PAUL SCHERRER INSTITUT


WIR SCHAFFEN WISSEN – HEUTE FÜR MORGEN

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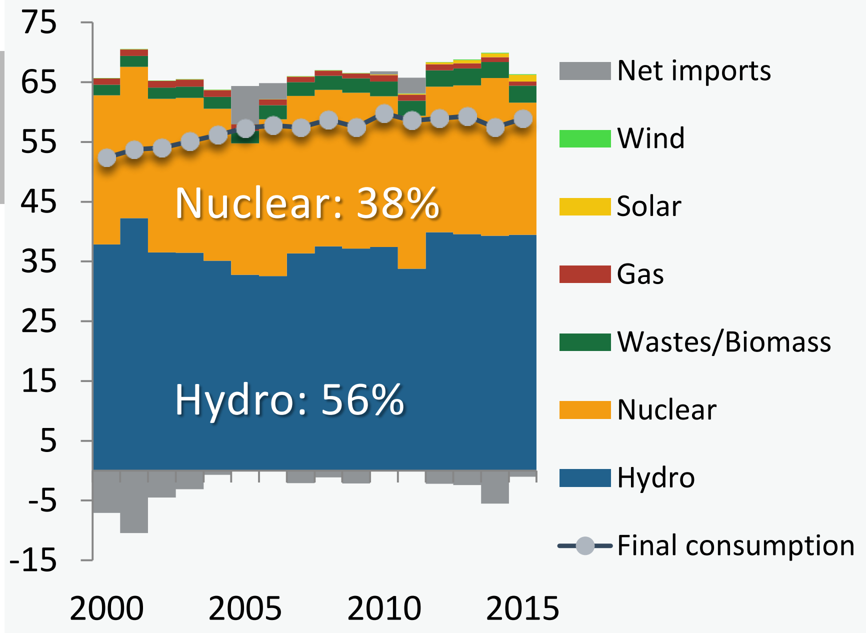
Strategies for integration of variable renewable generation in the Swiss electricity system

IAEE 2017 European Conference, Vienna, 3d – 7th September 2017

The Swiss electricity system, 2015

ELECTRICITY GENERATION & CONSUMPTION (TWh)



ELECTRICITY NET CAPACITY 2015: 19 GW*

Quelle: VSE, BFE (Statistik der Wasserkraftanlagen), Suisse Eole
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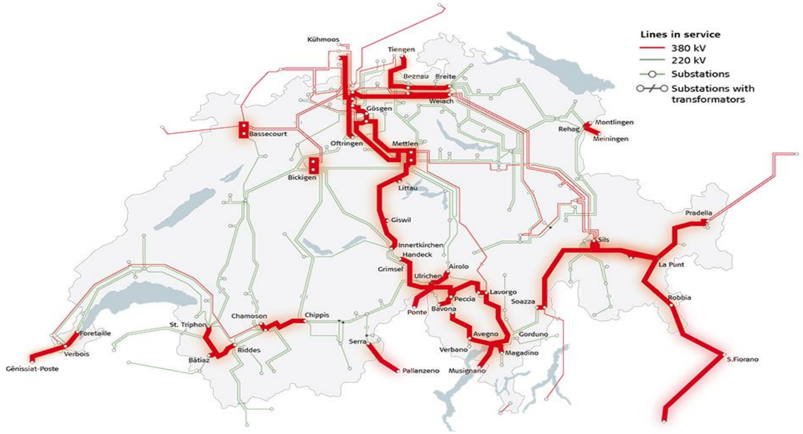
* Nuclear: 3.3 GW, Hydro: 13.7 GW, Solar : 1GW, Thermal: 1 GW

GRID CONGENSTION IN THE NORTH-SOUTH AXIS



Swiss energy strategy 2050 aims at gradually phasing out nuclear and promoting renewables and demand side efficiency:

- Challenges for electricity system stability (also due to congestion)

