House of
Energy Markets
& Finance

OR-models for the energy transition – coping with uncertainty and heterogeneity

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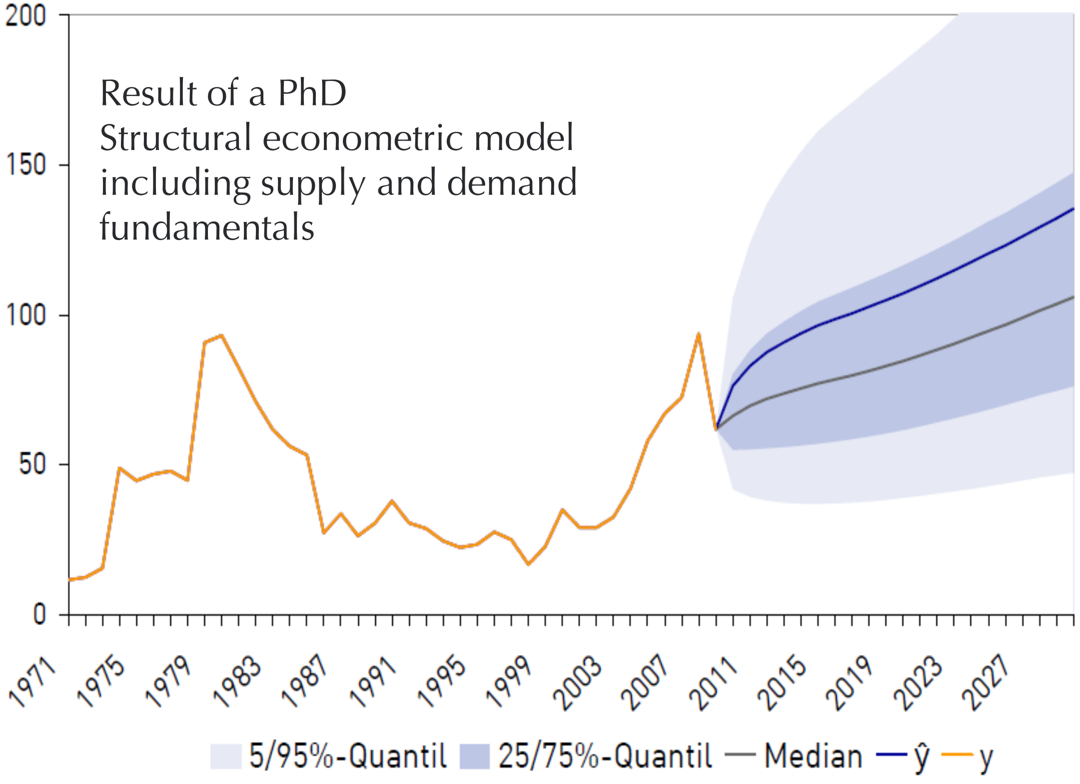
Energy has been a risky business…
… and will remain so:

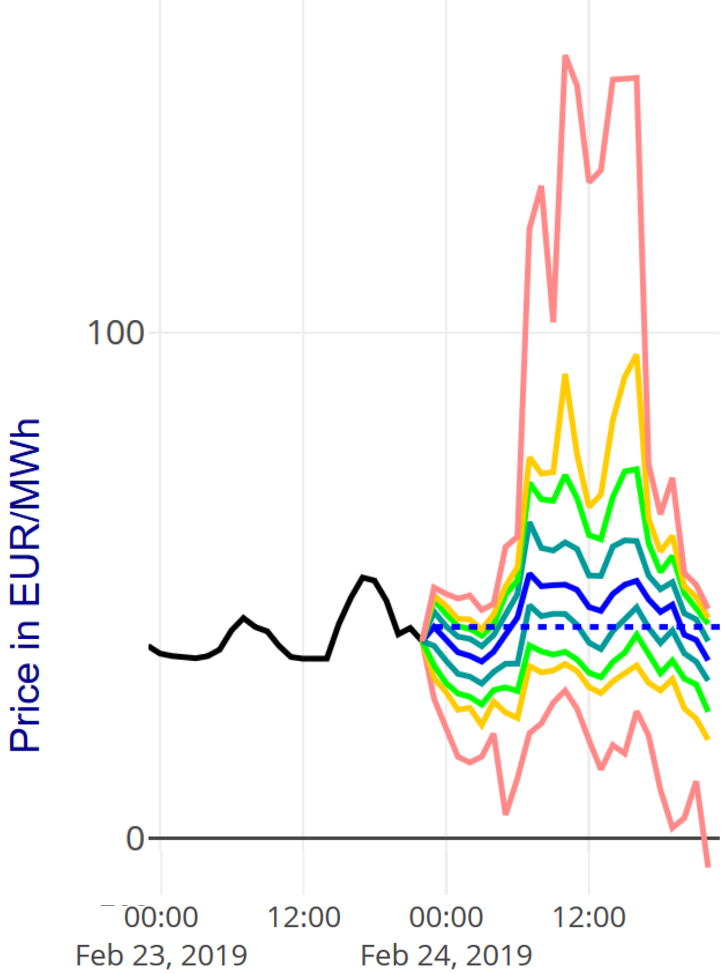
Oil price forecasts from 2009 onwards



Result of a PhD
Structural econometric model including supply and demand fundamentals

Source: Carolin March (2012)

