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Centre for an Energy Efficient and Competitive Industry for the Future

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High-temperature TES for industrial processes

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Abstract

Applying Thermal Energy Storage (TES) in the industry is becoming more relevant as the awareness grows and the technology is further developed. Within some temperature ranges and fields of application, the technology is mature (e.g. geothermal storage and hot water accumulation tanks). At higher temperatures, however, further technology development is required, both on component and system integration level.

The main objectives of this task were:

- To identify which HighEFF partners are the best candidates for TES implementation at high temperatures
- To illustrate the potential for TES with a theoretical case study

Several potential applications within the HighEFF consortium are mapped and briefly evaluated. The further need for research is stated, and a case study regarding steam storage is performed.

High-temperature thermal energy storage for industrial processes

A review of potential and applications

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Gerwin Drexler-Schmid, Anton Beck (AIT – Austrian Institute of Technology)

December 2018

Outline

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Relevant industry processes

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Background

Applying **Thermal Energy Storage (TES) in the industry** is becoming more relevant as the awareness grows and the technology is further developed. Within some temperature ranges and fields of application, the technology is mature (e.g. geothermal storage and hot water accumulation tanks). At higher temperatures, however, further technology development is required, both on component and system integration level.

The **request from the HighEFF consortium** has been significant with regards to utilizing excess heat from batch processes with the help pf TES. However, there is no **overview of relevant processes** for the involved partners so far.

The main objectives of this task were:

- ***To identify which HighEFF partners are the best candidates for TES implementation at high temperatures.***
- ***To illustrate the potential for TES with a theoretical case study***

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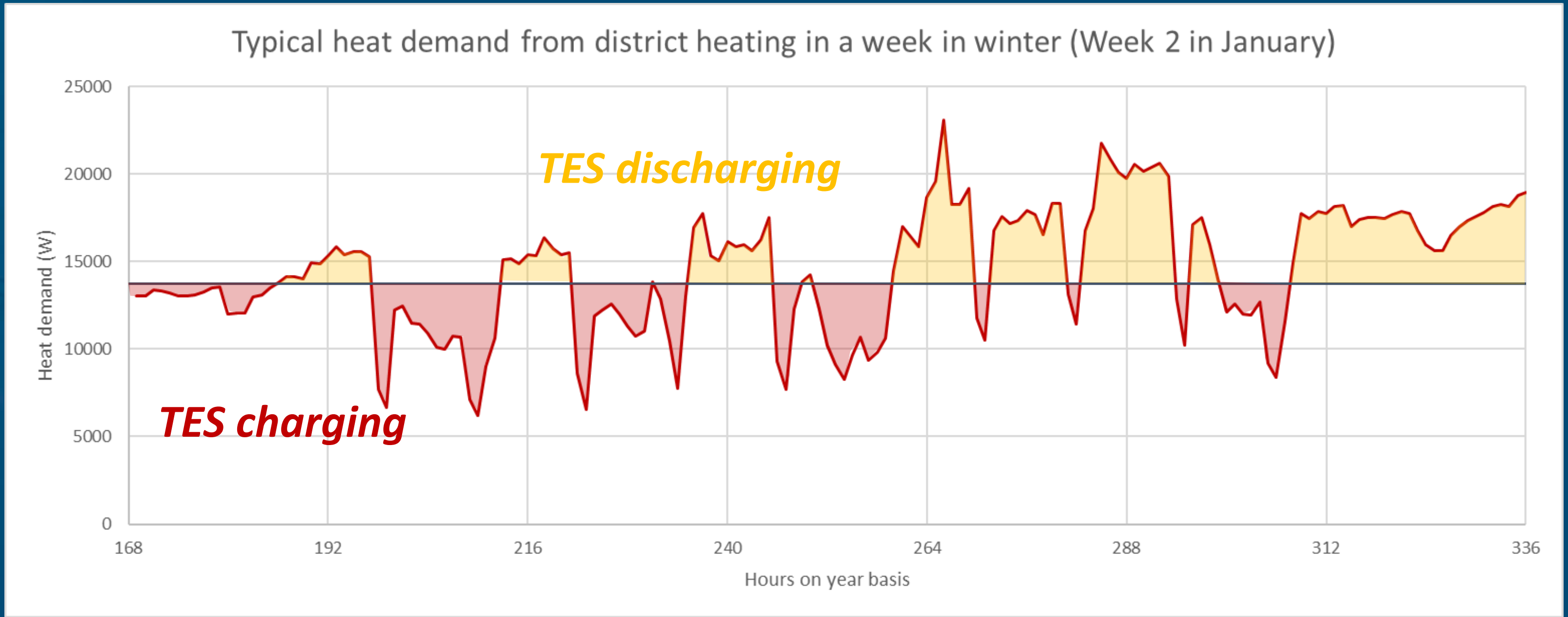
Thermal energy storage

Thermal energy storage

What do we mean by Thermal Energy Storage (TES)?

Needed whenever there is a **temporal mismatch between production and demand of thermal energy**, to store heat or cold during periods of overproduction of heat or electricity, to be able to utilize it at a later point of time.

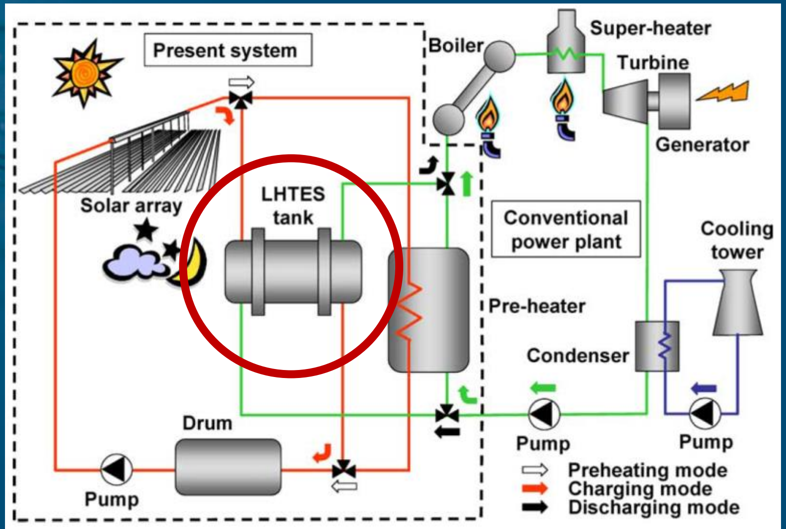
Exemplified below is a district heating network with a base load of 14 kW, and a variable demand. Implementation of an energy storage can avoid peak loads and the requirement for supplementary heating.



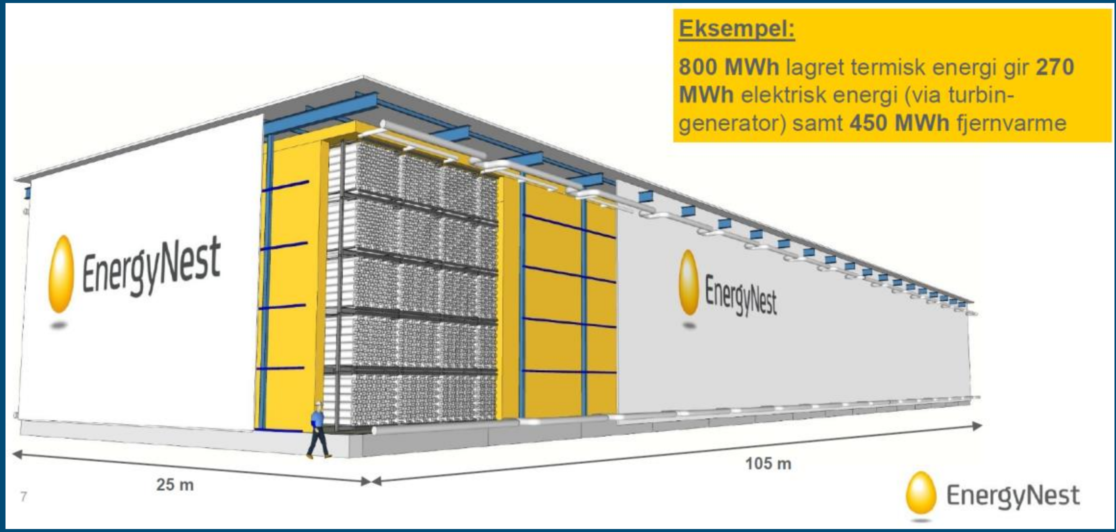
Source: SIP PCM-Eff project, SINTEF Energy Research, 2017.

Thermal energy storage

- Temperature range of interest for the present study: 70 - 300 °C
  - Below 70 °C: more relevant for space heating, TES technologies well proven
  - Over 300 °C: less available excess heat, possible applications for Heat-to-Power
- Technologies: large-scale hot water accumulator, steam accumulator, molten salts, concrete storage, geothermal storage, latent heat storage (LHTES – PCM)
  - Below to the left: LHTES – PCM to avoid peaks in a solar thermal power plant
  - To the right: an illustration of the EnergyNest concrete storage concept.



