High Temporal and Spatial Resolution Simulations of Increased Renewable Penetration in Interconnected Power Systems

Ndaona Chokani, ETH Zürich

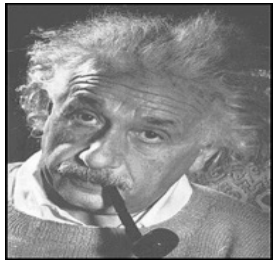
CRSES, Stellenbosch, 12 May 2016

Overview

- Introduction
- EnerPol Modelling Framework
- Applications
- Concluding Remarks

ETH Zürich – Who We Are

- **Swiss Federal Institute of Technology**
  - technical university of Swiss Confederation
  - founded 1855
  - 21 Nobel Laureates connected with ETH Zürich



Albert Einstein

  - 2015: ranked 9th in both Times Higher Education and QS World University Rankings
  - 18’000 people
    - including 370 professors, 2‘900 PhD candidates, 5‘000 technical personnel
  - 16 departments
    - including architecture & civil engineering, natural sciences & mathematics, …engineering sciences
    - Mechanical & Process Engineering Department: 36 laboratories

Laboratory for Energy Conversion (LEC)

- **Research Focus**
  - efficient use of resources and efficiency in energy systems
- **Research Teams**
  - turbomachinery
    - power generation & mobility
  - wind energy
    - full-scale & dynamically-scaled experiments
  - laser plasma
    - extreme ultra-violet light source
  - instrumentation
    - sensors, actuators & mechatronics
  - computational science
    - CPU & GPU codes for fluid & plasma dynamics
  - energy & policy
    - modelling of electricity, gas, heat, & built environment to support policy making

Year of Founding	1892
Ongoing Projects	20-22
Total Members	≈70
(PhD Assistants: 16-18)	
(Masters Students: 30-35)	
(Staff: 16)	
Peer-Reviewed, Archival Publications / year	20-22
Recent Outstanding Publication Awards	6
Spin-Off Companies	3

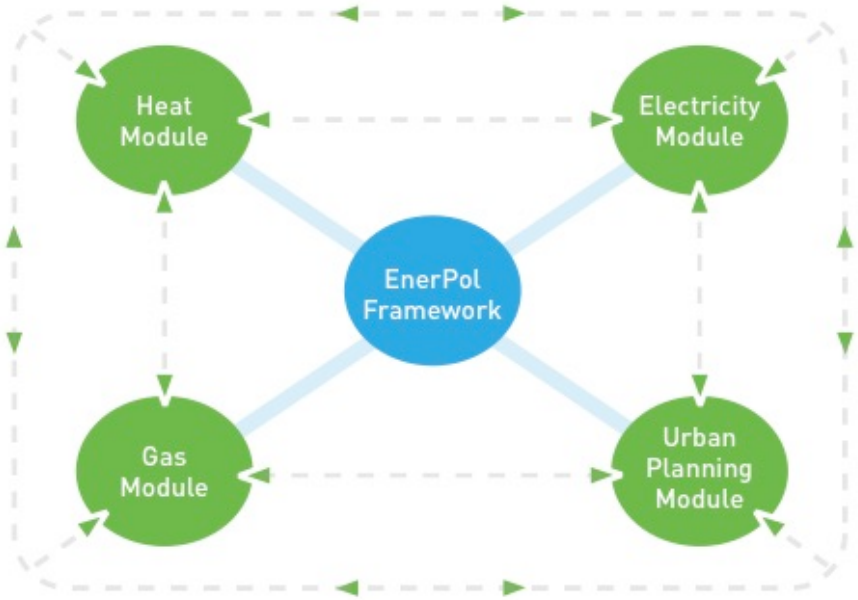
Overview

- Introduction
- EnerPol Modelling Framework
- Applications
- Concluding Remarks

EnerPol – Overview

- In development since 2009, EnerPol framework provides system-wide, bottom-to-top, scenario assessments of:
  - power generation mix,
  - electricity, gas & urban infrastructures,
  - market performance, and
  - impact of policy

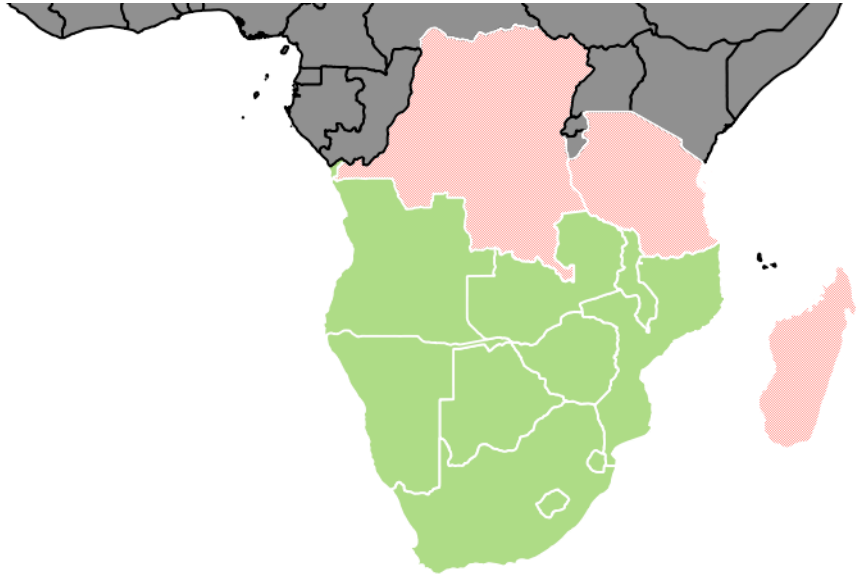
- Hourly chronological simulations (8'760 per year) of generation, transmission and demand of electricity and gas with high (30m × 30m) spatial resolution

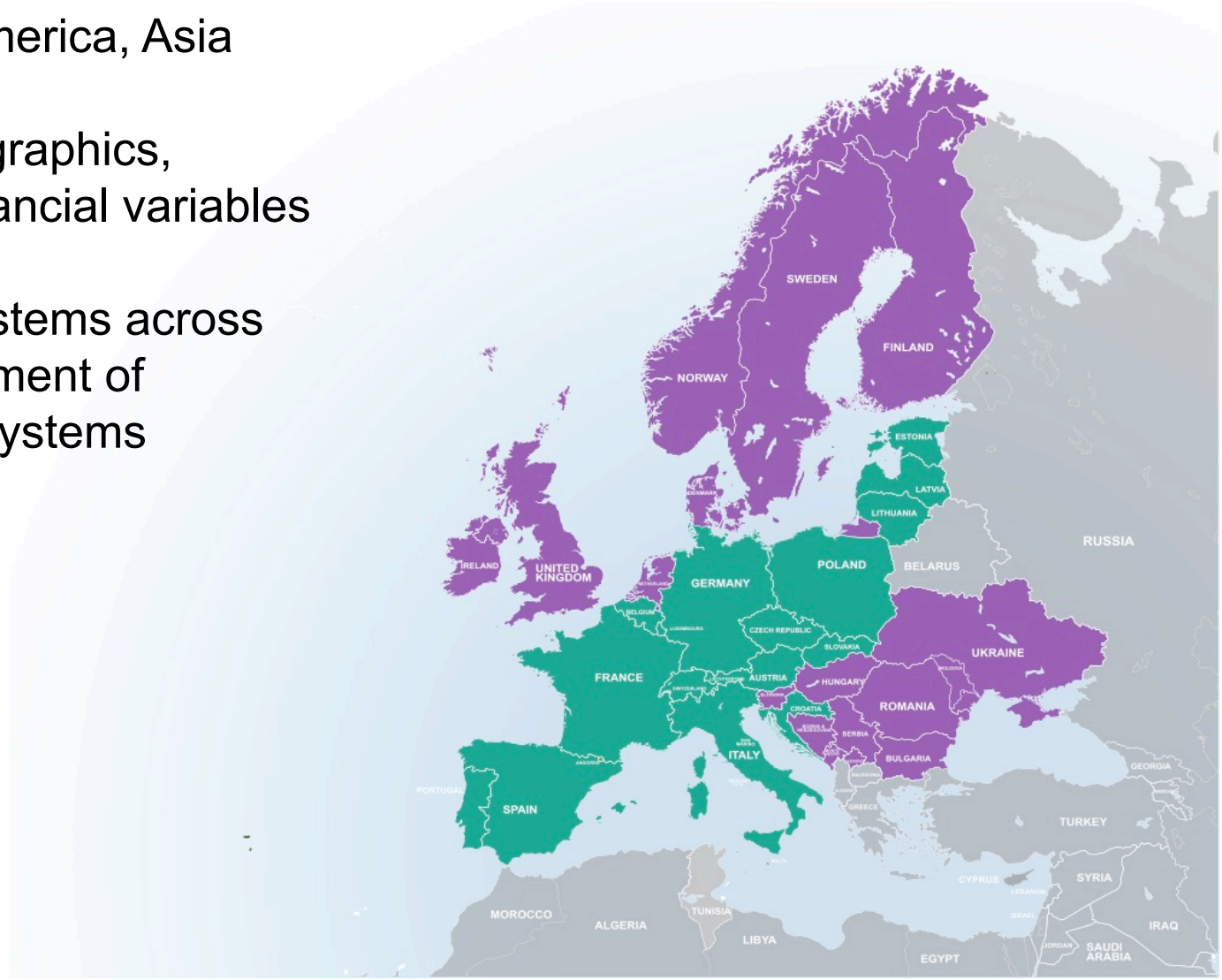


generation/ supply | transmission | demand

EnerPol – Global Geographic Coverage

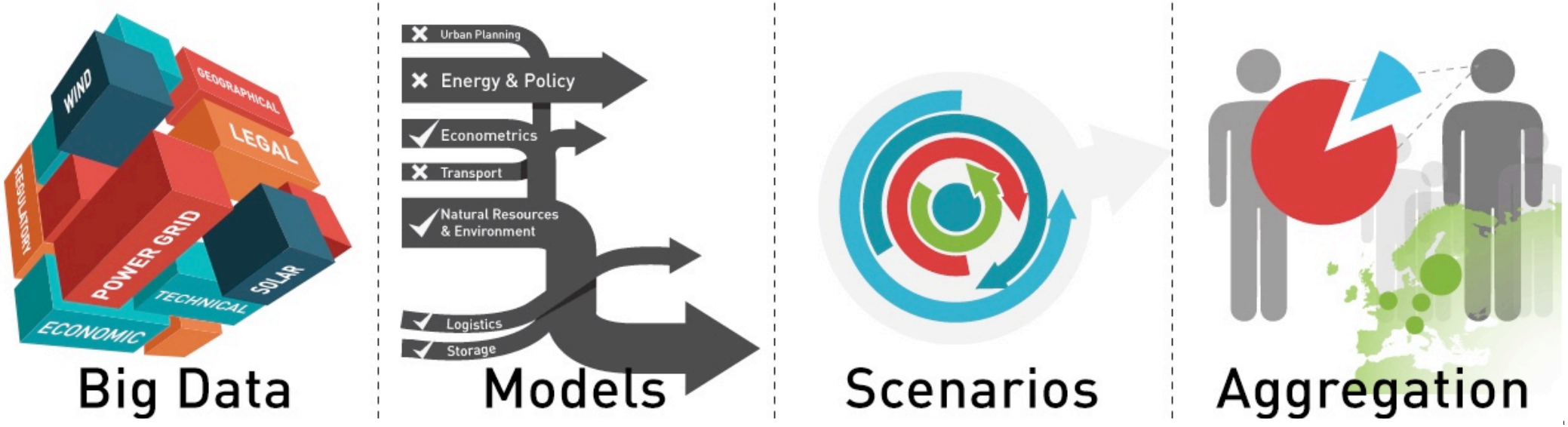
- Geographic coverage of Europe, North America, Asia and Africa
  - more than 200 anthropological, demographics, geography, climate, regulatory and financial variables
  - geo-referenced database developed
  - enables assessment of large-scale systems across continent, simultaneously with assessment of impacts on individual components of systems





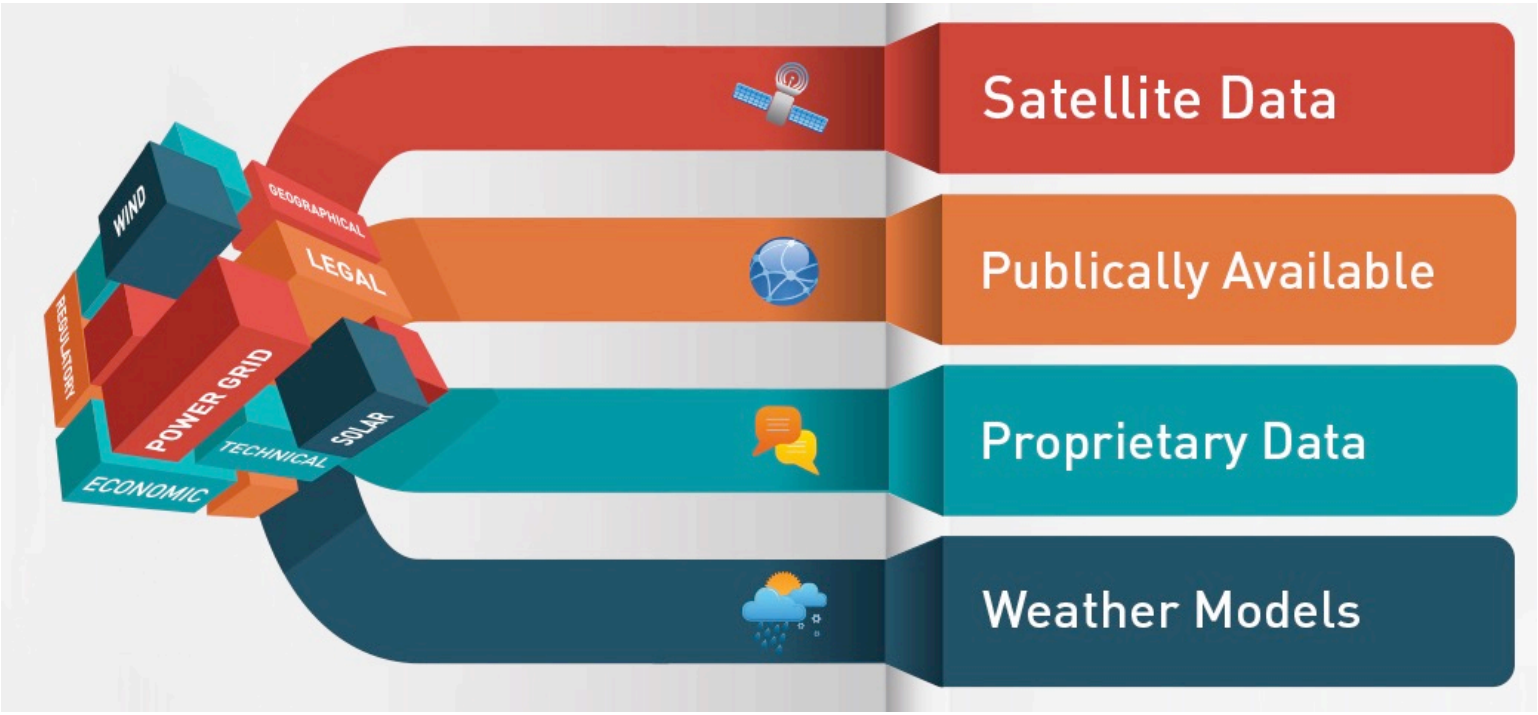
EnerPol – Components

- ‘Big data’ digitally represent infrastructure, environment, energy, mobility, economics and population
- Models interlink ‘Big data’ and large-scale computations performed on ETH’s high performance computing cluster