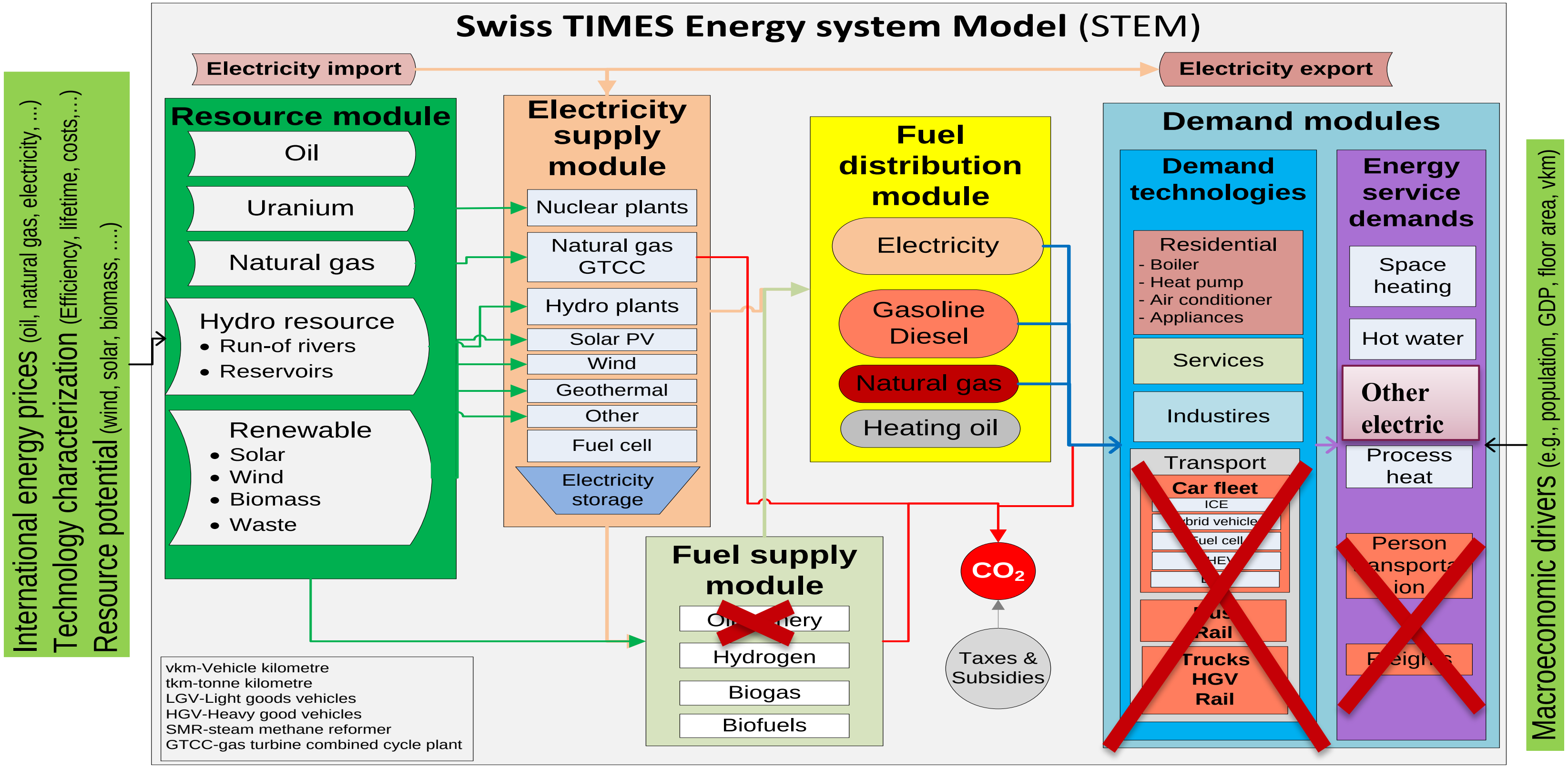
Objectives of the research

- We study integration measures for variable (and stochastic) renewable generation from wind and solar PV (VRES) in Switzerland for the horizon 2015 – 2050:
  - Reinforcing and expanding the **grid network**
  - Deploying local storage, complementary to pump hydro, like **batteries and ACAES**
  - Deploying dispatchable loads such as **P2G, water heaters and heat pumps**

- The study was performed in the context of the ISCHESS project, which is a collaboration between the Paul Scherrer Institute and the Swiss Federal Institute of Technology (ETH Zurich), funded by the Swiss Competence Center Energy and Mobility (CCEM) http://www.ccem.ch/ischess

Methodology – The Swiss TIMES Energy Systems Model (STEM)

- Bottom-up, cost-minimisation model, used for assessing long term Swiss energy policies
- High intra-annual resolution with 288 typical hours (3 typical days, 4 seasons, 24h/day)
- For the current research, the model was modified to include:
  - Higher detail in the electricity sector at the expense of detail at the demand sectors (oil-based transport is excluded and industrial sectors have aggregate representation)
  - Variability in the RES generation, ancillary services and power plant dispatching constraints



Swiss TIMES Energy system Model (STEM)

International energy prices (oil, natural gas, electricity, …)
Technology characterization (Efficiency, lifetime, costs,…)
Resource potential (wind, solar, biomass, ….)

Electricity import
Electricity export

Resource module
Oil
Uranium
Natural gas
Hydro resource
- Run-of rivers
- Reservoirs

Renewable
- Solar
- Wind
- Biomass
- Waste

Electricity supply module
Nuclear plants
Natural gas GTCC
Hydro plants
Solar PV
Wind
Geothermal
Other
Fuel cell
Electricity storage

Fuel distribution module
Electricity
Gasoline Diesel
Natural gas
Heating oil

Fuel supply module
~~Oil refinery~~
Hydrogen
Biogas
Biofuels

CO₂
Taxes & Subsidies

Demand modules

Demand technologies
Residential
- Boiler
- Heat pump
- Air conditioner
- Appliances

Services
Industires
~~Transport~~
~~**Car fleet**~~
~~ICE~~
~~ybrid vehicle~~
~~uel cell~~
~~HEV~~
~~**us Rail**~~
~~**Trucks HGV Rail**~~

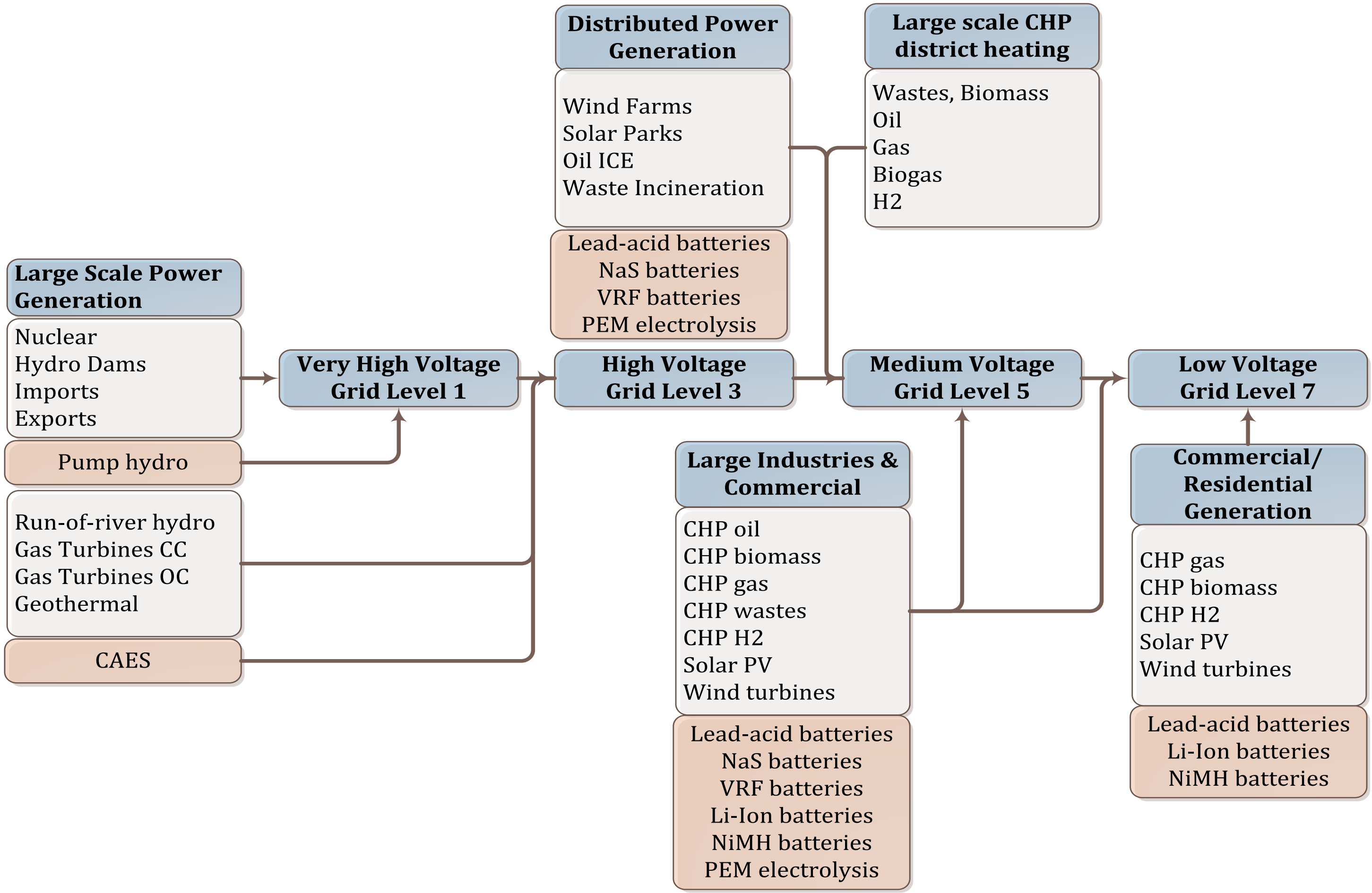
Energy service demands
Space heating
Hot water
Other electric
Process heat
~~Person ansporta ion~~
~~Freigh s~~

