Examples of studys made with FlexTool approach

LEAP-RE

Examples of regional scope:

- Example 1: TradeRES Backbone European level model
- Example 2: IRENA FlexTool 2.0 Panama national level model
- Example 3: Backbone city level model Finland

Examples of different purposes of modelling:

- Example 4: Backbone North European model for competitiveness of technologies
- Example 5: Interannual variability effects with eference system models
- Example 6: Flexibility comparison

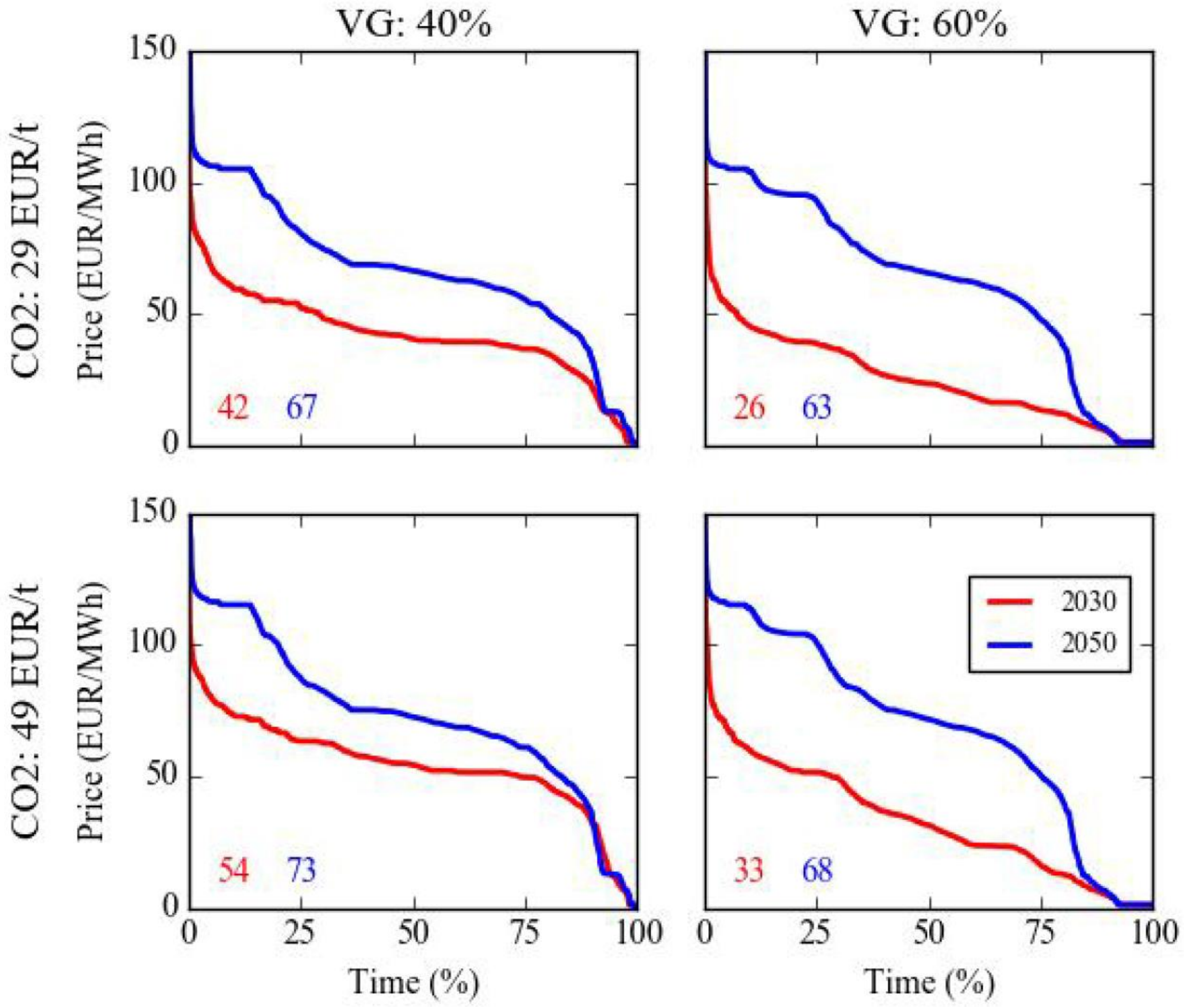
Examples of different selection of detail:

- Example 7: Thermal power plants in detail
- Example 8: Case Ireland with detailed power plants and reserves
- Example 9: Case Baltic countries multi-year modelling

TRADERES
BACKBONE EUROPEAN LEVEL MODEL

LEAP-RE

OASES

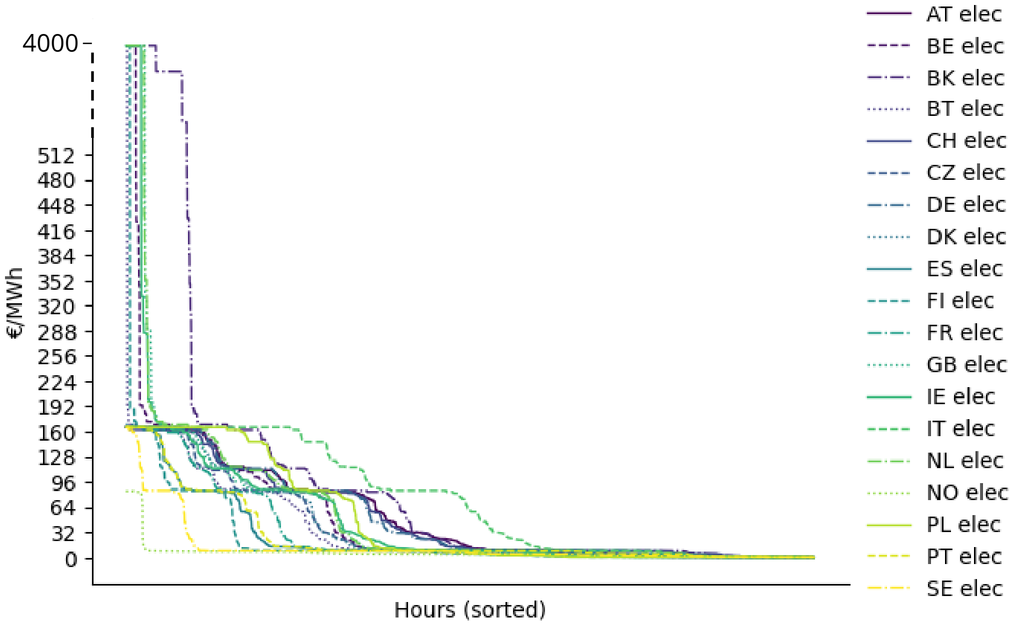


Analysing prices in future energy systems

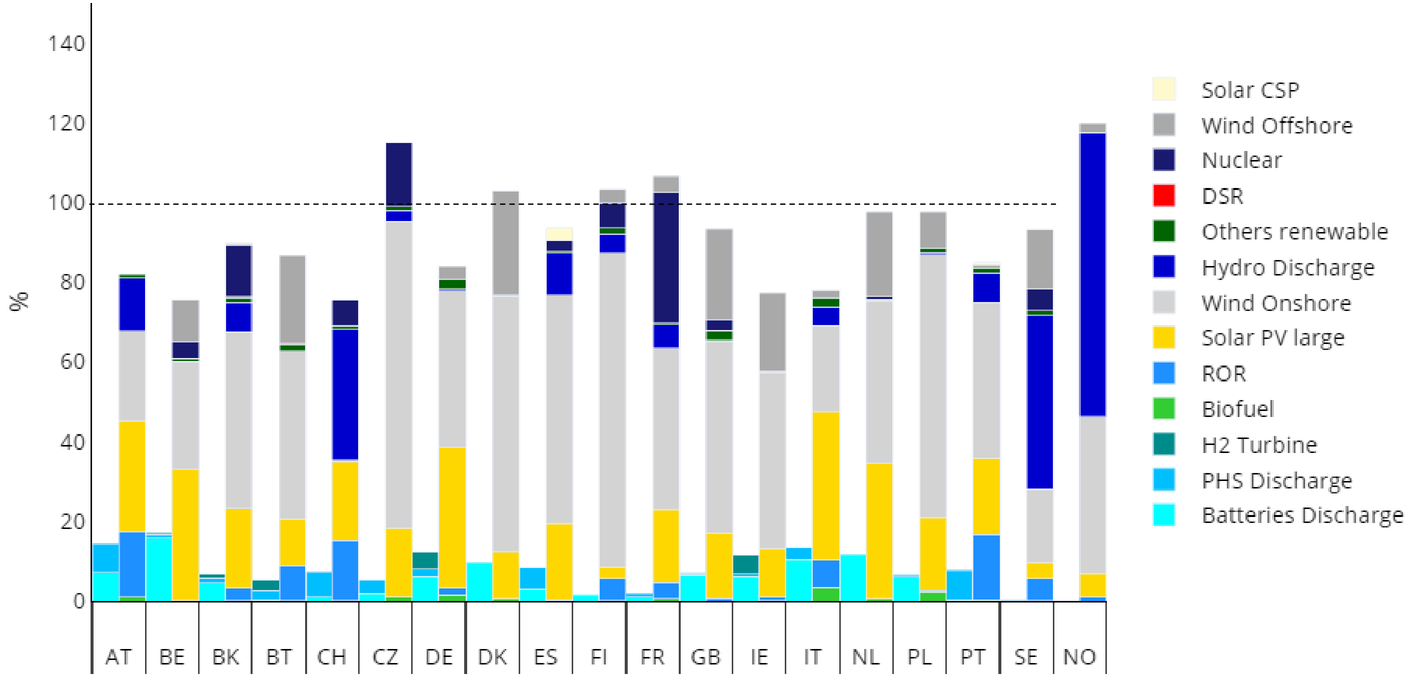
N. Helistö, J. Kiviluoma and H. Holttinen, "Sensitivity of electricity prices in energy-only markets with large amounts of zero marginal cost generation," *2017 14th International Conference on the European Energy Market (EEM)*, Dresden, Germany, 2017, pp. 1-6, doi: 10.1109/EEM.2017.7981893.

Reference System with ≥ 95% non-thermal renewables by constraint

Price Duration Curves



Electricity Generation Share by Type



IEEE's European Energy Markets Conference 2023
Lappenranta, 08.06.2023
Silke Johanndeiter

IRENA FLEXTOOL 2.0
CASE EXAMPLE

Panama power system flexibility assessment

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Flexibility analysis for the power system of Panama

LEAP-RE

- Panama expects total energy demand to more than double between 2017 and 2030, with peak demand growing from 1.6 GW to 3.5 GW

Country challenges

- High reliance on hydropower
- Low energy storage capacity
- Weak interconnection

Analysis undertaken

- Simulation of different VRE penetration scenarios according to national plans
- Assessment of the optimal generation capacity mix (including storage)
- Consideration of VRE share increase in long-term planning (mostly solar PV)

- Two scenarios for 2030:
  - Reference scenario: additional 2 GW of natural gas-fired generation
  - Renewables scenario: wind capacity increases from 270 MW to 1 156 MW, and solar PV capacity increases from 131 MW to 782 MW

Comparison between scenarios

LEAP-RE

- The renewables scenario has 5% lower annual costs and 20% lower carbon dioxide emissions.
- No flexibility issues were identified in either scenario

Figure 4: Power generation (annual share) and hourly dispatch over a week in 2030 with the highest VRE penetration: Reference and renewables scenarios

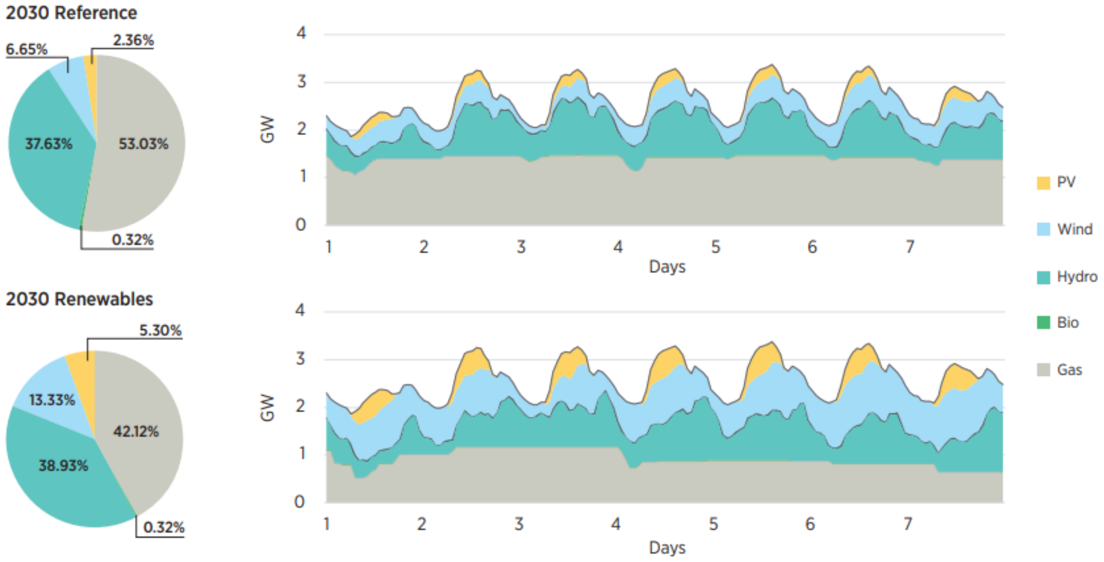


Table 2: Main flexibility indicators in Panama's power system in 2030 reference and renewables scenarios: No flexibility issues identified

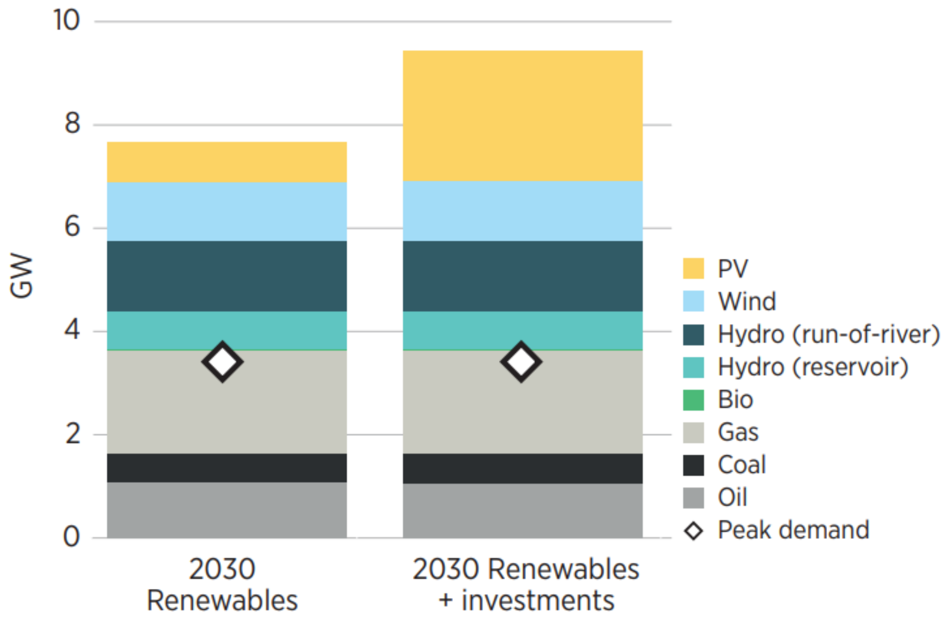
	2030 Reference		2030 Renewables	
	Total (GWh)	Peak (MW)	Total (GWh)	Peak (MW)
Curtailment	0	0	0	0
Loss of load	0	0	0	0
Spillage	0	0	0	0
Reserves inadequacy	0	0	0	0

Note: These flexibility indicators are defined in IRENA (2018b).

