WP4 - STATUS AND MAIN FINDINGS FROM MODELLING AND TEA

HUG Interim Results Seminar

Jan 22nd 2026

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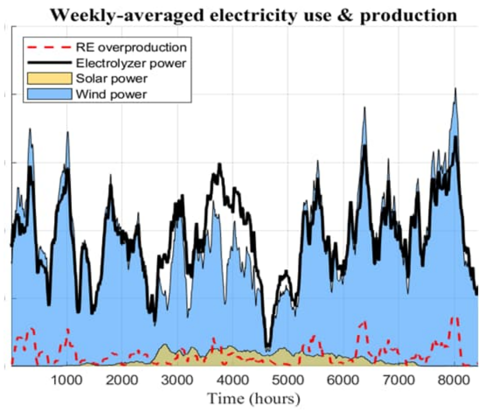
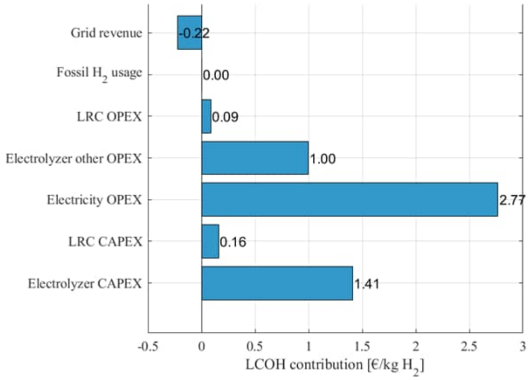
Contents

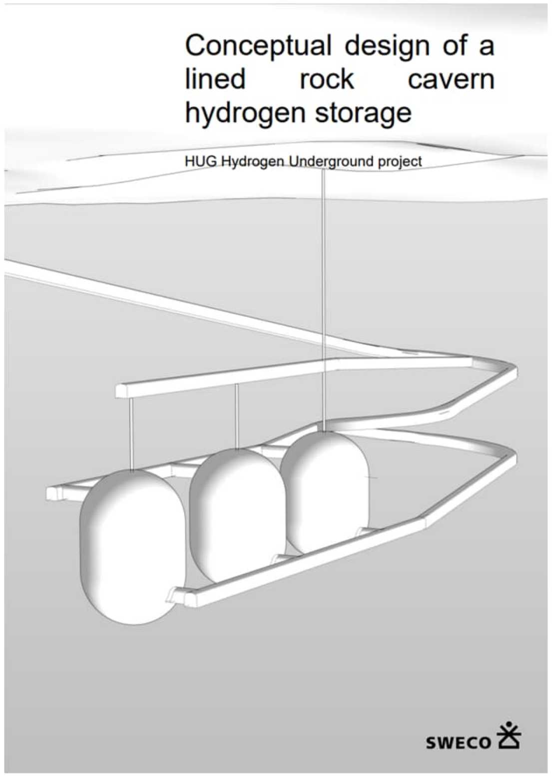
- Investment optimization, operation and feasibility – What have we achieved and learned
- Apros modelling / temperature control
- Compressor study