Macroeconomic drivers (e.g., population, GDP, floor area, vkm)

vkm-Vehicle kilometre
tkm-tonne kilometre
LGV-Light goods vehicles
HGV-Heavy good vehicles
SMR-steam methane reformer
GTCC-gas turbine combined cycle plant

Representation of the electricity sector in STEM

- Different grid levels, with different set of power plants and storage options in each level
- Each grid level is characterised by transmission costs and losses
- Power plants are characterised by costs, efficiency, technical constraints and resource availability
- A linearised approximation of the Unit Commitment problem is also formulated



Distributed Power Generation

Wind Farms
Solar Parks
Oil ICE
Waste Incineration

Lead-acid batteries
NaS batteries
VRF batteries
PEM electrolysis

Large scale CHP district heating

Wastes, Biomass
Oil
Gas
Biogas
H2

Large Scale Power Generation

Nuclear
Hydro Dams
Imports
Exports

Pump hydro

Run-of-river hydro
Gas Turbines CC
Gas Turbines OC
Geothermal

CAES

Very High Voltage Grid Level 1

High Voltage Grid Level 3

Medium Voltage Grid Level 5

Low Voltage Grid Level 7

Large Industries & Commercial

CHP oil
CHP biomass
CHP gas
CHP wastes
CHP H2
Solar PV
Wind turbines

Lead-acid batteries
NaS batteries
VRF batteries
Li-Ion batteries
NiMH batteries
PEM electrolysis

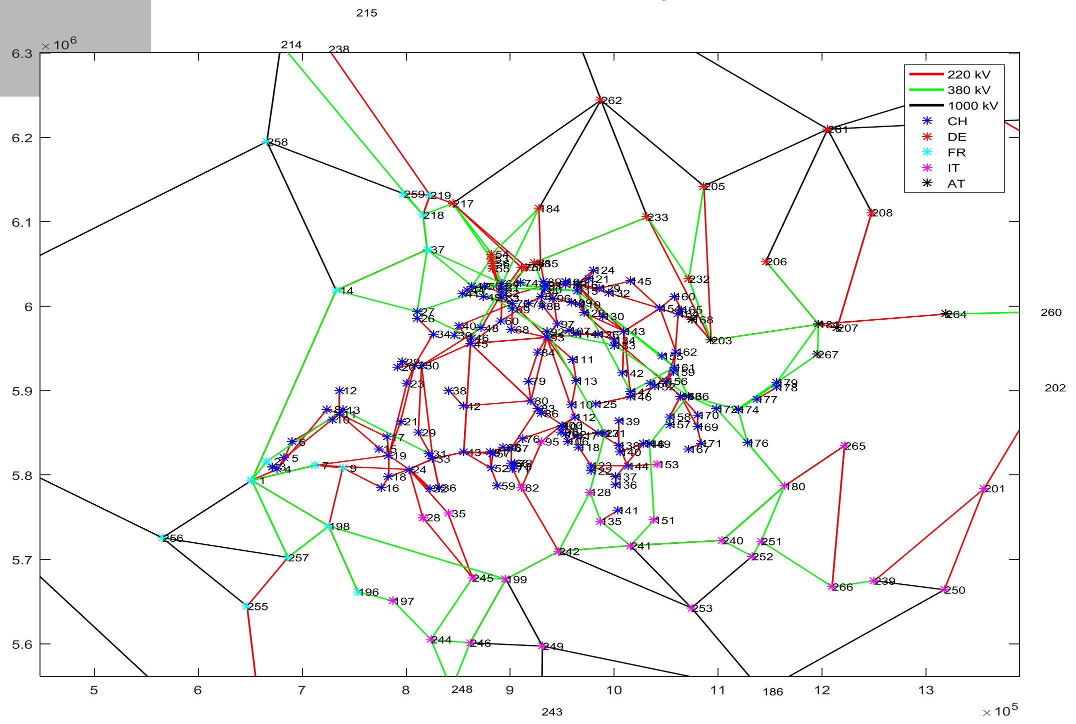
Commercial/ Residential Generation

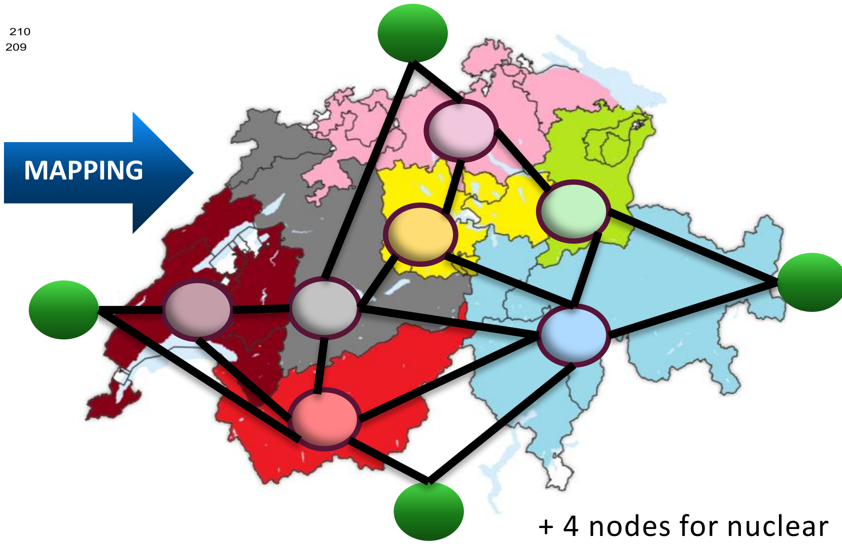
CHP gas
CHP biomass
CHP H2
Solar PV
Wind turbines

Lead-acid batteries
Li-Ion batteries
NiMH batteries

Representation of electricity transmission grid

- Based on a reduction algorithm from FEN/ETHZ that maps the detailed transmission grid to an aggregated grid with $N = 15$ nodes and $E = 319$ lines, based on a fixed disaggregation of the reduced network injections to the detailed network injections





+ 4 nodes for nuclear power plants

$$-\mathbf{b} \leq \mathbf{H} \times \mathbf{D} \times (\mathbf{g} - \mathbf{l}) \leq \mathbf{b}$$

