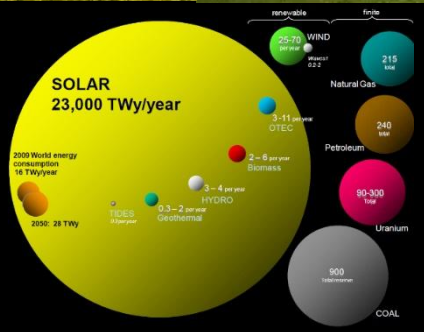




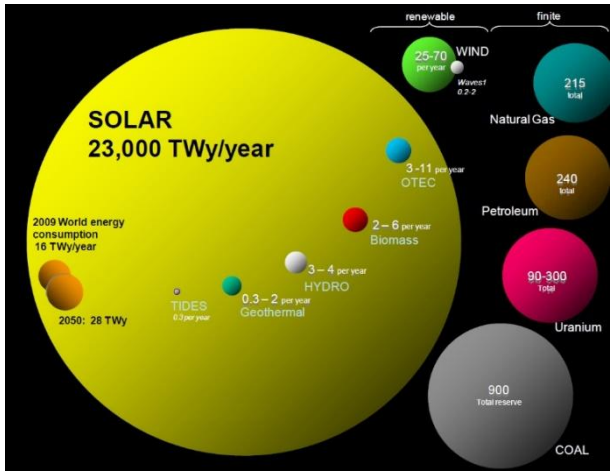



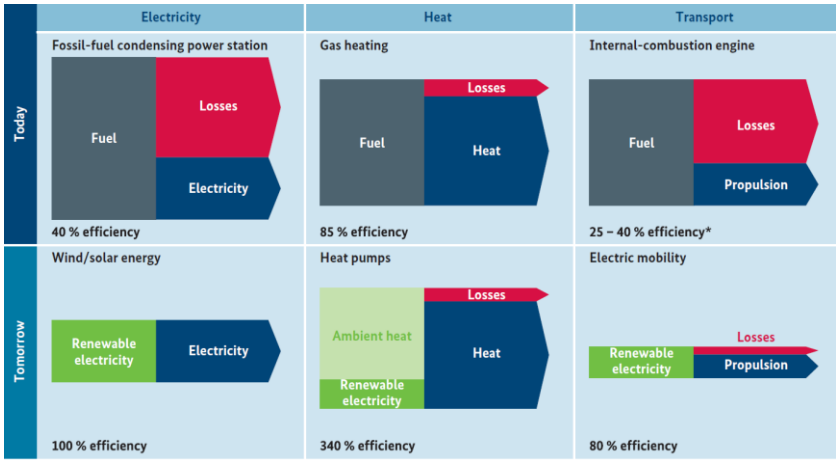
Role and Value of Solar Energy for the Finnish Energy Transition

Open your mind. LUT.
Lappeenranta University of Technology

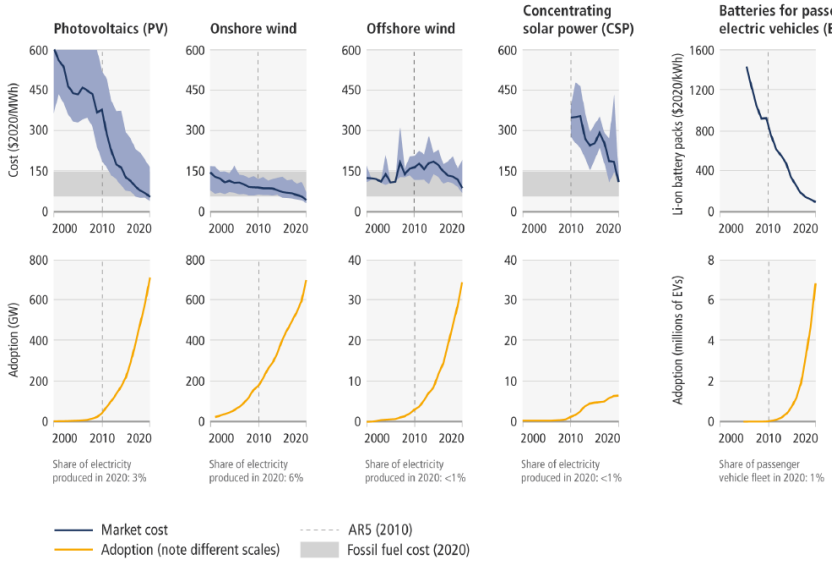
Christian Breyer
Solar 2026 – Renewables Finland
Helsinki, May 19, 2026

Drivers: Climate, Availability, Electrification, Cost





* The efficiency of internal-combustion engines in other applications (e.g. maritime transport, engine-driven power plants) can exceed 50 %.



Key insights:

- Climate change requires emissions phase-out asap
- Solar energy **resource availability** is 1000x larger than the global demand, plus 2-3x wind, plus others
- **Direct electricity** use is highly efficient
- **Indirect electrification** is important for remaining 50% of final energy demand
- Renewables **costs have declined** steeply and continued: solar PV, wind power, batteries, electrolyser, and others
- Combination of these three major drivers leads to massive uptake of renewables, esp. solar PV

source: Perez R. and Perez M., 2009. A fundamental look on energy reserves for the planet. The IEA SHC Solar Update, Volume 50
Brown, Breyer et al., 2018., Renewable and Sustainable Energy Reviews, 92, 834-847
IPCC, 2020. 6th Assessment Report WG III

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Power Market Development: 2008 - 2022

Empiric trends:

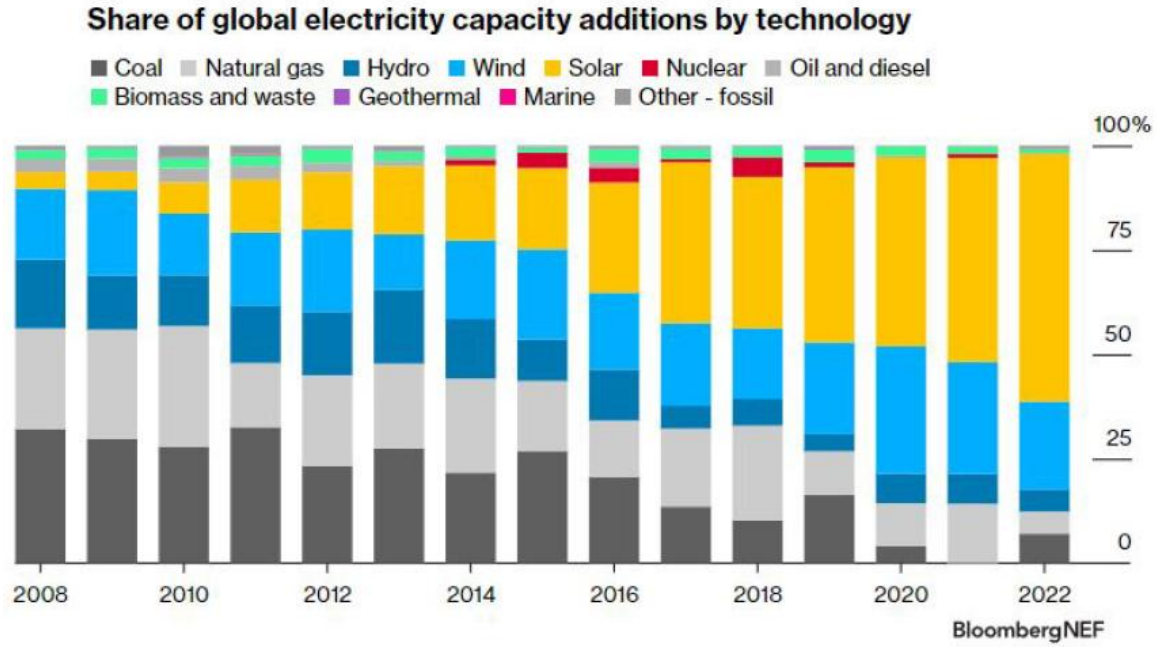
Electricity supply dominated by PV and wind power

Generation mix will adapt to the mix of new installations, year by year

Fossil-nuclear generation will be increasingly irrelevant

Solar PV grew by +30% YoY in 2022, +70% YoY in 2023, +24% YoY in 2024, +20% YoY in 2025
(note: newly PV electricity > wind)

PV is outside any historical experience



2025: 70% of all new global power capacity was solar PV

Key insights:

