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Conceptual Modelling of Seasonal Energy Storage Technologies for Residential Heating in a Dutch town Best

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Abstract. The increasing growth of modern renewables in countries with significant seasonal variations leads to a growing amount of excessive energy generated in peak seasons. This combined with the shortage of renewable energy in off-peak periods, creates an emerging need for seasonal energy storages. Best is a town located south in the Netherlands. Heating with natural gas in the cold season is the major energy consuming function in the residential sector, in Best. In this paper, we investigate storage technologies that have the potential to replace natural gas as a source of heating in Best. We observe and analyze Best and investigate storage technologies to uncover key considerations. We create conceptual models of three suitable storage technologies. We use these models to compare the storage technologies and enable discussion around the key considerations. The conceptual models provide insight and understanding of the technologies and the considerations. The comparison points to power-to-gas (PtG), with the production of methane and supply of electricity to heat pumps, as the most suitable technology for Best.

Introduction

Recent years has seen an increasing tempo in the development of renewable energy sources. The share of modern renewables (hydropower, solar, wind, and geothermal) has increased from 7.5% in 2000 to almost 11% in 2018 (International Energy Agency, 2019a). The total renewable power capacity is set to expand by 50% between 2019 and 2024. Solar PV and wind is set to account for 70% of the predicted global expansion (International Energy Agency, 2019b). The main challenge with these sources is their intermittent nature. They depend on certain conditions to generate energy. These conditions are non-controllable and challenging to forecast. A constant energy supply from such source is therefore unachievable. Letcher (2016) states that as renewable sources account for an increasingly large part for the energy generation, two problems emerge:

1. At the time of high demand and low renewable generation, energy shortfalls occur that can affect the stability of the electrical system.
2. At times of low demand and high renewable energy generation, surplus energy occurs. We must store or lose this energy.

These electric system imbalances between generation and demand present an opportunity for new types of energy storage to have an important role in future energy systems.

Context. Best is a town in the North-Brabant province south in the Netherlands (Figure 1). Best has a population of 30,000 citizens and holds about 12,500 residences. Best has an aim to become more sustainable. The town explores several measures that can contribute to reaching this aim. The town has seen a steady growth in solar panel installations in recent years. Best experience substantial seasonal variations. It is evident that solar panels in Best generate excess energy in the summer, while winter periods increase the energy demand and limit solar energy generation. Because of this, seasonal energy storage has emerged as a key measure for Best.

Figure 1: Best in North-Brabant in the south of the Netherlands

Seasonal energy storage technologies. Based on discharge time, seasonal energy storage classifies as long-term energy storages (Rohit, Devi and Rangnekar, 2017). Most long-term storage technologies have a low level of maturity, with seasonal technologies being the least mature technologies (GREBE, 2017). Most of these technologies are in a conceptual or testing phase. The only mature commercialized technology is pumped hydroelectric energy storage (PHES) (Aneke and Wang, 2016). However, this technology is geographical dependent, as it requires a large elevated water reservoir. Emerging technologies can theoretically store the same amount of energy as PHES, as well as being geographical independent.

Challenge(s). The need for seasonal storage increases in line with the growth in installations of intermittent energy sources in countries with seasonal variations. This growing need combined with emerging new technologies provides a knowledge gap. Understanding how to integrate energy storages into low-carbon energy systems is a difficult challenge (Letcher, 2016). The lack of insight and understanding of seasonal storage technologies makes it difficult to determine a direction for its application. A key challenge is the comparison of storage technologies and understanding the consequences each technology provides.

Conceptual modeling. Most seasonal storage technologies are in a conceptual phase. Full-scale assessments of most of these technologies are yet to become available. This makes it reasonable to apply a tool to better visualize and understand these technologies. A suitable tool for this study is conceptual modelling. Conceptual models are putting seasonal storage technologies into the context. They will address stakeholder needs and provide key considerations for discussion. Considerations should contribute to the way of thinking and enable discussion around the key aspects. They also may contribute to trigger technical considerations and provide recommendations.

Research questions.

- What are the key considerations to account for when evaluating seasonal storage technologies in Best?
- How can conceptual modelling contribute to the comparison and evaluation of storage technologies?
- How do the various storage technologies perform based on the key considerations?

Research design

Selection process. The first phase in this research is a selection of storage technologies. This phase will result in two to four suitable seasonal storage technologies. This makes it possible to make a comprehensive research on some suitable storage technologies, rather than a narrow research on suitable and unsuitable storage technologies. The application of various time boxes were used to limit the time spent on this phase. This phase involves of a four-step process:

1. This step consisted of finding as many various storage technologies as possible. The sources of information in this step were papers, websites, and magazines. This step resulted in 18 technologies and a few main properties.
2. This step is a simple evaluation of the 18 storage technologies from step 1. The researcher made the evaluations based on knowledge obtained from step 1. This results in what seems like suitable storage technologies for seasonal storage in Best.
3. This step is a more thorough research on the six suitable storage technologies from step 2. The goal is to find the advantages and disadvantages of each technology. Based on this the three most realistic storage technologies for Best are chosen.
4. This step is a validation of the findings from the first three steps. The researcher conducts a more comprehensive research on the three chosen storage technologies. In addition, the researcher discovered several solutions within two of the selected storage technologies. This resulted in an added selection of the most realistic solutions for these storage technologies.