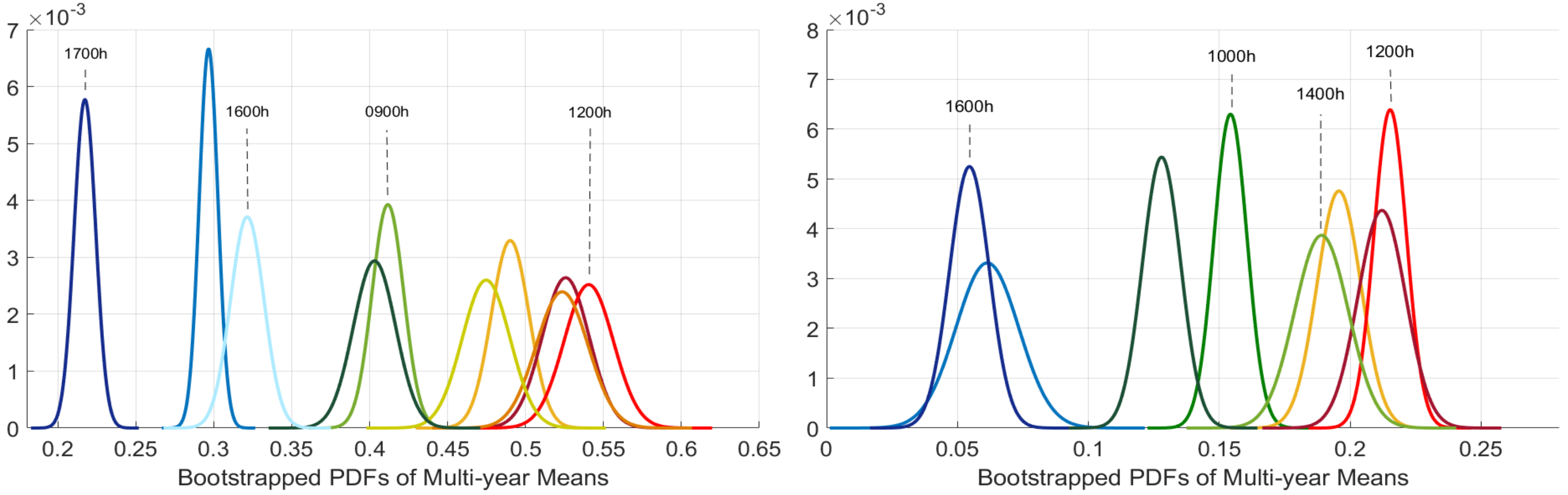
Where $\mathbf{H}$ is the PTDF matrix of the detailed network, $\mathbf{D}$ is the fixed dissagregation matrix, $\mathbf{g}$ is Nx1 vector with injections, $\mathbf{l}$ is Nx1 vector of withdrawals, and $\mathbf{b}$ is Ex1 vector of line capacities

The matrix $\mathbf{D}$ is not unique, since there are infinite ways in which an aggregate injection can be distributed between multiple nodes; here, it allocates power injections according to the original distribution of generation capacity in the detailed model

Representation of stochastic RES variability

- The STEM model has the concept of the **typical** day. Hence the mean wind/solar production is applied, and the **variance of the mean** is needed to capture stochasticity through the variability of the mean
- Bootstrap was applied to derive the variation of the mean for wind/solar generation and electricity consumption across the typical days of a 20-year sample data and then we moved ± 3 sd in the distribution of the mean for each our and typical day to obtain the variability.

Bootstrapped Distribution of Mean Photovoltaic Capacity Factors: Summer (left), Winter (right)



- The storage capacity must accommodate downward variation of the Residual Load Duration Curve (RLDC) and upward variation of non-dispatchable generation
- The dispatchable peak generation capacity (incl. storage) must accommodate upward variation of the RLDC and downward variation of non-dispatchable generation

Ancillary services markets – provision of reserve

- Power plants commit capacity to the reserve market based on their **operational constraints** and the trade-off between:
  - **marginal cost of electricity (covers generation costs)**
    → dual of the electricity supply-demand balance constraint
  - **marginal cost of reserve provision (covers capacity costs)**
    → dual of the reserve provision – demand balance constraint

- In each of the 288 typical hours the demand for reserve is calculated from the joint probability distribution function (p.d.f.) of the individual p.d.f. of forecast errors of supply and demand. We assume that the forecast errors are following the normal distribution
  - The sizing is based on both probabilistic and deterministic assessment
  - We move ± 3 s.d. on the joint p.d.f of the reserve demand to estimate the reserve requirements

$$R = 3 * \sqrt{{\sigma^2}_{solar} \cdot \left(G_{t\,solar} - S_{t\,solar}\right)^2 + {\sigma^2}_{wind} \cdot \left(G_{wind} - S_{t\,wind}\right)^2 + {\sigma^2}_{load} \cdot L_t^2} + P^{max}$$

sd. of forecast error distribution

Storage

Generation

Loss of a grid element (N-1 criterion)

Long term scenarios analysed

A range of “what-if” scenarios was assessed along three main dimensions:

1. Future energy policy and energy service demands

	Base case		*Climate change*		*Imports*		*Combined case*	
	P	**W**	**P-CO2**	**W-CO2**	**P-IMP**	**W-IMP**	**P-CO2-IMP**	**W-CO2-IMP**
POM based energy service demands	✓		✓		✓		✓	
WWB based energy service demands		✓		✓		✓		✓
Nuclear phase out by 2034	✓	✓	✓	✓	✓	✓	✓	✓
Zero net annual electricity imports	✓	✓	✓	✓				
-70% CO2 emission reduction in 2050 from 2010			✓	✓			✓	✓

2. Location of new gas power plants and installed capacity as % of the total national capacity

	Corneux (NE)	Chavalon (VS)	Utzenstorf (BE)	Perlen (LU)	Schweizerhalle (BL)
Case 3	20.0	20.0	20.0	20.0	20.0
Case 6	*No grid constraints, so the location of gas turbines does not play a role*				
Case 11	0.0	33.3	33.3	33.3	0.0
Case 26	33.3	33.3	0.0	0.0	33.3

3. Grid expansion: allowing grid reinforcement beyond the plans announced for 2025 or not

↳in total about 100 scenarios were assessed with the STEM model based on the Cartesian Product of the above combinations

