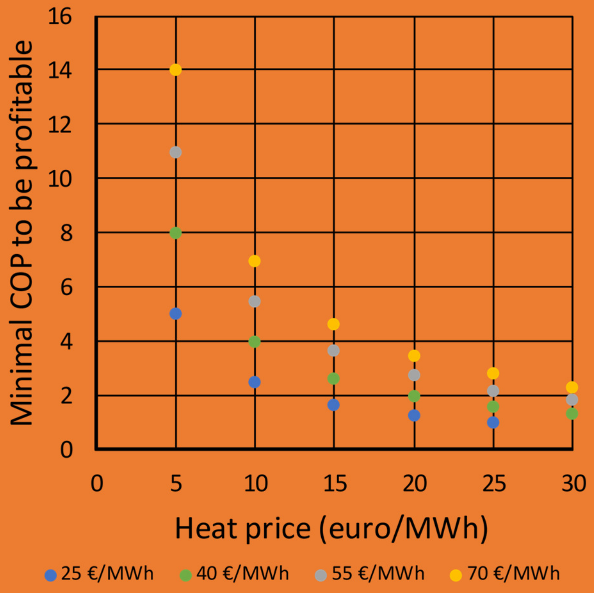
[55] CBS statline, https://opendata.cbs.nl/statline/#/CBS/nl/dataset/81309NED/table?ts=1606066533655. Prices are annual averages and include VAT, taxes and network costs. The largest industrial consumers use over 1000 TJ (28,433 $Mm^3$) of natural gas and over 150 GWh electricity at prices of 6,759 €/GJ (0,238 €/$m^3$) and 0,072 €/kWh. The selected households price classes use 20-200 GJ (569-5687 $m^3$) of natural gas and 2,5-5 MWh electricity at prices of 26,207 €/GJ (0,922 €/$m^3$) and 0,205 €/kWh.

assuming 4 DHS temperature curves. The other variable is the percentage of additional heat demand the SAS will supply; 0%, 20%, … 300%. This percentage is relative to the heat delivered by ecovat, so 300% means that the SAS delivers three times as much heat than the ecovat.

To determine whether the scenarios given in Box 12 are profitable, heat and electricity prices need to be included in the calculation. Box 13 shows $COP_{min,corr}$ values for several possible price scenarios. At lower heat prices, the required minimal $COP_{min,corr}$ increases. This means the SAS only provides heat profitably at lower temperatures. So, with a given temperature curve, the SAS will deliver a lower share of the heat. However, adding SAS increases the complexity of the system, so that adding a SAS will not be viable at low heat prices.

### Box 13 – COP required to be profitable

For a SAS to be profitable at each of the 4 electricity prices, $COP_{min,corr}$ should be above the plotted values.



Combining Box 12 and 13 results in the average electricity prices below which adding a particular $\%SAS$ is profitable, as displayed in Box 14. These tables are generated for different temperature curves (like the one in Box 11): 70℃–30℃, 60℃–30℃, 50℃–30℃ and 40℃–25℃ respectively. Within each table, each $\%SAS$ shows a particular ratio of electricity price over heat price, which also equals $COP_{min,corr}$, as plotted in Box 12. If it is possible to keep the average electricity price below the price shown in the table, adding a SAS is profitable. If not, it is better to purchase the heat and use the ecovat.

In 2019, average prices for the largest industrial consumers were 24,3 €/MWh for heat (natural gas) and 72,0 €/MWh for electricity[56]. This electricity price is lower than the maximum with a 70℃-30℃ temperature curve, so adding up to 280% SAS is economically feasible (with respect to heat generation cost). However, if the heat price would drop to 20 €/MWh, adding more than 160% SAS would not be beneficial. At a heat price of 15 €/MWh, it would be more economical to implement the ecovat without SAS, even when reducing the temperature curve to 50℃-30℃. However, as the electricity/heat price ratio for consumers in 2019 was lower (2,17 instead of 2,96 for large industrial consumers), adding up to 160% SAS would be most beneficial. So, with the assumptions in case 1, the business case of ecovat primarily depends on the electricity/heat price ratio, and less strongly on the DHS temperature curve.

The heat pump used for SAS might also be used to extract more usable heat from the ecovat and charge it more economically at low ecovat temperatures in early summer. If electricity is generated by PV systems that have surplus production in summer, lower electricity prices could apply. Case 2 will explore the most efficient use of electricity to provide heat through a combination of SAS and ecovat.

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[56] See previous footnote. For households these prices are 94,3 €/MWh and 205 €/MWh respectively.

## Box 14 – Average electricity prices below which adding SAS is profitable at a different DHS temperature curves

Table 1 – DHS temperature curve 70-30℃

| Heat price (€/MWh) | 40% SAS | 80% SAS | 120% SAS | 160% SAS | 200% SAS | 240% SAS | 280% SAS |
|---|---|---|---|---|---|---|---|
| 5 | 21 | 19 | 19 | 18 | 18 | 18 | 18 |
| 10 | 41 | 39 | 38 | 37 | 36 | 35 | 35 |
| 15 | 62 | 58 | 57 | 55 | 54 | 53 | 53 |
| 20 | 83 | 78 | 76 | 74 | 72 | 71 | 70 |
| 25 | 103 | 97 | 95 | 92 | 90 | 89 | 88 |
| 30 | 124 | 117 | 113 | 111 | 108 | 106 | 105 |

Table 2 – DHS temperature curve 60-30℃

| Heat price (€/MWh) | 40% SAS | 80% SAS | 120% SAS | 160% SAS | 200% SAS | 240% SAS | 280% SAS |
|---|---|---|---|---|---|---|---|
| 5 | 22 | 21 | 20 | 20 | 20 | 19 | 19 |
| 10 | 44 | 42 | 41 | 40 | 39 | 39 | 38 |
| 15 | 66 | 63 | 61 | 60 | 59 | 58 | 58 |
| 20 | 88 | 84 | 82 | 80 | 79 | 77 | 77 |
| 25 | 110 | 105 | 102 | 100 | 98 | 97 | 96 |
| 30 | 132 | 126 | 123 | 120 | 118 | 116 | 115 |

Table 3 – DHS temperature curve 50-30℃

| Heat price (€/MWh) | 40% SAS | 80% SAS | 120% SAS | 160% SAS | 200% SAS | 240% SAS | 280% SAS |
|---|---|---|---|---|---|---|---|
| 5 | 24 | 23 | 22 | 22 | 22 | 21 | 21 |
| 10 | 47 | 46 | 45 | 44 | 43 | 43 | 43 |
| 15 | 71 | 68 | 67 | 66 | 65 | 64 | 64 |
| 20 | 94 | 91 | 89 | 88 | 87 | 86 | 85 |
| 25 | 118 | 114 | 112 | 110 | 109 | 107 | 107 |
| 30 | 142 | 137 | 134 | 132 | 130 | 129 | 128 |