Context and stakeholder research. The aim of this research is to discover and understand key stakeholder, needs, challenges, and opportunities in Best. Gathering of data and information is the first step. Databases and websites provided by public authorities are the sources of information. The researcher visited Best to observe the town and interview relevant stakeholders. Observations were made of both residential and commercial areas. The focus was on building density and available areal. Interviews with people from the municipality gave insight in the political and social perspectives. People with technical background that work with development of sustainable solution in Best, were also interviewed. This gave insight to the challenges and opportunities the different technologies could provide. This research did provide the base for the criteria for comparison of technologies.

Technology research. The selection process provided general data and information on the selected storage technologies. Further research on storage technologies includes inputs from the stakeholder research. A set of criteria is the basis for the further research. These criteria consist of technical specifications and other key criteria for seasonal storage in Best. The research is then focusing on literature that includes data and information on these criteria.

The research on storage technologies revealed substantial diversity in available data and information. Seasonal storage is a maturing technology. Many numbers are context dependent and change due to technical and economic developments. Numbers and data on technical specifications and costs vary the most. These numbers are illustrative. They are not to be the basis for a final selection of a seasonal storage technology in Best. The numbers enable discussion and make it easier to visualize the challenges and opportunities each technology provides. This makes the selection of numbers more flexible as the discussion around is more important than the numbers themselves.

The amounts of information and data and the level of details available on each technology reflect on how mature the technologies are. Of the selected ones, LAES is the newest and most immature technology. Therefore, less literature about this technology is available. PtG and TES are more mature technologies. It is therefore easier to find detailed data and information about these technologies. The various levels of details are observable in the conceptual models.

Conceptual modelling literature.

Robinson (2008) defines conceptual modelling as the process of abstracting a model from a real system**.** This article discusses the different definitions of conceptual modelling. It gives insight on key aspect and activities within conceptual modelling. One statement appears several times: conceptual modelling is not a one-off process, but one that is repeated and refined a number of times. This statement pinpoints the importance of continuous development of the models, through the development process. The process of conceptual modelling defines as moving from a problem situation, through model requirements to a definition of what is going to be modelled and how.

Robinson, (2008) also defines conceptual modelling as the process of creating the conceptual model. This definition provides five key activities for conceptual modelling:
- Understand the problem situation.
- Determine the modelling and general project objectives.
- Identify the model outputs.
- Identify the model inputs.
- Determine the model content (scope and level of detail), identifying any assumptions.

These activities are useful as they give a generic recipe for how to perform conceptual modelling. The paper provides overreaching requirements that are important remembering when creating a conceptual model: keep the model simple.

Robinson (2009) explores the means and need for conceptual modelling. The article title is questioning who needs conceptual modelling. The answer to this is every simulation modeler. Everyone that is to create a simulation needs it. A simulation defines as the imitation of the operation of a real world process or system over time (Jacob, 2013). For instance, Best may create a simulation of how a seasonal storage technology performs over time in town. This is to get a better understanding of what benefits and challenges seasonal storage will provide over time.

Conceptual modelling is about abstracting a model that is fit-for-purpose and by this we mean a model that is valid, credible, feasible, and useful (Robinson, 2009). Conceptual models are defined as models that by simplification model at a high level of abstraction. These models are a combination of visualization (e.g. diagrams, timelines, graphs, and sketches), mathematical formulas, and quantitative calculations (Muller, 2014). This definition is the core for the understanding of conceptual models in this research. Models should make it simple to play around with the numbers. This enables the possibility to investigate how changes in various factors affect the evaluation.

Storage technologies literature

Power-to-Gas (PtG). Blanco & Faaij (2018) refer to PtG as the production of hydrogen through electrolysis or its subsequent conversion to methane with CO_2 from different sources. This paper is review of more than 60 papers, and 65 studies on PtG, on power and energy models based on simulations and optimization. This paper addresses the general need for long-term storage. It focuses on how PtG can contribute to fulfill this need. It introduced the basic technology behind PtG. PtG is described as a complex energy storage due to different choices in configurations, different markets it can serve, and different services it can provide. Components can be decoupled, with electrolysis, storage capacity, and discharge having different capacity ratios. This highlights the main benefit of PtG as it is flexible and adaptable. It gives an advantage to other storage technologies as the flexibility enables PtG to provide multiple revenue streams.

Liquid Air Energy Storage (LAES). LAES is a large-scale storage system, which is using liquefied air as storage medium. (Hüttermann *et al.*, 2019). According to (Alyami and Williams, 2015), LAES demonstrates great potential for delivering reliable and efficient power. Alyami & Williams also state that the potential of LAES is the best technology to overcome barriers of costs competitiveness, validation of performance specifications, uncertainty of regulations, and industry acceptance. This gives a good impression of the technology and makes it look like the best storage solution. The problem with this article is that is just addressing the theoretical potential. The actual performance of a physical large-scale LAES is not included in the paper. Brett & Barnett (2014) address this by looking at the Highview LAES performance. Again, the study addressed expected future competitiveness within costs and performance, however, not how it truly performs.

Thermal Energy Storage (TES). Sarbu & Sebarchievici (2018) define TES as a technology that stocks thermal energy by heating or cooling a storage medium. This thermal energy can discharge later for heating and cooling applications and power generation. This paper is a comprehensive review of TES technologies. It categorizes TES technologies in three main categories: Sensible, latent, and thermochemical storages. The paper focuses on a comparison of these three main categories. Sensible storages are commonly available with water as the most common storage medium. Latent and thermochemical are under development and demonstration and is at this point to immature and costly for commercial application.

