Tampere University

Hydrogen as an interacting component of future energy system

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Outline

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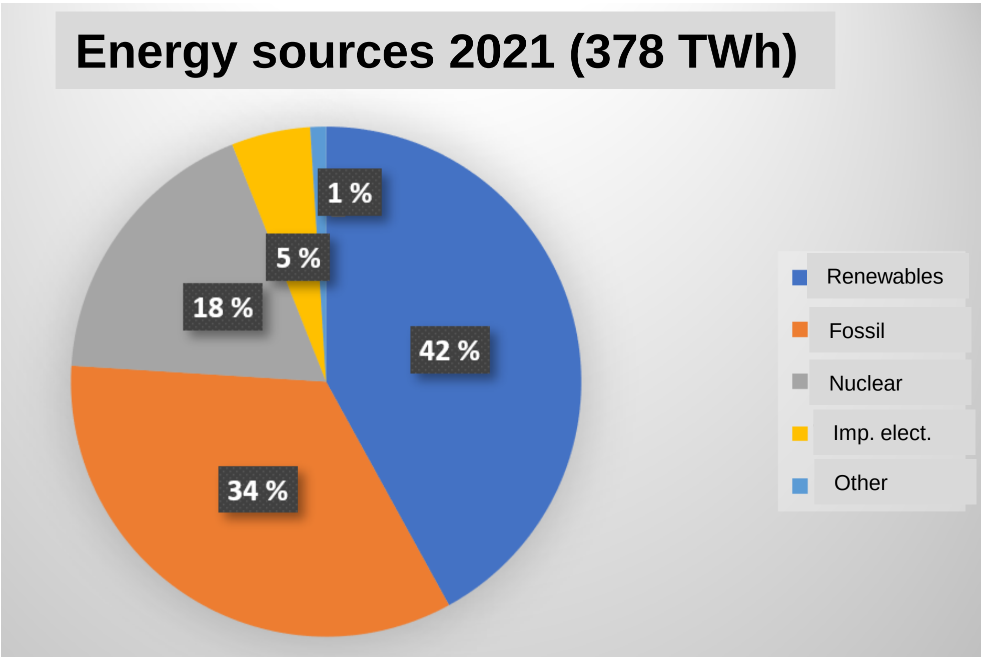
  - Decarbonization of the society and green hydrogen production
- System Dynamics
  - Renewable energy production
  - Power system inertia
  - Hydrogen production
- Hydrogen production as a flexible load
- Conclusions

Introduction

Decarbonization of the society and green hydrogen production

- Total energy consumption of Finland in 2021 was 378 TWh (1.36 milj. TJ)
  - Renewable sources 159 TWh(42%)
    - Hydro, wind, solar PV, biomass
  - Fossil fuels and peat, 129 TWh (34%)
    - Oil based 71.1 TWh
    - Hard coal 23.4 TWh
    - Natural gas 20.8 TWh
    - Peat 10.6 TWh
  - Nuclear energy 69 TWh (18%) -> 22.6 TWh electricity
  - Imported electricity 18 TWh (5%)



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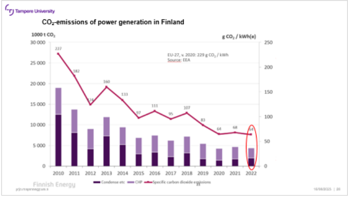
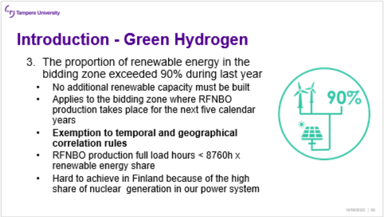
Introduction

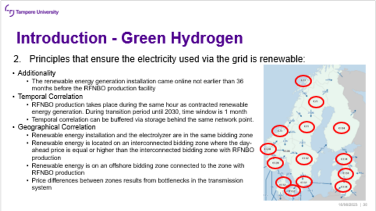
Decarbonization of the society and green hydrogen production

Rules for producing renewable fuels of non-biological origin - RFNBO

- Basic rule: Green Hydrogen should be produced by splitting water (electrolysis) using **renewable energy**
- Additionality
  - The renewable energy generation installation came online not earlier than 36 months before the RFNBO production facility
- Temporal Correlation
  - RFNBO production takes place during the same hour as contracted renewable energy generation. During transition period until 2030, time window is 1 month
- Geographical Correlation
  - Renewable energy installation and the electrolyzer are in the same bidding zone of the electricity spot market



