Aalto University
School of Engineering

Thermal energy storage in communities

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18.5.2022

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Benefits of community scale in thermal energy storage

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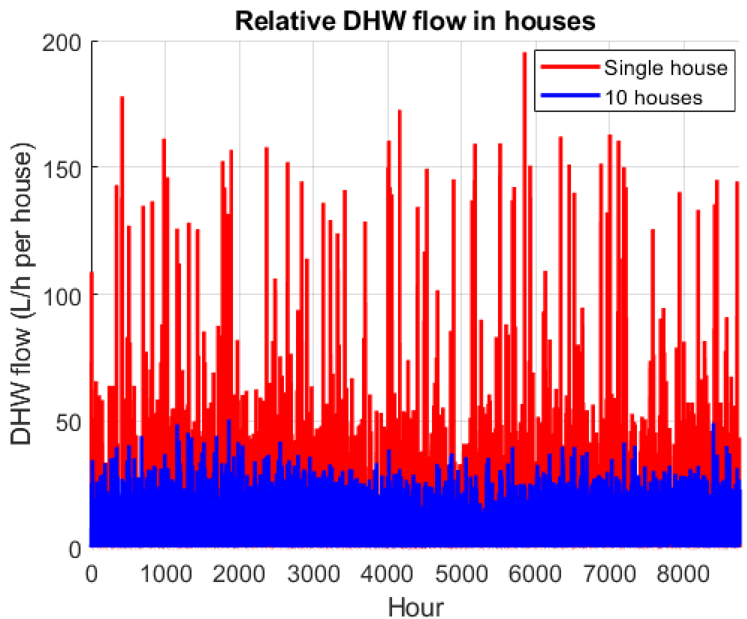
Demand smoothing, single house vs. community

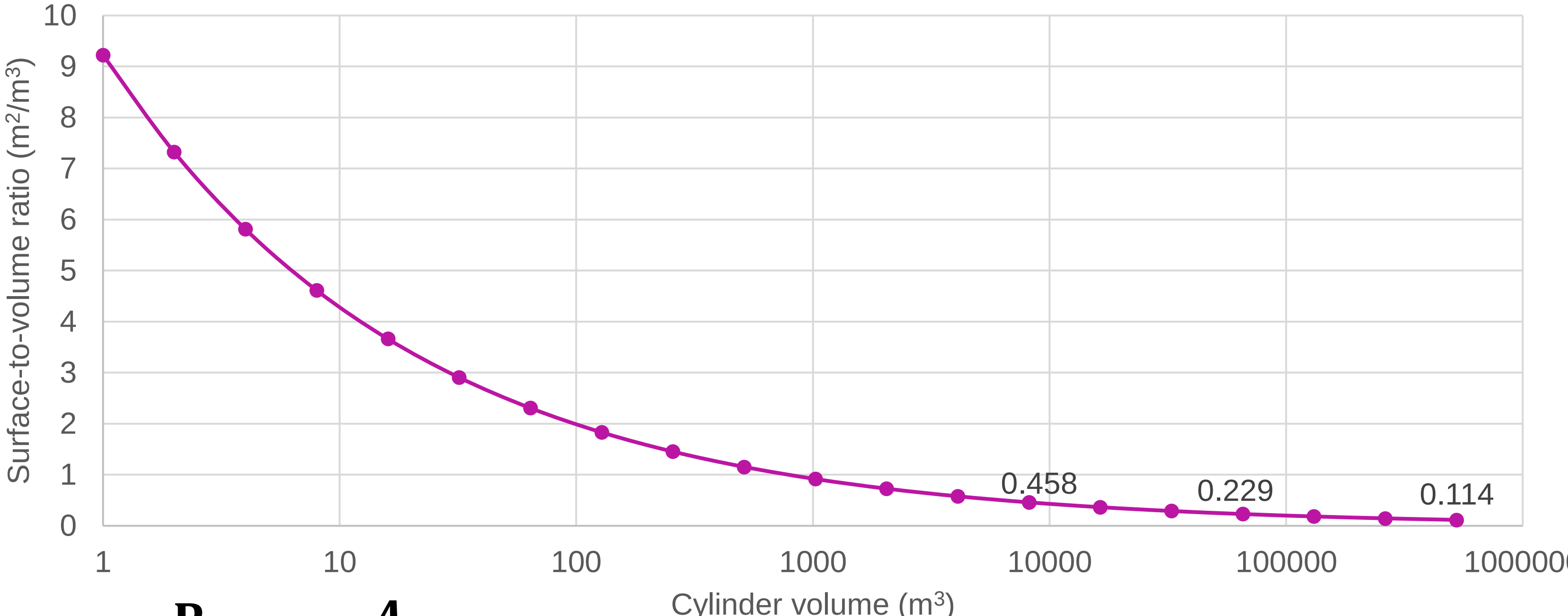


The same average demand!

- **The bigger the unit, the smaller the effect of inviduals**
  - Sudden variations reduced
    - *Easier to dimension energy generation and storage systems*
- **Communities average out individual differences**
  - More stable and predictable loads

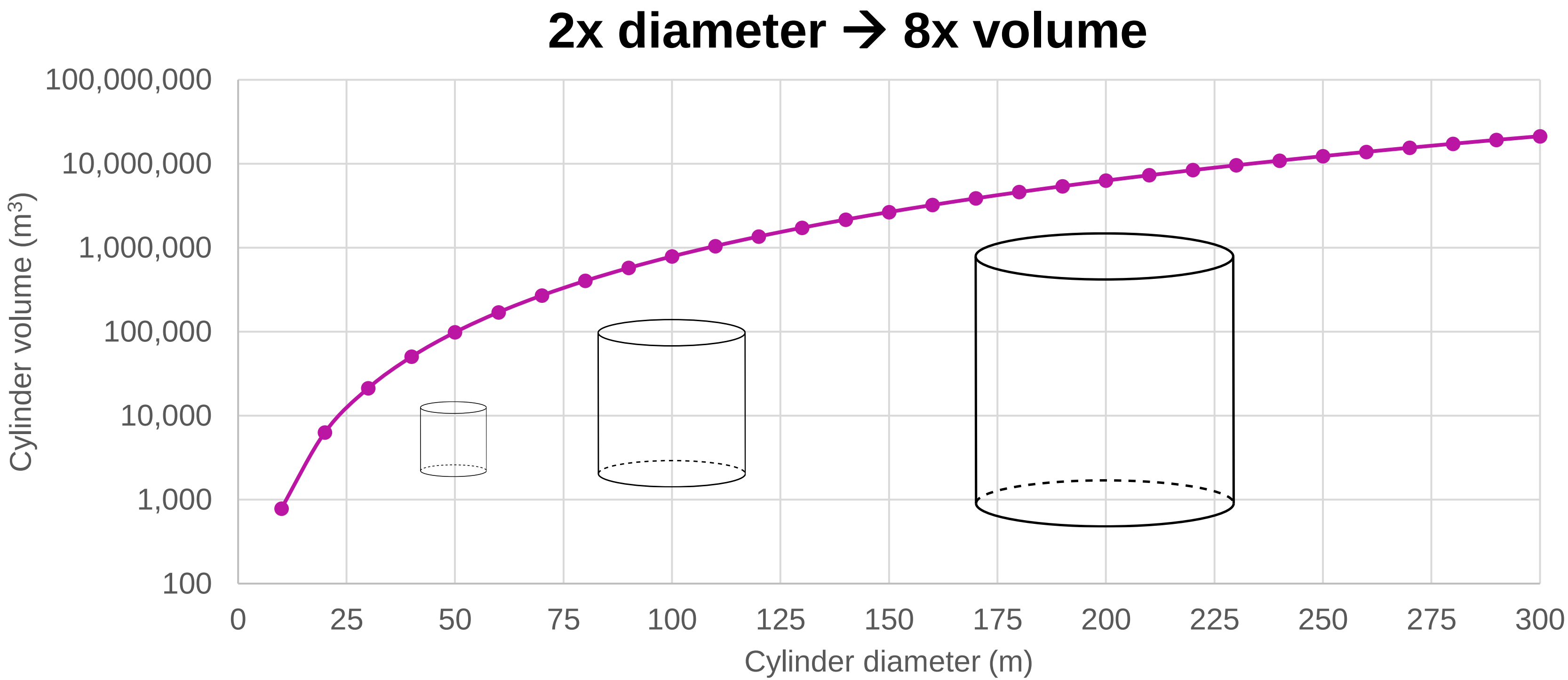
Storage surface-to-volume ratio

Affects thermal storage heat loss rate vs. storage capacity



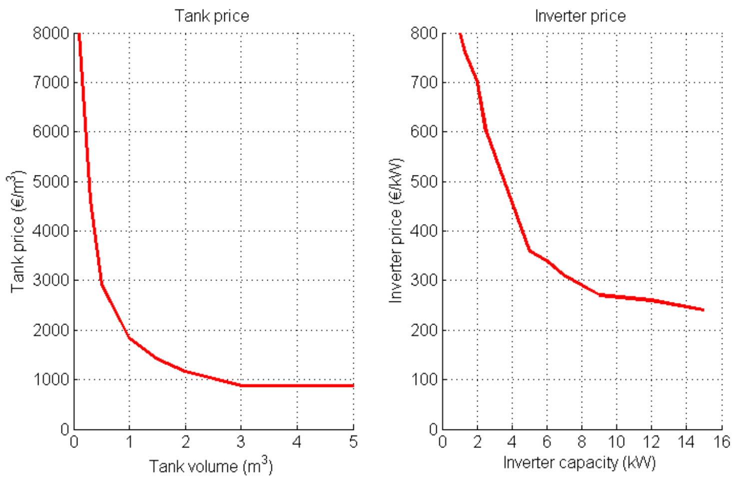
$$\frac{\mathbf{P}_{loss}}{\mathbf{E}_{storage}} \alpha \frac{A_{surface}}{V}$$