Table 4 – DHS temperature curve 40-25℃

| Heat price (€/MWh) | 40% SAS | 80% SAS | 120% SAS | 160% SAS | 200% SAS | 240% SAS | 280% SAS |
|---|---|---|---|---|---|---|---|
| 5 | 29 | 28 | 27 | 27 | 26 | 26 | 26 |
| 10 | 57 | 55 | 54 | 53 | 53 | 52 | 52 |
| 15 | 86 | 83 | 81 | 80 | 79 | 78 | 78 |
| 20 | 114 | 110 | 108 | 107 | 105 | 104 | 103 |
| 25 | 143 | 138 | 135 | 134 | 132 | 130 | 129 |
| 30 | 171 | 166 | 162 | 160 | 158 | 156 | 155 |

## 5.3. Case 2 – All heat generated via the electricity grid with heat pumps

### 5.3.1. Method

In this case, choosing whether the SAS or the ecovat supplies heat is determined differently from case 1. When charging the ecovat, the total of electricity costs and the total amount of charged heat are used to calculate the cost of one kWh of heat stored in the ecovat.

$$\frac{E_{Cost\_ecovat}}{Q_{Loaded\_ecovat}} = Q_{Cost\_ecovat} \quad \text{(equation 2)}$$

With

$E_{Cost\_ecovat}$ = the total cost of electricity used to charge the ecovat
$Q_{Loaded\_ecovat}$ = the heat loaded into the ecovat
$Q_{Cost\_ecovat}$ = the cost of one kWh of heat loaded in the ecovat

This is then used in the following equation:

$$\frac{COP_{SAS}}{1+\frac{1}{COP_{SAS_{Load}}}} * E_{Cost} < Q_{Cost\_ecovat} \quad \text{(equation 3)}$$

With

$COP_{SAS}$ = the would-be COP of the SAS if it were to supply the current heat demand
$COP_{SAS_{Load}}$ = the average COP when loading the SAS (assumed at 10)
$E_{Cost}$ = the current electricity cost of one kWh
$Q_{Cost\_ecovat}$ = the cost of one kWh of heat loaded in the ecovat

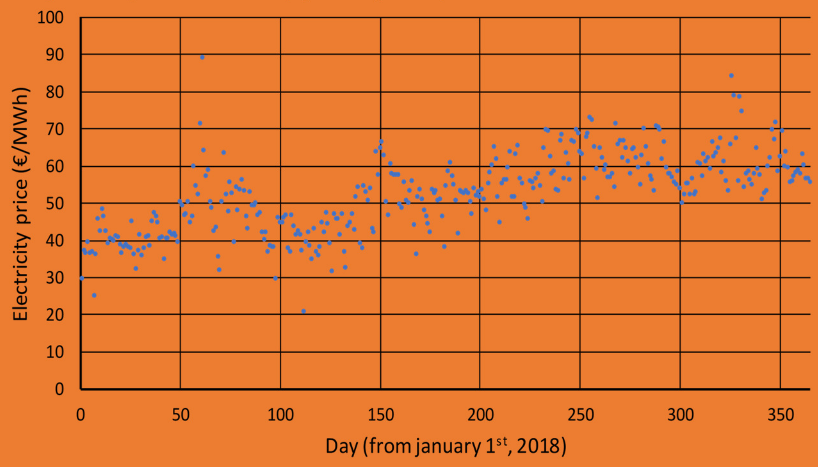
When this equation is true, the SAS will supply the heat demand. During simulations it became apparent that the fickle nature of electricity prices caused an erratic loading and unloading behaviour in the ecovat. Practical application of this method will depend on how this would affect heat diffusion in the ecovat. Therefore, all results from case 2 should be verified in additional studies.

In this case the ecovat is charged using a heat pump. The heat pump buys electricity from the grid, using hourly electricity price data supplied by Ecovat BV (Box 15). This means that it is possible to optimize the charging times by looking for moments when there is cheap electricity. Finding optimal loading times requires predicting market movement, which can be done with extensive algorithms and manual adjustments from traders. However, when a dataset is available with all price points in a year, picking loading moments can be done with data snooping.

A simple method is used: Charging occurs when the price of electricity falls below a certain value. This maximum price value is found by running the simulations, increasing the maximum price value incrementally, until there

Box 15 – Reference electricity prices

Daily averages of electricity prices paid by Ecovat in 2018.



is no more heat deficit in the system. When this happens, the simulated DHS works as intended, and can be used as a reference dataset. The next step is adding more heat demand, simulating more houses being connected to the DHS. When there is more heat demand, the ecovat will have exponentially more difficulty supplying heat, since not only will there be more heat demand, the ecovat will be supplying the high temperature heat. This will require a higher maximum price value. Therefore, several maximum price values were simulated, increasing loading costs but allowing more heat demand from the DHS.