Additional VRE investments

- Panama's power system would have enough flexibility to handle even higher penetration of VRE.
- Additional investment run: In the 2030 renewables scenario, cost-efficient to invest in 1.7 GW of additional solar PV capacity and 164 MW of battery storage.
- Curtailment becomes an issue when both solar PV and wind capacity reach 2 GW. By then VRE curtailment is around 3%, and further flexibility solutions are needed

Figure 5: Generation capacity in 2030 renewables scenario with and without investments for optimised system costs



CITY LEVEL MODEL
FINLAND

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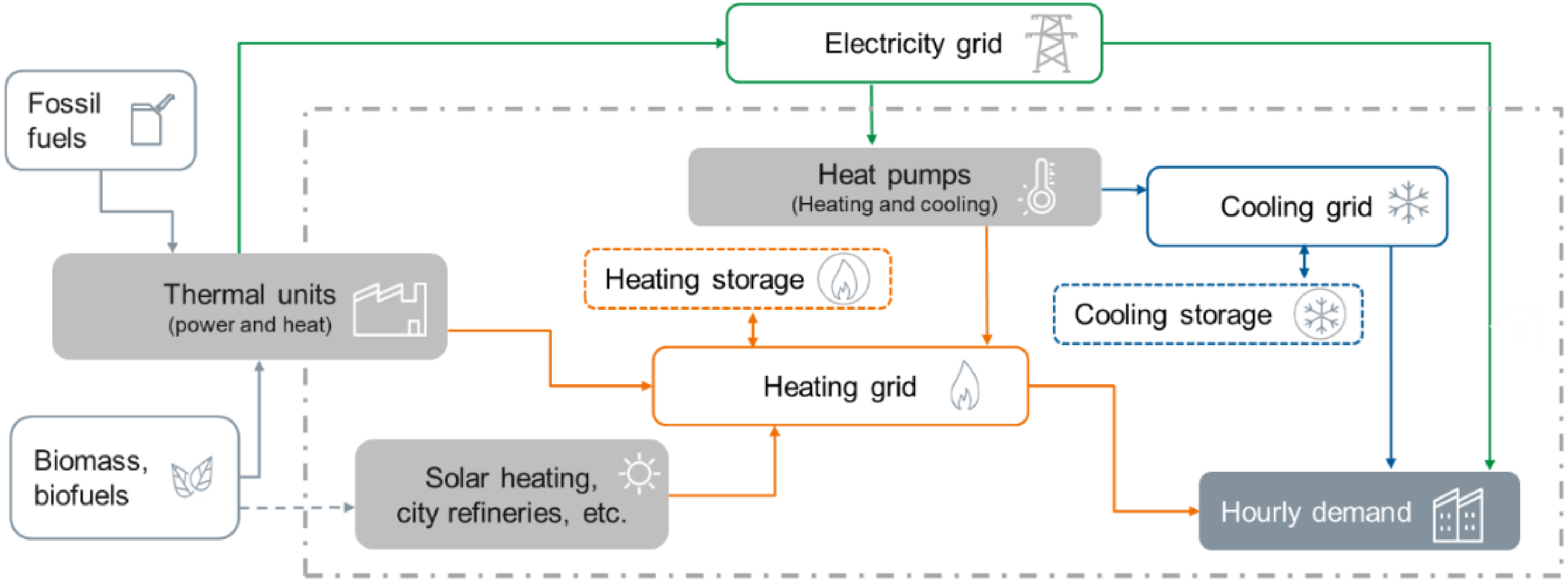
City model with electricity, heating and cooling



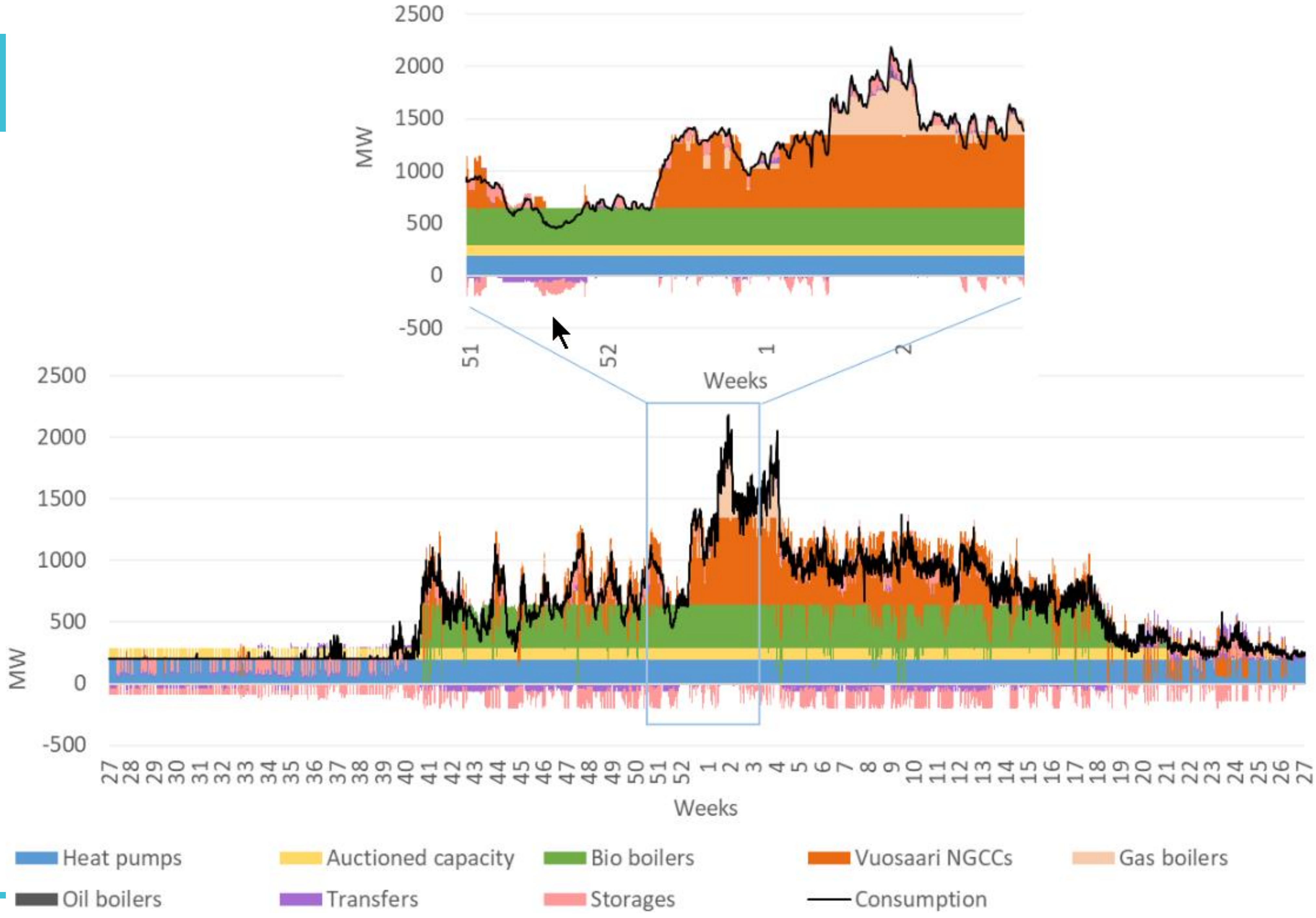
Inputs

- Unit data
- Grid data
- Demands
- CO_2 price
- Fuel costs
- Taxes

Results

- Energy balances
- CO_2 emissions
- Costs
- Unit operations

HELSINKI ENERGY CHALLENGE
Award winner
BEYOND FOSSILS



MW
2500
2000
1500
1000
500
0
-500
51
52
1
2
Weeks
MW
2500
2000
1500
1000
500
0
-500
27 28 29 30 31 32 33 34 35 36 37 38 39 40 41 42 43 44 45 46 47 48 49 50 51 52 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27
Weeks
Heat pumps
Auctioned capacity
Bio boilers
Vuosaari NGCCs
Gas boilers
Oil boilers
Transfers
Storages
Consumption

BACKBONE NORTH EUROPEAN MODEL

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Modelling Northern European energy system

LEAP-RE

Enables studying the competitiveness of different technologies in different future settings

- Includes countries in the map and years 2025, 2030, and 2040
- Electricity, district heat, and hydrogen
- Studying the impacts of modelled technologies and estimated when these technologies would become competitive

Backbone North European model

Built with Backbone open source modelling framework

Running the model requires three components

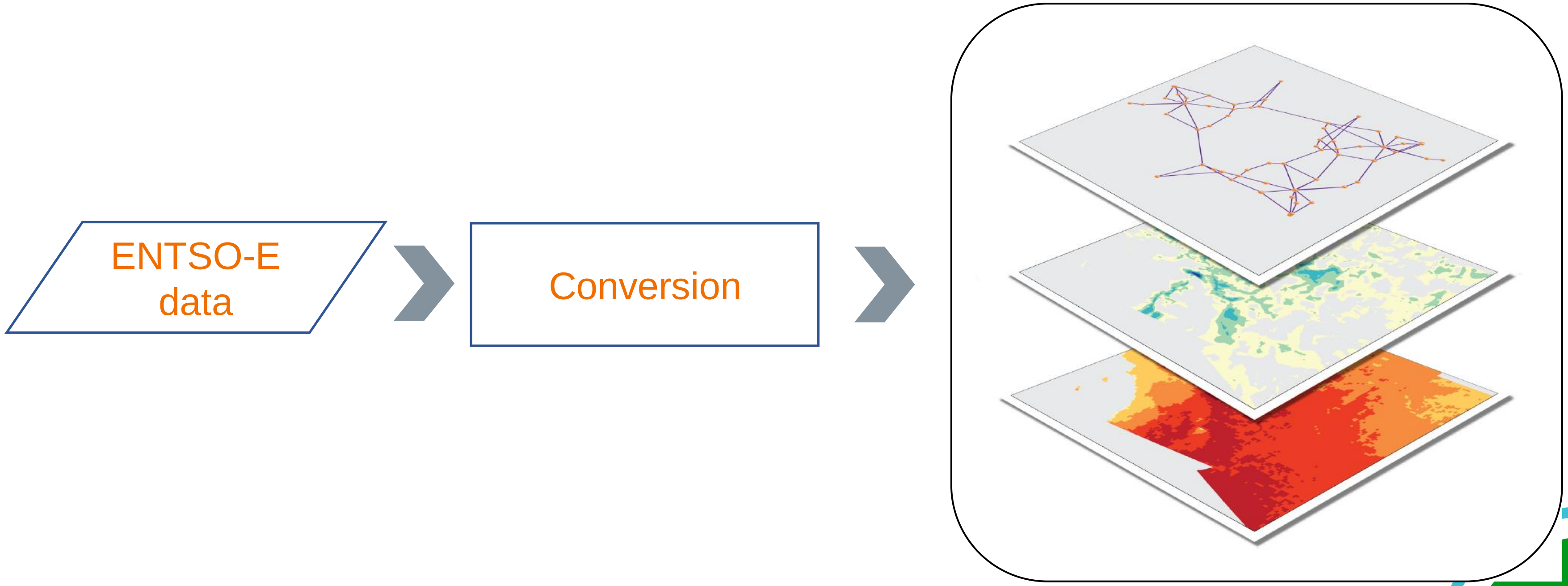
- Coding language and solver – commercial (https://www.gams.com/latest/docs/UG_MAIN.html)
- Backbone model framework - free (https://gitlab.vtt.fi/backbone/backbone/-/wikis/home)
- Northern European data set – free (https://gitlab.vtt.fi/backbone/models/europe-input)

Building the North European energy markets model

Input data mostly obtained from ENTSO-E

Open-access data

Conversion of data to model format using Python and Julia



Backbone Nordic model

Studying new energy technologies

Can model technologies related to

- Electricity
- District heat
- Hydrogen
- Or any combination

Can model technologies in different locations:

- Countries in the map (multiple areas in SE, NO, and DK)
- A number of towns in Finland (see map)

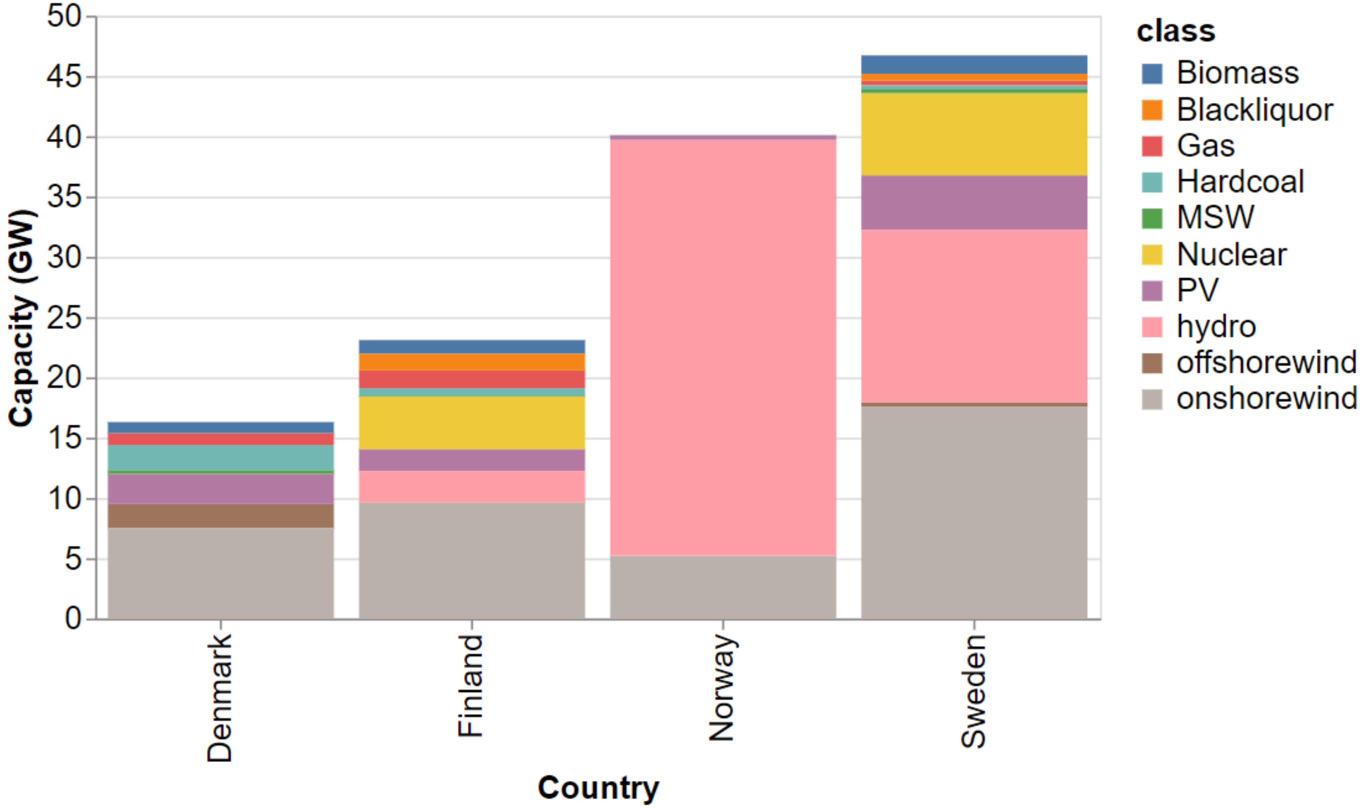
Nordic power plant capacities 2025

LEAP-RE

ENTSO-E TYNDP 2020, with updated values (e.g. VRES, CHP)