- **Solar PV and wind power dominate new installations, with clear growth trends for PV**
- **Hydropower share declines, a consequence of overall capacity rise, and sustainability limits**
- **Bioenergy (incl. waste) remain on a constant low share**
- **New coal plants are close to fade out**
- **New gas plants decline, with very high gas prices pushing them towards peaking operation**
- **Nuclear is close to be negligible, the heated debate about new nuclear lacks empirical facts**

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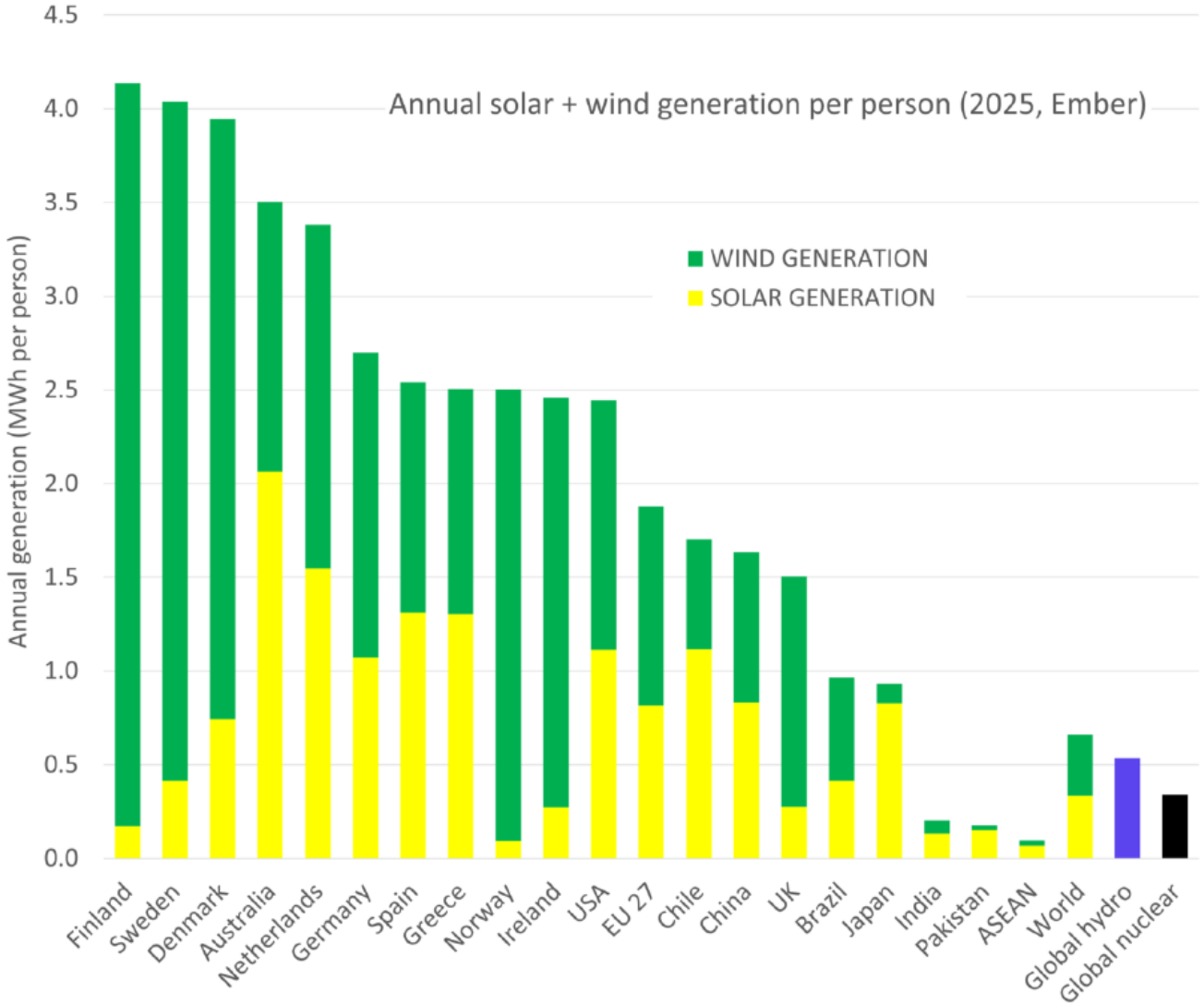
source: BNEF, Power Transition Trends 2023

Finland among the Global Top Leaders



Key insights:

- **Finland is the top leading country in the world in wind and solar electricity generation per capita**
- **Solar PV electricity per capita in Finland is comparable to India**
- **… however, there is still much room for improvement**

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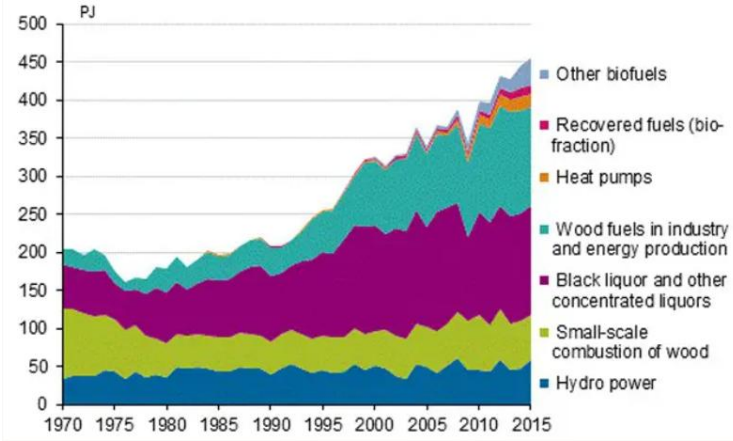
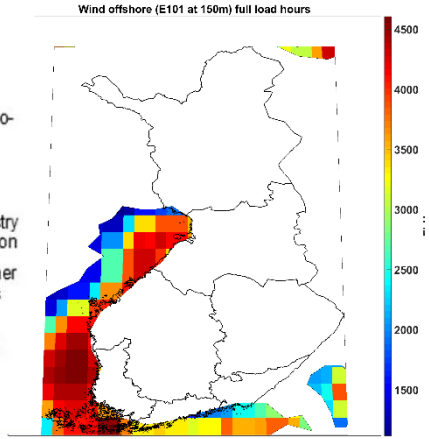
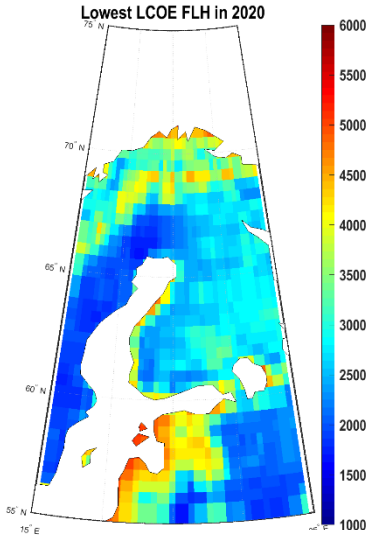
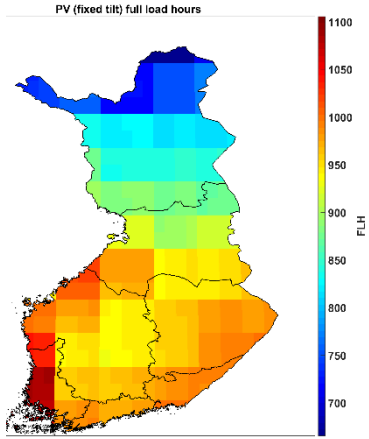
Resources in Finland



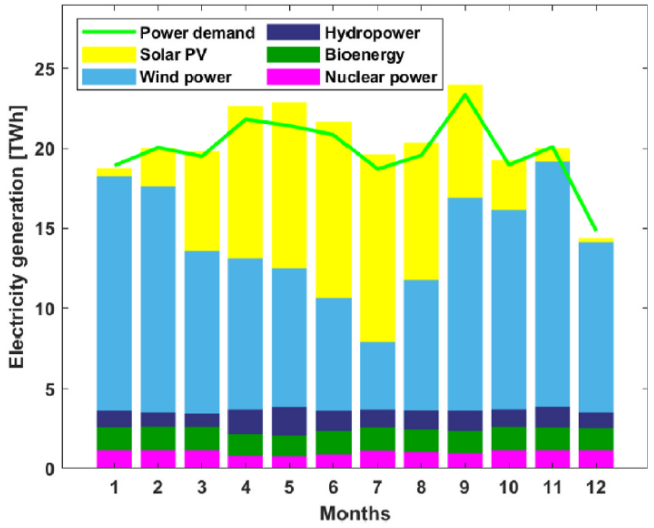






Key insights:

- **bioenergy is very important for Finland, however, will be limited, maybe even shrinking; right now, about 100-115 TWh_{th}**
- **Wind energy is excellent in northern hemisphere, also in Finland, onshore and offshore**
- **Solar energy is good in Finland maybe as low-cost as wind power in Finland in future**
- **Solar and wind energy is complementary in Finland plus bioenergy in times of lower wind-solar resources**



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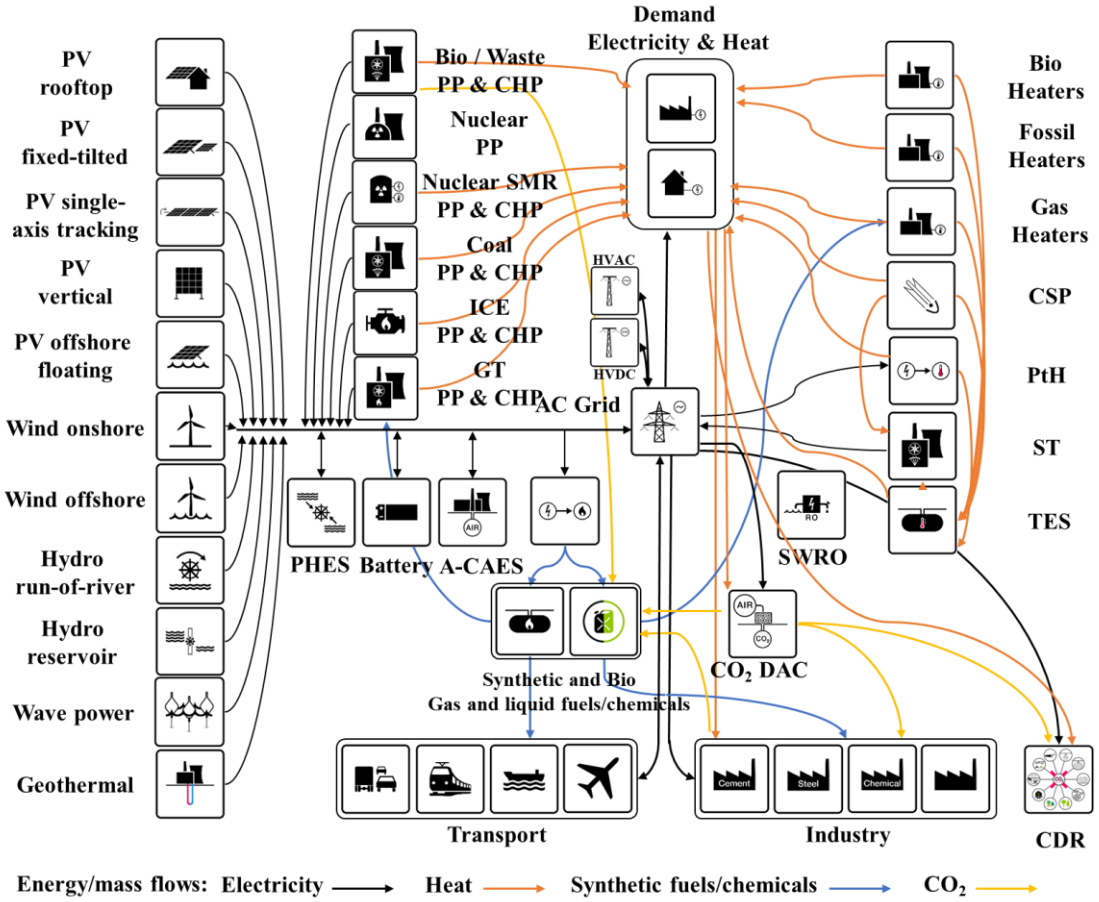
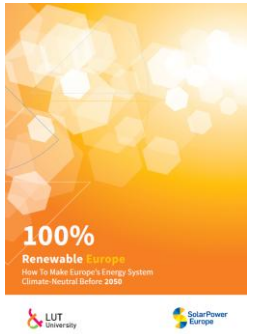
source: Satymov et al., 2025. Energy and industry transition to carbon-neutrality in Nordic conditions via local renewable sources, electrification, sector coupling and Power-to-X, Energy, 319, 134888

LUT Energy System Transition Model (LUT-ESTM)



reports



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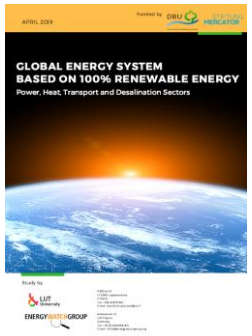

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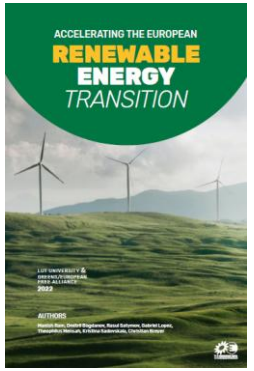

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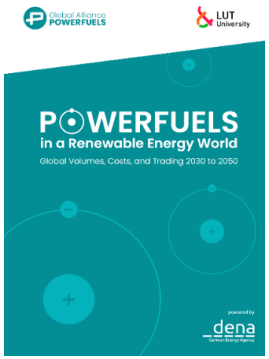

link to report

Key features:

- full hourly resolution in global-local studies for energy-industry-CDR systems, comprising 170+ technologies
- used for several major reports, in about 75+ scientific studies, published on all levels
- strong consideration on all kinds of power-to-X (heat, fuels, chemicals, materials, freshwater, CO_2, CDR, forests, food)

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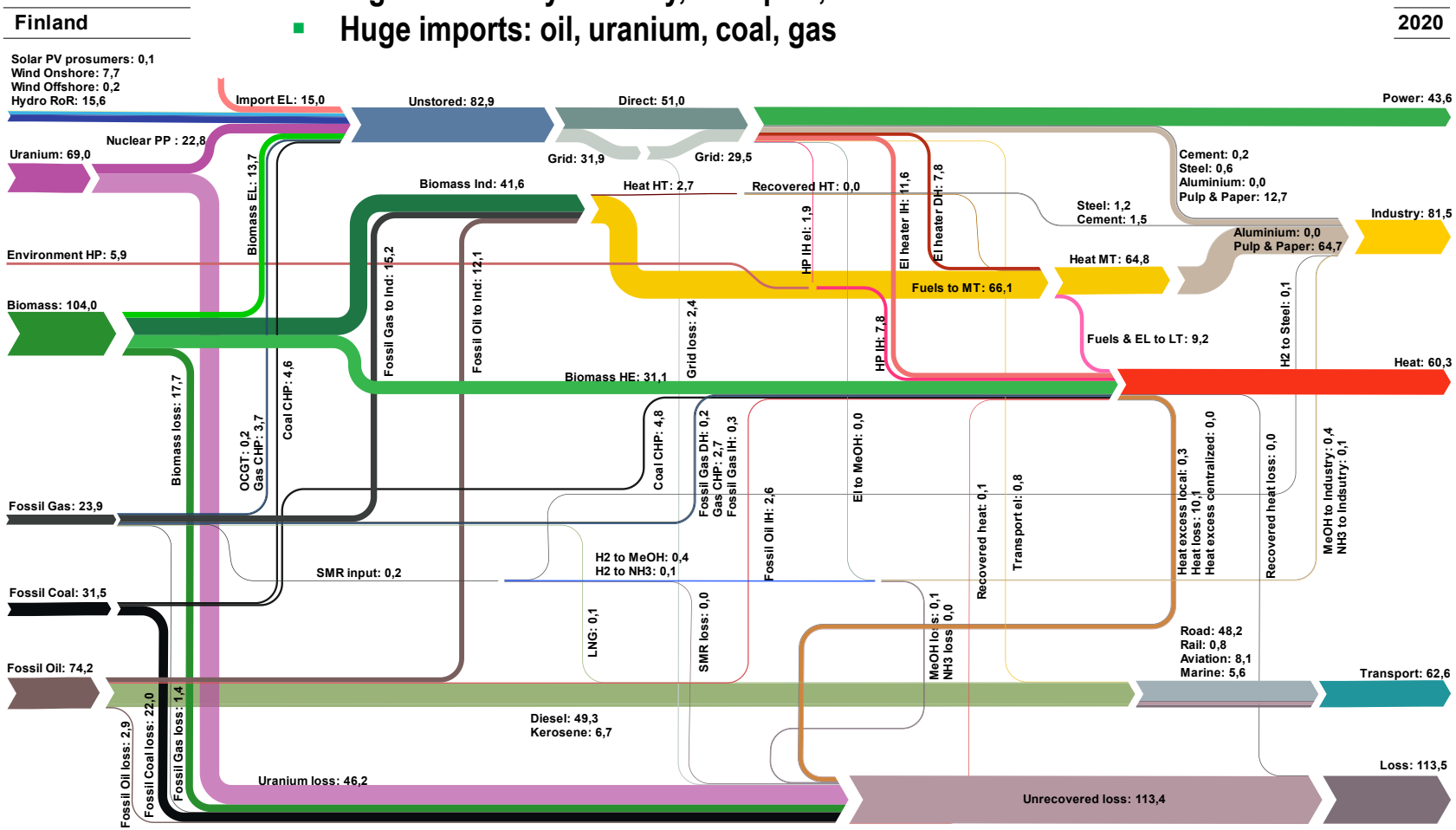
source: Bogdanov, Breyer et al., 2021. Applied Energy, 283, 116273
Bogdanov, Breyer et al., 2021, Energy, 227, 120467
Bogdanov, Breyer et al., 2023, Energy, 273, 127213