Storage volume vs. diameter



Storage capacity (kWh): $E = \rho V c_p \Delta T$

Storage and energy systems, cost vs. scale



- **The unit price of energy systems go down with higher capacity**

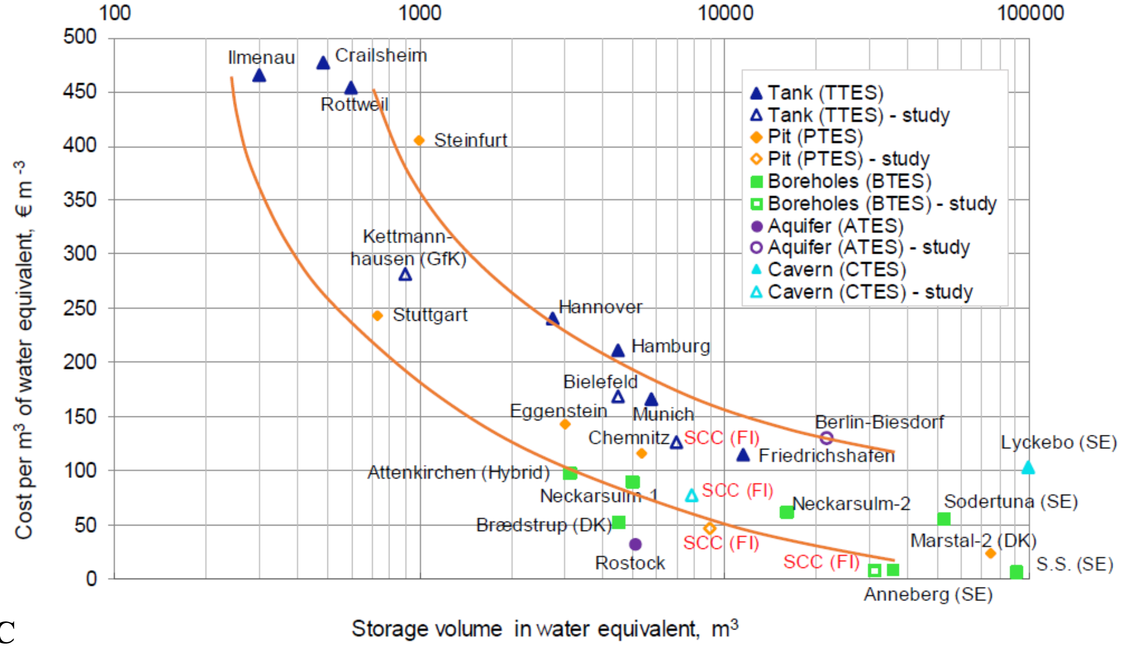
Seasonal thermal storage cost vs. size

Bigger is better: €/kWh goes down with size

7 €/kWh

3.5 €/kWh

0.9 €/kWh

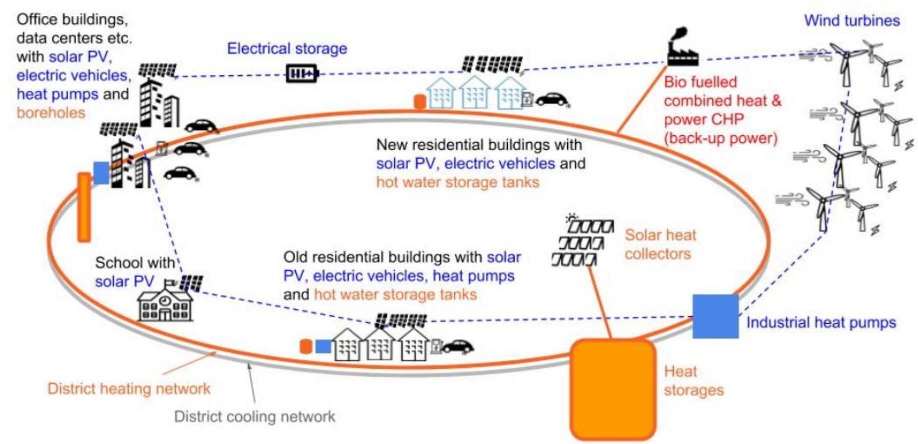


With ΔT 50 °C

https://aaltodoc.aalto.fi/handle/123456789/40606

Smart grids in communities & cities

- **Wide range of users have more varied demands**
  - Timing
    - *Seasonal, daily, hourly*
  - Type of energy
    - *Heating, cooling, electricity*
  - Demand response
- **District heating and cooling**
- **Local energy conversion**
  - Heat pumps, heat storage
  - Heating ← → Cooling



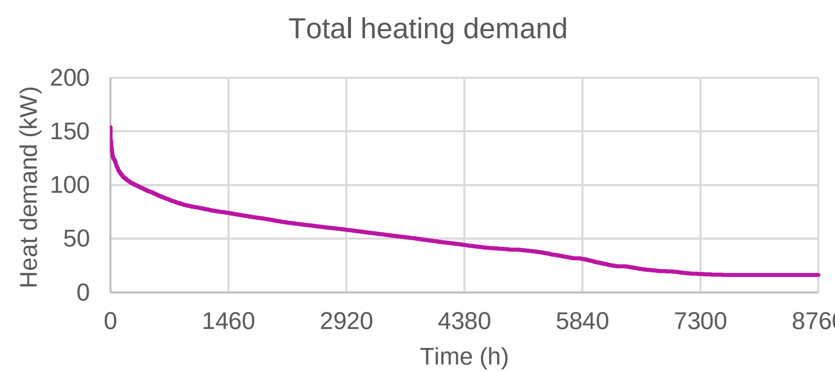
http://smartenergytransition.fi/en/clean-district-heating-and-cooling-system-how-can-it-work/

QUESTIONS?

Simulation-based design and case studies

Design considerations for communal thermal energy storage systems

- **Renewable energy fraction (REF)**
- **Off-grid or grid-connected?**
  - Backup systems
- **Climate**
  - Seasonal energy demand
  - Available heat sources
- **Peak and average demand**
  - Daily/weekly/monthly changes
  - Heating, cooling, electricity
- **Complex systems with many interdependent variables**
  - Simulation-based optimization helps to select the best system configuration



Solar community design & optimization

Variable	Minimum	Maximum
Solar collector area (m^2)	500	4000
PV capacity (kW)	100	1000
WW-HP capacity (kW)	60	360
AW-HP capacity (kW)	80	1280
Buffer tank volume (m^3)	50	500
BTES volume (m^3)	10 000	100 000
BTES shape (m/m)	0.5	3
Borehole density ($1/m^2$)	0.05	0.20
Borehole seriality (-)	1	9
BTES cover insulation (m)	0	2
House efficiency (kWh/m^2)	25	50