EnerPol – Sources of Data

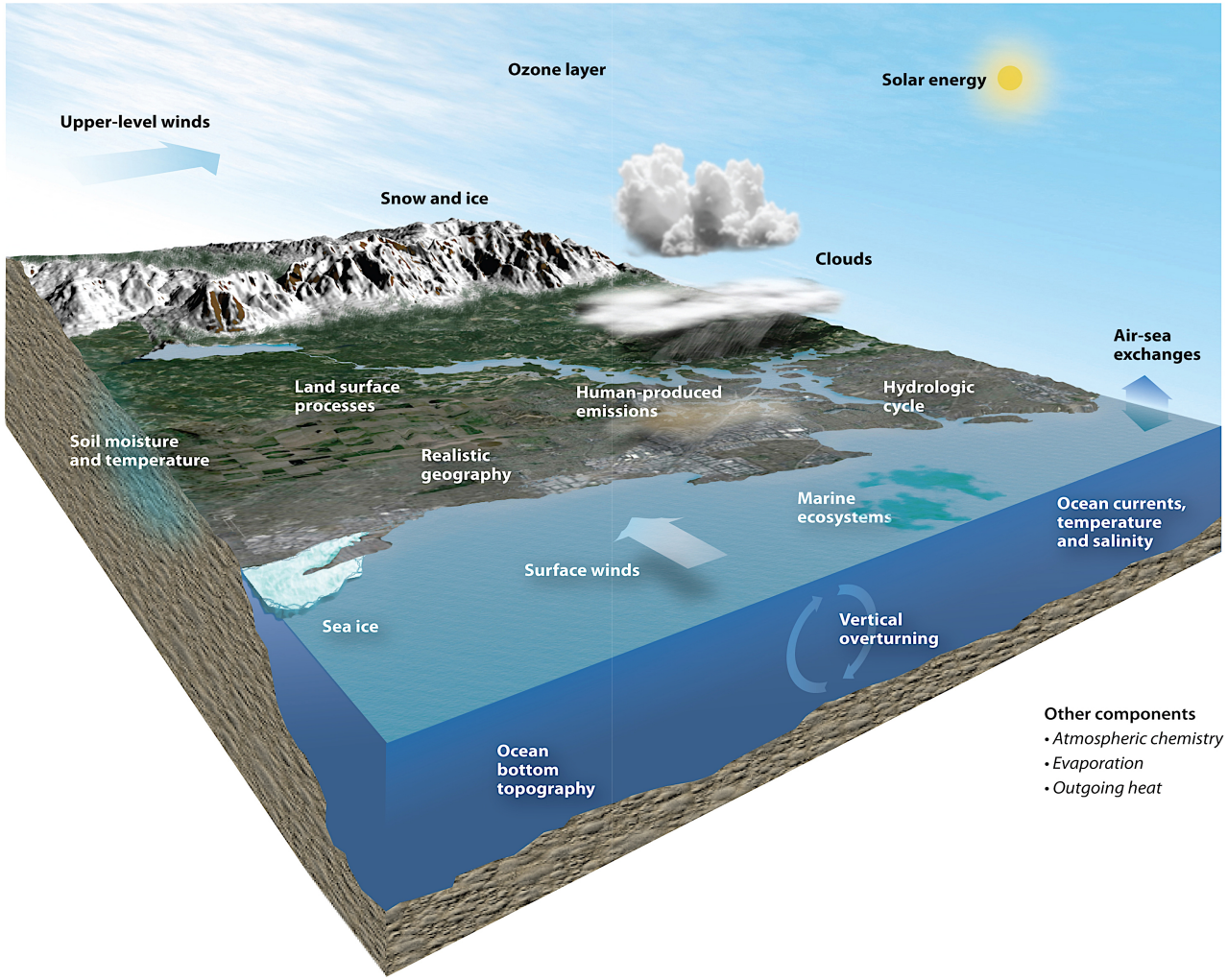
- Data are obtained from different sources, including satellites, open source, proprietary, etc., and converted into EnerPol-standardised formats



- multi-spectral image processing to identify natural resources and built infrastructure
- for example, TSOs, DSOs
- project partners
- mesoscale weather predictions integrated into EnerPol framework

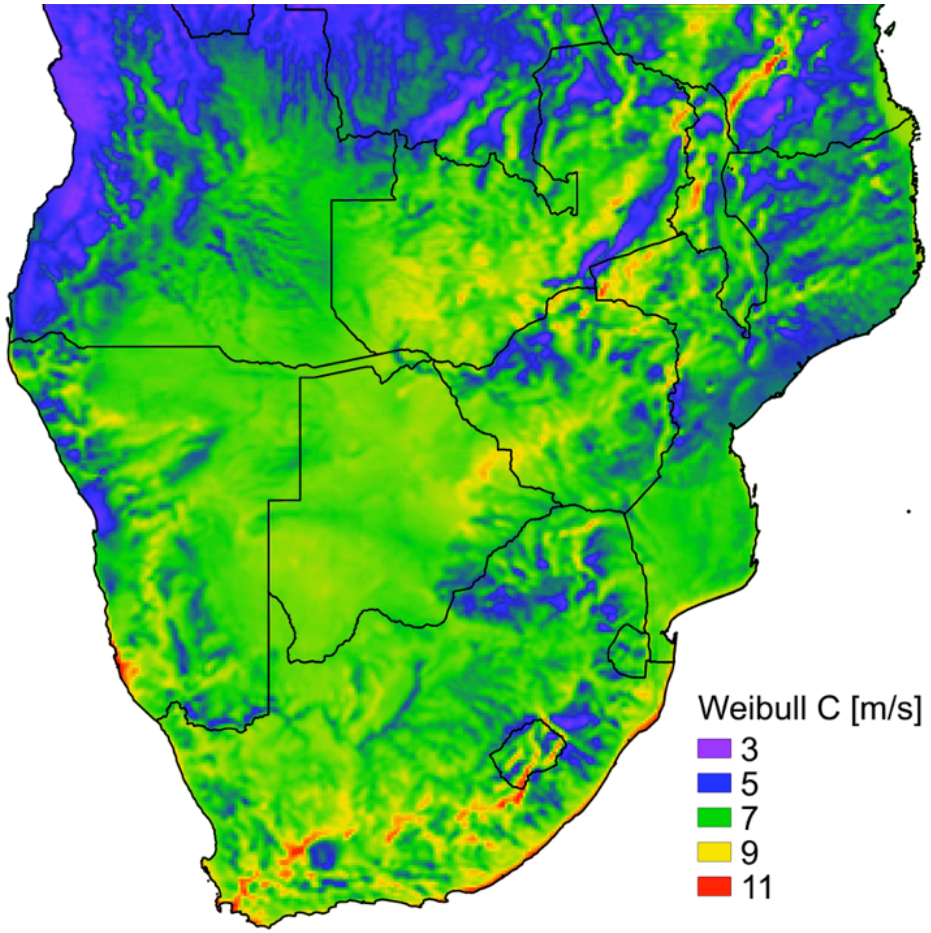
EnerPol – Mesoscale Weather Model

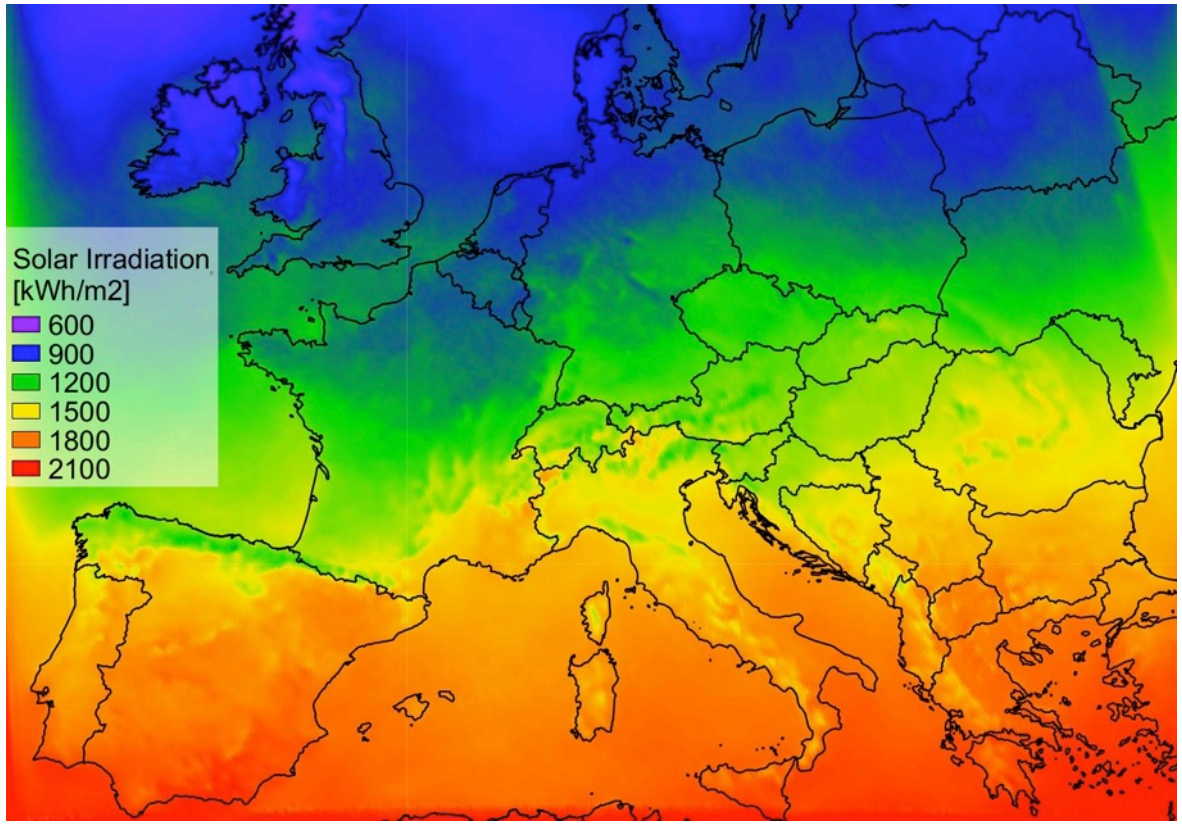
- Mesoscale weather simulations provide long-term predictions of wind speed, wind direction, rainfall, sunlight and temperatures
- Renewable (solar and wind) power generation and power demand are highly dependant on geographic location, time, and ambient weather conditions
- Spatial resolution of 10km x 10km x 20m and temporal resolution of 10 minutes
- Simulations run on ETH cluster Brutus



Renewable (Solar and Wind) Resources

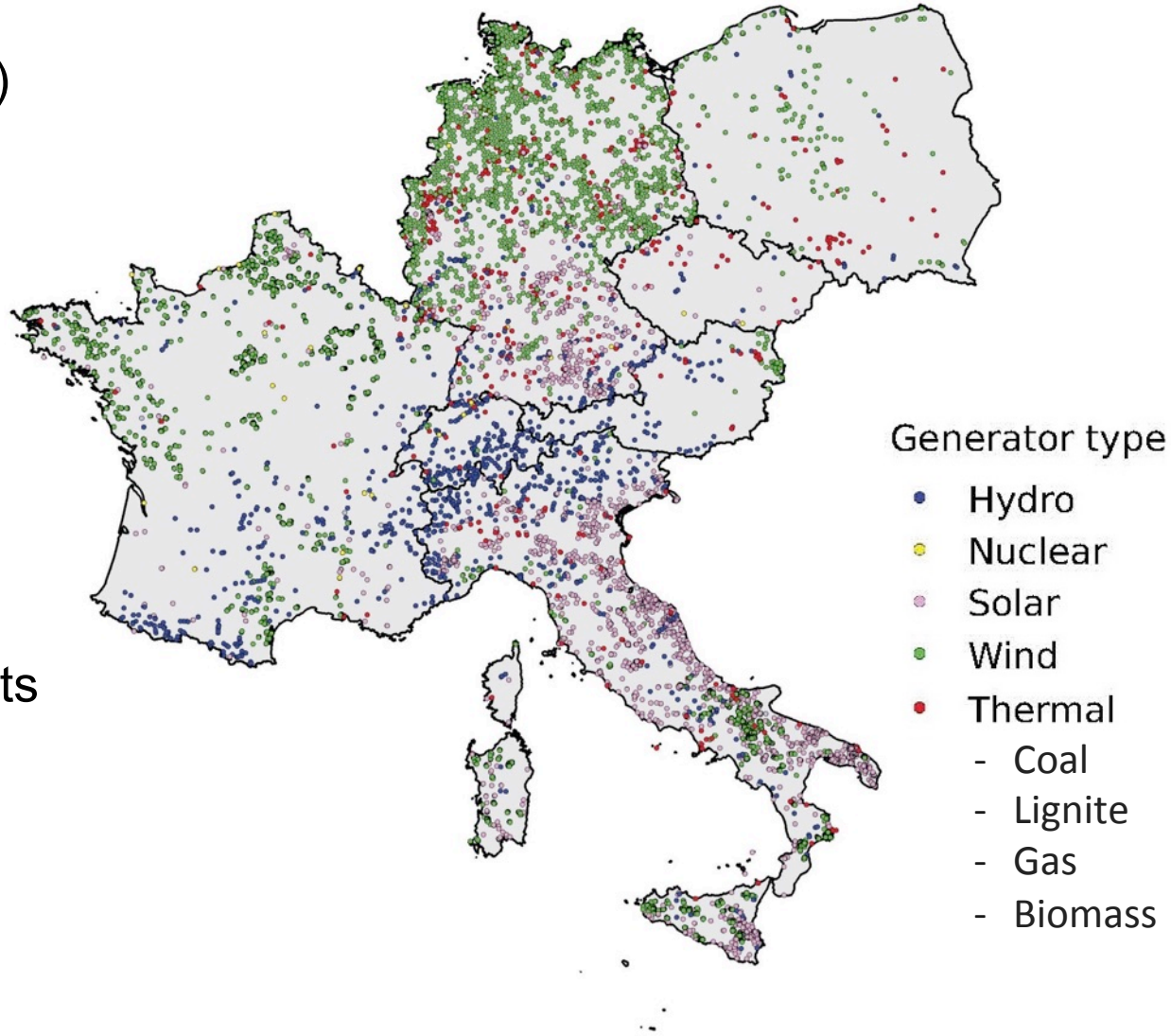
- Hourly time-series generation of renewable power plants derived from mesoscale weather model





EnerPol – Electricity Generation Model

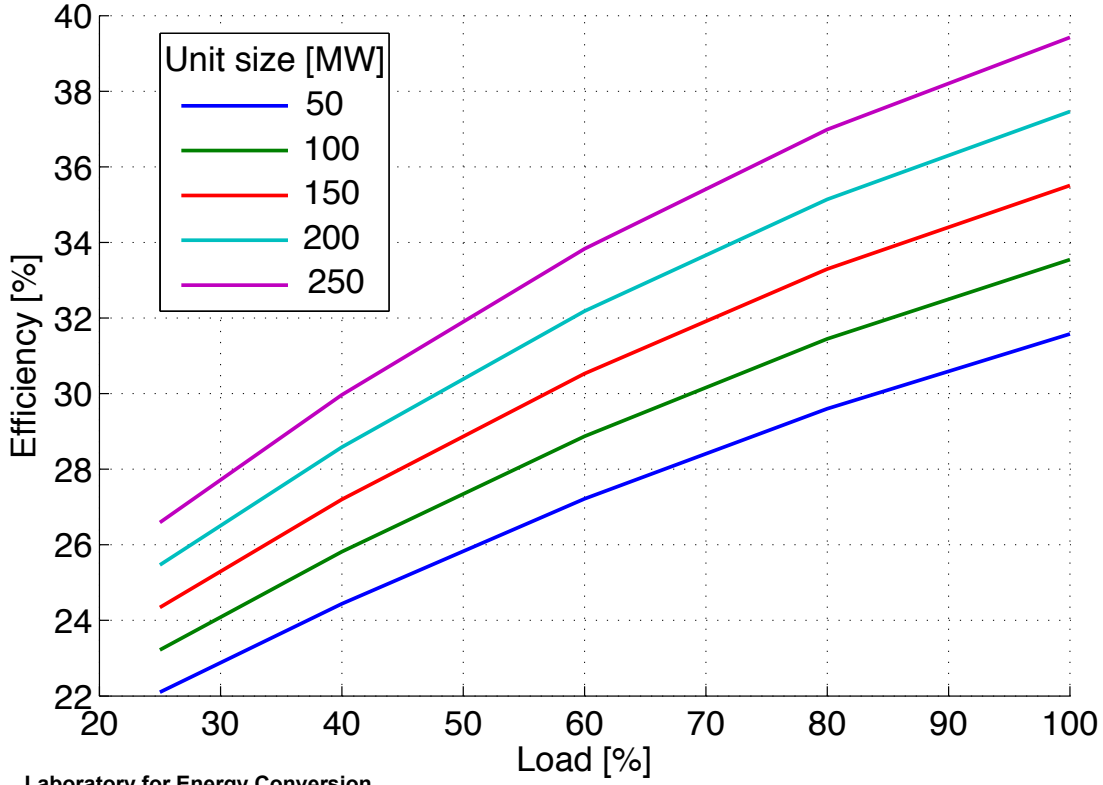
- Individual power plants (5’900 in central Europe 2013 baseline model; 205 in SAPP; 107 in RSA) are geo-referenced and modelled
  - power plants are differentiated by fuel type
  - variation of fuel prices is taken into account
  - cycling of thermal power plants is accounted for
  - run-of-river and pumped-storage power plants are modelled on basis of natural water flows
  - generation of renewable (solar and wind) power plants is derived from mesoscale simulations of weather