Source: *A. Hoshi, D.R. Mills, A. Bittar, T.S. Saitoh, Screening of high melting point PCM in solar thermal concentrating technology based on CLFR, Solar Energy, 79 (2005) 332-339*



Source: Høy-temperatur termisk energilager, Greiner Christopher J., Bellona Seminar energilagring, August 2016, EnergyNest

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Relevant industrial processes

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Relevant industrial processes

Requirements for thermal energy storage:

- Availability of non-synchronous excess heat and heat demand
- Heat energy demand at least in same range of magnitude as excess heat energy for one TES charging/discharging cycle
- Heat demand temperature lower than available excess heat temperature, otherwise heat pump required
- Relatively short distance between the excess heat source and heat user

➢ Batch processes are generally ideal candidates for TES

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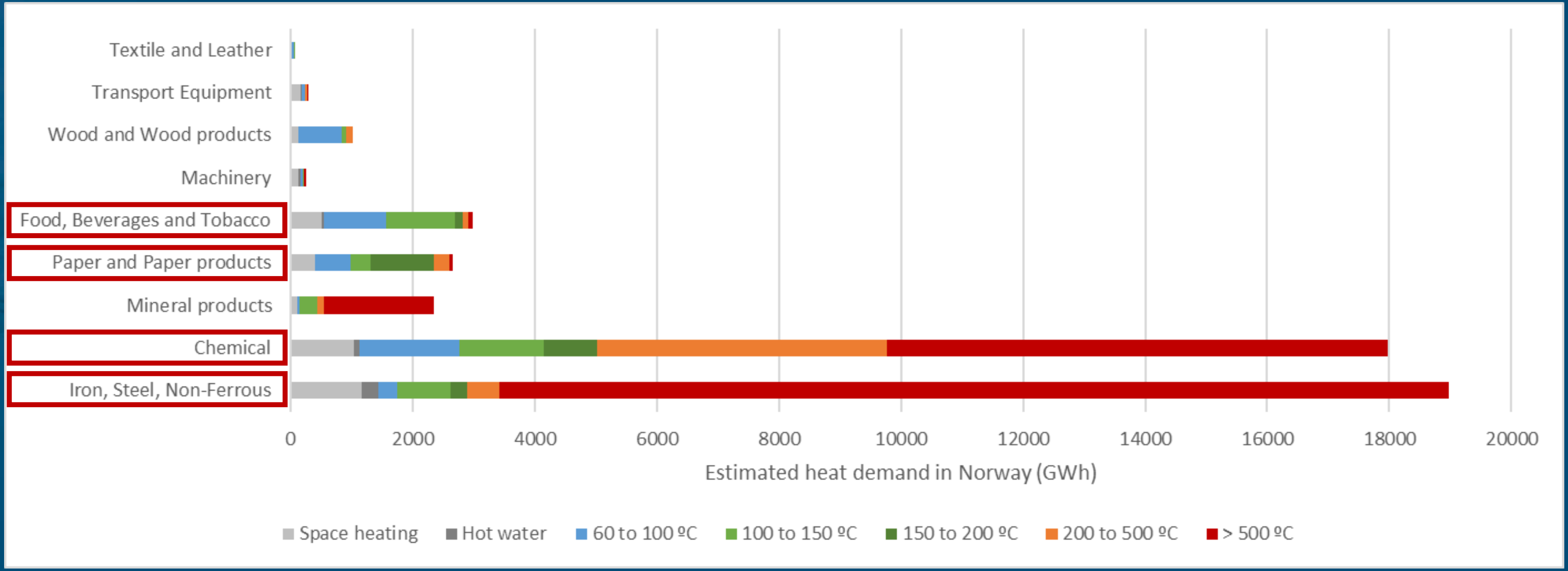
Relevant industrial processes

The graph below shows estimates of the heat demand and temperature levels for the Norwegian industry per sector for 2016. The temperature level considered in study is present mainly in the industries Food and Beverages, Paper, Chemical and Metal industries.

The objective is to identify batch processes within these industry sectors and their temperature levels.



Source: A. Sevault, O. Stavset, M. Bantle, Potential for steam regeneration in Norwegian industry, SINTEF Energy Research report TR A7610, 2017.

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Industry mapping

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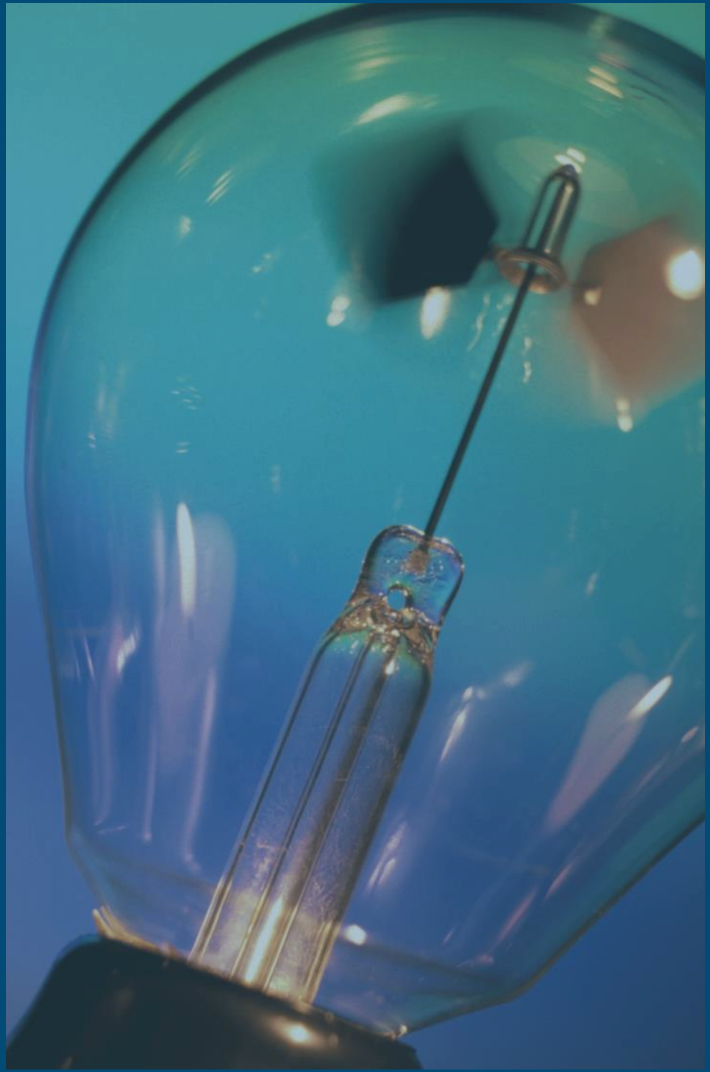
Industry mapping

Objectives:

- Identify relevant processes
- Find similarities across the partners
- Identify research needs
- Plan for future development within in HighEFF



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Alcoa

- Production of aluminum, anodes and cast alloys
- Two relevant batch processes identified:
  - Anode bakery
    - Heating of anodes from room temperature to approx. 1200 °C
    - Heating cycle is 14 days, in several hundred pits at the size of a football field
    - Cooling to room temperature with air before further treatment
    - Heat from the hot anodes is used to heat air for LNG burning and for heat exchange in the exhaust gas cleaning system
  - Casting process
    - Heating of alloys to 700 °C
    - Cooling during casting process to room temperature
    - Water is used as cooling medium

- Assessment of potential:
  - May be challenging to exploit the potential due to large heat source area and long time intervals. It will require technology development to be able to utilize the waste heat from casting. An evaluation of possible heat consumers is also necessary. More details regarding the casting process is necessary.

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Hydro

- Production of aluminum
- Potential applications identified:
  - Store high-temperature heat produced from intermittent renewable electricity to produce steam
    - Day-to-day storage
    - Process temperatures at 150-200°C
    - Delivery of steam at 15 bar of 1000 t/h
  - Heat-to-power from concentrated solar power
    - Day-to-day storage
    - Deliver steam to steam turbine
    - Temperature at 500 °C, 230 MW continuous delivery

- Assessment of potential:
  - The cases have high potential for application of TES. Need further mapping and development of technologies both for storage and for heat generation at high temperatures.

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Eramet

- Production of refined manganese alloys
- Potential applications identified:
  - Store heat from exhaust gas to utilize for heating purposes:
    - Batch process
    - Temperatures over 500°C
    - High amount of dust and contamination in the exhaust gas
    - The exhaust gas is water cooled before filtration

- Assessment of potential:
  - May be difficult to harvest the full potential of the exhaust gas, as the temperatures after the filter is low. However, it may be possible to examine the potential of water cooling in the process.

