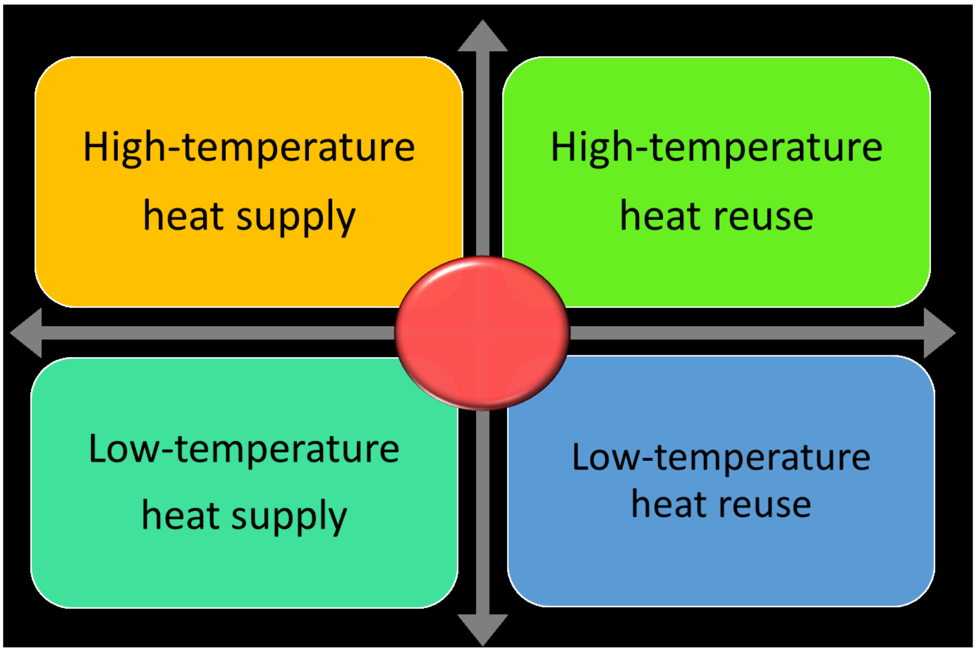
SUSTAINABLE PROCESS HEATING



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Background

SPOT is a part of the Sustainable PrOcess heaTing project. The overall objective of this SPOT project is to increase competitiveness and innovation power for industrial Heat Technology in order to achieve a coherent and consistent program that leads to more sustainable energy use, significantly reducing the use of fossil energy carriers in industry. It is aimed to reduce fossil fuel consumption in industrial heating by at least 100 PJ/year in 2030 and associated CO_2 emission by 6 Mton/year. Recoy is one of the main partners in work package 1 and it's main role lies in determining the opportunities of dynamic operation of heat technology in terms of economic value as well as grid stabilizing option. Recoy considers flexible heat storage technologies as one of the important options to match electricity supply and demand for stabilization and integration in Dutch energy market.

Objective

The objective of this work is to evaluate various combinations of chains of conversion and storage technologies that provide the industry with the most effective way of producing different temperature range of heat that eventually originates from sustainable electricity. A Python tool is built for the assessment of the efficiency and costs for different technology chains. In order to do so, capital investment costs of storage (in terms of €/ kWh energy component and €/ kW power component) and conversion technologies (in terms of €/ kW power component) are collected and validated. The chains are then assessed based on their total investment costs that includes conversion, storage, generation and infrastructure. Five scenarios are considered here where the goal is to be energy-neutral in 2050. They are based on the cases in Berenschot & Kalavasta report. These scenarios assume different industrial demand and they are dependent on energy supply originates from solar, wind and nuclear. Besides the industrial heat demand, there is also an electricity and hydrogen demand in the industry. Since more than 80% of the energy demand of these sectors is for process heating, requiring heat over a broad temperature range, in this report it will be concentrated only on Power-to-Heat chains.

Methodology

There have been one masters thesis and one PDEng thesis on this WP1 from TU Eindhoven where the methodology and the input parameters are given. Therefore, in this report, only the updated CAPEX costs and parameters which are validated further will be given that lead to the final results. Commissioned by the Dutch Ministry of Economic Affairs and Climate Policy, Berenschot & Kalavasta wrote a report about climate-neutral energy scenarios in 2050. Industrial demand and renewable generation in Berenschot & Kalavasta scenarios have been adapted for this study. TNO removed options from the original scenarios that would require CCS by including only technologies that do not emit any CO_2. Four scenarios have been developed here, based on different governance models, ranging from regional to international scenarios. A fifth scenario is added to include 9 GW of constant nuclear power to the European scenario. For the industry, the following assumptions in these scenarios apply:

- Regional control - is characterized by regional governance
- National control - national authorities lead the transition
- European CO2 control - a general CO2 tax is the main driving force to the energy transition
- International control - the transition is driven globally by the stimulation of free trade and trade infrastructures are promoted.

The industry needs heat at different temperature ranges as well as electricity and hydrogen for various types of processes. Demand per scenarios and per processes can be seen in Table 1.

Table 1. Power use in 2050 for five scenarios as estimated by TNO

Energy Demand	Regional control	National control	European CO_2 control	International control	European CO_2 control + nuclear
Heat > 200⁰C, [GW]	3.5	5.2	6.5	7.0	6.5
Heat < 200⁰C, [GW]	5.2	7.3	9.8	9.9	9.8
Electricity, [GW]	0.3	0.6	1.0	1.0	1.0
Hydrogen, [GW]	1.1	2.2	4.2	5.2	4.2
Total, [GW]	10.1	15.3	21.5	23.1	21.5

Main focus in this work is to evaluate Power-to-Heat chains which cover the processes that require heat below and above 200 ⁰C and everything lies in between (for which chemical chains will cover).

This research considers only energy supply technologies without CO2-emissions. Therefore, the supply is provided via onshore/offshore wind power and solar PV. Additionally, 9 GW nuclear energy is added in the fifth scenario as a continuous energy supply over the year.

Table 2. Installed capacities of carbon-free sources for each of the scenarios in 2050

Installed capacities	Regional control	National control	European CO2 control	International control	European CO2 control + nuclear
Installed solar, [GW]	125	106	59	53	59
Installed wind onshore, [GW]	20	20	10	10	10
Installed wind offshore, [GW]	43	72	42	38	42
Installed nuclear, [GW]	0	0	0	0	9
Total, [GW]	188	198	111	101	120

As can be seen from Table 1 and 2, the supply and demand per scenarios is known on GW bases. From the number of running hours, it can be calculated how much renewable electricity is produced by each source annually (in PJ). It is assumed that the industry demand is constant, which is a good approximation for large industries. Then, the total energy supply from the different sustainable sources can be compared with the total industry demand. This gives the scaling factor, which is the fraction of the sustainable generated electricity that is supplied to the industry.

Different Power-to-Heat chains have been created and evaluated in terms of chain efficiency and costs per scenarios. After consultation with TNO, number of technology chains were shortlisted in order to avoid duplications.

In chemical chains, only AEL electrolyser is taken into account in order to convert power to hydrogen. In electrochemical chains, more potentially relevant technologies are mainly concentrated, such as redox flow batteries which is new development, Li-ion batteries for the fastest cost development, NaS batteries which is the traditional solution for grid connected batteries and lead acid batteries. Finally, for processes that require heat below 200 ^{0}C, electric heating is removed as a conversion method since heat pump is already focussed here.

Resulting shortlists of 23 chains:

a. Heat storage <200 ^{0}C: 3 (HP + water/PCM/TCM)
b. Heat storage >200 ^{0}C: 2 (electric heating + rock/molten salt)
c. HP + Battery storage & Mechanical electric storage for <200 ^{0}C: 6 (HP+Li-ion/NaS/Redox/ACAES/LAES/PHP)
d. Electric heating + Battery storage & Mech electric storage for >200 ^{0}C: 6 (EL+Li-ion/NaS/Redox/ACAES/LAES/PHP)
e. Hydrogen storage: 6 (Cavern/Compressed H2/Liquid H2/metal fuel/NH3/LOHC)

Data validation

In order to validate the power and energy component costs of the storage and conversion technologies, different sources such as PNNL, BVES, EASE and HyChain are mainly referenced. As an input to the model, final data has been taken based on the mean value of these sources as shown in the Table 3 and 4. For each technology, Appendix 1 gives the mean storage cost, but also higher and lower bounds to indicate the asset cost range. The cost range has to do with the fact that for ex: if a storage is large, the price per kWh or kW becomes lower than for a smaller storage. Also, within certain storages, different materials can be used. An example of this is sorption storage, where a whole variety of thermo-chemical materials can be used such as zeolite or salt solutions. This causes a cost range for certain technologies.

Some assumptions have been made regarding the CAPEX table 3.