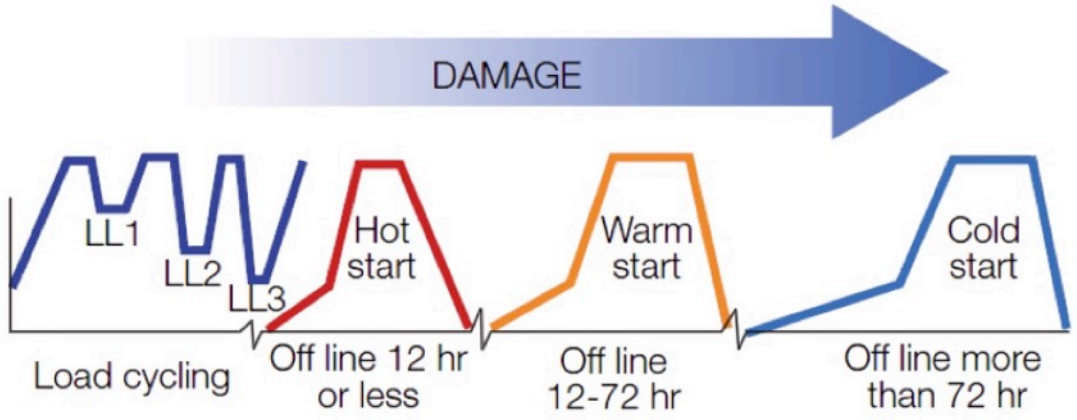


EnerPol – Modelling Costs of Thermal Power Plant Cycling

- Cycling costs are modeled as function of recent operational histories of individual units in thermal power plants

- Load-change operations of individual units that are accounted for, include start/stop, minimum load operation and load-change ramps



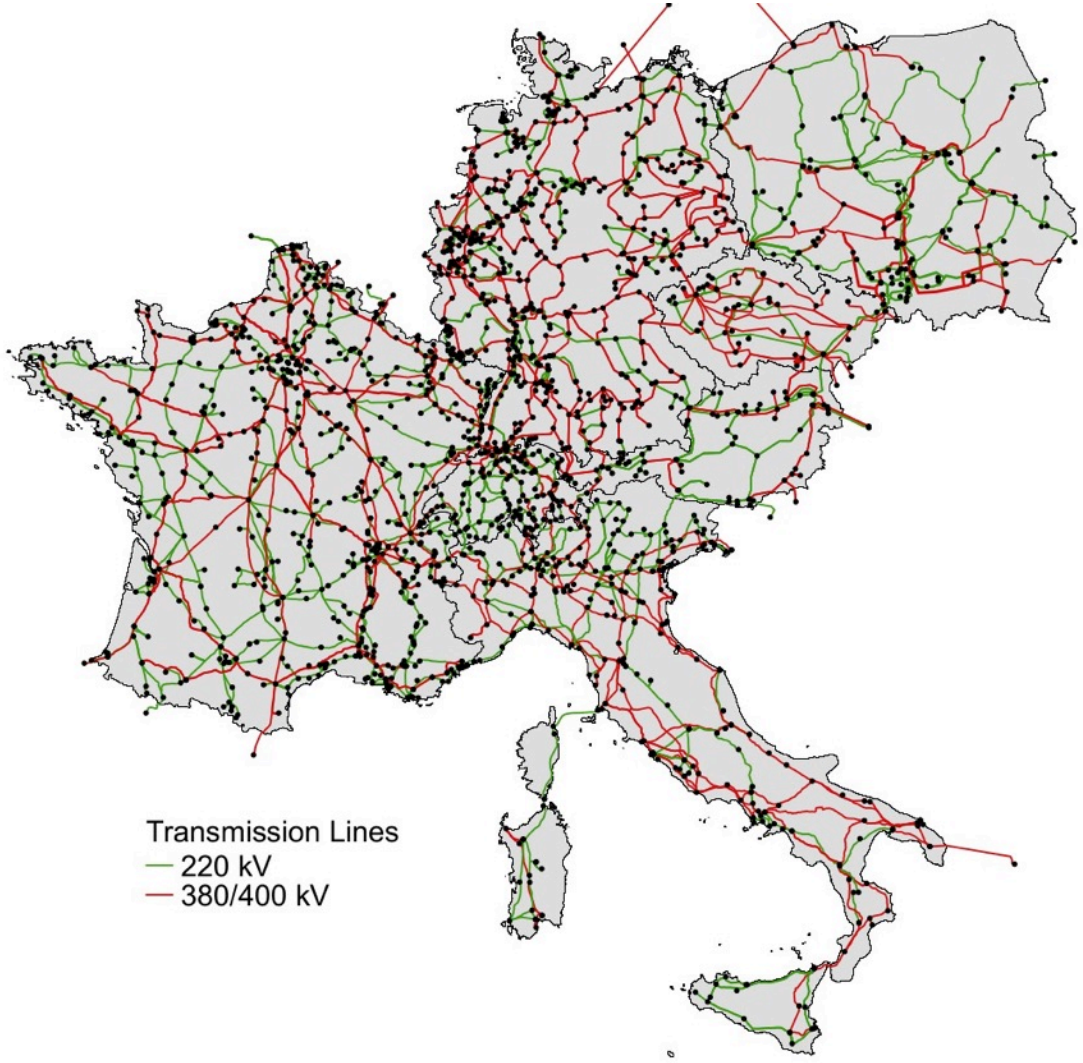


EnerPol – Electricity Transmission Model

- Individual transmission lines and sub-stations are geo-referenced, characterised and modelled

	Sub-stations	Transmission lines (km)
Europe	2’000	130’000
SAPP	520	58’247
South Africa	215	22’637

  - impact of weather, derived from mesoscale weather simulations, on ampacity and sag clearance of individual lines is modelled

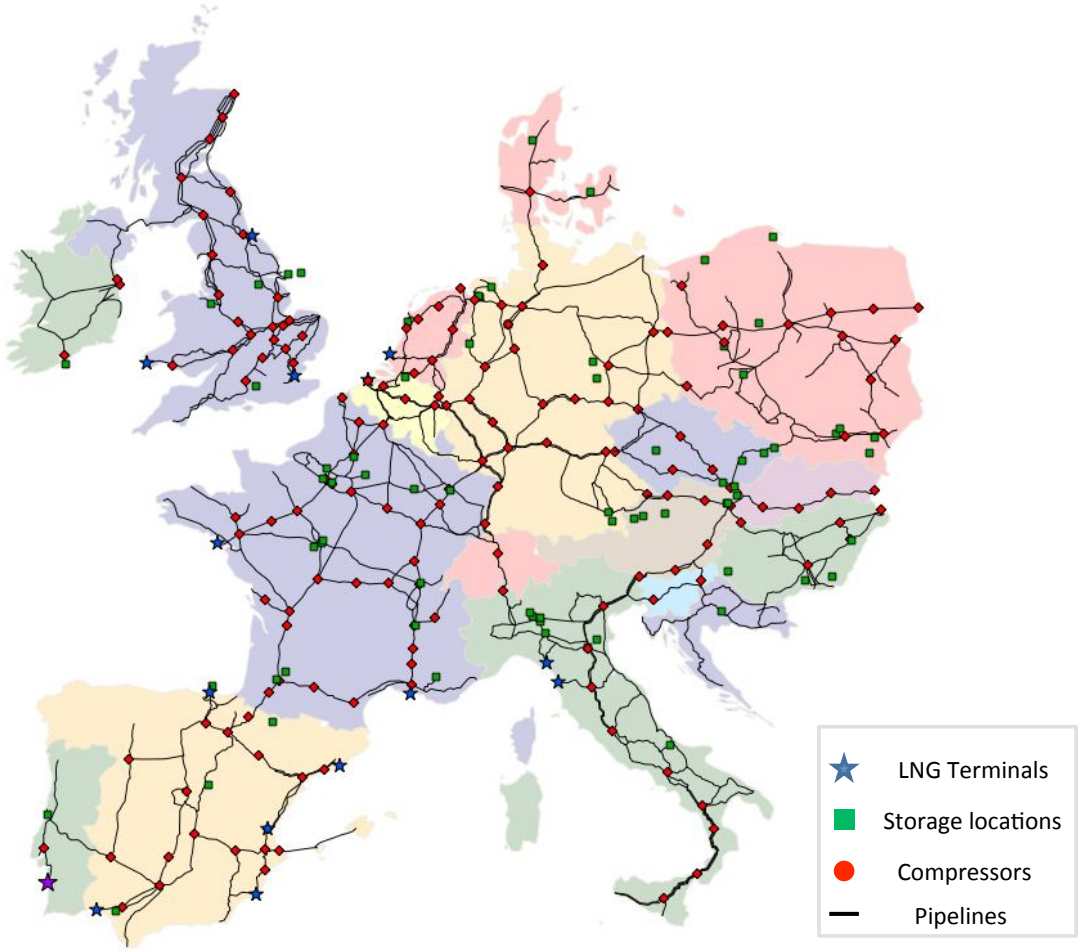


EnerPol – Gas Supply and Transmission Models

- Individual pipelines (44’000km in central Europe model), as well as all compressors (91), gas storages (52) and LNG stations (6) are geo-referenced



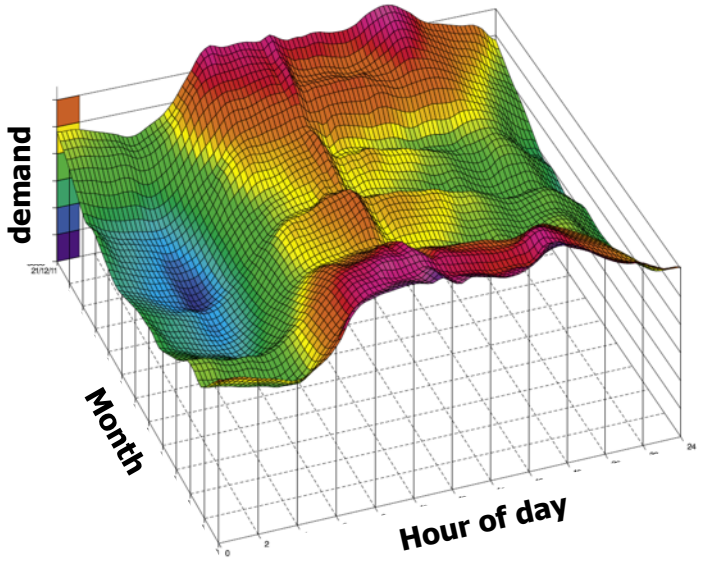
- Operational characteristics of all network components are modelled
  - storage vessels are linked to gas network through compressor-expander units
  - intermediate storage in pipelines is also modelled
  - booster stations to compensate pressure losses in pipelines are modelled



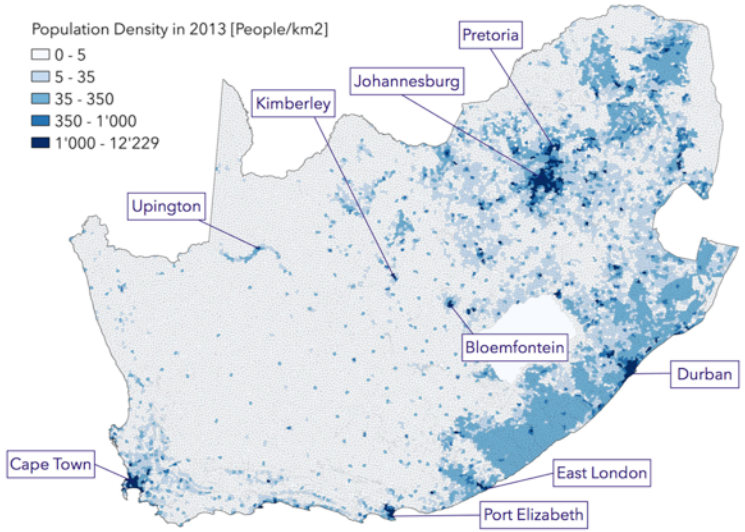
EnerPol – Electricity Demand Model

- Hourly electricity demands of spatially-resolved, household, commercial, industrial and transportation sectors are modelled

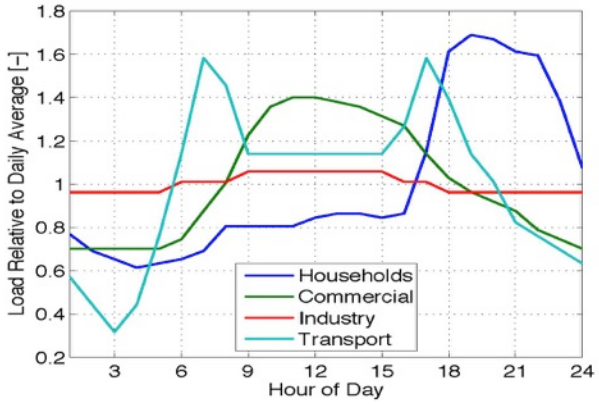
Annual electricity demand in Switzerland