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Finnfjord

- Production of ferrosilicon
- Potential applications identified:
  - Cooling of metal after casting every 40 minutes
    - Cooling from 1500 °C to under 80 °C
    - Casting in beds with water cooling between each layer
    - After a certain cooling, the metal is piled up for further air cooling
  - Boiler tapping:
    - Water cooling at random time intervals (monthly)
  - Heating demands:
    - 130℃ continuous delivery of heat

- Assessment of potential:
  - High potential if possible to utilize the waste heat from the casting process. Further mapping of potential and technology development is needed.

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Elkem

- Production of silicon
- Potential applications identified:
  - Tapping process:
    - Discontinuous process with exhaust gases approx. every 2 hours
    - Huge amounts of air (v = 100 000 m^3/h) with relatively low temperatures
  - Casting process
    - Discontinuous process
    - High temperatures of up to 1500°C
    - Air cooled

- Assessment of potential:
  - High energetic potential for utilization of waste heat but requires development of concept and technology to exploit the full potential of the cooling during casting. Both processes are air cooled, which is a challenge. Harvesting the heat with water cooling or other means could be evaluated

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Glencore

- Production of nickel, cobalt, copper and sulphuric acid
- Potential applications identified:
  - Several batch processes that operate at 60-80 °C
  - The waste heat from these processes is not utilized today

- Assessment of potential:
  - Uncertain potential, more information on the process is required. Temperature range is possible to cover with existing TES technologies

Borregaard

- Production of biochemicals
- Potential applications identified:
  - Borregaard already has a steam accumulator to stabilize the steam system at the plant. The steam accumulator is used to even out fluctuations between steam supply and demand and replaces the need for oil or electric boilers.
- References:
  - http://www.energi.no/artikler/583-norsk-energi-prosjekterer-akkumulator-ved-borregaard

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Wacker

- Production of silicon
- Potential applications identified:
  - Casting process:
    - Casting of 140 t/day
    - Cooling from 1450 to 25 °C in open beds of 25-75 m^2
    - Ten batches every day on top of the old layer
    - Cooled with large amounts of air at 30-100°C, 25000 Nm^3/h
  - Furnace off-gas:
    - Large volumes of off-gas at 200-250°C

- Assessment of potential:
  - Utilization of the waste heat from cooling during casting can be a large heat source. Development of technology to harvest this heat is necessary. Both processes are air cooled, which is a challenge. Harvesting the heat with water cooling or other means could be evaluated

TripleNine

- Production of fish meal and fish oil
- Potential applications identified:
    - Possible future utilization of intermittent electricity sources for steam generation
    - Will require storage capacity as a buffer between periods with low prices and periods with high consumption

- Assessment of potential:
    - Application that will become more important in the future with increasing introduction of intermittent renewable sources to the electricity grid. Steam accumulator is the state-of-the-art technology for this application (see the case study later in the presentation).

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Rema/Norsk Kylling

- Production of chicken products
- Potential applications identified:
  - Production and storage of heat and steam for poultry processing
  - Input from a heat pump delivering heat during low-peak hours

- Assessment of potential:
  - Steam accumulator is the most relevant technology. High potential for implementation.

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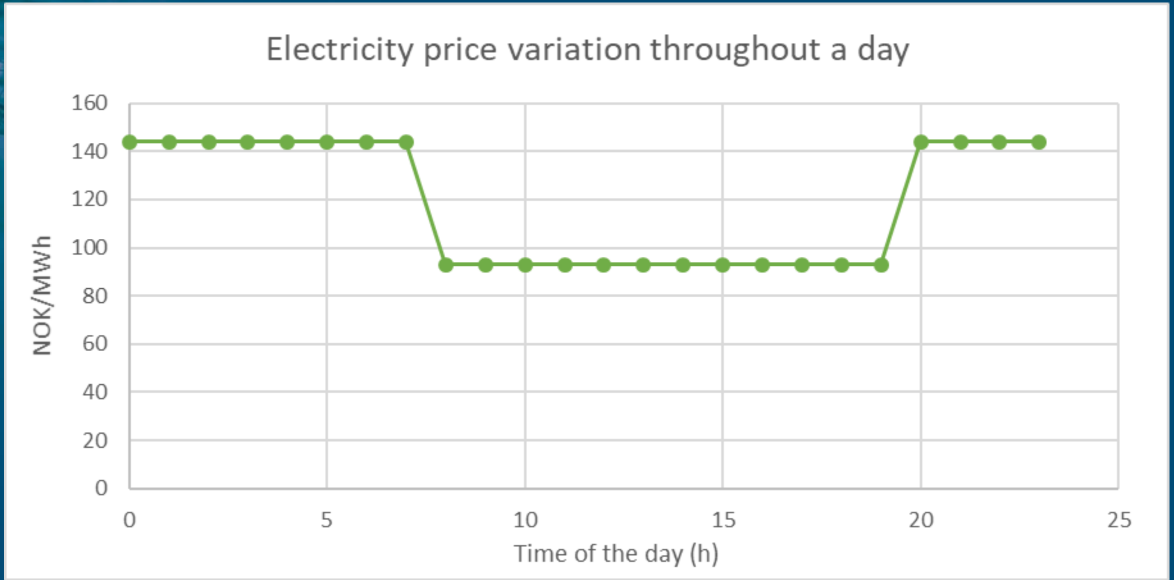
Theoretical case study:

Production of heat and steam from intermittent renewables

Background

- Steam demand at 400 tons/hr and desire to shift from fossil-based steam production to an electric boiler
- Electricity comes mostly from solar photovoltaic production and electricity price is driven by availability (low price during the day, high price during the night)



Proposal:
Implement TES technology to produce more steam during low-price hours and deliver it during high-price hours

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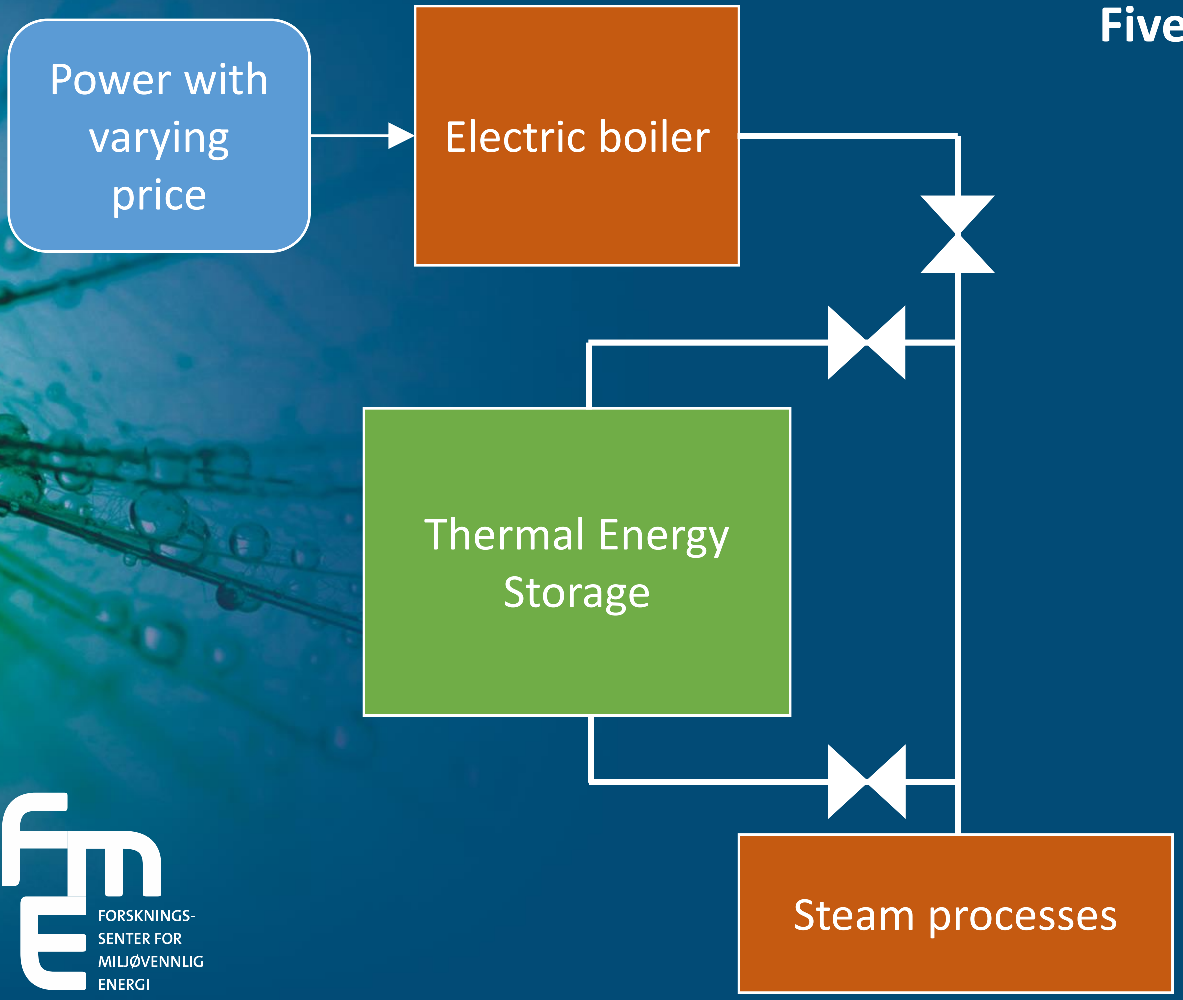
Scenarios for TES implementation