Energy Flow Finland today

- Energy supply based on bioenergy, oil, uranium, coal, gas, hydropower, wind power
- High losses due to thermal processes
- High demand by industry, transport, heat
- Huge imports: oil, uranium, coal, gas



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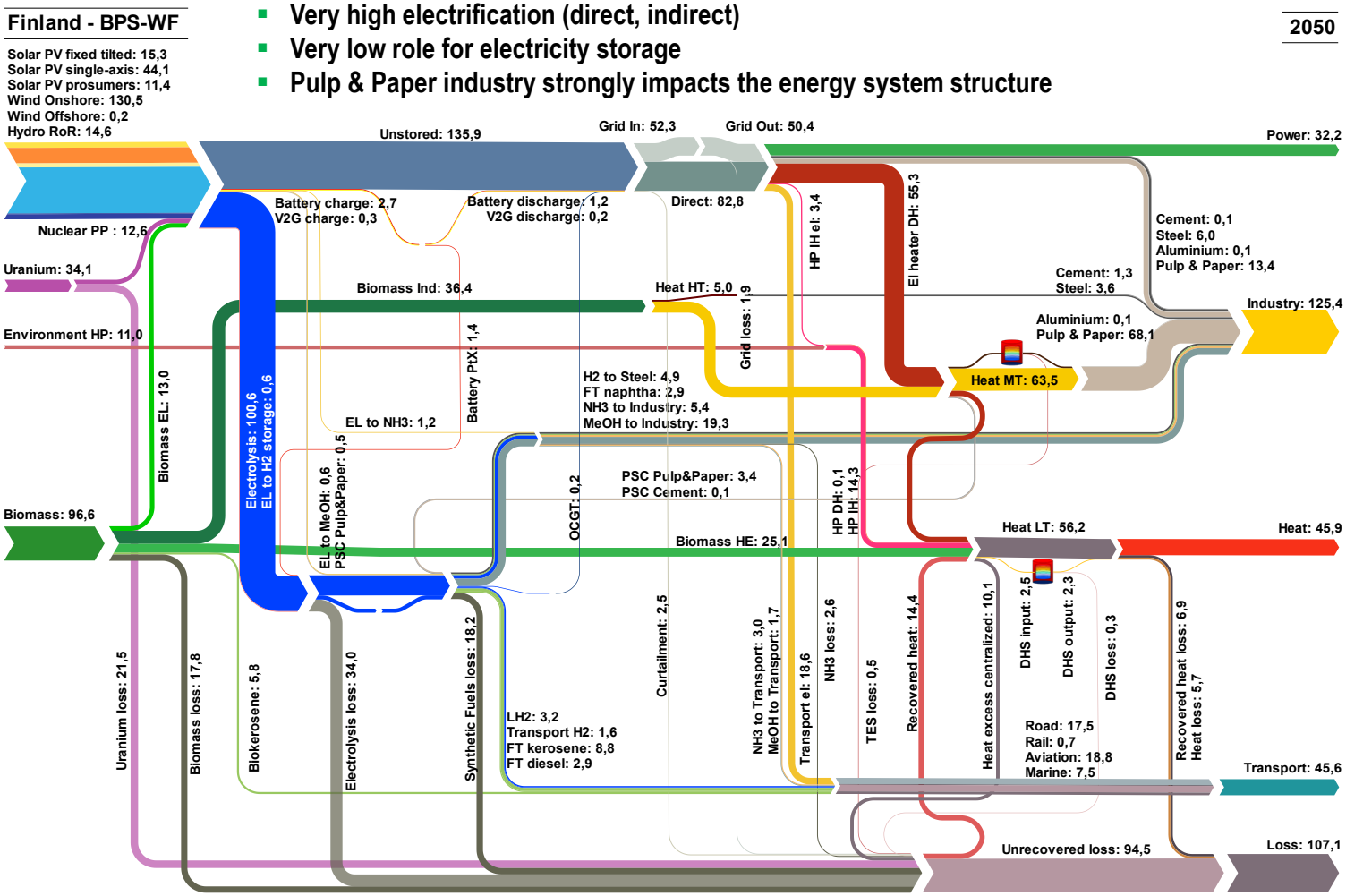
source: Satymov et al., 2025. Energy and industry transition to carbon-neutrality in Nordic conditions via local renewable sources, electrification, sector coupling and Power-to-X, Energy, 319, 134888

Power-to-X Economy: Energy Flow in Future

- Case: self-supply of energy needs in Finland (except uranium supply)
- Energy supply based on wind power, bioenergy, solar PV
- Bioenergy largely for heat
- Very high electrification (direct, indirect)
- Very low role for electricity storage
- Pulp & Paper industry strongly impacts the energy system structure



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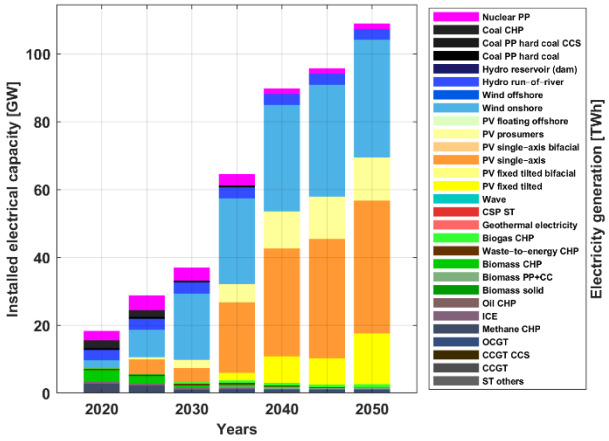
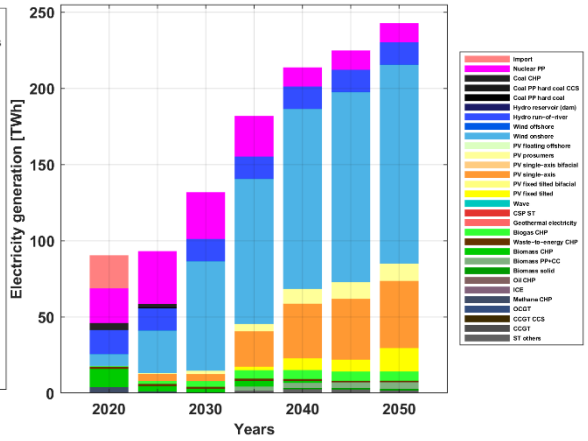
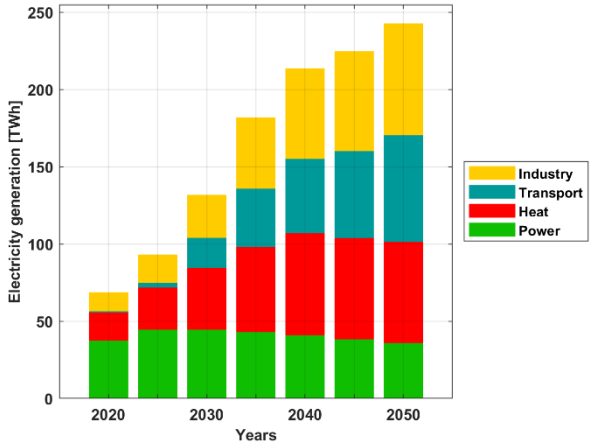
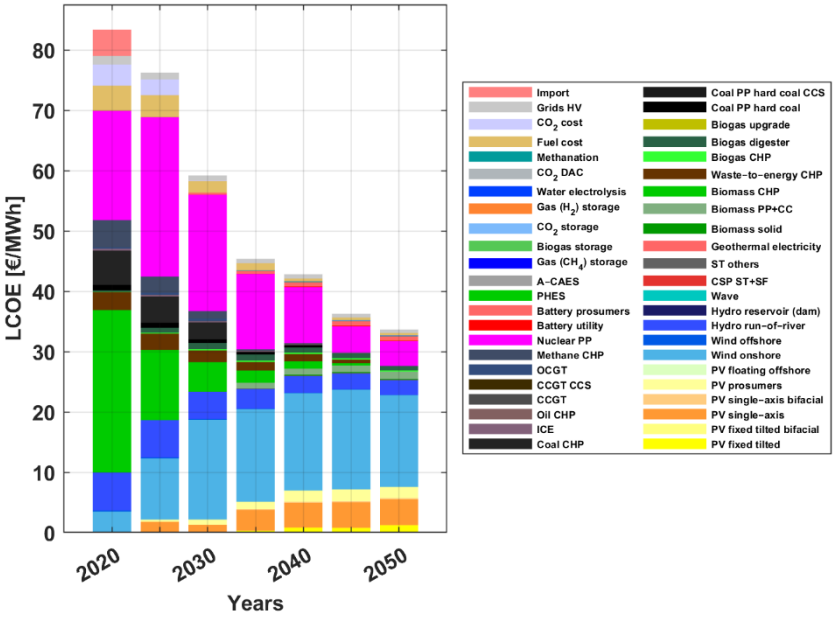
Electricity the Basis for a Sustainable Energy System