Energy generation

Short-term energy storage capacity

Long-term energy storage capacity

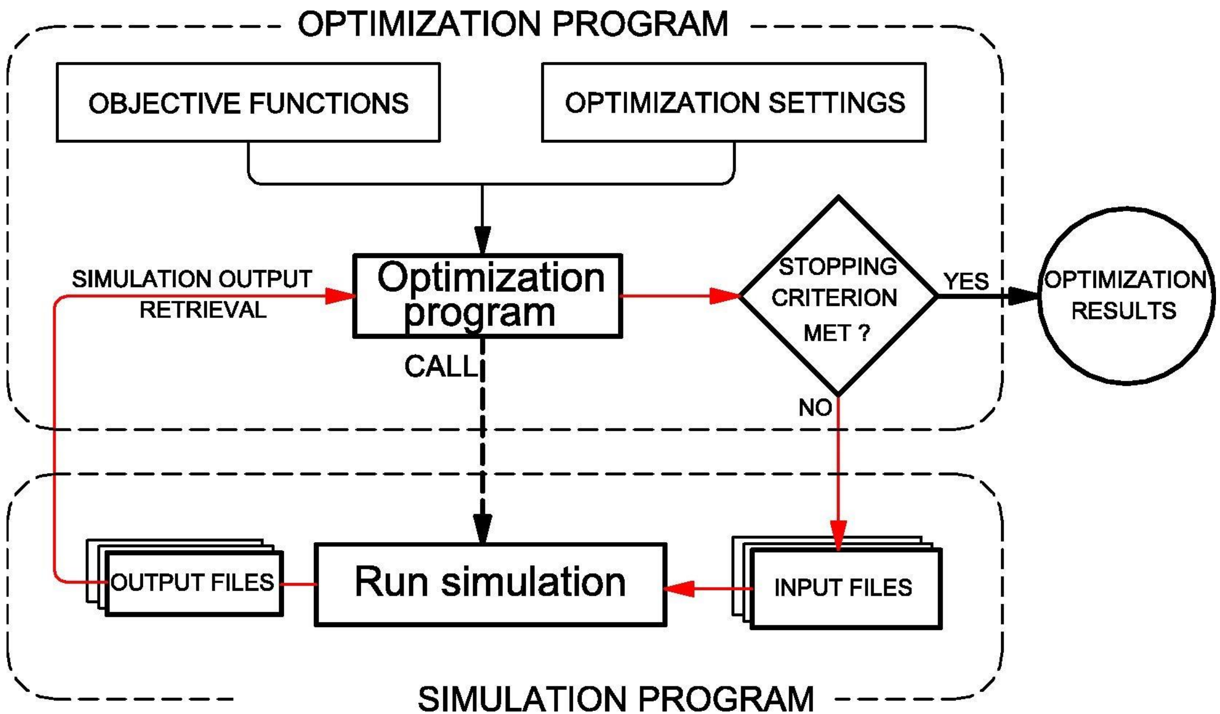
Heat storage (dis)charging power

Heating demand

Simulation-based optimization

MOBO

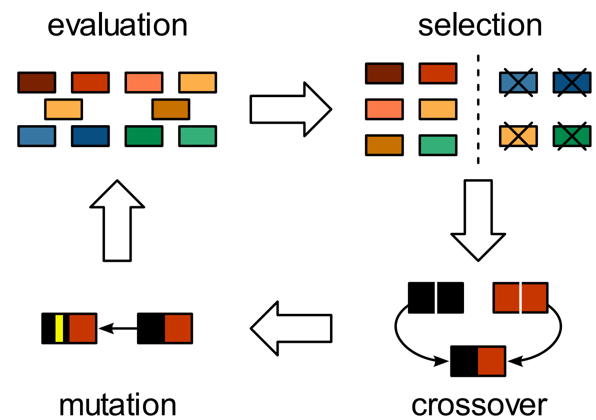
TRNSYS
IDA-ICE



https://doi.org/10.1016/j.apenergy.2013.08.061

Evolutionary optimization

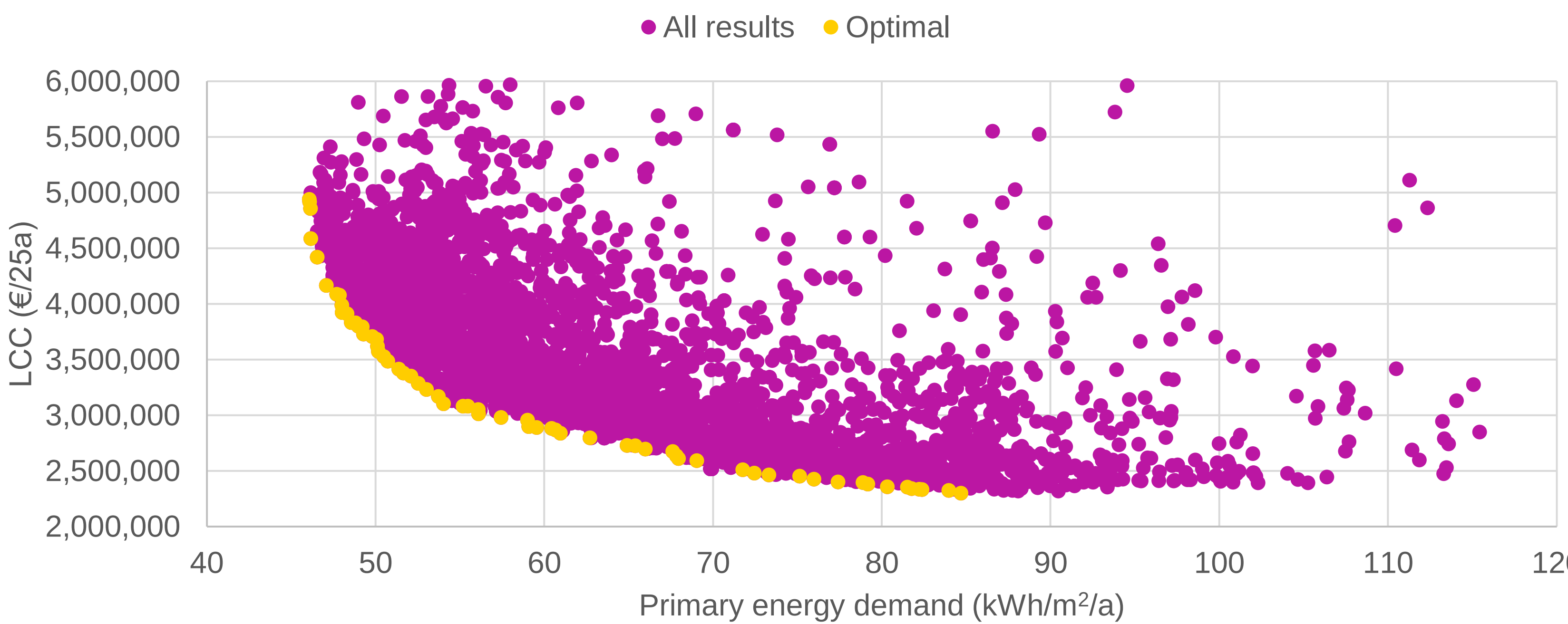
- **Black-box algorithm**
  - No information about the function or derivatives needed
    - *Good for simulation-based optimization*
- **Evolutionary principles**
  - Combine good solutions to generate new and better solutions
- **MOBO software**
  - Integration to simulation tools
  - Parallel calculation



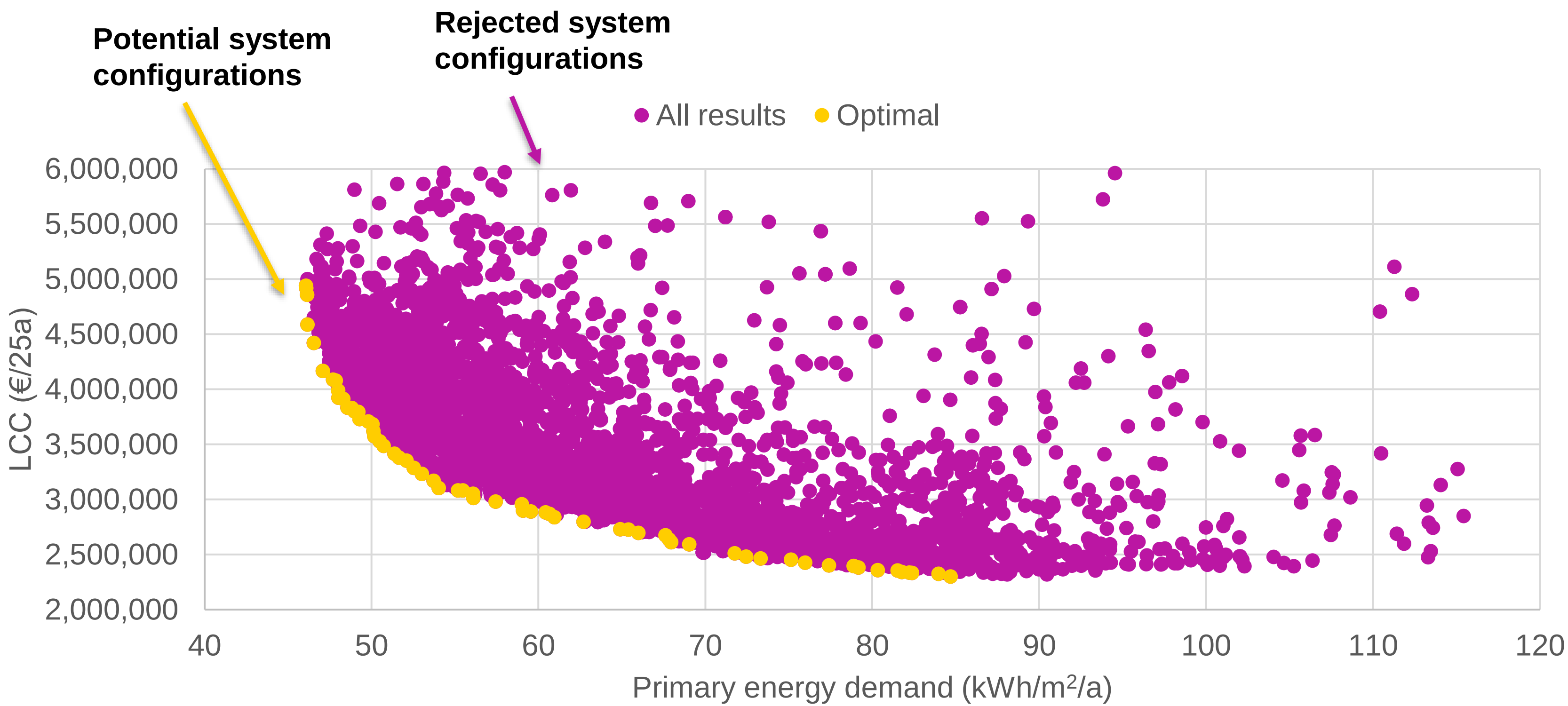
https://ibpsa-nordic.org/tools

https://www.strong.io/blog/evolutionary-optimization

Results of multi-objective optimization



Results of multi-objective optimization

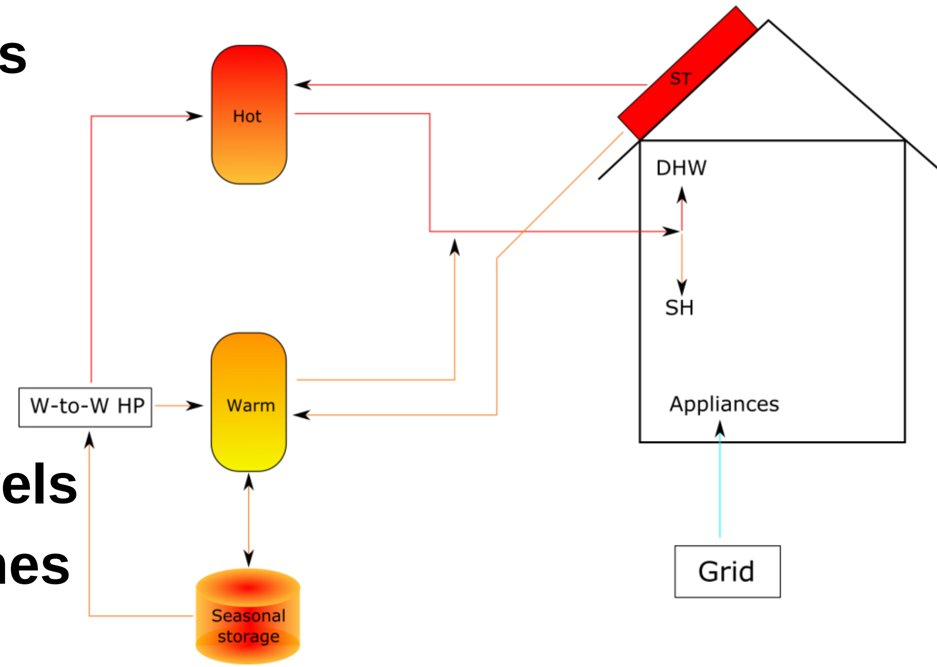


Simulation case studies with BTES

- **Solar community of single-family houses**
  - Solar thermal + heat pumps
  - Solar electric + heat pumps
- **Solar community of apartment buildings**
  - Solar electric + heat pump
- **Waste incineration**
  - DH connection, no heat pumps