Selection Process

We define a base case in the form of a set of system requirements for the storage. These are Power [kW], Capacity [kWh], Energy Density [kWh/m^3], and Lifetime [Years]. We base the selection process on a set of pre-determined criteria how practical and economic the options are. The criteria for comparison are

- Scalability
- Ease of distribution and transport
- Impact on townscape
- CAPEX and OPEX

Table , Table , and Table show the four steps of the selection process. The color red indicates that the technology is unsuitable. Green indicates that a technology seems suitable in the particular step. The main reason for evaluating a technology suitable or not is visible in Table . A storage technology in this process defines as a technology with the ability to charge energy with a renewable energy source, store the energy over time, and discharge the energy. We can view the identified storage technologies in Table . The process results after Step 3 in three technologies suitable for seasonal storage for Best.

Table 1: Step 1-2 - Storage technologies and initial selection

Technology	Suitable?	Reasoning
Compressed Air	Yes	Looks suitable
Power-to-Gas	Yes	Looks suitable
Thermal	Yes	Looks suitable
Saltwater Battery	Yes	Looks suitable
Pumped Hydro	No	Geographical dependent
Flywheels	No	Short-term technology
Capacitor	No	Short-term technology
Supercapacitors	No	Short-term technology
Supercapacitors Magnetic	No	Short-term technology
Lead-Acid Battery	No	Short-term technology
Sodium-Sulphur Battery	No	Short-term technology
Flow Battery	No	Short-term technology
Nickle Cadmium Battery	No	Short-term technology
Lithium-ion Batteries	No	Short-term technology
Liquid Air	Yes	Looks suitable
Vanadium Renox Battery	Yes	Looks suitable
Load Shifting	No	Short-term technology
Molten Salt Storage	No	Short-term technology

Table 2: Step 3 – Selection of the most suitable technologies for Best

Technology	Reasoning
Compressed Air	Requires natural caverns to be feasible. Geographical dependent
Power-to-Gas	Sufficient capacity, geographical independent, mature components
Thermal	Sufficient capacity, geographical independent, mature components
Saltwater Battery	Insufficient capacity. Low energy density and power delivery
Liquid-Air	Sufficient capacity, geographical independent, mature components
Vanadium Battery	Insufficient capacity. Short- to medium-term technology

Table 3: Step 4 – Evaluation of the selected technologies

Technology	Reasoning
Power-to-Gas	Two alternatives: hydrogen and methane. Both seem feasible and suitable for Best.
Thermal	Three main alternatives: Sensible, latent, and thermochemical. Latent and thermochemical seem to have insufficient capacity for seasonal storage and costs are too high. Sensible water storage (SWS) seems feasible and suitable for Best.
Liquid-Air	One alternative seems feasible and suitable for Best.

Context

Need. Best is located near Eindhoven Airport. This limits the possibility for the utilization of wind power to maximum three windmills. This research will therefore consider solar energy as the only available renewable energy source. The substantial seasonal variations Best experiences are the root-cause for their seasonal storage need. Summers seasons are hot and sunny. These seasons allow for high utilization of solar energy and the heating need is low. Winter seasons are cold and cloudy. This limits the utilization of solar energy and the heating need is high. Therefore, winter periods create a large gap between the energy need and available renewable energy. Figure 2 clearly shows how peak solar PV production does not align with gas consumption.

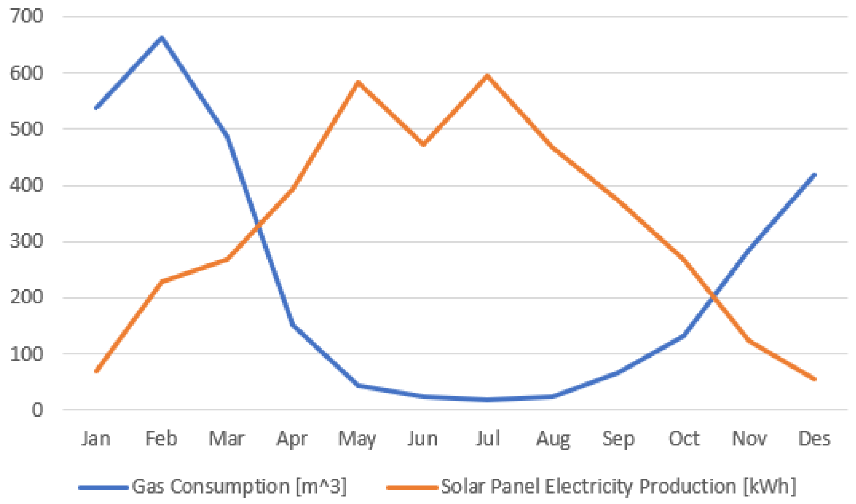

Figure 2: Example from a de-attached house in Best.

Today, Best copes with this gap by importing natural gas. In 2018, natural gas stood for 76% of the total energy consumption, in the residential sector (Rijkswaterstaat, 2019). Heating is the main consuming function in this sector. Cutting natural gas consumption in the residential sector will be a large step toward becoming a sustainable town. Best is using 160 GWh of thermal energy from natural gas. We assume that 85 % of this energy is for heating in the cold seasons (October to March). That results in a heating demand of 136 GWh_th that we use as benchmark in this paper.