Strong additions to especially onshore wind and some to PV

Some decrease of CHP capacity in Finland



REFERENCE SYSTEM MODELS

Seasonal variability of renewables

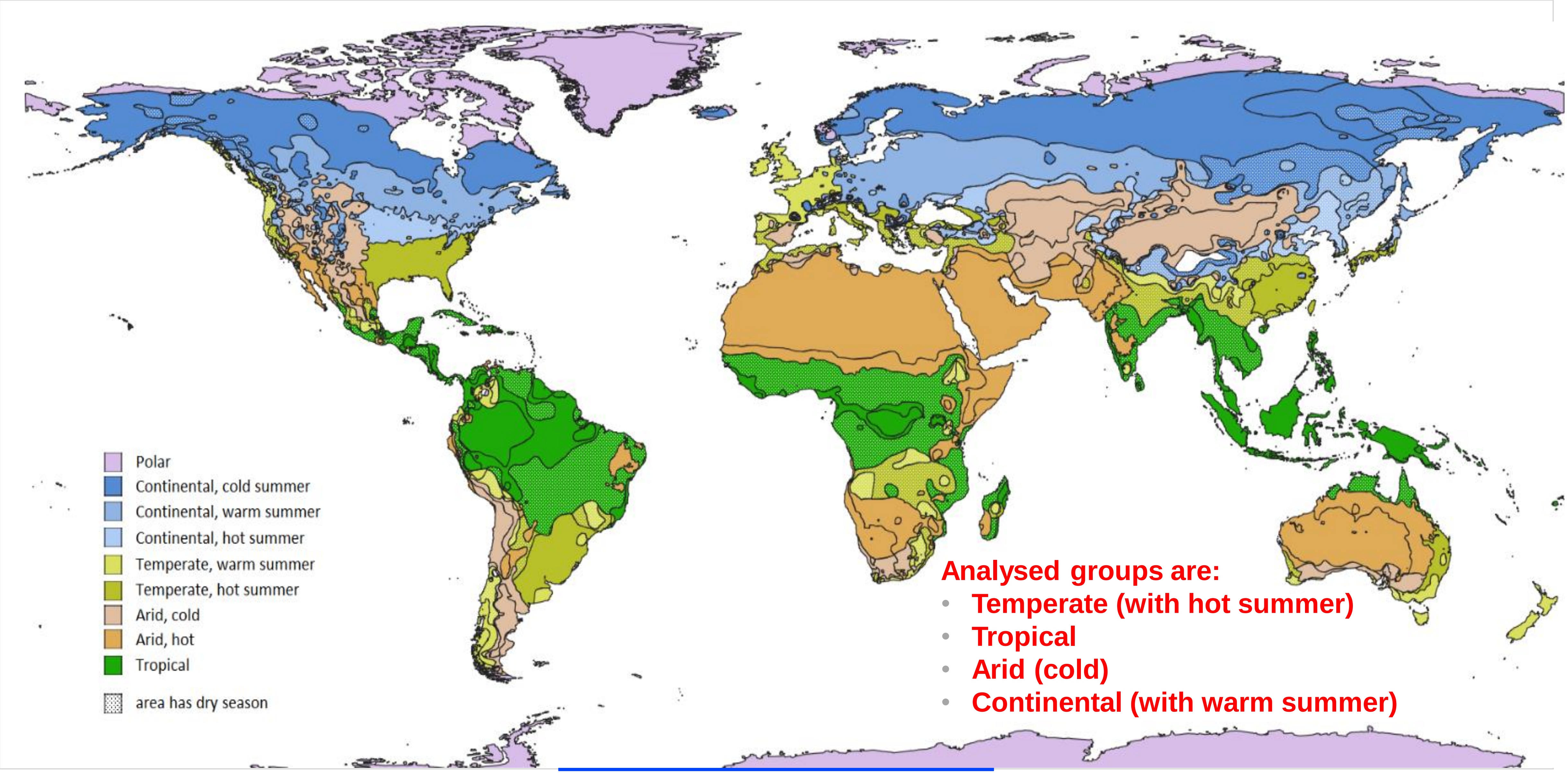
International Energy Agency

Seasonal variability of renewables

Project highlights and outcomes

Japan G7

Climate can be classified into similar groups



Analysed groups are:

- **Temperate (with hot summer)**
- **Tropical**
- **Arid (cold)**
- **Continental (with warm summer)**

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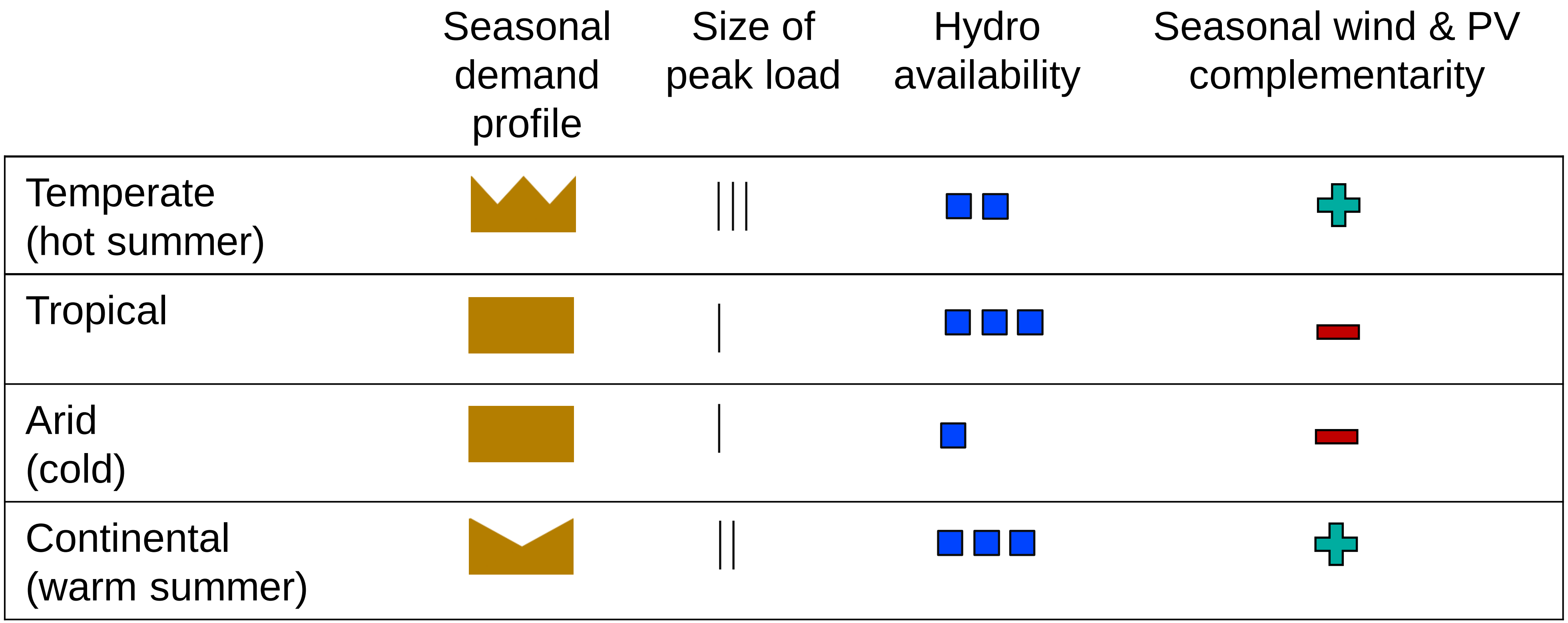
Seasonal patterns emerge from the interaction of demand and renewables supply

Key seasonal attributes of analysed climate groups.



Challenges to integrate renewables in high-VRE systems increase with strong mismatches between energy demand and renewables supply on a seasonal scale.

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Main assumptions and methodology in modelling “example systems”

- Parameters derived from the APS 2040 scenario
  - Technology costs and performances
  - Prices
  - Capacity mixes for thermal (coal, natural gas, oil, biomass and nuclear) and hydro power
  - Share of battery electric vehicles in transport fleet
- The model optimises investments in wind, solar PV and flexibility resources to minimise overall system costs under USD 120/tCO_2 carbon price.
- The optimisation is carried out separately for each example system.
- Results are normalised to 1 million persons to facilitate easy comparison across different systems.

Technology options considered in all models:

- Solar PV and wind (onshore & offshore) units
- Fossil, nuclear and biomass units,
- Reservoir hydro
- VRE curtailment
- Battery energy storages
- Pumped hydro storages
- EV flexible charging
- H2 storages, including industrial DSM
- Fuel cells
- H2 co-firing in NGCC units
- Ammonia storages
- Ammonia co-firing with coal
- 100% ammonia combined cycle units

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Renewable assumptions

Example system	Modelled weather years	Hydro inflow (TWh)	Wind onshore (capacity factor)	Wind offshore (capacity factor)	Solar PV (capacity factor)
Tropical	2015-2021	1.1	0.34	0.37	0.16
Arid	2010-2021	0.40	0.45	0.62	0.20
Temperate with dry season	2006-2016	0.86	0.39	0.50	0.22
Temperate with hot summers	2005-2021	0.88	0.36	0.56	0.15
Continental	2006-2017	1.1	0.40	0.53	0.12

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Existing conventional capacities

Example system	Coal MW/mp	NGCC MW/mp	Oil MW/mp	Nuclear MW/mp	Bioenergy MW/mp	Hydro MW/mp
Tropical	371	331	102	10	41	445
Arid	144	825	160	33	8	130
Temperate with dry season	526	322	30	63	23	336
Temperate with hot summers	465	301	17	117	41	358
Continental	256	500	11	142	25	442

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Technology	Investment cost		Fixed O&M	Efficiency	Variable O&M	Additional Info
	USD / kW_elec	**USD / kWh_elec**	**% of capex**	**%**	**USD / MWh_elec**	
Bio	2560	-	3%	36%	3.9	
Coal	2000	-	3%	46%	2.8	NH_3 co-firing with coal, up to 60% (energy)
Diesel	600	-	5%	35%	6.0	
NGCC	1000	-	3%	55%	1.7	H_2 co-firing with NG, up to 50% (energy)
Gas engine	600	-	5%	35%	2.7	
Nuclear	5760	-	3%	33%	9.0	
PV	400	-	2%	100%	0.1	
Wind, onshore	1000	-	2%	100%	2.7	
Wind, offshore	1600	-	2%	100%	1.4	
Batteries	-	145	2%	86%	3.6	
PHS	1000	100	3%	76%	1.0	
PEM electrolyser	485	-	3%	71%	1.5	
Fuel cell	60	-	4%	54%	2.0	
CCGT Ammonia	1300	-	3%	44%	1.7	100% NH_3

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Fuel prices

		Biomass	Coal	Natural gas	Oil
All regions	Price (USD/MWh)	22	22	37	50
All regions	CO_2 content (tCO_2/MWh)	0	0.340	0.200	0.265

Hydrogen

Technology	Investment cost		Fixed O&M	Efficiency	Variable O&M	Add. Info
	USD / kW_H_2	**USD / kWh_H_2**	**% of capex**	**%**	**USD / MWh_H_2**	
H_2 storage	100	1	4%	95%	0	

Constant industrial hydrogen demand

Ammonia

Technology	Investment cost		Fixed O&M	Efficiency	Variable O&M	Additional Info
	USD / kW_NH_3	**USD / kWh_NH_3**	**% of capex**	**%**	**USD / MWh_NH_3**	
Haberbosch + air separation unit	750	-	2%	74%	0	Efficiency calculated from H_2 and electricity inputs
NH_3 storage	10	0.1	-	100%	0	

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Generic parameters

	Parameter	
Investments	Interest rate for wind and solar	5%
	Interest rate for all other investments	8%
	Economic lifetime (years)	20
Grid parameters	Maximum hourly VRE share	100%
Other main parameters	Capacity margin	15%
	CO2 price unless varied in sensitivity run	120 USD/tCO_2