Solar thermal heating for a community

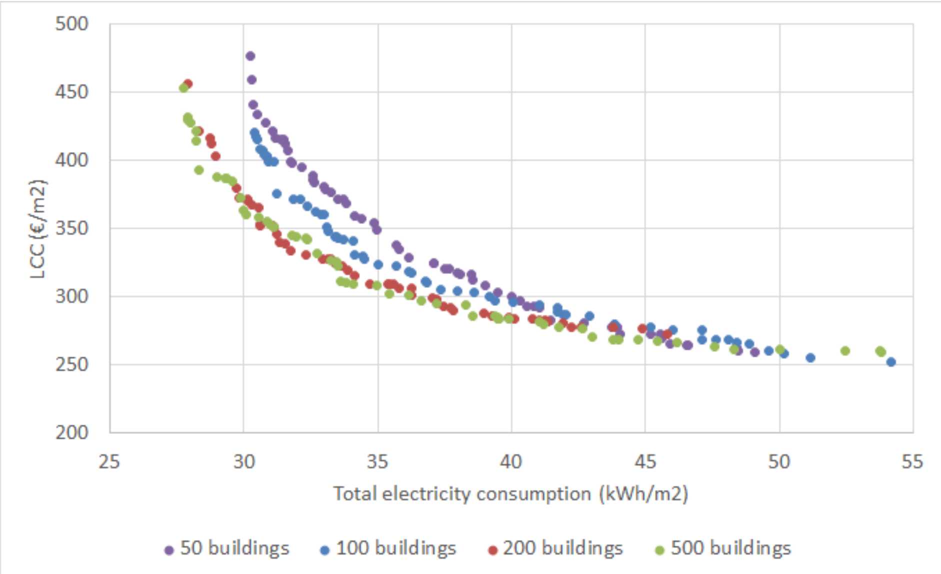
- Solar thermal system heats up short-term storage
- Short-term storage moves heat to and from the seasonal storage
- Heat pump raises the temperature to desired levels
- 50 – 500 single-family homes



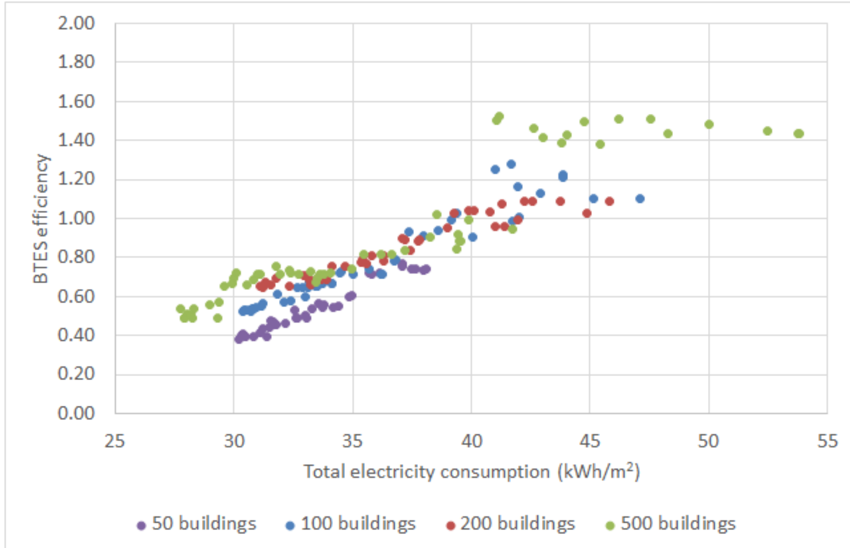
https://doi.org/10.1016/j.solener.2018.01.052

Optimization with different community sizes

System cost for different community sizes



Seasonal storage efficiency

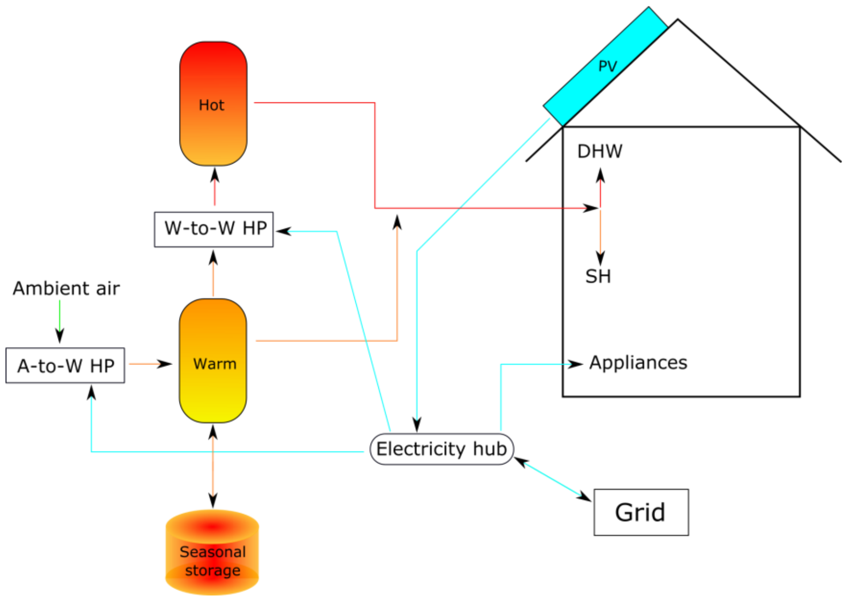


Bigger is better

Efficiency is above 100% when very little energy is stored

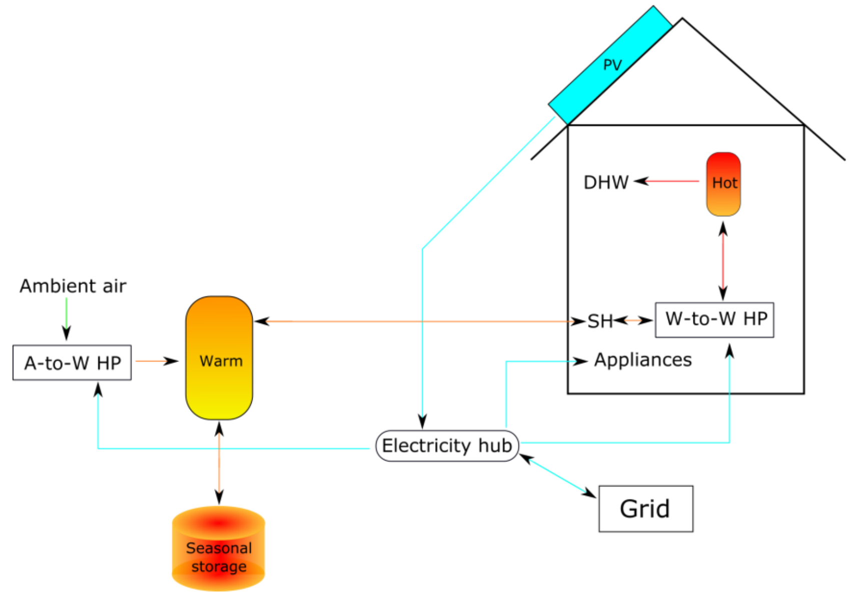
Fully electric solar heating system

Centralized



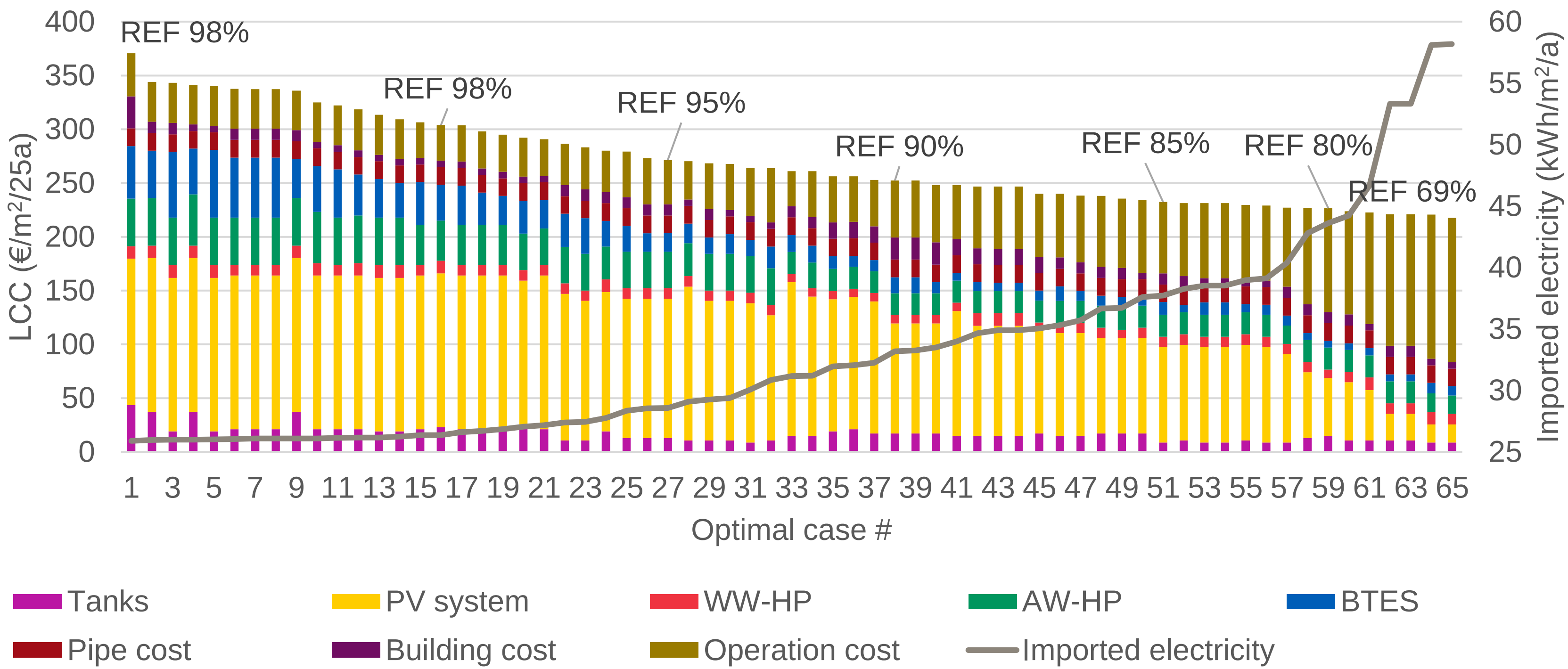
https://doi.org/10.1016/j.renene.2018.04.028