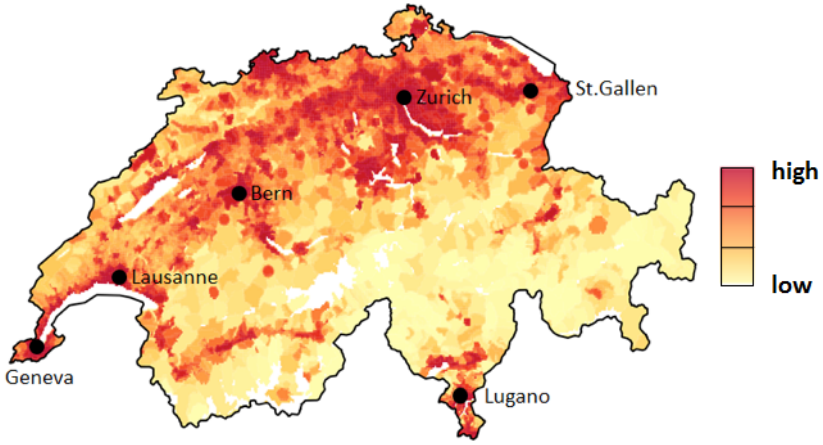
Spatial distribution of sector



Temporal demand by sector

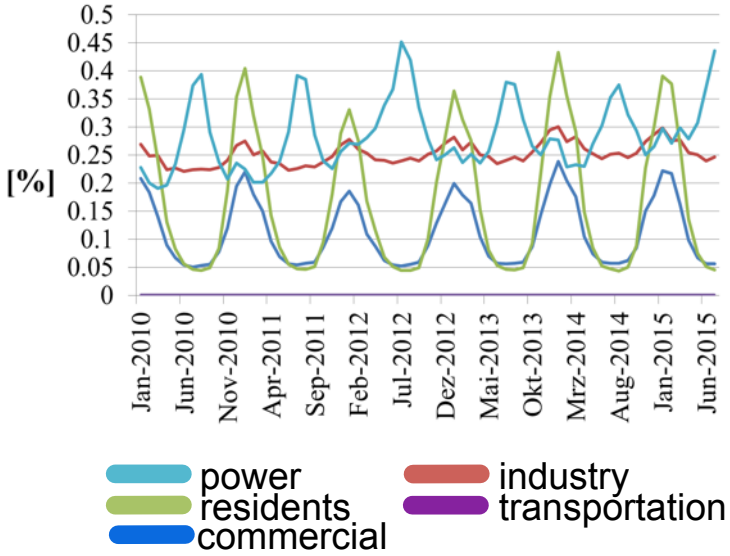


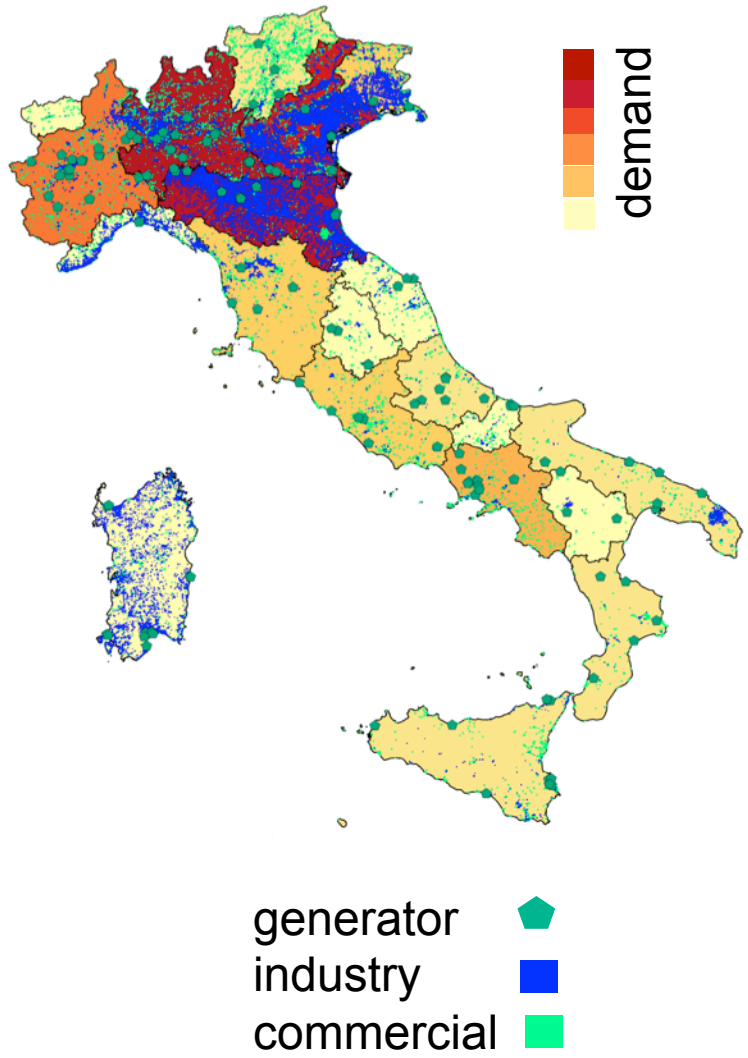
Snapshot of electricity demand



EnerPol – Gas Demand Model

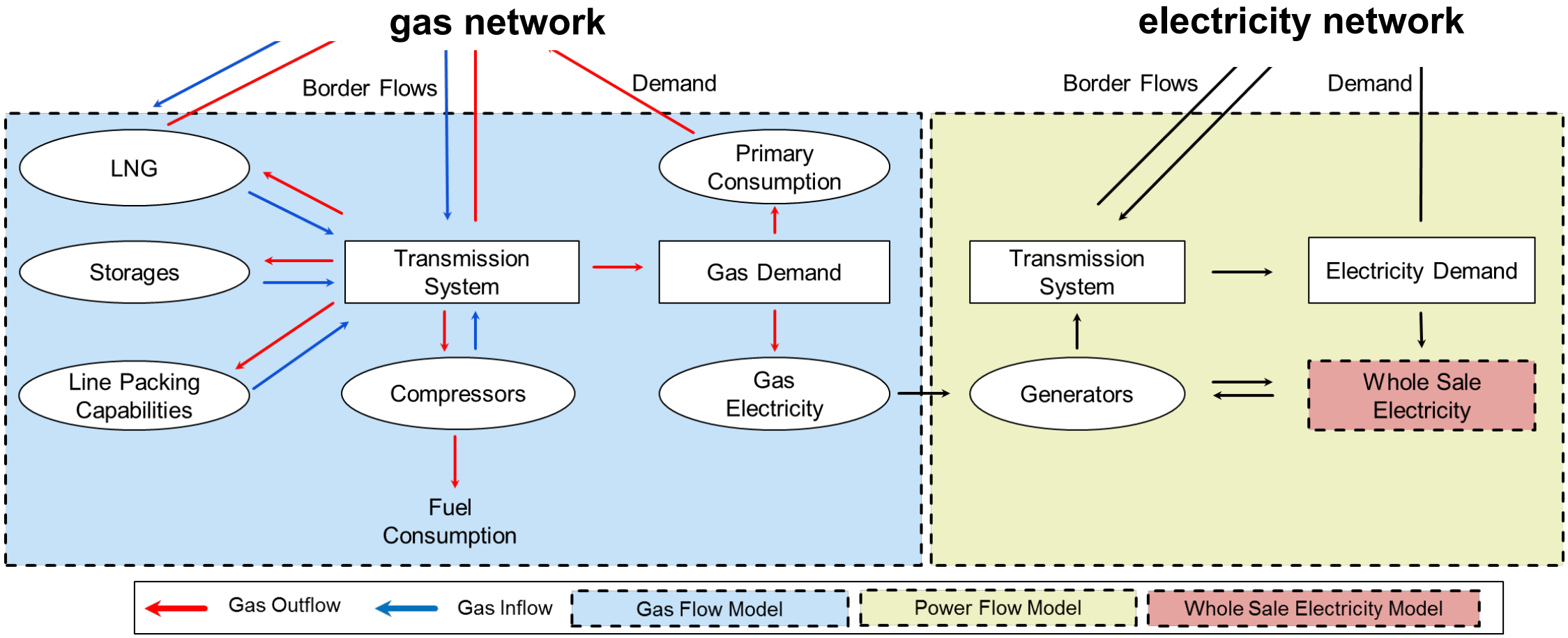
- Hourly gas demand is modelled at level of distribution grids in market areas
  - demand is allocated to electric power generation, residential, commercial, industrial, and transportation sectors
  - effects of local temperatures are included





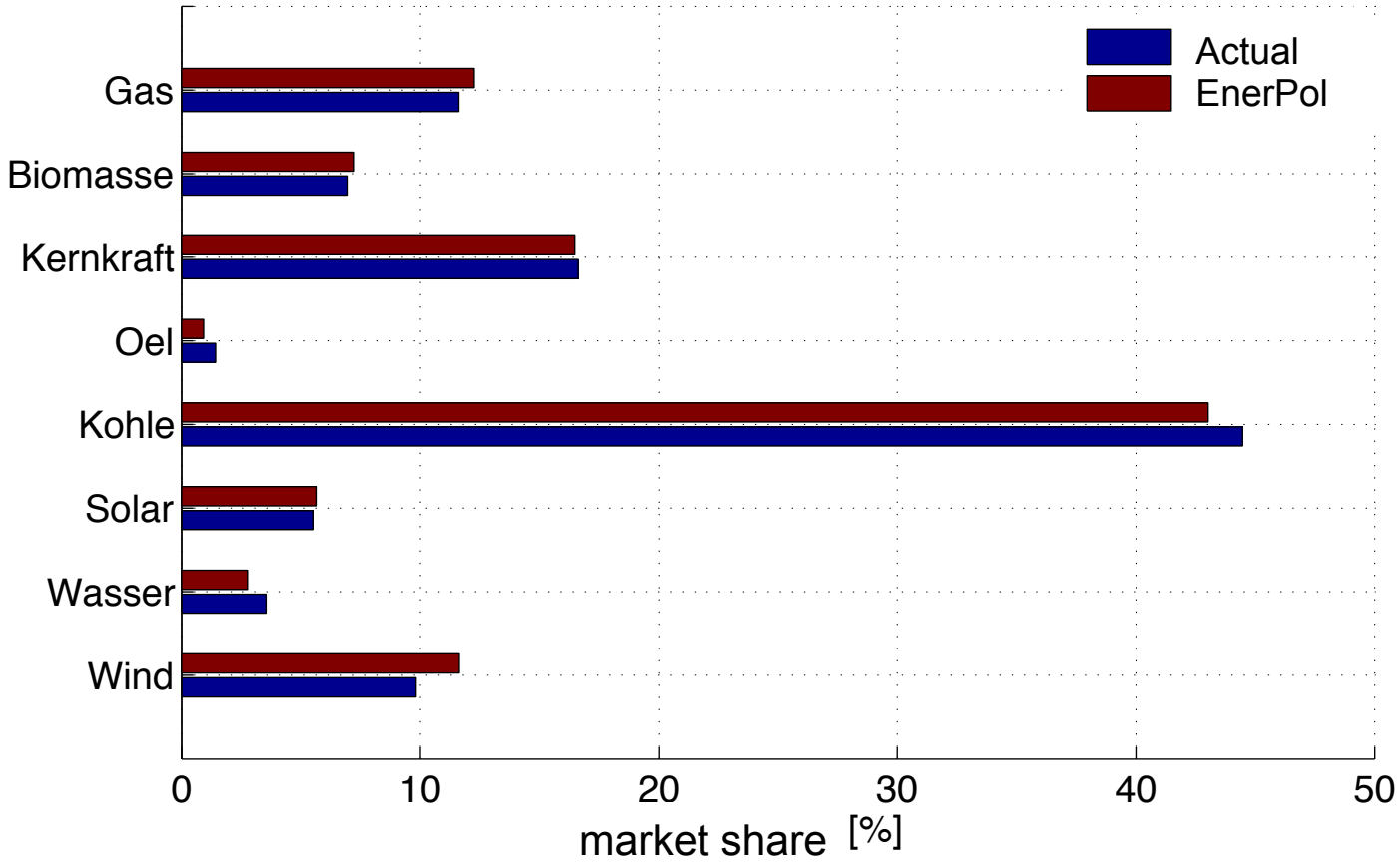
EnerPol – Coupled Gas and Electricity Networks

- Electricity demand for gas power plants, derived from EnerPol's AC optimal electrical power flow model couples EnerPol's gas model



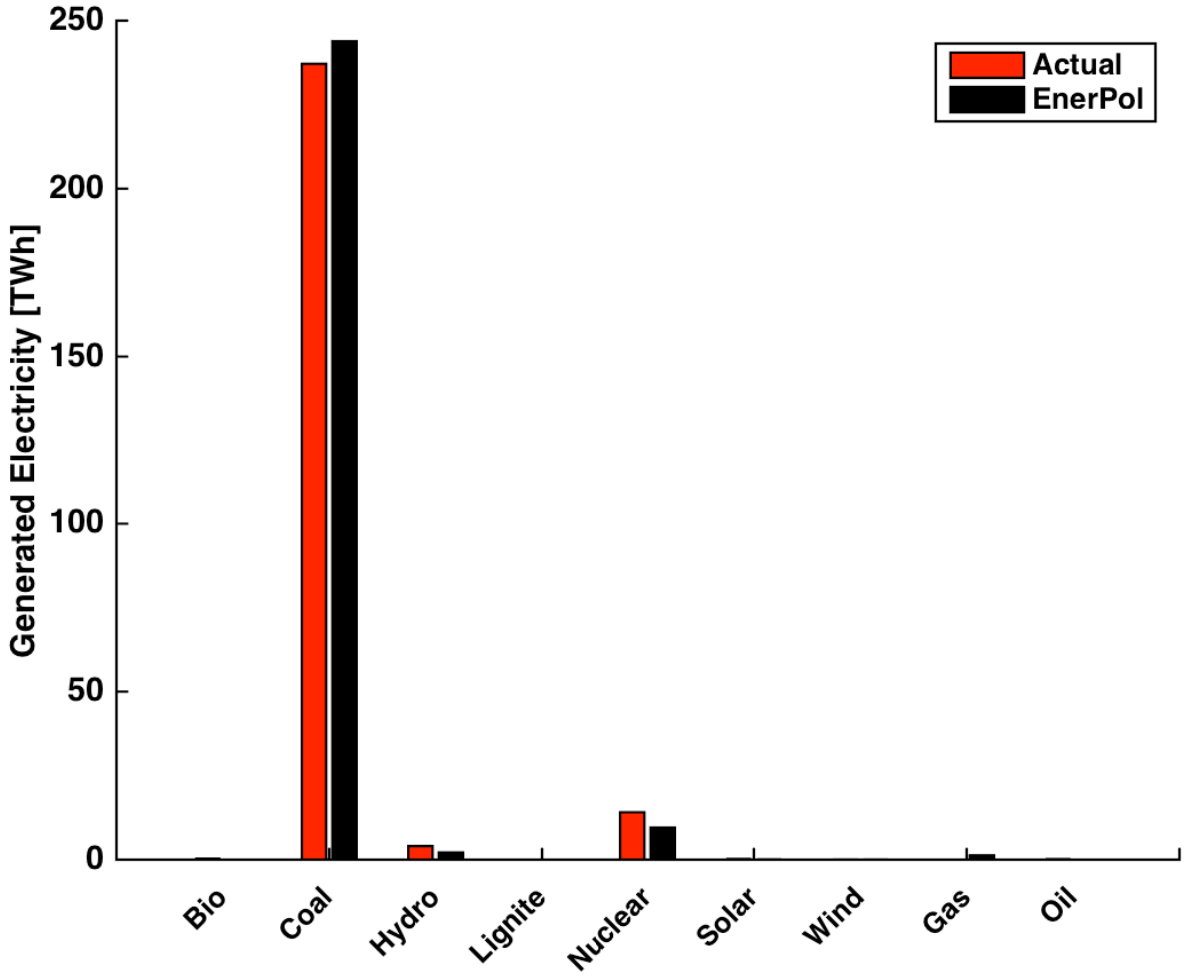
Validation: Accurate Simulation of Electricity Dispatch

- EnerPol's full-year simulation for Germany in 2013 shows good agreement of predicted electricity mix with actual mix



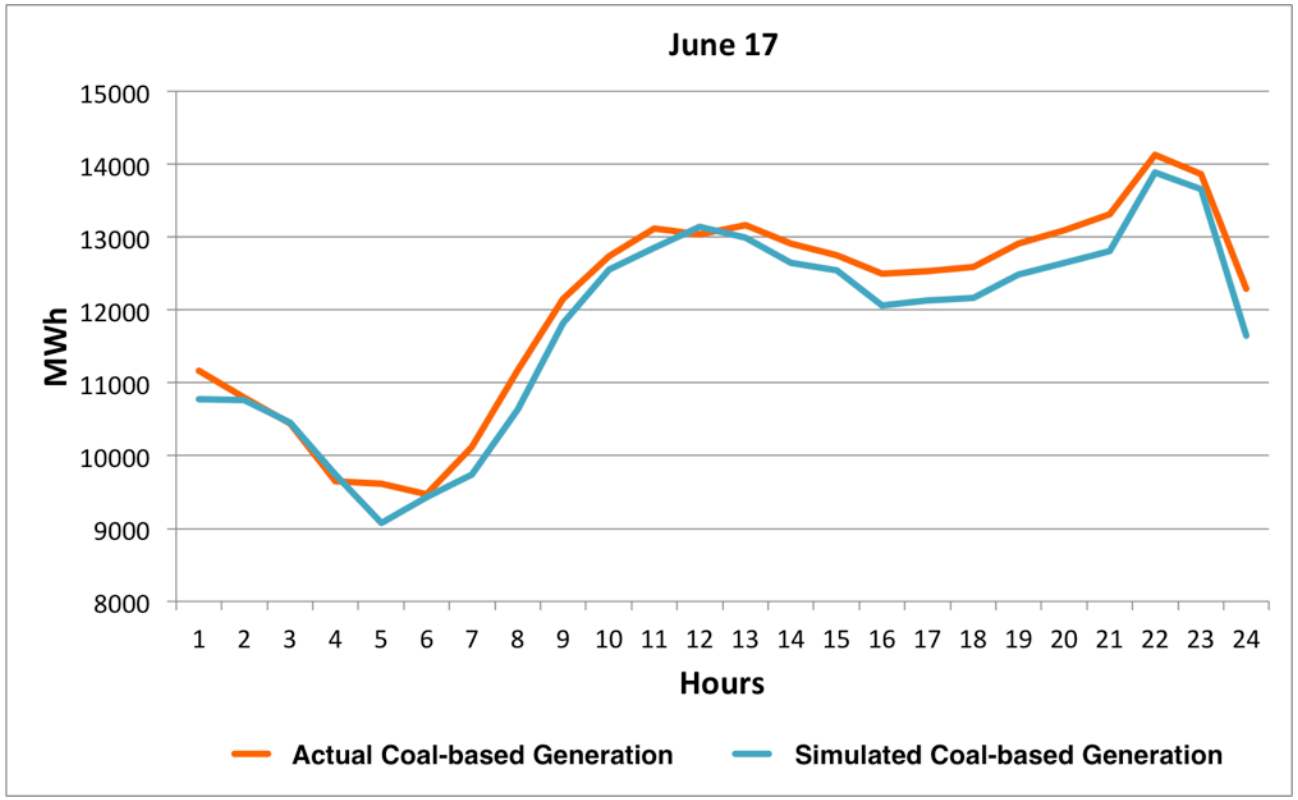
Validation: Accurate Simulation of Electricity Dispatch

- For South Africa in 2013, actual mix is well captured in EnerPol's full-year simulation



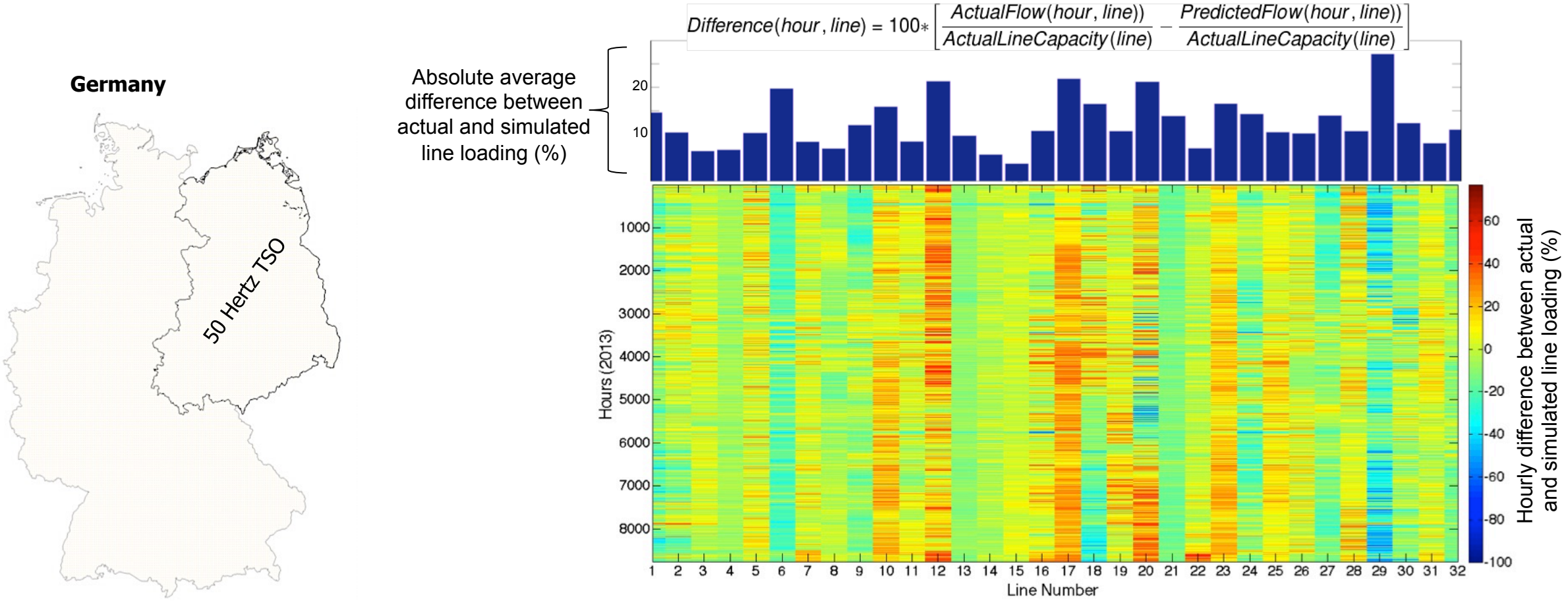
Validation: Accurate Prediction of Thermal Power Plant Dispatch