Five scenarios are compared:

1. Business as usual, no TES
2. TES for **25%** of steam demand in high-price hours
3. TES for **50%** of steam demand in high-price hours
4. TES for **75%** of steam demand in high-price hours
5. TES for **100%** of steam demand in high-price hours

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Scenario 3

Business as usual, no TES 1

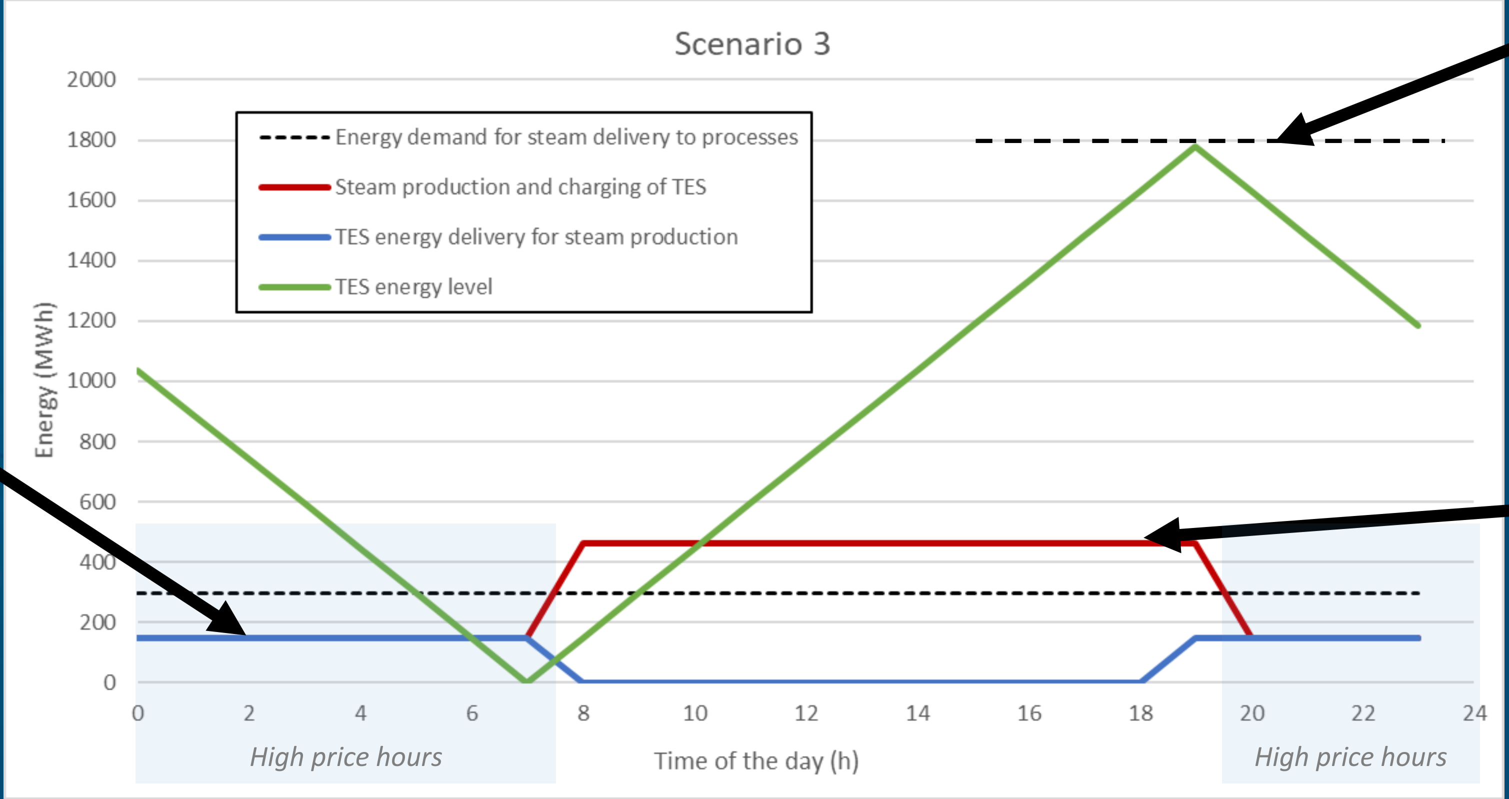
TES for **25%** of steam demand in high-price hours 2

TES for **50%** of steam demand in high-price hours 3

TES for **75%** of steam demand in high-price hours 4

TES for **100%** of steam demand in high-price hours 5

-> Boiler should deliver about 55 % higher steam output compared to Scenario 1 during low price hours, and 50 % of steam demand during high price hours.



Maximum level gives thermal storage capacity of ~1800 MWh

TES and boiler each deliver 50 % steam demand during high-price hours

Boiler delivers 100 % of steam demand and charges TES

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Scenario 5

Business as usual, no TES 1

TES for **25%** of steam demand in high-price hours 2

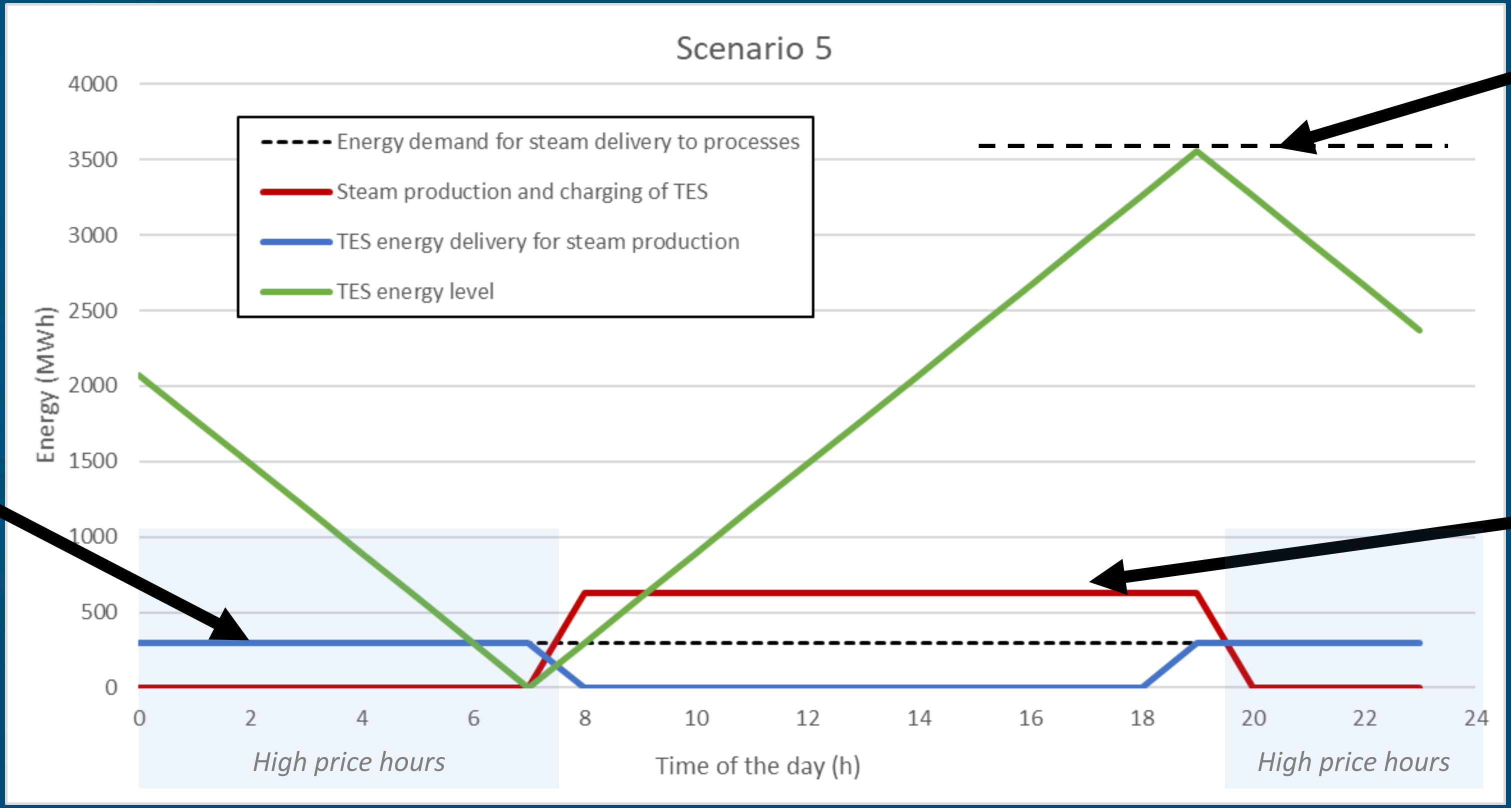
TES for **50%** of steam demand in high-price hours 3

TES for **75%** of steam demand in high-price hours 4

TES for **100%** of steam demand in high-price hours 5

-> Boiler should deliver over twice the steam output compared to Scenario 1, but only during low price hours.