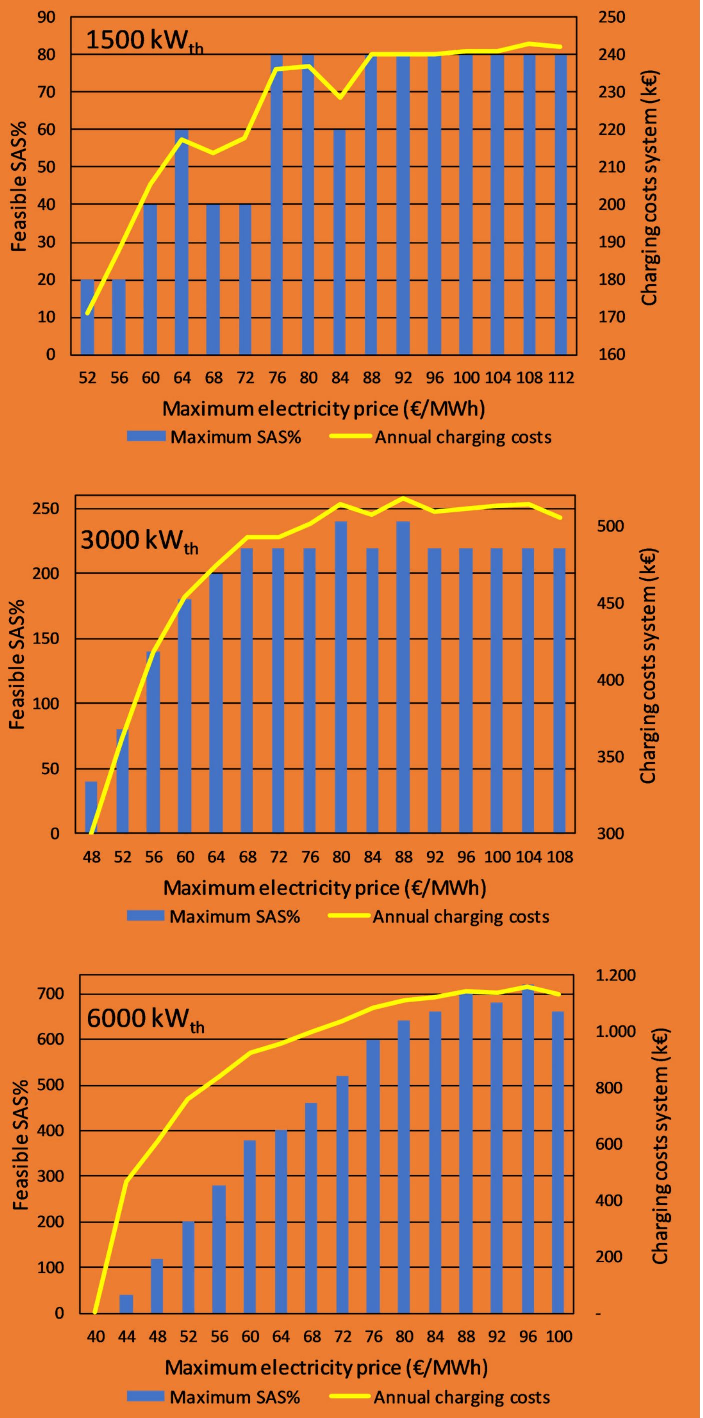
Following Ecovat B.V.'s Arnhem case, the DHS temperature curve was set at 55℃ @-10℃ ambient temperature and 35℃ @18℃ ambient temperature. 27 GJ annual heat consumption per house was assumed to calculate the annual heat generation cost per house (Box 17).

### 5.3.2. Results

Box 16 shows the simulation results assuming 3 heat pump capacities. At all heat pump capacities, both *%SAS* and charging costs plateau at the maximum electricity price recorded in that year (88 €/MWh, Box 15). At that point, electricity is used continuously, regardless of its price. This indicates that the maximum system capacity is reached. The maximum number of homes being served varies from 760 (80% SAS) at 1500 kW$_{th}$, to 1350 (220% SAS) at 3000 kW$_{th}$ and 3300 (680% SAS) at 6000 kW$_{th}$. However, the total system charging costs increase as well.

Box 17 shows that annual heat generation costs at maximum heat pump utilisation do not dependent much on heat pump capacity. The difference is related to the division of heat pump capacity between charging the ecovat and delivering directly to the DHS. The ecovat status

Box 16 – Possible SAS additions and charging costs for different maximum electricity prices at 3 heat pump capacities

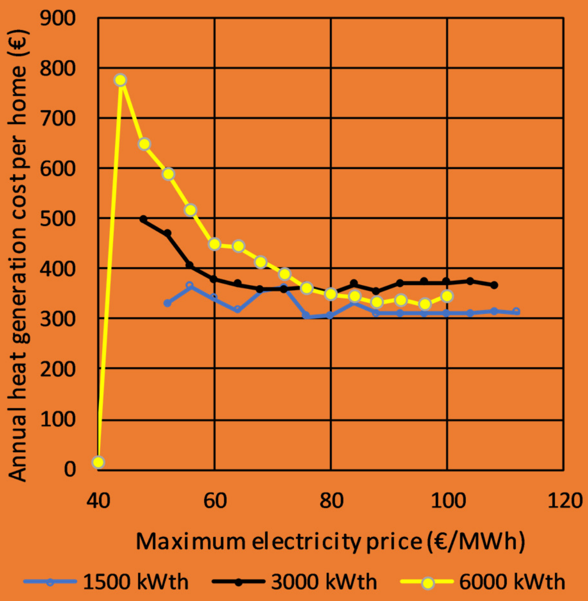


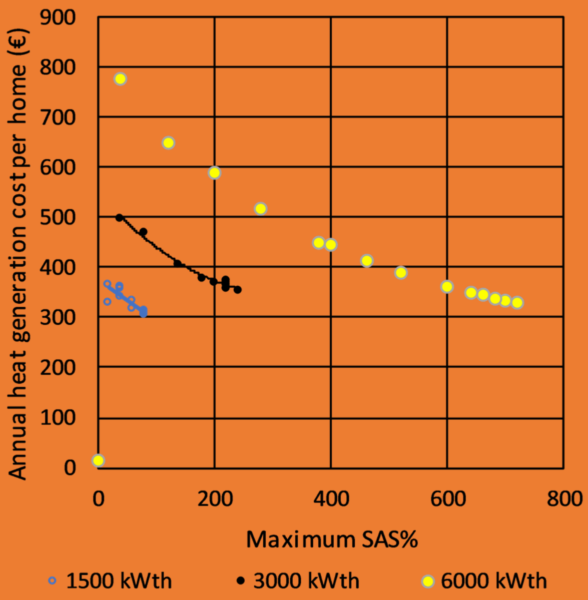
depends on previous DHS temperatures and loading opportunities at moments of favourable electricity prices. As heat pump utilization approaches maximum, loading opportunities become scarcer, so the ecovat begins to struggle keeping its temperature high enough to supply the DHS. As mentioned before, this is a fickle process.

Interestingly, the possible SAS addition in Box 16 sometimes decreases after increasing the maximum electricity price. This happens because the model does not consider the COP of the heat pump when choosing whether to charge or not. When the electricity price is high at favourable COP, the cost of one kWh heat loaded into the ecovat could drop. This would decrease the amount of heat the SAS can supply, lowering the possible SAS%.

One would expect that a larger heat pump would make better use of low electricity prices, resulting in lower heat generation costs at similar %SAS. In Box 17, the opposite is the case. This is because the model does not consider the COP and ecovat state of charge when choosing whether to charge or not.

Box 17 – Annual heat generation cost per home as related to maximum electricity price and maximum %SAS at 3 heat pump capacities





## 5.4. Impact on the business case

Although the loading strategy implemented in the model needs improvement, Box 17 shows that adding SAS decreases the annual heat generation costs per home. Adding SAS also proved economically feasible in case 1, because low-temperature heat can be generated more efficiently by a heat pump using SAS as a source. This means the investment cost of an ecovat could be divided over many more buildings that it was initially designed for (422 homes if annual heat consumption equals 27 GJ/home, as assumed in Box 17. The Arnhem case assumed 559 homes, in Box 18). Box 18 shows that the effect of adding SAS on CAPEX is much more significant than the effect on heat generation costs.