- CAPEX is excluding Engineering, Procurement& Construction (EPC) cost and Grid Integration (GI) cost
- Costs for electrolyser and burner are excluded from cost as they are modelled separately
- Conversion rate 1 US$ = € 0.89
- Source: PNNL, BVES, EASE, HyChain, various

Table 3. Projected investment cost assumptions (Capital Expenditure) for energy storage technologies in 2030

Category	**Long name**	**Short name**	**Power component (€/kW)**	**Energy component (€/kWh)**
Mechanical Storage technologies				
	Pumped Hydropower	PHP	860	65
	Compressed Air Energy Storage	ACAES	902	60
	Liquid Air Energy Storage	LAES	1150	100
Electrochemical Storage technologies				
	Redox Flow Batteries	REDOX	113	409

	Sodium Sulphur Batteries	NA-S	313	414
	Lithium-ion Batteries	LI-ION	69	252
	Lead Acid Batteries	LEAD ACID	113	295
Thermal Storage technologies				
	Thermochemical storage	TC storage	149	78
	Sensible Thermal Storage - molten salt	STS molten salt	106	60
	Sensible Thermal Storage - rock	STS rock	106	35
	Sensible Thermal Storage - Water vessel	STS water vessel	7	5
	Latent Thermal Storage - High Temp.	LTS-HT	255	76
Chemical Storage technologies				
	Pressurised Hydrogen	Pres H2 vessel	45	11,5
	Liquid Hydrogen	Liquified H2	847	4,9
	Metal Fuel	Metal fuel	562	0,16
	Ammonia	NH3	903	0,22
	Liquid Organic Hydrogen Carrier	LOHC	635	0,42
	Salt Cavern Hydrogen Storage	Salt cavern H2	45	0,23

Table 4. Projected investment cost assumptions (Capital Expenditure) for conversion technologies in 2030

	Final data (2030)		
	€/akW	€/lkW	€/hkW
Heat pump	350	200	500
Electrical heating>200	115	30	200
Electrolyser	260	230	280
H2 furnace	10	9	11
Metal burner	200	180	220
NH3 furnace	35	31,5	38,5
Metal reduction	562	505,8	618,2
ASU	289	260,1	317,9
NH3 reactor	569	512,1	625,9
LOHC hydrogenation	320	110	530
LOHC dehydrogenation	270	140	400
Compressor	45	40,5	49,5
Liquefaction	802	721,8	882,2

The CAPEX for energy storage technologies are given in in Figure 1 below where it can be seen whether power component or energy component costs are dominant per storage method. Power component costs (€/kW) are significantly dominant in mechanical and chemical storage technologies and slightly in thermal storage technologies whereas energy component costs (€/kWh) are dominant in battery technologies.

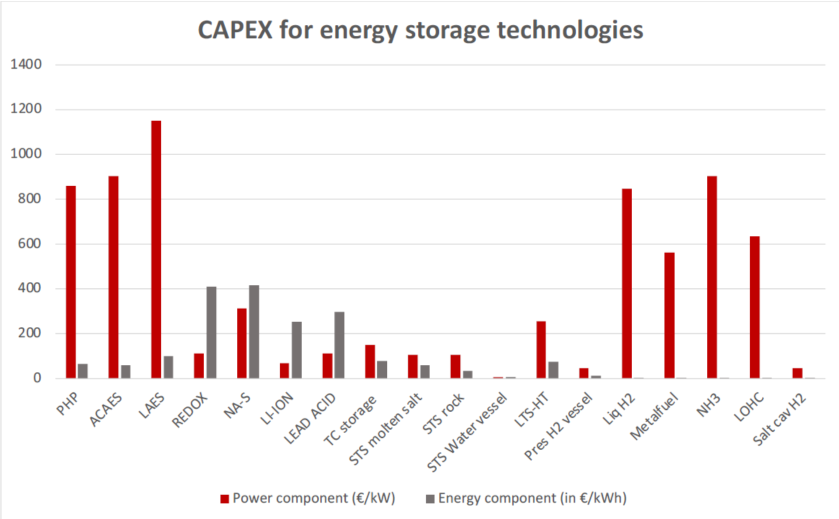


Figure 1. CAPEX for energy storage technologies in 2030

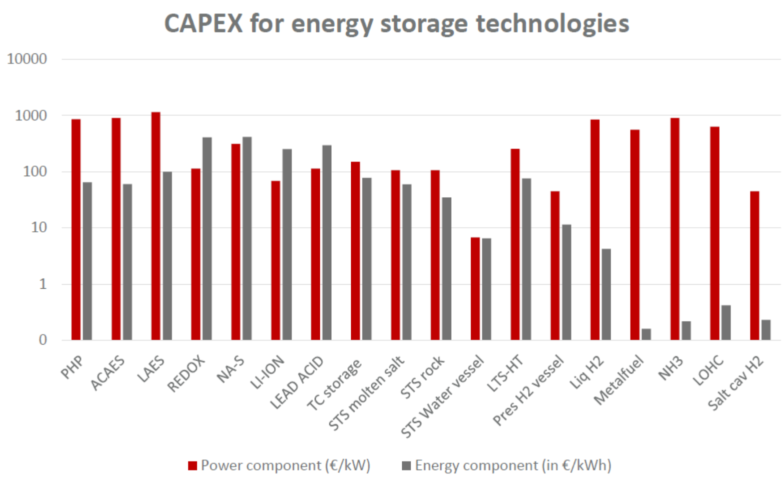


Figure 2. CAPEX for energy storage technologies in 2030 – log scale

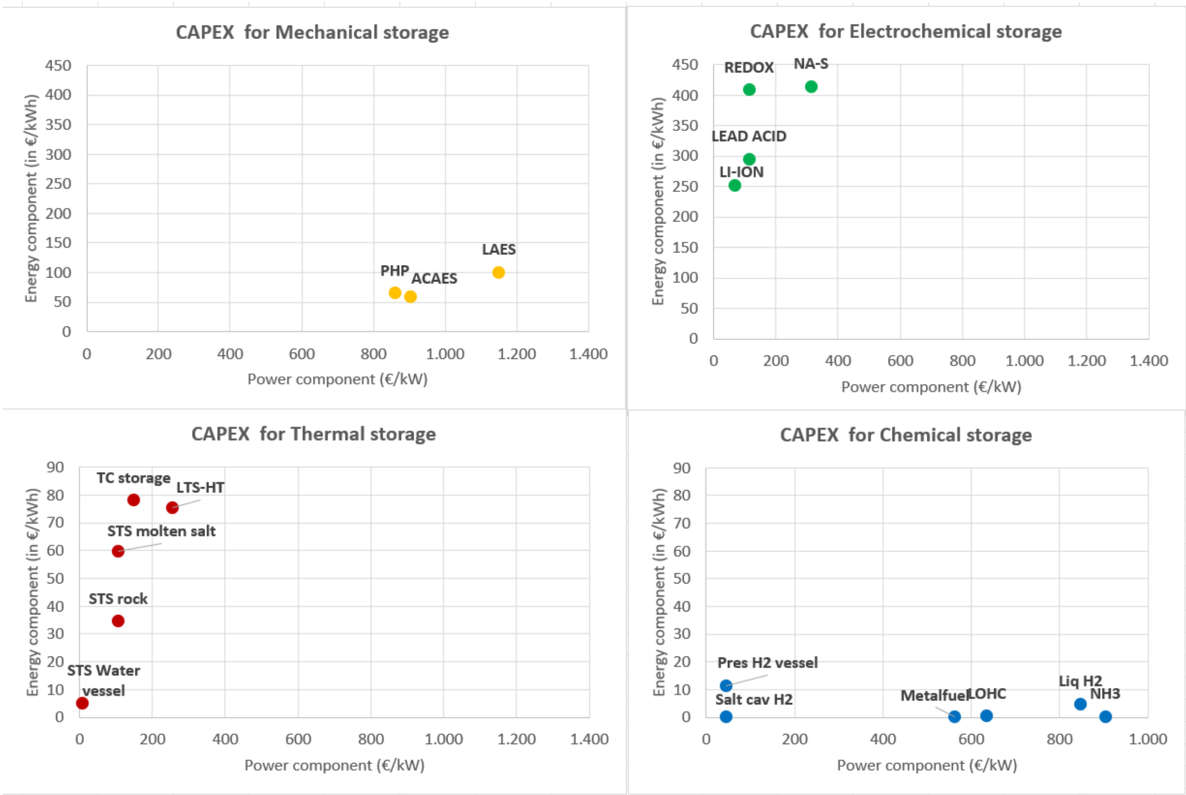


Figure 3. Energy component costs vs power component costs per storage technologies (Scale of X-and Y axis differs per category)