Maximum level gives thermal storage capacity of ~3550 MWh



TES delivers 100 % steam demand during high-price hours

Boiler delivers 100 % of steam demand and charges TES

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Energy diagrams for the four scenarios with TES

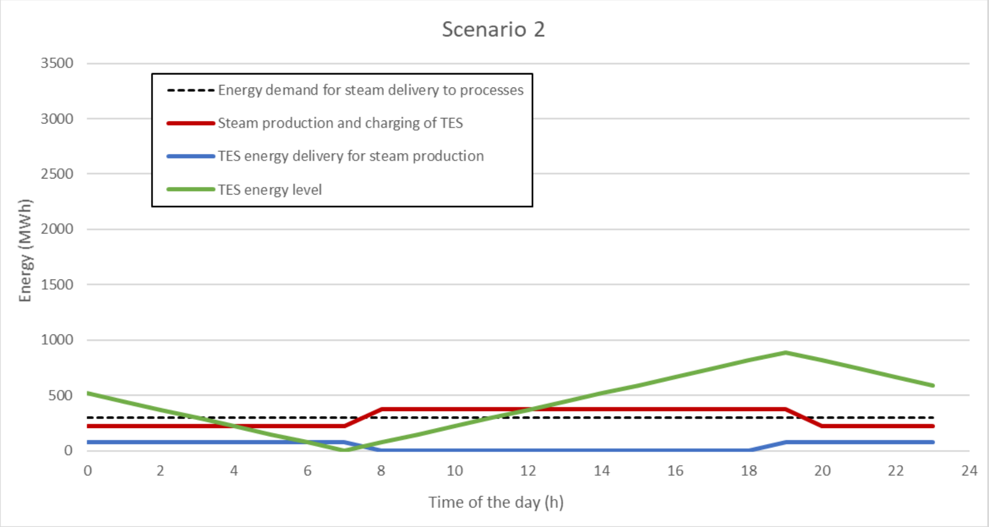
Business as usual, no TES 1

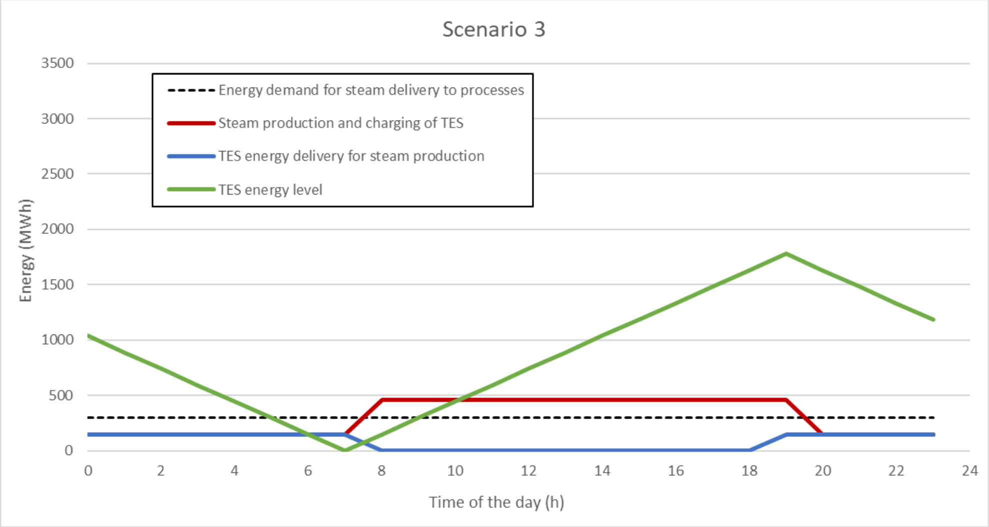
TES for **25%** of steam demand in high-price hours 2

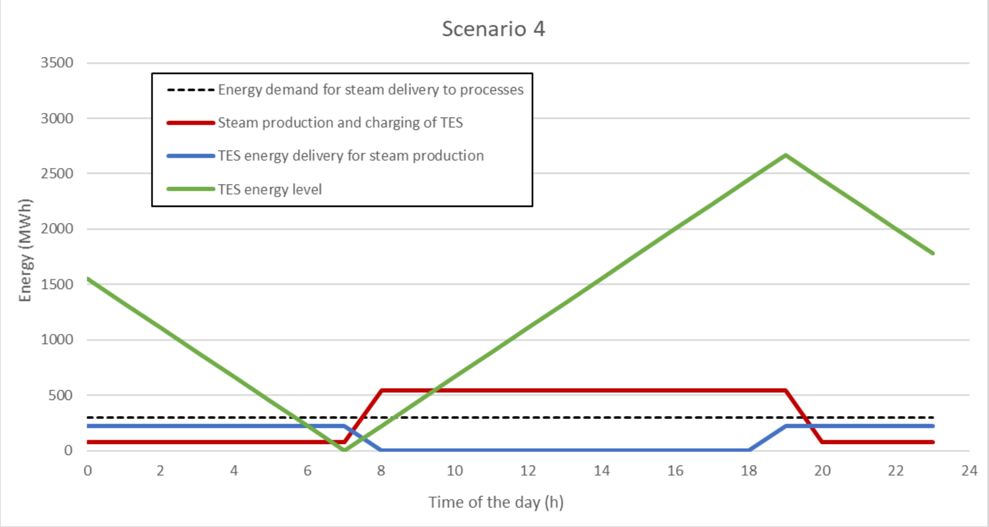
TES for **50%** of steam demand in high-price hours 3

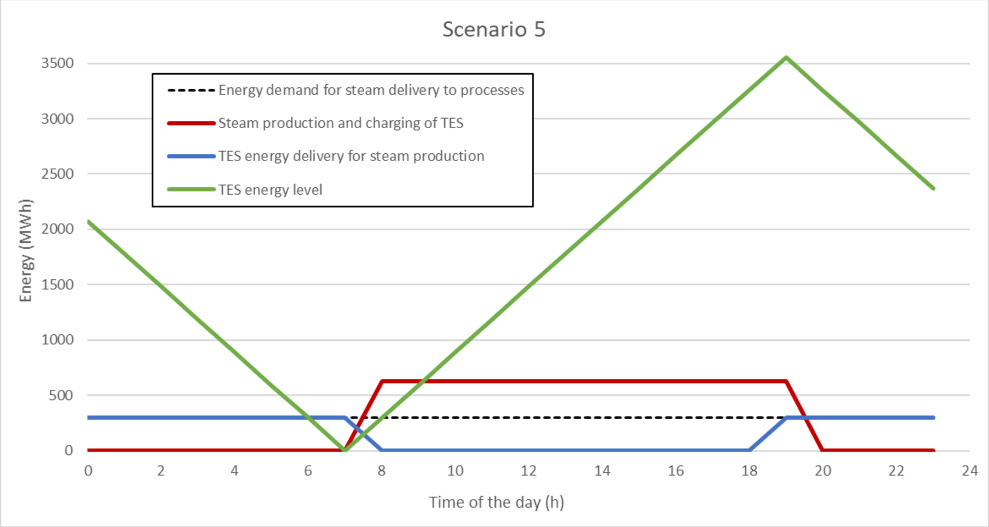
TES for **75%** of steam demand in high-price hours 4

TES for **100%** of steam demand in high-price hours 5









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Resulting heat effect

Input parameters:

Steam delivery	*t/h (200 C, 15 bar)*	400
Overall steam production efficiency of boiler	*%*	90
Thermal efficiency TES system	*%*	90

Results:

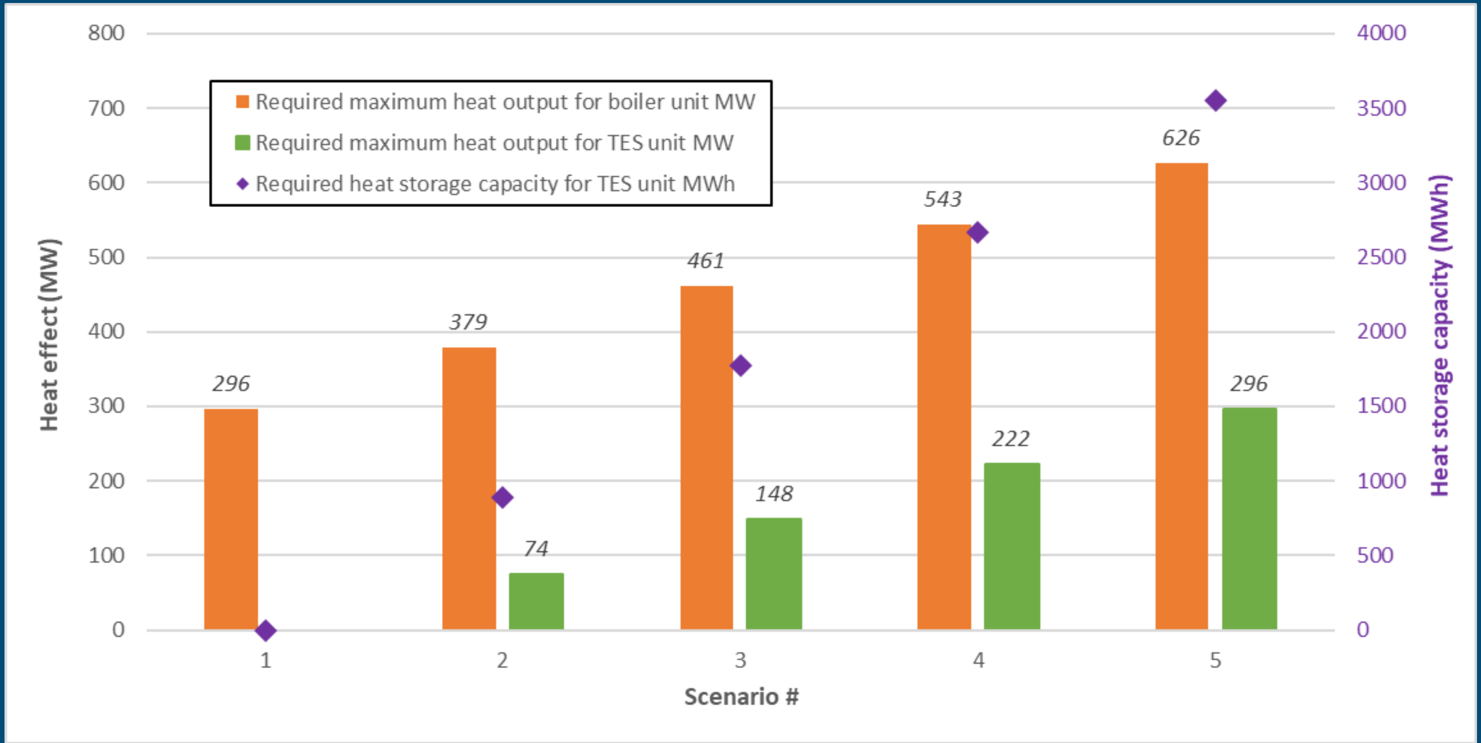
Business as usual, no TES 1

TES for **25%** of steam demand in high-price hours 2

TES for **50%** of steam demand in high-price hours 3

TES for **75%** of steam demand in high-price hours 4

TES for **100%** of steam demand in high-price hours 5



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Immediate savings

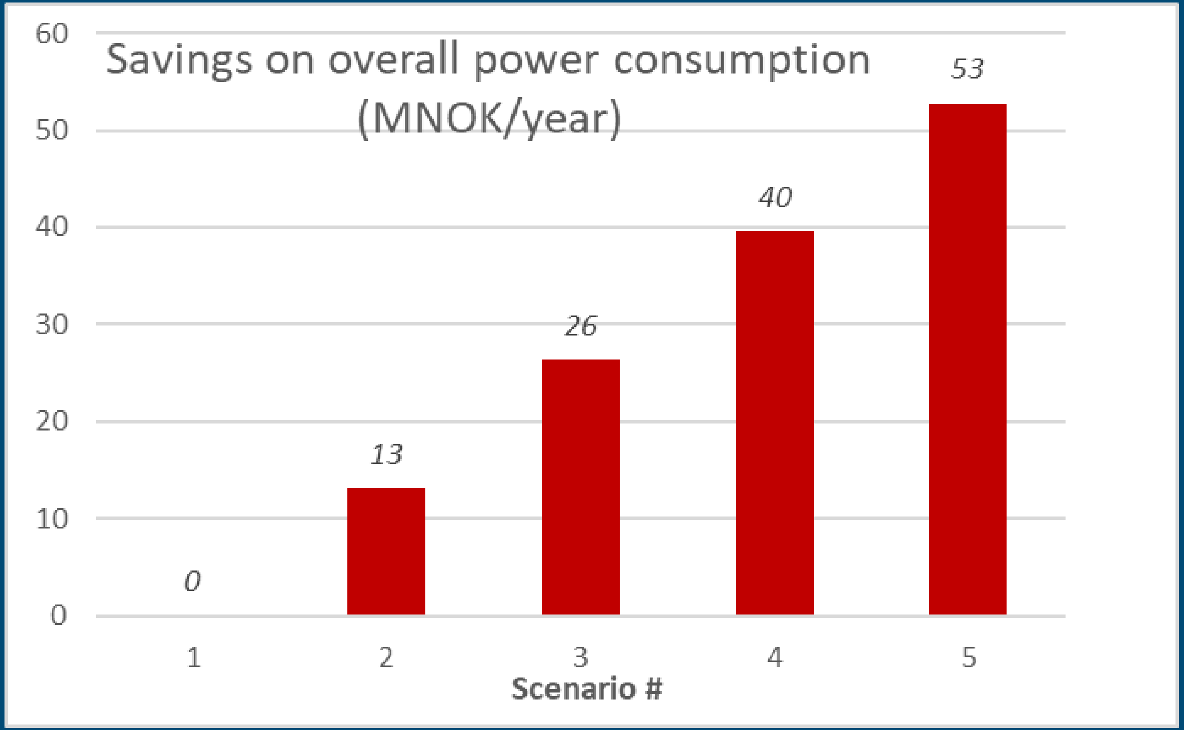
Business as usual, no TES
1

TES for **25%** of steam demand in high-price hours
2

TES for **50%** of steam demand in high-price hours
3

TES for **75%** of steam demand in high-price hours
4

TES for **100%** of steam demand in high-price hours
5



Savings on overall power consumption should be balanced with the ***cost to access additional power from the power network****, whose cost is very dependent on location and industry size.*

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Cost estimates for applicable thermal storage technologies

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Objective

Identify appropriate thermal storage technologies, maturity and development needs for power to heat to be attractive when applied to serve processes at 150 ^oC – 200 ^oC.

Key aspects to determine:

- Appropriate storage technology, temperatures, medium, thermal transfer solutions
- Relevant thresholds for scale of the facility
- Thermal cycling properties
- Cost vs. complexity considerations between storage facility and supporting infrastructure
- Recommended technology development approach to improve, mature and de-risk application

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Example of commercially available TES technology: Ruths steam accumulator

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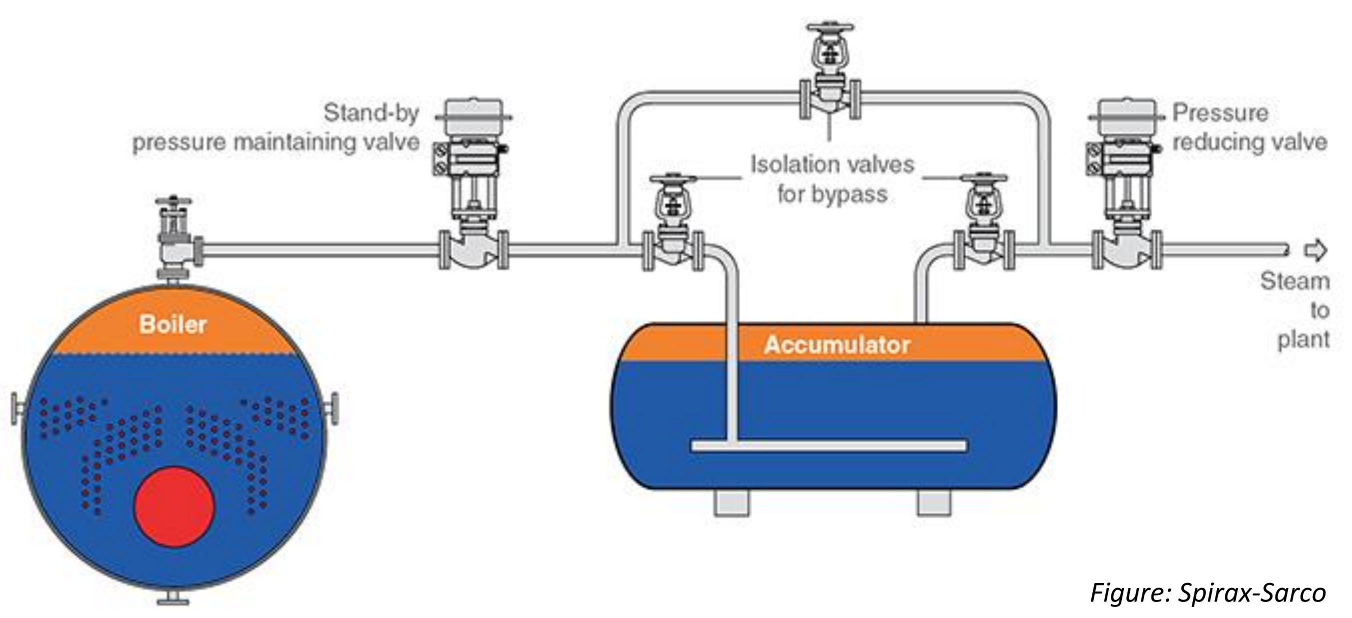

Figure: Spirax-Sarco

Main principle:

(1) <u>During periods of low steam demand:</u> the surplus steam available is injected into a mass of water stored under pressure in the **steam accumulator**.