### Box 18 – Economics of adding SAS storage to an ecovat system, excluding the effect of %SAS on the cost of the DHS system

| | 0% SAS | 40% SAS | 80% SAS | 120% SAS | 160% SAS | 200% SAS | 240% SAS | 280% SAS |
|---|---|---|---|---|---|---|---|---|
| Total investment (k€) | 5.856 | 6.261 | 6.667 | 7.072 | 7.477 | 7.882 | 8.287 | 8.693 |
| Total storage (MWh) | 3166 | 4432 | 5698 | 6964 | 8230 | 9497 | 10763 | 12029 |
| Houses connected | 559 | 783 | 1006 | 1230 | 1453 | 1677 | 1901 | 2124 |
| Investment €/house | 10.476 | 8.001 | 6.626 | 5.750 | 5.145 | 4.700 | 4.360 | 4.092 |
| Investment €/MWh | 1.850 | 1.413 | 1.170 | 1.015 | 908 | 830 | 770 | 723 |

It should be mentioned that Box 18 does not account for the cost of the expanded DHS network. The price of a SAS will largely depend on peak power. Since the methods used to determine when the SAS supplies power are not optimal, peak power of the SAS cannot be determined. Therefore, we used investment costs mentioned in a previous Ecovat publication[57]: 1850 euro/MWh for ecovat and 160 euro/MWh for SAS. Considering that a SAS has half the lifetime of an ecovat, the investment cost of the SAS are doubled. Nevertheless, adding a SAS would be approximately 80% cheaper per MWh storage than increasing the DHS coverage with and additional ecovat.

## 5.5. Conclusions

Case 1 shows that when local heat is available, there is a sweet spot to add a SAS. When the heat is relatively cheap, it is better to just use an ecovat, but when heat is relatively expensive, using the electricity grid to power a heat pump + SAS + ecovat combination would be more economical. In the last situation, case 2 would apply to optimize allocation of variable electricity prices to either charging the ecovat or supplying the DHS directly through heat pumps that use SAS as a heat source.

In case 2, adding a SAS increased charging costs, but the investment per house and the annual heat generation cost per house dropped significantly. The maximum percentage SAS is limited by the power of the heat pump. Although the heat pump needs to deliver a larger portion of the heat at higher temperatures as the %SAS increases, the annual generation cost per home will drop if the higher electricity prices can be avoided. The model's algorithm needs further rationalisation and refinement to deliver more representative results.

It should be emphasised that these simulations assume a DHS supply temperature that varies on an hourly basis. Although this is not common practice, it is main cause for the profitability of combining ecovat with a heat pump and aquifer storage. The authors think that exergy-efficient DHS operation is an important key to create sound business cases for the ecovat:

- The perspective of being able to lower the initial required investment per home could convince potential customers to keep the ecovat in consideration longer. This increases ecovat's chance to be chosen to be a part of the DHS system to provide cheap high-temperature heat during the coldest days and reduce investment in backup facilities and heat pumps.
- With many DHS systems, improving the insulation of connected homes reduces income from heat sales and deteriorates the DHS business case. On the other hand, improved insulation reduces the required DHS supply temperature. Thus, adaptive supply temperatures could enable DHS expansion by connecting more homes over time, whereas high supply temperatures can still be delivered when needed.

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[57] Ecovat, 2020. Economic and thermal performance of Ecovat and comparable thermal energy storage technologies.

## 5.6. Discussion and recommendations for further research

This simulation study has simplified several things, decreasing the accuracy of its results. Therefore, further research is needed to pinpoint the exact optimal SAS portion of the heat supply. In further studies, the following issues should be considered more carefully:

- Loading logic of the SAS and ecovat. This has a large impact on loading costs and electricity grid usage.
- Heat diffusion in the ecovat. When loading and unloading the ecovat, the mixing of temperature layers is assumed to occur instantly and homogeneously. When a large SAS is added, the usage of the ecovat intensifies strongly in winter, requiring large heat transfer in a short amount of time. In such situations the assumption might not hold.
- When the DHS is expanded, more houses are connected to a single ecovat. This means that when the ecovat is in use, it must spread high temperature heat further than originally designed. This will increase heat losses, requiring a higher temperature to be delivered from the ecovat in order to reach the houses with an adequate temperature. This will reduce the effectiveness of the ecovat.
- The ecovat’s potential to provide cooling is not incorporated in the model. A heat pump could also use the ecovat as a source, so the remaining state of charge could be utilised for heating, thus replacing some SAS capacity. Using the ecovat this way could alleviate flow restrictions posed by SAS.
- Including the effect of return temperature and the possibility to preheat using heat pump and afterheat by ecovat might increase the efficiency of the heat pump and the share of heat delivered by SAS.
- The minimal COP calculated in case 1 could become even lower when considering that the CAPEX of the entire system decreases when a SAS is added.
- It would be interesting to run the model with maximum heat costs (maximum electricity price · $COP_{SAS}$) instead of maximum electricity price. That would force ecovat charging more to the summertime.

# 6. Summary of conclusions and recommendations

**1** Although several local energy collectives recognise the need for seasonal heat storage, it is very difficult to justify a 6 M€ investment for an ecovat in their business case. The benefits to the energy system outside the project boundary are not financially rewarded to the investors. How then to improve opportunities for Ecovat? The authors envision two pathways, one at the national and regional level and one at the local level:

**a)** As national policies focus on expanding solar and wind generation capacity, storage is perceived as a technical matter to alleviate grid integration problems, which are to be solved by network operators and energy producers. Therefore, the system benefits of seasonal heat storage should receive most consideration in the development of regional energy strategies (RES). There, the cost of (heat) storage could be balanced against cost of electricity grid reinforcements and converting the natural gas grid to hydrogen, or other issues such as enabling more solar energy in the mix to conserve the open landscape. Ecovat could seek involvement in developing models, providing datasets or case studies that help appraise the value of seasonal heat storage (see 2.2.2).

**b)** Develop a DHS + central seasonal heat storage project after clusters of 5-30 homes have been optimized and can provide detailed data on temperature and heat demand patterns (see 4.2 and conclusion 3). This results in a more accurate business case and more professional interaction with the cluster operator, as a cluster connects to the DHS by one connection and has an own control system to manage local storages and heat pumps. Combine this with a staged business case approach (see 2.3.3) and help customers think wisely about sound business cases of long-lived assets (see 2.3.4).

**2** In developing TVW's (*Transitie Visie Warmte*), municipalities probably underestimate the potential of low-temperature DHS (district heating systems) in neighbourhoods where

- there are no heat sources but with abundant space for solar energy on roofs or open spaces,
- far-reaching insulation measures are expensive, and
- local storage combined with demand-side management could avoid electricity grid reinforcements.