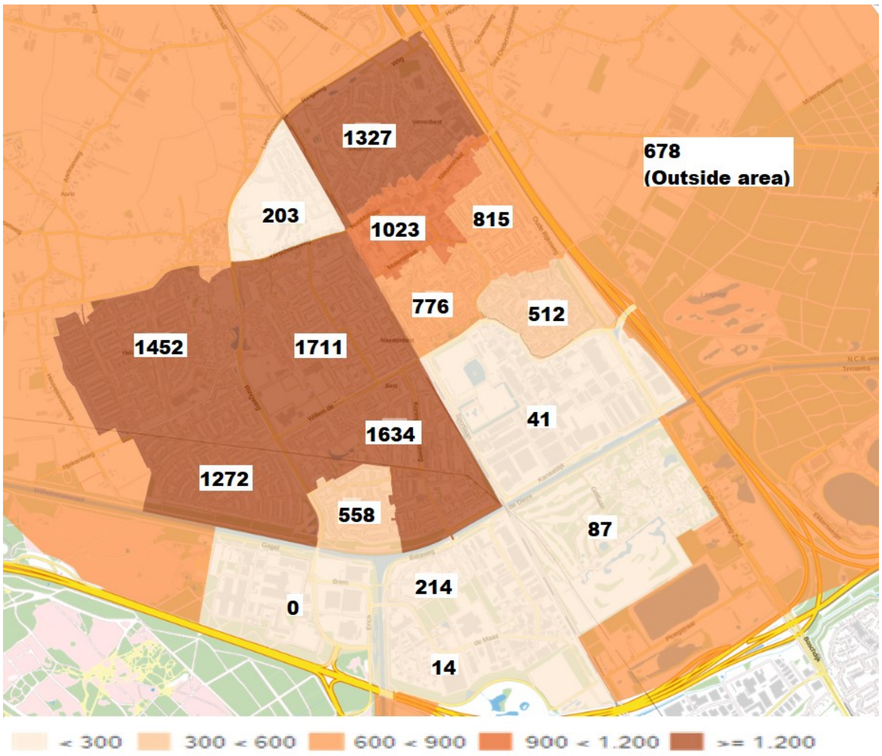

Figure 3: Residences per section in Best (Rijkswaterstaat, 2019)

Urban layout. Best has a total area of 35 km^2, with a population density of 869 inhabitants/km^2 (StatLine, 2015). Best has a high building density. Figure 3 shows the number of residences per neighborhood in Best. This clearly shows a high density in most of the town. The outside area has a low density. The lowest numbers are in neighborhoods with mostly industrial areas. Residences at the edge of the town have gardens, but not large ones. In general, there is little space around buildings. There are areas without buildings. These are parking areas, public areas and parks, and sports areas. There is not much available space in the commercial areas around the town.

Political and social. The municipality focuses on sustainable development. Politicians investigate several possible measures that can be taken to become more sustainable. The inhabitants are the most important stakeholder. They must be on board with the measures taken to become more sustainable. 50% of the residences in Best are rentals and not privately owned (Rijkswaterstaat, 2019). The average stay in residences is therefore varying. This creates a mindset where residents are thinking why care if I am just living here for a brief time. Measures must therefore have minor impact on their daily lives. Costs are a key factor for consumers. Changing to a renewable source of energy should therefore just have a minor or no impact on the energy price.

Conceptual models

The conceptual models are the core of this research[1]. We use the models to simplify the storage technologies at high-level of abstraction. The models create a visual impression of the technologies. This makes it easier to understand the technologies and enables easier communication of what are key considerations. The main contribution from the models is that they should help to estimate and think about the main considerations. We have created four models, one for the needs (to understand the problem space) and three for the various technologies (to explore the solution space).

We have used simplified needs in this research. We based the needs on a cycle of one year divided into two seasons, a cold season (October to March) and a warm season (April to September). We only consider the gas consumed in the cold season as the needed amount of energy to be stored. The charging will happen in the warm season and the discharging will happen in the cold season only. Each technology model contains the same conceptual models. Figure 4 to 7 shows examples of the conceptual models included in each technology model.

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[1] https://gaudisite.nl/figures/INCOSE2021figuresDrilen/INCOSE2021figuresDrilen.html