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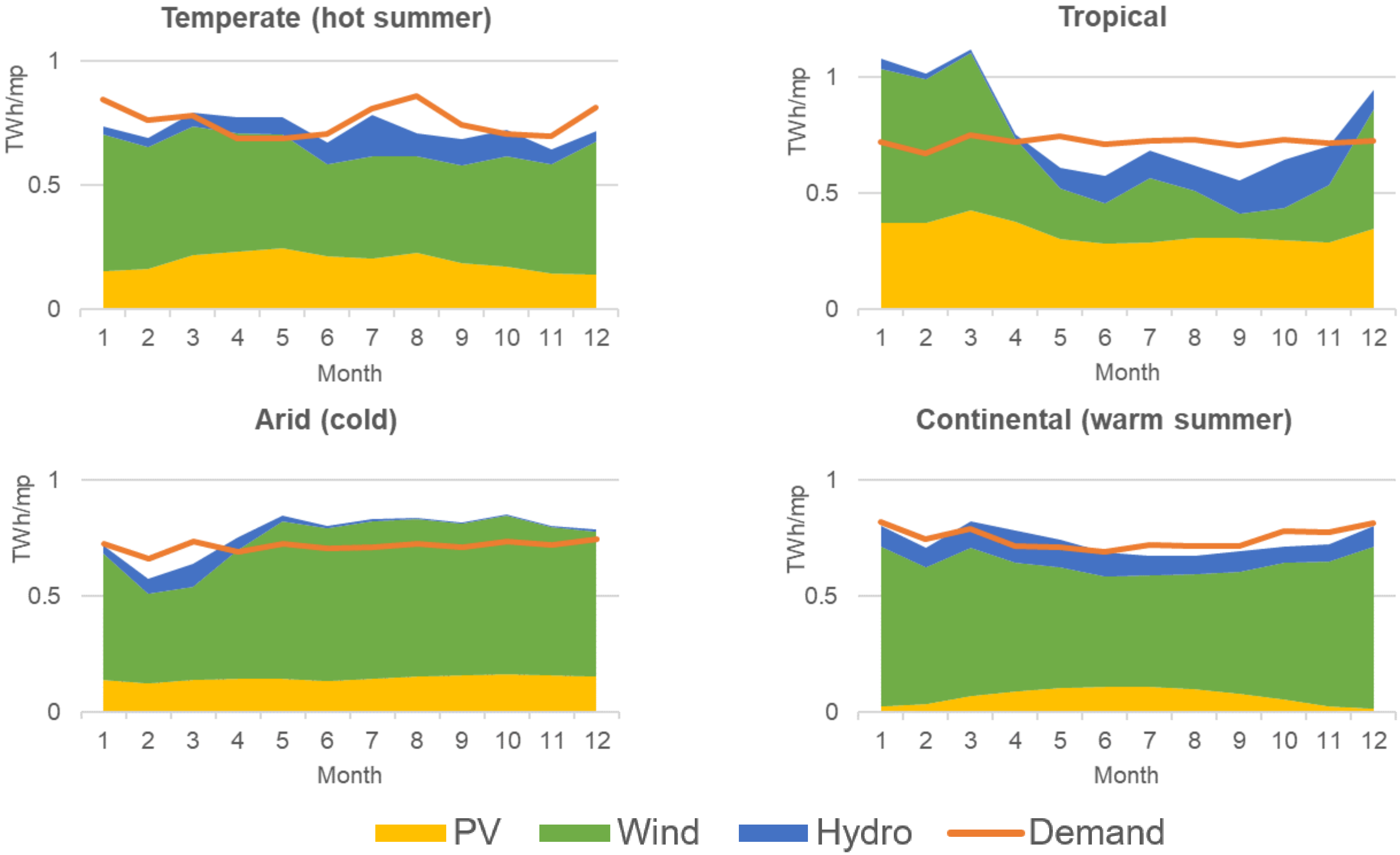
Climate drives seasonal variability of renewables in high-VRE systems

Monthly variation in electricity demand and in generation potential from solar, wind and hydro by example system.



The seasonal patterns in the generation potential from wind, solar VP and hydro and how they complement patterns in electricity demand are unique to each example systems.

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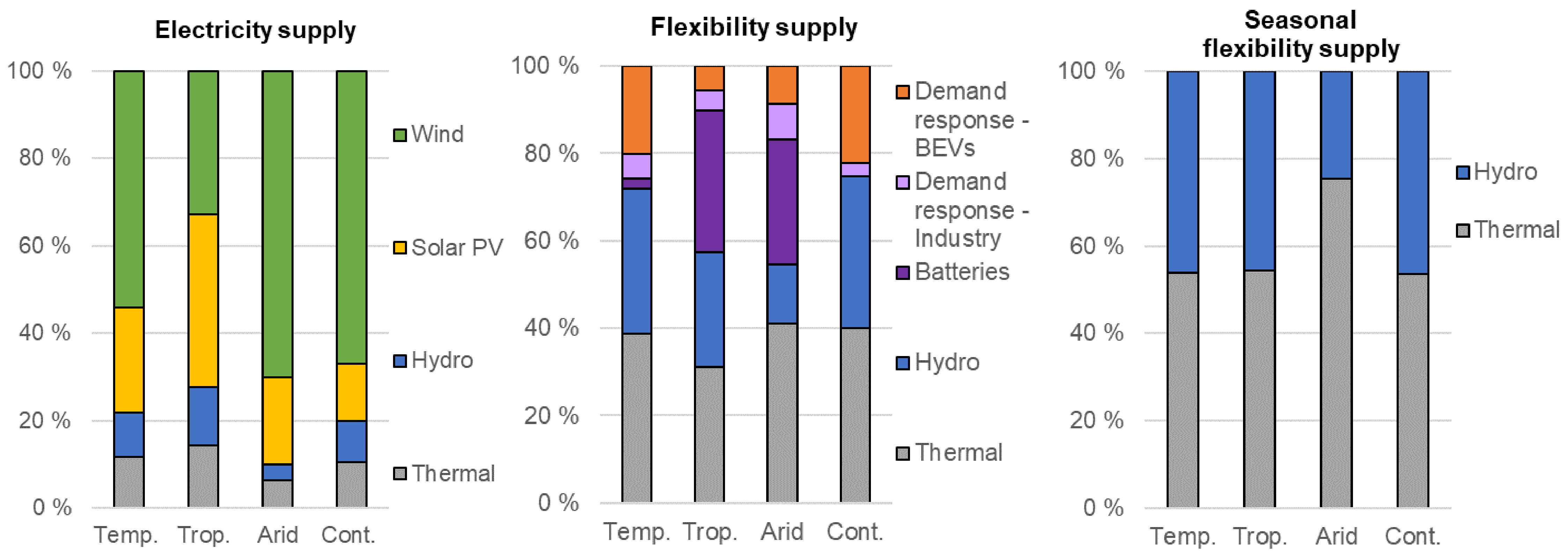
Thermal plants are the main source of seasonal flexibility

Electricity and flexibility supply by technology in the example systems.



VRE share is 70%-90% of annual generation, but thermal plants cover 55%-75% of seasonal flexibility supply. Carbon intensity range is 30-60 gCO2/kWh, which is relatively low but not compatible with net-zero targets.

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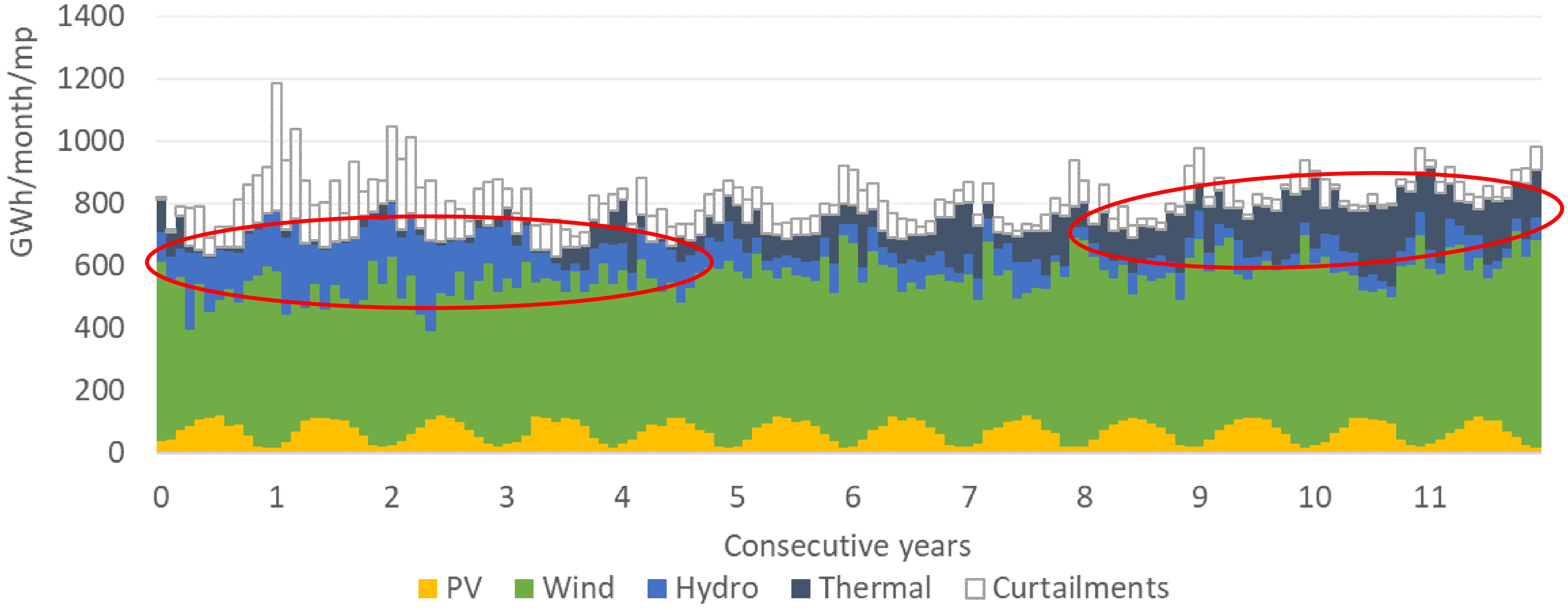
Inter-annual variation is driven by hydro power generation

Monthly generation by technology over a period of 12 years in the continental (warm summer) reference system.



Solar PV and wind do not demonstrate significant inter-annual variability in any of the studied example systems. Consecutive years of lower-than-average hydro generation can be only managed with thermal plants.

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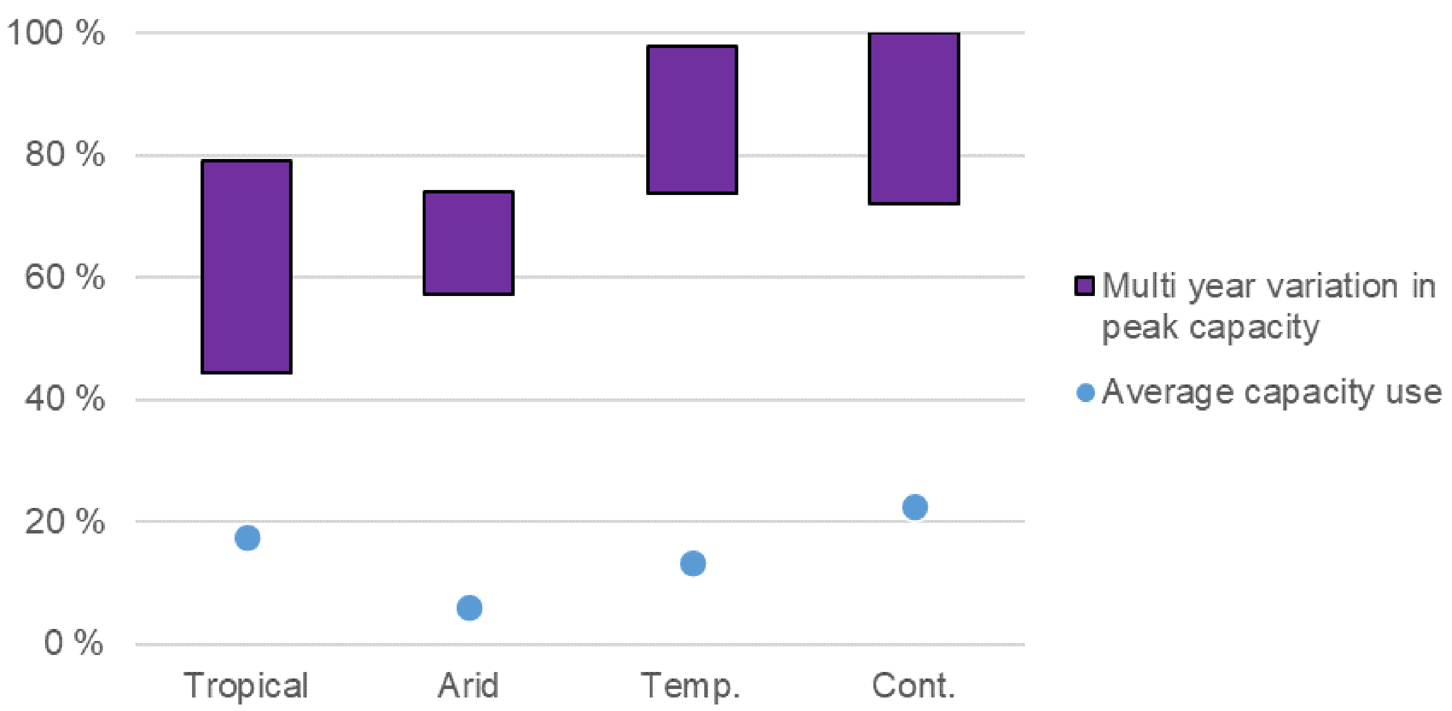
Thermal plants are needed for managing inter-annual variability but they have low overall availability

Variation in the use of legacy capacity over multi year periods in the example systems.



Depending on the year, 45%-80% of legacy capacity is dispatched in the Tropical and Arid systems, and 75%-100% in the Temperate and Continental systems. However, the overall utilisation of the fleet is only 5%-22% across all systems.

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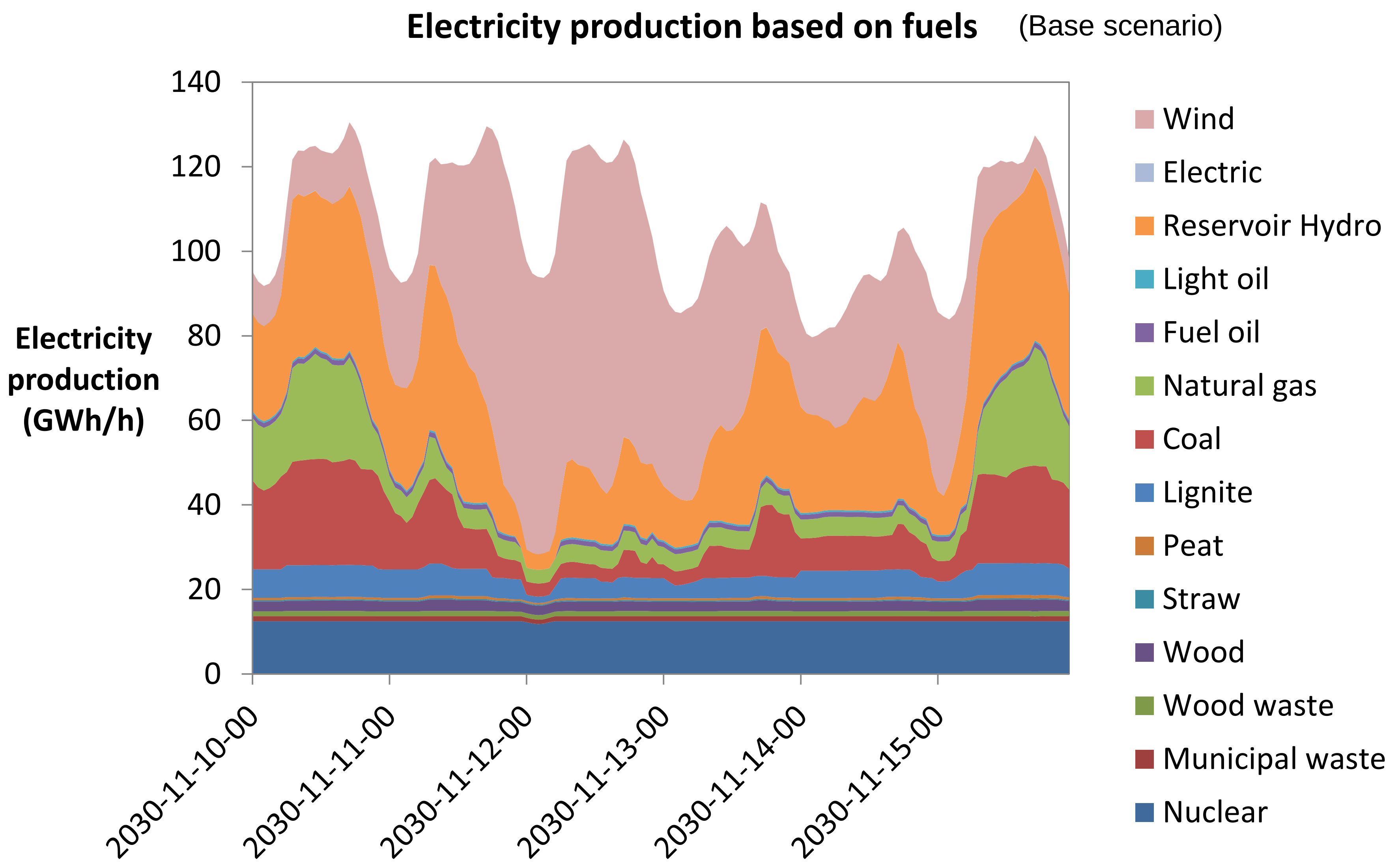
FLEXIBILITY COMPARISON