Semi-decentralized

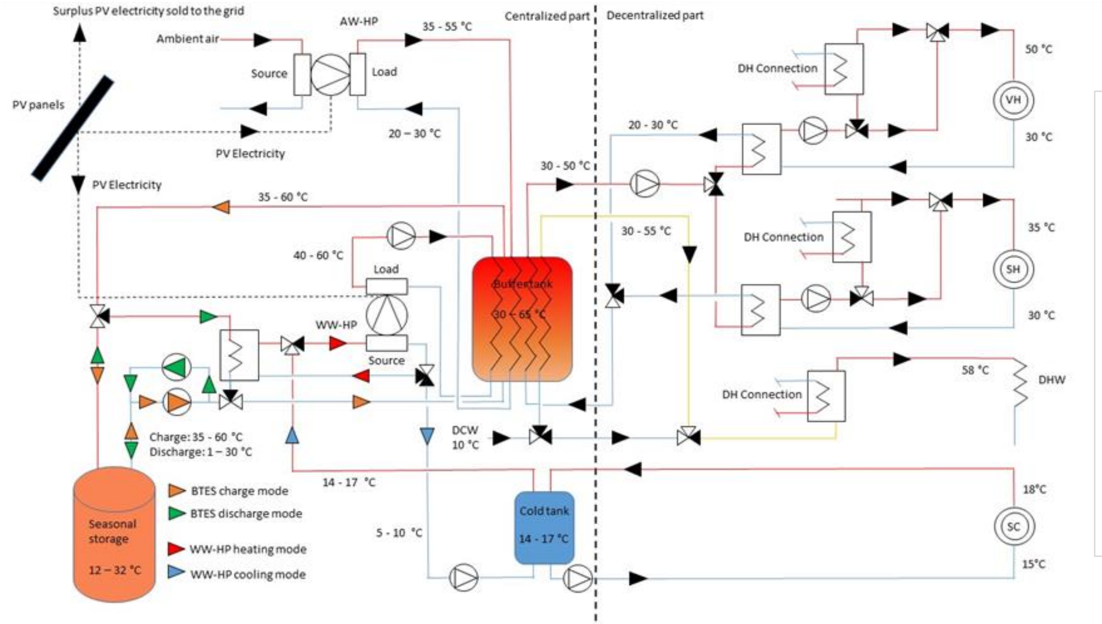


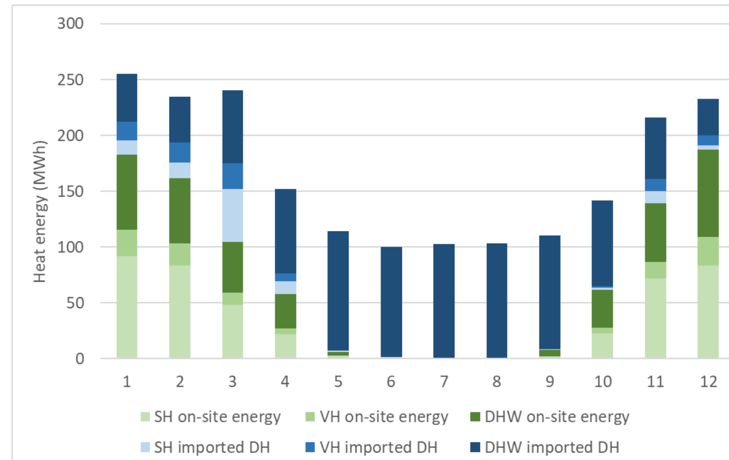
https://doi.org/10.1016/j.apenergy.2018.08.064

Solar community cost distribution



Solar heating for apartment buildings



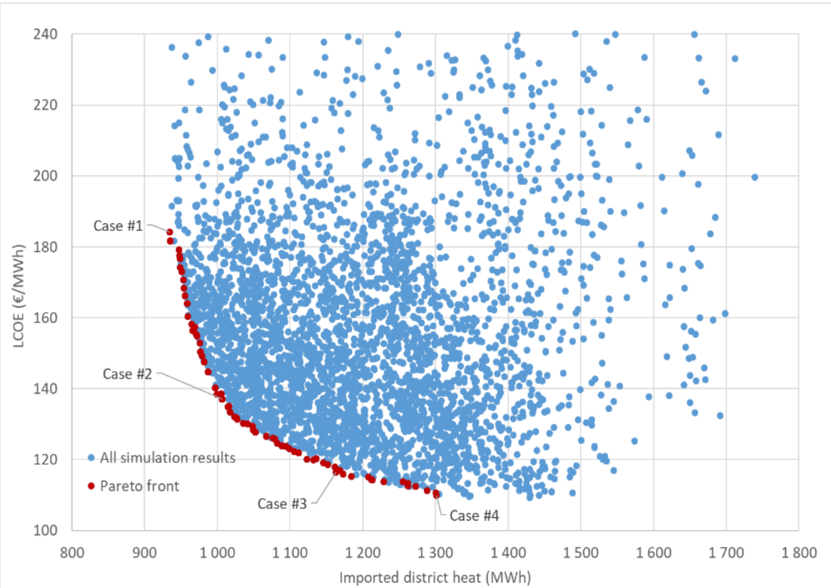


All summertime solar energy stored for winter

https://aaltodoc.aalto.fi/handle/123456789/39827

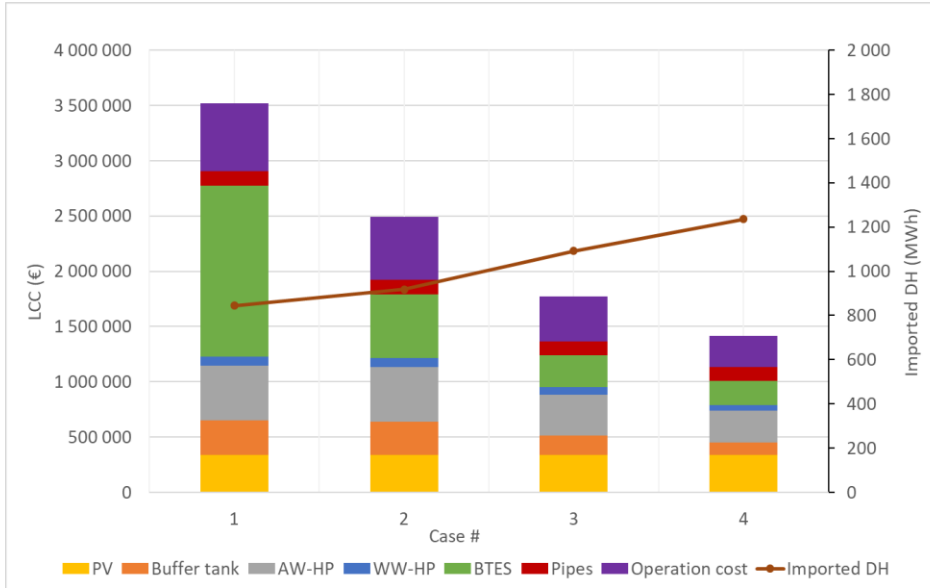
Apartment building system optimization

Optimization of energy cost



LCOE 110 – 180 €/MWh

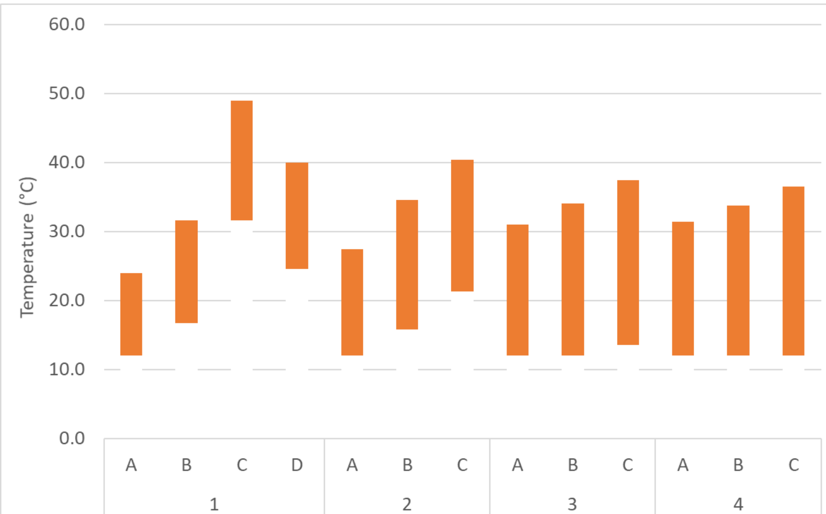
Cost distribution of selected solutions



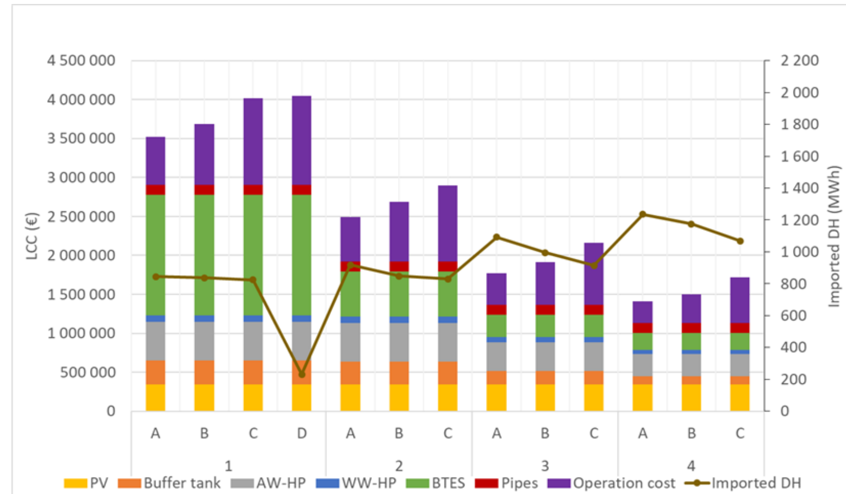
Solar capacity limited by roof space
Storage capacity increases solar fraction