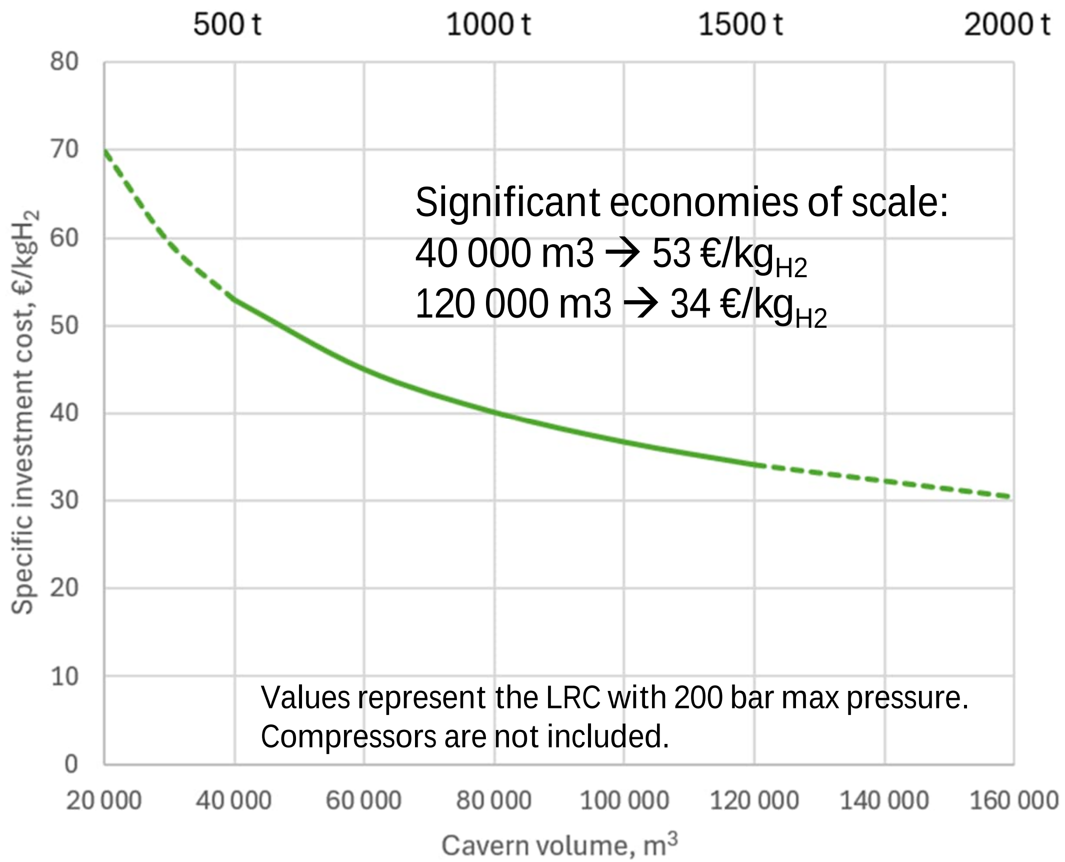
Investments, operation & feasibility





Finland-specific costs for the LRC storage have been determined

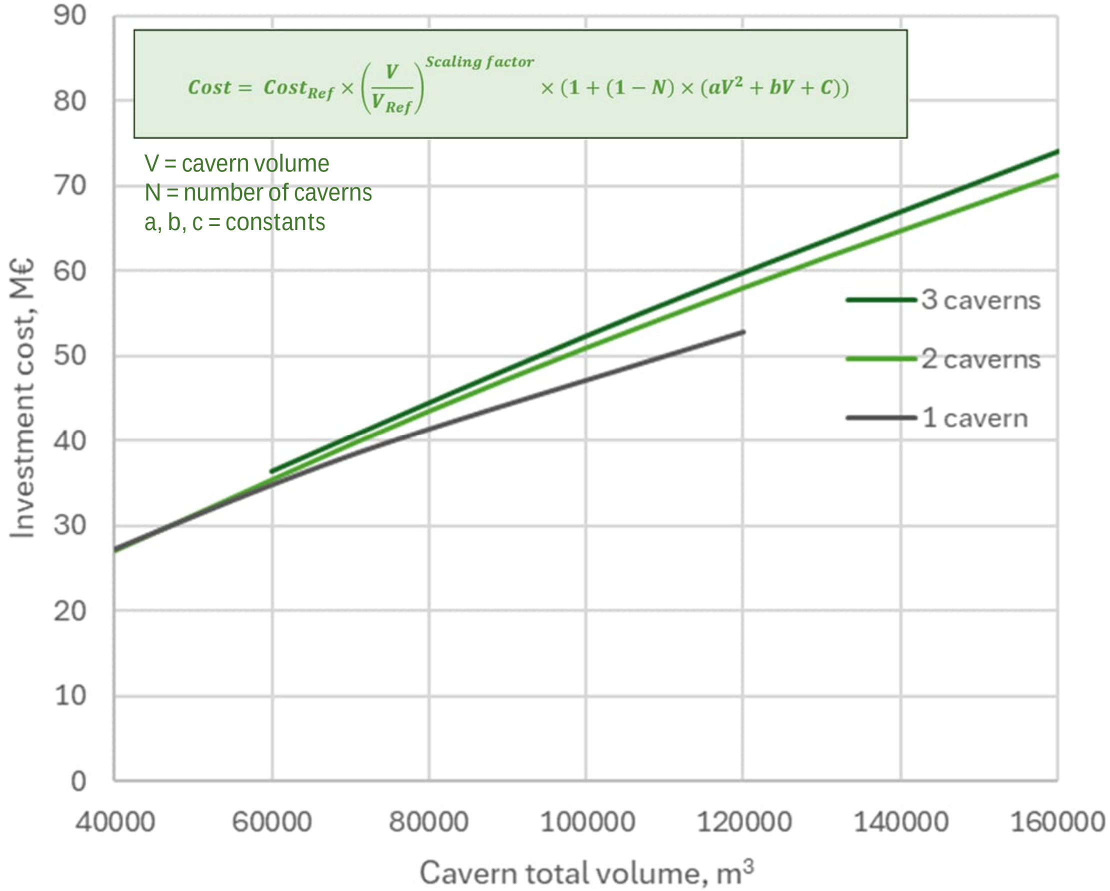




It is not so much more expensive to build multicavern storages

Total storage volume is more important in terms of costs

Multicavern storages would be more resilient to operational issues especially if storage is not connected to a large hydrogen pipeline



What has been studied / what have we learned?

- The effect of hydrogen demand
  - 1.6, 6.0 and 11.4 t/h (53 , 200 and 380 MW_{LHV})

→ No marked difference (LCOH 5.2->4.9 €/kg)

- The effect of year (2019 vs 2023)