These traits apply to rural areas where DHS are usually not being considered because of the relatively long distance between homes. The perspective could change if heat and electricity are generated and stored (for short periods) in or near homes, so DHS piping could be cheaper (no peak loads, thinner piping) while reducing heat losses (thinner pipes, variable temperatures, temporary shutdown of DHS flow). Innovations that increase DHS exergy efficiency and alleviate limitations posed by low linear heat density could have a considerable positive effect on business cases for DHS and seasonal heat storage.

**3** Both municipalities and local energy collectives lack methods that enable citizens to really participate in considering options and decision making regarding collective heating solutions such as DHS. Therefore, participation comes down to informing and convincing or seducing citizens to participate in an offered plan. Although local energy collectives are run by volunteering citizens, they are not equipped to develop plans for DHS and local storage. Nevertheless, they can play an important role by taking initiatives, raising municipality support and facilitating fellow citizens in their transition process.

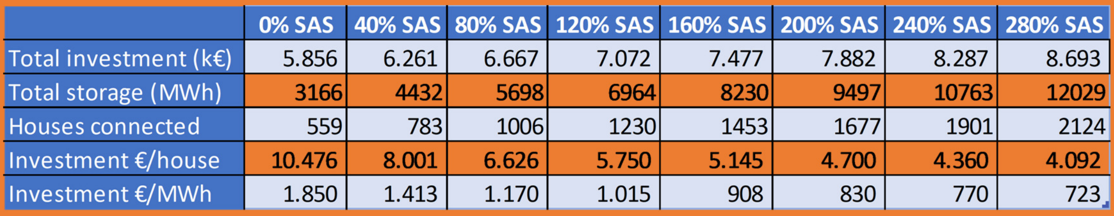
Together with energy collective Durabel and municipality Het Hogeland, a 4-phase method to develop a cluster-DHS was conceived, which could be supported by local energy collectives and municipalities. The first step is to optimise insulation and installations in homes, balancing those investments with the heat generation costs of individual and collective installations in a transparent way. After a period of monitoring, optimising installation settings and control, and feedback to homeowners on energy-efficient behaviour, clusters of 5 to 30 homes can decide on further improvements. These improvements are to be suggested and elaborated by technical experts, using monitored usage patterns and temperatures in the cluster and home installations. In this way the DHS, heat sources and storages at the cluster level and central level can be dimensioned properly.

This process could make the business case more accurate and future proof, whereas the various stakeholders can play a role that matches their existing competences. This process would make it easier for Ecovat B.V. to develop projects. Ecovat B.V. could facilitate this approach by contributing to the development of DHS configuration software (e.g. Comsof heat and TNO's WarmingUp initiative)

**4** Model simulations and simple cost calculations show that the ecovat investment could be shared by many more homes when an ecovat is combined with seasonal aquifer storage and a heat pump. Assuming the DHS supply temperature varies in time and matches the space heating demand, the heat pump would supply low-temperature heat in spring, summer and autumn. The ecovat supplies the peak demand and higher temperatures in winter. Thus, increasing the number of homes per ecovat would significantly decrease both the capital costs per home (Box 18) and the heat generation costs (Box 17 in chapter 5).

This means aquifer storage is not a competing but a complementary technology to Ecovat, because the strengths of both are being combined. The optimum dimensioning of heat pump and aquifer storage depend on the ratio of heat (buying) price and electricity price and on DHS supply temperatures. The heat pump could be dimensioned smaller than with conventional peak generators and can be used to charge the ecovat when electricity prices are low (in summer). From this perspective, ecovat's competing technologies are the peak boilers (natural gas, biogas, electric) and CHP.

### Box 18 – Economics of adding aquifer storage to an ecovat system, excluding the effect of network expansion on the DHS system cost



| | 0% SAS | 40% SAS | 80% SAS | 120% SAS | 160% SAS | 200% SAS | 240% SAS | 280% SAS |
|---|---|---|---|---|---|---|---|---|
| Total investment (k€) | 5.856 | 6.261 | 6.667 | 7.072 | 7.477 | 7.882 | 8.287 | 8.693 |
| Total storage (MWh) | 3166 | 4432 | 5698 | 6964 | 8230 | 9497 | 10763 | 12029 |
| Houses connected | 559 | 783 | 1006 | 1230 | 1453 | 1677 | 1901 | 2124 |
| Investment €/house | 10.476 | 8.001 | 6.626 | 5.750 | 5.145 | 4.700 | 4.360 | 4.092 |
| Investment €/MWh | 1.850 | 1.413 | 1.170 | 1.015 | 908 | 830 | 770 | 723 |

# 7. Appendix

The model uses weather data from the Netherlands (year 2010 to 2013, hourly data, from KNMI) to simulate the heating demand, required DHS temperature, and solar collector yield per hour. This is used to choose between supplying heat from the ecovat or the SAS, and to charge the ecovat or SAS.

## 7.1. Starting parameters

When the simulation is started, some parameters are generated. These will now be described:

**Temperature of layers in the ecovat**

The starting temperatures are set at the minimum temperature values as defined in the document "Thermal efficiency Ecovat" [58]. This is done at the virtual date of January 1st, 2010.

*Table 1 Maximum and minimum temperatures Ecovat*

| Layer | Maximum temperature [ºC] | Minium temperature [ºC] |
|---|---|---|
| 1 | 85 | 45 |
| 2 | 85 | 30 |
| 3 | 80 | 5 |
| 4 | 80 | 5 |
| 5 | 80 | 5 |
| 6 | 80 | 5 |
| 7 | 60 | 5 |
| 8 | 30 | 5 |

**R-value homes**

In order to calculate the heat demand on an hourly basis, the R-value of the to-be-heated homes is calculated:

$$R_H = \frac{Q}{\sum_n (T_H - T_{amb})}$$

With:

$R_H$ = R-value of all homes heated by the DHS
$Q$ = heat demand over two years
$n$ = sum of hours over two years
$T_H$ = ambient temperature below which heating is needed
$T_{amb}$ = temperature around home, taken from weather data from the Netherlands

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[58] As specified in Bosch R van den, 2018. Thermal efficiency Ecovat. Validation of the thermal efficiency based on the demonstration Ecovat Uden. Ecovat Werk BV, Veghel.