Electricity price forecasts from 2019



Probabilistic forecasts available online on

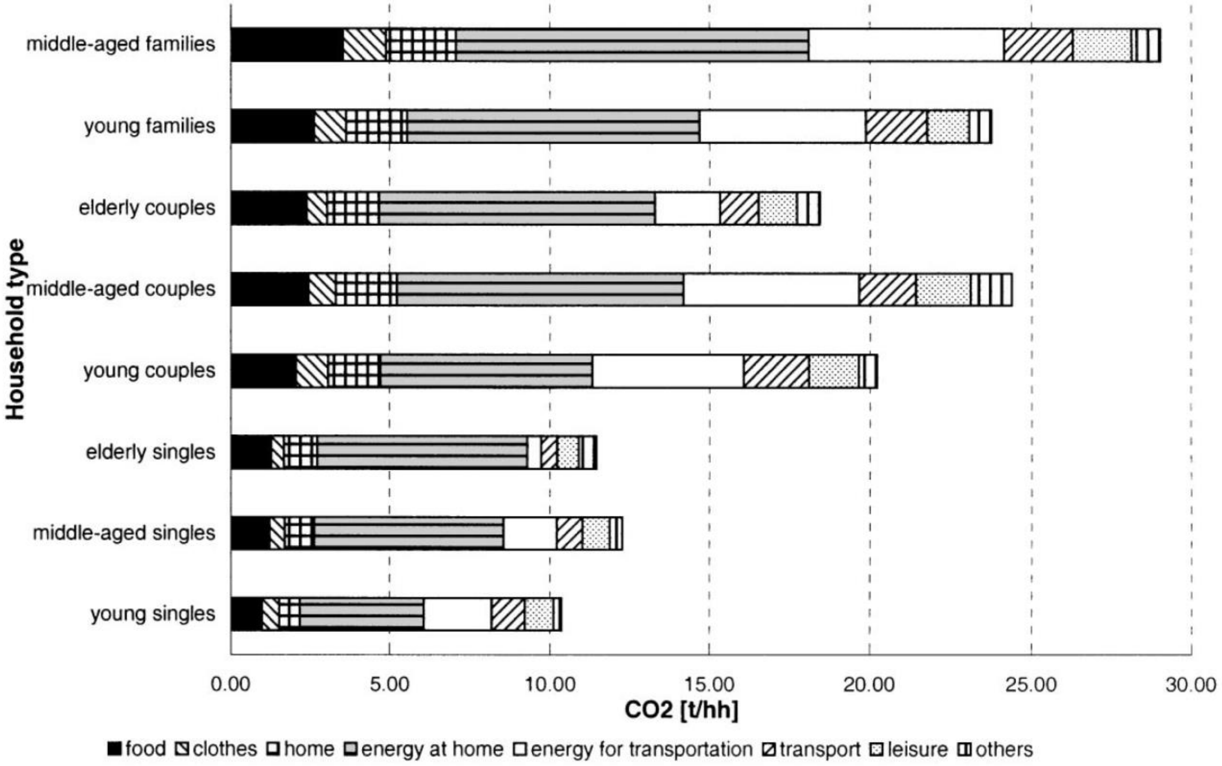
https://www.uee.wiwi.uni-due.de/forschung/prognose-von-strompreisen/

- Short-term forecasts
- Huge uncertainties
  - Red: 1%/99% quantiles
  - Green: 25%/75% quantiles

Source: Florian Ziel (2019)

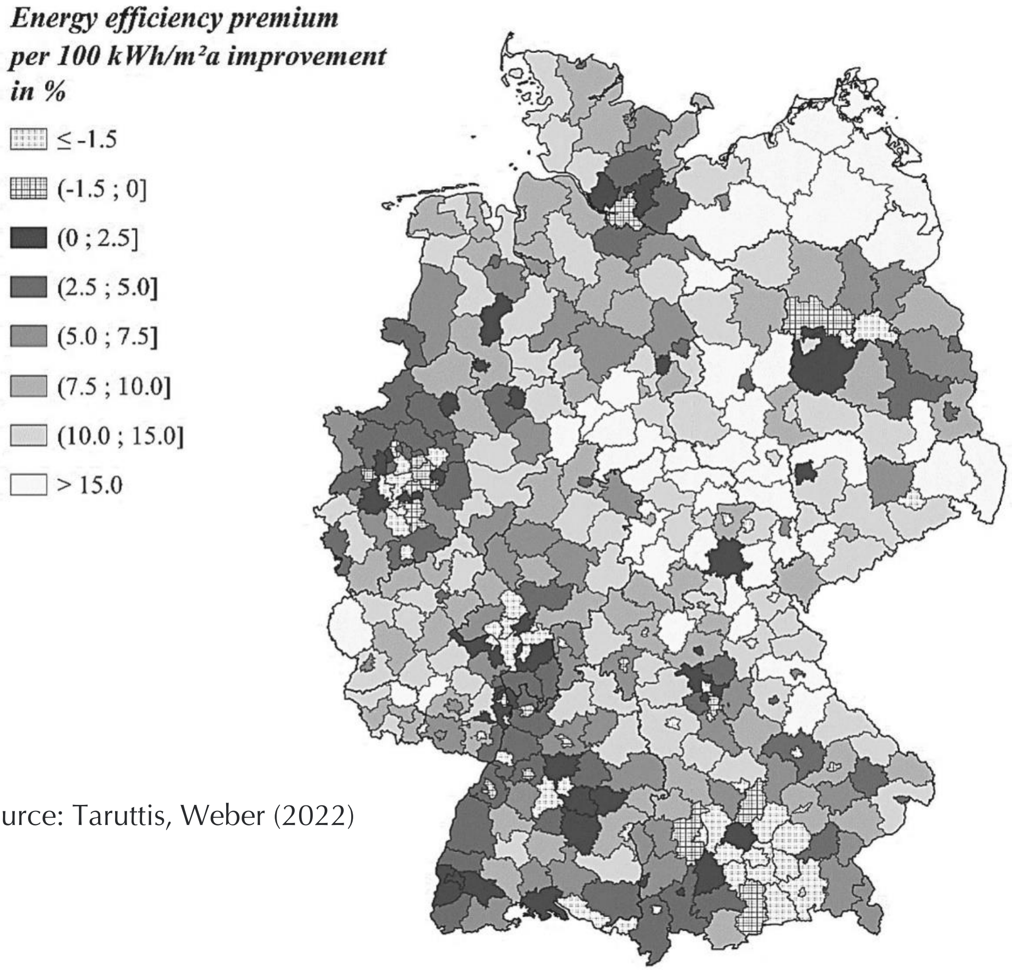
The energy world has always been heterogenous… … and this gets even more important recently

Cumulative CO2 emissions of German households 1990



Source: Weber, Perrels (2000)
Weber (1998)

Premia for energy efficiency in German house prices 2014 - 2018



Source: Taruttis, Weber (2022)

Challenges for decision support and OR

- **Uncertainty and risk** have been around in energy and climate for decades

- Also **heterogeneity** among **households, policy makers and countries** play a role for a long time