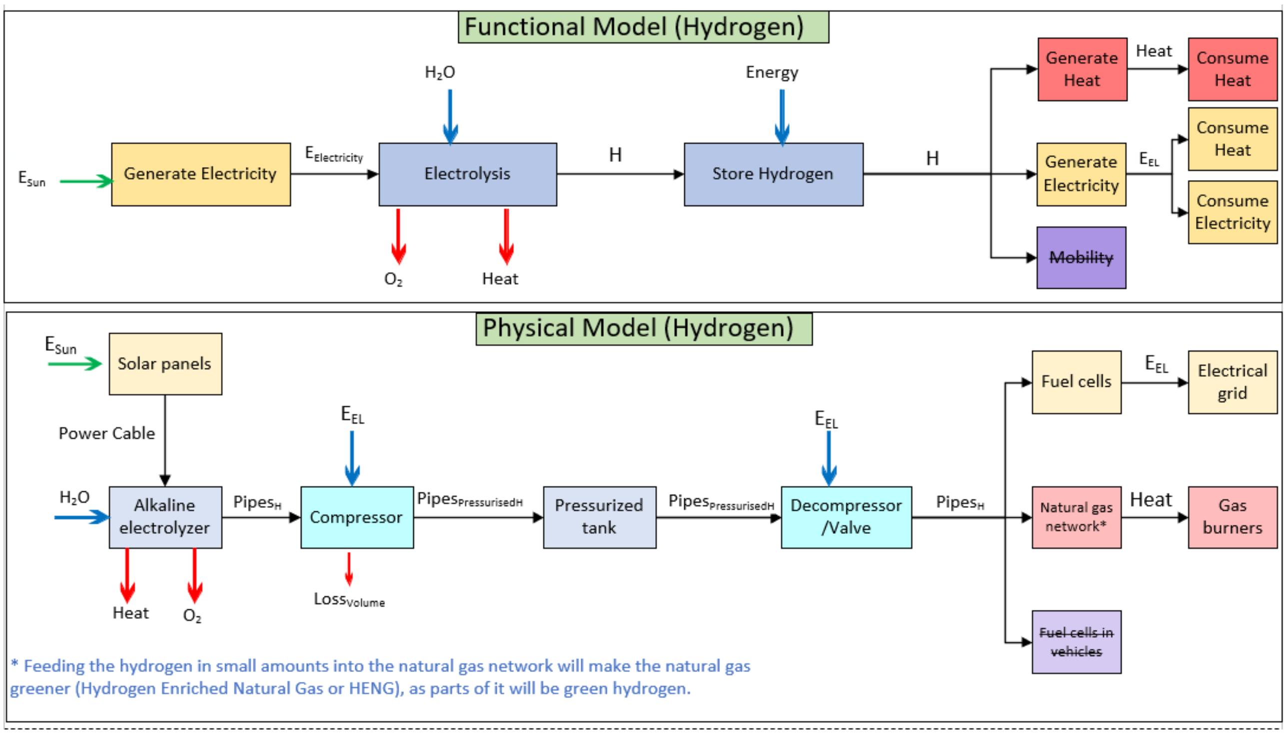

Figure 4: PtG functional and physical model

The storage technologies provide two separate ways to consume the output energy. SWS and PtG without re-electrifying supplies heat through heat-transfer and gas combustion. LAES and PtG with re-electrifying supply electricity. We must convert this electrical energy to heat to be able to compare all the technologies correctly. To convert this electrical energy to heat we have chosen heat pumps. Compared to other heating devices, heat pumps have the highest coefficient of performance (COP) (Martinopoulos, Papakostas and Papadopoulos, 2018). We use air-to-air heat pumps with a COP of 3 in this research. Air-to-air heat pumps are widespread and not dependent on an external heat source. A COP of 3 means that the heat pump will supply 3 kWh worth of heat for every kWh put into the heat pump. Figure 5 shows the impact heating with heat pumps has on the required amount of the energy to be stored, in the case of PtG.

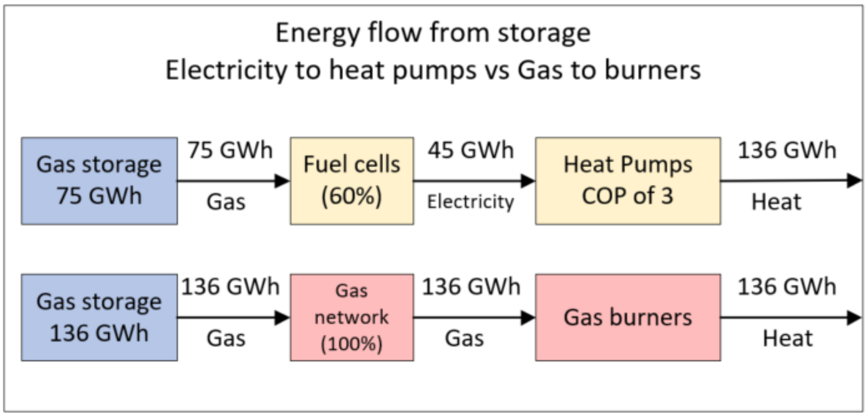

Figure 5: PtG energy flow from storage

This research focuses on the costs of the thermal energy (COSE_Thermal) the stored energy provides. COSE_Thermal is the cost of storage per kWh of heat provided to the consumer. Therefore, we have just included the main cost related to charging, storing, and discharging the energy. Figure 6 shows the cost model for PtG with hydrogen. COSE_Thermal is a simplification of the levelized cost of energy (LCOE) and leveled cost of storage (LCOS) (Schmidt, Oliver; Melchior, Sylvian; Hawkes, Adam; Staffell, 2019). LCOE is a result of the cost of input energy and the cost of storage. Due to time restriction and the uncertainty related to this cost, we have excluded the input energy cost. Therefore, we only focus on the cost of stored energy (COSE) in this research. We have used COSE_Thermal to normalize the cost of heat provided and not just the energy output from the storage. COSE_Thermal = Total lifetime cost/Total retrieved heat energy.