- EnerPol's hourly simulation for Poland in 2013 accurately predicts daily trends and magnitudes of dispatch from coal power plants



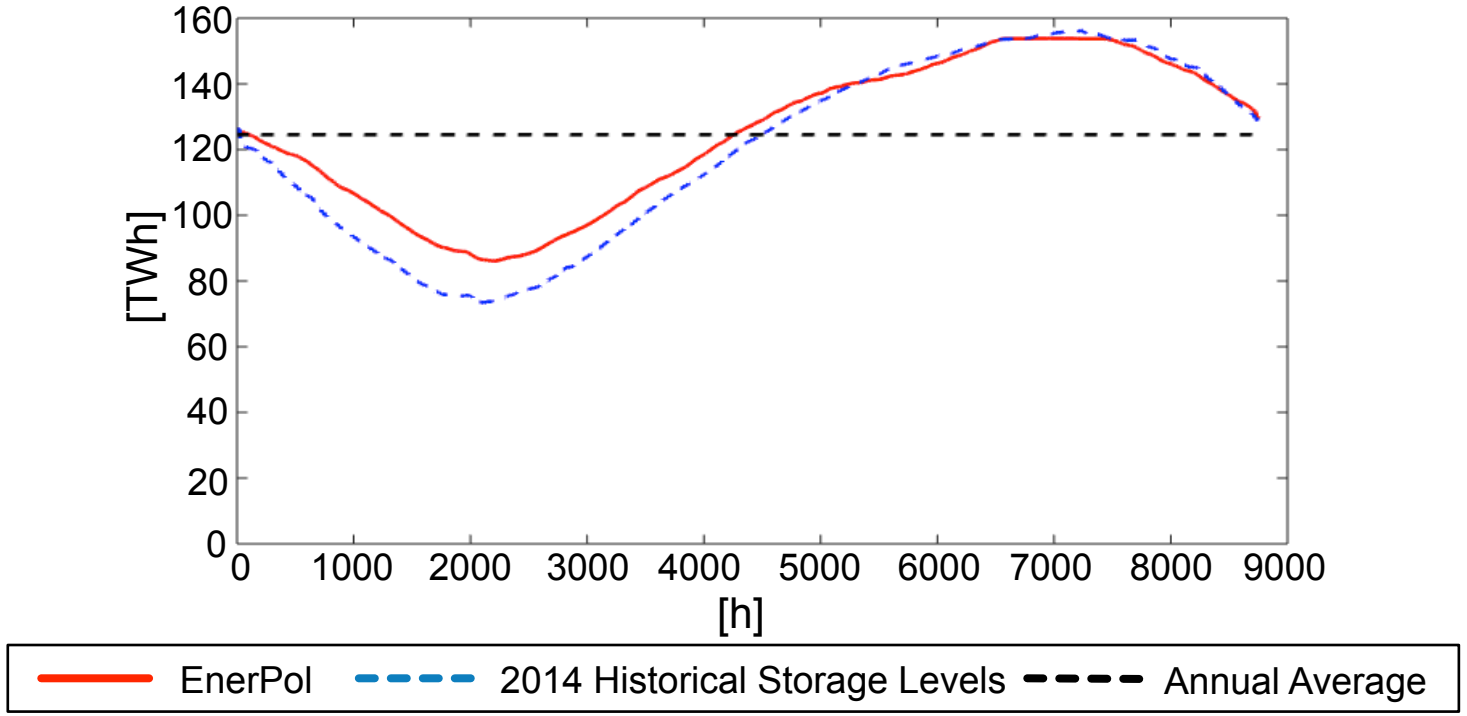
Validation: Accurate Prediction of Transmission Line Flows

- EnerPol's hourly prediction of transmission line flows in 50Hz TSO region have, for 2013, overall difference of 12% compared to historical data



Validation: Accurate Prediction of Gas Storage Levels

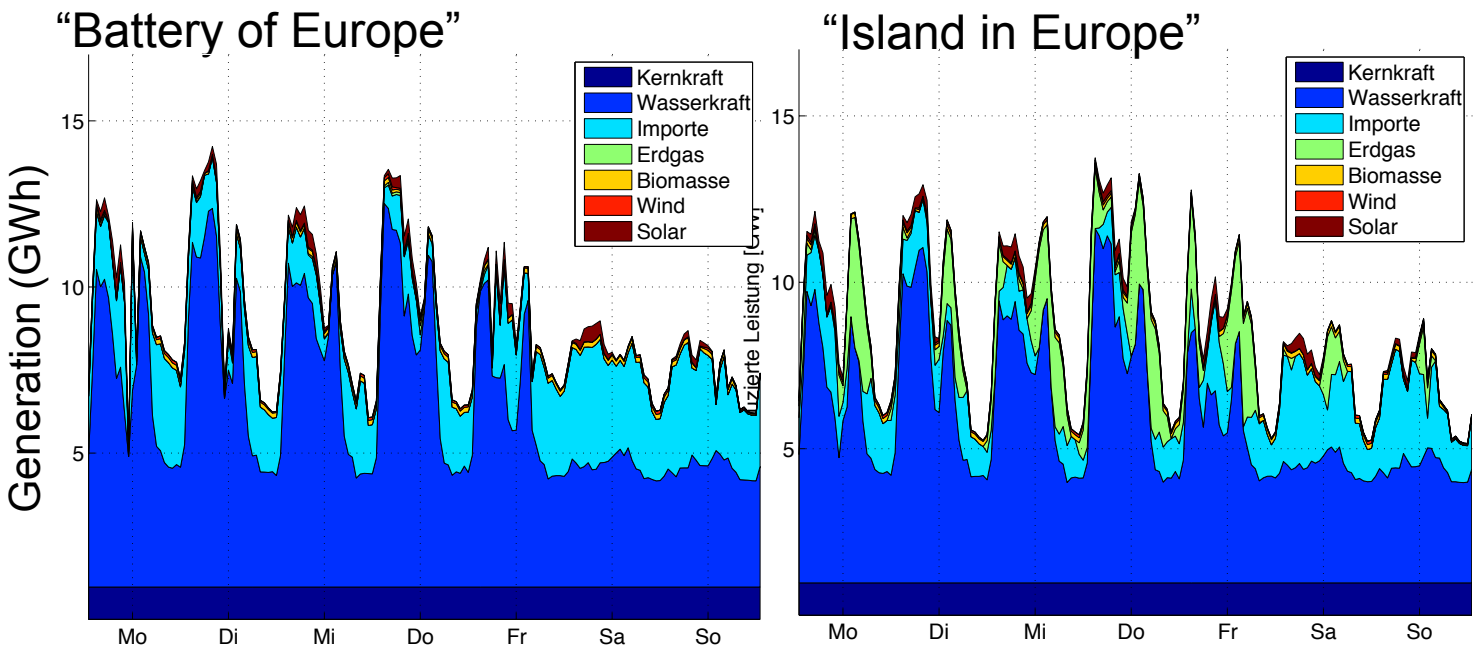
- EnerPol's hourly prediction of gas storage levels in Italy, for 2014, have difference of 5.8% compared to historical data



Application: Assessment of Energy Mixes for Different Scenarios

"Battery of Europe" scenario
- additional 4.4 GW of pumped hydro
- transmission capacity upgraded by 60% (Germany, Austria) and 40% (Italy)

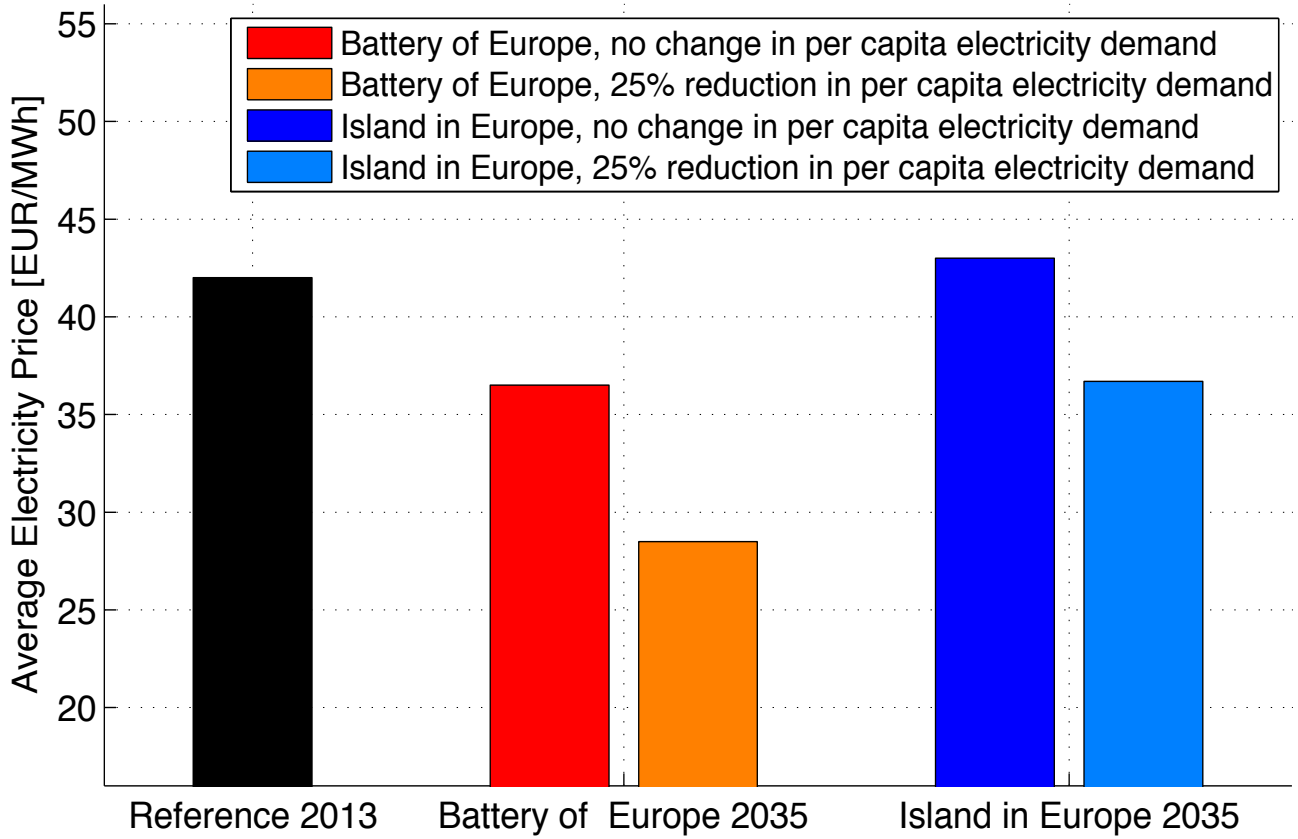
"Island in Europe" scenario
- 3.5 GW combined cycle gas plants at location of mothballed nuclear power plants



- EnerPol simulations show that, for a summer week in 2035, in Switzerland's "Battery of Europe" scenario additional hydro in Switzerland can meet peak demand instead of gas power plants in Switzerland's "Island of Europe" scenario

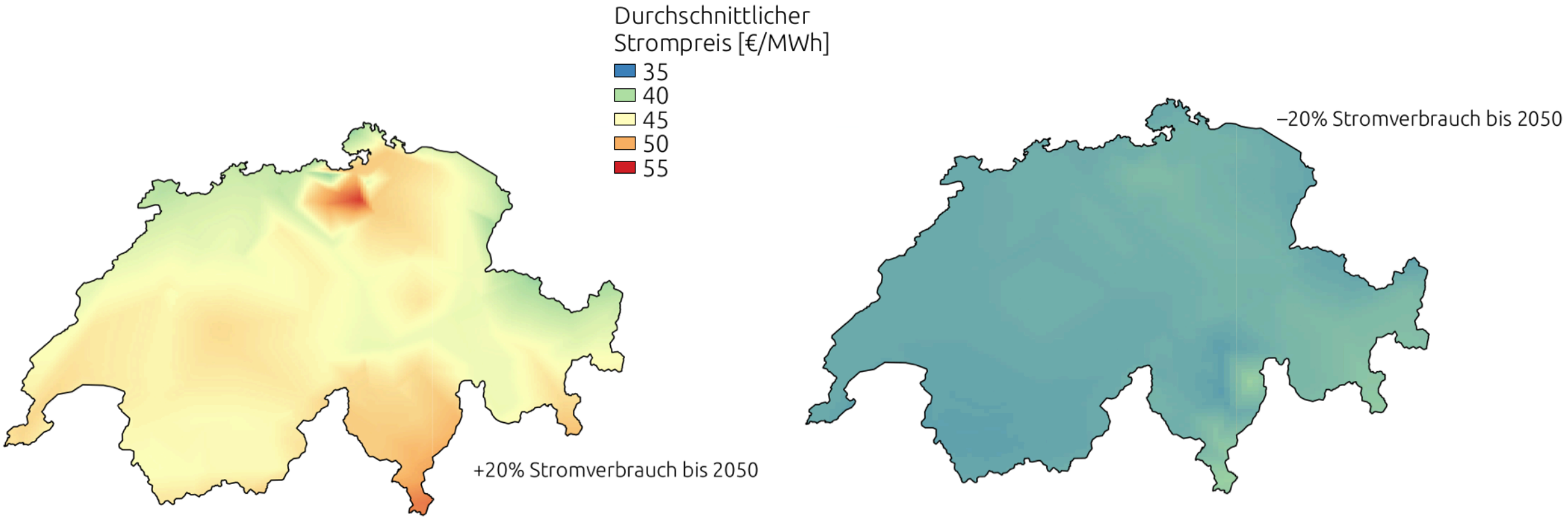
Application: Impact of Electricity Demand on Prices

- In both “Battery-of-Europe” and “Island-in-Europe” scenarios, increase in energy efficiency yields up to 25% reduction of domestic electricity prices by 15% (in 2035)



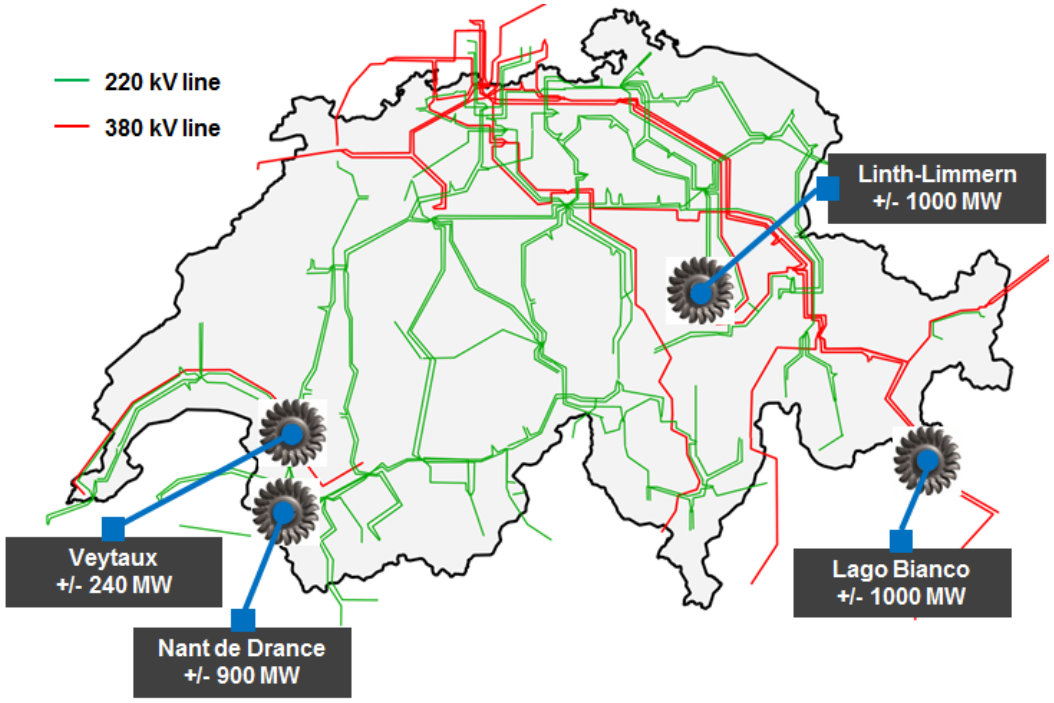
Application: Energy Efficiency Reduces Electricity Prices