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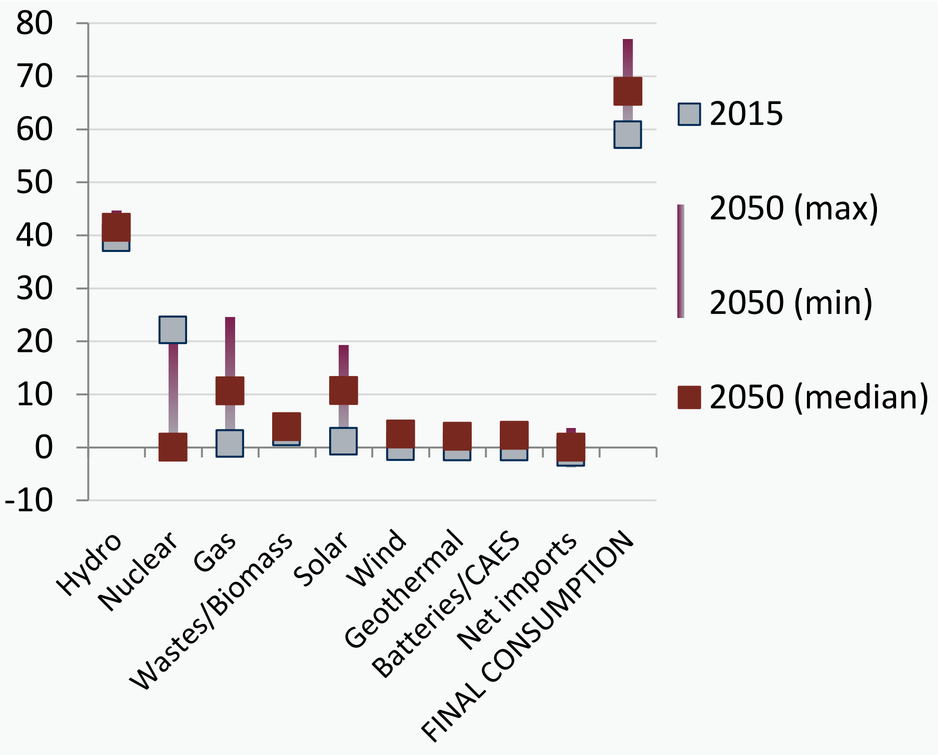
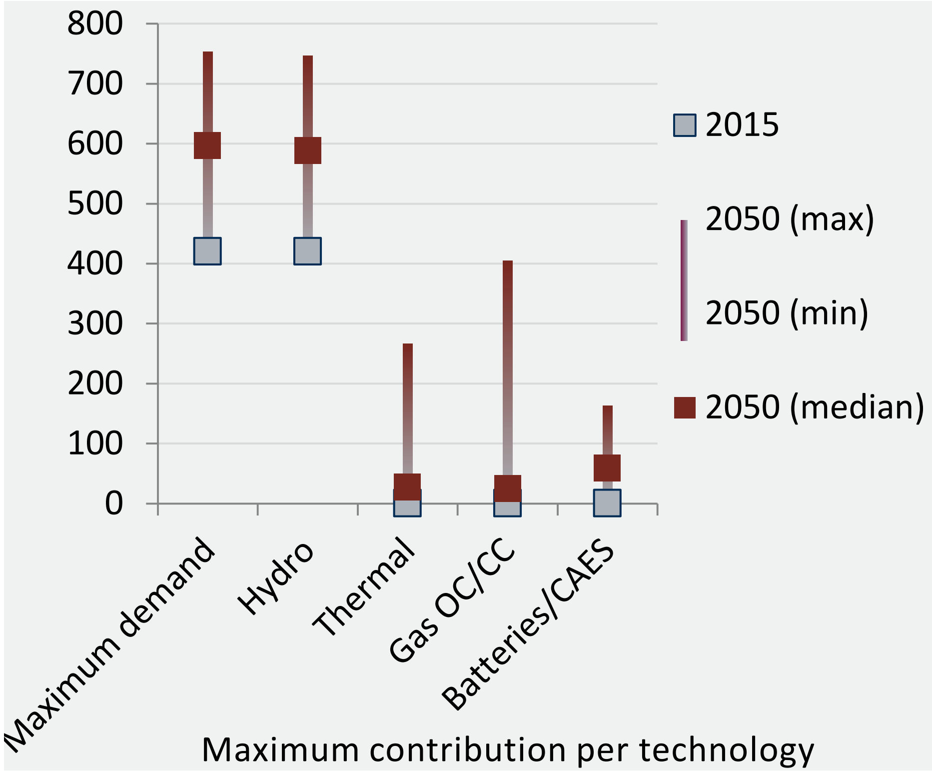
Electricity consumption continues to increase and gas, VRES & imports replace nuclear by 2050

- Electricity consumption increases 4 – 30% from 2015 (0.1 – 0.8% p.a)
- New gas power plants replace existing nuclear capacity
- Under climate policy VRES provides 28% of the supply (close to the current share of nuclear)
- The requirements for secondary reserve almost double in 2050 from today's level and peak demand shifts from winter to summer; hydro is still the main contributor to reserve

ELECTRICITY GENERATION & CONSUMPTION IN 2050 (TWh)



REQUIREMENTS IN SECONDARY RESERVE IN 2050 (MW)