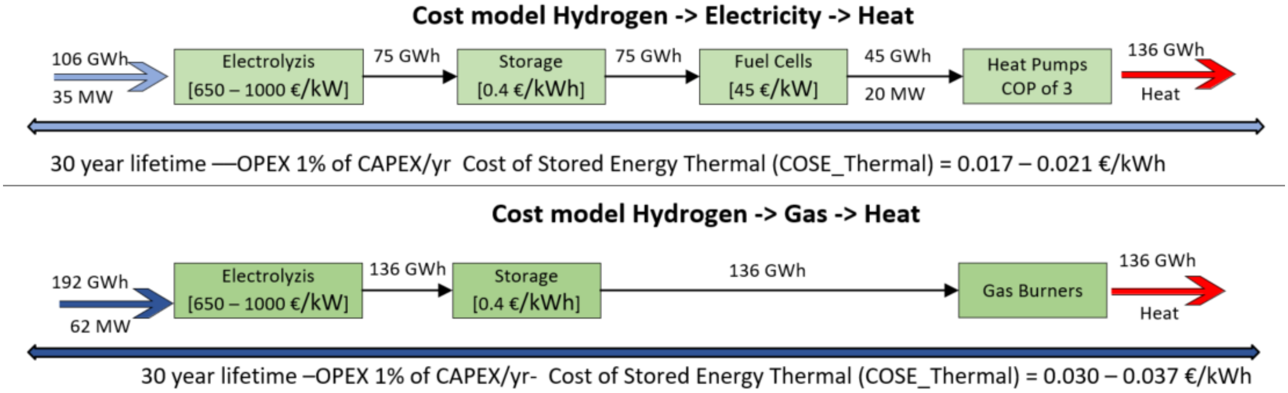

Figure 6: PtG cost models for hydrogen

Each model includes conceptual models showing the distribution and transport opportunities, like Figure 7. We have included technical specifications, required solar PV or solar thermal area calculations, and power plant size estimates.

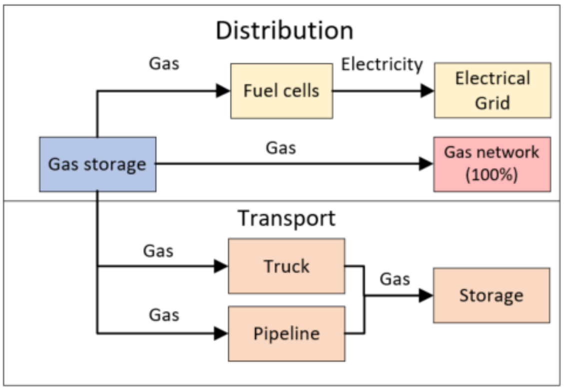

Figure 7: PtG distribution and transport model

When we put numbers in all these models, then we get Table 4. Most of these numbers are coarse estimates or a snapshot of 2019 costs. This table shows how the models come together. However, given the coarseness and uncertainty of the ingoing data, we should not use the current table or any conclusion.

Table 1: Key numbers for each technology

Technol-ogy	RTE [%]	Area [m^2]	E_{Stored} [GWh]	V [10^6*m^3]	CAPEX-P [M€]	CAPEX -S [M€]	OPEX [M€]	COSE_Thermal [€/kWh]
SWS (Heat)	80	-	170	2	-	78 - 452	-	0.029 – 0.166
LAES (ELEC)	54	4000	70	0.65	10 - 70	4218	42	1.36 – 4.13
PtG [H_2] (Heat)	71	8500	136	0.5	40- 62	54	0.95- 1.16	0.024 – 0.062
PtG [H_2] (ELEC)	43	8500	75	0.3	23- 35	30	0.53- 0.65	0.048 – 0.164
PtG [CH_4] (Heat)	56	8500	136	0.17	62- 94	19	0.81- 1.13	0.026 – 0.036
PtG [CH_4] (ELEC)	34	8500	75	0.09	35 – 52	11	0.45- 0.62	0.014 – 0.020

ELEC = Electricity, RTE = Roundtrip efficiency, E = Energy, V = Volume CAPEX-P = Capital expenditure for power plant, CAPEX-S = Capital expenditure for storage, OPEX = Operational expenditure, COSP = Cost of storage power, COSE_Thermal = Cost of storage energy (Thermal energy delivered to consumer)

Discussion

We have created specific models for each technology for storage volume, plant size, economics, distribution and transport, and required solar panel or thermal collector area. We include key calculations, formulas, and estimates for each conceptual model. Conceptual modes are most useful, when they are complementing calculations and estimates. In the following sections, we will define the purpose of the specific models. We will also provide a discussion around the contribution these models have to the understanding and evaluation of these technologies.

Functional and physical models. We have created the functional and physical models to provide a simplified visualization of the technologies. They provide insight to the inputs, outputs, functions, flow of energy, and required components. Understanding the technologies is crucial when creating relevant and helpful conceptual models. Without the proper understanding of the technologies, the models will become less valuable. Functional and physical models provide in this case a base for the specific models. The specific models will be easier to explain and understand with the insight provided by the functional and physical models.

Storage requirements models. The energy flow models, like Figure 5[2,3,4], show the energy flow from storage to consumers. To determine the required amount of stored energy we must understand what happens with the energy after releasing it. This is one place where the functional and physical models become helpful. As views in the SWS model[2], this technology only provides one option, heat transfer through heat network. This figure, with the other ones, clearly illustrates that the energy need and the losses that occur between energy releasing and consumption is determining the required amount of energy stored.

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[2] https://gaudisite.nl/figures/INCOSE2021figuresDrilen/SensibleWaterStorageConceptualModel.pdf
[3] https://gaudisite.nl/figures/INCOSE2021figuresDrilen/LiquidAirEneryStorageConceptualModel.pdf
[4] https://gaudisite.nl/figures/INCOSE2021figuresDrilen/PowerToGasConceptualModel.pdf

PtG and LAES are not as straight forward as the SWS model. As the functional and physical models show, PtG provides two opportunities for distribution, directly as gas and as electricity. PtG consumed directly as gas has a 100% efficiency as we do not have to re-electrify the gas. When utilizing gas or liquefied air as electricity, the storage medium must be re-electrified. The models show the effect these processes have on the energy flow. The reduction in energy is equal to the inefficiency of the re-electrifying process. The models highlight the effect heat pumps have on such systems. Heat pumps convert one unit of energy to three units worth of heat. This is three times more efficient than heating with gas, making the total efficiency of the process more efficient with electricity consumed through heat pumps. Therefore, the options that look least efficient in fact are the most efficient ones, resulting in a lower storage requirement for energy.