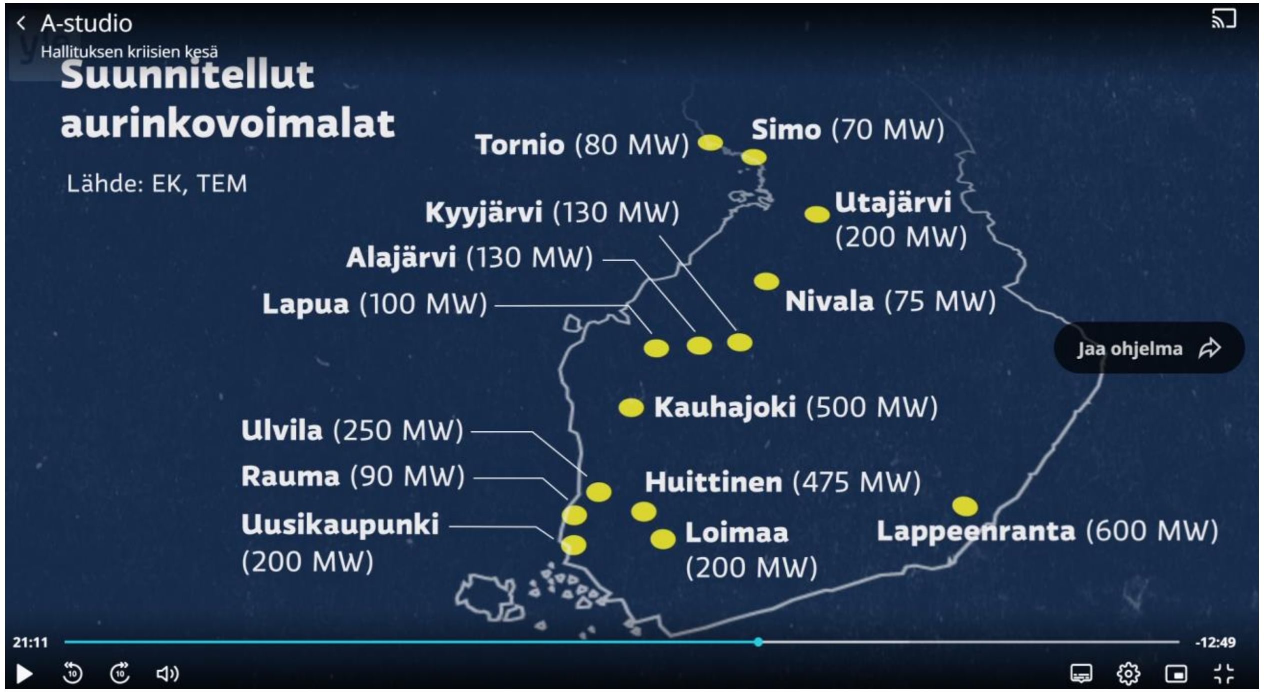




Variable renewable energy production and power system dynamics

Power System dynamics
Solar PV Production

- Planned PV plants now (3100 MW) and prognosis to 2030



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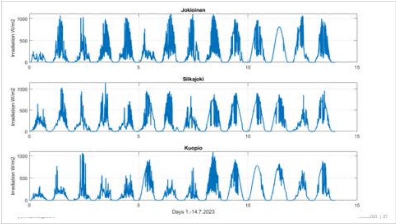
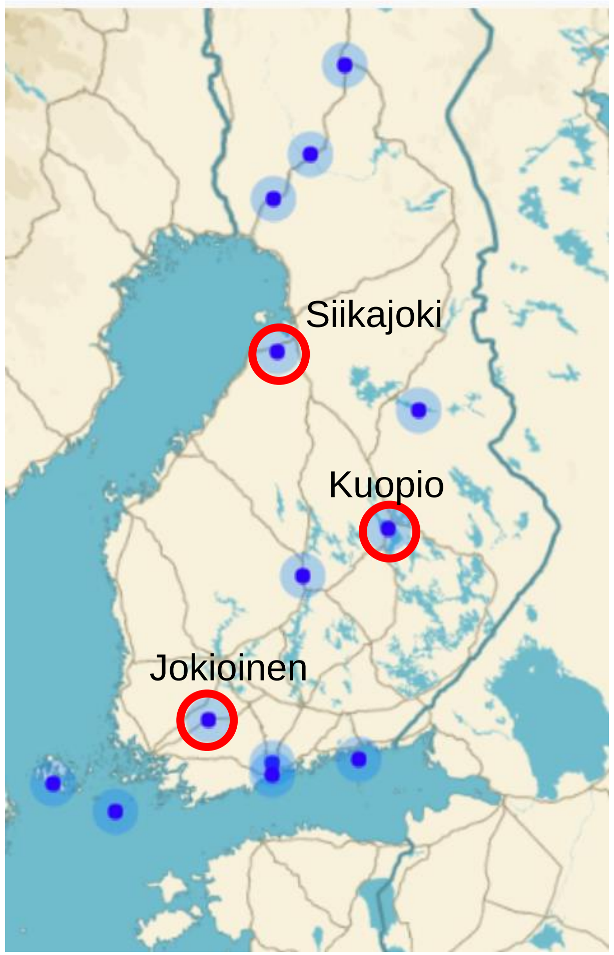
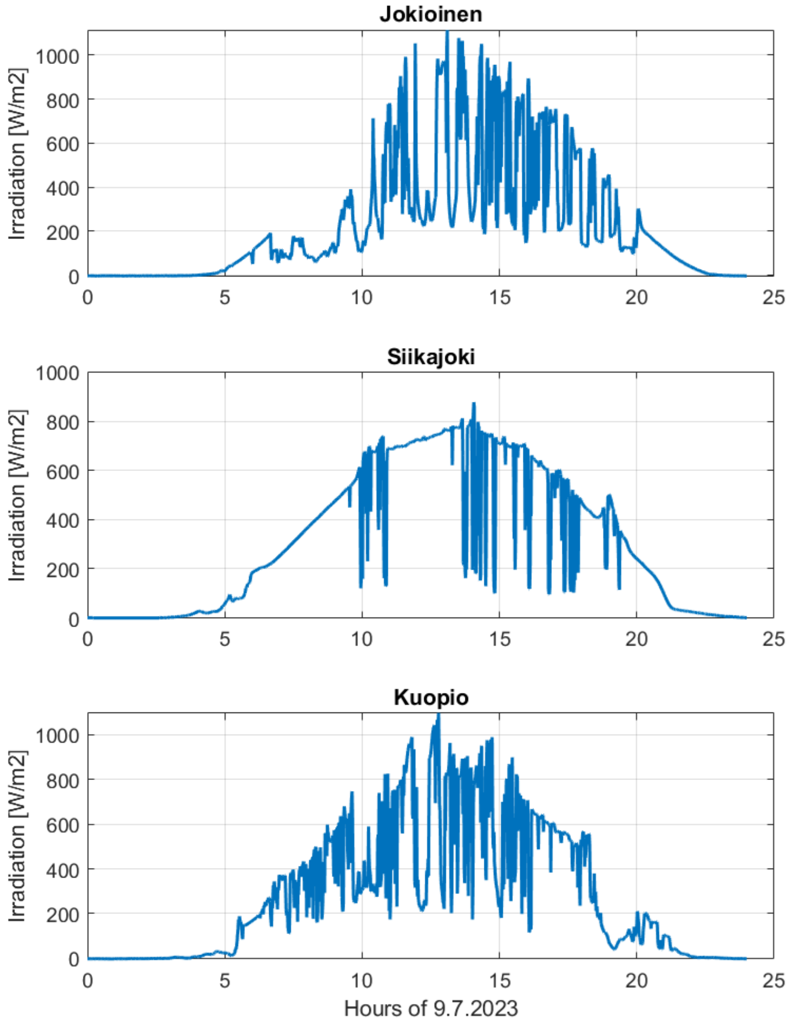
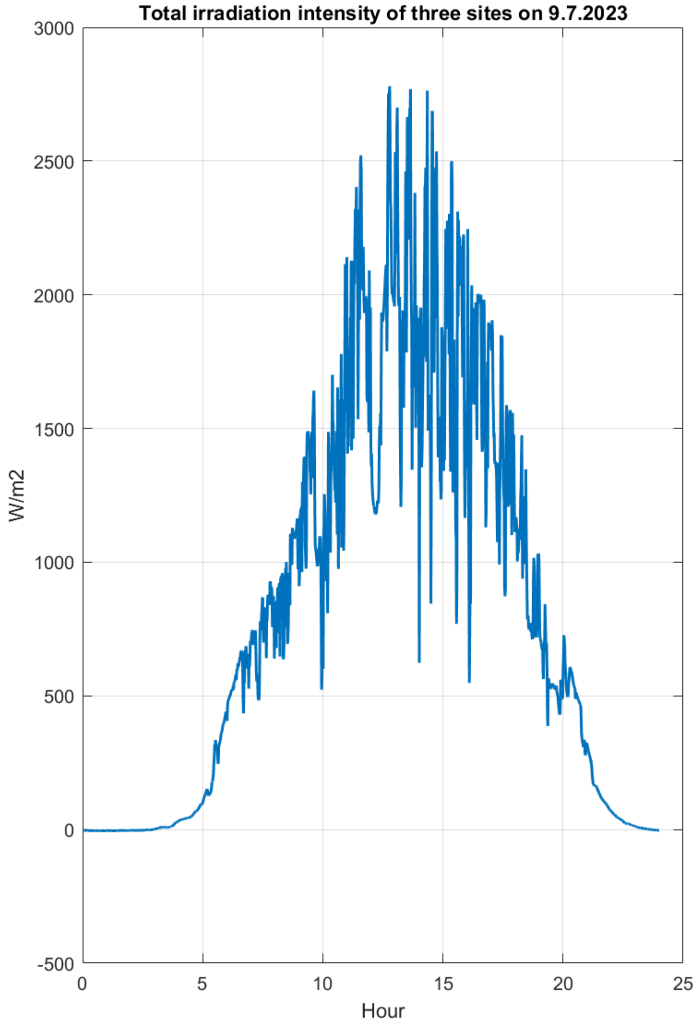
System dynamics
Solar PV Production