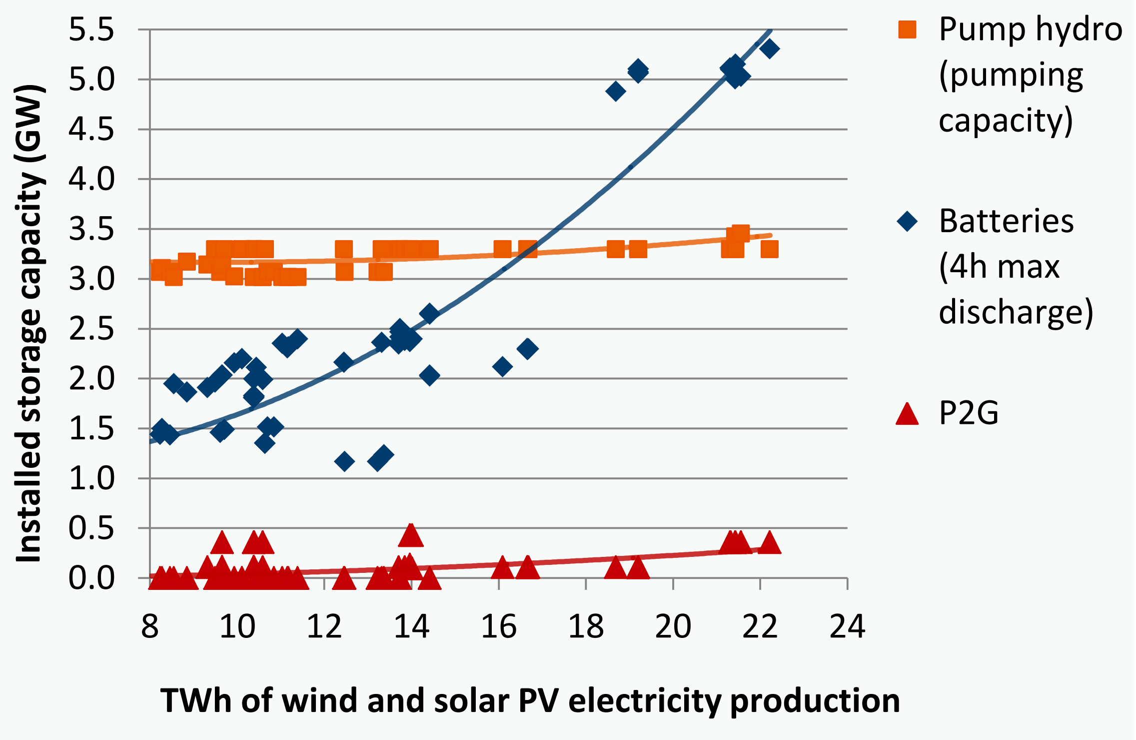


The results correspond to ranges among the 100 scenarios assessed

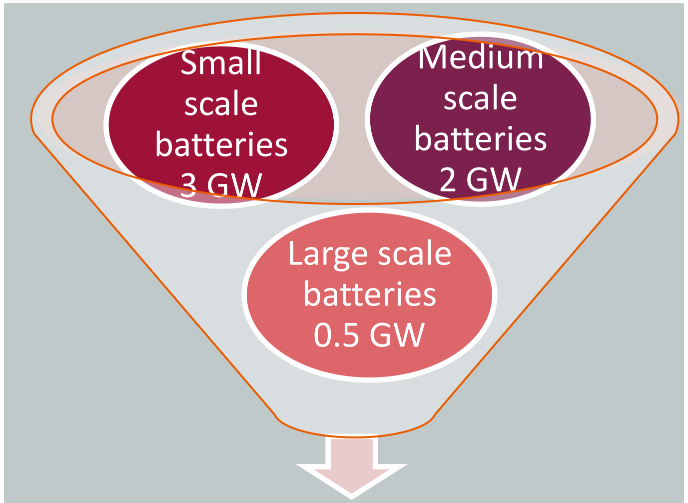
Storage needs increase with VRES deployment

- High shares of VRES require electricity storage peak capacity of ca. 30 – 50% of the installed capacity of wind and solar PV (together)
- Above 14 TWh of VRES generation, significant storage deployment is needed
- About 13% of the excess summer VRES production is seasonally stored in P2G (~ 1 TWh_e)

ELECTRICITY FROM WIND AND SOLAR PV VS INSTALLED PEAK STORAGE CAPACITY IN DIFFERENT SCENARIOS AND YEARS



Each data point in the graph corresponds to a different long term scenario and year



Small scale batteries 3 GW

Medium scale batteries 2 GW

Large scale batteries 0.5 GW

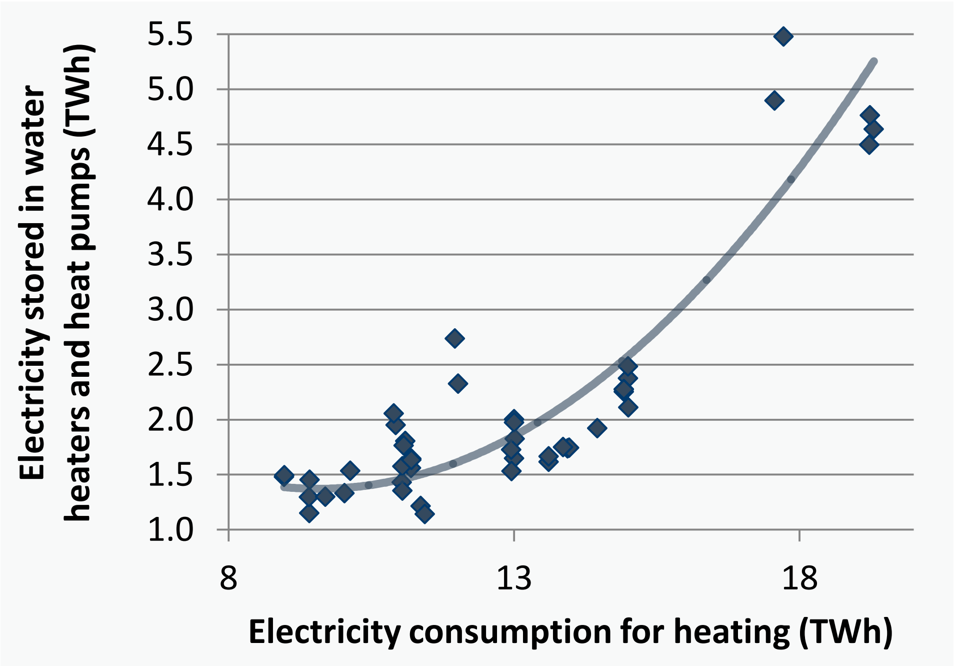
Max. Total battery capacity 5.5 GW

- Small scale batteries are driven by distributed solar PV installations
- Medium scale batteries are driven by wind and large scale PV and CHP
- Large scale batteries complement pump hydro storage when it is unavailable

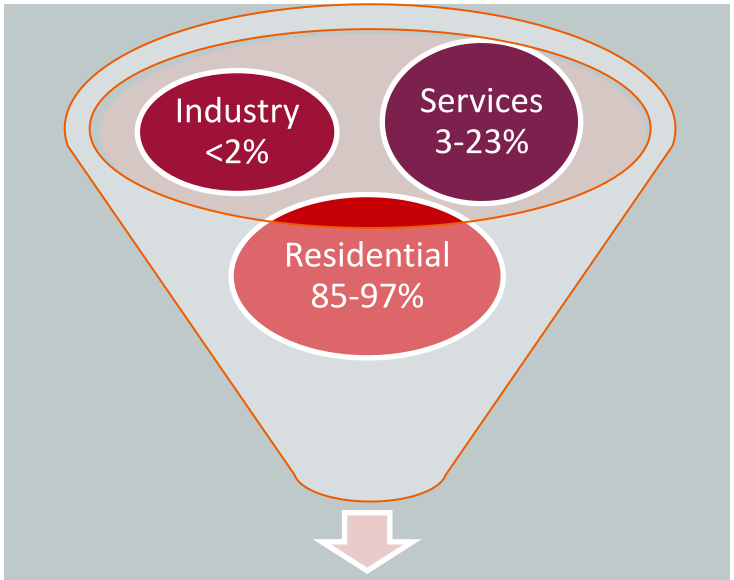
Dispatchable loads help in easing electricity load peaks in the stationary end-use sectors

- Electricity storage in water heaters and heat pumps accounts for 8 – 24% of the total electricity consumption for heating
- Above 13 TWh of electricity for heating there is an accelerated deployment of dispatchable loads to mitigate peak
- Large potential for load shifting is in water heating (resistance heating) followed by space heating in buildings

ELECTRICITY STORED IN WATER HEATERS AND HEAT PUMPS VS ELECTRICITY CONSUMPTION IN HEATING IN 2050 (TWh)