**R-value heating installations**

To calculate the required DHS temperature at each hour within the simulated time period, the R-value of the heating installation needs to be calculated. This is done by keeping track of the highest dT in the integral of the R-value homes calculation, and then using that dT in the following equation:

$$R_{HI} = \frac{R_H * dT_{max}}{T_{HGMax} - T_H}$$

With:

$R_{HI}$ = R-value of heating installation

$R_H$ = R-value of all homes heated by the DHS

$dT_{max}$ = the largest dT $(= T_H - T_{amb})$ found in the R-value homes calculation

$T_{HGMax}$ = maximum DHS temperature

$T_H$ = ambient temperature below which heating is needed

**Maximum temperature SAS**

In the starting parameters, the amount of heat demand the SAS will deliver is specified. This will be used to calculate at what temperature the SAS is active. This is done with the following statement:

$$Q_{\mathrm{SAS}} \leq \int_0^{T_{DHS\_SAS}} Q_{T\_DHS}$$

With:

$Q_{\mathrm{SAS}}$ = heat demand to be supplied by SAS

$Q_{T\_DHS}$ = sum of heat demand at a particular DHS temperature

$T_{DHS\_SAS}$ = maximum temperature of DHS at which the SAS will deliver heat. Heat above this temperature will be delivered by the ecovat

## 7.2. Loading logic ecovat

The ecovat is divided into 8 layers, with thermal resistances and a minimum and maximum temperature specified for each layer (see Table 1). Each layer is assumed homogenously mixed. When the solar collectors produce more heat than the current demand, this heat will be stored in the ecovat. A layer will be selected to receive the heat, while a colder layer will be used to provide a flow of water. This flow of water will be heated by the solar heat, and then pumped into the to-be-heated layer. Then, the flow will continue down to the layer used to provide a cold flow. This process will now be described:

The model cycles through all layers from top to bottom, until the following condition is met:

$$T_{Layer} < T_{MaxLayer}$$

With:

$T_{Layer}$ = temperature of the layer being checked

$T_{MaxLayer}$ = maximum temperature of the layer being checked (specified in Table 1)

When this condition is met, the layer is selected to receive the surplus heat. Another check is performed to check if this layer can receive all the heat available for storage within the timestep without exceeding the layer's maximum temperature. If this check is passed, the model with cycle through the layers below the receiving layer from bottom to top, until the following condition is met:

$$T_{Layer} < T_{MaxLayer}$$

With:

$T_{Layer}$ = temperature of the layer being checked

$T_{MaxLayer}$ = maximum temperature of the layer being checked

This layer will be providing a flow of water, which will be heated to the maximum temperature of the receiving layer as specified in Table 1. The flow is calculated using the following equation:

$$Flow = \frac{Q_{surplus}}{c_p * (T_{col} - T_{Layer})}$$

With:

$Flow$ = water volume passing from the delivering to the receiving layer within the timestep
$Q_{surplus}$ = surplus amount of heat in the simulation timestep
$T_{col}$ = temperature (supplied by solar collectors) that the flow will be heated to
$T_{Layer}$ = actual temperature of the delivering layer
$c_p$ = heat capacity of water

Now, the temperatures of the used layers will be updated. For the receiving layer, the following equation is used:

$$T_{Layer} = T_{Layer} * \frac{Volume - Flow}{Volume} + T_{col} * \frac{Flow}{Volume}$$

With:

$Flow$ = water volume displaced in one timestep
$Volume$ = volume of one ecovat layer
$T_{col}$ = temperature (supplied by the solar collectors) that the flow will be heated to
$T_{Layer}$ = temperature of the receiving layer

For each consecutive layer, the following equation is used:

$$T_{Layer} = T_{Layer} * \frac{Volume - Flow}{Volume} + T_{UpLayer} * \frac{Flow}{Volume}$$

With:

$Flow$ = water volume displaced in one timestep
$Volume$ = volume of one ecovat layer
$T_{UpLayer}$ = temperature of the layer above the selected layer
$T_{Layer}$ = temperature of the layer

**Example**

At the start of the simulation, all layers will have their minimum temperature. This means that when there is surplus heat, the first and last layer will be selected, since none of the layers have reached their maximum temperature.

*Figure 1 Ecovat; Layer selection*

## 7.3. Loading SAS

If the electricity price is favourable, the SAS will be charged. First, the COP will be calculated:

$$COP = \frac{T_{\mathrm{SAS}} + dT_1 + 273.15}{(T_{\mathrm{SAS}} + dT_1) - T_c} * \eta$$

With:

$COP$ = Coefficient of Performance
$T_{SAS}$ = the temperature of the hot well of the SAS
$dT_1$ = the temperature difference between the SAS and the heat pump's condenser
$T_c$ = the temperature of the heat pump's evaporator
$\eta$ = the efficiency of the heat pump's compressor

The temperature $T_c$ is determined as follows:
If the ambient temperature is lower than 3℃: $T_c = T_{amb} - dT_1$
Otherwise $T_c = 3°C$

This is used to prevent the hot and cold side of the heat pump from flipping, and giving a negative COP.
Then, the electricity usage is calculated. Since the heat pump charging the SAS has a fixed thermal power, only the electricity usage varies when charging.

$$E = \frac{Q_{heatpump}}{COP}$$

With:

$COP$ = Coefficient of Performance
$Q_{heatpump}$ = the thermal power of the heat pump
$E$ = the electricity usage

## 7.4. Unloading the SAS

When the SAS is used to supply heat, the following formula is used to calculate the COP:

$$COP = \frac{T_h + 273.15}{T_h - (T_{\mathrm{SAS}} - dT_1)} * \eta$$

With:

$COP$ = Coefficient of Performance
$T_{SAS}$ = the temperature of the hot well of the SAS
$dT_1$ = the temperature difference between the SAS and the heat pump's evaporator
$T_h$ = the temperature of the heat pump's condenser (required DHS temperature + dT1)
$\eta$ = the efficiency of the heat pump's compressor

The electricity usage depends on the amount of heat demand and the COP:

$$E = \frac{Q_{heatpump}}{COP}$$

With:

$COP$ = Coefficient of Performance
$Q_{heatpump}$ = the thermal power of the heat pump
$E$ = the electricity usage

## 7.5. Thermal losses Ecovat

The thermal resistances of the ecovat are copied from the document “Thermal efficiency Ecovat”, using the Ecovat Arnhem case. This means that each layer has the following specifications:

*Table 2 Thermal resistances of each layer*

| Part | Assumed thermal resistance [m2*K/W] |
|---|---:|
| Top | 24,60 |
| Wall1 | 7,18 |
| 12 | 2,38 |
| Wall2 | 7,18 |
| 23 | 2,38 |
| Wall3 | 7,18 |
| 34 | 2,38 |
| Wall4 | 6,03 |
| 45 | 2,38 |
| Wall5 | 6,03 |
| 56 | 2,38 |
| Wall6 | 6,03 |
| 67 | 2,38 |
| Wall7 | 4,60 |
| 78 | 2,38 |
| Wall8 | 4,60 |
| Bottom | 1,82 |

With this, the thermal losses are calculated every hour.
For the top layer:

$$T_{Layer} = T_{Layer} - \frac{\frac{(T_{Layer} - T_{amb}) * A_{top}}{R_{top}} + \frac{(T_{Layer} - T_{amb}) * A_{wall}}{R_{wall1}} + \frac{(T_{Layer} - T_{DLayer}) * A_{top}}{R_{12}}}{Volume * cp}$$

With:
$cp$ = heat capacity of water
$Volume$ = the volume of one layer
$T_{DLayer}$ = the temperature of the layer below the selected layer
$T_{Layer}$ = the temperature of the layer
$T_{amb}$ = the temperature around the ecovat
$A_{top}$ = the surface area of the top and bottom of the layer
$A_{wall}$ = the surface area of the wall touching the layer
$R_{top}$ = the thermal resistance of the top surface
$R_{wall1}$ = the thermal resistance of the wall
$R_{12}$ = the thermal resistance between the layers

Using an hourly timestep means that the thermal losses are slightly larger than in reality, since the temperature used to calculate heat transfer would in reality decrease during the 1-hour timestep.