Control methods for storage operation

A: Solar charging
B: Charging with grid electricity (>15 ℃)
C: Charging with grid electricity (>5 ℃)

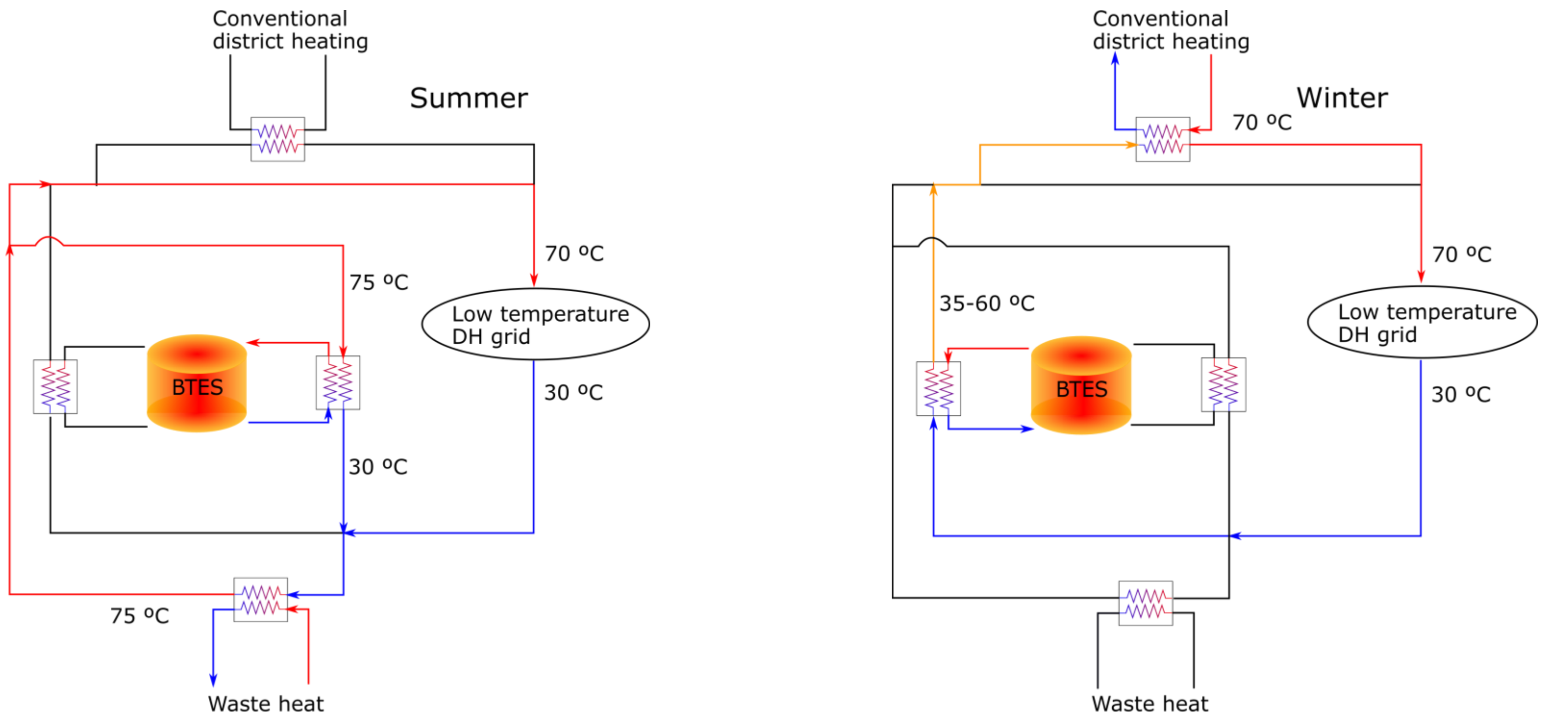


Annual temperature range of BTES



Small reduction in imported energy
Increased cost

Waste incineration heat storage (BTES) for apartment buildings



https://doi.org/10.3390/buildings10110205

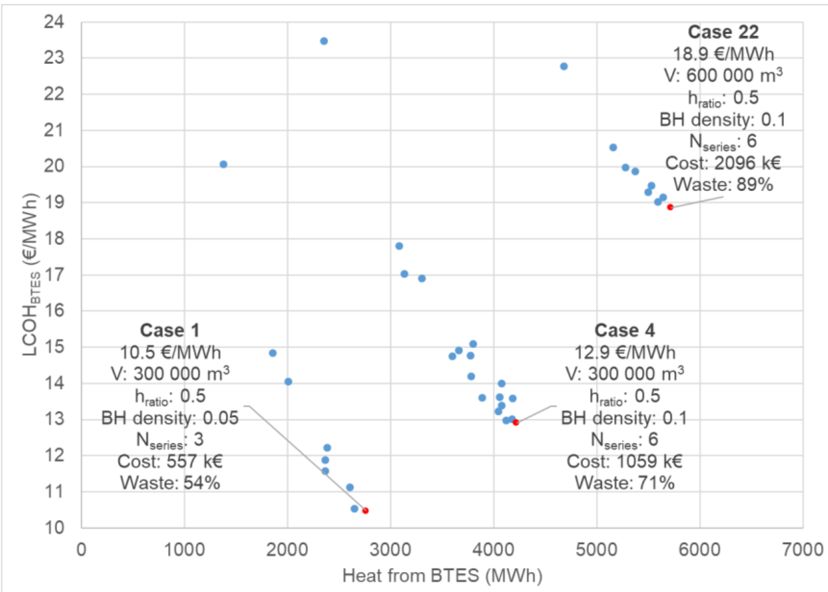
Preliminary design with parametric run

Parameter	Values
V_{BTES} (m^3)	300 000, 600 000
H_{ratio} (m/m)	0.5, 1, 2
BH density ($1/m^2$)	0.05, 0.1
N_{series} (-)	3, 6, 9

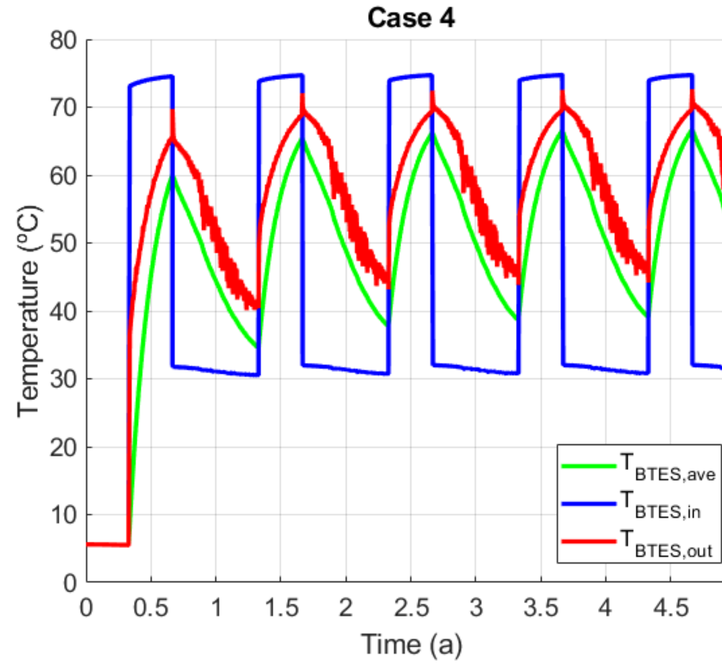
- **Parametric run**
  - "Brute-force optimization"
  - Go through all parameter combinations
    - *Limited amount of options to cover*