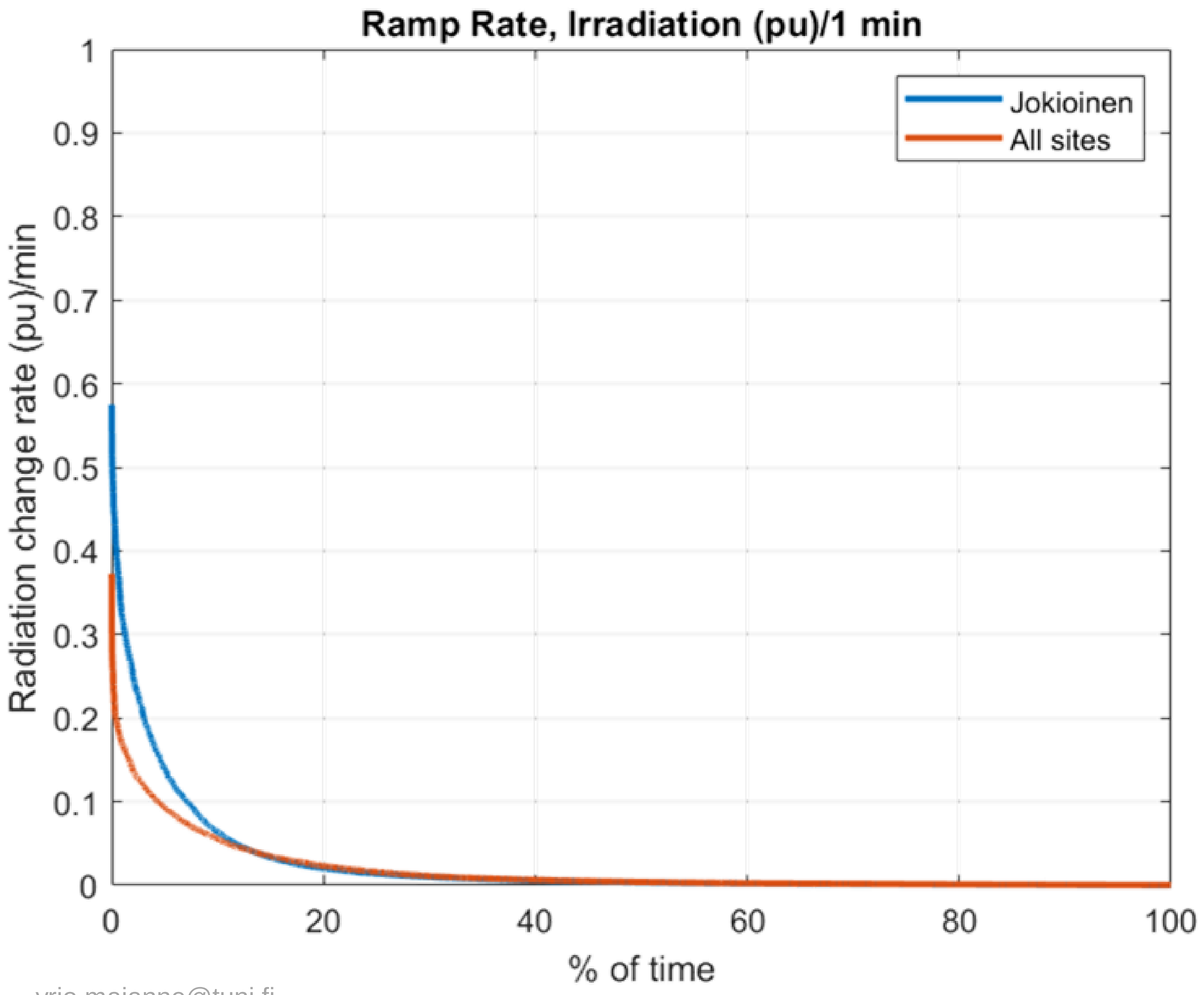






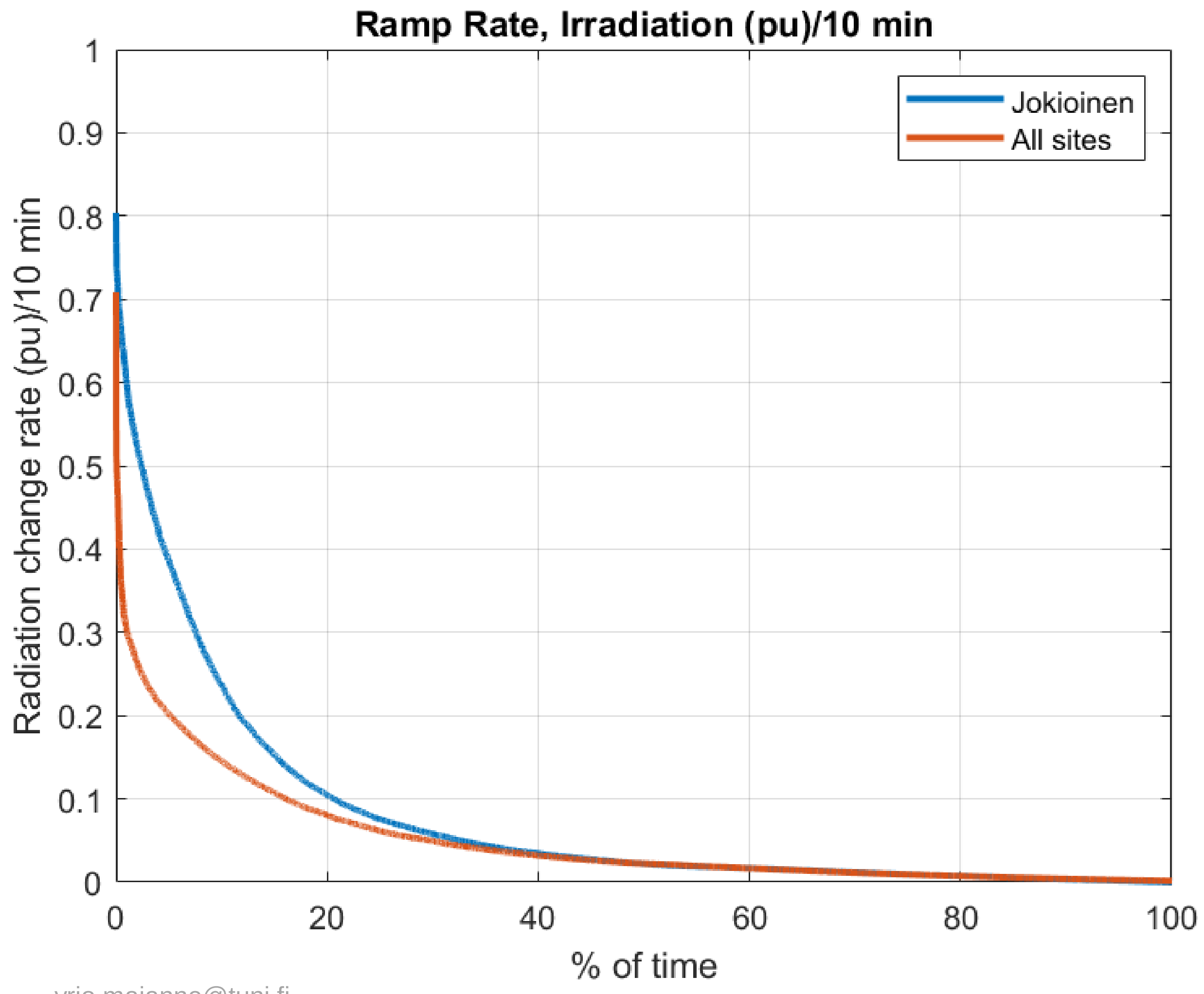


System dynamics
Solar PV Production



- 1 min relative ramp rate duration curves on 1.-14.7.2023
- Single site, Jokioinen
  - maximum 1 min ramp rate 57% / min from max. intensity
- All sites summary
  - maximum 1 min ramp rate 37% /min from max. intensity

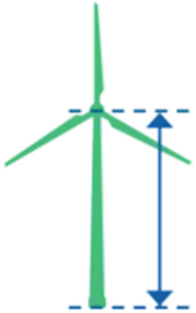
System dynamics
Solar PV Production



- 10 min relative ramp rate duration curves on 1.-14.7.2023
- Single site, Jokioinen
  - maximum 10 min ramp rate 80% / 10 min from max. intensity
- All sites summary
  - maximum 1 min ramp rate 71% / 10 min from max. intensity