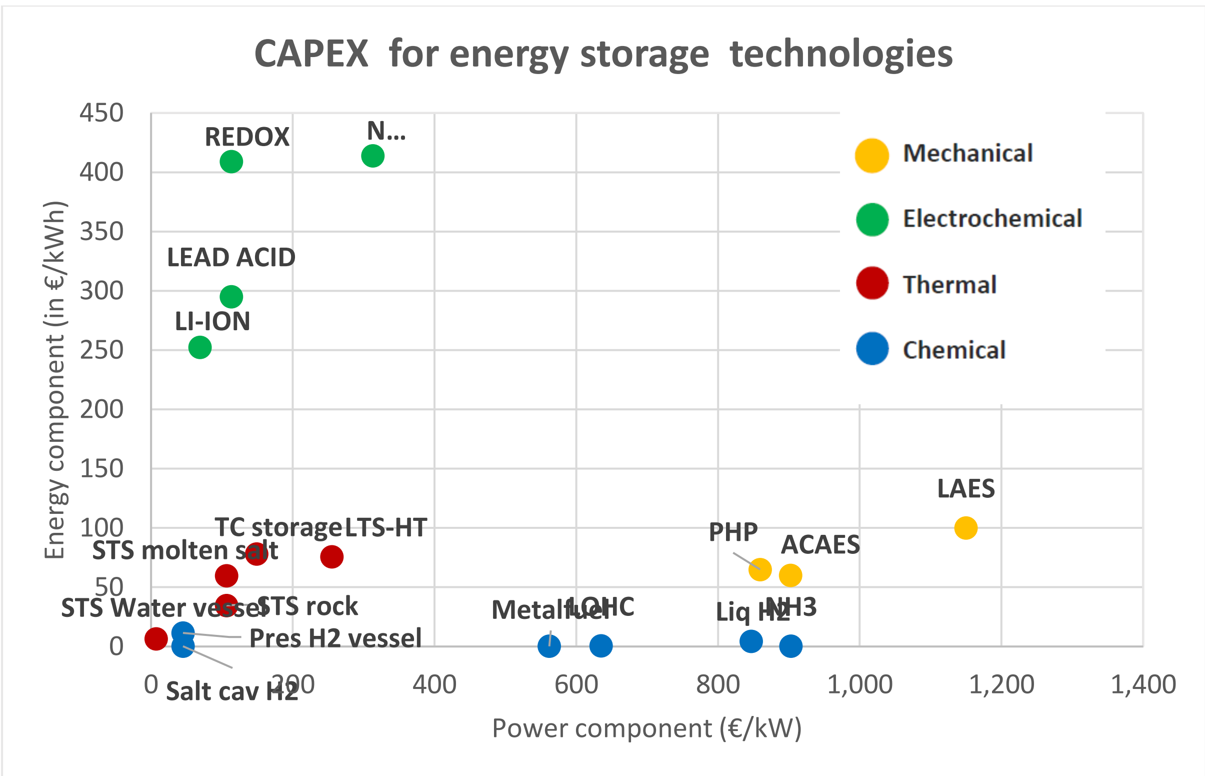


Figure 4. Energy vs power component costs for different storage techniques

The latter figure shows that batteries are expensive in terms of energy component costs and mechanical storage types are the most expensive for their power component costs.

Besides CAPEX costs, there are also other parameters that are used as an input to assess the overall chain performance, such as efficiency, energy density (Wh/l), lifetime and OPEX. Those parameters are shown in Table 5 and 6 and they are the main inputs of the Python model.

Table 5. Key parameters for Mechanical, Electrochemical & Thermal storages

	Efficiency (%)	Energy density (Wh/l)	Lifetime (years)	Capex (€/kW)	Capex €/kWh	Opex (%)
PHP	80	1	50	860	65	2
ACAES	70	4.5	30	902	60	2
LAES	60	135	30	1150	100	2
Redox flow	77.5	25	8	113	298	2
Sodium sulfur	89	200	13	313	414	2
Lithium-ion	92.5	350	10	69	154	2
Lead acid	77.5	65	10	113	208	2
Sorption	92.5	180	10	149	56	2
Molten salt	95	138	20	106	43	2
Rock	98	110	20	106	25	2
Water	70	80	25	7	5	2
Latent	89	95	10	255	54	2

Table 6. Key parameters for Chemical storage technologies

	Efficiency (%)	Energy density (Wh/l)	Lifetime (years)	CAPEX (€/kW)	CAPEX (€/kWh)	OPEX(%)
Pressurised H_2	89	1370	20	45	11.5	3
Liquified H_2	65	2358	20	847	4.9	3
Metal fuel	100	4166	20	562	0.16	3
NH_3	100	3527	20	903	0.22	3
LOHC	90	1700	20	635	0.42	2.5
Salt cavern	95	492	30	45	0.23	2

Results

Investment costs that is required to build Power-to-Heat chains are calculated and given below for the regional scenario. Chains have been categorized for the processes require heat below 200 ^{0}C which are mainly applicable for processes in the food industry and for those chains heat pump is used as conversion method, above 200 ^{0}C where electric heating is the conversion method. The third category of the chains concern chemical chains with which broader range of temperature can be covered and the electricity is first converted to H2 via electrolysis method. In Figure 5, it can be seen how the technology chains are defined for different storage techniques. Figure 5 is a part from the infographic that Recoy have communicated it online via different channels. The full infographic can be seen in Appendix 2.

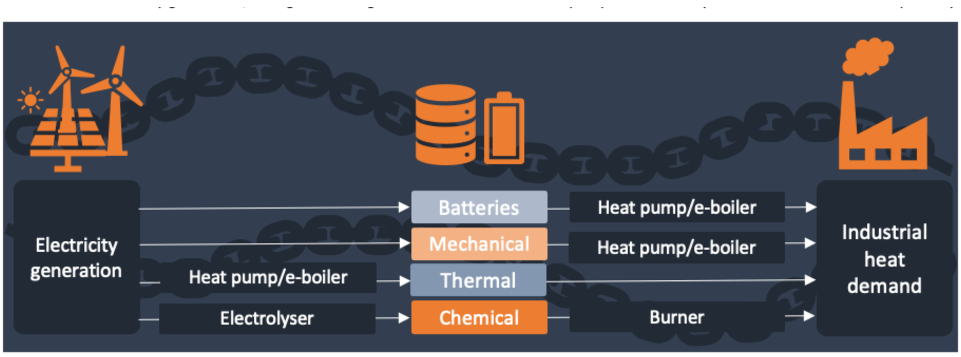


Figure 5. Power-to-Heat technology chains

Below in Figure 6, the investment costs are given per each category for regional scenario. As can be seen, the cheapest chain in <200 ^{0}C category is heat pump with water storage which requires 27 billion € investment cost to meet the demand of regional scenario. Battery technologies are expensive in general and for >200 ^{0}C category, electric heating + rock storage is the cheapest option with 70 billion € investment requirement. For chemical chains, salt cavern seems to be the most favourable with 74 billion € investment costs. It is not fair to compare those three category between one another as their demand is different. The power demand is given in Table 1. For chemical chains, it is assumed that for ex, for regional scenario 8.7 GW (5.2+3.5) is required. By taking the same industrial demand, the chains will be compared with different categories and the results will be given further in this report.

Figure 6. Total investment cost of the technology chains with their cost breakdown

In Figure 6, cost breakdown for each chain can be seen as well. The total costs include conversion, storage, generation and infrastructure costs. For the chains with the combination of heat pump and electric heating, storage costs are dominating in the total cost breakdown. The chains with heat pump + water storage and electric heating + rock storage came out as the cheapest options in their category is because water and rock storages can be simple storages with an inexpensive storage material. Although, infrastructure and power generation costs are low in chains<200 ^{0}C, they are somewhat higher for chains>200 ^{0}C. The reason behind it is mainly because the total efficiency of the chains in combination with heat pumps are higher due to the high COP of the heat pump. Overall chain efficiency figure is given in Appendix 4. For chemical chains, generation costs are dominating due to the low overall chain efficiency. Infrastructure cost will consist of reinforcing the electricity grid to transport the energy to the industry throughout the whole country for the chains below and above 200 ^{0}C. Besides, for chemical chains, it is assumed that electrolysis takes place centrally in wind or solar parks and the generated hydrogen is stored centrally and then transported to the factory via partly new dedicated and partly reimbursed H2 pipelines.

Investment CAPEX that are required for each chain can be seen in Appendix 5 with exact billion € costs. The costs that are in this report are based on the mean costs. However, higher and lower bounds of the costs for each technology is assessed for the year of 2030 (As 2050 is too far to find the correct cost figures) and they are also given in Appendix 6.

As mentioned previously, the same industrial demand is taken to compare low temperature chains vs chemical chains and high temperature chains vs chemical chains as in Figure 7.