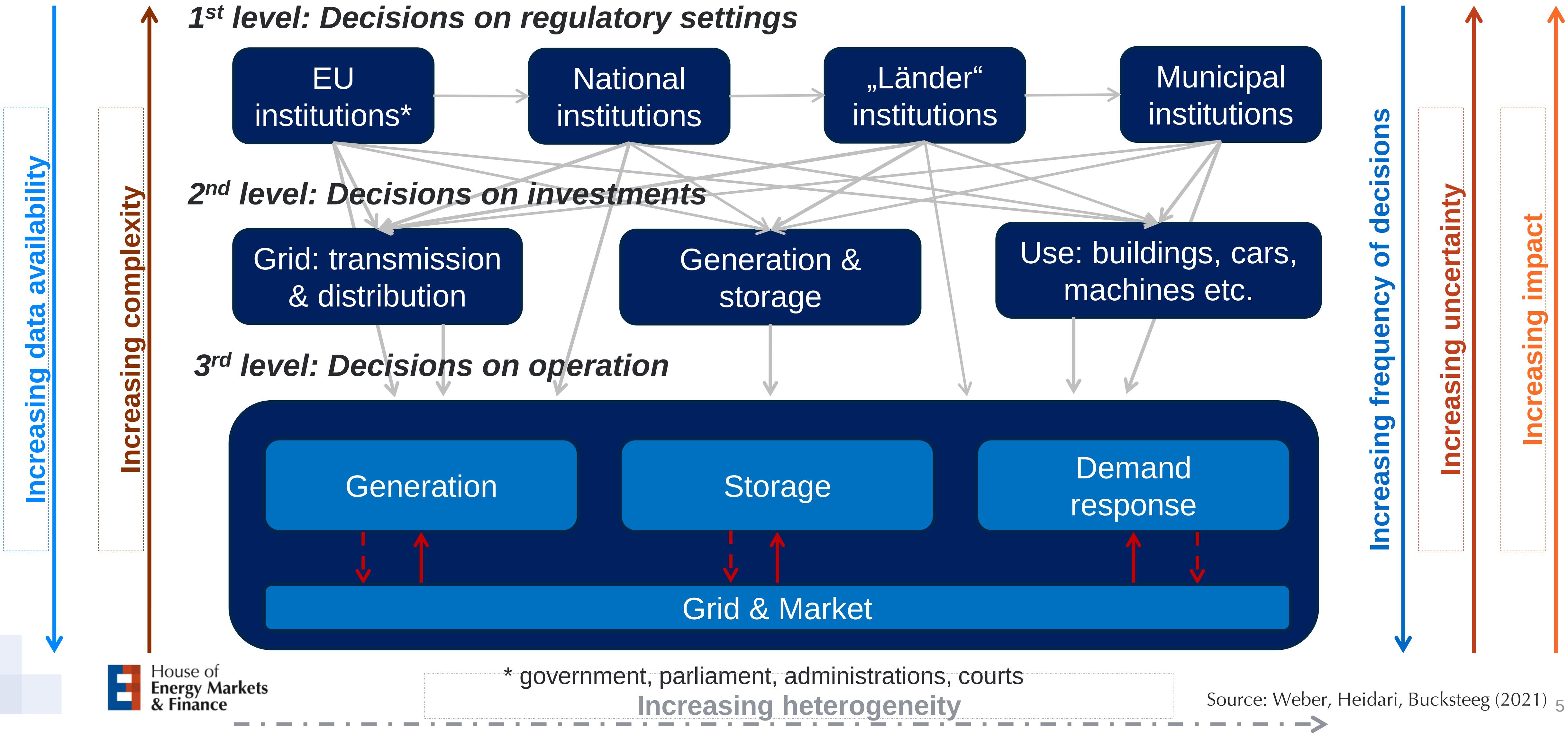
- ➢ Especially uncertainty and risk have also been in the focus of **Operations Research** for years

- ➢ **What OR approaches may be used to cope with them?**
- ➢ **What is useful and for what purposes?**

- ➢ A few examples & some more general thoughts

A major challenge: Multiple and intertwined decision making

Simplified picture: Decisions and decision makers in energy systems



Increasing data availability

Increasing complexity

1st level: Decisions on regulatory settings

- EU institutions*
- National institutions
- „Länder“ institutions
- Municipal institutions

2nd level: Decisions on investments

- Grid: transmission & distribution
- Generation & storage
- Use: buildings, cars, machines etc.

3rd level: Decisions on operation

- Generation
- Storage
- Demand response
- Grid & Market

Increasing frequency of decisions

Increasing uncertainty

Increasing impact

Increasing heterogeneity

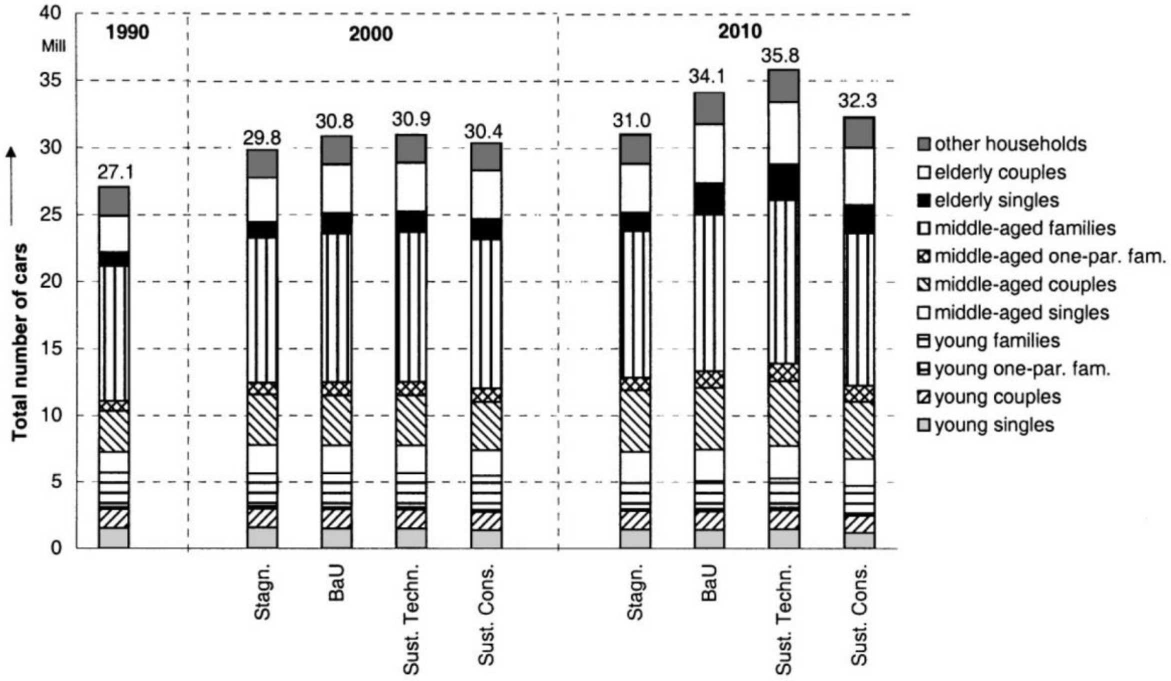
* government, parliament, administrations, courts

Source: Weber, Heidari, Bucksteeg (2021)

An early example: **Weber, Perrels (2000): Modelling lifestyle effects on energy demand and related emissions**

Scenarios

- Distinction of **descriptive and normative scenarios**
  - Two **descriptive scenarios**:
    - **Stagn**ation (or “Tendencial Bleak”)
    - **Business As Usual** (or “Tendencial Rosy”)
  - Two **normative scenarios**:
    - **Sustainability** through **Technological** Breakthrough
    - **Sustainability** through Reflective **Consumption**