- Massive ramping of wind power, then solar PV, bioenergy largely for heat supply, existing nuclear used
- Seasonal match of wind and solar power with bioenergy seasonal balancing – massive PV capacities
- Additional demand from heat, transport and industry; direct and indirect electricity applications
- Low-cost wind and solar and phasing out of higher cost fossil/nuclear leads to cost reduction



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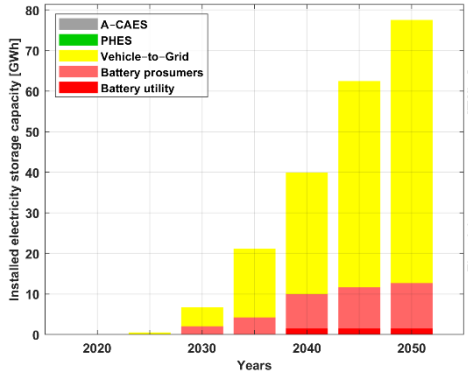
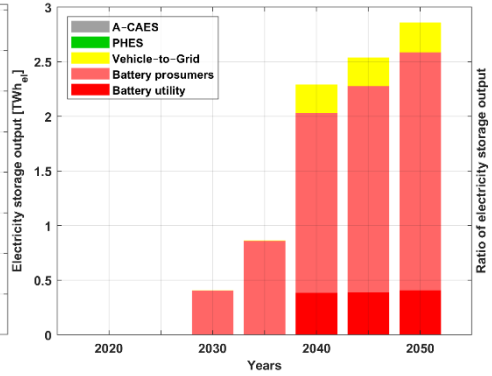
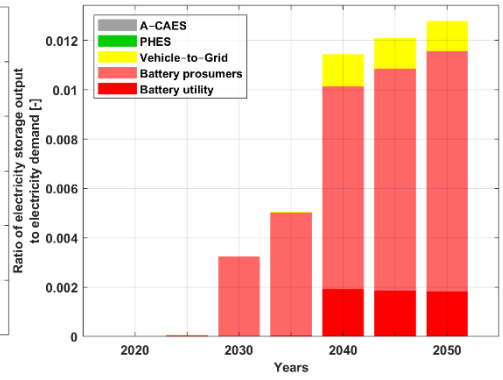
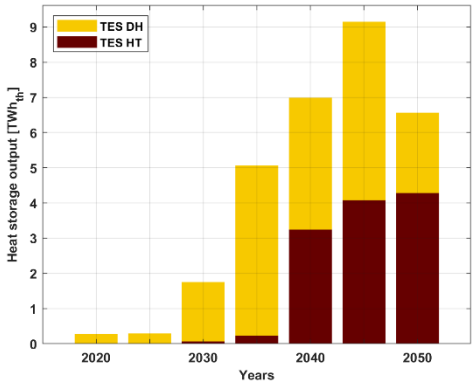
Electricity Storage is surprisingly low

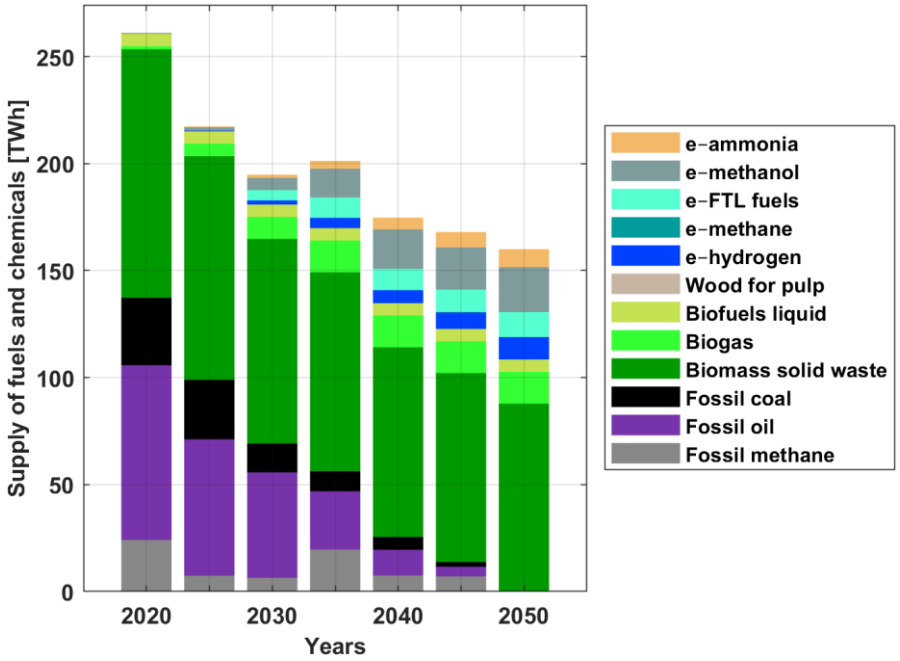








- Electricity storage grows substantially, based on batteries (stationary, vehicles), but also gas (H_2)
- Storage potential in vehicles is very high, but usage is assumed to support stationary batteries
- Overall electricity storage supply is low: 3% in total supply, thereof almost all by batteries
- Hydrogen as final energy carrier is almost negligible



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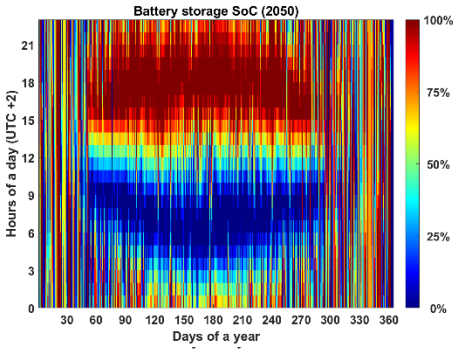
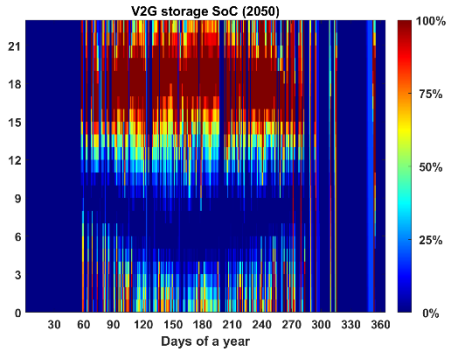
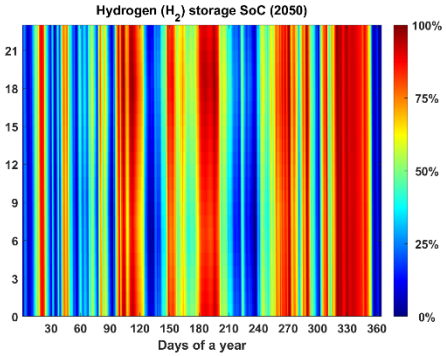
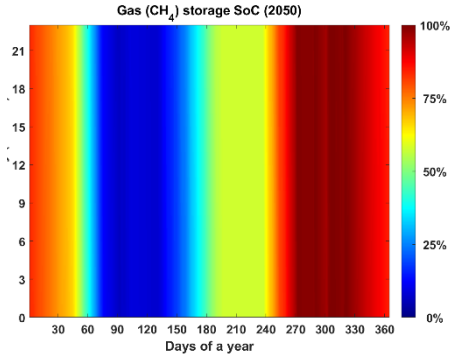
source: Satymov et al., 2025. Energy and industry transition to carbon-neutrality in Nordic conditions via local renewable sources, electrification, sector coupling and Power-to-X, Energy, 319, 134888