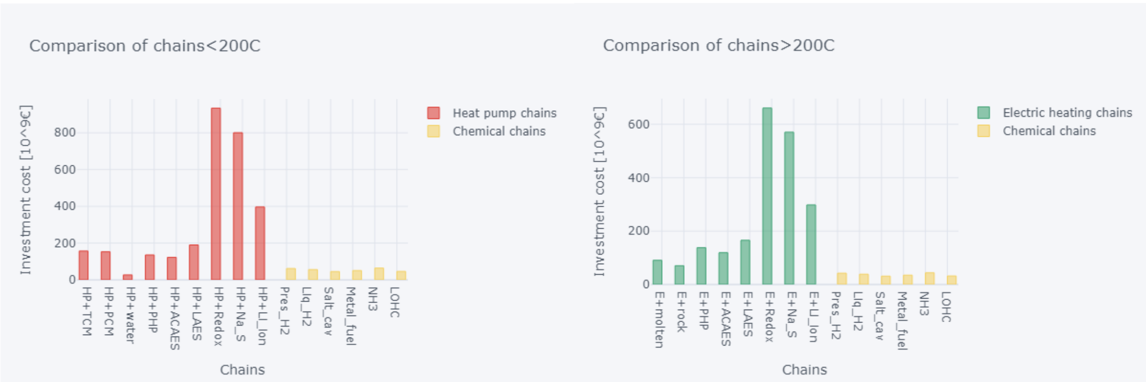


Figure 7. Investment cost of all the technology chains

Heat pump with water storage is the most attractive chain for the processes lower than 200 ^{0}C while Salt cavern H2 storage with electrolyser and burner is the best performing chain for high temperature processes.

Apart from the investment costs, it is also interesting to compare the levelized cost for each technology chain. The levelized cost gives information about the price of heat for different chains. In this research, the chains provide heat, hence the term levelized cost of heat (LCOH). This gives valuable information about each chain since it includes investment costs, operational expenditures, lifetime, and chain efficiency. Figure 8 shows the levelized cost of heat of the technology chains.

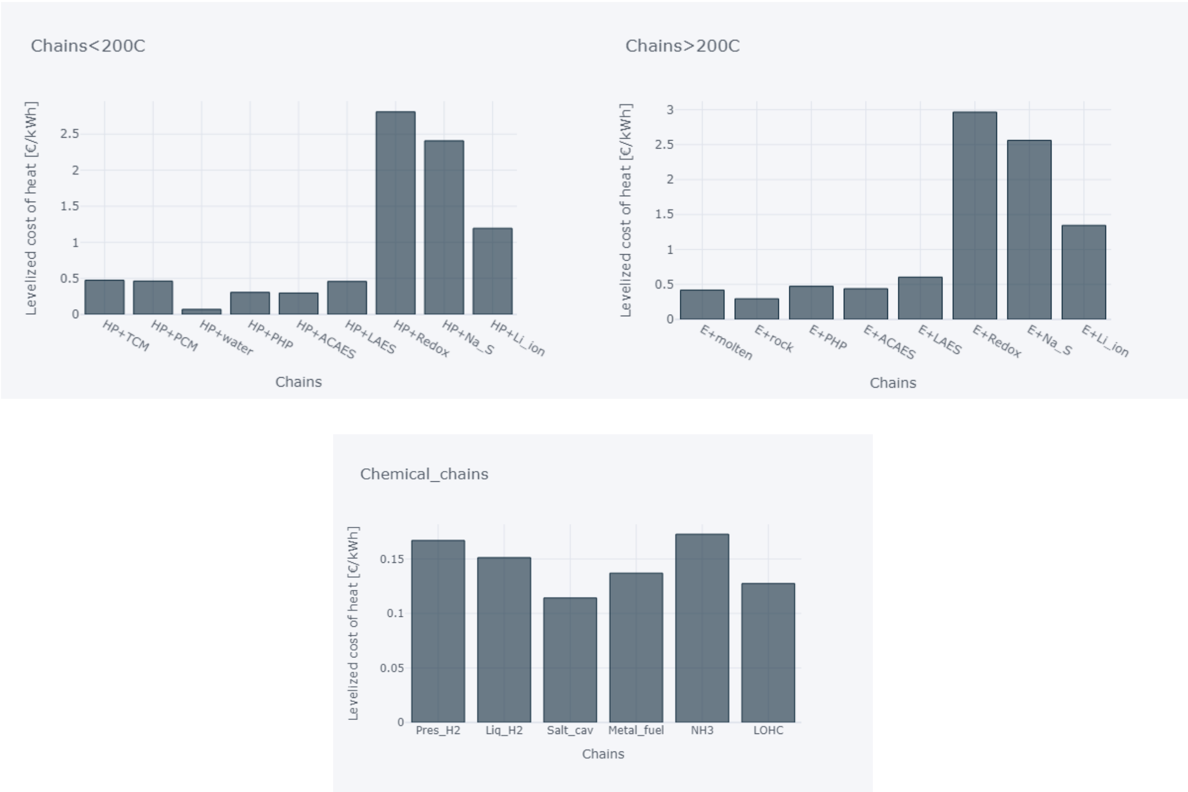


Figure 8. Levelized cost of heat of the technology chains

To compare the values of the LCOH with other heating systems, the price of natural gas can be used. The costs of Dutch gas are assumed to be 0.134 C. For HP + Water chain, the LCOH equals 0.07 €/kWh. With the current gas prices which is affected very largely after the Russian-Ukrainian war, it seems like supplying heat to the industry via sustainable energy supply is much more favourable. In calculating the LCOH, the WACC is assumed to be 8% . If the value of the WACC would be smaller, this also decreases the LCOH. For the chains above 200 ^{0}C, El + Rock has the lowest levelized costs which is 0.29 €/kWh. This is in agreement with Figure 6 that also shows that the total investment costs for this chain are also the lowest. Also, PHP and ACAES show low levelized costs, due to their good lifetimes which can be found in Table 5. For the electrochemical chains, levelized costs are again the highest because of the relatively low lifetimes and high investment costs. LCOH for salt cavern chain is calculated to be 0.114 €/kWh which is again lower than the cost of supplying heat to the industry via the gas combustion.

Based on Berenschot & Kalavasta report, 5 scenarios have been mentioned in the Methodology part which are regional, national, European, international and European + nuclear control scenarios. In Figure 9, CAPEX for the heat pump and chemical chains will be given based on each scenario and the scenarios are numbered accordingly. It gives information about the required investment costs per scenario and cost breakdown of power generation costs per scenarios.

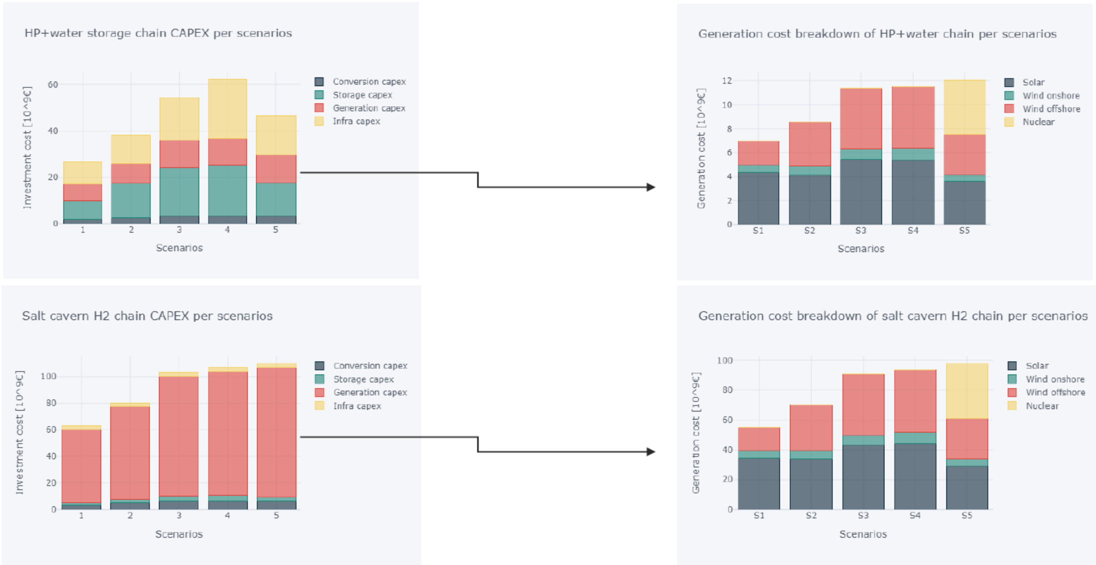


Figure 9. CAPEX and generation cost breakdown per scenarios

Total cost components are conversion costs, storage costs, generation costs and infrastructure costs. For chemical chains, conversion cost includes electrolyser and burner costs. It can be seen that for S1, regional control, the share of solar is more than wind power. Scenario 3 and 5 are comparable with the same annual industrial demand and nuclear addition. For heat pump + water storage, total investment cost for Scenario 5 is lower than scenario 3 which is due to the addition of 9 GW nuclear power plant if the plant is used as a must-run plant. It is interesting to see that for Salt cavern H2 chain, storage cost in scenario 5 (2.73 billion euros) is less than in scenario 3 (3.5 billion euros) even though their industrial demand is the same. This is because nuclear power is present in scenario 5. Since a nuclear power plant produces energy continuously, it guarantees a constant energy supply over the year and decreases the dependency on fluctuating wind and solar energy. Thus, required storage size and storage costs decrease when nuclear power is added as a carbon-free energy source. However, the generation costs then show a slight increase as the price of nuclear power per GW is higher than all other sources.