## 7.6. Thermal losses SAS

The thermal losses of the SAS are strongly simplified. The following equation is used to account for the losses:

$$Q_{SAS} = Q_{SAS} * (1 - \left(\eta^{\frac{1}{8760}}\right))$$

With:

$Q_{SAS}$ = Current heat stored in SAS

$\eta$ = Yearly thermal losses

This calculation is executed for every hour in the model.

## 7.7. Selected model outputs

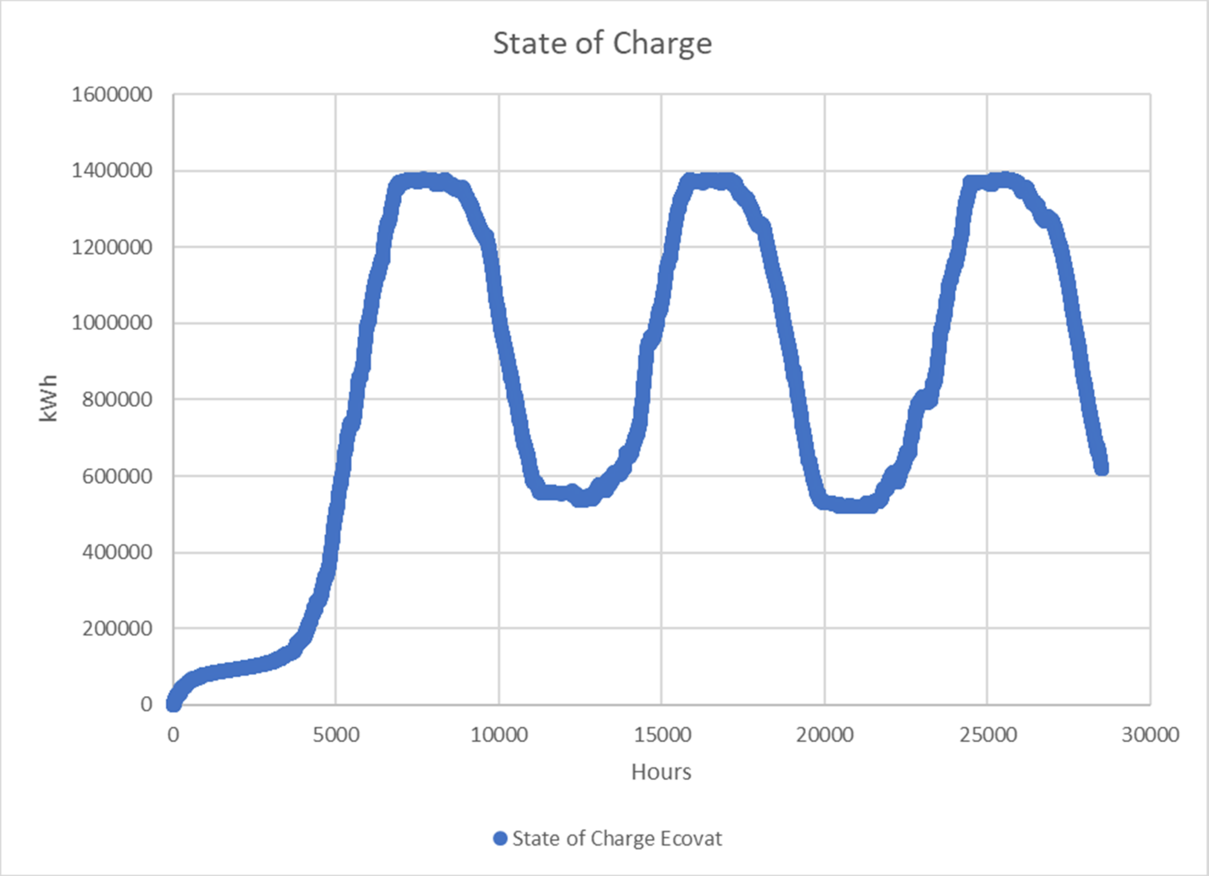

*Figure 2 State of Charge Ecovat*

Figure 2 depicts the State of Charge of the ecovat over three years, for a yearly heat demand of 11.398 GJ (3166 MWh). This demand is only partially supplied by the ecovat. This scenario has no aid from a SAS and has a maximum DHS temperature of 70℃. The State of Charge is specified as the energy stored in all layers, with the all layers at the minimal temperature as 0 State of Charge.