→ Large differences in invested capacities mainly due to the differences in hours of cheap grid electricity
LCOH 4.99 vs. 3.95 €/kg

- Optimizing capacities for year 2019 and running the plant with 2023 data and vice versa

→ System optimized for year 2019 had LCOH 4.7 €/kg in 2023 (2023 optimal 3.95€/kg)
→ Optimum prices do not represent the costs for the whole lifecycle of the project

- The effect of forcing smaller than optimal storage size

→ Similar cost can be achieved with lower storage capacity

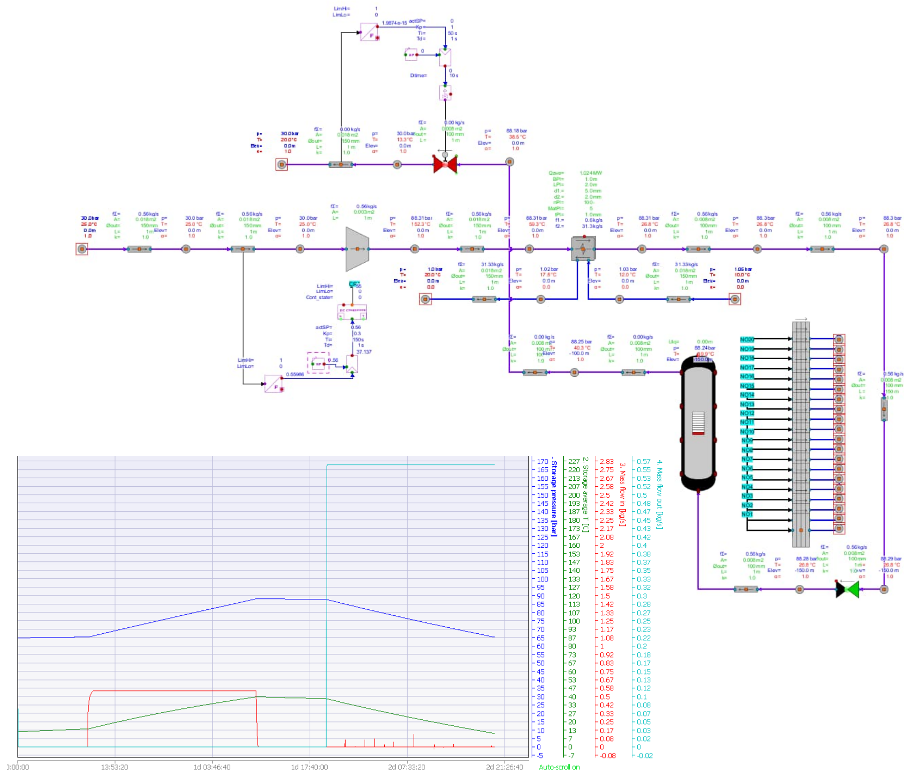
Cost-optimal solutions lead to very high storage capacities but basically same cost can be achieved with smaller storages