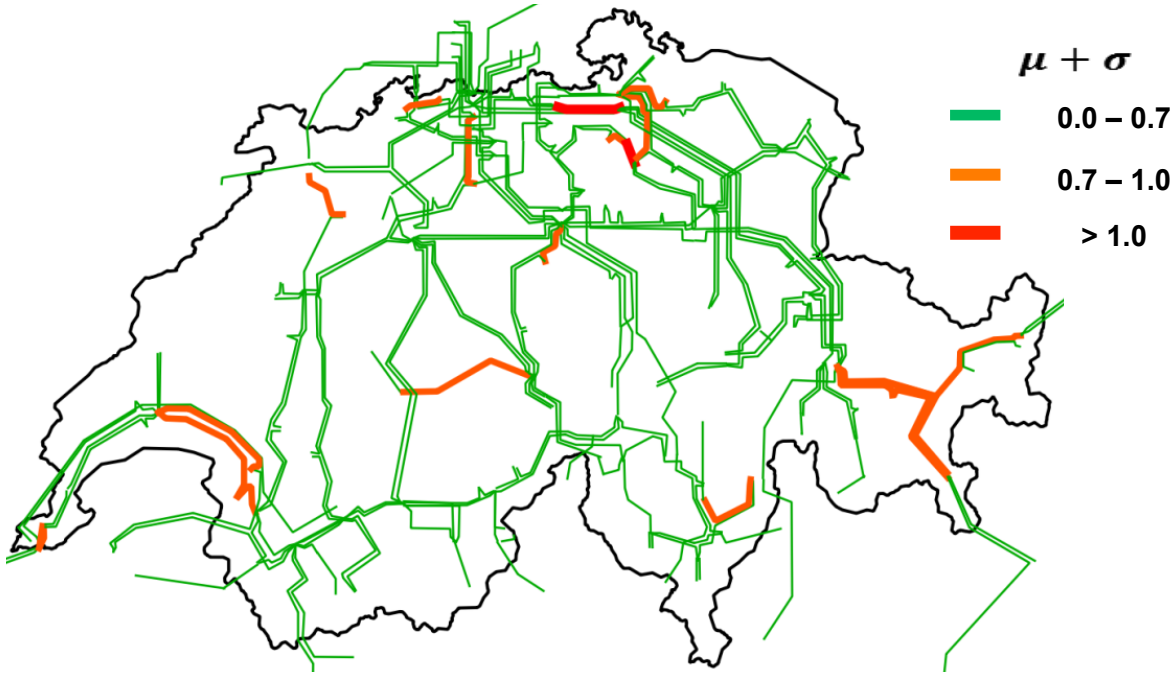
- Energy efficiency (20% reduction in power demand by 2050) results in lower and more uniformly distributed electricity prices across Switzerland



Application: Expansion of Switzerland's Pumped Hydro Capacity

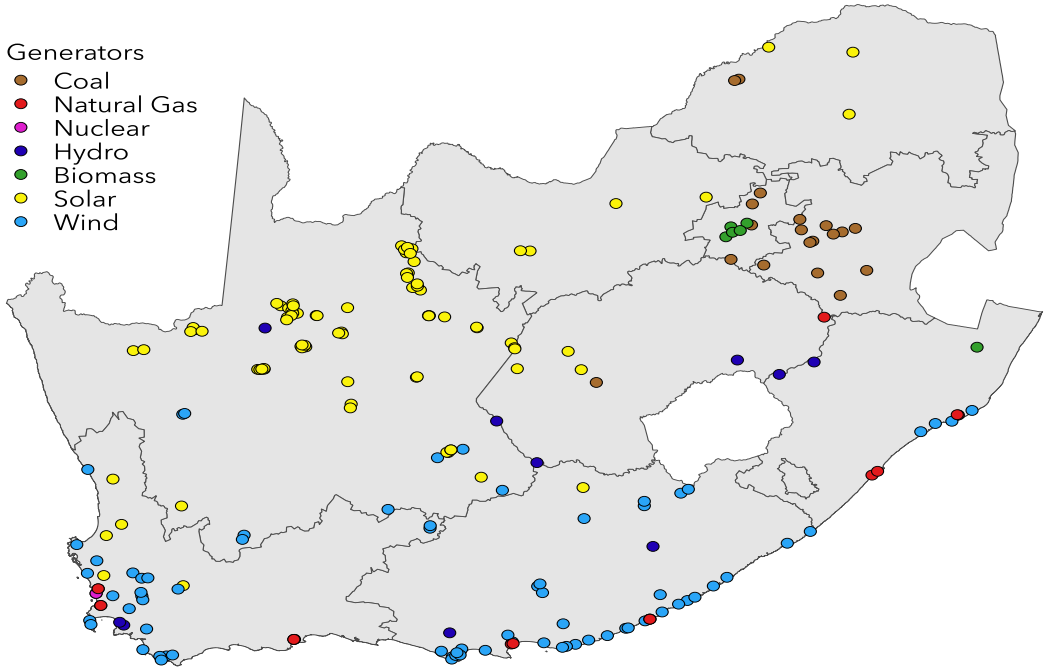
- Using EnerPol, identified up to 5.8 GW of new pumped hydro storage capacity, whose exploitation requires grid reinforcements in eastern Switzerland (canton Grisons) and in region of Lake Geneva



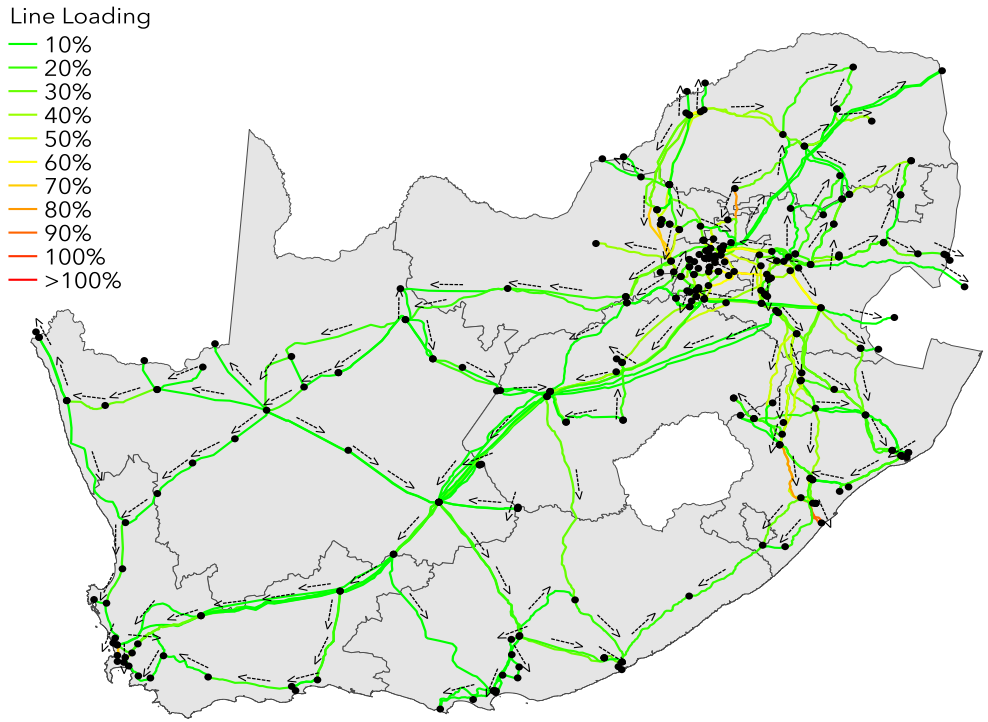


Increased Penetration of Wind Can Be Dispatched in 2025 Transmission Grid

- Line loadings are not critical in regards to dispatch of wind-generated electricity



generation

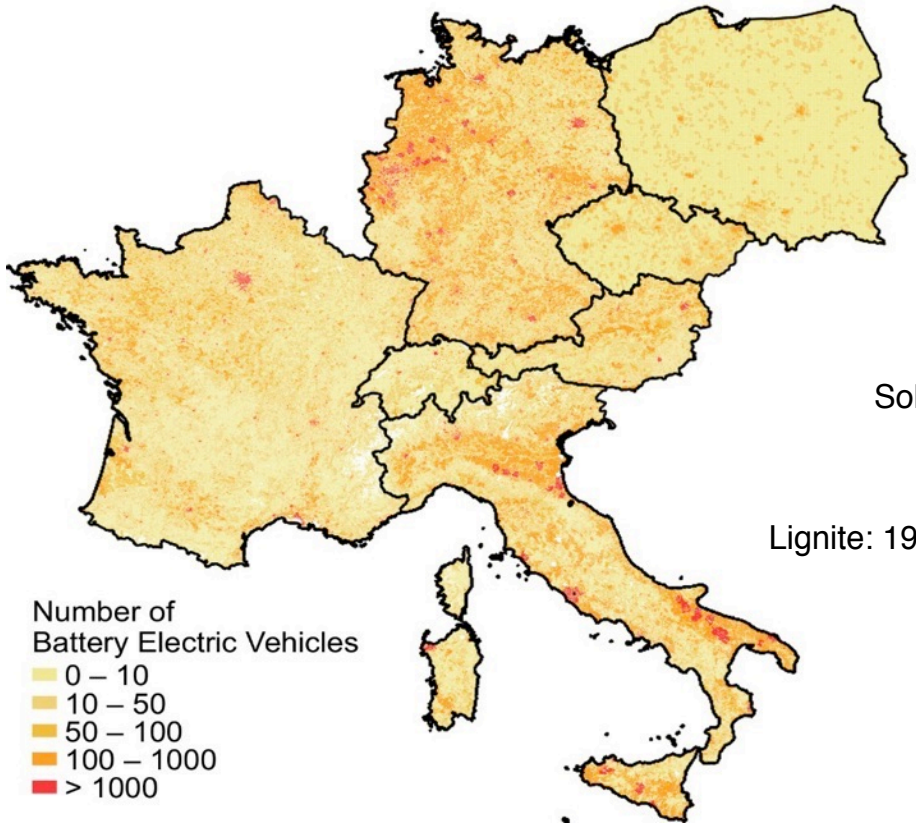


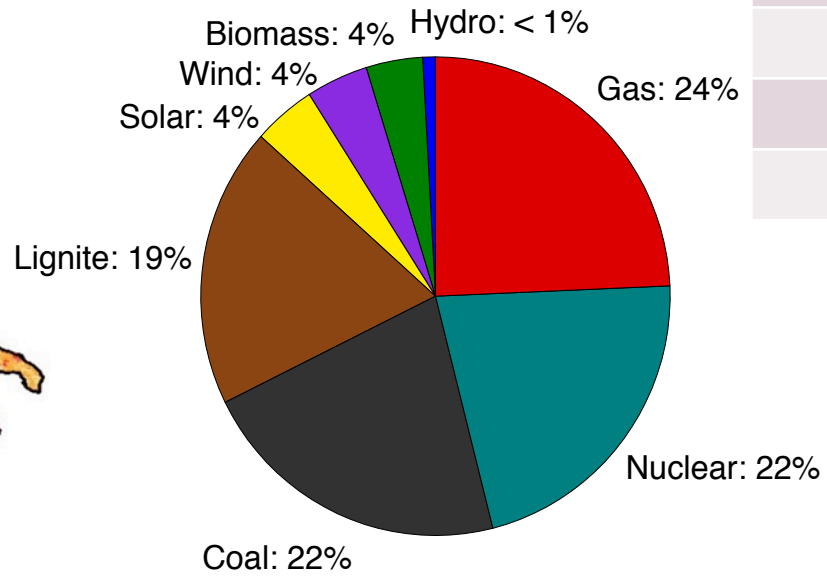
mean line loading

2025 SAWEA high scenario

Application: Impact of Electric Vehicles on CO_2 emissions

- Due to low share of renewable power that is used to charge Battery Electric Vehicles (BEVs), overall CO_2 balance in replacement of gasoline cars with BEVs is negative

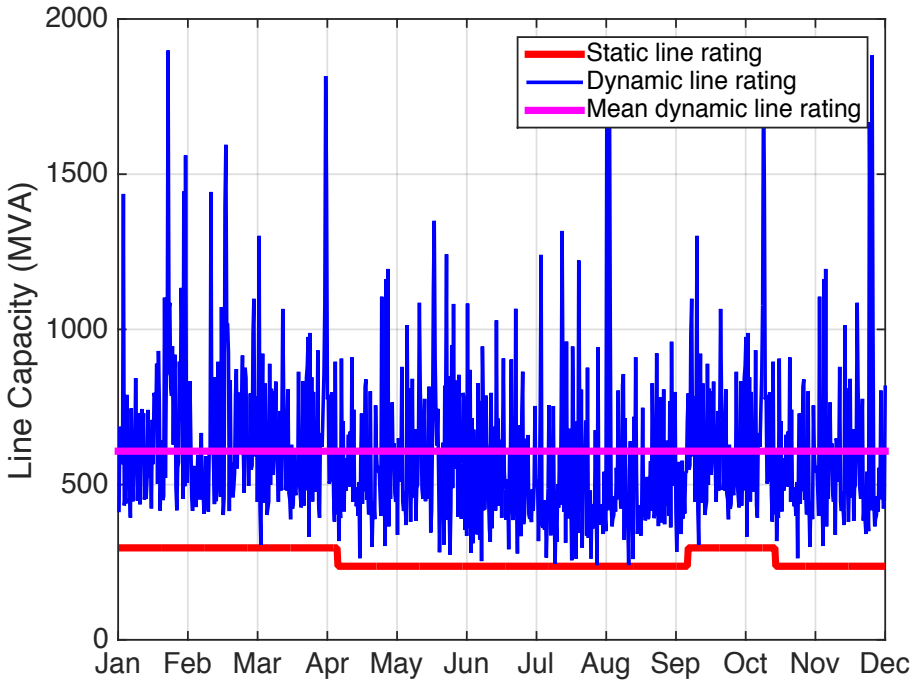


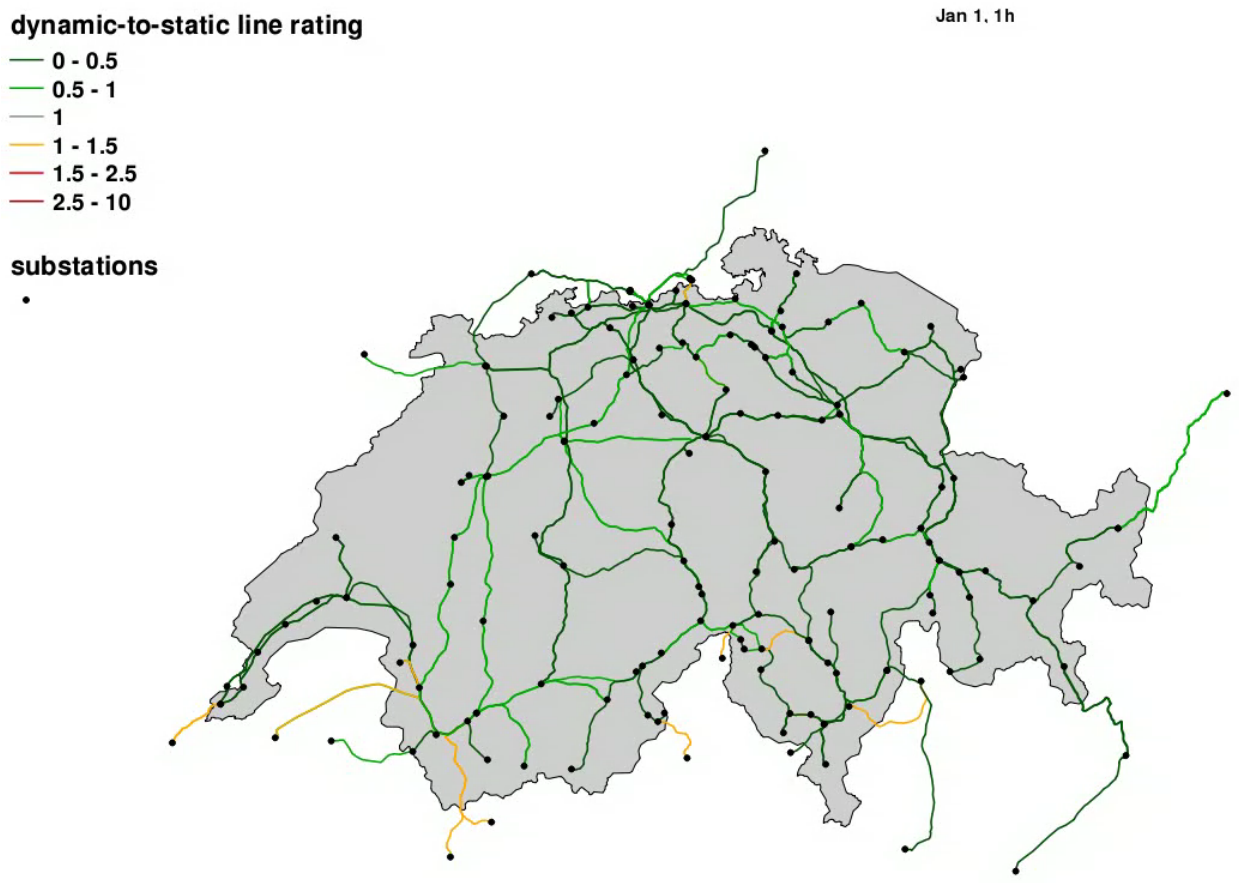


	Baseline	25%	50%	100%
	CO_2 emissions [Mton CO_2 per year]			
Gasoline cars	22.4	16.8	11.2	0
BEVs	0	6.4	13.5	28.0
Sum	22.4	23.2	24.7	28.0
Relative change compared to baseline [%]				
	–	+4	+10	+25