(2) <u>During periods of high steam demand:</u> the high pressure, saturated water in the **steam accumulator** will be exposed to a pressure drop, flashing off an amount of the water into steam by using excess sensible heat in the water.

(3) This operational design enables the boiler to work in normal conditions, unaffected by the steam accumulator or varying steam demand.

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Example of commercially available TES technology: Ruths steam accumulator

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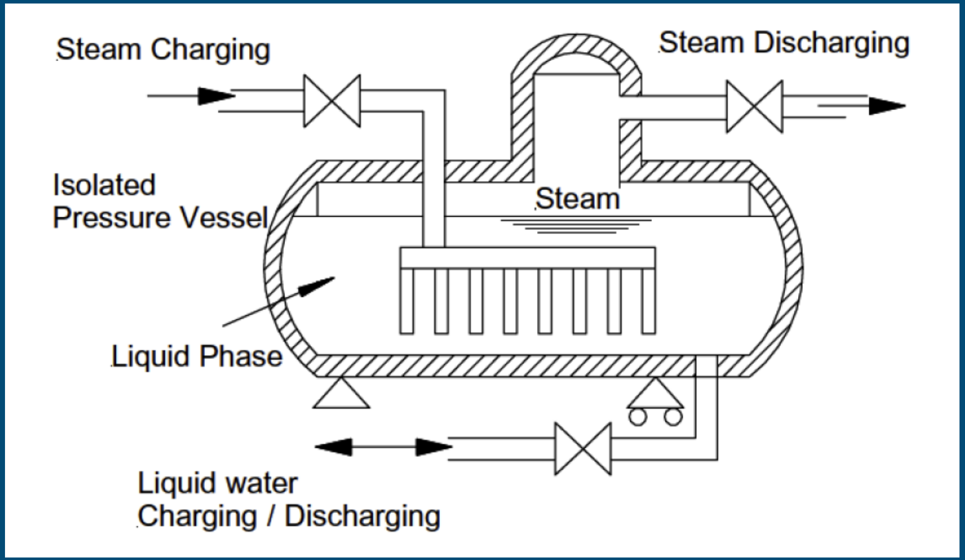
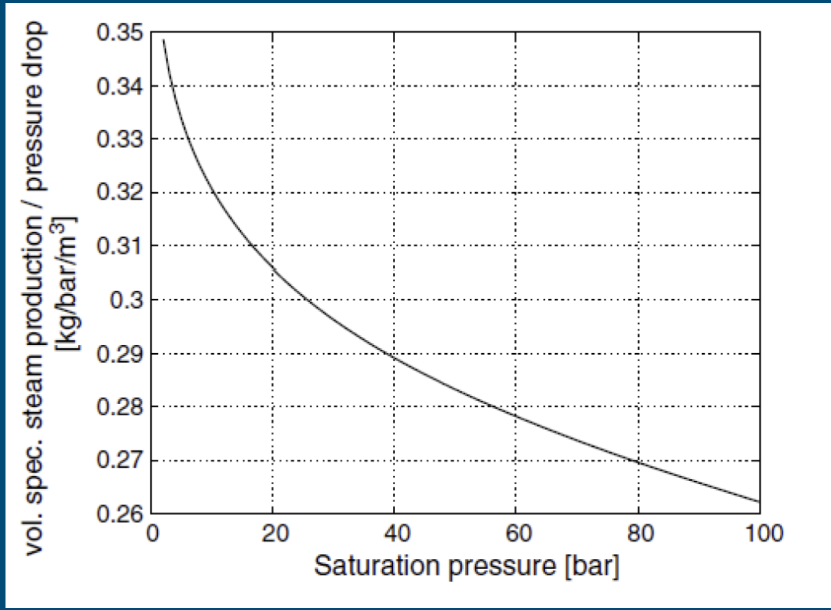
Characteristics

- Storage medium: Water, steel
- Direct storage
- Variable power to energy ratio
- Storage density:
  - ~ 40 kWh/m³ at 30 bars
  - ~ 31 kWh/m³ at 100 bars
- Costs: 4 €/ton of water, 6000 €/t steal
- Wall thicknesses 3-10 cm





Pros

- Simple
- Commercially available
- Short storage time with high output power

Cons

- Low storage density at high pressures
- High costs of steel

Sources: VDI, DLR, TU-Wien

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Example of upcoming TES technology: Latent Heat Storage

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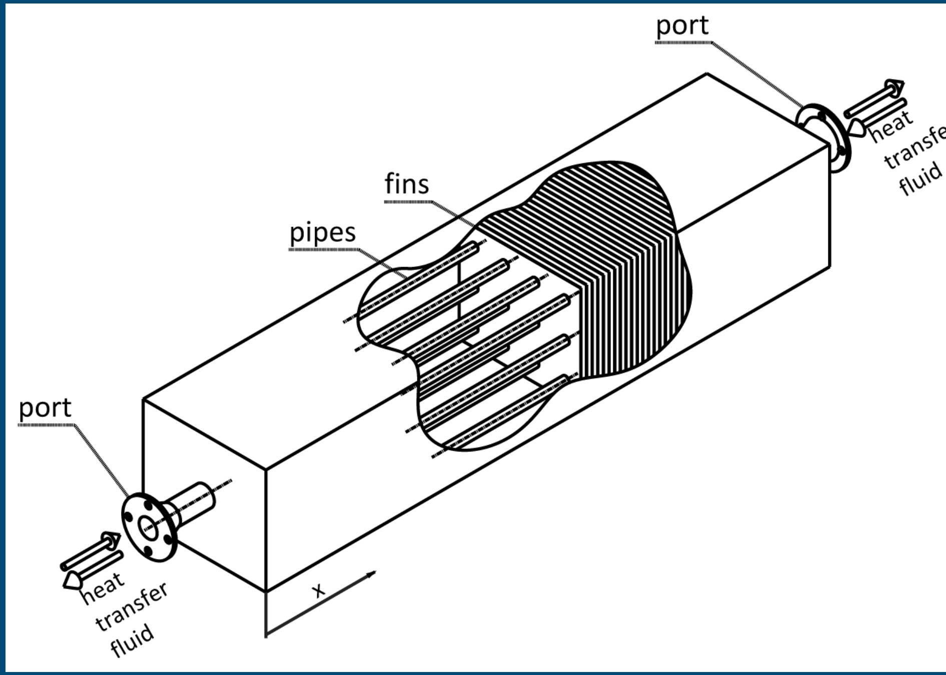
Characteristics

- Storage medium: phase change material (PCM)
- Indirect storage
- Variable power to energy ratio
- Storage density:
  - ~ 100 kWh/m³ at atmospheric pressure
- Unpressurized storage vessel
- Costs: 300-600 €/ton PCM, 6000 €/t steel



Design sketch of the shell and tube latent heat thermal energy storage (Ind. Eng. Chem. Res., 2016, 55 (29), pp 8154–8164)

Pros

- High energy density
- Low cost of steel
- Unpressurized storage vessel

Cons

- TRL 5-7

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Cost estimates

Case definition:

Energy source/ available heat:

- Electricity market with hourly resolution, modelled in 3 cases. All with diurnal variation with high and low level, in a step function:
- Cases 1 and 2: hourly variation in power prices, stable over the year. “High” from 20.00-08.00, “Low” from 08.00-20.00 .
- In Case 3, there is a seasonal difference in day/night prices. First period from Jan-May, second period from June-December.