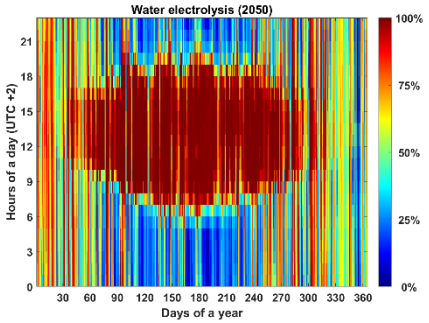
Electricity Storage Operation

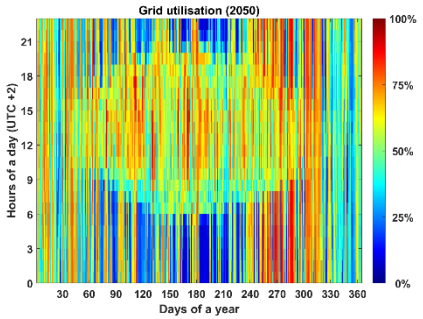








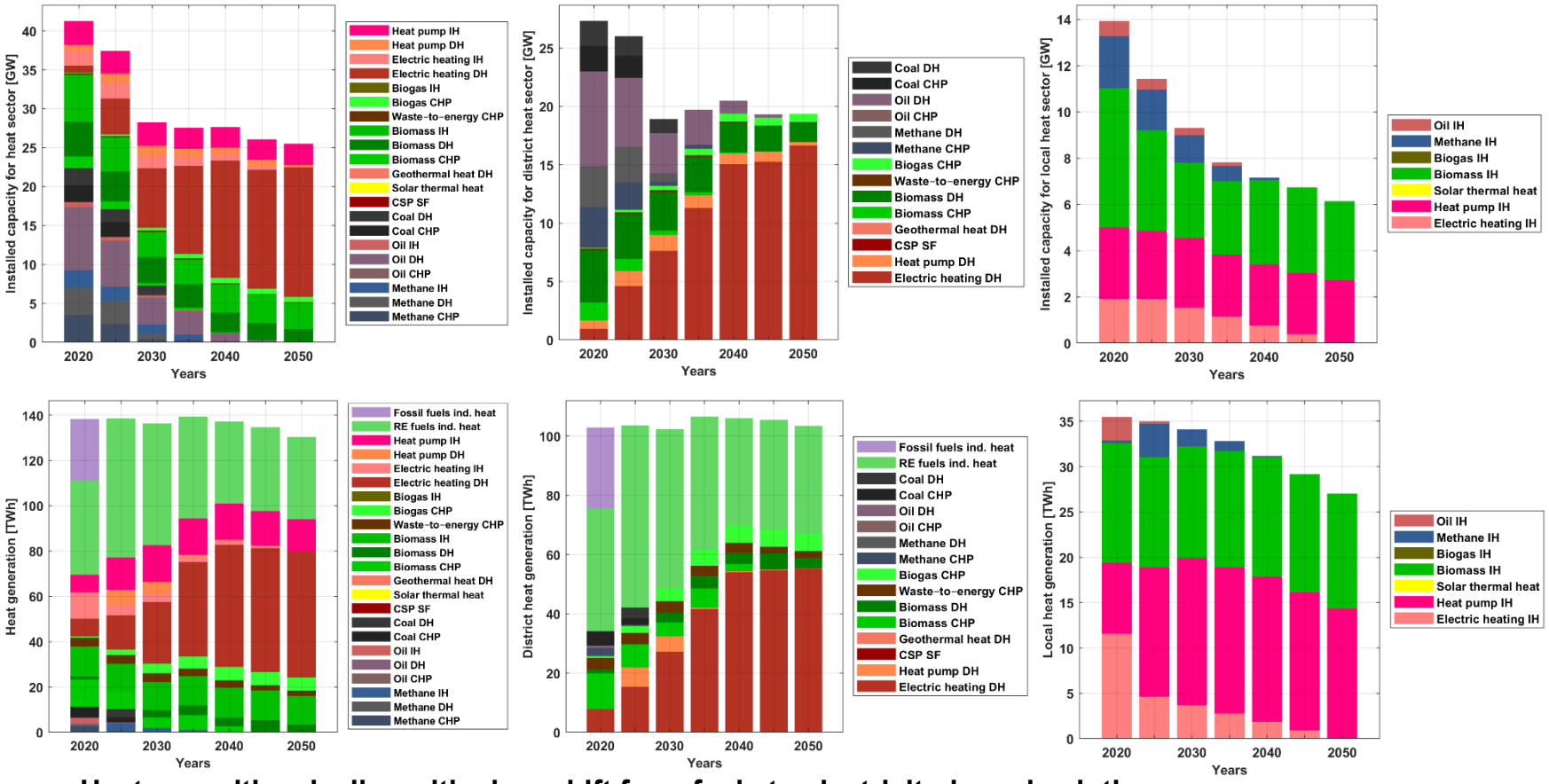




- Operation in hourly resolution shows day-night battery dispatch & wind support
- Hydrogen storage as classical buffer storage for H_2-to-X, mainly for synthesis
- Methane storage is used as seasonal storage
- Electrolysers use wind and PV electricity, and much of the latter
- Grid utilisation reflects wind and solar supply, high use in winter, PtX in summer

source: Satymov et al., 2025. Energy and industry transition to carbon-neutrality in Nordic conditions via local renewable sources, electrification, sector coupling and Power-to-X, Energy, 319, 134888

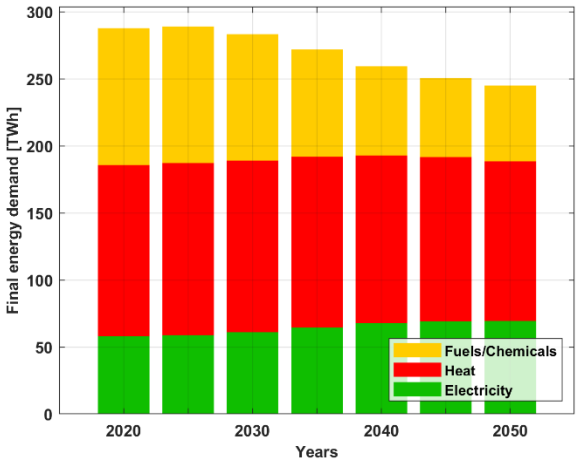
Heat Supply in Energy Transition

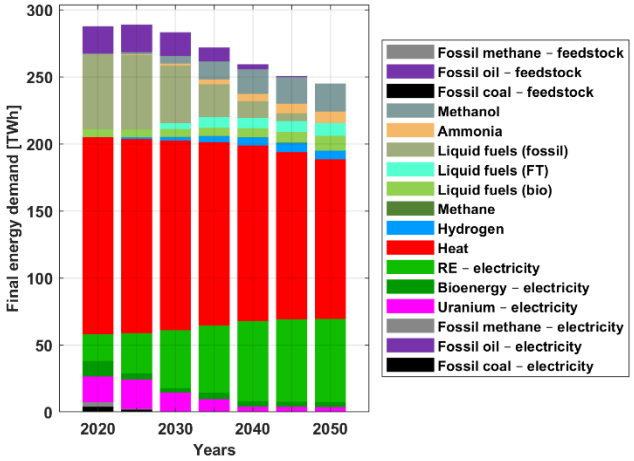


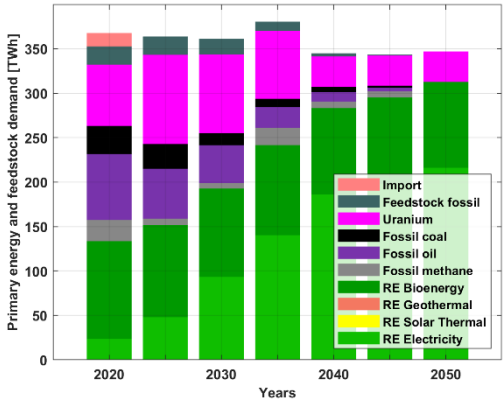
- Heat capacities decline with clear shift from fuels to electricity-based solutions
- Heat generation district heating includes industrial heat
- District heating heat pumps grow in next years and remains stable until 2040s
- Local heating benefits from building efficiency gains, with stable bioenergy and with more heat pumps