Application: Congestion Management with Dynamic Line Rating

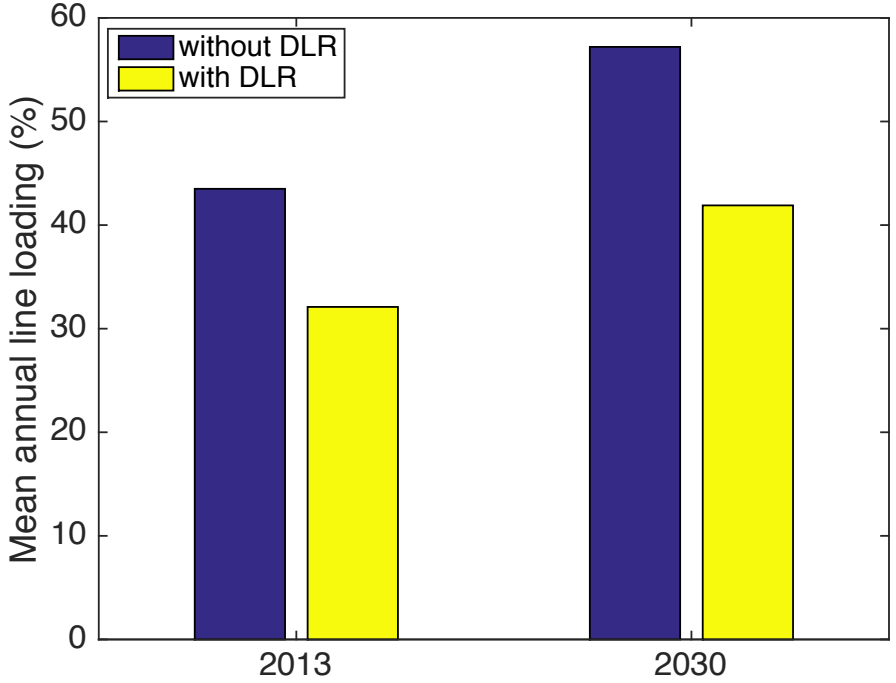
- Dynamic line rating provides up to 2 times more line capacity on critical lines, in place of more lengthy and costly upgrades of lines

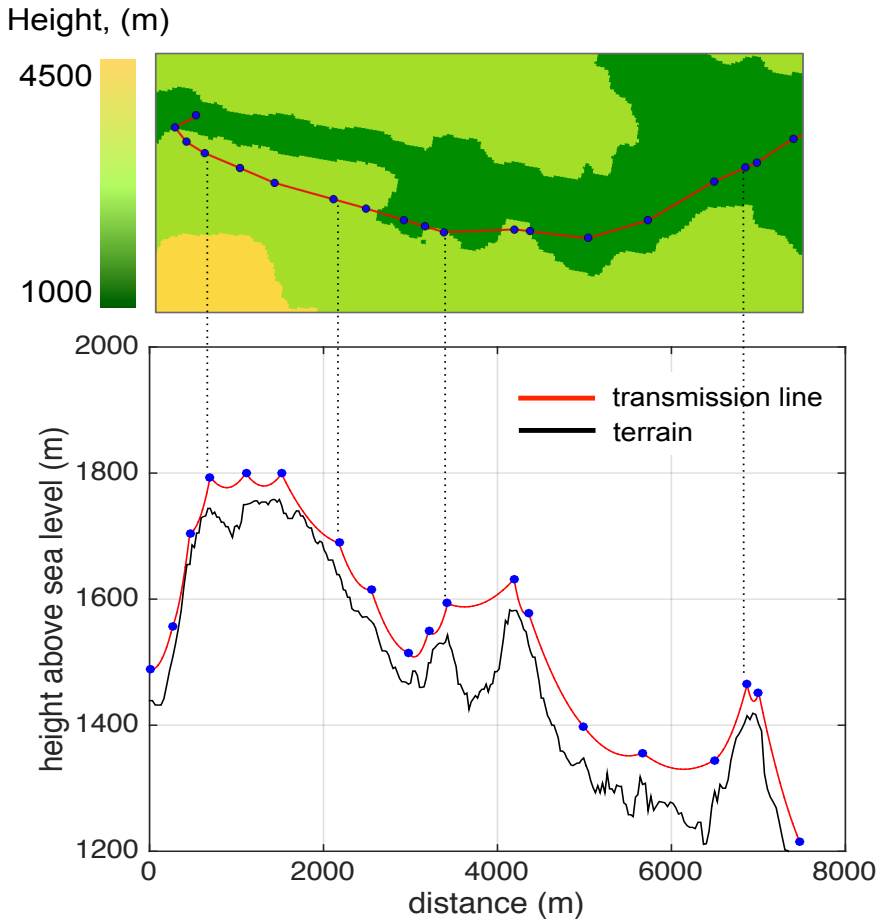




Application: Management of Transmission Infrastructure

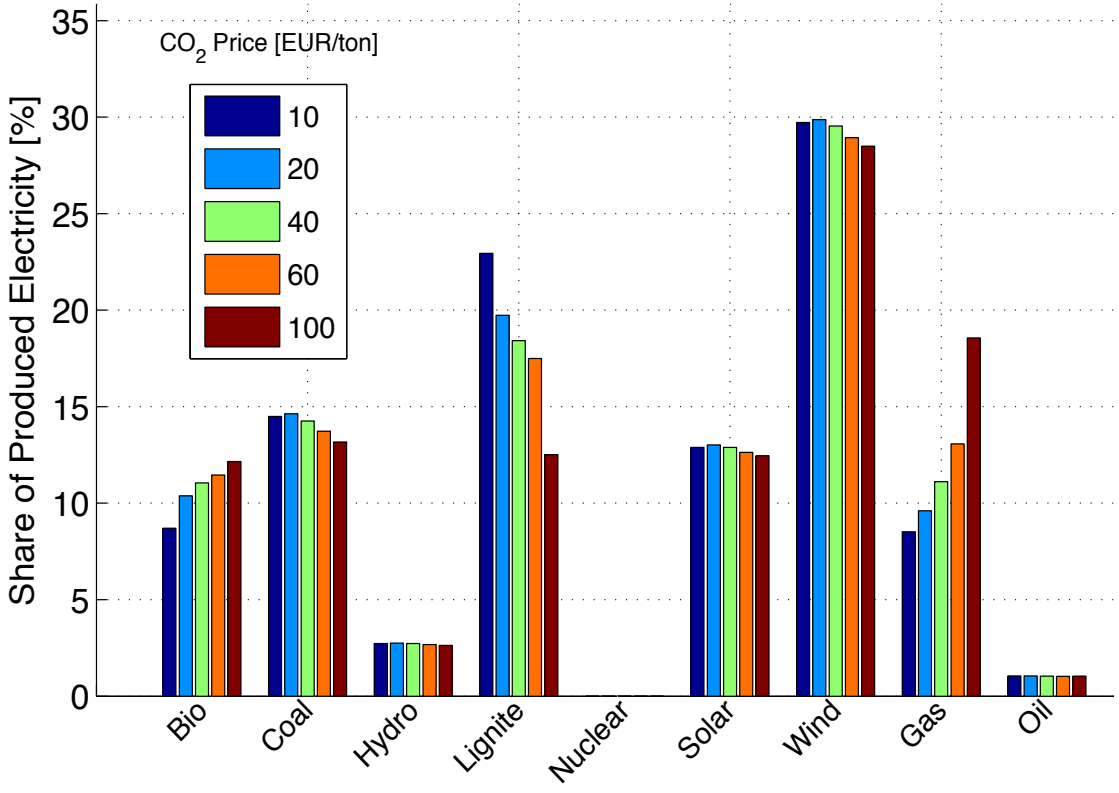
- Lines where sag clearance may be comprised, using dynamic line rating (DLR), can be identified

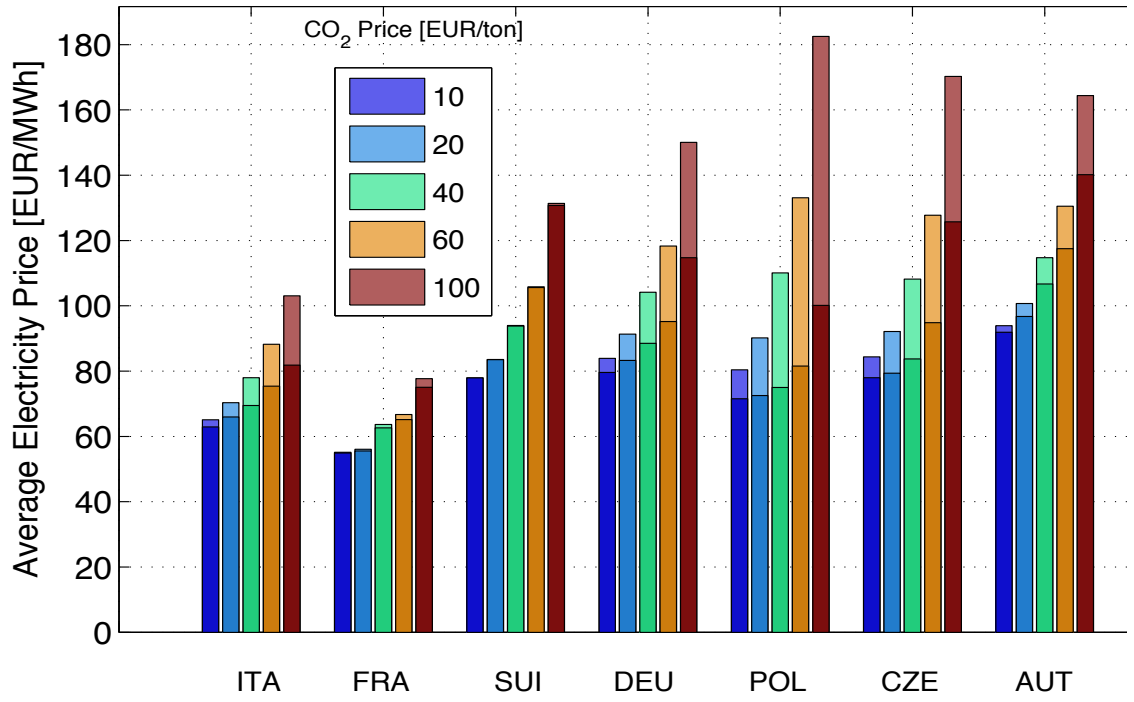




Application: Impact of Carbon Taxes on European Power System

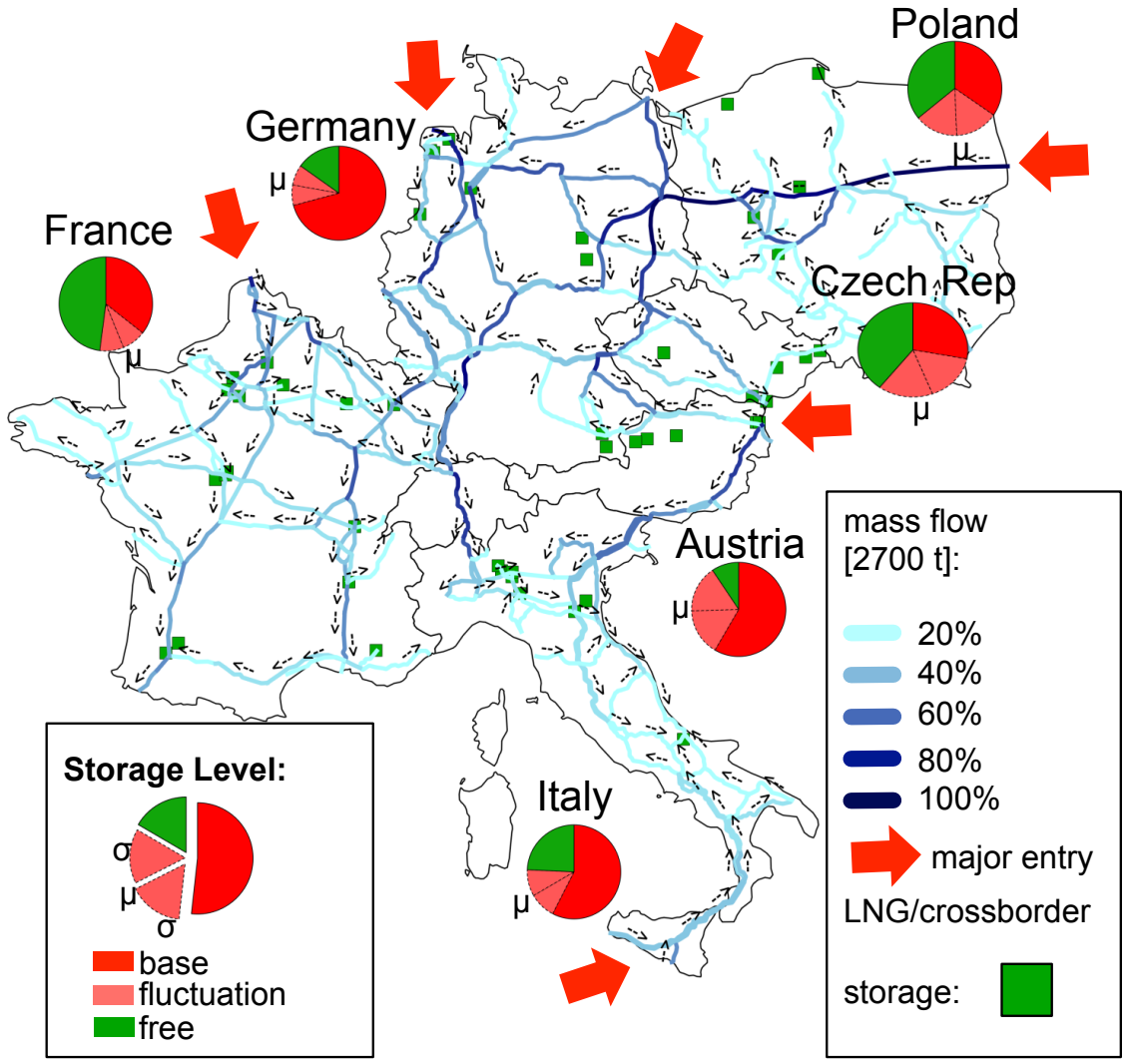
- In Germany, for 2030, increasing CO_2 prices shifts power production from lignite and coal to cleaner biomass and natural gas
- National electricity prices increase with increasing CO_2 prices due to added CO_2 tax and use of cleaner, more expensive fuels such as natural gas over highly emissive, cheaper fuels like lignite





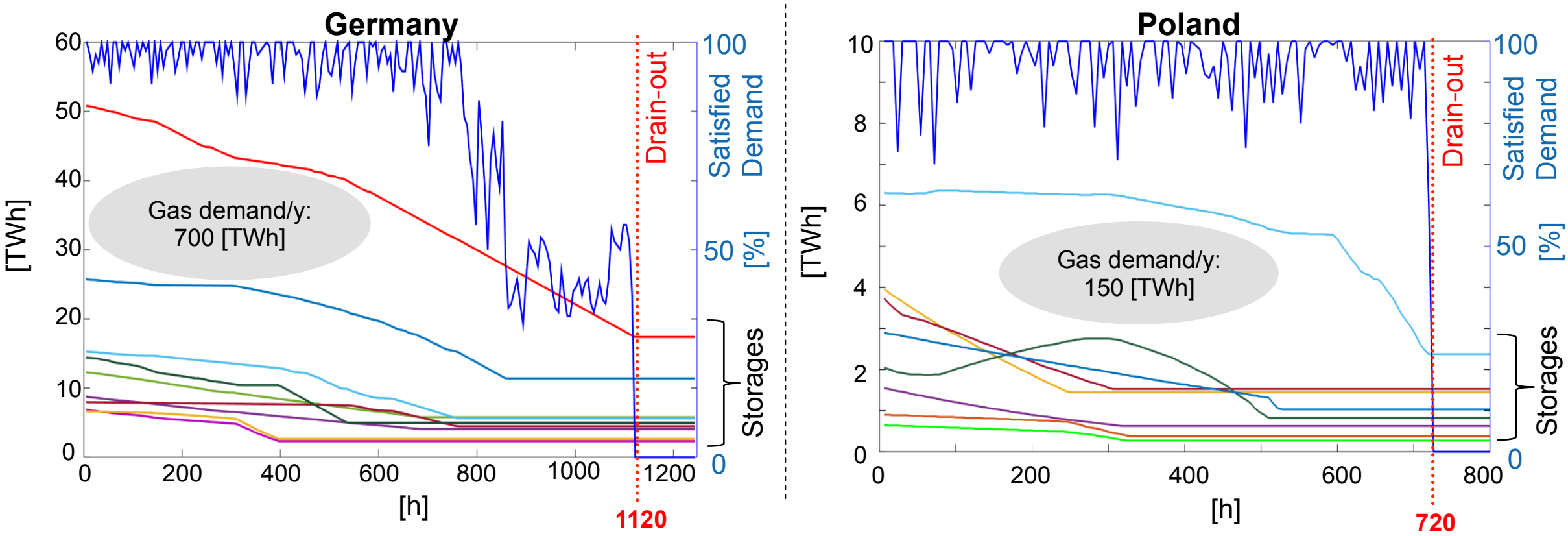
Application: Interdependence of Europe's Gas Flows