Parameter	Optimal storage 171 000 m3	120 000 m3 storage	80 000 m3 storage
Wind capacity (MW)	1000	1111	1130
Solar capacity (MW)	335	335	604
Electrolyzer capacity (MW)	670	605	594
Storage volume (m^3)	170 970 (2 x 85 485 m3)	120 000 (forced)	80 000 (forced)
Storage capacity (d)	21	14.6	9.7, disch rate limited to 5.6 t/h
Storage cycles (/y)	5.7	7.45	9.8
Electrolyzer utilization rate	49%	55%	56%
Electrolyzer operating hours	7499	7679	7805
LCOH (€/kgH_2)	4.99 grid sales 0.15	5.00 grid sales 0.38	5.00 grid sales 0.56

- 6 t/h (200 MW_{LHV}) H2 demand
- 2019 electricity market and wind/solar data

- In case a smaller storage is forced, model invests more in RE PPAs → Smaller electrolyzer with higher utilisation & more excess electricity to be sold to the spot
- At 80 000 m3, the filling and withdrawal rates are capped (assumed max 0.4%/h) → Faster storages than Skallen could be needed
- These simulations will be done also for 2023 data and going to even smaller storages.

Apros modelling



Temperature control in LRC is a key issue

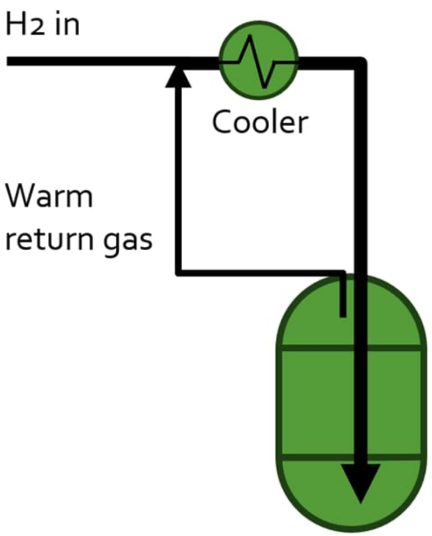
- Temperature control is needed to ensure the integrity of liner materials and prevent freezing of water outside of the storage
- It can be used to maximize the storage capacity (colder gas is more dense) but this effect is lot smaller with H2 compared to natural gas
- During filling the storage, it will heat up and when gas is withdrawn, the storage will cool down
  - The rate of the temperature changes are directly related to filling and withdrawal rate
  - With proper heat management, filling and withdrawal rates can be increased
- By implementing predictive/anticipatory control strategies, the storage could be prepared to better cope with the expected situations
  - For example, in case weather forecasts indicate that it will be very calm next week, the storage could be heated up beforehand to cope with the expected need to withdraw a lot of gas next week (calm weather = low wind power production & high spot electricity price)

How to control the temperature?

- Temperature can be controlled by implementing gas re-circulation and heating/cooling of the recirculating gas as explained in the (expired) US patent 6,374,844
- Patent considers natural gas but similar system can be used also for hydrogen

Filling the storage

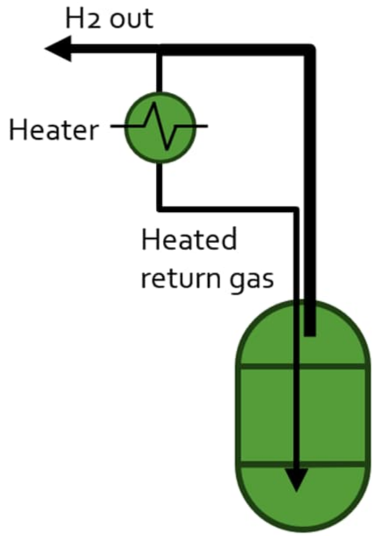
Part of the warm gas from the top of the cavern is recirculated and cooled in the same heat exchanger as the feed flow



Temperature gradient will form leading to higher gas temperatures at the top of the cavern