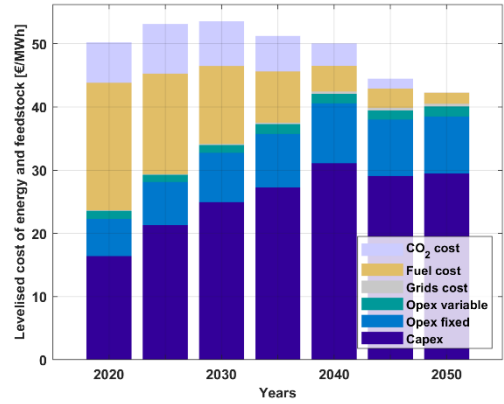
source: Satymov et al., 2025. Energy and industry transition to carbon-neutrality in Nordic conditions via local renewable sources, electrification, sector coupling and Power-to-X, Energy, 319, 134888

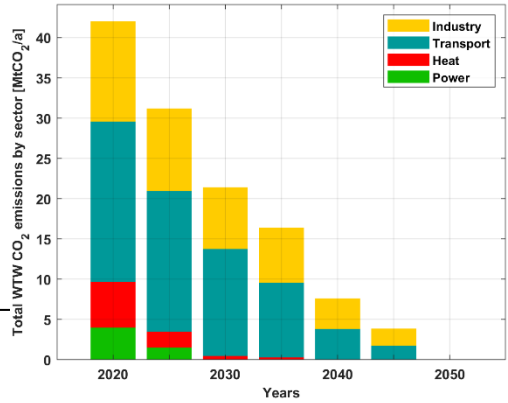
Overall Trends in Energy System





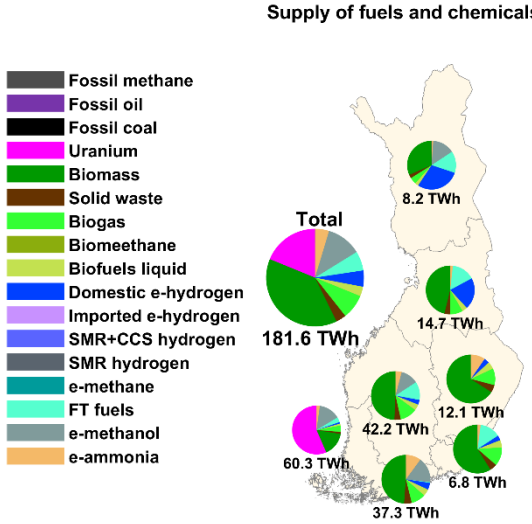


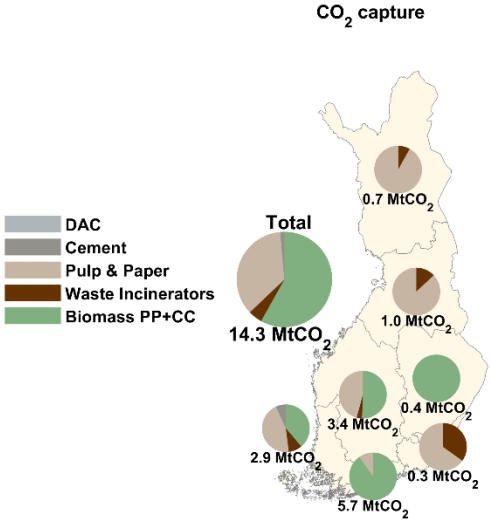


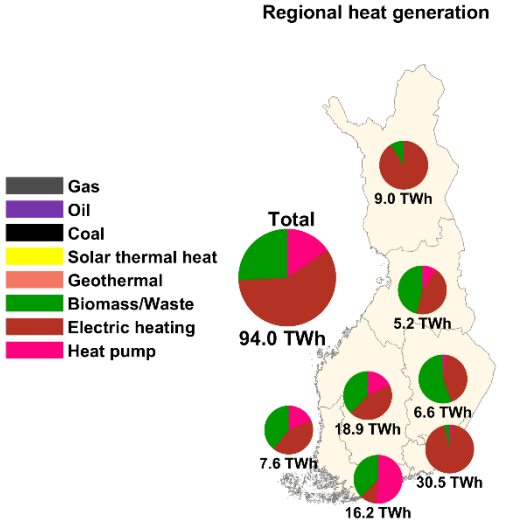


- Final energy demand roughly stable, shift towards electricity, fuels decline, heat stable
- Primary energy supply is roughly stable, fossil fuels phase out, bioenergy stable, renewable electricity dominates
- Energy system cost is roughly stable with a tendency to decline in 2040s
- Net emissions in 2035 are below 6.5 $MtCO_2$, meeting the target of the Finnish government, transport sector has to deliver

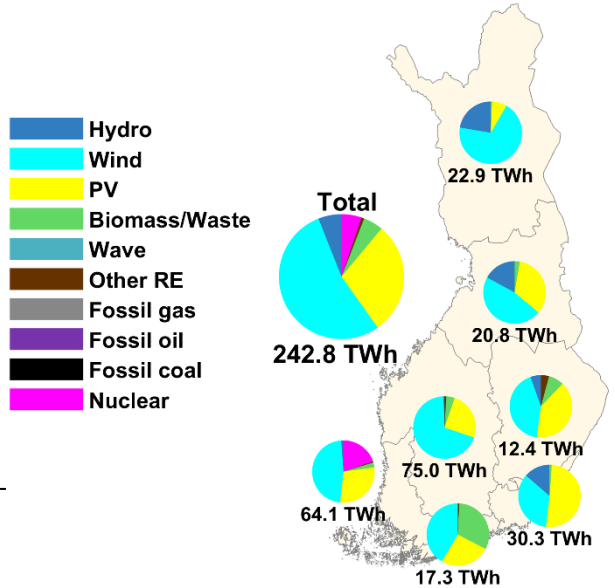
Regional Energy System Trends by 2050



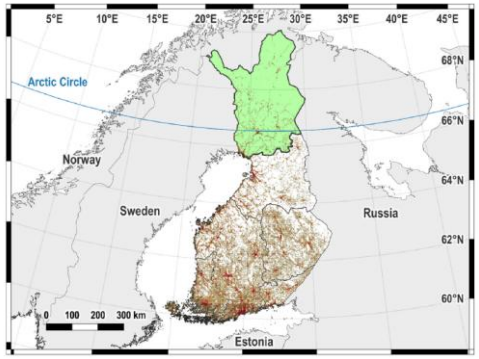


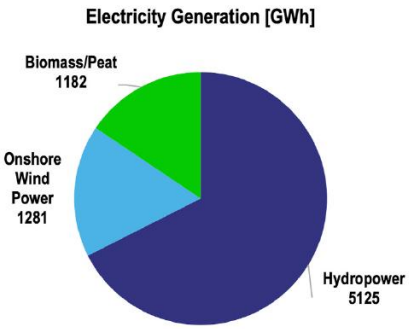


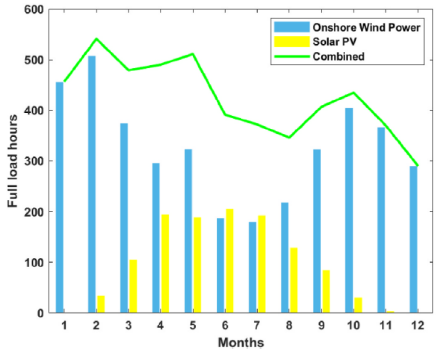
- Wind power in the north and west, solar in the south and east
- However, all regions enjoy wind and solar energy
- Wind share in generation 54% and solar PV share 30%
- Heat supply dominated by electricity-based options
- Lots of e-fuels/e-chemicals, about 85-90% of hydrogen further converted
- Biogenic CO_2 is an enormous asset for Finland