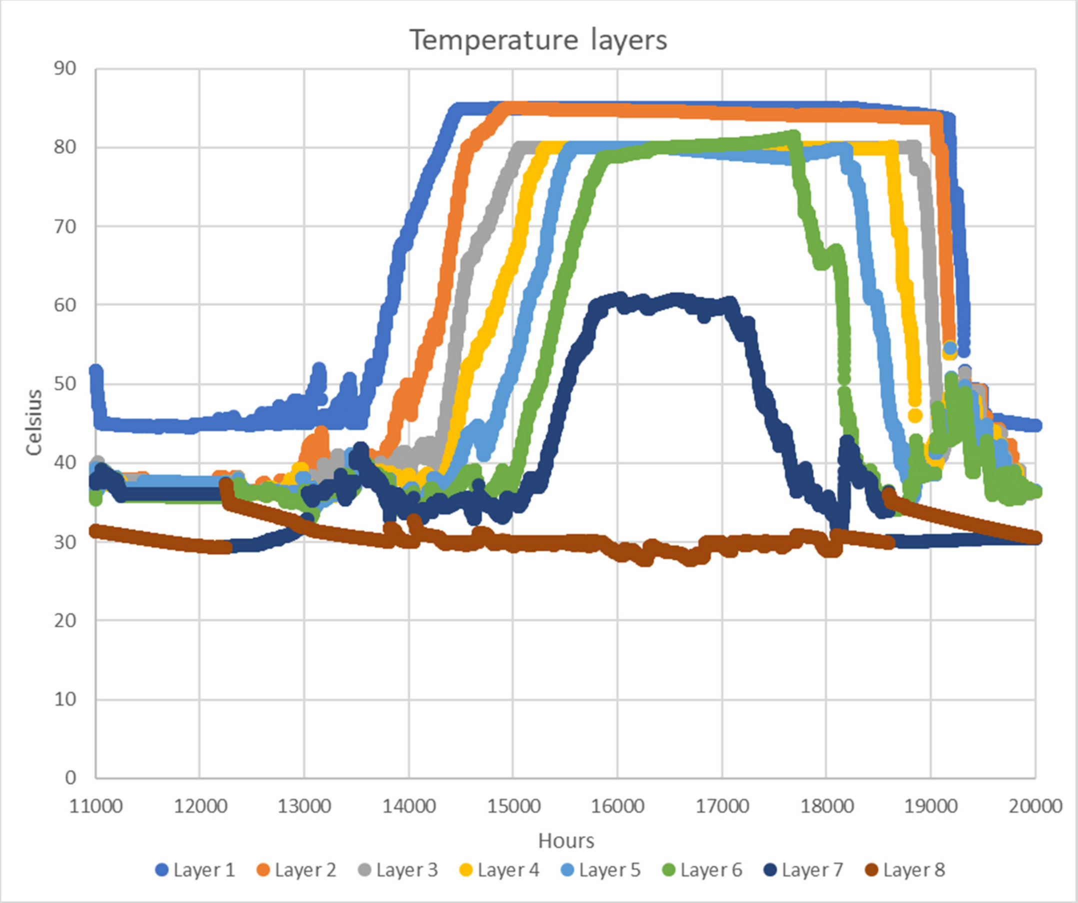

*Figure 3 Temperature of all ecovat layers throughout the second year of a test simulation*

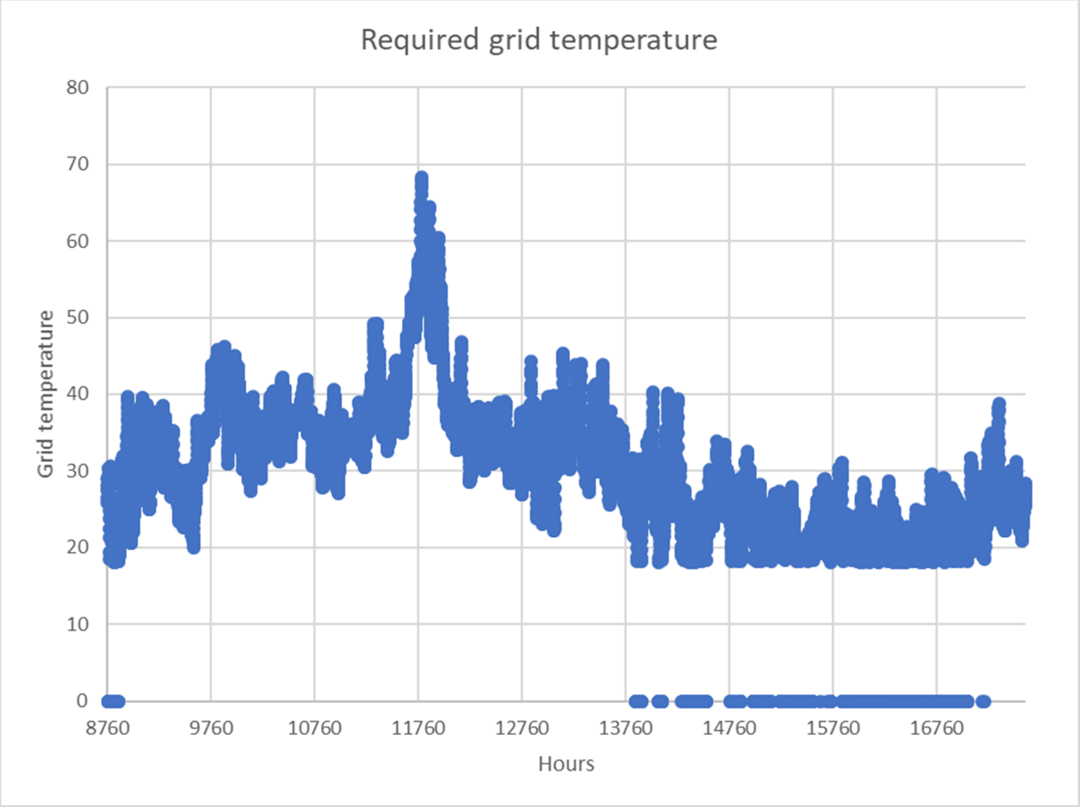

*Figure 4 Required DHS temperature throughout year two of a test simulation.*

## 7.8. Case 2 specifics

In this case, choosing whether the SAS or the ecovat supplies heat is determined differently from case 1. When loading the ecovat, the total of electricity costs and the total of amount of heat charged are used to calculate the cost of one kWh of heat stored in the ecovat.

$$\frac{E_{Cost\_ecovat}}{Q_{Loaded\_ecovat}} = Q_{Cost\_ecovat}$$

With

$E_{Cost\_ecovat}$ = the total cost of electricity used to charge the ecovat

$Q_{Loaded\_ecovat}$ = the amount of heat loaded into the ecovat

$Q_{Cost\_ecovat}$ = the cost of one kWh of heat loaded in the ecovat

This is then used in the following equation:

$$\frac{COP_{SAS}}{1 + \frac{1}{COP_{SAS_{Load}}}} * E_{Cost} < Q_{Cost\_ecovat}$$

With

$COP_{SAS}$ = the COP of the SAS if it were to supply the current heat demand to the DHS, using the energy stored in SAS as a source

$COP_{SAS_{Load}}$ = the average COP when loading the SAS (assumed at 10)

$E_{Cost}$ = the current electricity cost of one kWh

$Q_{Cost\_ecovat}$ = the cost of one kWh of heat loaded in the ecovat

When this equation is true, the SAS will supply the heat demand.

## 7.9. Parameter settings

| | |
|---|---|
| Delta T heat exchangers (dT1) | 5°C |
| Heat pump thermal power | 1500 kW |
| Heat pump compressor efficiency | 55% |
| Temperature hot side SAS | 12°C |
| Temperature cold side SAS | 8°C |
| Annual losses SAS | 5% |

## Contactgegevens

Dr. ir. D.A.G. Kurstjens
Instituut voor Engineering, Hanzehogeschool
Zernikeplein 11, kamer C1.51
9747 AS Groningen
d.a.g.kurstjens@pl.hanze.nl