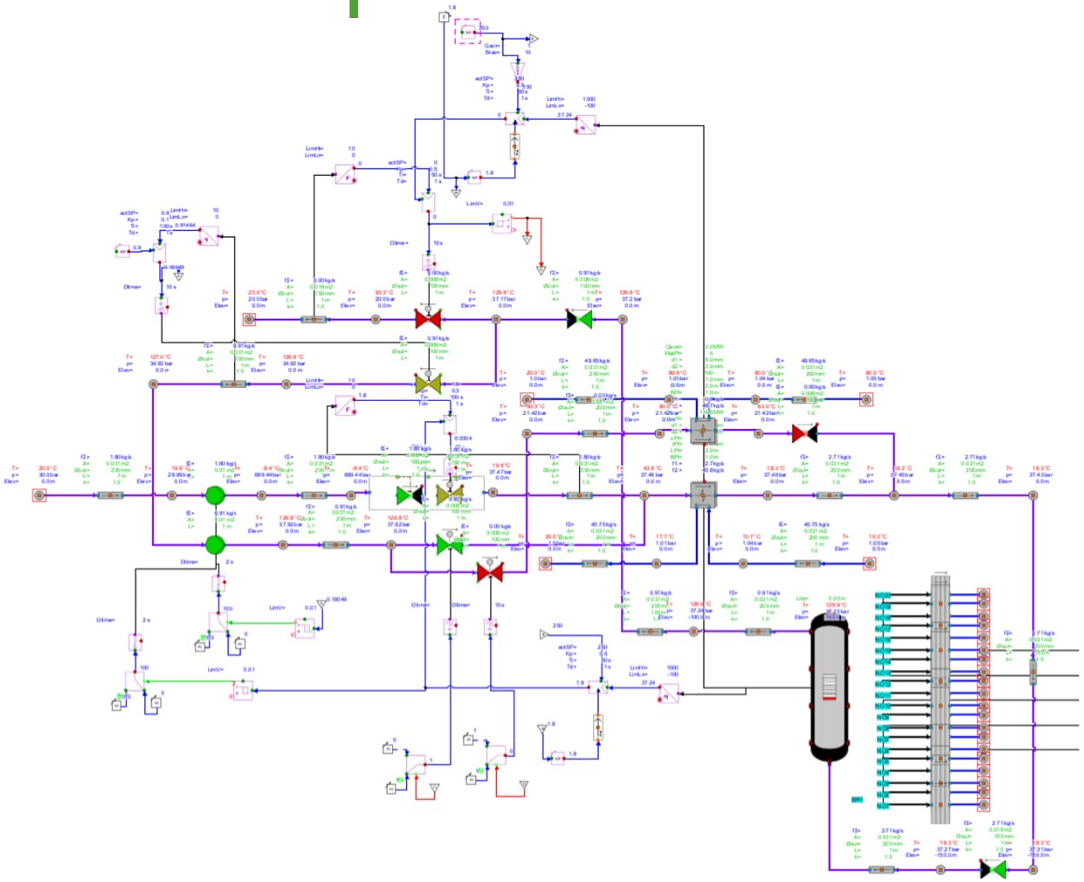
Withdrawing gas

More gas is withdrawn than is needed and part of it will be heated and sent back to the storage



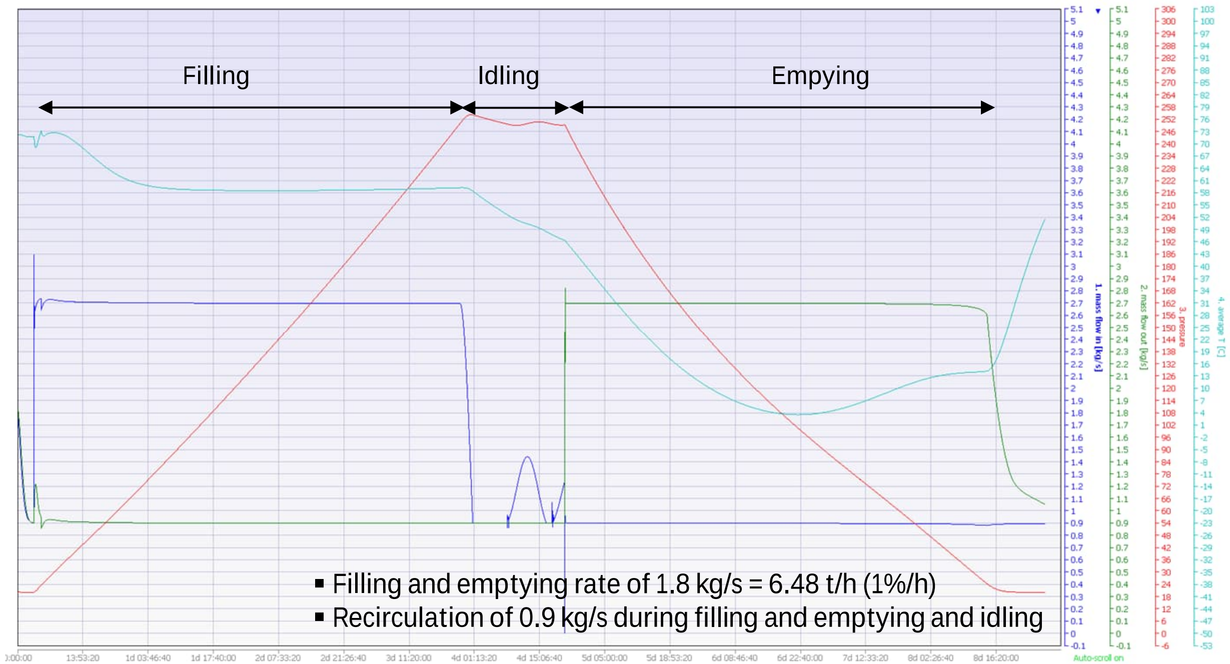
Recirculation temperature control has now been implemented in Apros