Curtailment

Another step in analysing the performance of the technology chains is by applying more generation power than necessary with the aim of reducing the required storage capacity. By supplying more energy than required, a part of the energy supply is discarded, which is known as curtailment.
In Figure 10, the first estimate of required storage profiles are demonstrated for every scenario. It is for the processes that cover whole temperature range(100-1500 ^{0}C).

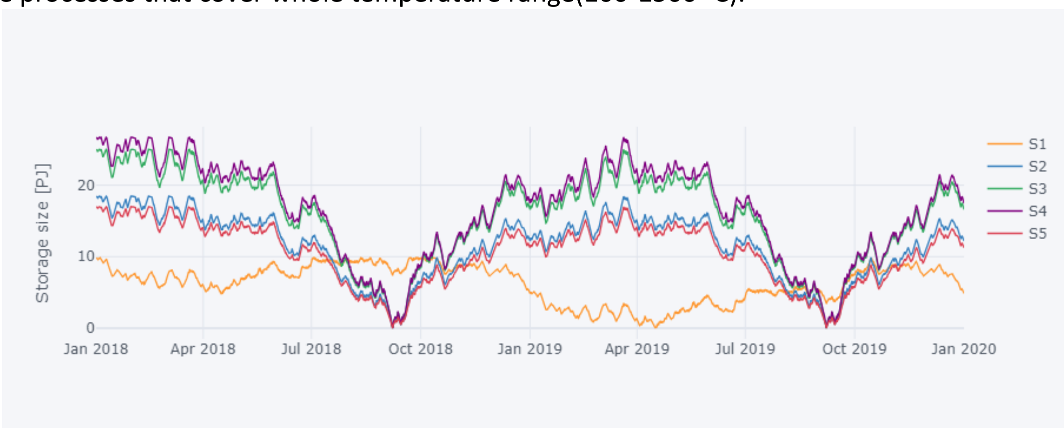


Figure 10. First estimate of required storage

Besides Fig. 10, below at Table 7, the required storage capacity is given in more detail. It can be seen that the required seasonal storage capacity varies from 3.3% – 5.0% of Industrial Heat demand for the first estimate calculations. Later on in order to assess the effect of the overcapacity in all the sustainable sources, different factors are checked. In the original scenario, the overcapacity factor was taken as 1 meaning that there is no overcapacity in the system and the demand and supply are perfectly matched. Later on, overcapacity factor of 1.15, 1.2, 1.3, 1.4 and 1.5 were applied meaning that the share of the renewable supply sources on the industrial heat demand (so-called scaling factor) is increased by 15, 20, 30, 40, 50 %. For the installed capacities, the ratios between the different energy sources are kept the same. Table 7 summarizes also the effect of overcapacity factor 1.15 on the required storage size. It can be seen that the required storage size can be reduced significantly by only applying 15% more generation capacity. The aim here is to find the optimum overcapacity (curtailment) factor where the total investment cost is the lowest.

Table 7. Required seasonal storage capacity

	Industrial heat demand [PJ/year]	Storage size [PJ]		Storage fraction as % of industrial heat demand [%]
Scenarios		Original case	Overcapacity factor = 1.15	Original case
S1 -regional	274	9.84	3.48	3.6
S2 - national	394	18.45	4.43	4.7
S3 - European	514	25	6.43	4.9
S4 - international	532	26.68	7.08	5.0
S5 – European + nuclear	514	16.98	3.10	3.3

Figure 11 shows the storage profile where the system has 15% more generation capacity. It can be seen that the peaks are less here as expected. As the generation capacity increases than required, more sustainable electricity is directly fed to the Power-to-Heat chains and there is less requirement for the storage.

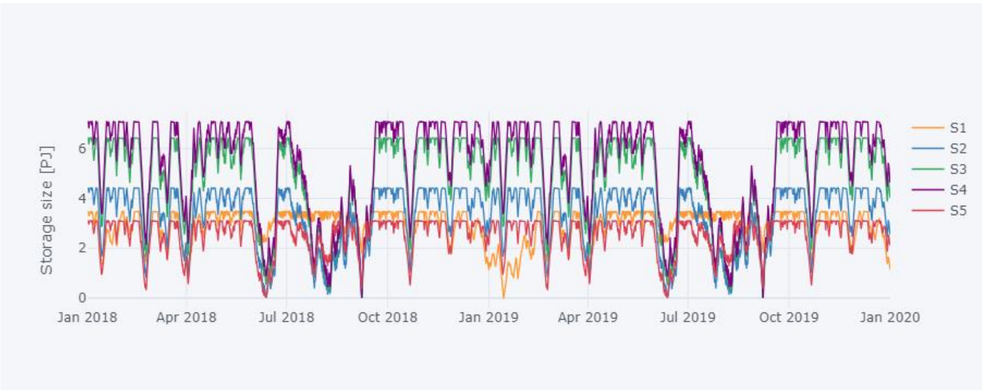


Figure 11. Required storage capacity for overcapacity factor of 1.15

As can be seen from the Figures above, all scenarios show similar patterns, except for scenario 1. In scenario 1, the energy content shows a decline in the first part of the year and starts to increase in the second half of the year. This can be explained with the high installed capacity of solar power (125 GW) in this scenario. Since the year starts from January, there is a low energy supply from solar panels and therefore, supply is less than demand. Halfway the year, energy content increases because of the high availability of solar energy in summer and thus supply is larger than the demand.

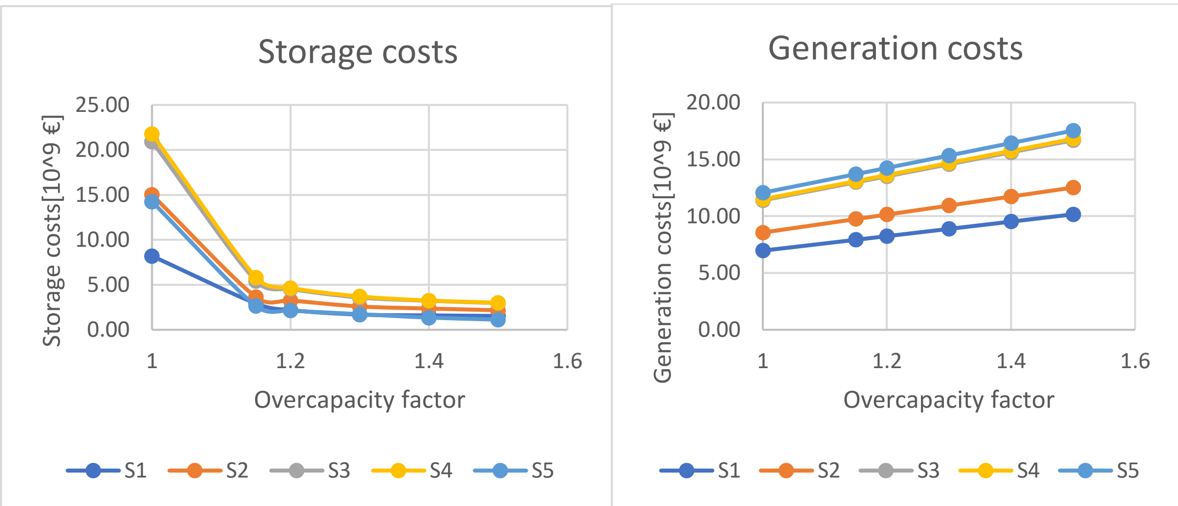
For the other scenarios, the installed capacities differ in such a way that wind power is relatively higher, which is larger in winter. The difference in the installed capacities changes the curvature of the cumulative energy content throughout the year.

One of the basic criteria's for the storage is that it must be large enough to meet the demand during the largest consecutive shortage (cumulative shortage) period. And the overcapacity must be large enough to fill the storage. For all the scenarios except S1, from April to October are the months with low renewable generation. Considering those, the renewable data of 2018 is extended for the next year of 2019 to see the largest peaks in the storage requirement.

Figure 12. Required storage size for 1.15 overcapacity factor for Scenario 1.

Above in Figure 12, it can be seen obviously that January is the month when the storage is needed the most for the first scenario.