Assumptions

- Nordic countries and Germany
- Fuel prices as in 2010
- CO_2 price 25 €/MWh
- Demand as in 2010
- New power plants from Platts database (until ~2020)
- Nuclear phase-out in Germany + older thermal plants retired
    - Capacity balance rather tight
- 20% energy penetration for wind power scenarios Twenties onshore
- PV not included (focusing on wind integration)
- Transmission from TYNDP 2010 plus Tradewind 2030 scenarios
- Investment costs from EnergiNet report, except transmission from project estimates

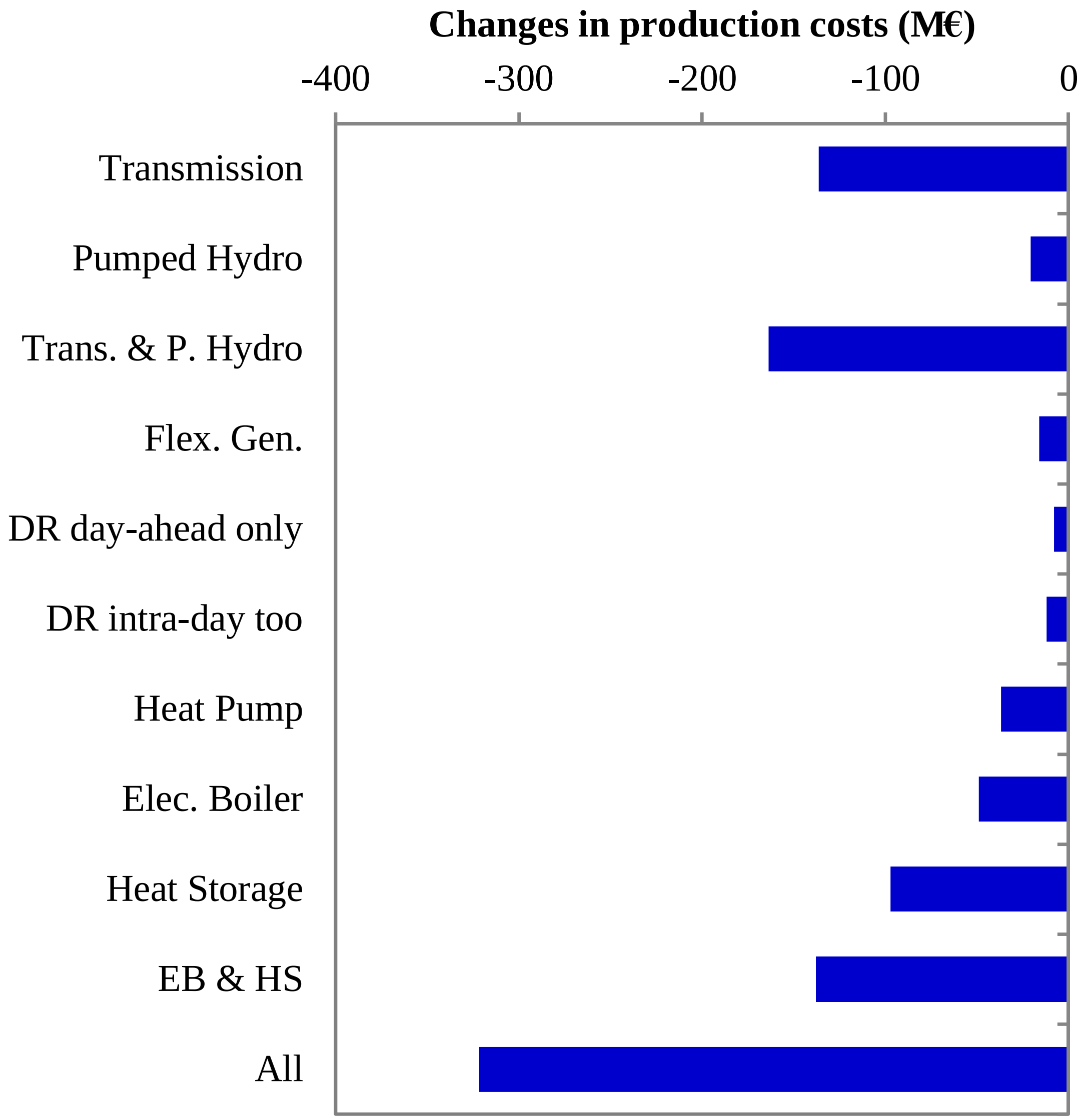
Scenario assumptions

	Assumption	*Estimated cost*
Transmission	2,800 MW additional tranmission between Nordic countries and Germany	2000 M€, published TSO plans
Flexible Gen.	14,665 MW of conventional generation with 10 percentage points lower minimum load factor	No estimate
Electric Boiler	3,079 MW of resistance heater capacity split into heat areas	216 M€
Heat Pump	308 MW_{elec} of heat pumps (COP 3.5) split into heat areas	216 M€
Heat Storage	98,536 MWh (assuming 8 hours for full charging) of heat storage split into heat areas	89 M€
Pumped Hydro	6,094 MW of pumped hydro replacing 3047 MW of reservoir hydro	~2000 M€
Demand Response	Four price levels of demand response split between regions Block 1: ~80 €/MWh; 900 MW Block 2: ~150 €/MWh; 1,800 MW Block 3: ~290 €/MWh; 2,700 MW Block 4: ~580 €/MWh; 3,600 MW Not used	No estimate


Electricity production based on fuels (Base scenario)
Electricity production (GWh/h)
140
120
100
80
60
40
20
0
2030-11-10-00
2030-11-11-00
2030-11-12-00
2030-11-13-00
2030-11-14-00
2030-11-15-00
Wind
Electric
Reservoir Hydro
Light oil
Fuel oil
Natural gas
Coal
Lignite
Peat
Straw
Wood
Wood waste
Municipal waste
Nuclear

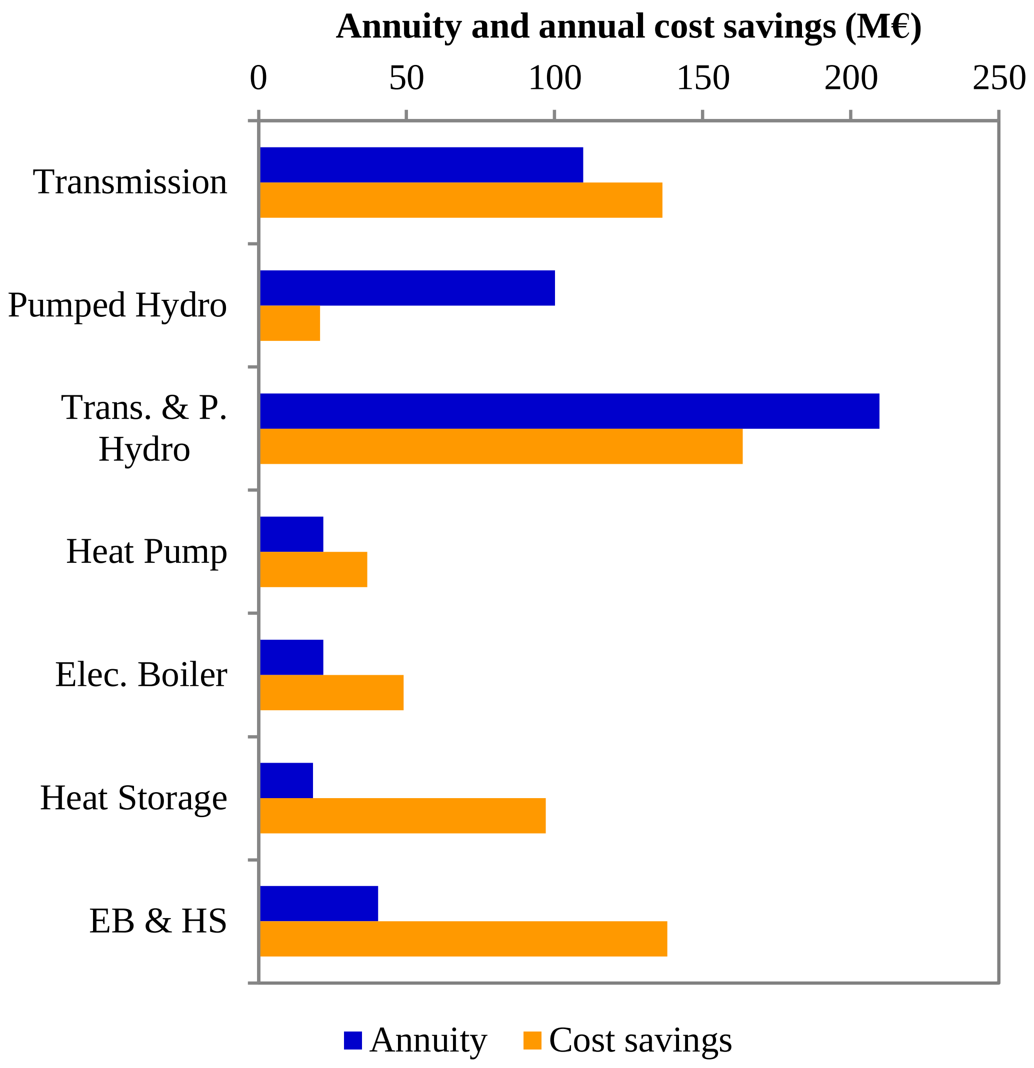
Results — system costs

- Not comparable without investment annuity
- The impact from flexible generation, demand response and pumped hydro is surprisingly small
- Transmission and pumped hydro 4% **less** cost savings together than separately
- Electric boilers and heat storages 6% **more** cost savings together than separately
- 12% less cost savings when all scenarios together than if summed separately



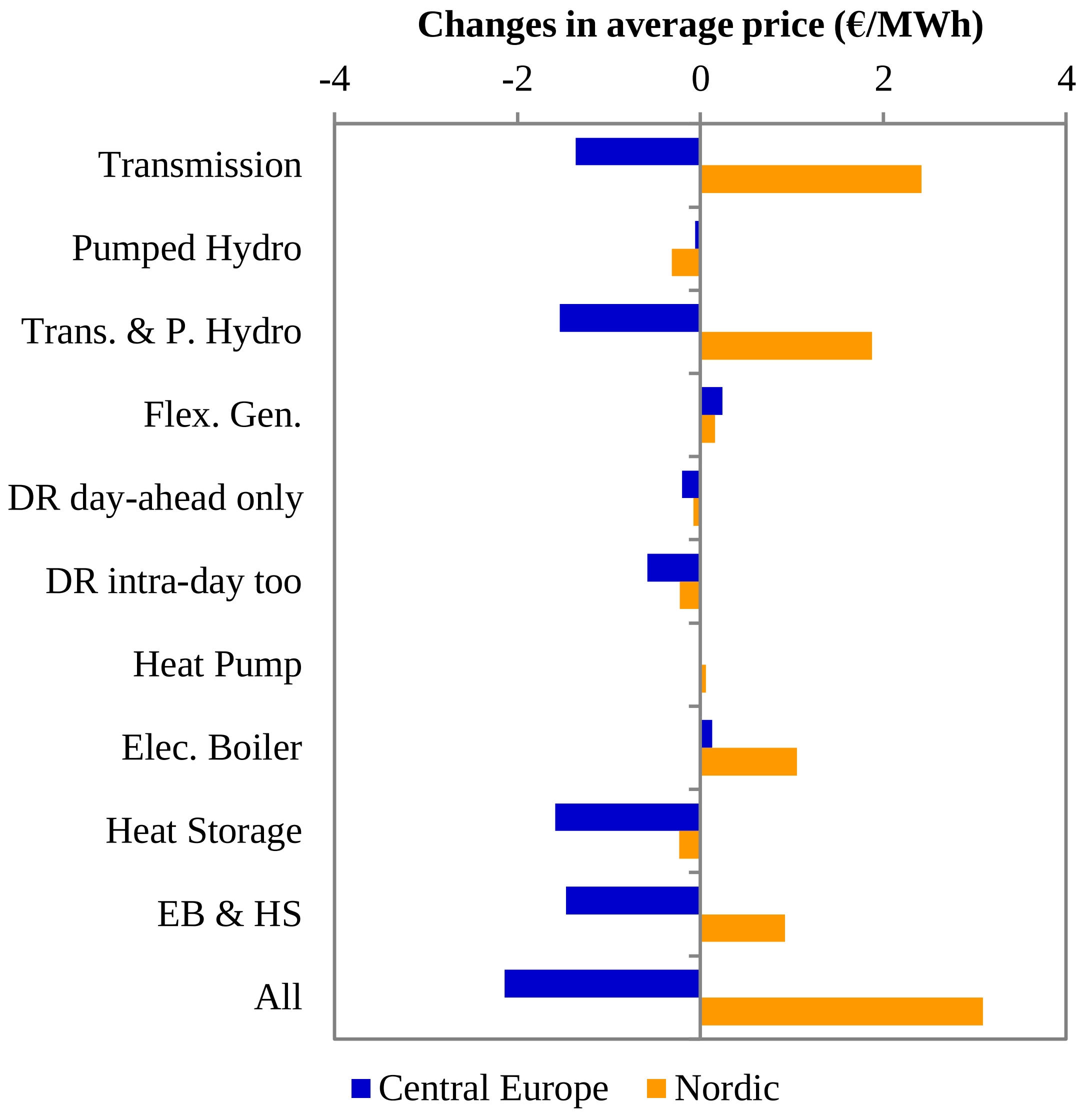
Results — annuity and cost savings

- Demand response and flexible generation: no investment cost estimate
  - But flex gen profits would allow about 10 k€/MW investment
- Transmission (between Germany and Nordic) and heat measures are profitable
- Pumped hydro (in Norway) is not profitable