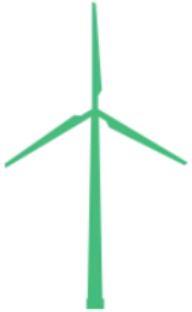
Example wind power site

10 kpl

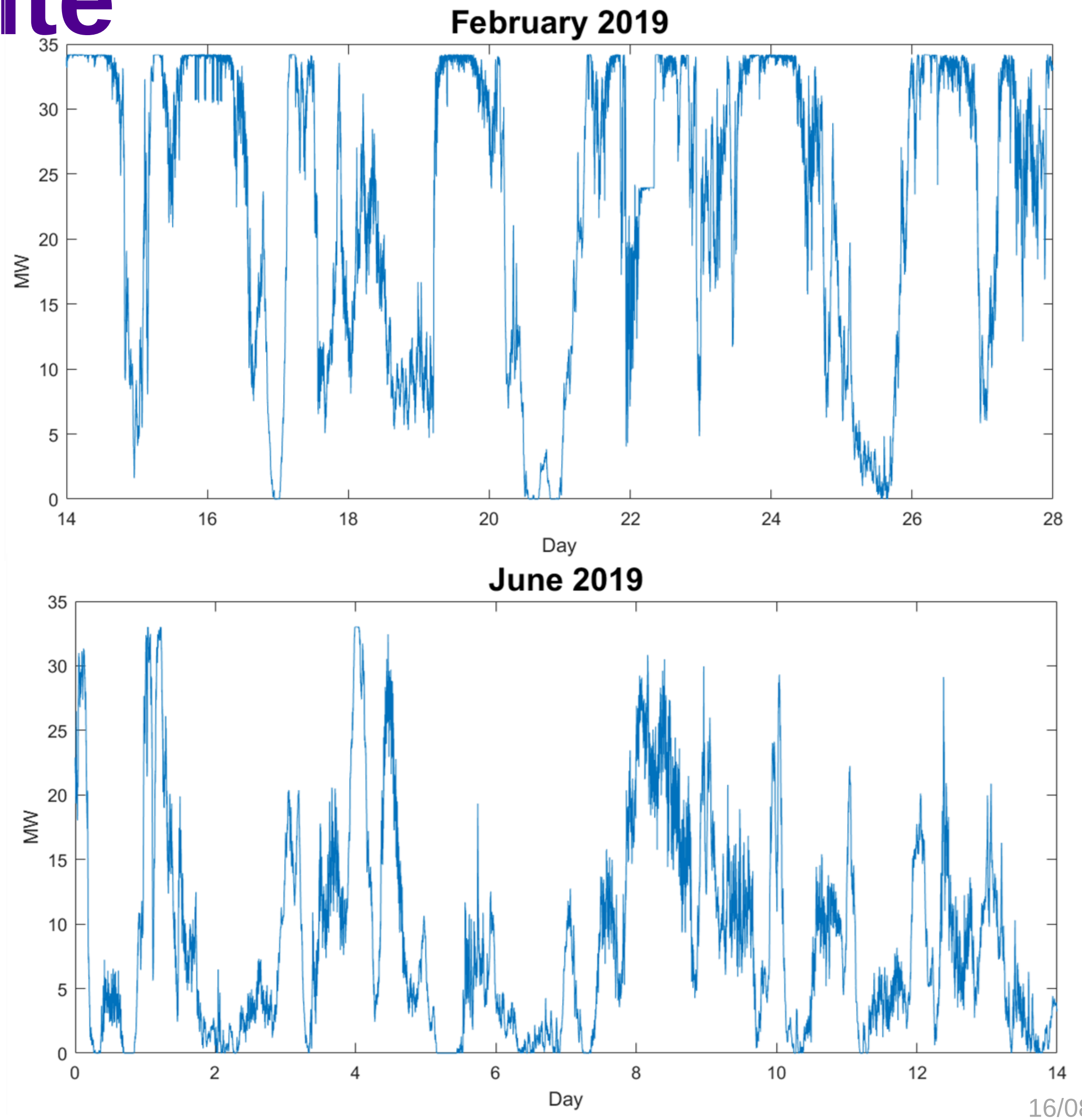


137 m

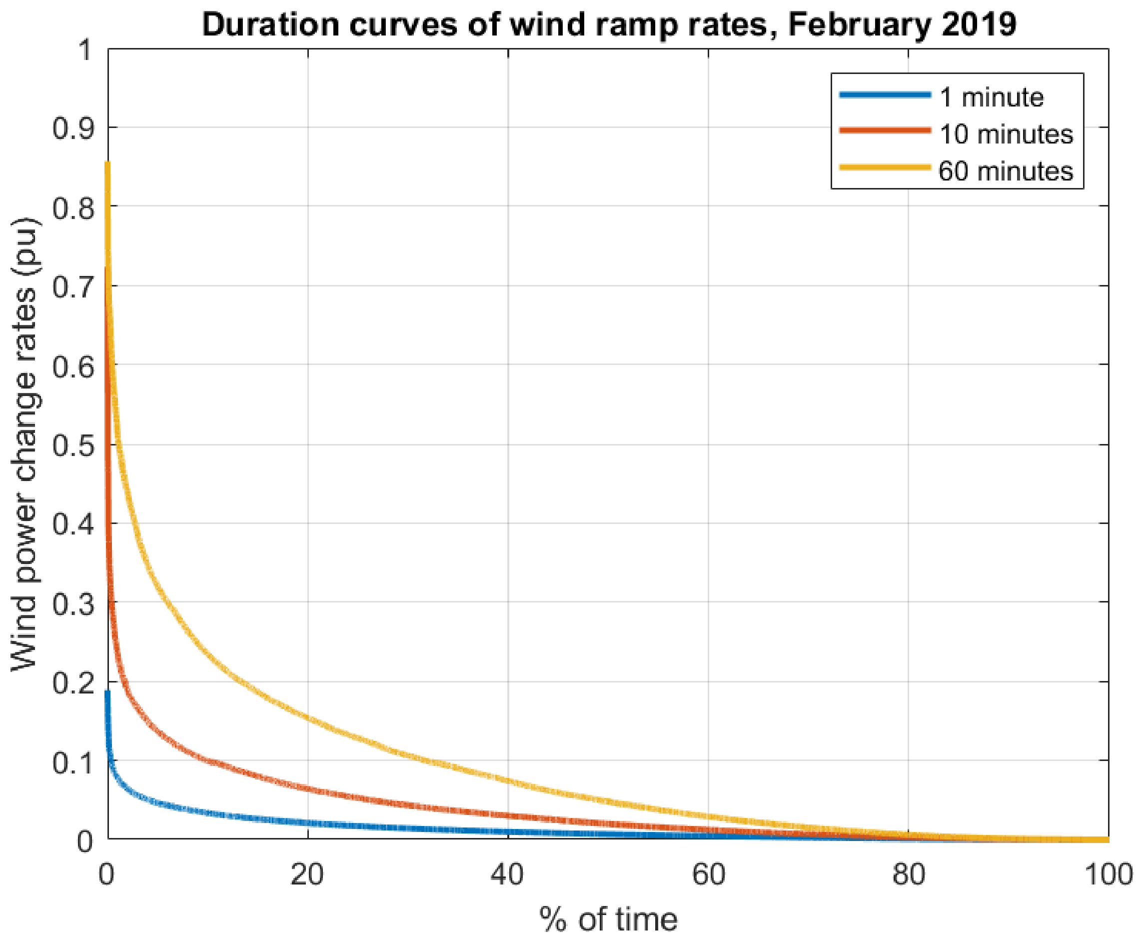
126 m

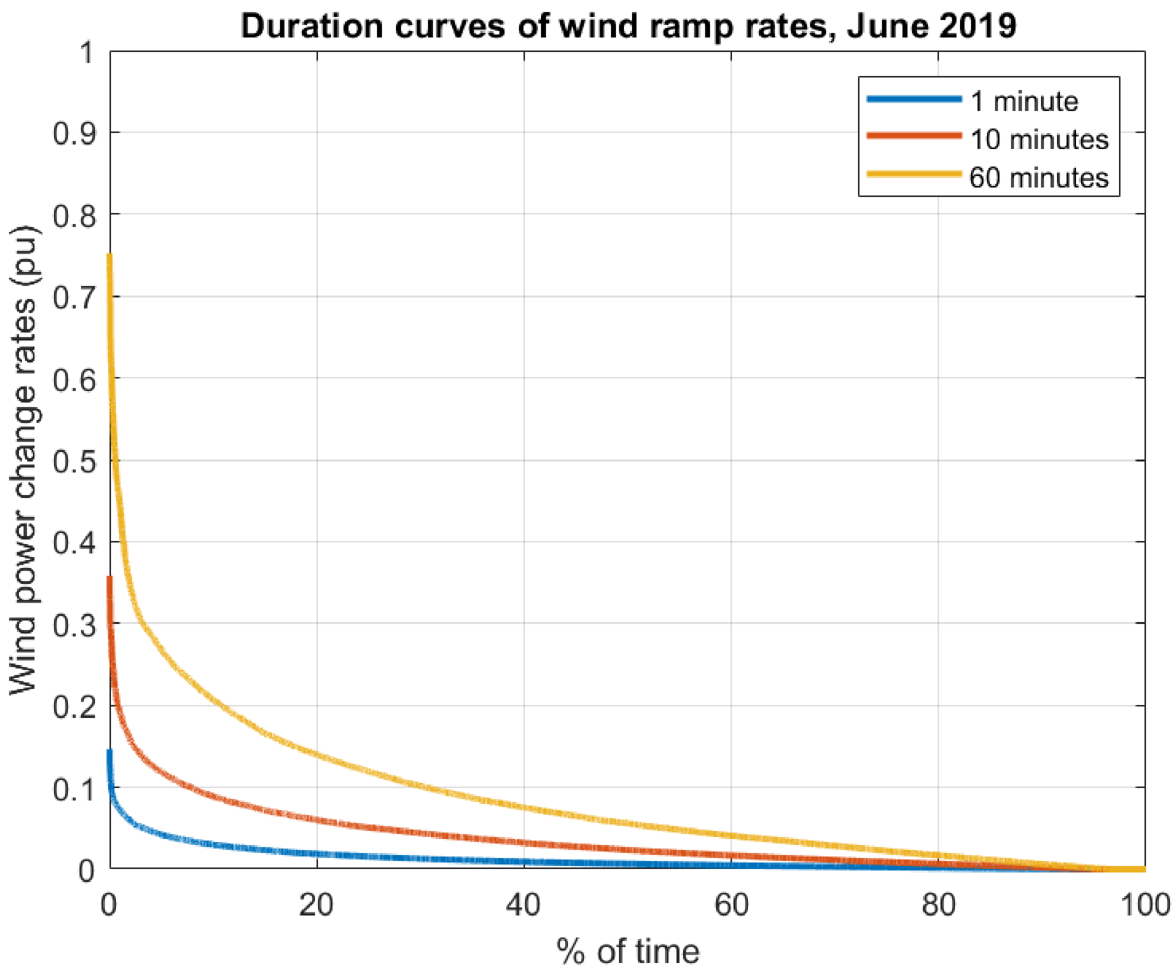


3,45 MW

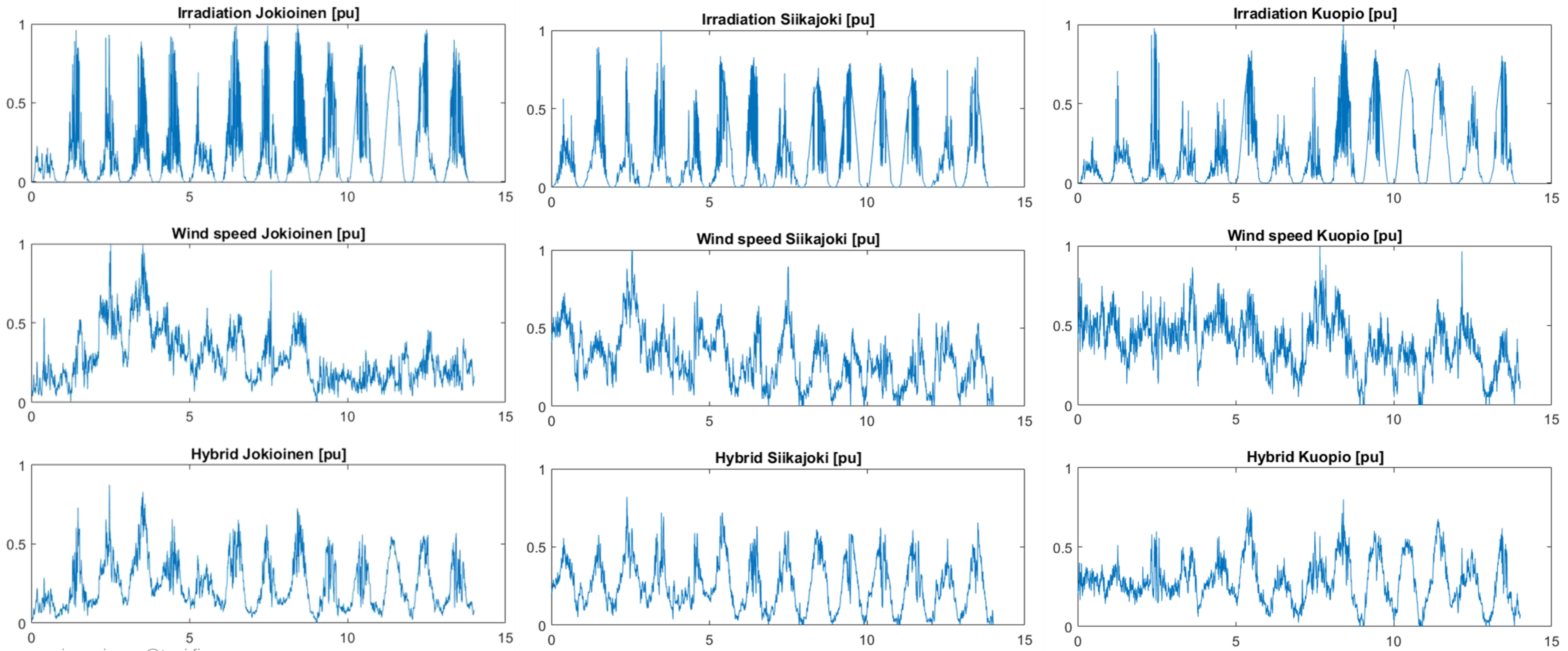


Example wind power site, ramp rates



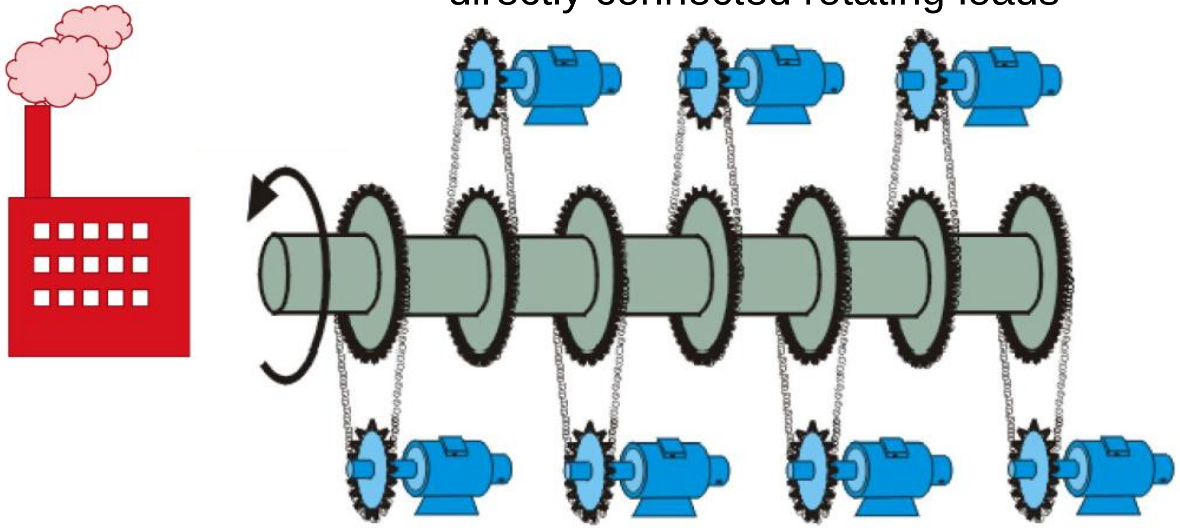


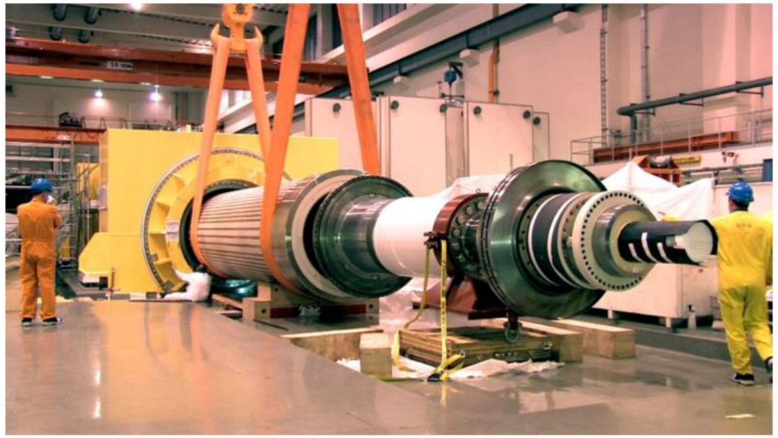
Hybrid behaviour during 1. – 14.7.2023