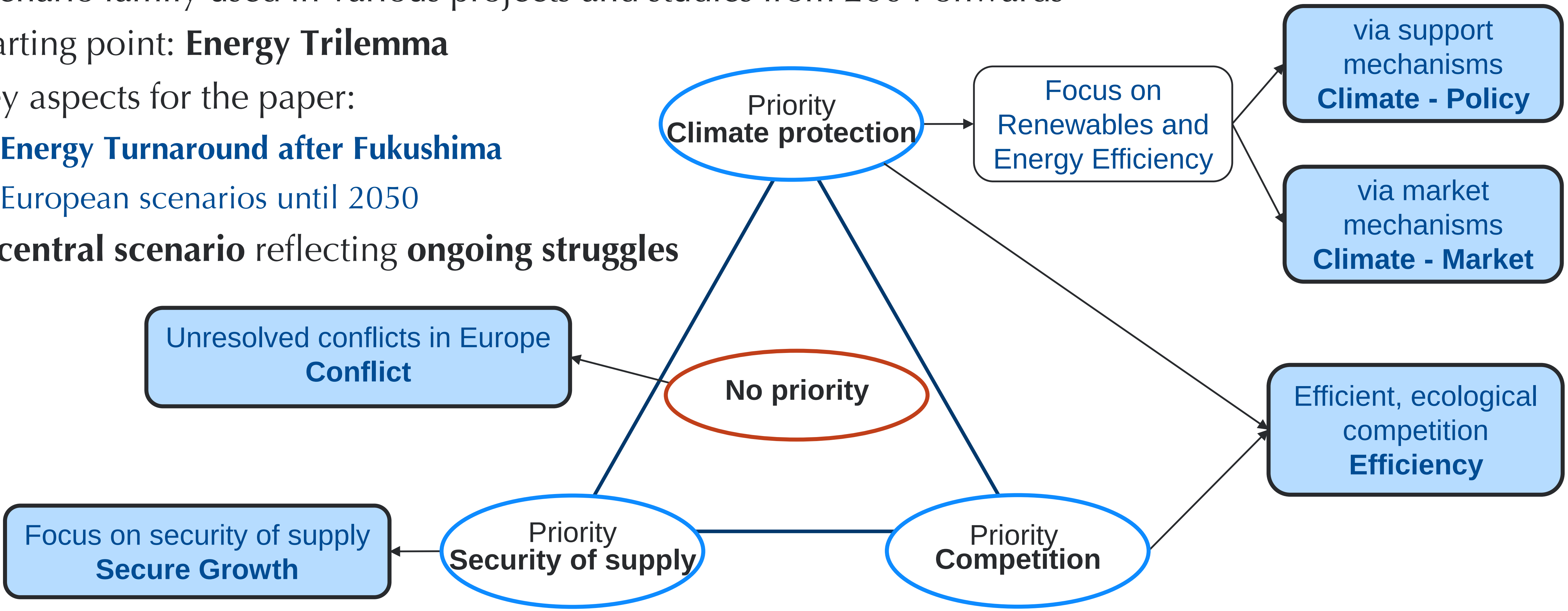
Development of car stock in West Germany

- Lessons learnt: (cf. Weber, Heidari, Bucksteeg 2021; also Weber 2005)
  - **Descriptive scenarios** should reflect
    - multiple **possible futures**
    - **uncertainties** regarding variables **outside the control** of the decision maker
  - **Normative scenarios** should help decision makers
    - to make the best **decisions on variables under their control**
  - **Optimizing decisions not directly under the control** of the decision maker: **Potentially misleading results**

Descriptive General Energy Policy Scenarios:
Spiecker, Weber (2014): The future of the European electricity system and the impact of fluctuating renewable energy – A scenario analysis

Scenarios

- Scenario family used in various projects and studies from 2004 onwards
- Starting point: **Energy Trilemma**
- Key aspects for the paper:
  - **Energy Turnaround after Fukushima**
  - European scenarios until 2050
- A **central scenario** reflecting **ongoing struggles**



Priority
Climate protection

Focus on Renewables and Energy Efficiency

via support mechanisms
Climate - Policy

via market mechanisms
Climate - Market

Efficient, ecological competition
Efficiency

No priority

Unresolved conflicts in Europe
Conflict

Priority
Security of supply

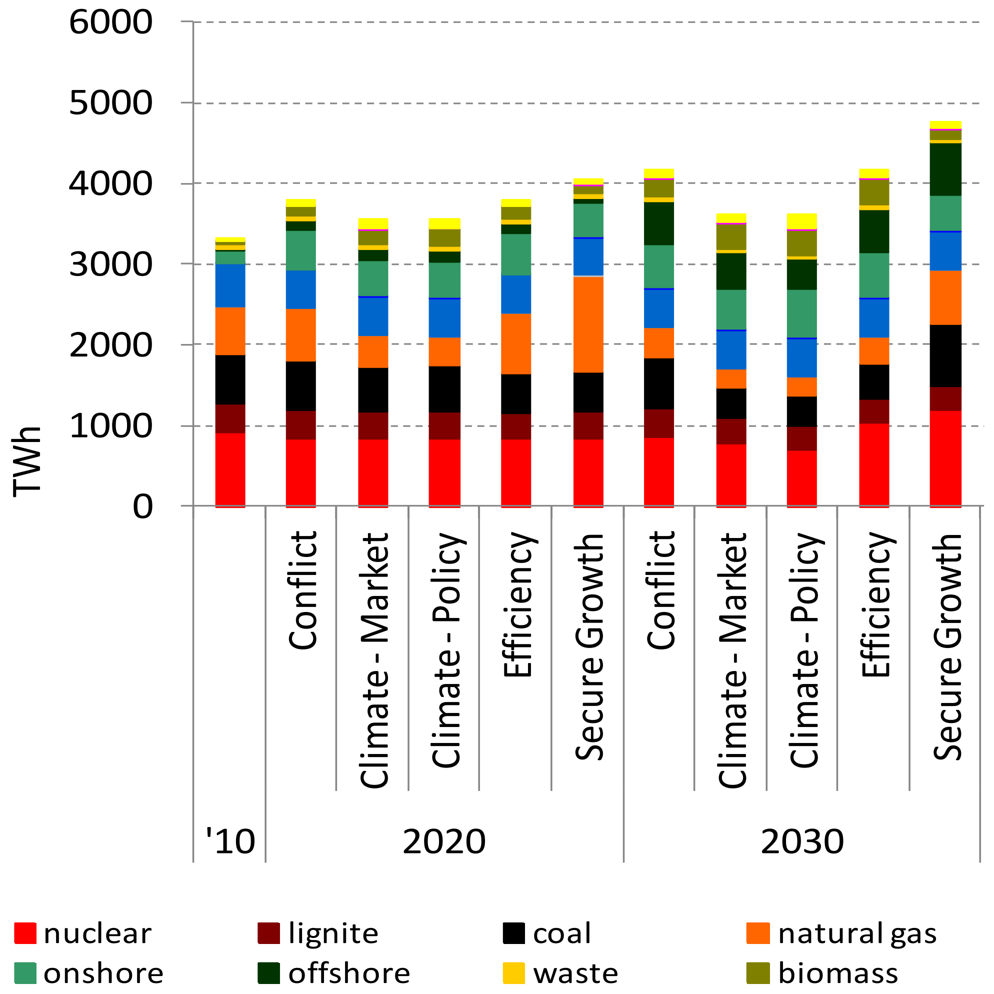
Focus on security of supply
Secure Growth