The effect of overcapacity factor on storage and power generation costs, thus total investment costs is given in the figures below for the best performing chain of heat pump + water storage for the processes <200 ^{0}C



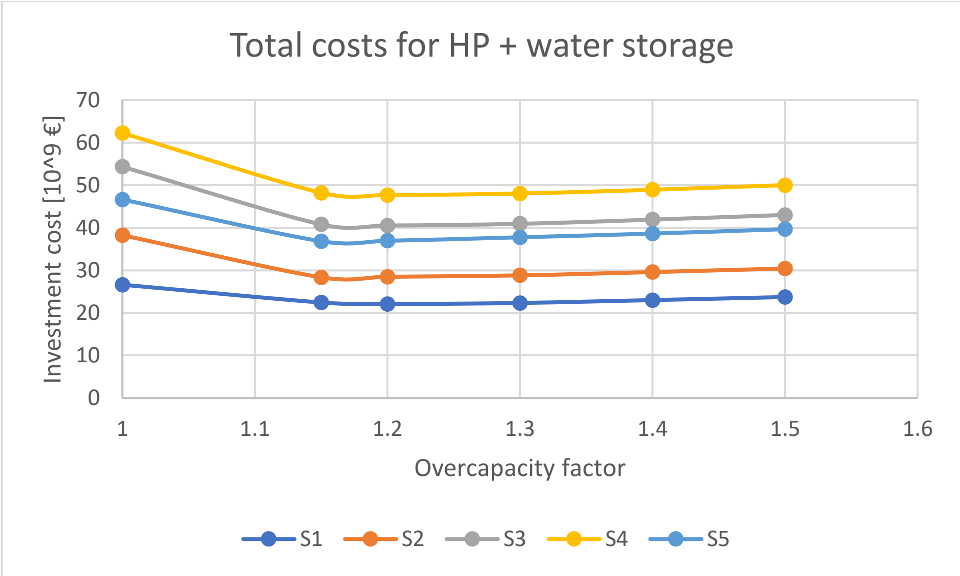


Figure 13. Storage costs (left) as function of curtailment factor for a HP + Water storage chain and Generation costs (right) and total costs (below) for five scenarios

Due to overcapacity in the system, storage size (As shown in Table 7) decreases, thus the storage costs as in Figure 13. Generation costs increase as there is more generation capacity than required in the system. Infrastructure costs is showing very little change similar to generation profile and the conversion costs are assumed not to be affected. Thus, the total investment costs give the indication of optimum factor. In Appendix 7, more detailed information can be found on total investment costs versus varying overcapacity factors. It can be seen that an increase of 11 to 25% of the generation capacity yields the lowest total costs and results in 18-27% decrease in total investment costs.

Below in Figure 14, the results of overcapacity in Salt cavern H2 chain is given as it is selected the best performing chain in the category of the processes that can cover the whole temperature range. There, storage costs go down and generation costs increase with overcapacity factor. Infrastructure and conversion costs perform similar to heat pump + water chain. As a result, the total investment costs increase with increasing overcapacity factor due to the fact that capacity related costs (€/kWh) is very small share of the costs and generation costs are the dominating ones. Thus, it is found that the optimum is at when the overcapacity factor is equal to 1.

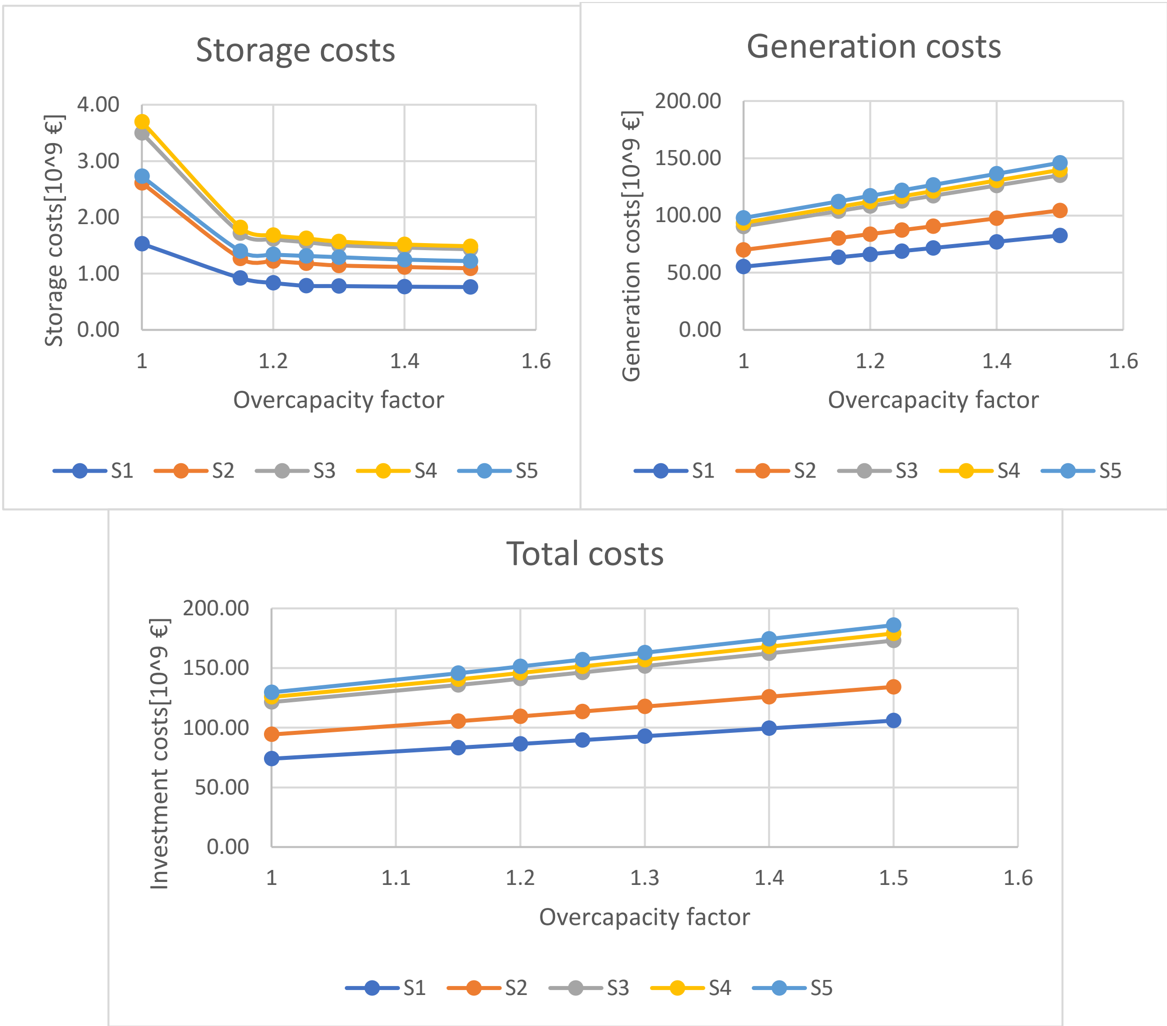


Figure 14. *Storage costs (left) as function of curtailment factor for a Salt cavern H2 chain and Generation costs (right) and total costs (below) for five scenarios*

The similar analysis has been carried out for Electric heating + rock storage chain which is selected as the best performing chain in the category of the industrial processes that require temperature above 200 ^{0}C. Optimum shows a similar trend to HP+ water chain. Here, cost reduction of 23-33% can be reached by installing, again, 11-25% more generation capacity due to the higher percentage of the storage costs on the total costs. The details of this analysis is shown in the Appendix 8.

Appendices

Appendix 1. Data validation sources

		Final data (2030)					
		€/lkW	€/hkW	€/akW	€/lkWh	€/hkWh	€/akWh
PHP	PNNL (2030)	554	1184	869	51	79	65
	BVES (2030)	500	1200	850	-	-	-
	Mean (sources)	527	1192	860	51	79	65
ACAES	PNNL (2030)	781	1129	955	1	9	5
	BVES (2030)	700	1000	850	40	80	60
	Mean (sources)	741	1064	902	40	80	60
LAES	BVES(2030)	900	1400	1150	40	160	100
REDOX	PNNL (2030)	72	155	113	166	430	298
NA-S	PNNL (2030)	231	395	313	267	601	414
LI-ION	PNNL (2030)	40	98	69	116	193	154
LEAD ACID	PNNL (2030)	72	155	113	179	237	208
TC storage (sorption)	BVES (2020)	100	250	175	54	70	62
	Reduction factor	15%	15%	15%	15%	15%	15%
	Cost (2030)	85	213	149	49	63	56
STS molten salt	BVES (2020)	100	150	125	25	70	48
	Reduction factor	15%	15%	15%	15%	15%	15%
	Cost (2030)	85	128	106	23	63	43
STS rock	BVES (2020)	100	150	125	15	40	28
	Reduction factor	15%	15%	15%	15%	15%	15%
	Cost (2030)	85	128	106	14	36	25
STS Water vessel	BVES (2020)	1	15	8	0	10	5
	Reduction factor	15%	15%	15%	15%	15%	15%
	Cost (2030)	1	13	7	0,36	9	5
LTS-HT (NaNO3/KNO3 -60/40%)	BVES (2020)	200	400	300	20	100	60
	Reduction factor	15%	15%	15%	15%	15%	15%
	Cost (2030)	170	340	255	18	90	54