System dynamics
Power System Inertia (Kinetic Energy)

Synchronous generators and
directly connected rotating loads





OKG Photo-library. http://www.okg.se/en/Media/Photo-library Noudettu 21.11.2013

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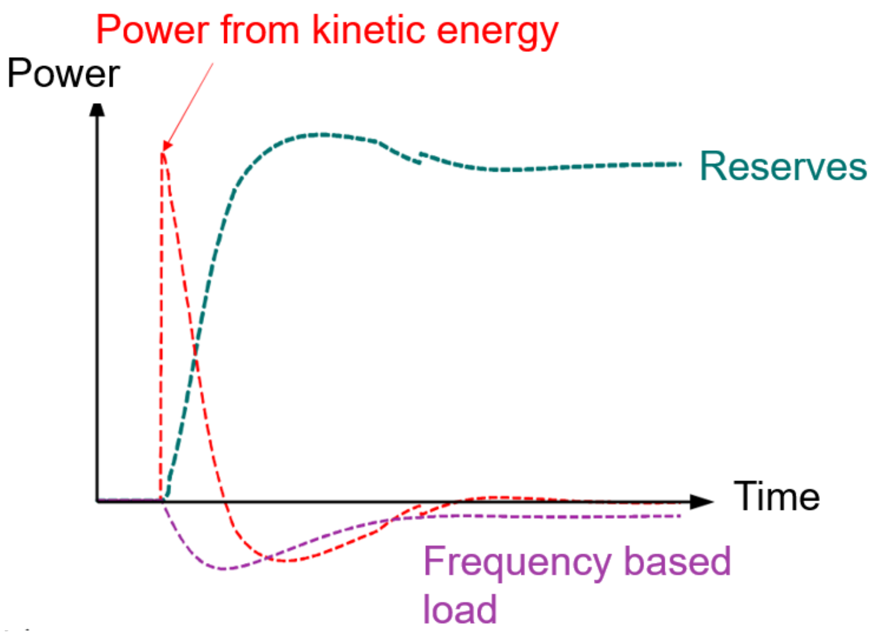
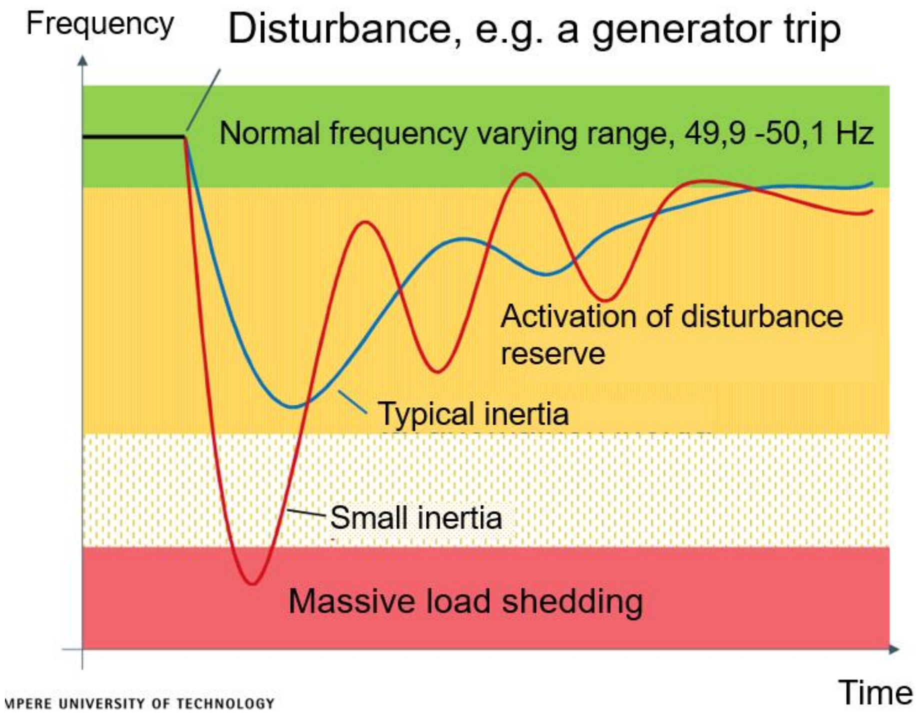
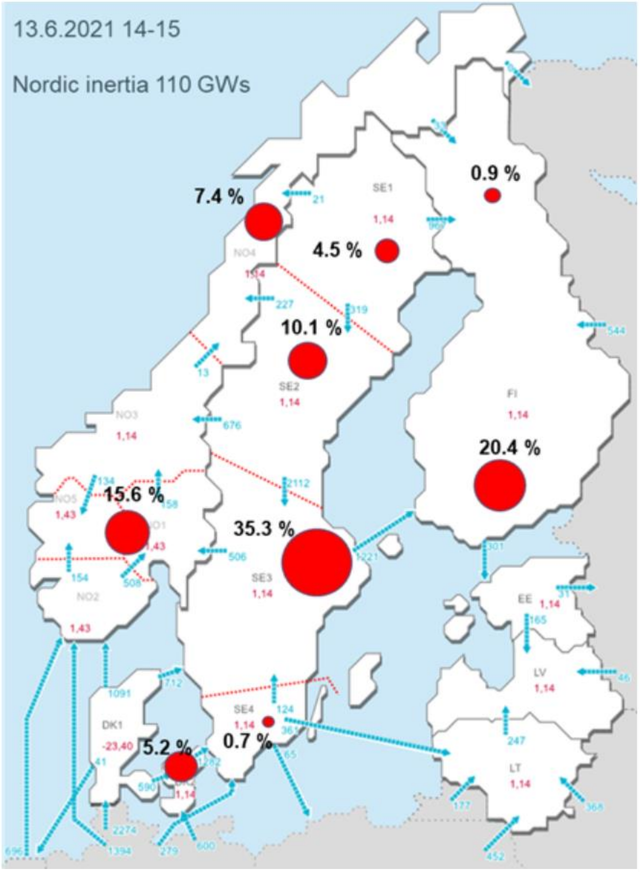
System dynamics
Power System Inertia (Kinetic Energy)