Priority
Competition

Key scenario assumptions & Scenario results: electricity production development

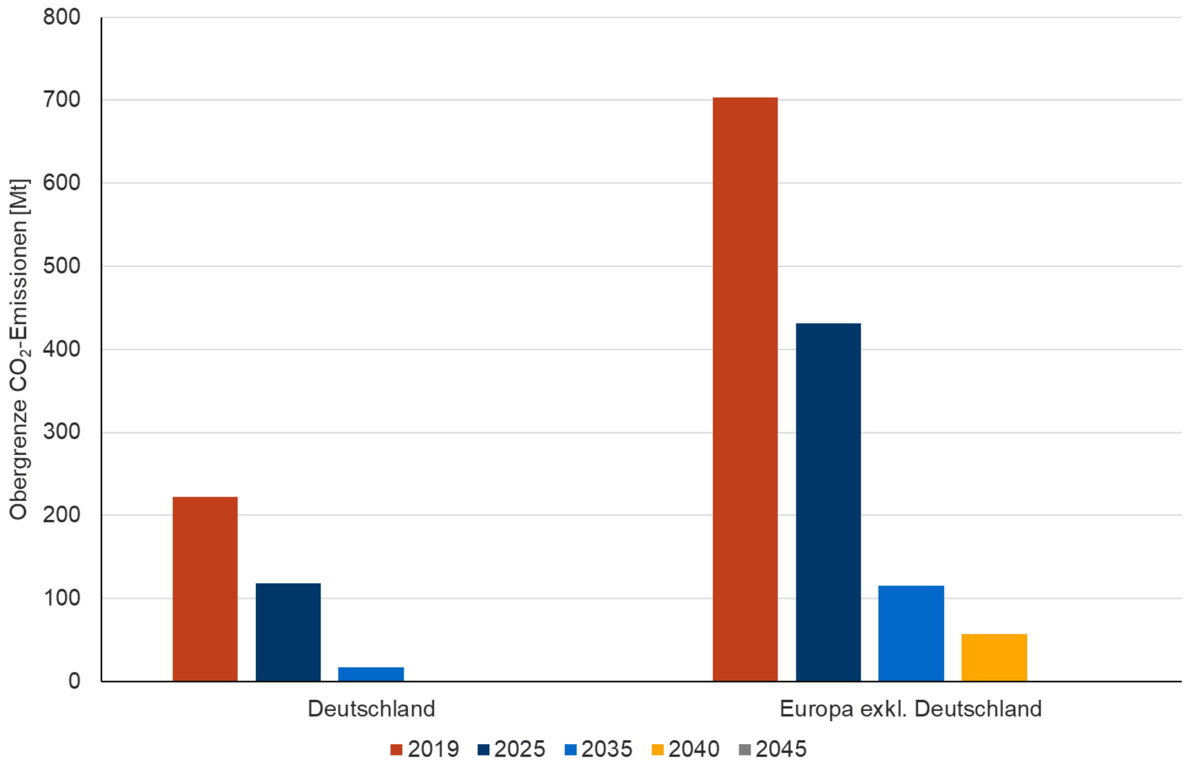
Scenarios

	Conflict	Climate - Policy	Climate - Market	Efficiency	Secure Growth
Demand	mid	low	low	mid	high
Politically driven RES development	mid	high	high	mid	low
Fuel prices	mid	high	high	high	low
CO2-reduction compared to 1990	60%	95%	95%	80%	30%
Acceptance of nuclear power	low	low	low	high	high
RES policy change [year]	**2030**	**(-)**	**2020**	**2030**	**2040**



Normative scenario: **Radek et al. (2022): Final report for the German regulator BNetzA (Gutachten NEMO VIII, Los 3) – so-called Paris scenario**

- Main objective:
  Achieve climate neutrality at lowest cost in 2045 for Germany and in 2050 for Europe as a whole
- Modelling of electricity, (district) heat and hydrogen in the context of the electricity grid development plan
- ➢ At the time not the central scenario
  - ➢ Study was mandated in 2020 before the constitutional court mandated the German government to provide detailed emission targets for future years
- ➢ But intended to inform the regulator
- ➢ CO_2 emission limits were derived using a carbon budget approach



CO_2 emission constraints for Germany and Europe (w/o Germany) in a Paris scenario

Radek et al. (2022): Final report for the German regulator BNetzA (Gutachten NEMO VIII, Los 3) – so-called Paris scenario
Selected results