		Final data (2030)					
		€/lkW	€/hkW	€/akW	€/lkWh	€/hkWh	€/akWh
Pres H2 vessel	Electrolyser	Included seperately in the model, so excluded here from cost					
	Burner	Included seperately in the model, so excluded here from cost					
	Compressor	41	50	45			
	Pressure vessel				6,9	16,1	11,5
	Mean (sources)	41	50	45			11,5
Liquified H2	Electrolyser	Included seperately in the model, so excluded here from cost					
	Burner	Included seperately in the model, so excluded here from cost					
	Compressor	41	50	45			
	Cryogenic installation	721	882	802			

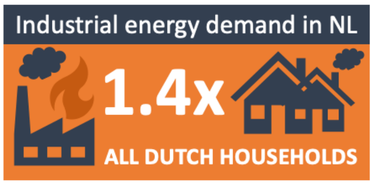
	Cryogenic vessel				4,23	5,5	4,9
	Mean (sources)	762	932	847			4,9
Metal fuel	Electrolyser	Included seperately in the model, so excluded here from cost					
	Burner	Included seperately in the model, so excluded here from cost					
	Reduction furnace	506	618	562			
	Hopper silo						0,16
	Mean (sources)	506	618	562			0,16
NH3	Electrolyer	Included seperately in the model, so excluded here from cost					
	Burner	Included seperately in the model, so excluded here from cost					
	Compressor	41	50	45			
	Chilled atmospheric tank						0,22
	Air Separation Unit	260	318	289			
	Reactor	512	626	569			
	Mean (sources)	813	993	903			0,22
LOHC	Electrolyer	Included seperately in the model, so excluded here from cost					
	Burner	Included seperately in the model, so excluded here from cost					
	Compressor	41	50	45			
	Atmospheric tank						0,42
	Hydrogenation reactor	110	530	320			
	Dehydrogenation reactor	140	400	270			
	Mean (sources)	291	980	635			0,42
Salt cavern	Electrolyer	Included seperately in the model, so excluded here from cost					
	Burner	Included seperately in the model, so excluded here from cost					
	Compressor	41	50	45			
	Salt cavern						0,23
	Mean (sources)	41	50	45			0,23

Appendix 2. Infographic

SPOT PROJECT

SUSTAINABLE PROCESS HEATING

In the SPOT project the costs of power-to-heat supply chains have been researched, that would be able to supply the whole Dutch industry with sustainably generated and stored heat.

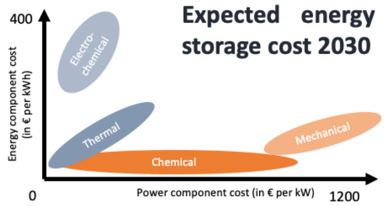


Electrochemical
- Redox
- Na-S
- Li-ion

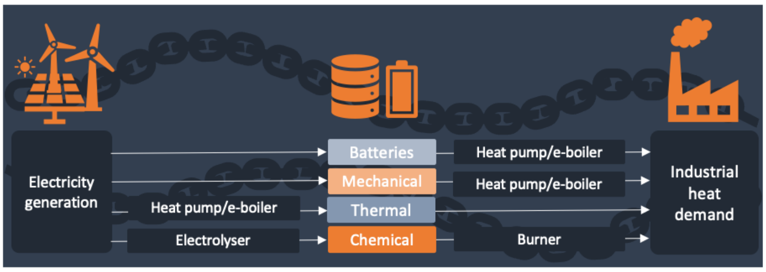
Mechanical
- Pumped hydro PHP
- Compressed air ACAES
- Liquid air LAES

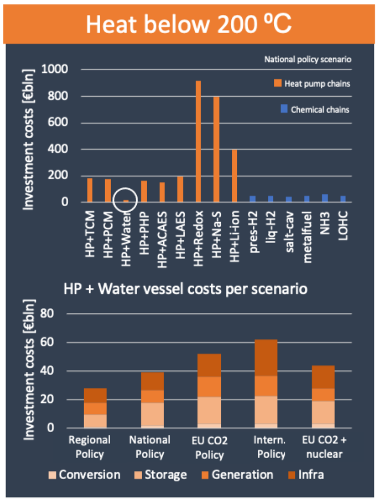
Thermal
- Sorption
- Molten salt
- Water vessel
- Rock
- Latent

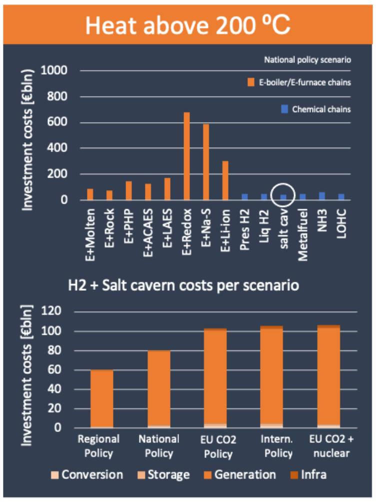
Chemical
- Pressurized H2
- Liquified H2
- Metal fuel
- NH3 & LOHC
- Salt cavern H2



The costs of electricity generation, storage technologies and conversion like heat pumps and electrolysers have been modelled separately.





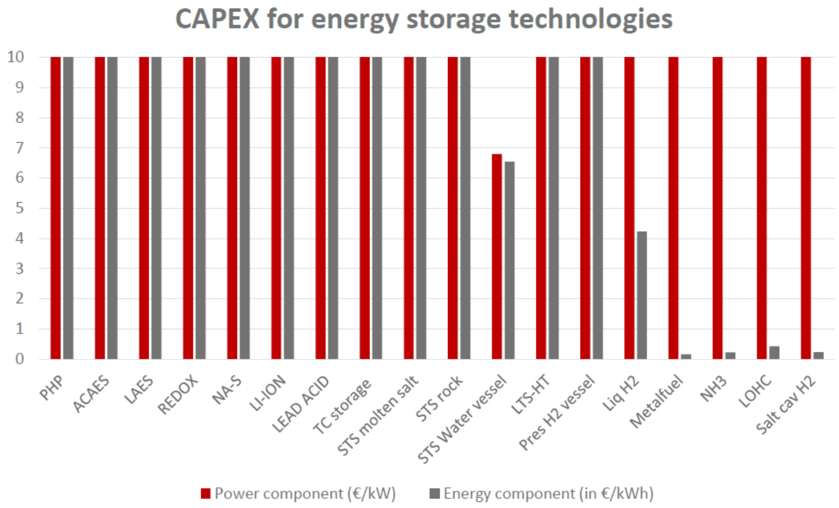


CONCLUSIONS

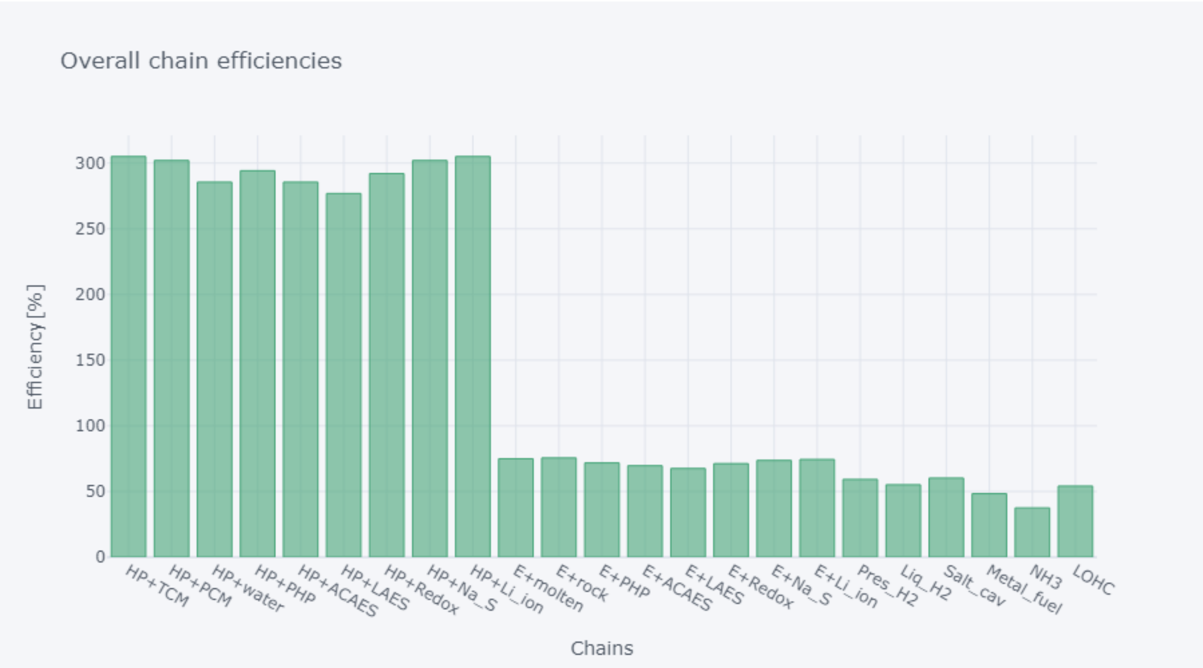
- The power generation mix (ratio solar/wind/nuclear) is an important factor for the amount of energy storage required.
- Long-duration energy storage will be given a place in the chain from generation to 100% sustainable heat production.
- Energy storage costs will become a major contributor to total energy system costs.
- Energy storage in a water vessel with a heat pump is the most attractive option for heat chains below 200 degrees C.
- Energy storage in the form of hydrogen in underground salt caverns in combination with a hydrogen burner is the most attractive option for heat chains above 200 degrees C.
- CO2-free baseload generation such as nuclear energy results in lower requirements for long-duration energy storage and may result in lower overall investment costs depending on chain efficiency. Nuclear energy thus competes with seasonal energy storage, not with renewable energy generation.