Cost models. The flow of energy is also important in the cost models, like Figure 6[5]. This again shows the value of the functional and physical models. These cost models include the costs of the components related to the technologies. Power requirements are also important in the costs model. We will use the cost models for hydrogen to electricity to heat, as an example.

The energy and the power required to convert this amount of energy to hydrogen in the given period is the input. The price per kW is determining the cost of electrolysis. The required power from the input and the cost of electrolysis per kW does then provide the total cost for electrolysis. The output from the electrolysis is the required amount of energy to be stored, which also is the input for the storage. The cost of storage is based on the cost of storing the storage medium (cost per kWh), hydrogen in this case. The energy we release from the storage will then become the input for the fuel cells. We determine the cost of fuel cells in cost per kW. Because of this, we cannot use the energy input to determine fuel cell costs. We must use the power output. At the bottom of each model, we have included the normalized cost of stored energy, using the expected lifetime of the technologies. We have not included the costs related to energy distribution (heat pumps, gas burners, and heat network) as the focus is solely on the cost of storage (from energy input up to distribution) in this research.

The main purpose with these models is to show how the cost of storage is related to the flow of energy and required power. We can also see the correlation between the cost models and the storage requirement models. Changes in storage requirement models will have a direct impact on the cost models. It is therefore beneficial to use these together when trying to understand and communicate key finding from the cost models.

Transport and distribution models. These models, like Figure 7[6] are simple block diagrams. The distribution part of these models is identical to the last part of the physical models. We have created these models to provide a simple overview of the opportunities each technology offers. These models are valuable since transport and distribution are two important considerations in the evaluation of storage technologies. These models give us the opportunity to make easy comparisons. This is beneficial when evaluating and communicating.

Solar panel/collector models. For a technology to be realistic we must know if it can generate enough energy, in the limited areas around Best. SWS collects energy through solar thermal collectors. PtG and LAES generate energy through solar panels. We created a general model, similar to Figure 4[7], for all technologies to provide insight to this element. This model will be the same for each technology, only the numbers will vary. Therefore, we have created a table that provides insight. This allows for easy comparison.

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[5] https://gaudisite.nl/figures/INCOSE2021figuresDrilen/CostModels.pdf
[6] https://gaudisite.nl/figures/INCOSE2021figuresDrilen/DistributionAndTransportModels.pdf
[7] https://gaudisite.nl/figures/INCOSE2021figuresDrilen/SolarPanelCollectorRequirementModel.pdf

Key findings. When comparing the technologies using these conceptual models, we discovered a number of key findings. Using these findings will provide a base for us to conclude which technology looks most promising. Eventually, we may conclude which technology is most promising for Best.

Looking at the cost models, we can easily see which options have the lowest COSE_Thermal. This is a good indication what option looks economic. However more important than the numbers is the understanding why the COSE_Thermal varies this much. From these models, we can see that the option (methane to electricity) with the most process steps and costly elements has the lowest COSE_Thermal. To be able to understand this we must look at the energy flow and power requirements together with the costs. This is what the cost models provide.

If we look at just the energy flow and power requirement, SWS and LAES look like the most realistic storage options. They are the most efficient technologies, which is a key factor for energy storage. If we include the cost per kWh for implementing liquid air storage or water tanks, we get another impression. Compared to the PtG options these costs are so much higher that the benefit from better efficiency does not weigh up for the costs. We can also provide another example looking at the PtG options. Hydrogen consumed as gas seems like the cheapest option when looking at just the costs. This is because it has just two costly elements. Compared to methane as electricity that has four costly elements, it may feel intuitive that hydrogen as gas is cheaper. This is the opposite of what the COSE_Thermal says. When we include the energy flow and power requirements, we can see that the combination gives us the understanding needed.

The main reason the electricity models have the lowest COSE_Thermal is the utilization of heat pumps. Until now, we have discussed the storage efficiency in the key findings section. This excludes the distribution of the released energy, including heat pumps. The options with heat pumps have the lowest COSE_Thermal because heat pumps increase the total efficiencies of these energy systems.

A finding that we must highlight is the impact heat pumps have in an energy system like this. As we discussed, heat pumps increase the total efficiency of the whole energy system. Higher total efficiency is beneficial for every aspect in energy storage. It strongly contributes to make a storage system more feasible. This highlights the importance of including the distribution of energy when looking into energy storages. This research has shown us that the way we distribute the stored energy is a decisive part of the analysis.

Comparison of technologies. Conceptual models are the observable results of the research. These models contribute to the understanding and provide insight of the technologies. In the case of evaluating storage technologies, these models must have one more purposes. They are key to the comparison of technologies based on how they answer to Best's needs, requirements, and challenges. Therefore, we can say that how the models, with their key findings, contribute to make the comparison of technologies more understandable and efficient is a key factor. In the following section, we will make a simplified comparison of the technologies. We base this comparison on the key finding and the needs, requirements, and key challenges in Best.