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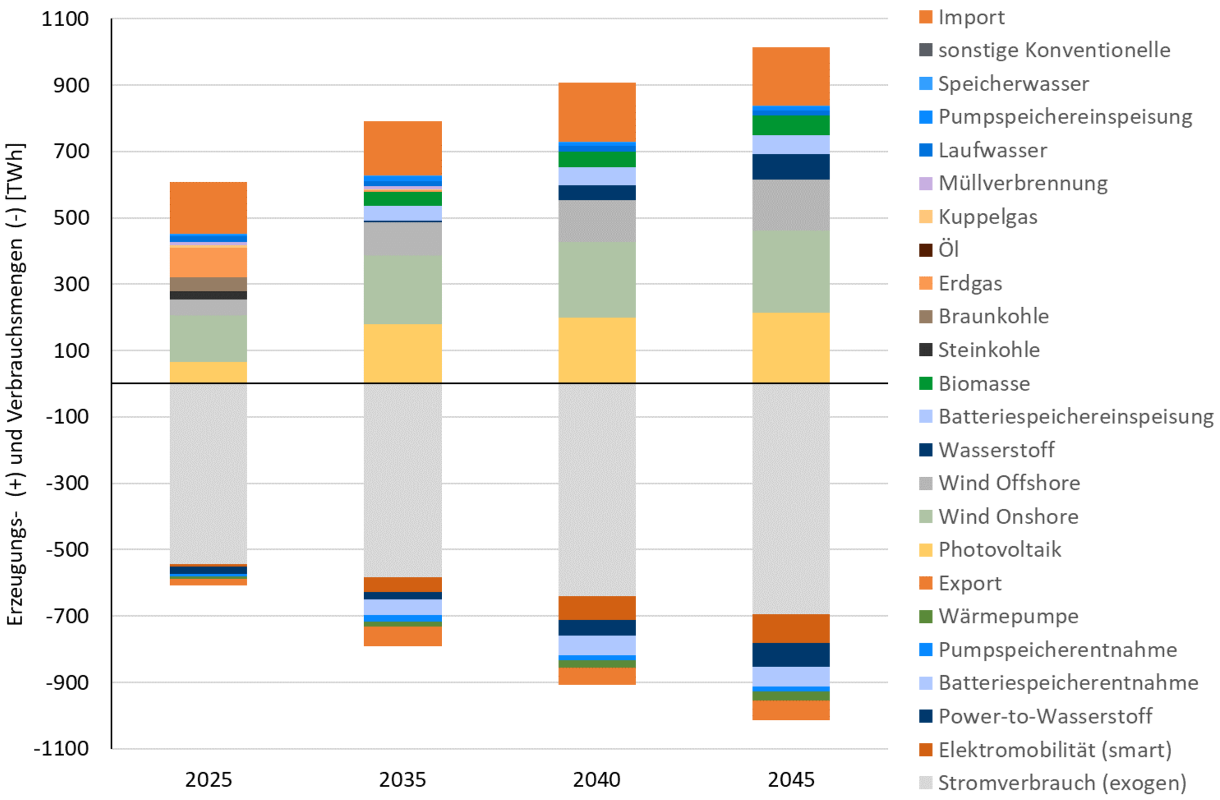
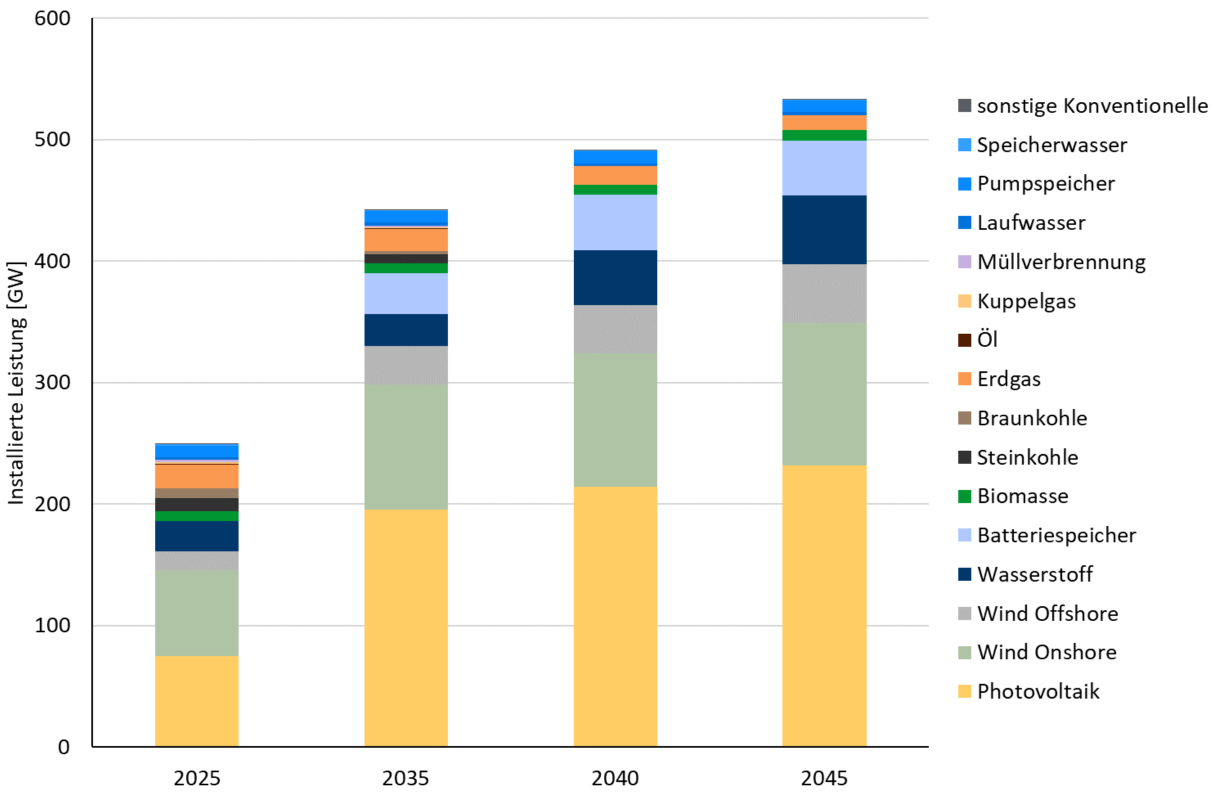
Scenarios

Electricity supply and demand (annual values)



Installed capacities generation and storage



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The WILMAR-JMM Model: Stochastic Optimization Model to Study the Operational Impacts of High RES penetration

Key ingredients: **Three-stage stochastic program**

$$\min \begin{cases} \sum\limits_{s\in S} \pi_S \sum\limits_{t\in T} \sum\limits_{i\in I} c_i^{Operation} (P_{i,t}^{Day} + P_{i,s,t}^{+} - P_{i,s,t}^{-}) \\ + \sum\limits_{s\in S} \pi_S \sum\limits_{t\in T} \sum\limits_{i\in I} c_i^{Start-up} (V_{i,s,t}^{Onl}, V_{i,s,t-1}^{Onl}) \\ - \sum\limits_{s\in S} \pi_S \sum\limits_{i\in I} c^{Opp}_{i,s,t^{End}} (V_{i,s,t^{End}}^{Onl}, K_{i,s,t^{End}}^{Sto}) \\ + \sum\limits_{s\in S} \pi_S \sum\limits_{t\in T} \sum\limits_{r\in R} (l^L Q_{r,s,t}^{INT} + l^{SP} Q_{r,s,t}^{SPIN} + l^{RP} Q_{r,s,t}^{RP}) \\ + \sum\limits_{t\in T} \sum\limits_{r\in R} l^L Q_{r,t}^{DAY} \end{cases} \tag{1}$$