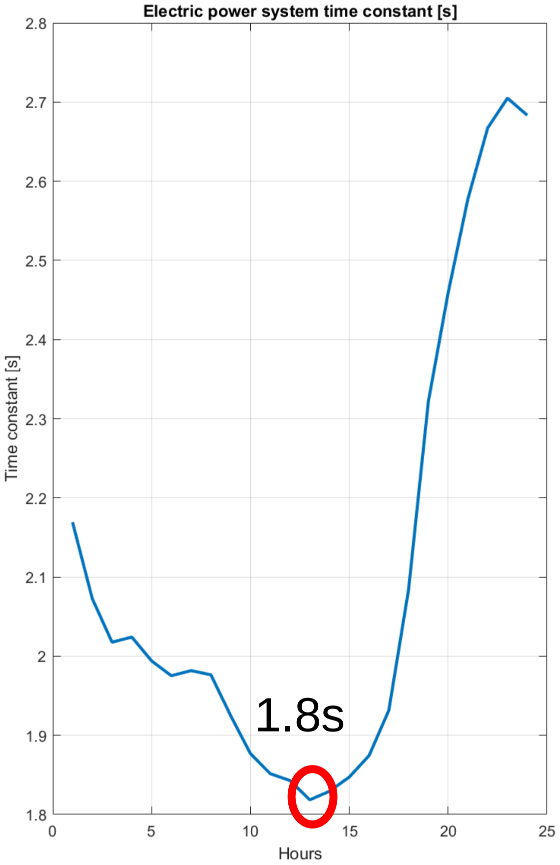
- System inertia plays a VERY important role in maintaining frequency stability
  - responses first, within 0.1 - 2 seconds, to frequency disturbances by injecting energy to a system in case of power deficit and vice versa in case of excessive power
- After 2-5 seconds fast controllable resources start to take the responsibility of balancing the system

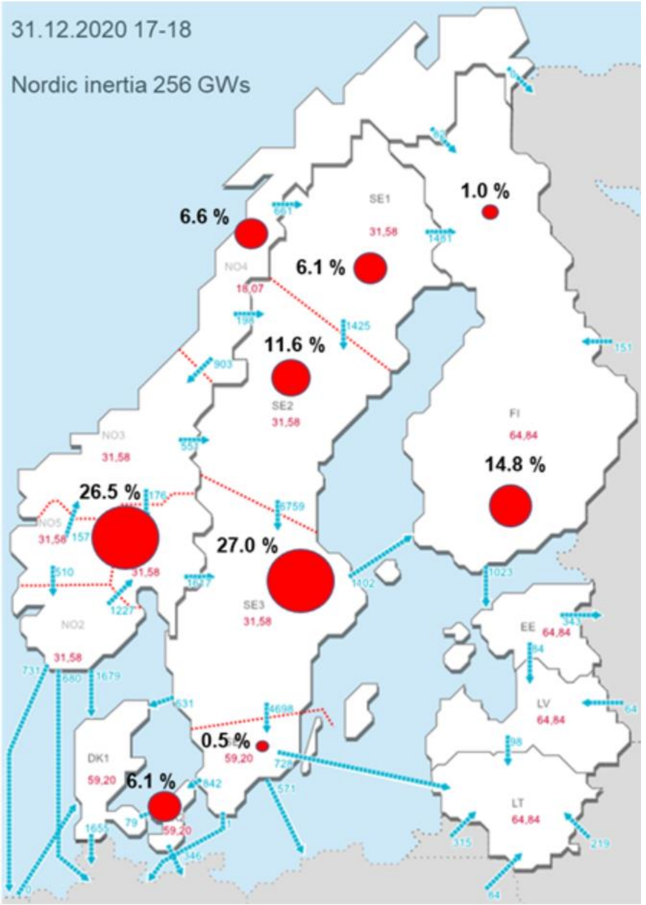


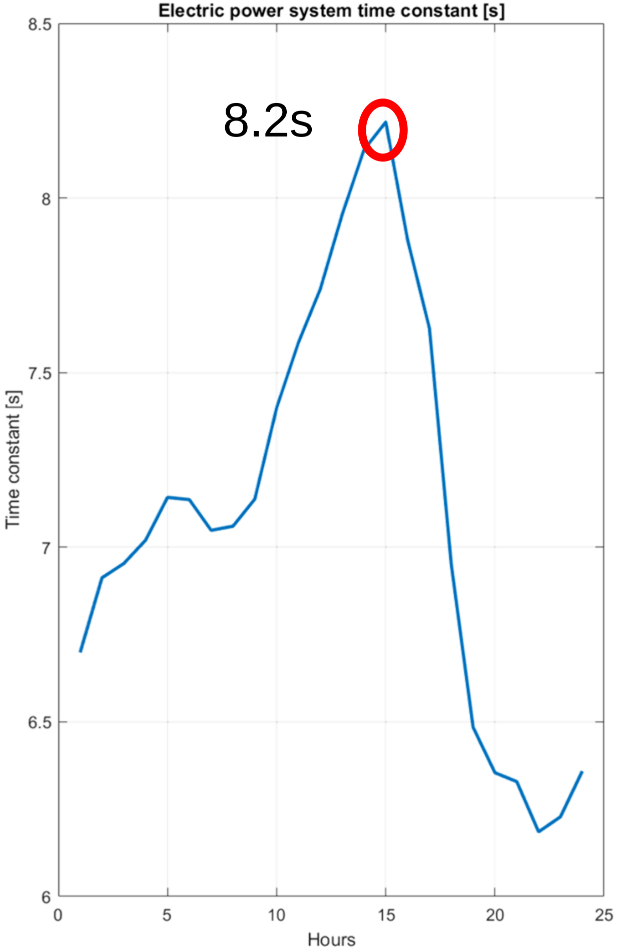


Power System Inertia (Kinetic Energy)









Evolution of Power System Dynamics

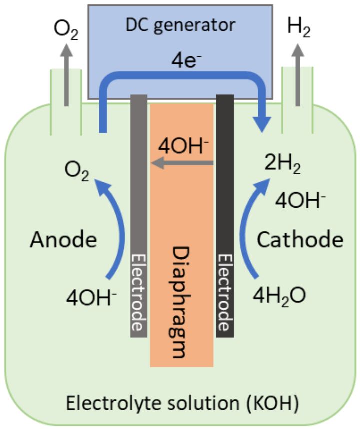
- Increased variable renewable generation
  - Induces big and fast disturbances to power balance
  - Pushes out controllable generation capacity from the power market
- Increased share of frequency converter connected production in the system reduces system inertia
  - Makes disturbance dynamics faster -> increases need for faster compensation resources
- Evolution of loads to frequency converter controlled motors and resistive loads reduce system inertia and reduce system's ability to adapt consumption as a function of the change of system frequency

THERE IS A HUGE NEED FOR FASTLY CONTROLLABLE CONSUMPTION TO BE USED FOR BALANCING THE POWER SYSTEM

Hydrogen production as a flexible load

Hydrogen Production by electrolyzers

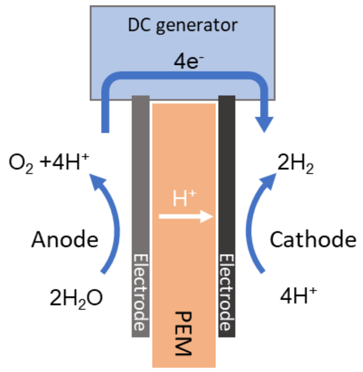
Alkaline



Anode: $4OH^- \leftrightarrow 2H_2O + O_2 + 4e^-$

Cathode: $4H_2O + 4e^- \leftrightarrow 2H_2 + 4OH^-$

Proton Exchange Membrane



Anode: $2H_2O \leftrightarrow O_2 + 4H^+ + 4e^-$

Cathode: $4H^+ + 4e^- \leftrightarrow 2H_2$

	Alkaline	PEM
Operating temperature	80–90 °C	50–80 °C
Operating pressure	≤32 bar	≤50 bar
Hydrogen purity	≥99.8 %	≥99.99 %
Corrosion	Alkaline corrosion	No
Operating characteristics	Isobaric operation	Differential pressure operation
Volume and weight	Large	Small (~1/3 of the alkaline electrolyser)
Manufacturing cost	Low	High

- Alkaline electrolyzers are robust, reliable and their **flexibility is also on a high level**.
  - Can be started and run at maximum power in 30 minutes and that in 10 minutes capacity can be changed from 15% to 100%.
- PEM electrolysis has faster start-up time, faster response in ramp-up and ramp-down capability, wide dynamic operating range from 0% to 100%, cheaper maintenance costs and more compact structure.