The SPOT project has received funding from the Netherlands Enterprise Agency (RVO) (Grant agreement No. TEEI119018)

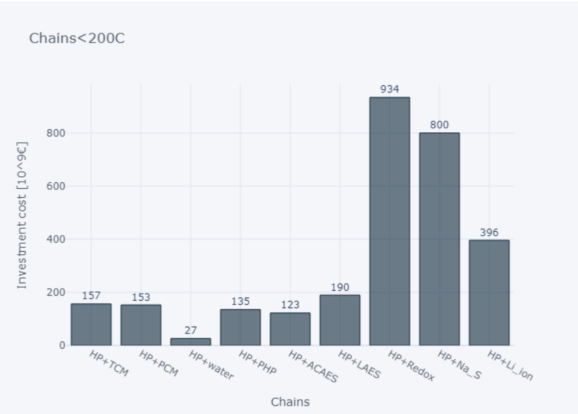
Appendix 3. Projected investment cost assumptions (Capital Expenditure) for energy storage technologies in 2030 (<€10/kWh)

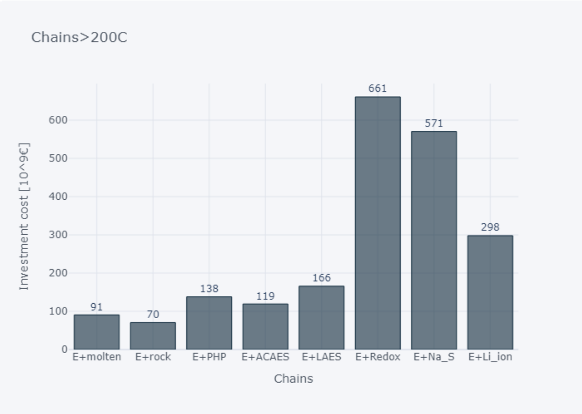


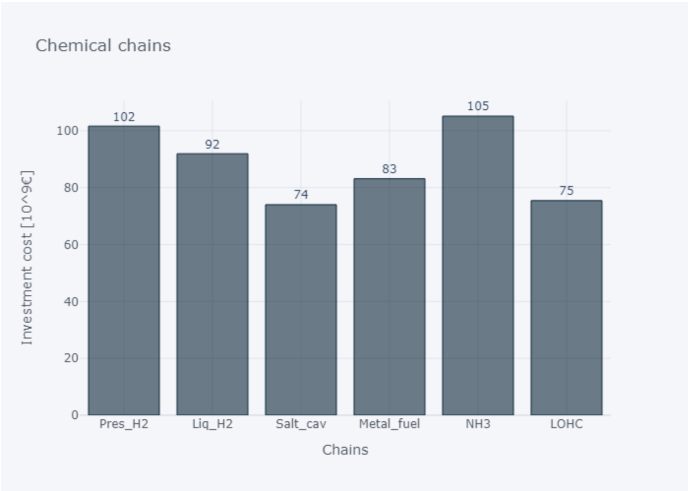
Appendix 4. Overall chain efficiencies



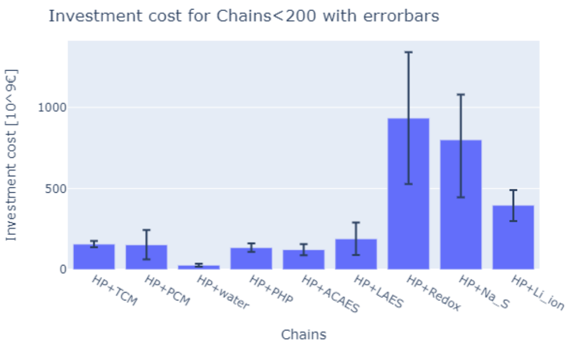
Appendix 5. Total investment cost figures

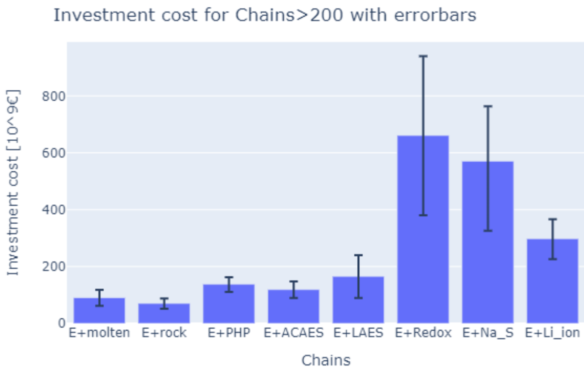


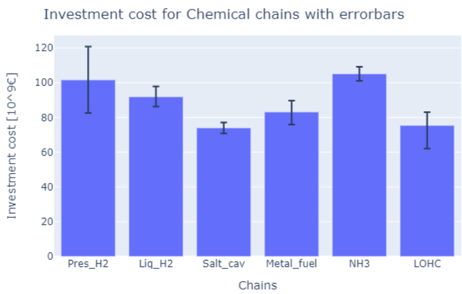




Appendix 6. Investment costs with margin bars







Appendix 7. Total investment costs table vs varying overcapacity factors

HP+water storage													
Overcapacity													
	1	1,1	1,11	1,15	1,16	1,18	1,2	1,25	1,3	1,4	1,5	min	Difference
S1	26,618995	22,862899	22,778641	22,44358	22,360071	22,193488	22,07699	22,005567	22,336267	23,00927	23,71991	22,00557	-17%
S2	38,248434	30,199519	29,83054	28,355933	28,368617	28,425259	28,48239	28,62716	28,816511	29,59502	30,42312	28,35593	-26%
S3	54,327815	43,241357	42,749186	40,782164	40,385245	40,460593	40,53658	40,729558	40,927115	41,9085	43,01202	40,38525	-26%
S4	62,25586	50,705664	50,206916	48,214465	47,71687	47,618058	47,6884	47,867904	48,053519	48,93228	50,02002	47,61806	-24%
S5	46,637512	36,934735	36,81196	36,835348	36,842262	36,856835	36,94208	37,333009	37,761471	38,62979	39,66841	36,81196	-21%

Salt cavern H2							
Total costs	1	1,15	1,2	1,25	1,3	1,4	1,5
S1	74,01	83,21	86,40	89,61	92,88	99,41	105,95
S2	94,31	105,40	109,50	113,60	117,71	125,97	134,23
S3	121,48	135,79	141,04	146,35	151,66	162,34	173,03
S4	125,72	140,49	145,89	151,39	156,88	167,92	178,98
S5	129,62	145,63	151,35	157,11	162,86	174,38	185,92

Electric heating + rock storage											
Total costs	1	1,11	1,15	1,16	1,18	1,2	1,25	1,3	1,4	1,5	Difference
S1	70,47	57,24	55,99	55,67	55,05	54,59	54,18	55,11	57,00	59,00	-23%
S2	110,48	80,00	74,55	74,55	74,65	74,75	75,00	75,41	77,63	80,01	-33%
S3	146,26	107,28	100,53	99,16	99,29	99,42	99,75	100,09	102,68	105,66	-32%
S4	177,88	134,84	127,60	125,80	125,34	125,49	125,85	126,22	128,71	131,90	-30%
S5	123,37	90,49	90,52	90,53	90,54	90,71	91,83	93,06	95,52	98,51	-27%

Appendix 8. Storage costs (left) as function of curtailment factor for a El heating + rock storage chain and Generation costs (right) and total costs (below) for five scenarios