Electricity prices:

[USD/MWh]	Case 1	Case 2	Case 3
High	17	34	17 (Jan-May) - 34 (June- Dec)
Low	11	11	11-11

- Sink:
  - Delivery quality: Heat requirement of 150 ºC. To achieve this and overcome inherent system inefficiencies the delivery requirement is saturated steam at 15 bar
  - Delivery volume – 3 steady state volumes to be considered:
    - 400 t/h
    - 800 t/h
    - 1200 t/h
- Return flow – water / condensate - a mix of:
  - 30 % make-up water at 25 ºC
  - 70 % return condensate at 95 ºC
- Storage temperature must enable delivery at required temp.
- Operational assumption: Assume system only applied for time shift of steam delivery from low to high cost electricity price
- Scale: delivery up to steam volume of 1000 t/h

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Cost estimates: Ruths steam accumulator

Ruths steam storage

- Steel: P460NH / K12202 / WSt460

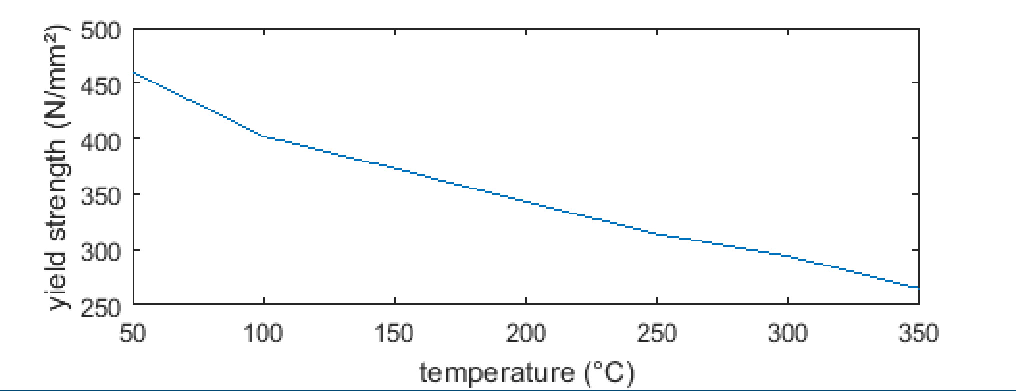
(http://www.lob-gmbh.de/de/werkstoffe/1.8935.html)

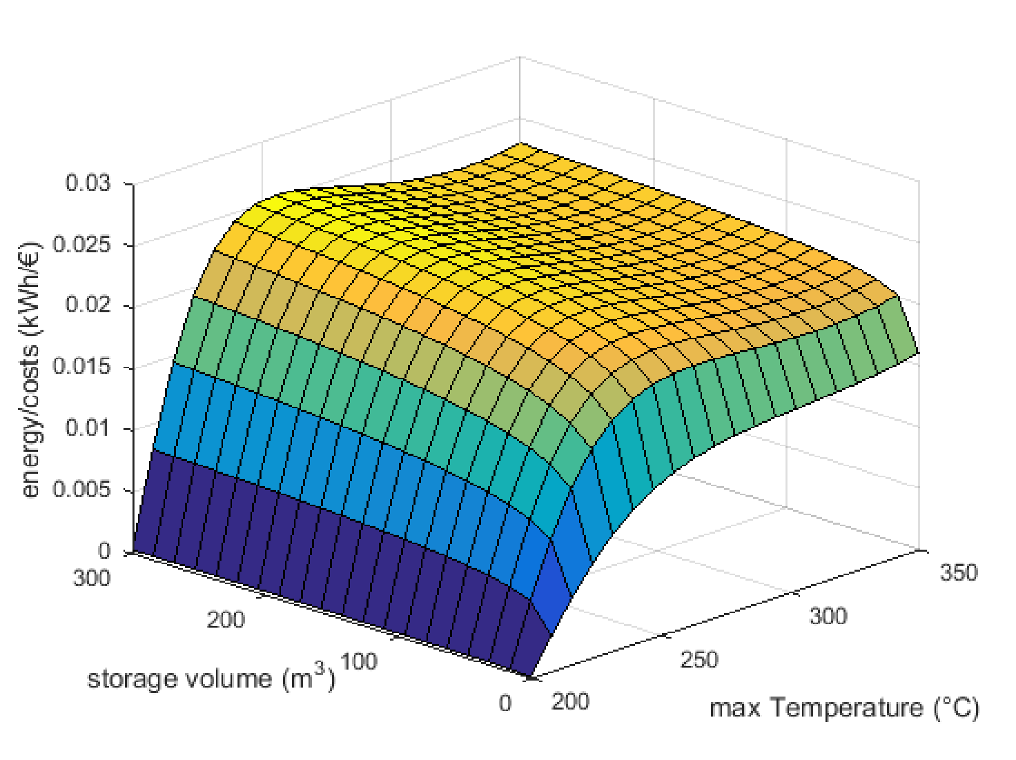
- Safety: $p_{max} * 1.5 = p_{ad}$

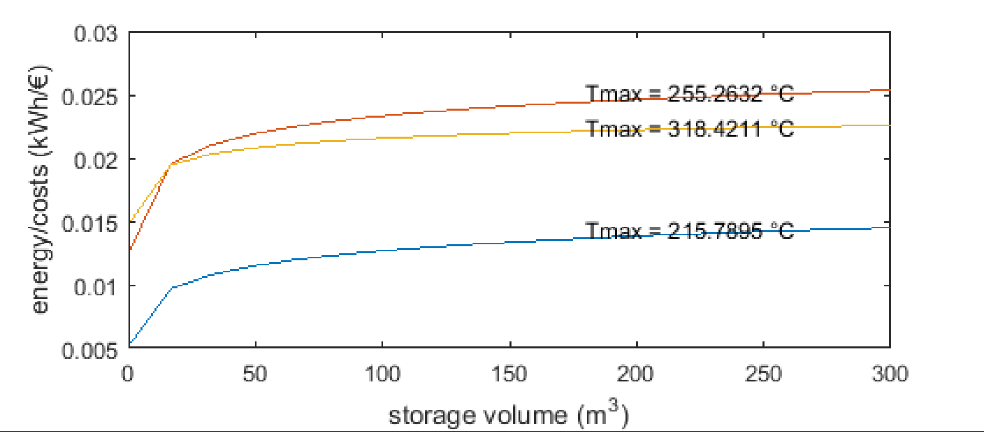
Optimal storage:

- Volume= 300 m³ (max)
- Tmax= ~255 °C

Resulting energy cost: 0.025 €/kWh







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Cost estimates: latent heat storage (LHS)

Assumptions for 1200 t/h:

- 2 cm diameter piping
- 6 EUR/kg steel
- 0.5 EUR/kg PCM
- Tmax= ~255 °C
- Effective enthalpy 140 kJ/kg within usable temperature range
- No additional heat transfer measures

- Costs more independent of storage size
- Costs are mostly effected by pipe diameter
- Cost for PCM/Steel ~50/50
- Additional heat exchanger structures can decrease costs
- EUR/USD = 1.14

Resulting energy cost: 0.041 €/kWh

Cost estimates for thermal storage technologies: main results

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Electricity prices:

[USD/MWh]	Case 1	Case 2	Case 3
High	17	34	17 (Jan-May) - 34 (June- Dec)
Low	11	11	11-11

Cost estimates:

Tech. type	Steam (t/h)	Thermal storage capacity (MWh)	Number of storage units	Storage tech. costs (mill. EUR)	Payback (yr) Case 1	Payback (yr) Case 2	Payback (yr) Case 3
Ruths	400	3164 MWh	154	125	20.1	5.2	7.5
Ruths	800	6328 MWh	307	250	20.1	5.2	7.5
Ruths	1200	9493 MWh	461	375	20.1	5.2	7.5
LHS	1200	9493 MWh	NA	230	12.3	3.2	5.2

Payback times should be balanced with the ***cost to access additional power from the power network and cost of additional boilers to charge the TES units****.*

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Conclusion of case study

Identified limitations

- Modern boilers should operate close to their nominal capacity (to avoid radiation losses). This leads to either:
  - **One boiler** with Scenario 2, operating at more than twice the capacity of Scenario 1
  - Or **two boilers of different capacity** with Scenarios 3,4 or 5
- Additional costs should be taken into account in the case studies (e.g. *additional boilers and access to additional power from network*)
- Large steam accumulators or other TES tech. of **such high scale might not be realisable** for constant steam delivery over 12 hours

Next steps for the case study

- **Feasibility** with regards to the large scale of TES
- Evaluation of potential alternative storage technologies, e.g. concrete storage
- **Techno-economics to evaluate payback times**
  - Cost estimates for large electric boiler
  - Cost estimates for access to additional power from the network

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Conclusions

Conclusions (1/2)

In the process of mapping the possible industrial fields of application for thermal energy storage at high temperature, two applications are pointed out as the most promising:

- **Casting processes**
  - High temperatures (100-1500 °C)
  - Batch-process on an hourly basis
  - High energetic potential
- **Production of heat and steam from intermittent renewables**
  - Availability of renewable electricity at variable prices is increasing
  - Often constant, high duty demand of heat or steam
  - Storage at temperatures of 100-250 °C

The main **identified research needs** are the following:

- Technology to harvest heat from casting processes
- Thermal storage concepts for high thermal duty and temperature
- Integration methods of thermal storages into industrial processes
- Demonstration of concepts

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Conclusions (2/2)

Throughout the theoretical case study, several benefits and barriers were identified for the implementation of TES in industrial processes:

Benefits

- Possiblity for **immediate savings on electricity consumption** with intermittent energy sources and variable power price
- TES can also **provide back-up capacity** to produce steam in case of power shortage

Barriers

- Immediate **savings must be balanced** with additional costs (e.g., additional boiler, access to higher power from network)
- While several TES technologies can be found commercially, large **scale technologies are still limited** for very large heat storage capacity and high output power

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