- Based on US patent 6,374,844
- Recycle stream heated with 80°C water to about 72°C
- Recycle stream cooled with 10°C water together with feed hydrogen
- Recirculation is mass flow controlled
  - Possible to test the effect of different flow rates
  - More advanced controls can be implemented

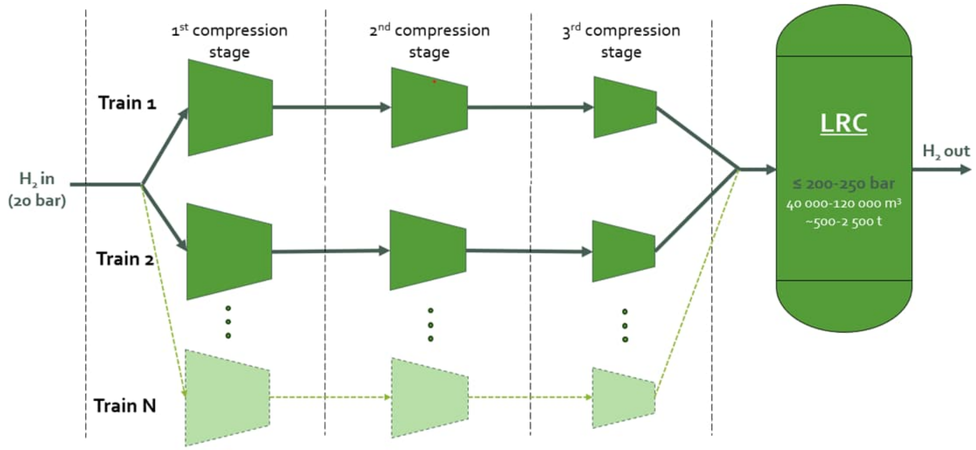


Very first test runs for gas recirculation have been done

- Model seems to work fine
- Average temperature of the storage is not sufficient to describe temperature management - temperatures at different heights need to be considered
  - Apros model has 20 nodes
- Process control / automation is key
- More test runs will be run and results will be analysed in more detail in the upcoming months



Compressor technology screening & compressor train design LRC



Compressor technology screening

Objective:
Select the most suitable compressor technology and design a flexible compressor system concept for an LRC storage

Challenge:
The pressure of the LRC can vary between ~20–250 bar and flow rates can be up to several hundred thousands of normal cubic meters.

Electrolyzer load can for example vary between ~5–110%. → Compressors may become a limiting factor for flexible operation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Screening of suitable H_2 compressor technologies for LRC storage – HUG project

Jeremias Hopsu

1/21/2026 VTT – beyond the obvious

VTT

Contents

- Key LRC storage characteristics in the HUG project
- Compressor technology screening
- Compressor system design
- Potential manufacturers with suitable compressor solutions
- Cost information (CAPEX & OPEX)