Each data point in the graph corresponds to a different long term scenario

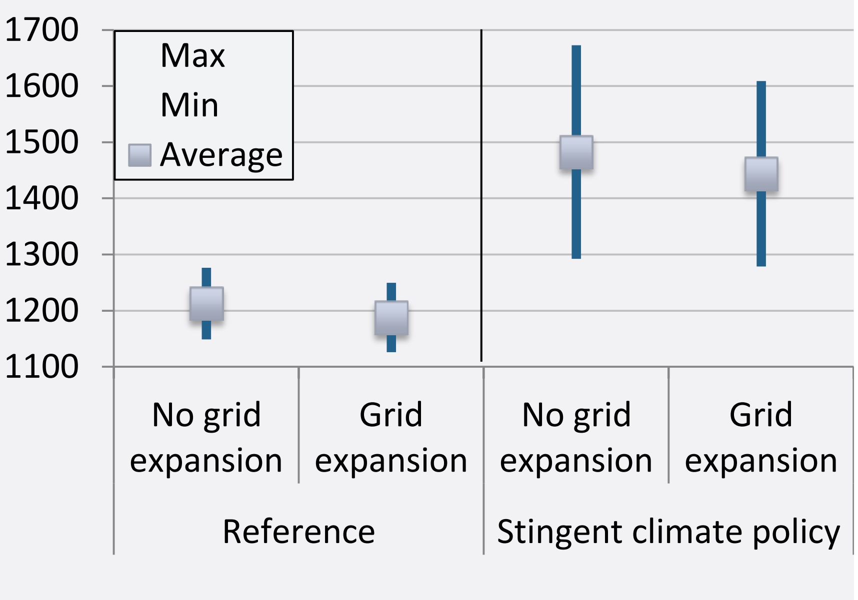


Contribution of each sector to electricity stored in water heaters and heat pumps

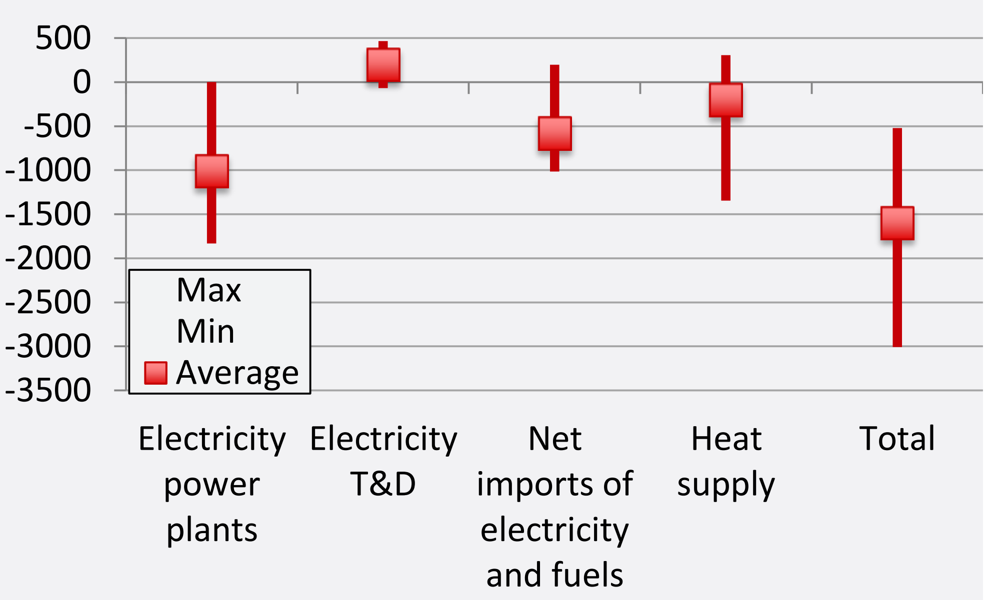
The system-wide benefits from the electricity grid expansion outweigh the costs

- Restrictions in grid expansion lead to higher system costs of up to 90 BCHF (+10%) over the period of 2020 – 2050 because of congestion that results in:
  - non-cost optimal options for electricity supply and less VRES deployment
  - less electrification of demand and reliance on fossil-based heating
- Much of the cost savings due to grid expansion result in the heating sectors, directly (e.g. technology change via heat pumps) and indirectly (e.g. less costs for imported fuels)

CUMULATIVE UNDISCOUNTED ELECTRICITY AND HEAT SYSTEM COST, BHCF/yr, 2020 – 2050



DECOMPOSITION OF ELECTRICITY AND HEAT SYSTEM COSTS SAVINGS DUE TO GRID EXPANSION, MCHF/yr, 2020-2050

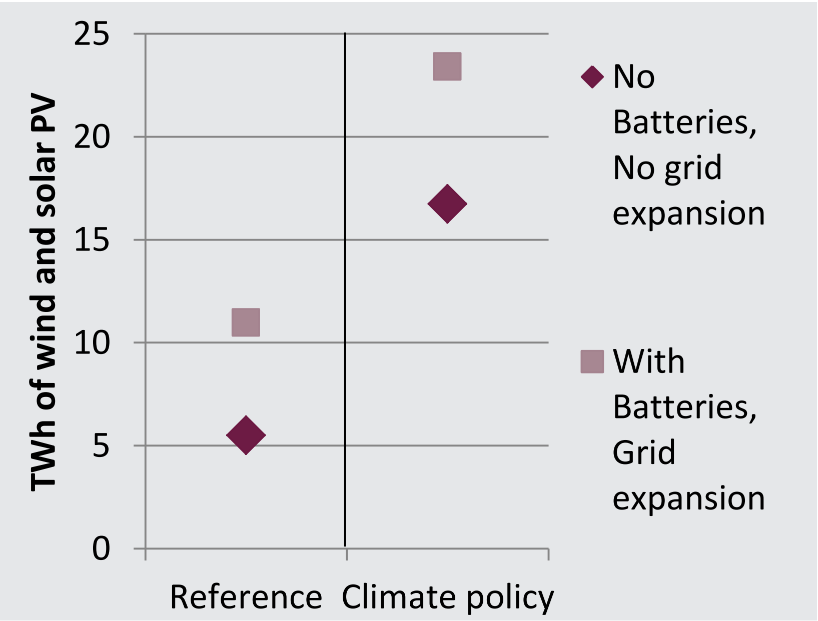


The results correspond to ranges among the 100 scenarios assessed

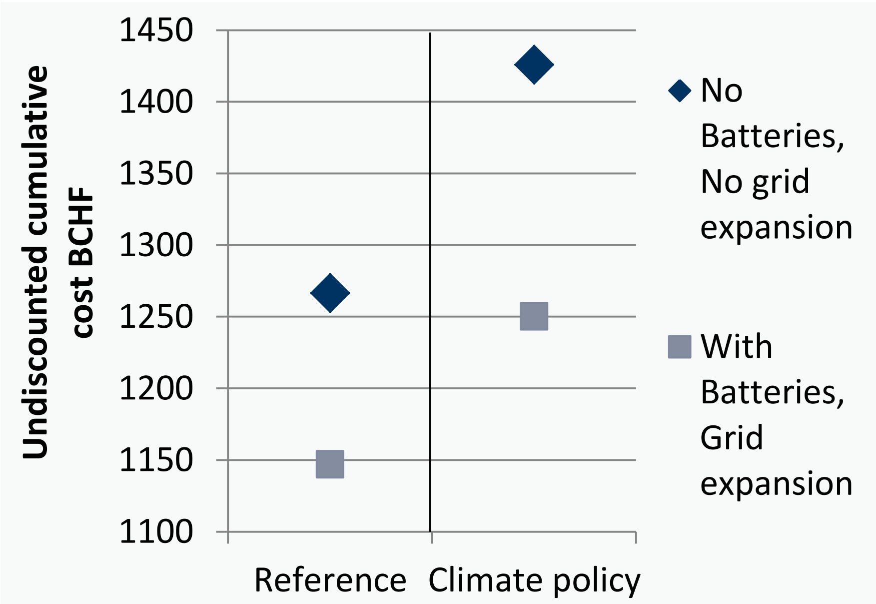
Storage and grid expansion are required to realise the VRES potential and lower climate policy costs