Results — intra-day prices

- Transmission decreases price differences
- Demand response decreases prices
- Electric boilers increase power prices
- Heat storages reduce producer surplus (larger impact in Germany)

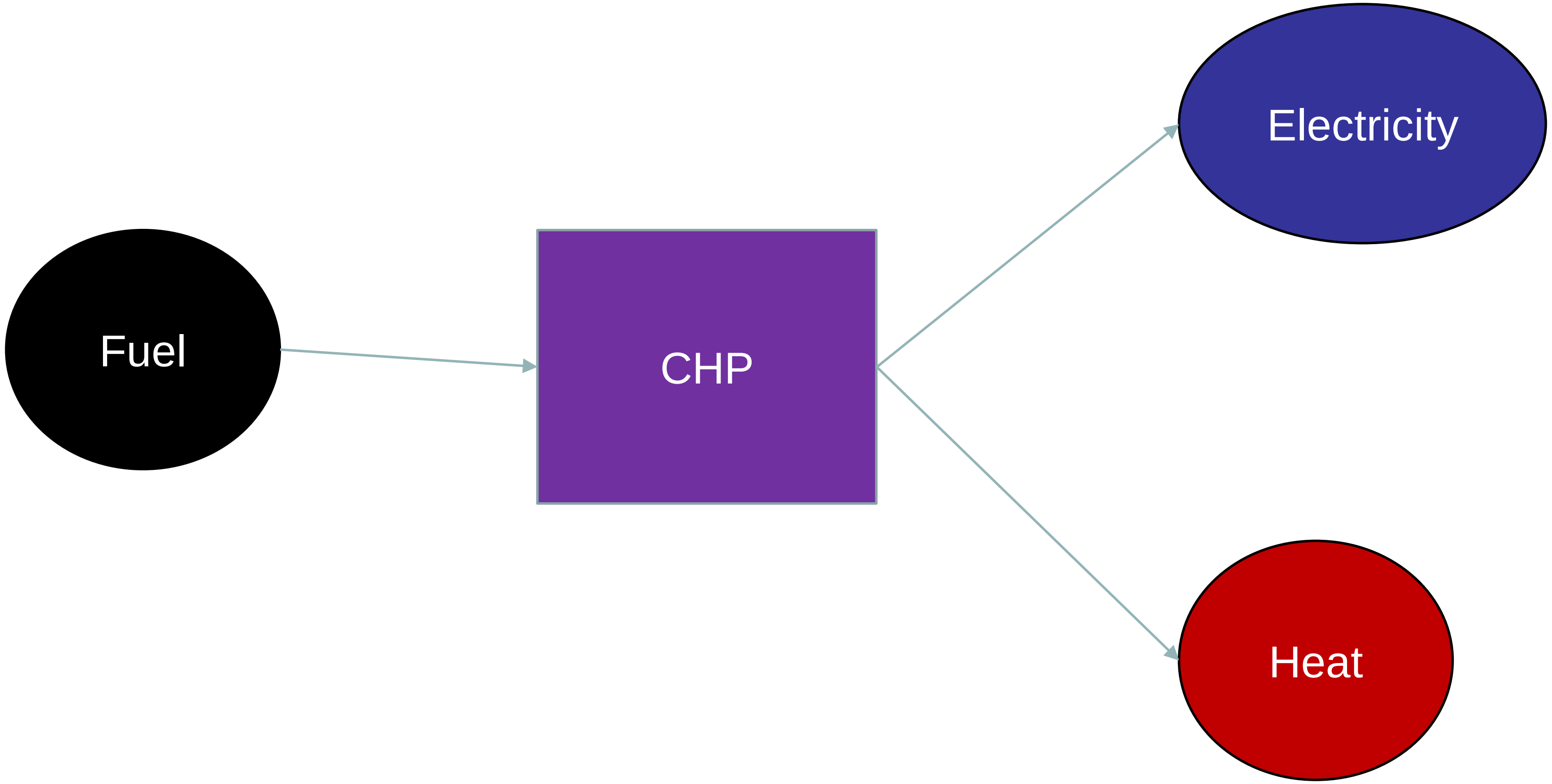


THERMAL POWER PLANTS IN HIGHER DETAIL

LEAP-RE

OASES

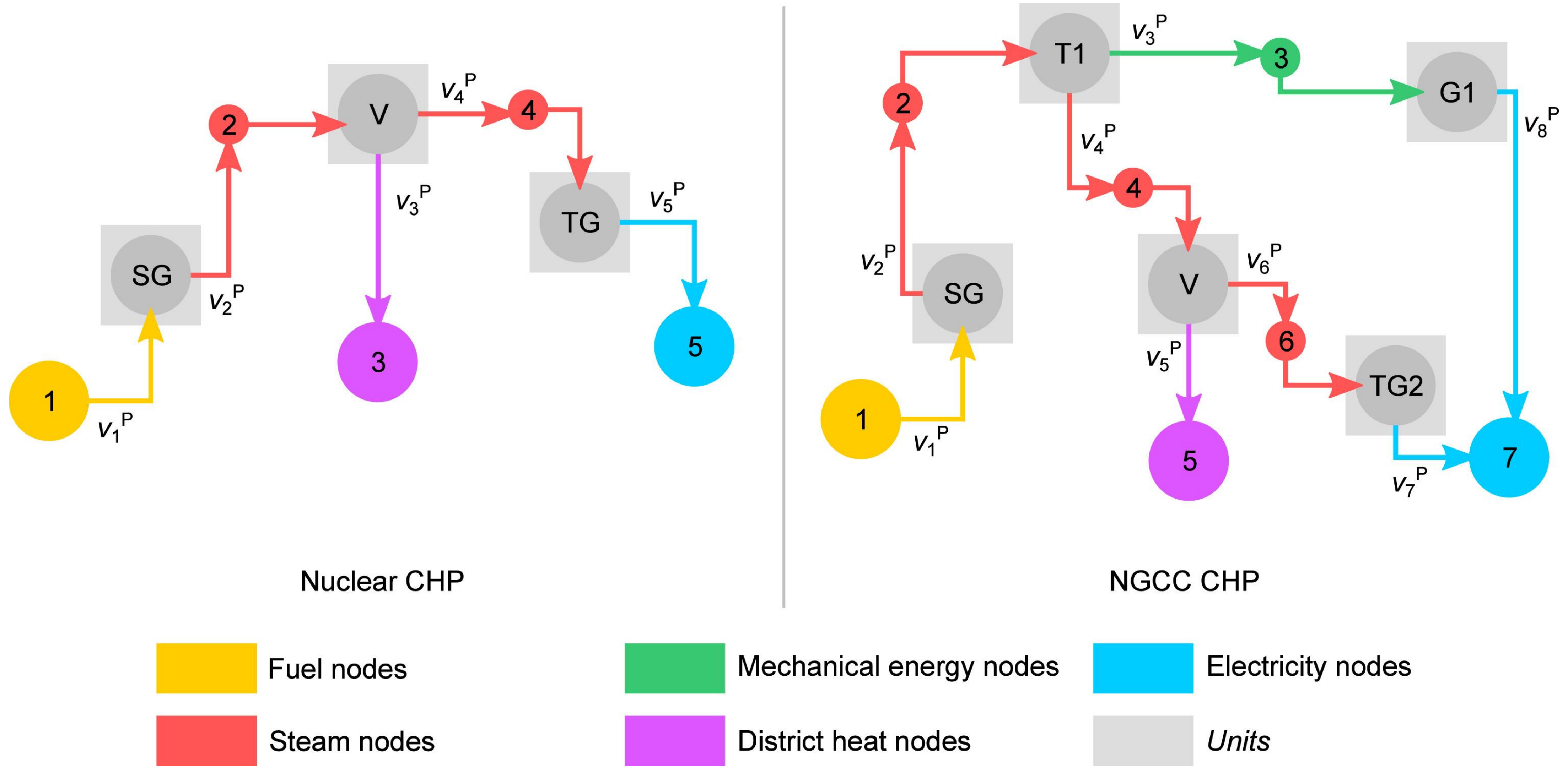
Basic version



Niina Helistö, Juha Kiviluoma, German Morales-España, Ciara O'Dwyer (2021); Impact of operational details and temporal representations on investment planning in energy systems dominated by wind and solar. Applied Energy, Vol. 290, 116712.

Energy conversion units in high level of detail

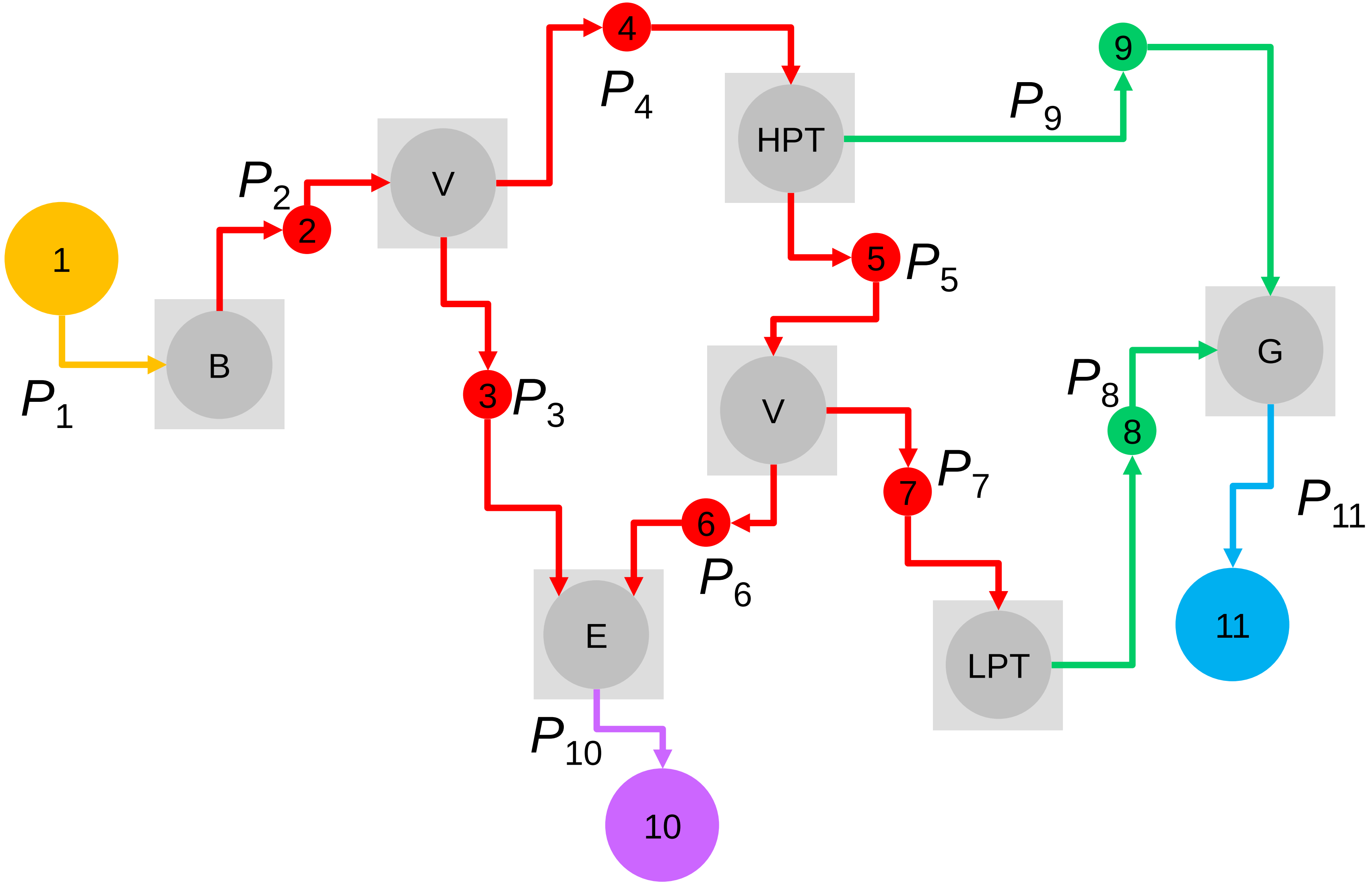
IRENA FlexTool



Niina Helistö, Juha Kiviluoma, German Morales-España, Ciara O'Dwyer (2021); Impact of operational details and temporal representations on investment planning in energy systems dominated by wind and solar. Applied Energy, Vol. 290, 116712.

Steam CHP plant Backbone diagram

VTT



Components/units:
B: boiler/steam generator
C: condenser
E: heat exchanger
G: generator
HPT: high-pressure turbine
LPT: low-pressure turbine
V: valve

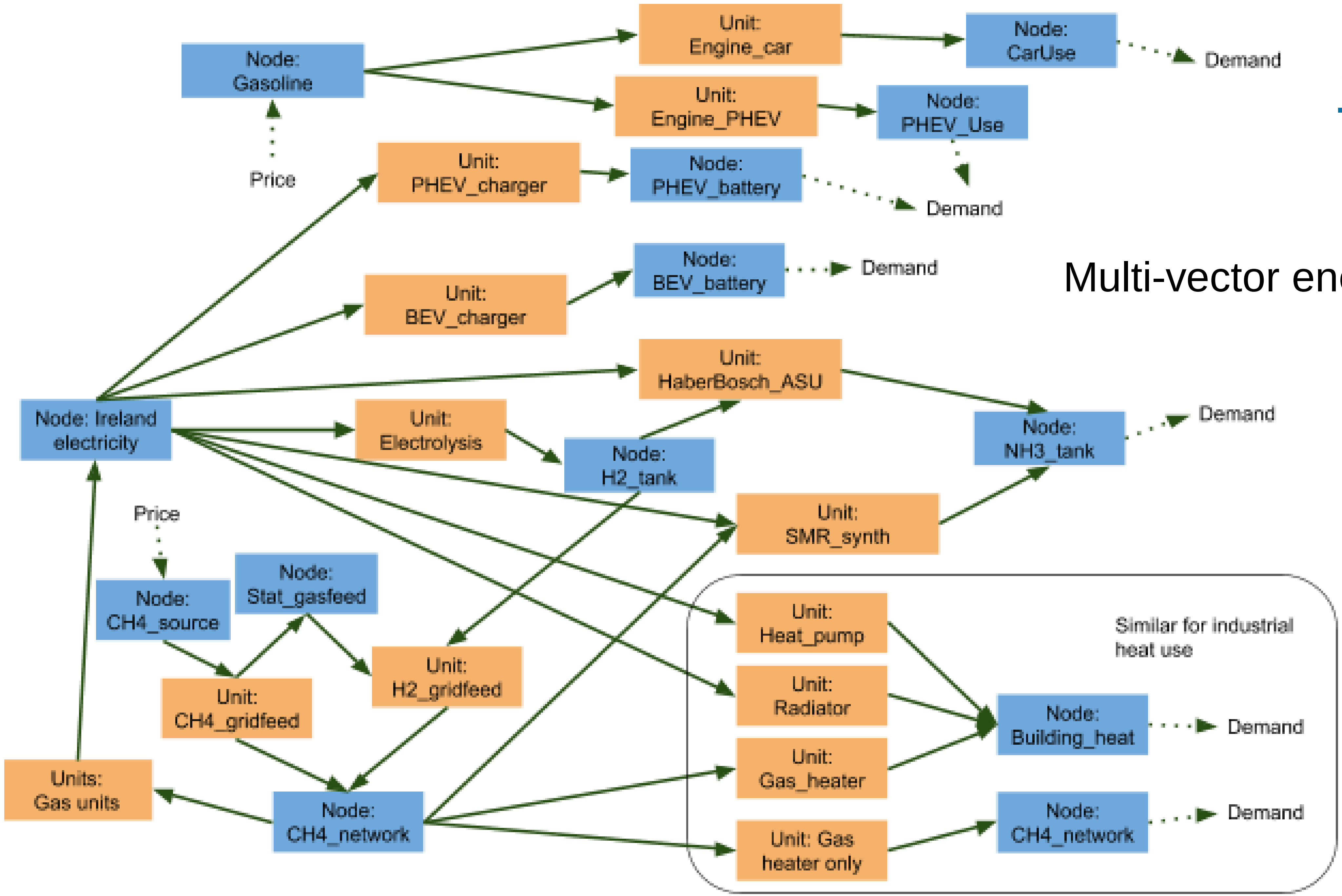
Grids/nodes:
1: fuel
2-7: steam
8-9: mechanical energy
10: district heating
11: electricity

CASE IRELAND WITH MULTIPLE SECTORS

LEAP-RE

OASES

Multi-vector energy systems



IRENA FlexTool

Juha Kiviluoma, Ciara O'Dwyer, Jussi Ikäheimo, Rinalini Lahon, Ran Li, Dana Kirchem, Niina Helistö, Erkka Rinne, Damian Flynn (2022); Multi-sectoral flexibility measures to facilitate wind and solar power integration. IET Renewable Power Generation, rpg2.12399.