objective function

s.t

$$\sum_{i\in I_r} P_{i,t}^{Day} + p_{r,t}^{ExpW} + \sum_{\bar{r}\in R} ((1 - c_{r,\bar{r}}^{Loss}) \cdot R_{r,\bar{r},t}^{Day}) = \sum_{i\in I_r^{Stor}} W_{i,t}^{Day} + \sum_{\bar{r}\in R} R_{\bar{r},r,t}^{Day} + d_{r,t}^{Exp} - Q_{r.t}^{DAY} \quad \forall t \in T^{Day};\ r \in R \tag{2}$$

day-ahead energy balance

$$\sum_{i\in I_r} (P_{i,s,t}^{+} - P_{i,s,t}^{-}) + \sum_{\bar{r}\in R} ((1 - c_{r,\bar{r}}^{Loss})(R_{r,\bar{r},s,t}^{+} - R_{r,\bar{r},s,t}^{-})) + \sum_{i\in I_r^{Stor}} (W_{i,s,t}^{-} - W_{i,s,t}^{+}) - P_{r,s,t}^{-,W} = \sum_{\bar{r}\in R} (R_{\bar{r},r,s,t}^{+} - R_{\bar{r},r,s,t}^{-})) + p_{r,t}^{ExpW} - \left(p_{r,s,t}^{UpdW} - P_{r,t}^{SpW}\right) - \left(d_{r,t}^{Exp} - d_{r,s,t}^{Upd}\right) - Q_{r,s,t}^{INT} \quad \forall\ s \in S;\ t \in T;\ r \in R \tag{3}$$

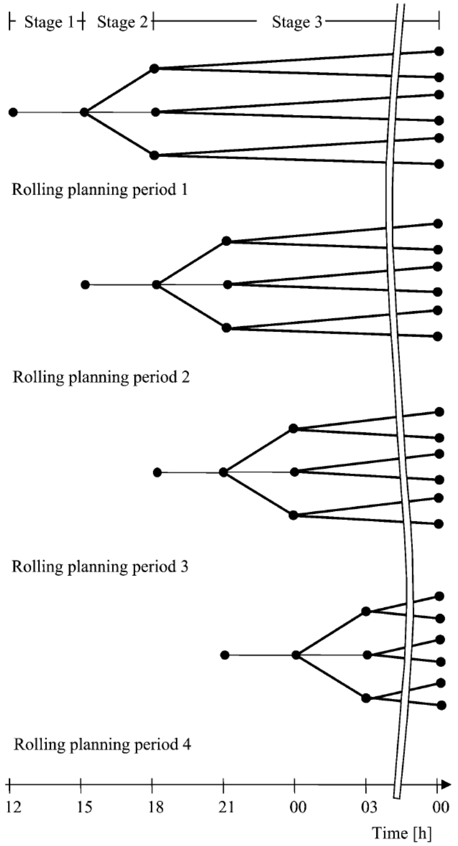
intraday energy balance

$$\sum_{i\in I_r} P_{i,s,t}^{Sp,+} + \sum_{i\in I_r^{Stor}} W_{i,s,t}^{Sp,+} + P_{r,t}^{SpW} \geq d_{r,s,t}^{Sp,+} - Q_{r,s,t}^{SPIN} \quad \forall s \in S;\ t \in T;\ r \in R \tag{4}$$

reserve provision

& many more equations …

Rolling Planning



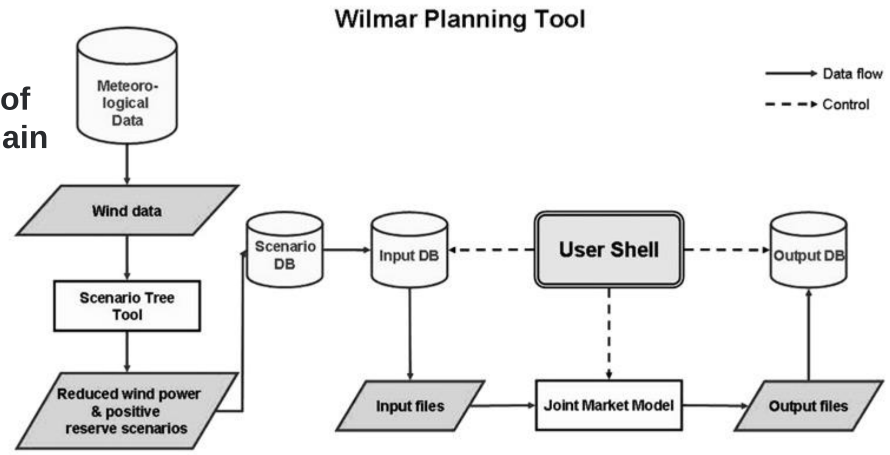
detailed model formulation cf. Weber et al. 2009)

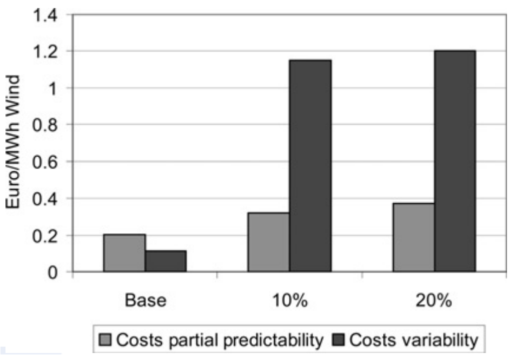
- ➢ **Focus on operation of future energy systems with high shares of renewables**

Applications of the WILMAR-JMM model

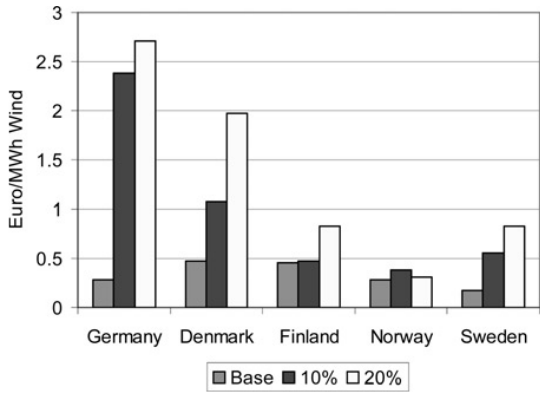
Meibom, Weber, Barth, Brand (2009): **Operational costs induced by wind energy**