System dynamics
Synthesis processes, Methanation

- Methanation is typically implemented by hydrogenation of CO_2 via Sabatier process or by hydrogenation of CO via Fischer-Tropsch process
- End products can be methane (CH_4) or methanol (CH_3OH)
- Operational temperatures of these processes range typically between 250 and 350 °C and operating pressure around 25 - 100 bar.
- **Operation range 20…40 – 100%**
- **Load ramp rate 5 – 20%/h**

System dynamics
Synthesis processes, Ammonia

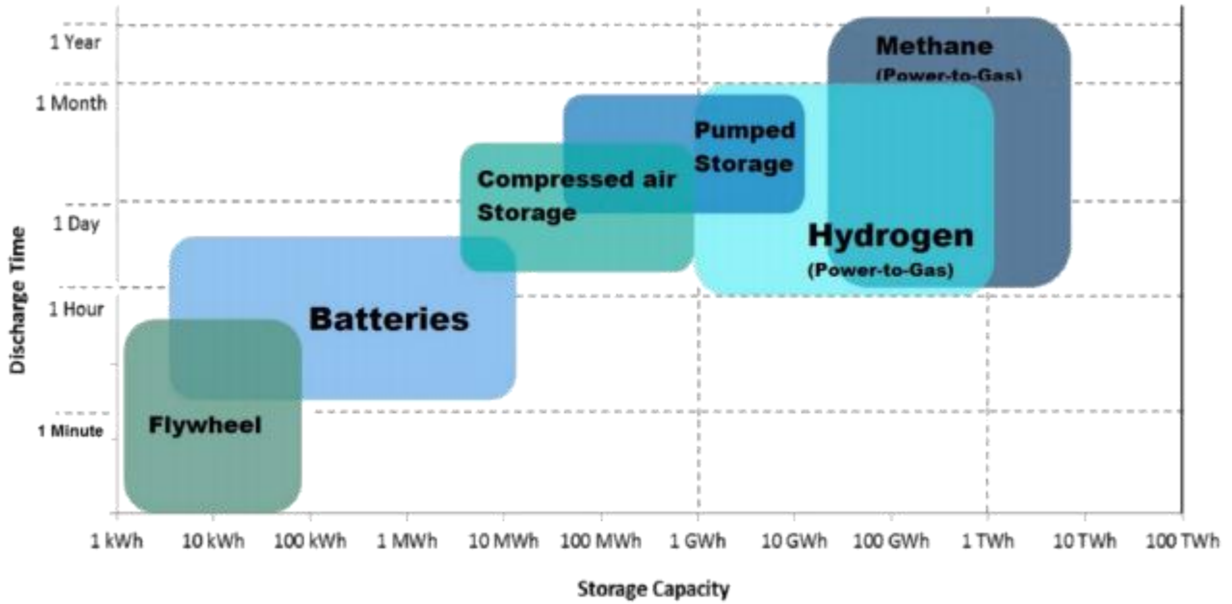
- Ammonia via Haber – Bosch process
  - Atmospheric nitrogen and hydrogen are converted to ammonia using a metal catalyst.
  - Operating temperature 400–650 °C
  - Operating pressure 20–40 MPa
  - **Continuous operation of the process should be ensured to prevent damaging the catalyst**
  - Haber-Bosch process is highly energy intensive
  - Also, the provision of the required heat and pressure and the production of nitrogen through air separation need to be powered by renewable energy.

System dynamics
Direct industrial H_2 utilization

- Steel manufacturing, hydrogen reduction of iron oxide (HYBRIT)
  - Reduction process must be operated at steady state at constant operation point
- Hydrogenation processes in oil refineries
  - Hydrogenation processes must operated at steady state at constant operation point
- NO FLEXIBILITY AVAILABLE

Storages

- Electricity



Source: School of Engineering, RMIT University (2015)

Figure 3. Available storage technologies, their capacity and discharge time.

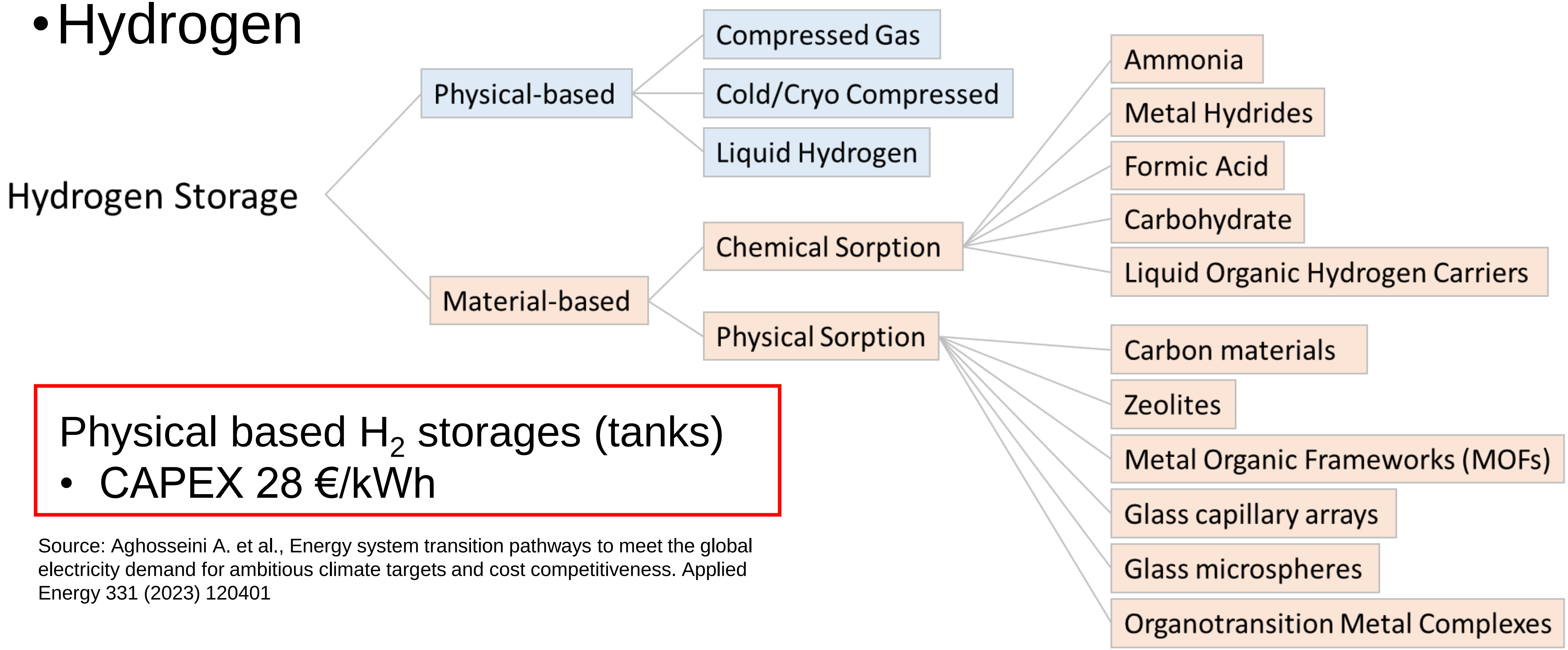
Battery storage

- CAPEX
  - 110 €/kWh 2030
  - 61 €/kWh 2050

Source: Aghosseini A. et al., Energy system transition pathways to meet the global electricity demand for ambitious climate targets and cost competitiveness. Applied Energy 331 (2023) 120401

Storages

- Hydrogen



Physical based H_2 storages (tanks)

- CAPEX 28 €/kWh

Source: Aghosseini A. et al., Energy system transition pathways to meet the global electricity demand for ambitious climate targets and cost competitiveness. Applied Energy 331 (2023) 120401

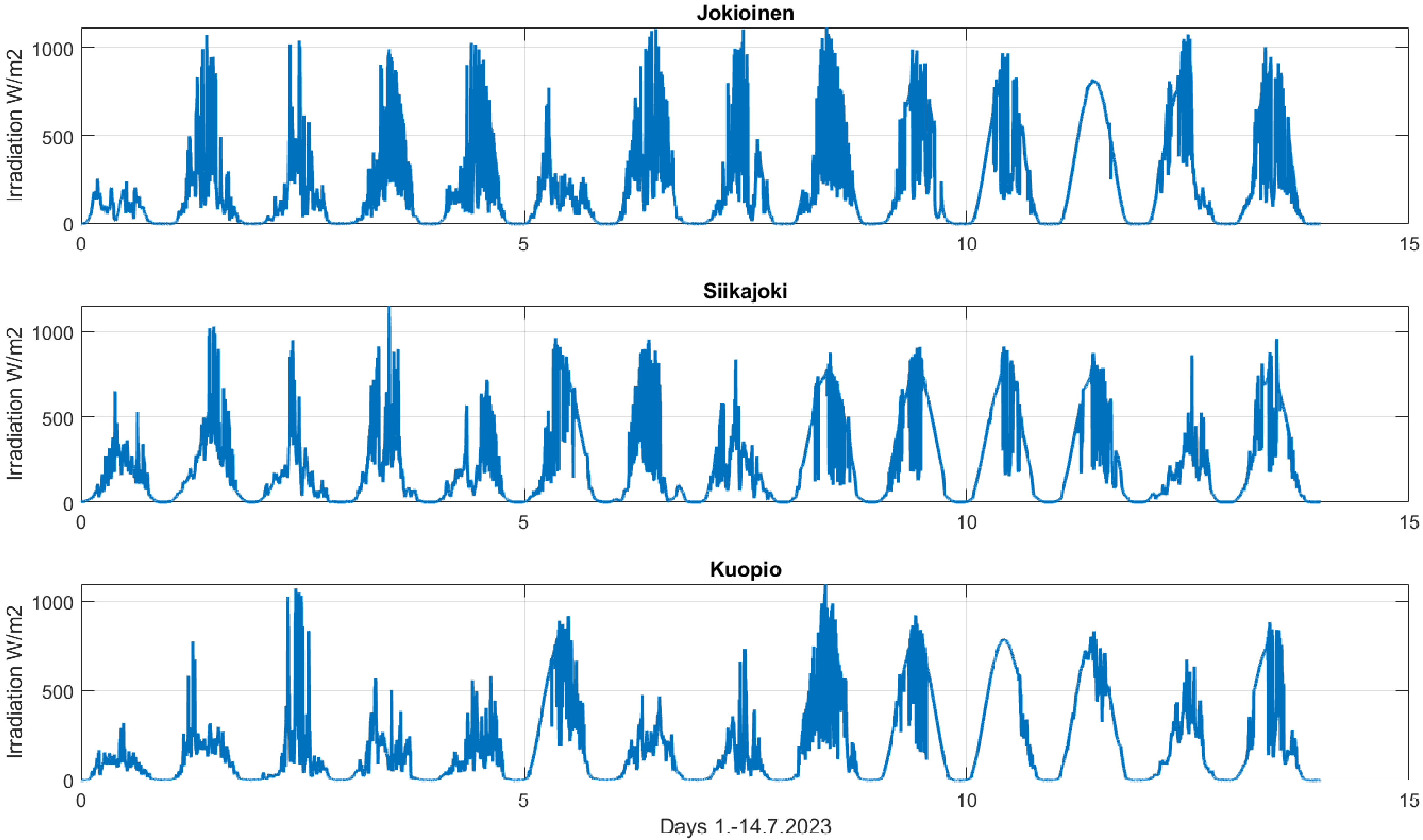
Storing electricity or hydrogen?