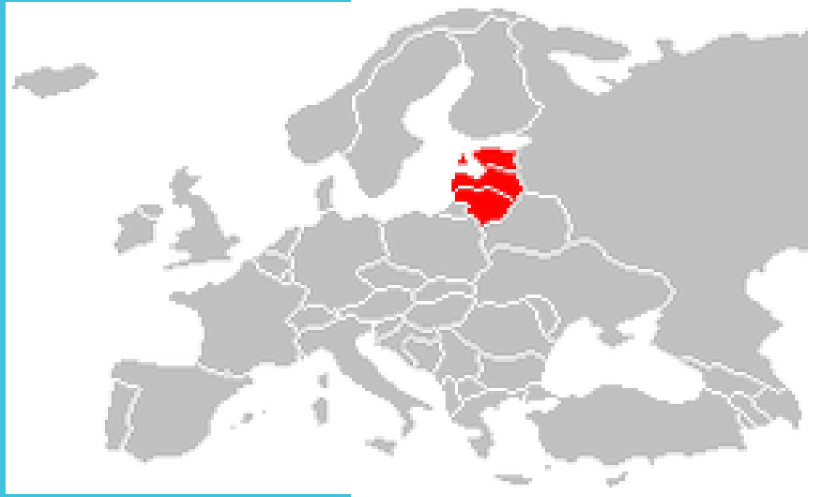
Temporal representation	Operational detail	Continuous full year using at least hourly resolution	Number of representative weeks	Number of high-resolution weeks (other weeks at daily resolution)	Scaled time series in repr. weeks (according to annual capacity factors)	Continuous (CO) or cyclic (CY) storage between repr. weeks	Repr. or high-resolution weeks selected using random sampling (RS) or regular decomposition (RD)	Highest resolution (1h, 15min, 5min)	Online variables	FCR requirement	FFR requirement	Ramp limits	Flexible output ratios of CHP units
unscaled, cyclic storage, 7wks/RD/	(no oper. details)	N	7	–	N	CY	RD	1h	N	N	N	N	N
unscaled, cyclic storage, 7wks/RS/	(no oper. details)	N	7	–	N	CY	RS	1h	N	N	N	N	N
scaled, cyclic storage, 7wks/RD/	(no oper. details)	N	7	–	Y	CY	RD	1h	N	N	N	N	N
scaled, cyclic storage, 7wks/RS/	(no oper. details)	N	7	–	Y	CY	RS	1h	N	N	N	N	N
	online							1h	Y	N	N	N	N
	online, FCR							1h	Y	Y	N	N	N
	online, FFR							1h	Y	N	Y	N	N
	online, FCR+FFR							1h	Y	Y	Y	N	N
	online, ramp limits							1h	Y	N	N	Y	N
	online, ramp limits, 15min							15min	Y	N	N	Y	N
	online, ramp limits, 5min							5min	Y	N	N	Y	N
	online, CHP flex							1h	Y	N	N	N	Y
scaled, continuous storage, 7wks/RS/	(no oper. details)	N	7	–	Y	CO	RS	1h	N	N	N	N	N
5wks/RS/+aggr	(no oper. details)	N	–	5	–	–	RS	1h	N	N	N	N	N
	online							1h	Y	N	N	N	N
	online, FCR							1h	Y	Y	N	N	N
	online, FFR							1h	Y	N	Y	N	N
	online, FCR+FFR							1h	Y	Y	Y	N	N
	online, ramp limits							1h	Y	N	N	Y	N
	online, ramp limits, 15min							15min	Y	N	N	Y	N
	online, ramp limits, 5min							5min	Y	N	N	Y	N
	online, CHP flex							1h	Y	N	N	N	Y
7wks/RS/+aggr	(no oper. details)	N	–	7	–	–	RS	1h	N	N	N	N	N
cyclic storage, 52wks	(no oper. details)	N	52	–	–	CY	–	1h	N	N	N	N	N
full year	(no oper. details)	Y	–	–	–	–	–	1h	N	N	N	N	N
	online							1h	Y	N	N	N	N
	online, FCR							1h	Y	Y	N	N	N
	online, FFR							1h	Y	N	Y	N	N
	online, FCR+FFR							1h	Y	Y	Y	N	N
	online, ramp limits							1h	Y	N	N	Y	N
	online, ramp limits, 15min							15min	Y	N	N	Y	N
	online, CHP flex							1h	Y	N	N	N	Y

MODELLING RESERVES

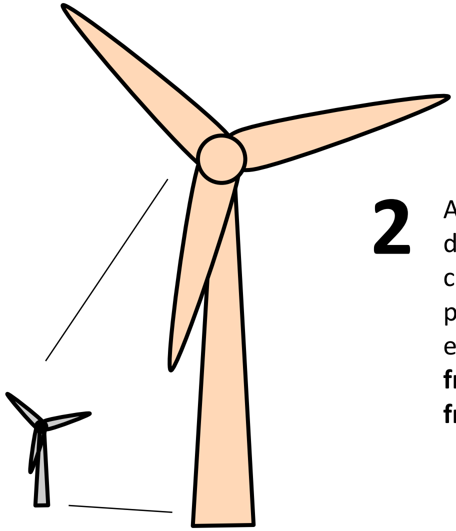
Testing the impact of model detail on the results

Niina Helistö, Juha Kiviluoma, German Morales-España, Ciara O'Dwyer (2021); Impact of operational details and temporal representations on investment planning in energy systems dominated by wind and solar. Applied Energy, Vol. 290, 116712.

BALTIC MULTI-YEAR MODELLING



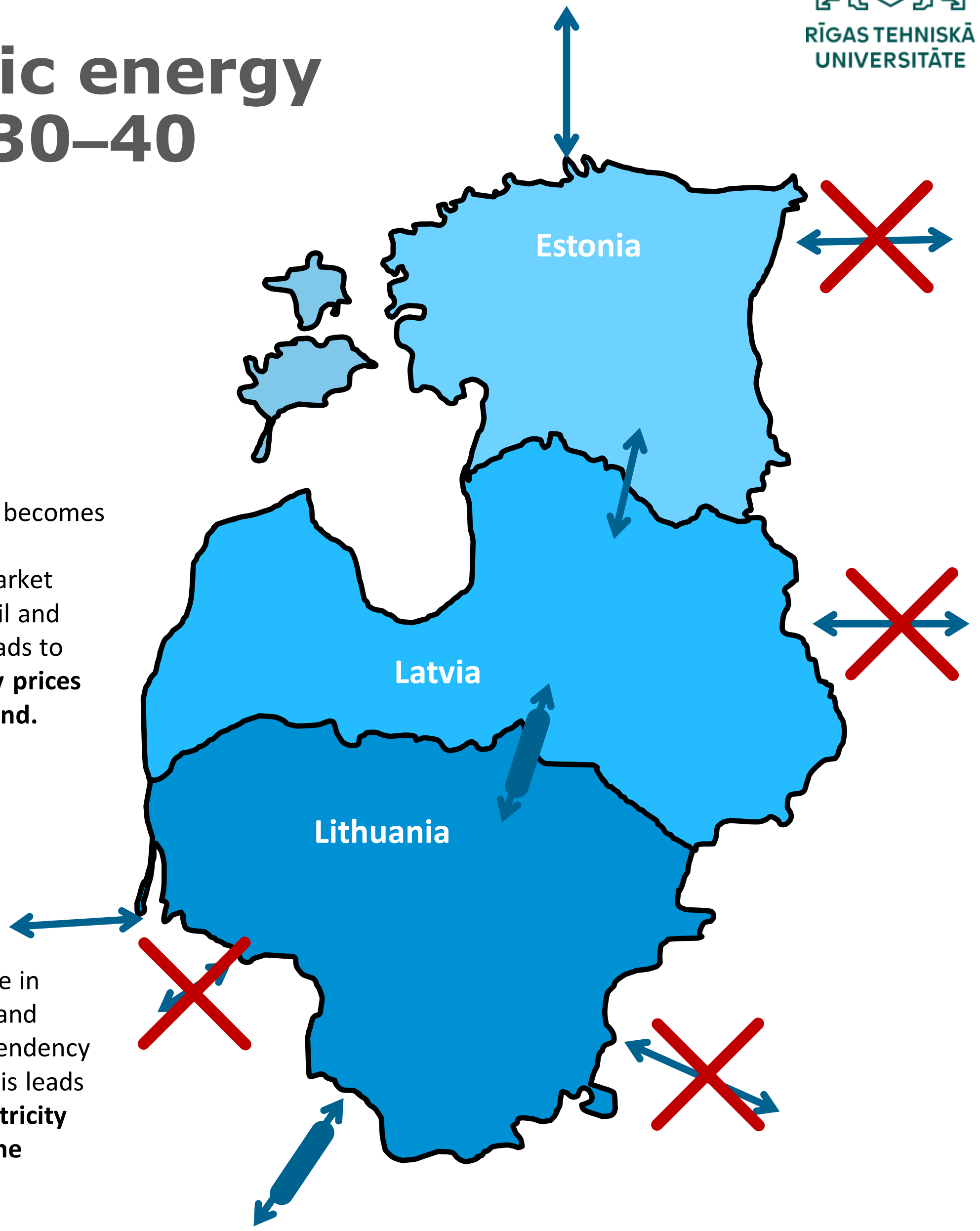
Changes in the Baltic energy system towards 2030–40



1 Substantial expansion of domestic wind and solar **generation increases generation variability and flexibility demand.**

2 As share of renewables becomes dominant in the Nordic countries, electricity market prices detach from fossil and emission prices. This leads to **frequent low electricity prices from Sweden and Finland.**

3 Renewable energy share in Central Europe and Poland remains lower and dependency on fossil fuel persist. This leads to **regularly higher electricity prices in Poland than the Nordics.**



4 **Personal transport and building heating electrify**, leading to increased electricity demand, but improved energy efficiency. End-use sectors become increasinbly available for demand response.

5 Increased natural gas prices and reduced availability **encourage fossil phaseout and domestic renewable investments, but can challenge energy security and energy affordability.**

6 Changes in transfer connections (detachment from Russian syncronous grid and reinforcement of transmission lines to Poland and inside the Baltic region) **increase integration with Europe, but reduce overall import capacity.**

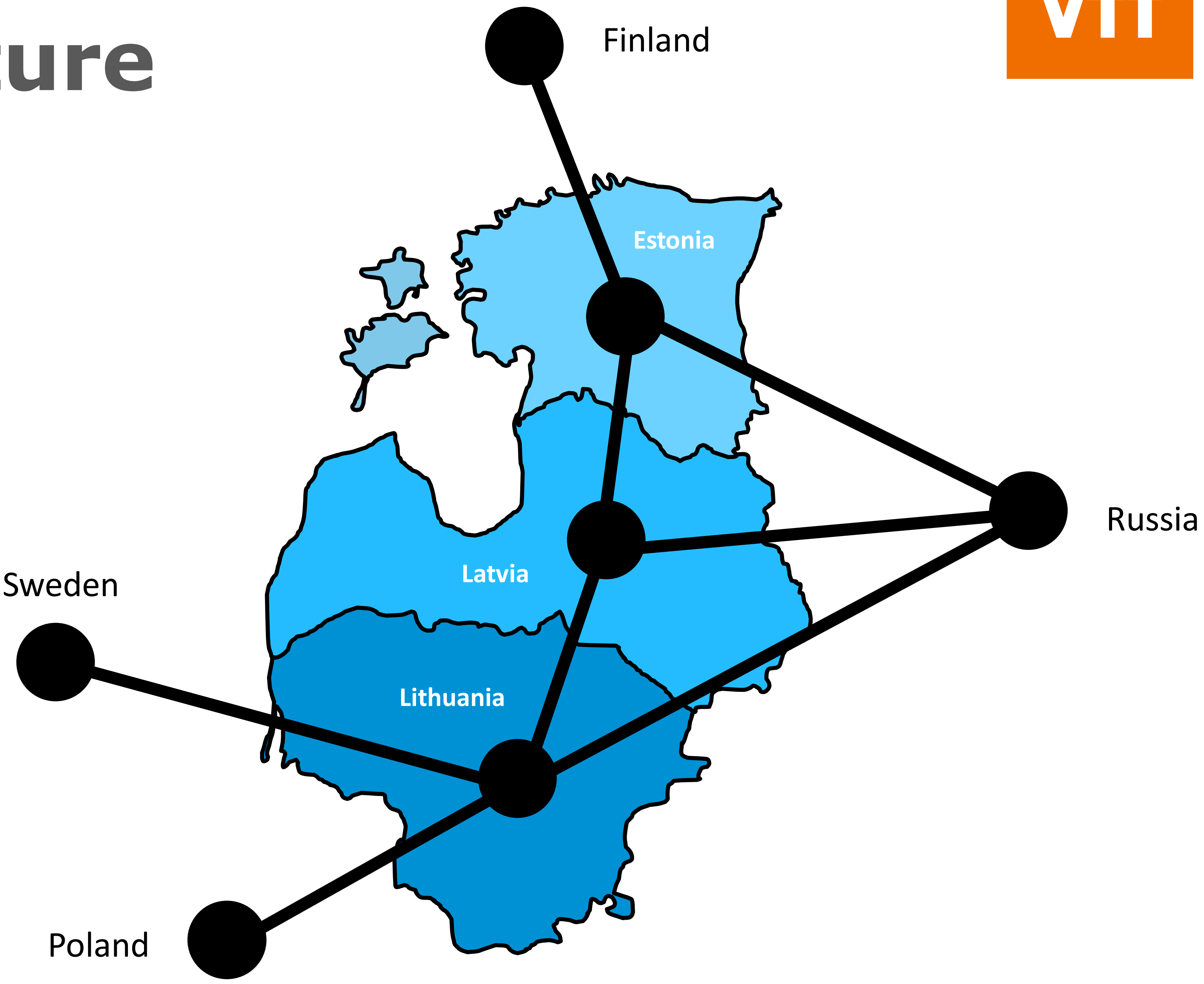
7 **The Baltic region will remain highly impacted by the policies of other countries in the Nordic and Central Europe.** The Baltic countries may economically benefit from the large planned renewable capacity installations in other countries, but this may contradict with feasibility of own domestic generation and domestic generation goals.