Waste heat storage, cost & performance

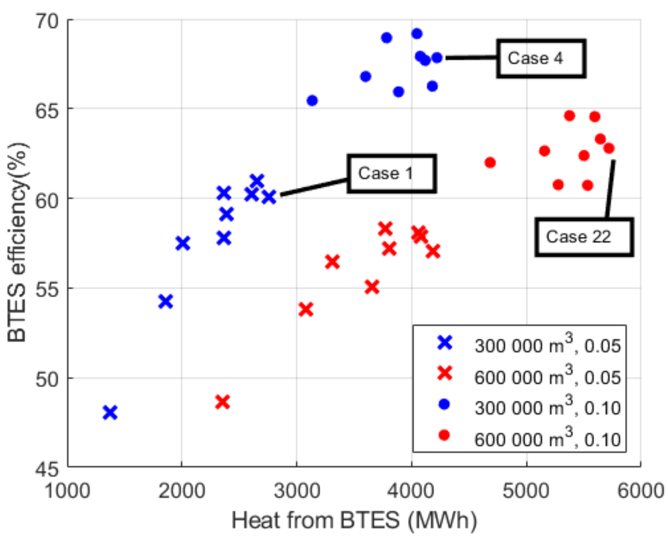
Levelized cost of heat



Temperature in the BTES



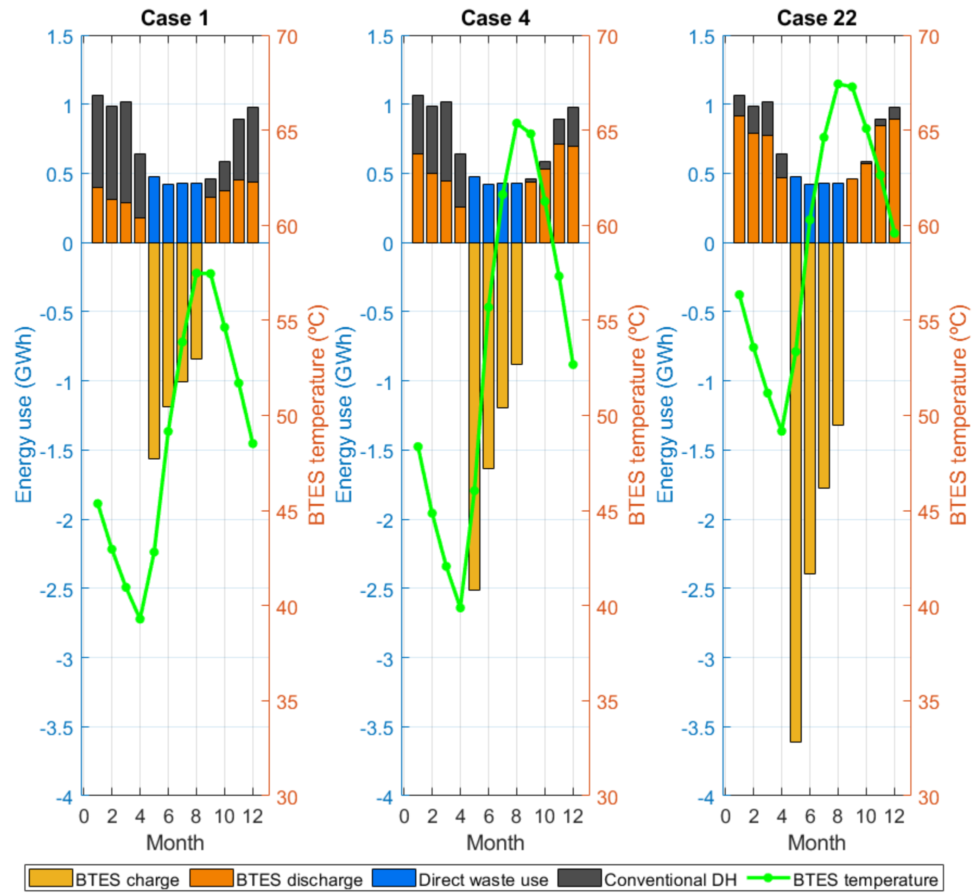
Waste heat storage, efficiency



η_{BTES} = 60%
X_{waste} = 54%

η_{BTES} = 68%
X_{waste} = 71%

η_{BTES} = 63%
X_{waste} = 89%



Design guidelines for seasonal thermal energy storage

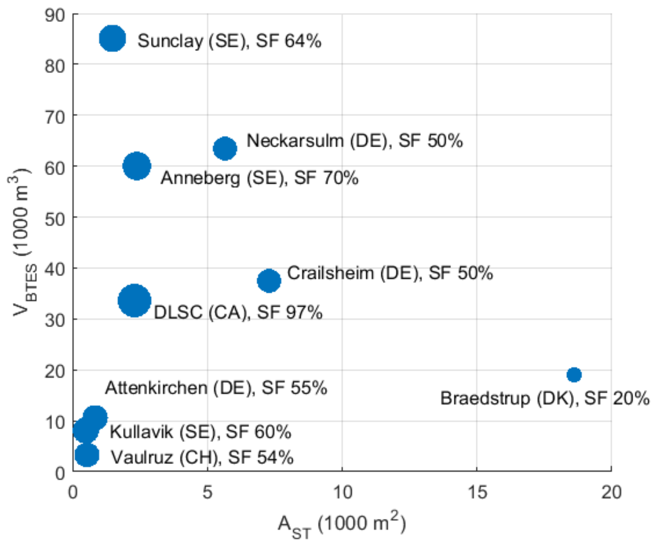
- **IEA SHC Task 45 – Subtask B: Storage**
  - https://www.iea-shc.org/publications-category?CategoryID=159
- **Finnish seasonal storage guidebook (in Finnish, not free)**
  - https://www.rakennustietokauppa.fi/sivu/tuote/rt-103137-lampoenergian-kausivarastointi/2742552
- **MyCourses material bank also has lots of sources**

QUESTIONS?

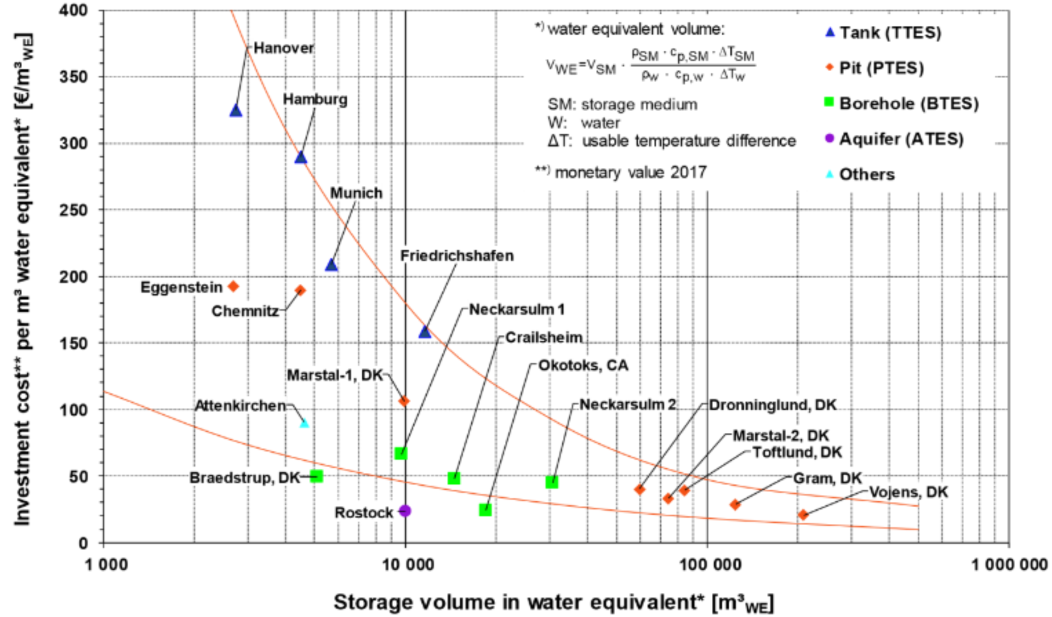
Real-life examples

Seasonal storages around the world

Storage volume vs. solar generation with Solar Fraction



Cost vs. storage capacity

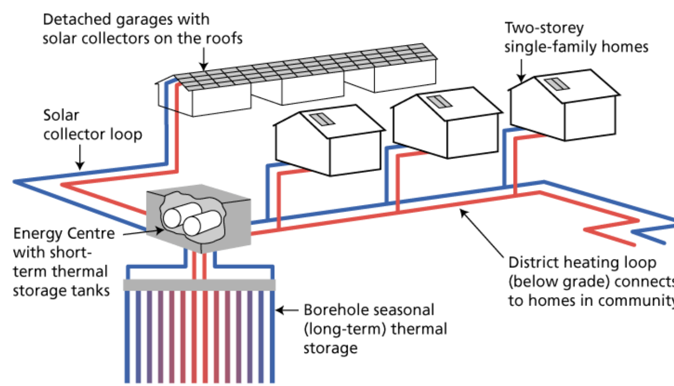


https://www.solar-district-heating.eu/wp-content/uploads/2019/10/Best-practice-Br%C3%A6dstrup-Marstal-Dronninglund-and-Gram-003.pdf

Drake Landing Solar Community, BTES, Okotoks, Canada

- 35 000 m^3 storage volume
- 2300 m^2 solar collectors
- 98% solar fraction for space heating
- ~45% storage efficiency
- Temperature 30 – 70 ℃
- Uneconomical due to small size

https://www.dlsc.ca/



Solar district heating plant, PTES Vojens, Denmark

http://solarheateurope.eu/2020/05/19/vojens-district-heating/

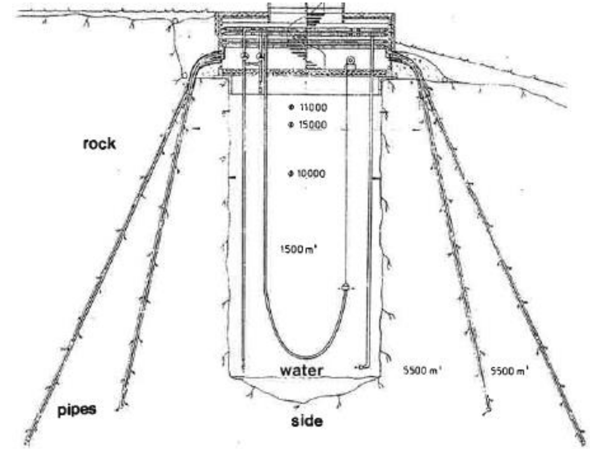
- **200 000 m^3 water pit storage**
  - Max temperature 80°C (95°C)
- **70 000 m^2 solar collectors**
  - 50% of annual heating
- **3 gas engines**
- **10 MW electric boiler**
- **Absorption heat pump**
- **Gas boilers**
- **Storage cost 24 €/m^3**
  - 0.41 €/kWh (ΔT 50 °C)

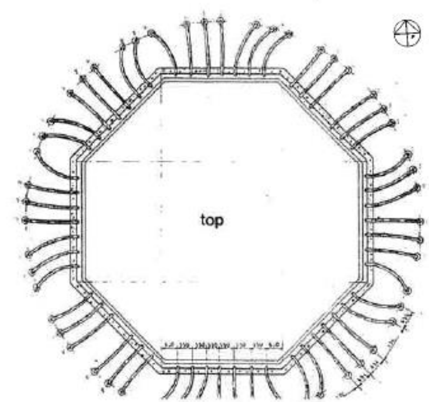
Kerava solar community, Finland (dismantled)

Ground-embedded thermal storage

- 1500 m^3 water tank
- 11 000 m^3 surrounding rock
- 2 rings of boreholes
- In operation 1983 – 1985

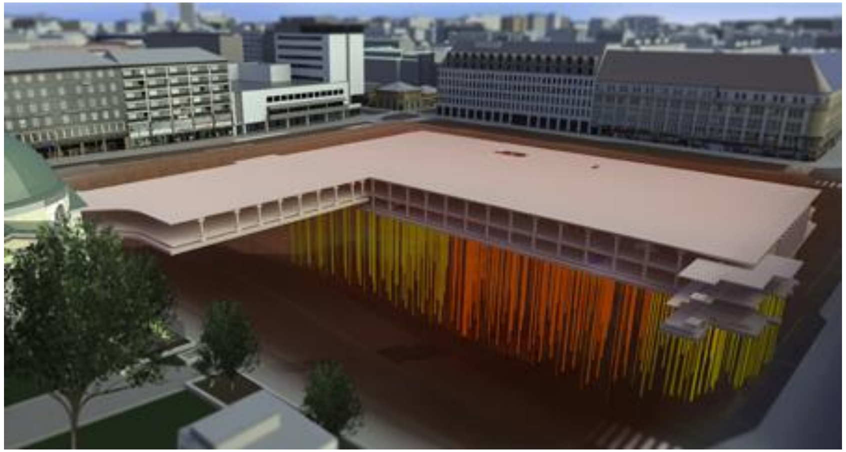
- Tank undersized
- Replaced by district heating
  - DH company did not allow keeping the solar collectors