- In general, electrolyzers are flexible enough to follow fluctuations of electric power production => electricity storages are not needed
  - Effects of wide range load tracking to electrolyzer efficiency and expected life time must be studied
- Hydrogen storages are remarkably cheaper compared with battery electricity storages => invest on hydrogen storages when ever it is possible
- On the other hand, operation costs of hydrogen storages are higher compared with BES because of the compression, liquefaction and leakage losses, but expected lifetime for H_2 storages is higher compared with batteries
- Future hydrogen grids serve as storages as well.

Conclusions

- Decarbonization of the energy system requires utilization of variable renewable power production or other carbon free power production methods
- Balancing of the electric power system in this situation requires huge capacity of controllable consumption such as electrolyzer based hydrogen production
- Requirements for renewable energy for green hydrogen production makes the system very expensive and difficult to operate
  - What is the value of green hydrogen compared to pink hydrogen?
- More research capacity should be directed to develop flexibility of electrolyzers, methanation and ammonia processes

Thank you
Questions?


Jokioinen
Irradiation W/m2
1000
500
0
0
5
10
15
Siikajoki
Irradiation W/m2
1000
500
0
0
5
10
15
Kuopio
Irradiation W/m2
1000
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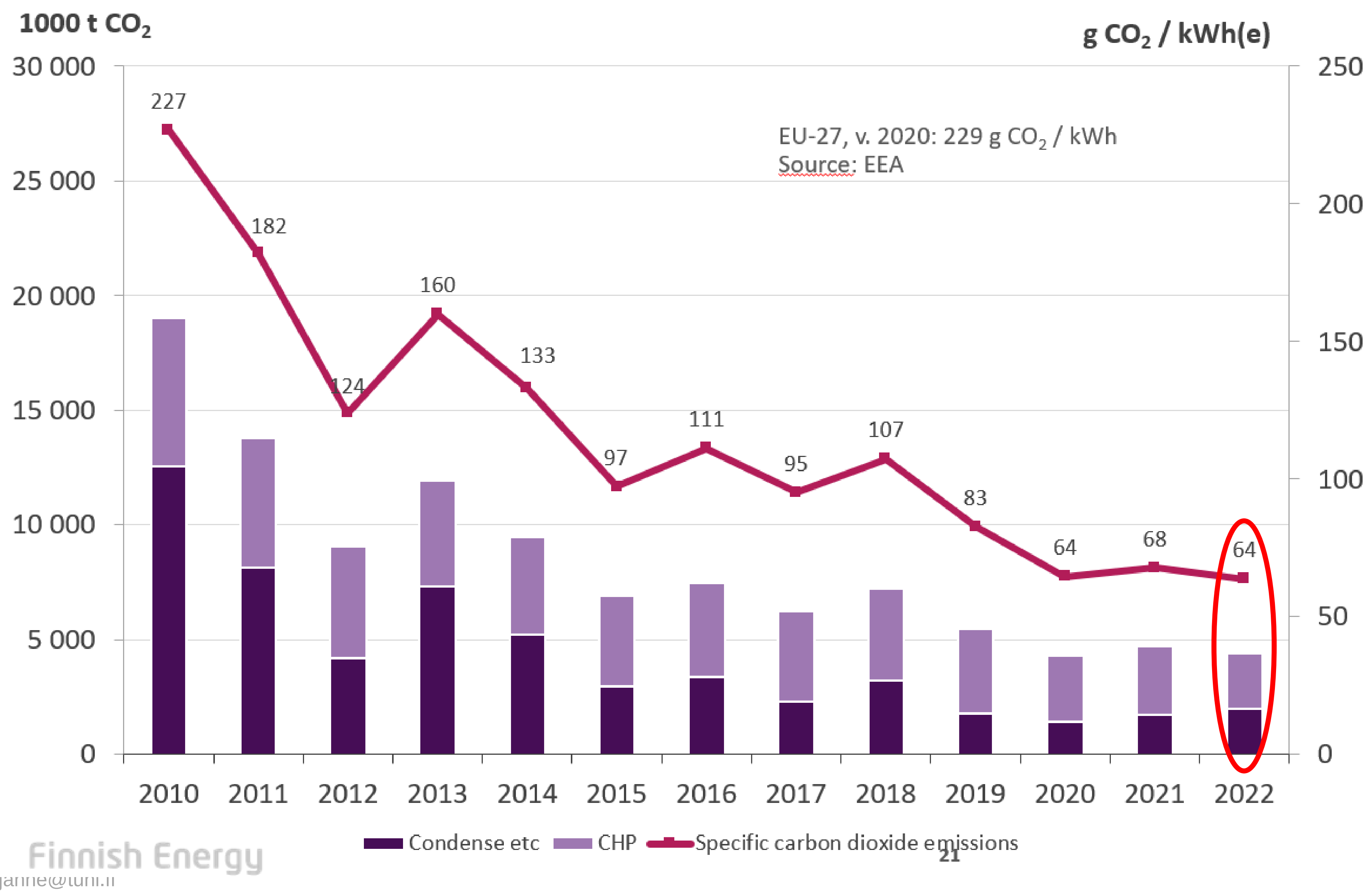
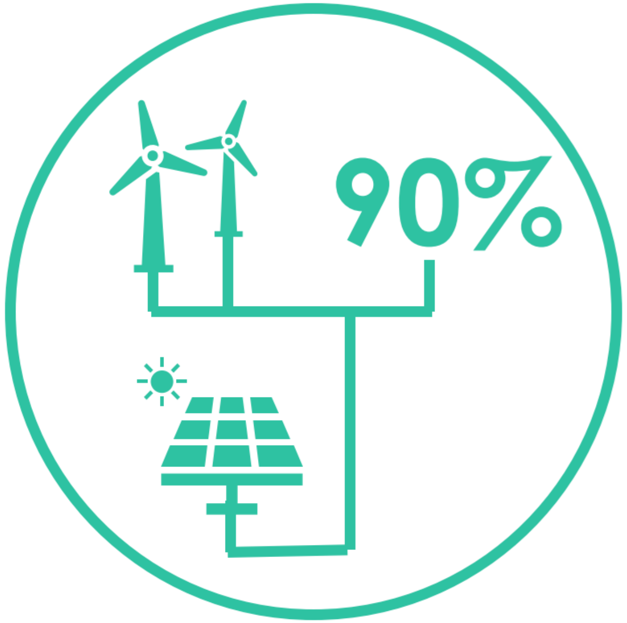
5
10
15
Days 1.-14.7.2023

CO_2-emissions of power generation in Finland



Introduction - Green Hydrogen

3. The proportion of renewable energy in the bidding zone exceeded 90% during last year
    - No additional renewable capacity must be built
    - Applies to the bidding zone where RFNBO production takes place for the next five calendar years
    - **Exemption to temporal and geographical correlation rules**
    - RFNBO production full load hours < 8760h x renewable energy share
    - Hard to achieve in Finland because of the high share of nuclear generation in our power system



Introduction - Green Hydrogen

2. Principles that ensure the electricity used via the grid is renewable:

- Additionality
  - The renewable energy generation installation came online not earlier than 36 months before the RFNBO production facility
- Temporal Correlation
  - RFNBO production takes place during the same hour as contracted renewable energy generation. During transition period until 2030, time window is 1 month
  - Temporal correlation can be buffered via storage behind the same network point.
- Geographical Correlation
  - Renewable energy installation and the electrolyzer are in the same bidding zone
  - Renewable energy is located on an interconnected bidding zone where the day-ahead price is equal or higher than the interconnected bidding zone with RFNBO production
  - Renewable energy is on an offshore bidding zone connected to the zone with RFNBO production
  - Price differences between zones results from bottlenecks in the transmission system