Model structure

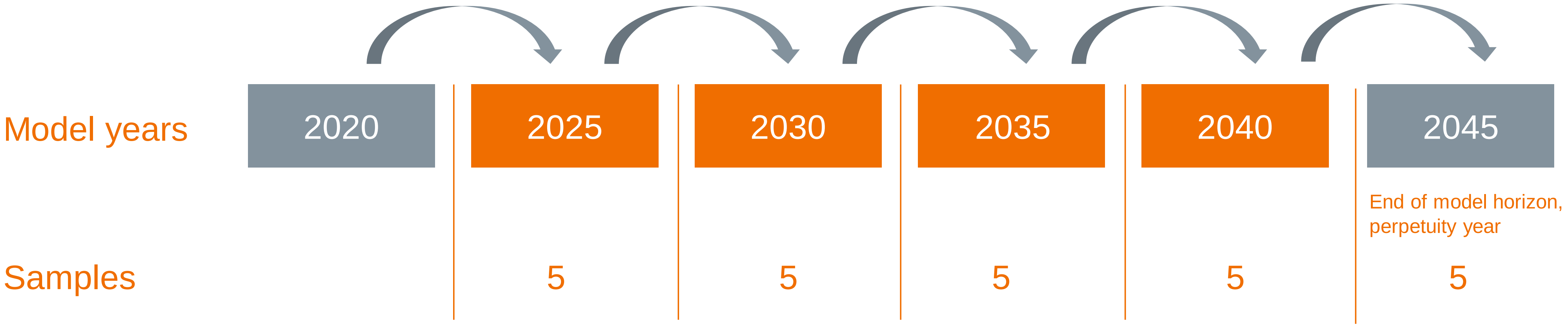
SECTORS
Electricity, district heat, private road transport and building heating in three countries

UNITS
Generation units aggregated to approx. 100 units

RESOLUTION
Hourly time series on country level + heating divided between capital/other regions



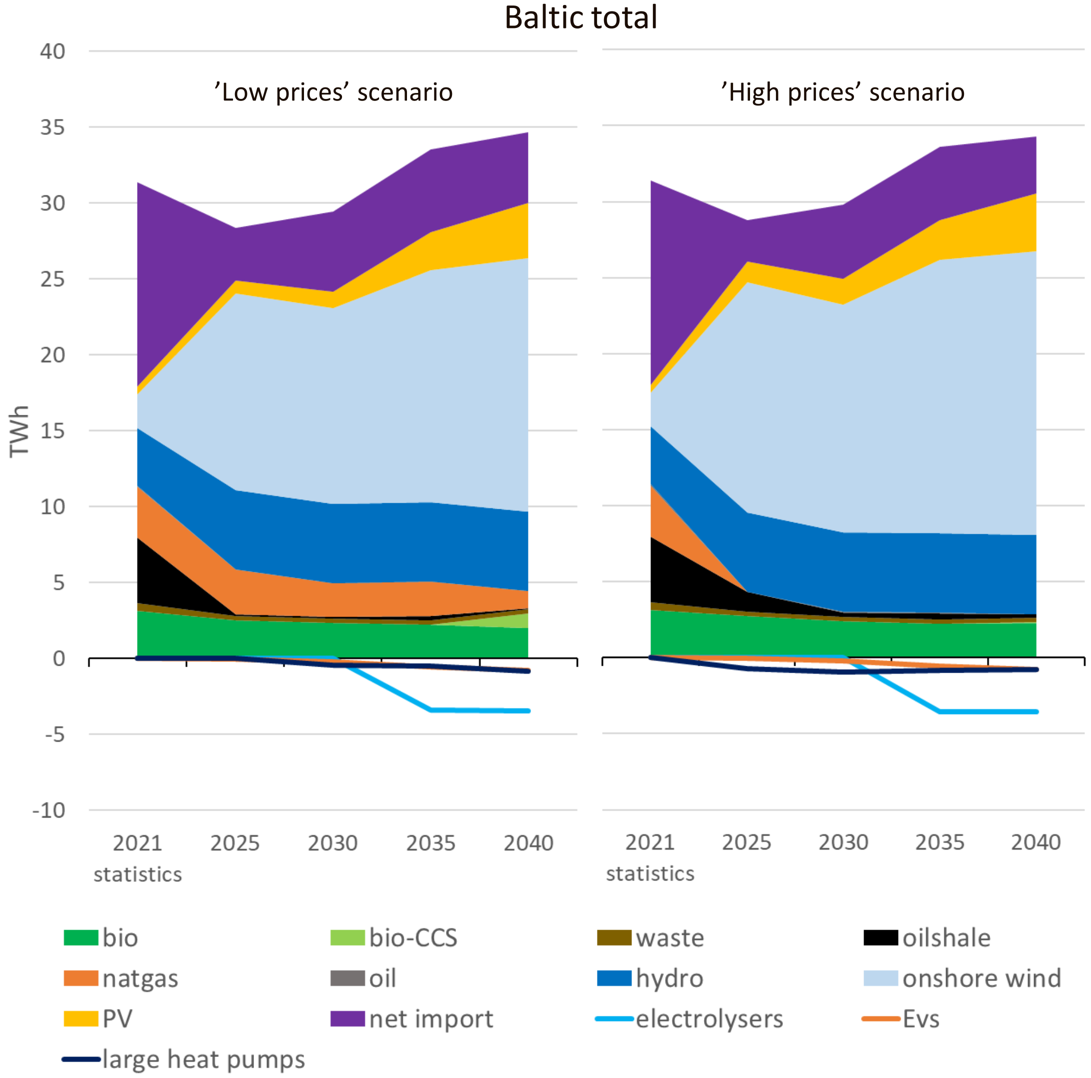
Temporal structure: Pathway multi-year investments



1. Invest optimization run for entire model horizon
   - 45 technology options

2. Individual schedule runs for each model years

Modelled electricity generation mix 2021-2040



1 **Invest optimized results in both scenarios lead to a very high wind share in the Baltic region. Also PV share is considerable.**

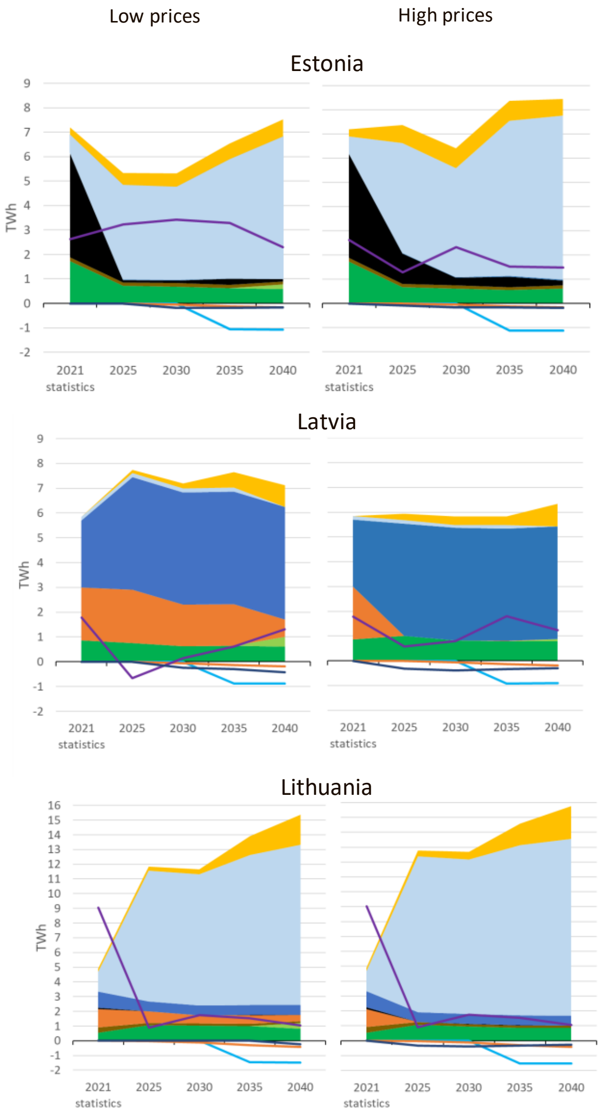
2 Large investments in wind power and PV increase domestic generation share and decrease net imports. **High natural gas prices in ’High prices’ scenario may further increase domestic generation and investment in new domestic capacity.**

3 **’High prices’ scenario speeds up and advance the phaseout of natural gas, but delays the phaseout of oilshale.**

4 Generation by biomass with CCS from 2035 onwards may become feasible, especially in ’Low prices’ scenario (see slide 15 for details).

5 Electrification advances faster in ’High prices’ scenario, but demand impact from transport and district heat remain small. The demand of electricity for hydrogen production is highly uncertain.

Note that due to regional optimization approach the model does not distribute wind power investments equally, but favors investments in Estonia and Lithuania. Note also that 2021 was a below average hydrological year, while the modelled hydro years 2025-2040 represents an above average hydrological year (annual variation was not considered).



Statistics on 2021 electricity generation based on IEA data

Modelled Baltic pathway scenarios with free invest optimization

The Baltic pathway invest modelling 2025-2040 compared two main scenarios:

’LOW PRICES’ SCENARIO

- Natural gas prices **lower to 35 €/MWh after 2025**
- Other fuel prices remain **moderate**
- Electricity trade prices from Nordic European modelling based on assumed fuel prices: average prices from Finland **4-10 €/MWh**, from Sweden **39-53 €/MWh** and from Poland **98-105 €/MWh**
- EU ETS allowance price **80 €/CO_2tonne**

- **Realistic** invest speed of rooftop-PV, energy renovations in buildings and EV expansion

- Biomass growth limitation (1,2 times 2017 level)

’HIGH PRICES’ SCENARIO

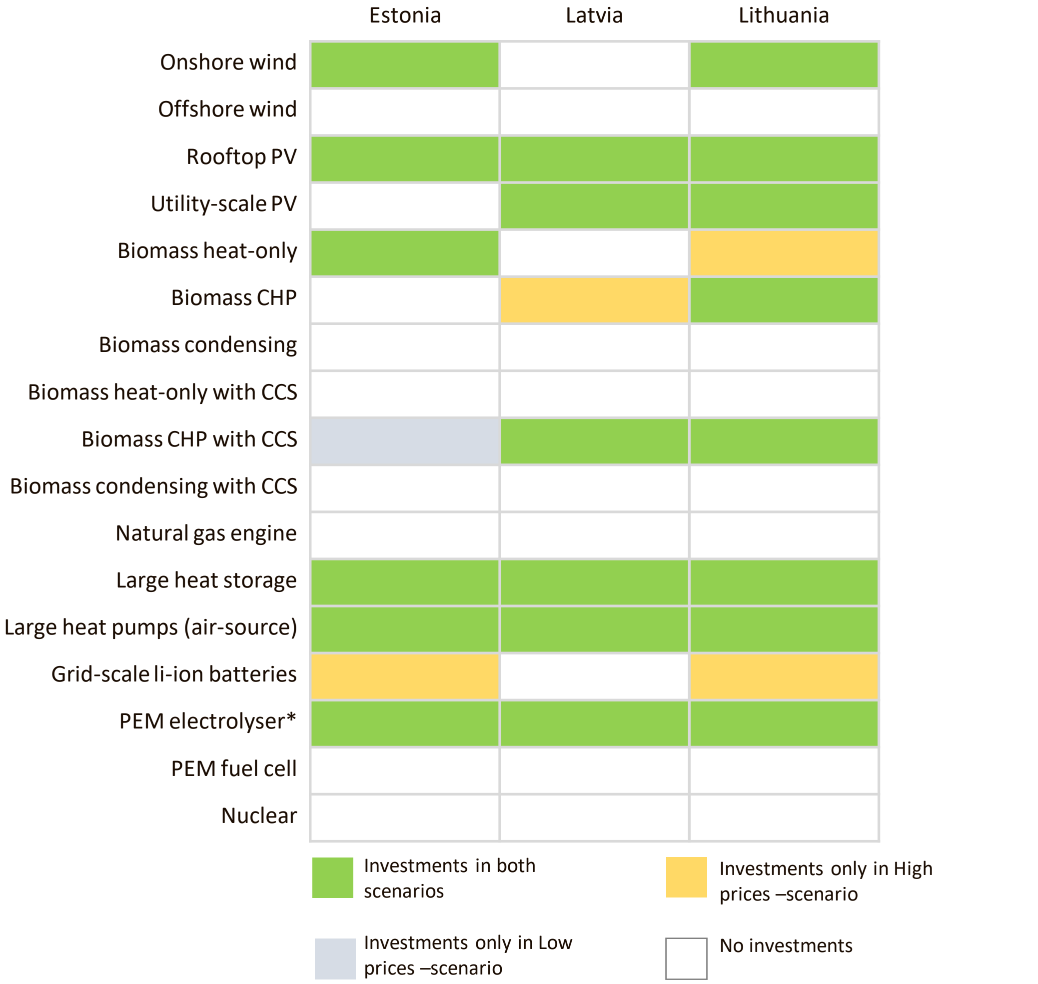
- Natural gas prices **remain at high level 80 €/MWh after 2025**
- Other fuel prices remain **costly**
- Electricity trade prices from Nordic European modelling based on assumed fuel prices: average prices from Finland **5-14 €/MWh**, from Sweden **51-73 €/MWh** and from Poland **114-125 €/MWh**
- EU ETS allowance price **80 €/CO_2tonne**

- **Optimistic** invest speed of rooftop-PV, energy renovations in buildings and **realistic** EV expansion

- Biomass growth limitation (1,2 times 2017 level)

See slide 21 for more detailed assumptions and methodology

Summary of available technologies and invest results:



*with industrial H2 demand assumed