Toriparkki, energy pile storage, Turku, Finland

- **Horizontal heat collection pipes under the market square**
  - Solar energy
- **Structural support piles under the parking garage**
  - Some piles fitted with heat exchangers
    - *Seasonal thermal energy storage*
- **Heat used to melt snow and to heat the garage**



- **Wet clay**
- **40 m deep piles**
- **Stored heat 11,2 GWh**
- **Expected power 6,6 MW**

Smart solar village, BTES, Kirkkonummi, Finland (planned)

Solar plant

https://www.ekoalykyla.fi/

- **1000 person community**
  - Single-family homes
- **3 MW ground-mounted PV panels**
  - Also some roof-mounted panels
- **Heat pumps**
- **BTES seasonal storage**
- **Electric grid connection**

- **Development on hold**

District heating buffer storage, Helsinki, Finland (Helen)

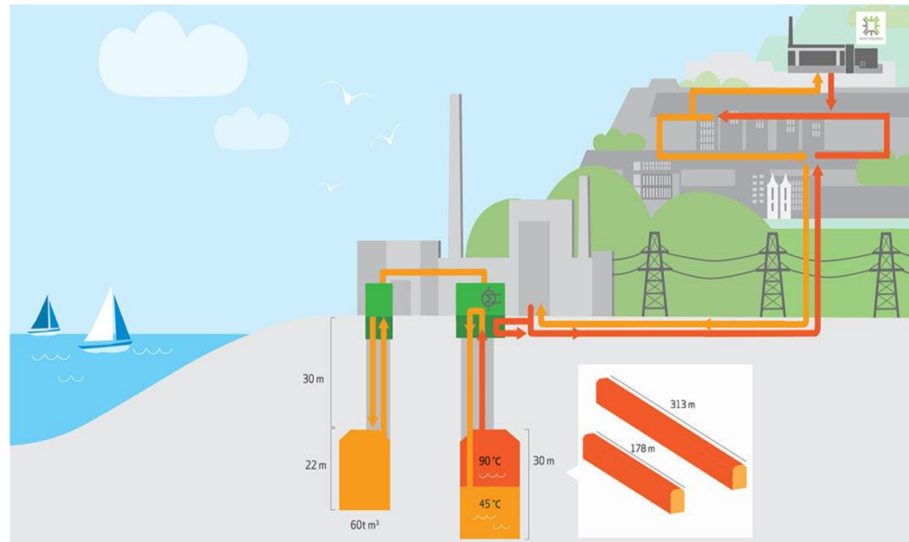
Mustikkamaa

https://www.helen.fi/helen-oy/vastuullisuus/ajankohtaista/blogi/2020/mustikkamaa

- **320 000 m^3 water cavern**
  - Old oil storage system
  - Daily/weekly buffer
  - 120 MW heating power
    - *4 days of continuous operation*
  - Filling the newly completed storage with water takes 3 months ☺

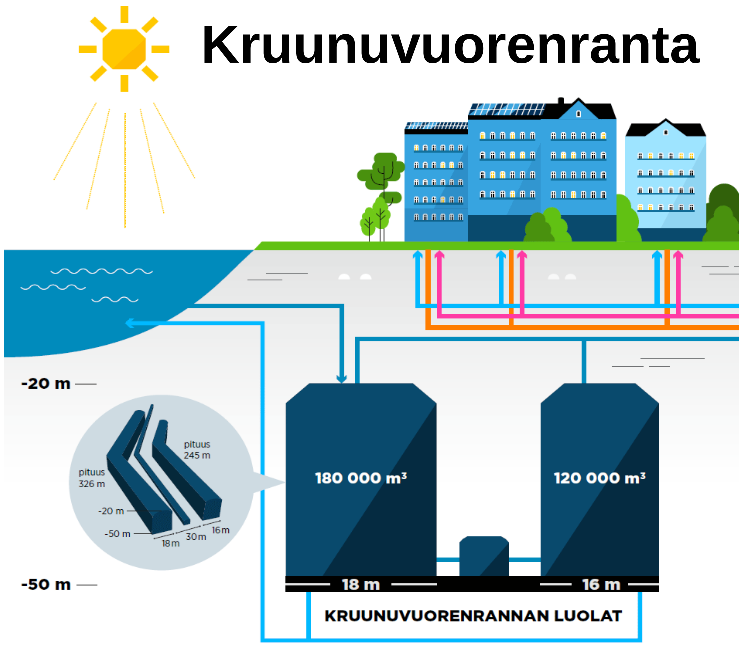
District heating buffer storage, Vaasa, Finland (Vaasan Sähkö)

- **210 000 m³**
  - Old oil storage system
  - 90 °C storage temperature
  - 100 MW power
  - 7 – 9 GWh capacity
- **Heat sources**
  - Wind power
  - Industrial waste heat



https://www.vv.fi/2019/09/20/massiivinen-maanalainen-energiavarasto-vaasan-vaskiluotoon/

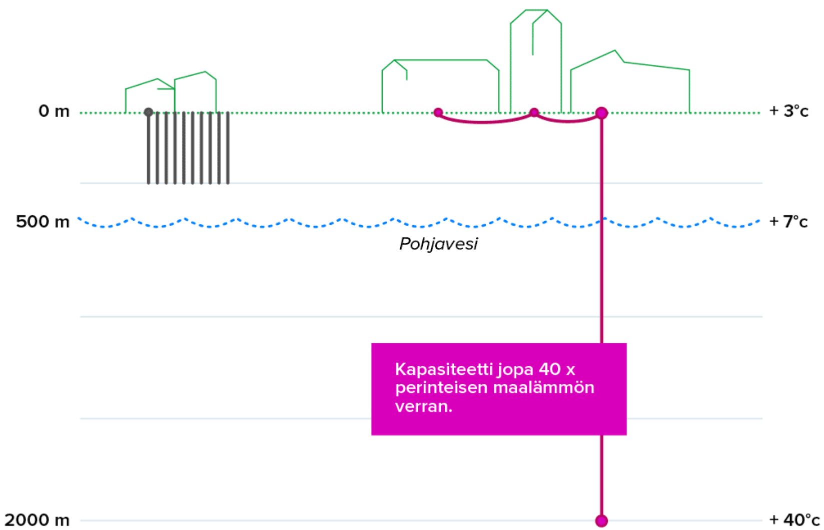
Seasonal thermal energy storage, Helsinki, Finland (Helen, planned)



- **300 000 m3 water cavern**
  - Old oil storage system
  - Low temperature (<20 °C?)
    - *Charged with warm surface sea water in summer*
    - *Charged with residential excess heat from cooling*
  - Utilized with heat pumps

https://www.helen.fi/en/news/2018/seasonal-energy-storage-facility-is-planned-for-the-kruunuvuorenranta-rock-caverns

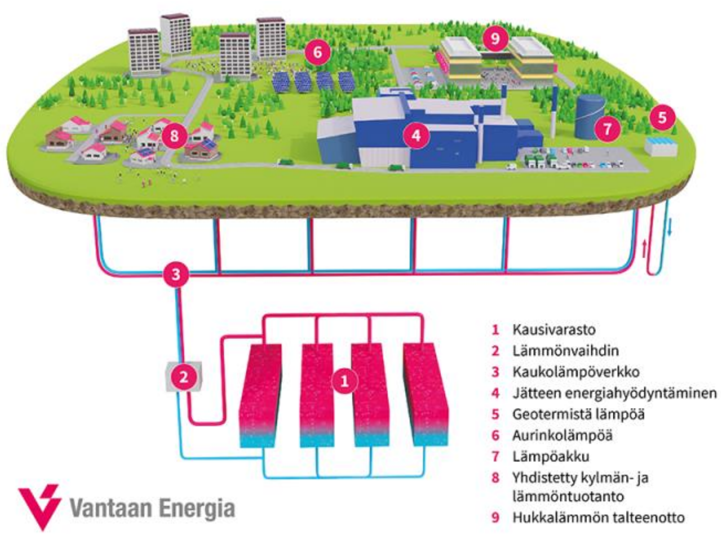
Seasonal thermal energy storage, Salo, Finland (under construction)



- **2 km deep boreholes**
  - 1-6 boreholes planned
    - *Might need 20 for optimal power*
  - Co-axial heat transfer pipe
  - 8 – 10 GWh to be stored per year
- **Charged with excess heat from waste incineration plant**

https://gnf.fi/wp-content/uploads/2020/12/Hukaton_loppuraportti_Web.pdf

Seasonal thermal energy storage, Vantaa, Finland (under construction)



https://www.vantaanenergia.fi/fossiiliton-2026/maailman-suurin-lammon-kausivarasto-vantaalle/

- **1 000 000 m³ hot water storage**
  - The biggest in the world!
  - High temperature, 140 °C
  - 90 GWh
    - *Vantaa DH consumption ~1800 GWh*
- **Heat sources**
  - Waste incineration (50% of city heat)
  - Geothermal heat
  - Solar heat
  - District cooling
  - Waste heat recovery

Practicalities of large projects

- **40 designers working on the Vantaa project**
  - Rock mechanics
  - Geoenergy
  - Structural design
  - Process design
  - Building design
  - HVAC automation
  - Street design

QUESTIONS?

Summary

- **Community systems have benefits over individual systems**
  - Larger community improves predictability of energy demand
  - Different types of users improve the utilization of waste heat
    - *Demand response and virtual power plants*
- **Bigger is better in thermal energy storage systems**
  - Higher efficiency, lower cost
- **Complex systems can be designed through multi-objective optimization methods**
- **Increased interest in large-scale energy storage projects**