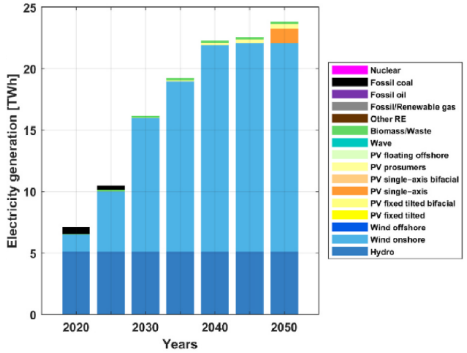


Arctic Solar

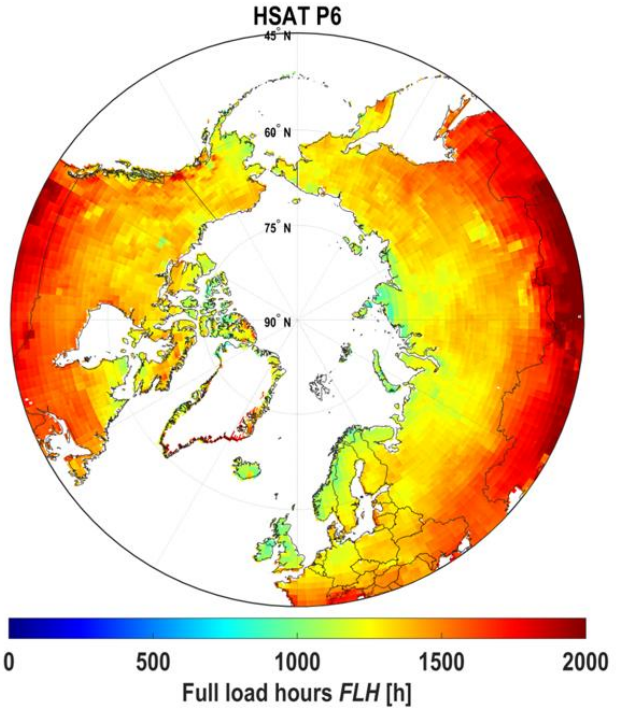








- Lapland leads in renewable electricity generation in Finland
- Solar PV is excellent in in the Arctic … in the summer
- Solar PV part of a least cost solution for the Arctic, globally (even with higher shares in Alaska, Canada, Iceland, Greenland)
- Single-axis tracking PV may be even better than fixed tilted PV systems in Arctic conditions
- Technically, snow reflection and cold temperature increase yield



source: Satymov et al., 2025. From winter wind to summer sun: Unlocking the Arctic regions sustainable energy potential, Energy, 335, 138106
Arachchi et al., Prospects and competitiveness of solar PV portfolios in the Arctic, under review

Role and value of solar energy for the Finnish ET
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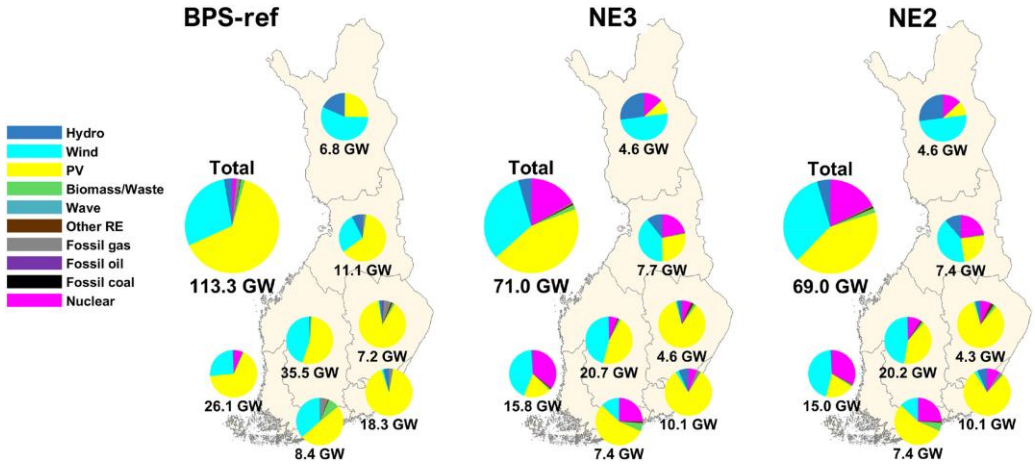
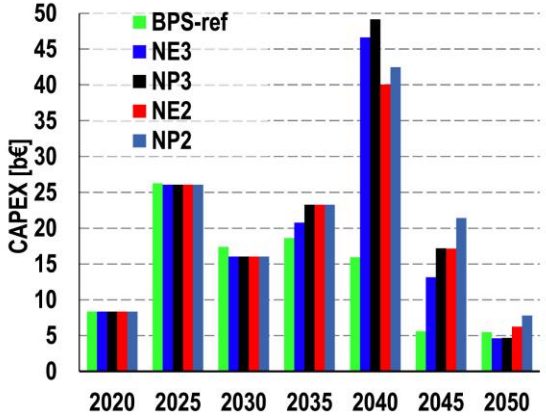
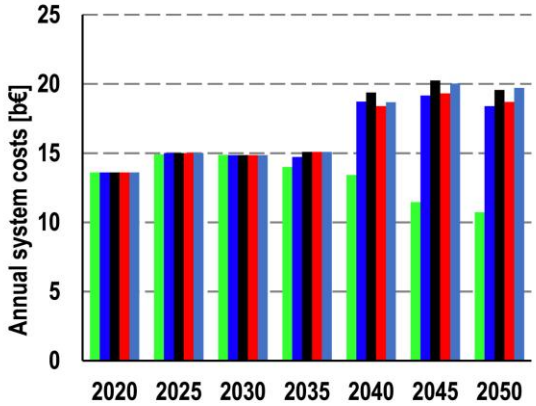
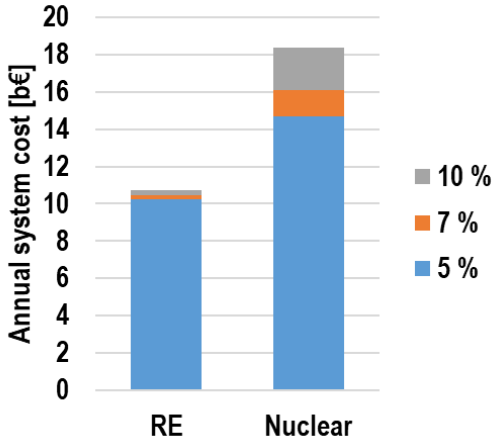
Any Hope for Nuclear Power in Finland?



- Finland pledged for tripling nuclear at COP28 in 2023 until mid-century
- Scenarios reflecting the nuclear pledge were investigated, with small modular nuclear reactors (SMR), nuclear CHP, large-scale nuclear
- Identical technical specification met by renewables vs much new nuclear investment
- Nuclear scenarios cost 71-84% more, even at subsidised nuclear financing it costs 37% more.
- no technical value-add for non-affordable cost







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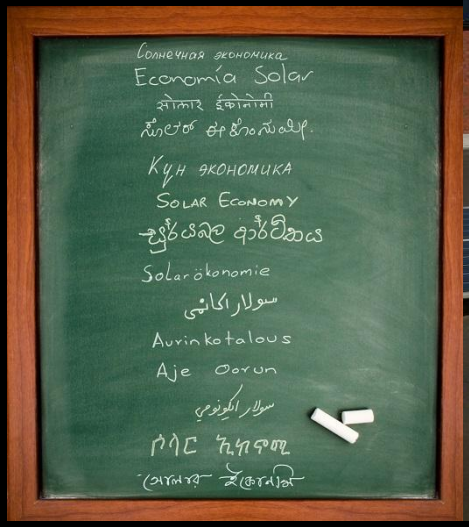
source: Satymov et al., 2025. Who will foot the bill? The opportunity cost of prioritising nuclear power over renewable energy for the case of Finland, Energy, 337, 138630

Summary

- Solar PV is a core energy solution for Finland
- About 30% of all electricity generation in Finland from solar PV
- Excellent match to wind, solar, and bioenergy resources for stable energy supply
- Power-to-X Economy pushes electricity-based solutions
- Single-axis tracking PV creates value-add
- Biogenic CO_2 is a very valuable asset for Finland and wind power & solar PV together enable the valorisation, most likely for e-methanol-to-X routes
- Agrivoltaics for increased incomes of farmers

Thank you for your attention …
… and to the team!



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