- EnerPol demonstrates strong interdependence of Europe's gas flows
  - north-south gas flows in Germany are overall dominant
  - highest gas flow rates are in Poland's Yamal pipeline
  - highest gas storages are in Germany and Austria



Application: Gas Reserves for Contingencies

- EnerPol demonstrates that in case where no gas imports are possible, Germany and Poland have reserves of respectively 1120 hours (16% of annual demand) and 720 hours (11%) respectively

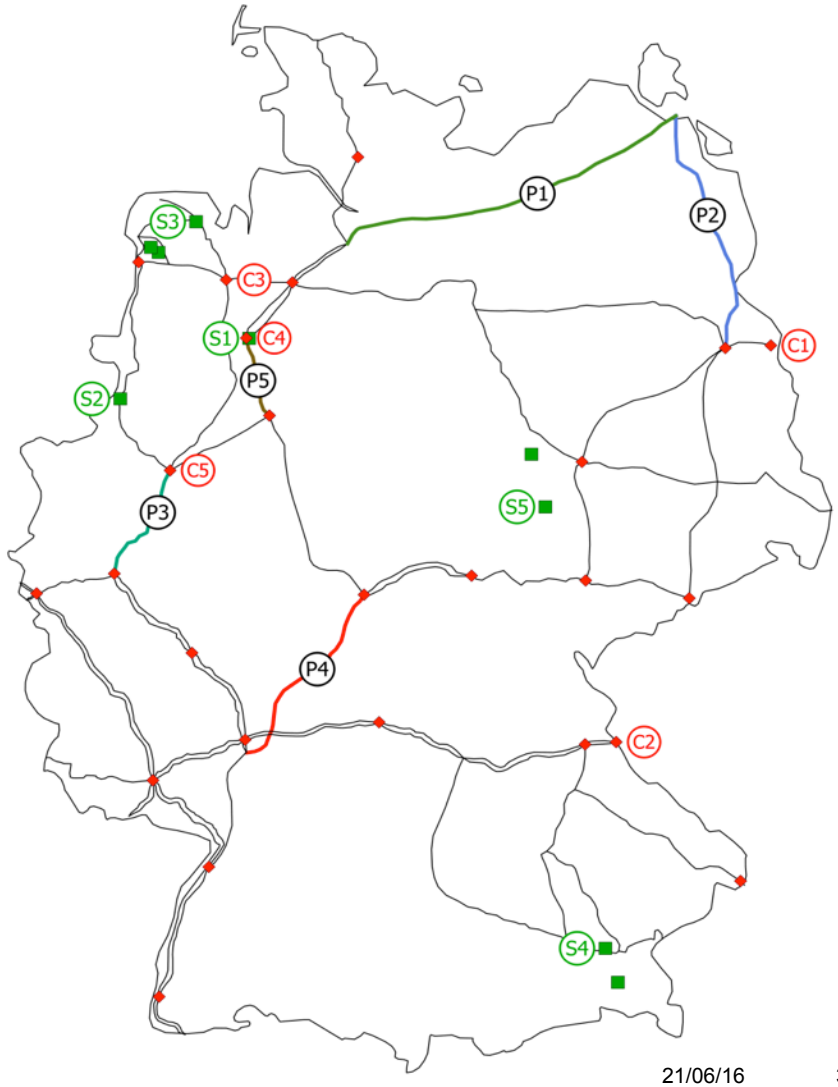


Application: Risk Analysis of Gas Networks

- Impact of failures of gas network components can be assessed based on N-1 analysis and chronological simulations

- Failures assessed include compressor, storage or pipeline failures

WEDAL pipeline: P3
MIDAL pipeline: P4

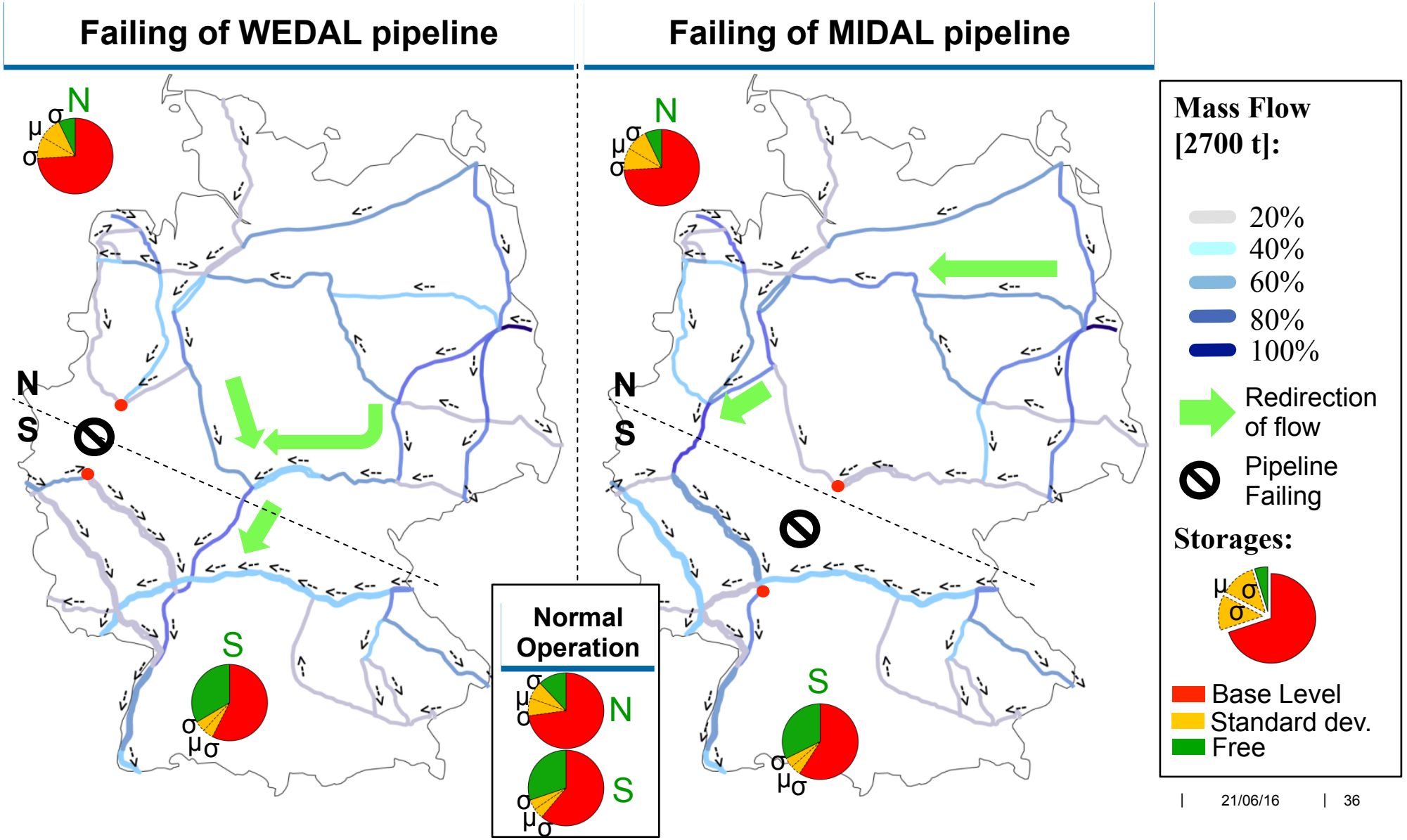


Application: Assessment of North-South Pipeline Failures

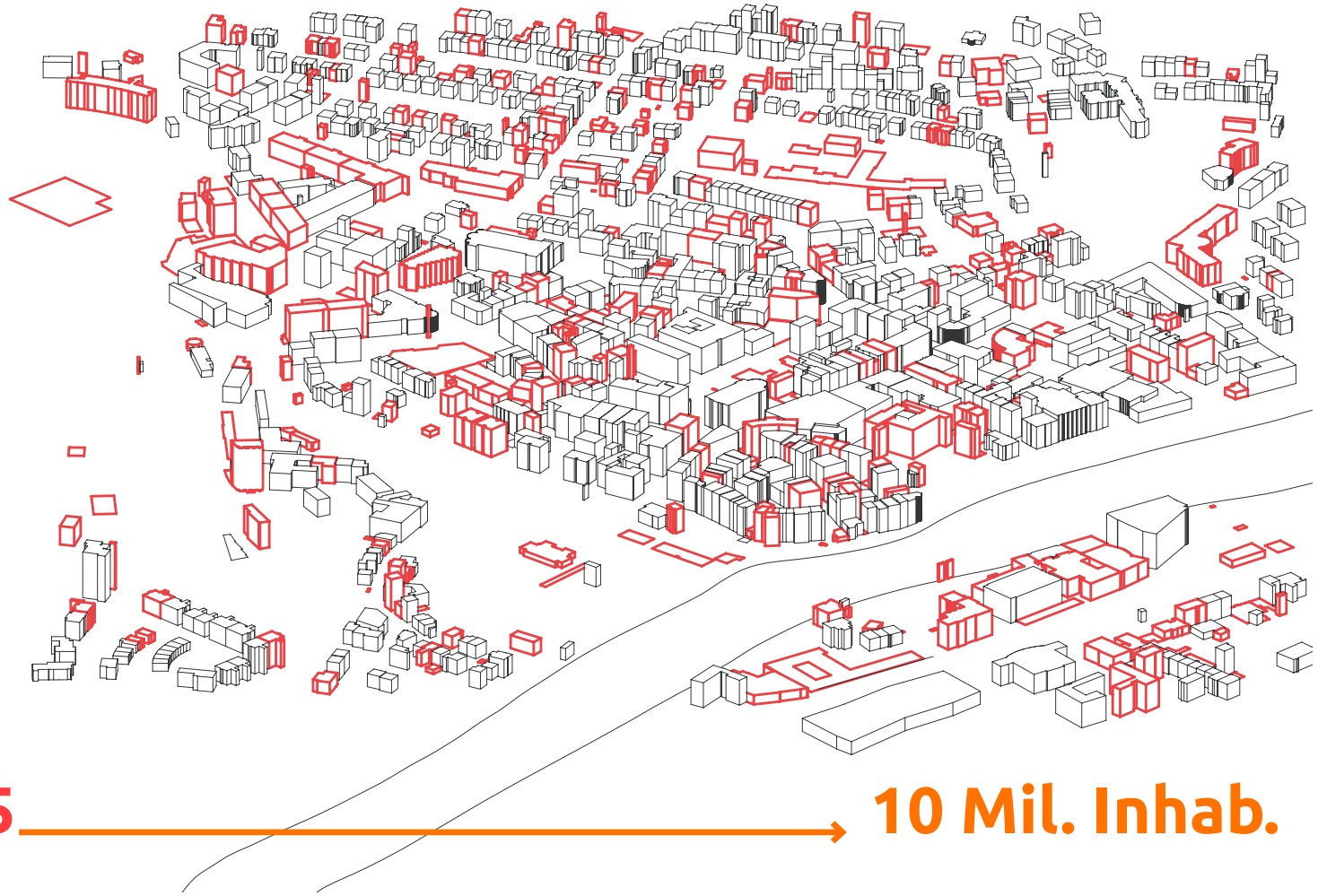
- Pipeline failures redirect flows leading to congestion
- Line packing increases in north

Change in Line Packing

	WEDAL	MIDAL
N	-28%	-34%
S	+1%	-17%



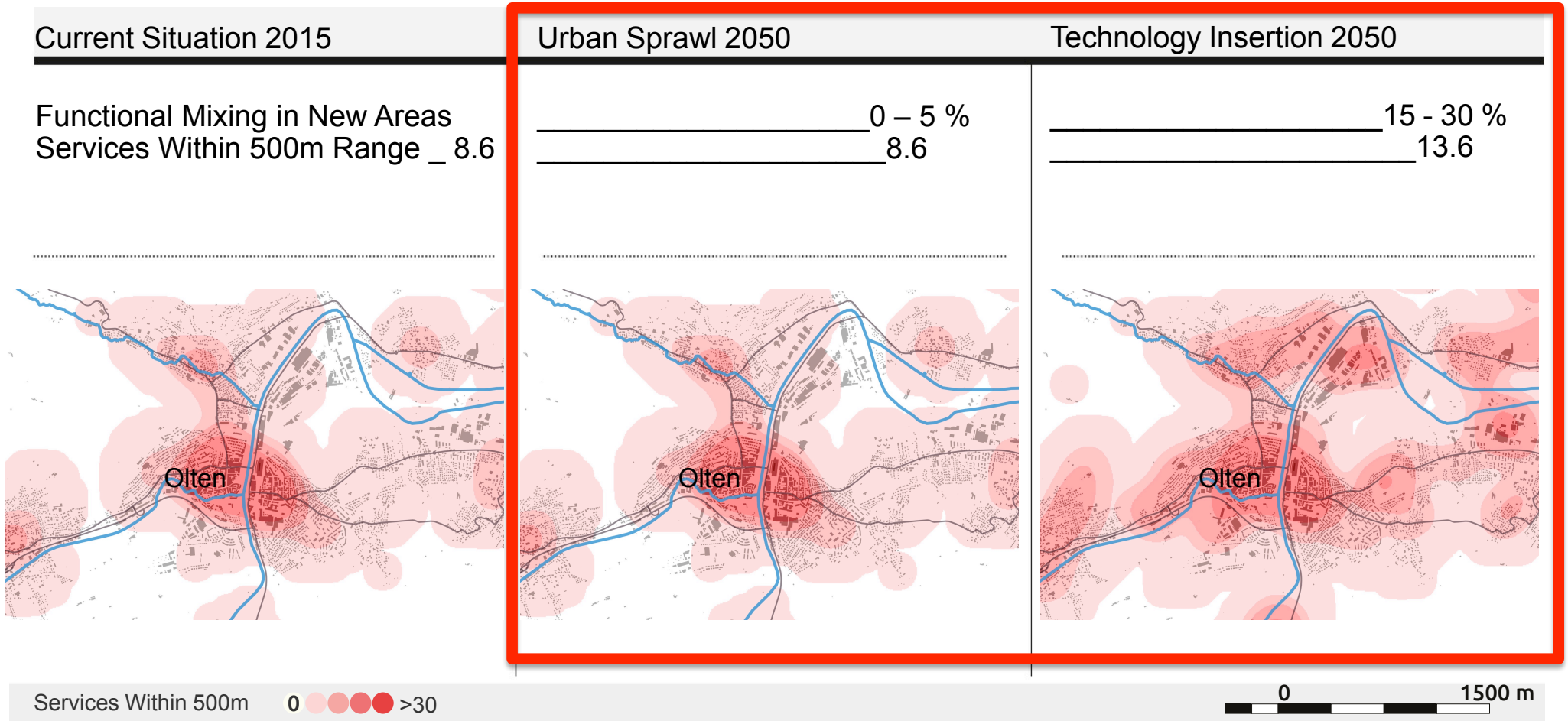
Addressing Urbanisation in Switzerland



building built before **1980** → building built from **1980** to **2015** → **10 Mil. Inhab.**

Application: BauWerk Schweiz 2050

- Functional Mixing in newly built areas in Technology Insertion allowed 58% increase of services within 500 m.



Application: BauWerk Schweiz 2050

Personal Mobility

more than
2000 cars/hour

no cars/hour

Concluding Remarks

- EnerPol framework provides system-wide, bottom-to-top, scenario assessments
- EnerPol – big data analysis and advanced models – can be used to quantitatively assess different transition pathways of energy-economic systems
- EnerPol's bottom-up technology evaluation approach is very time-efficient to assess impacts under new scenarios
  - Enables data-driven cost-benefit analyses
  - Reduces decision making times
  - Provides simultaneous assessments of generation, transmission and demand

Thank You for Your Attention.
Questions?