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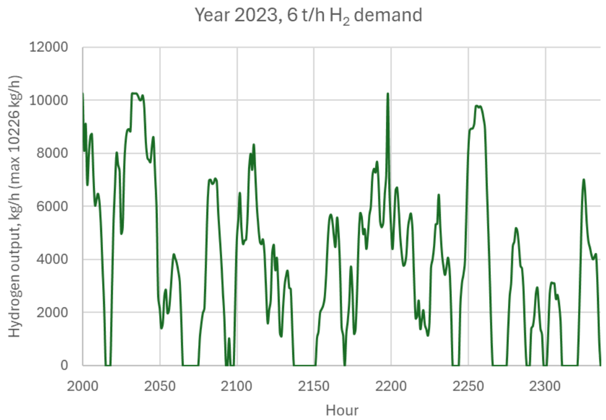
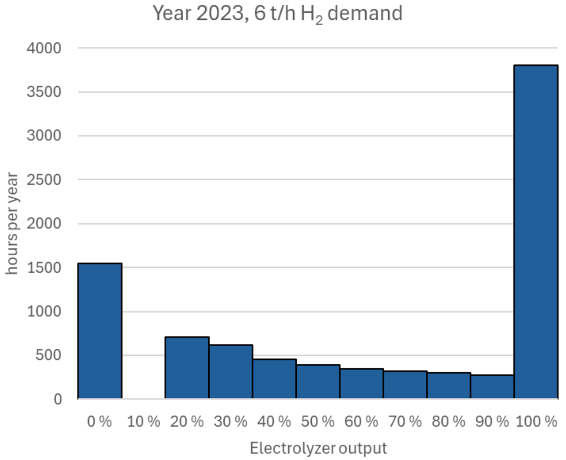
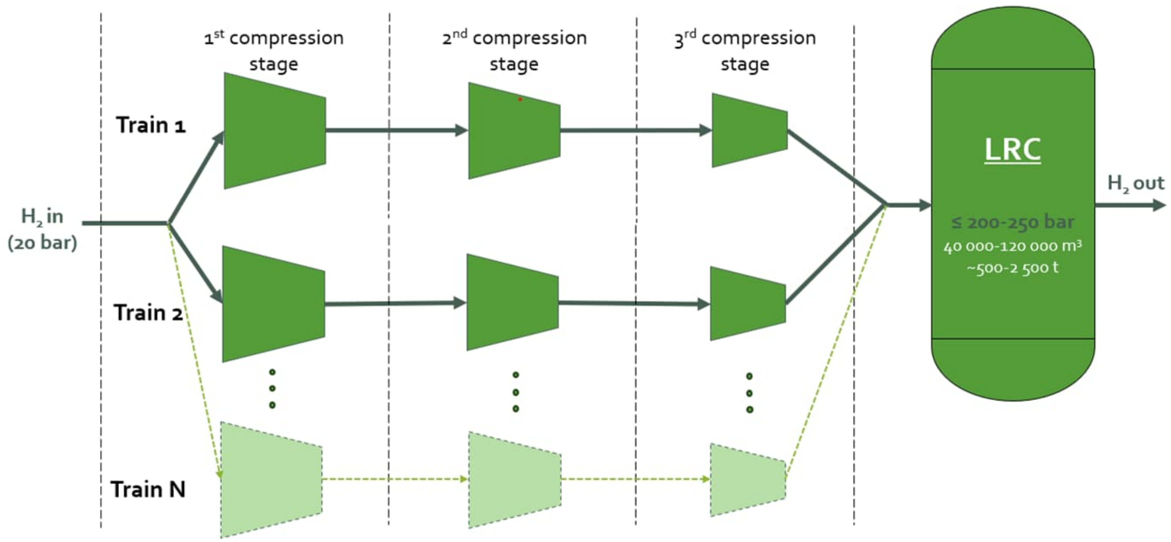
Compressors will need to be operated flexibly

Example H2 production from a 2 week period



Yearly distribution of electrolyzer output





- As production of green hydrogen will fluctuate, compressors need to have sufficient turn-down.
- Typically minimum load of piston compressors is ~50-60%
  → Parallel compressor trains
- Parallel trains will also help to increase the reliability of the system

Compressor technology screening

Main research questions:

- What compressor types are suitable for required flow rates and pressure levels?
- What is the minimum load or “turn-down ratio” of these compressors?
- What is the efficiency of compressors (at different operating points)?
- How can compressor flexibility be improved?
- Availability of suitable large-scale H2 compressors / manufacturer mapping
- Investment cost of compressors?

The findings from the study will be presented on HUG Meeting Square on Feb 13th by Jeremias Hopsu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1/21/2026 VTT – beyond the obvious

Thanks! Questions?