- Without batteries and grid, there is 30 – 50% less deployment of wind and solar electricity compared to the case when both options are available
  - Batteries are important for the integration of VRES to cope with their variability
  - Grid expansion is important to integrate large amounts of VRES production (>16 TWh)
- Total system costs can be 10 – 14% higher if both batteries and grid expansion are unavailable
  - In particular climate policy costs could increase by more than 50% (from 103 to 160 BCHF)

IMPACT OF BATTERIES AND GRID EXPANSION IN THE DEPLOYMENT OF WIND AND SOLAR PV POWER



IMPACT OF BATTERIES AND GRID EXPANSION IN THE TOTAL SYSTEM COSTS



Results on the left graph corresponds to ranges; results on the right graph is for a scenario with high demand and electricity imports

Conclusions and further work

- **Electricity consumption** continues to increase by 0.1 – 0.8% p.a. and **could reach over 70 TWh/yr** by 2050

- **VRES** can contribute **up to 24 TWh$_e$** (or 28% of the domestic supply) but this requires:
  - **Storage peak capacity** investments about **30 – 50% of the installed wind and solar PV** capacity; beyond 14 TWh$_e$ accelerated deployment of storage is inevitable
  - **Grid reinforcement** beyond the expansion plans anounced for 2025

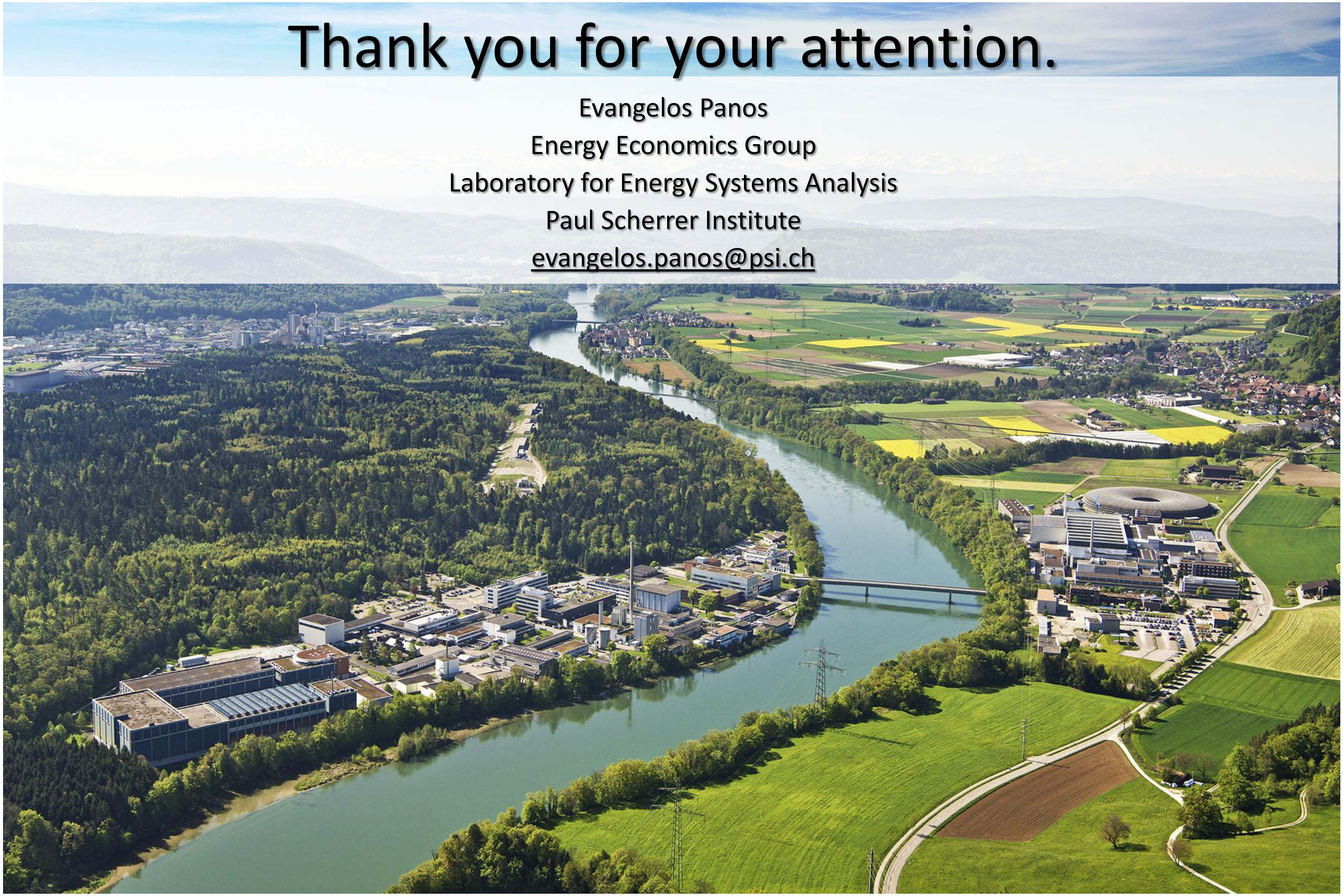
- About **13% of the excess electricity production** from VRES in summer is seasonally stored **in P2G pathways**

- **Water heaters and heat pumps** could contribute in easing electricity peaks and **could shift 8 – 24% of the electricity** consumption for heat

- **Grid reinforcement results in net economic benefits** for the whole electricity and heat supply system of Switzerland on the order of **0.5 – 3.0 BCHF/yr**.

- When both electricity **storage and grid expansion are unavailable**, **VRES generation** could be up to **50% less** and **climate costs** could increase by **more than 50%** compared to the opposite case

- **Further work** is needed to overcome some **important limitations**:
  - Regional representation also for the heat supply and not only for electricity
  - Consideration of N-2 grid security constraints
  - More detail in technical representation of storage technologies (e.g. depth of discharge)



Thank you for your attention.

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