One key challenge in Best is the high building density and limited space around the town. Therefore, we would prefer an efficient technology with high energy density. From the key finding, we can state that PtG and LAES with the utilization of heat pumps are the most efficient options. Looking at the density, we can see that PtG has a higher energy density compared to LAES, with methane having the highest energy density. This highlights the importance of combining conceptual models with data and calculations. If we look at just the models will it seem like LAES will be the most suitable options as it is the most efficient one. When we include the energy density data, we can see that liquid air has a significant lower energy density compared to hydrogen and methane. Therefore, we prefer methane as it has the highest energy density.

The conceptual models we have created make it easy to compare the economical perspectives. The key cost when considering storage technologies is the levelized cost of energy (LCOE). Models that are more detailed would be able to provide the LOCE. In this research, we have a simplified cost of stored energy when consumed as heat (COSE_Thermal). Having LOCE or COSE_Thermal does not change the fact that these models make the comparison simple. We can just look at, in this research, the COSE_Thermal and see which technology that has the lowest cost. The conceptual models make it easier to understand why methane has the lowest COSE_Thermal.

Comparing the distribution and transport options is a simple task. We can look at the model and see that PtG has the most options for distribution and transport. With PtG will we also be able to utilize the existing gas infrastructure for distribution, transport, and storage. SWS is the optimal option if we look at just the required area of solar panels/collectors. Best has the potential to fit in up to about 0.8 km^2 (Muller, 2019) of solar panels/collectors. This means that LAES and PtG with heat pumps also are realistic options.

It is hard to make political and social factors as a part of the conceptual models. Therefore, we must try to use these models to communicate the benefits and disadvantages with each technology. It may be easier for the municipality to initiate a large energy storage if they and the inhabitants understand the technologies better. The inhabitants are the most important stakeholder. Cost is the most crucial factor for the consumers. The option with the lowest cost will therefore be preferable. If we want these models to be more valuable for the inhabitants, we have to include a model that describes today's situation. This will make it easier to compare and understand the impact a potential energy storage will have on the inhabitants.

Conclusion

By analyzing Best and investigating storage technologies, we have identified the following key considerations for the evaluation of seasonal storage in Best: storage efficiency, size, economics, transport and distribution, required solar panel area, and political and social factors. The conceptual models contain simplified visualization of the technologies and the specific models for key considerations. We can see the importance of models with the purpose of providing insight to functionality and physical elements. The insight they provide makes it easier to create and understand the specific models. All models combine to make it easier to analyze and compare the technologies. This contributed to the discovery of the key finding we have discussed.

The key findings make a good base for the comparison of how well the storage technologies answer to the needs, requirements, and key challenges in Best. Key findings from the models provide the most important elements to compare. This makes the comparison more manageable, instead of comparing every element to every need, requirement, and key challenge. The comparison highlighted the importance of supplementing conceptual models with relevant data and calculations. As demonstrated in this paper may the conceptual models themselves provide another impression compared to the conclusion we made when combining them with data and calculations. From the key findings and the comparison in this research, we can see that PtG with methane is the most suitable option for Best.

Future research

In this research, we have used a simplification of the need and made assumptions and simplification for the technologies. We recommend making models that are more detailed. These models should have less simplifications and assumptions. This is to show that conceptual modelling still provides the necessary insight and enable easy comparison, when moving one or several levels up in the model hierarchy. We also recommend investigating whether conceptual modelling can provide the necessary insight of technologies to recommend a combination of technologies. Can we use models to connect two technologies and then see what consequences such combination will have? It would be interesting to investigate how conceptual modelling can contribute to provide a shared understanding of seasonal storage in Best, by communicating various aspect of the matter to various stakeholders, including the inhabitants.

Reflection

At the beginning of the project, I did have a clear plan and I managed to follow this plan to a certain point in the project. The initial research on the storage technologies was not a problem as there is a lot of literature addressing energy storages in general. The research of Best also did not provide many challenges. It was very educational and important that I visited Best myself. I observed the town myself and created my own impression of the challenges and opportunities Best provided. Interviews with the municipality and other relevant persons gave new perspective and provided a lot of knowledge.

The challenges started when I had to connect the inputs from technologies and Best, and in addition look at it from a seasonal storage perspective. Unlike energy storage in general, there is little literature that addresses the challenges, requirements, and costs related to storing a season worth of energy for a long period. This made it challenging to find relevant data and information. I also had to look at the storage from a new perspective that is little addressed. This made it more challenging to create useful conceptual models. It took time to really understand seasonal perspective and what it did to technical performance of the technologies.

One main thing I experienced and learned was the challenge of making something simple, without losing the information and insight to the matter. Simplifying a complex system like an energy storage system demands a lot more understanding and insight, compared to making a “report” that explains the technologies with the use of text and numbers. The value of the conceptual models, when combined with calculations and data, was something that took me some time to understand. The development of a conceptual model is an iterative process, where changes and improvement are made continuously. Creating a model with a time limit is hard as I never felt that the models where complete, making it easy to get stuck in the models.

The steepest part of leaning-curve was at the late stage of the project. At this point, I started to get a better understanding of the technologies and the consequences related to them. With the increasing knowledge came an increasing understanding of what was missing or what I should improve. A learning from this is that with more knowledge, comes more questions. This created a chaotic final stage of the project. As I ended up with many new questions that I had to answer in a short period.

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Biography

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