Overview of the toolchain





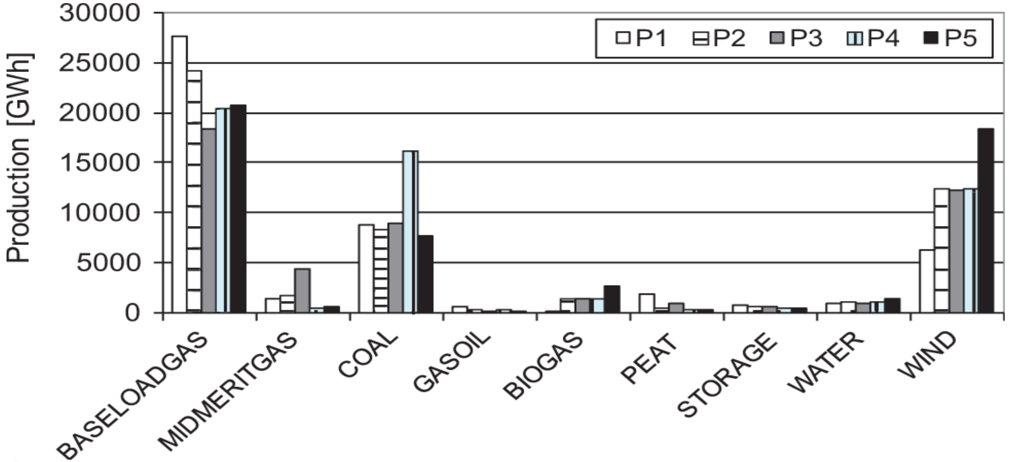
Increase in system operation costs due to variability and forecast errors of wind energy



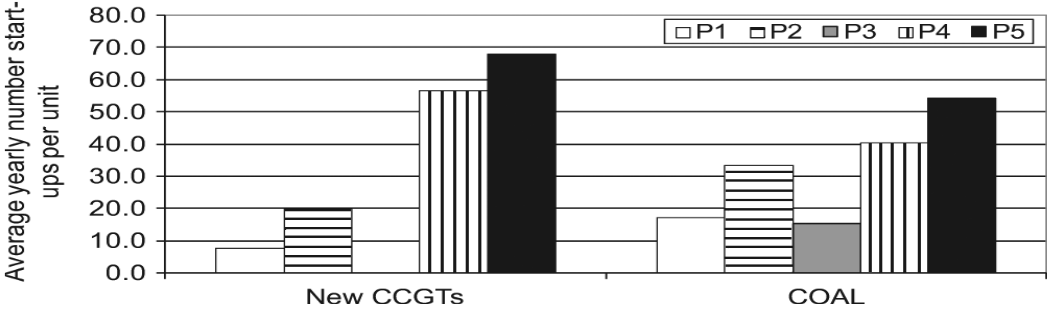
Increase in system operation costs per country

Meibom *et. al.* (2011): **Operational impacts of high wind penetrations in Ireland**

Electricity generation per technology for 5 different portfolios



Average number of start-ups per technology and portfolio



Use of wind energy for provision of reserves

	P1	P2	P3	P4	P5
Duration [h]	0	17	62	4	239
Average/installed wind capacity [%]	0	0.4	0.4	0.1	0.4

The E2M2s model: Modelling future energy scenarios with fluctuating renewables and endogenous capacity expansion

Key ingredients: **Linear program with operational and fix cost** & **Recombining tree of renewable realizations**

objective function: total cost

$$TC = \sum_{n}\sum_{u}\sum_{t}\sum_{n}(d_t f_t \psi_{s(t),n} (OC_{r,u,t,n} + SC_{r,u,t,n} + FC_{r,u,t,n}))$$

$$OC_{r,u,t,n} = \frac{p^{FUEL}_{r,u,t} + \varepsilon^{CO2}_{u} p^{CO2}_{t}}{\eta^{m}_{u}}(P_{r,u,t,n} - l_u L^{onl}_{r,u,t,n}) + \frac{p^{FUEL}_{r,u,t} + \varepsilon^{CO2}_{u} p^{CO2}_{t}}{\eta^{0}_{u}} l_u L^{onl}_{r,u,t,n} + c^{oth,op}_{u} P_{r,u,t,n}$$

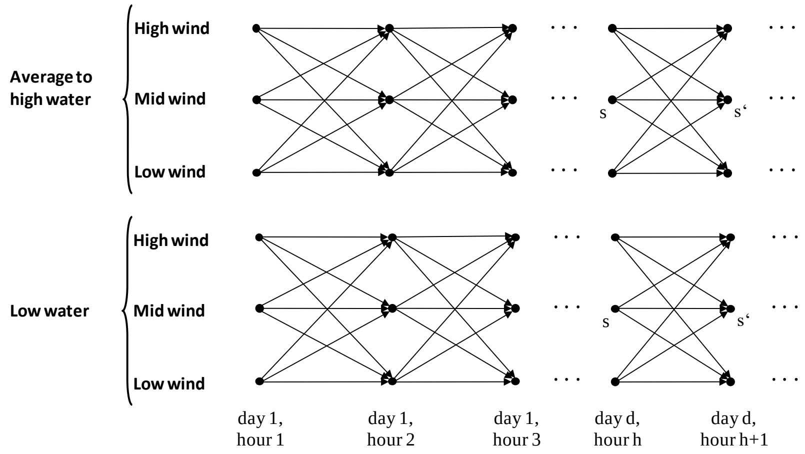
operating fuel costs considering part-load efficiency

$$SC_{r,u,t,n} = c^{stu}_{u} L^{stu}_{r,u,t,n}$$

start-up cost

$$FC_{r,u,t,n} = a(i, T^{life}_{u}) c^{inv}_{u} L^{new}_{r,u,t} + c^{oth,fix}_{u} L_{r,u,t}$$

fix cost



operating capacity and generation

$$L^{onl}_{r,u,t,n} \le \rho_{u,t} L_{r,u,t}$$

capacity online limited by installed capacity

$$\left.\begin{aligned} P_{r,u,t,n} &\ge l_u L^{onl}_{r,u,t,n} \\ P_{r,u,t,n} &\le L^{onl}_{r,u,t,n} \end{aligned}\right\}$$

upper and lower bounds on generation

$$L^{stu}_{r,u,t,n} \ge \frac{1}{\sum_{n'} \psi_{s(t-1)\to s(t),n'\to n}} \sum_{n'} \tau_{s(t-1)\to s(t),n'\to n} \left(L^{onl}_{r,u,t,n} - L^{onl}_{r,u,t-1,n'}\right)$$

capacity started up

storage operation

$$H_{r,u,t,n} \le \frac{1}{\sum_{n'} \psi_{s(t-1)\to s(t),n'\to n}} \sum_{n'} \left(\psi_{s(t-1)\to s(t),n'\to n} H_{r,u,t-1,n-1}\right) - P_{r,u,t,n} + W_{r,u,t,n} + \eta^{cyc}_{u} P^{pum}_{r,u,t}$$

daily storage

$$P^{pum}_{r,u,t,n} \le \rho_{u,t} L^{pum}_{r,u,t}$$

$$H_{r,u,m,n_H} \le H_{r,u,m-1,n_H} - \sum_{t\in m}\sum_{n\in n_H} \left(d_t f_t \psi_{s(t),n} \left(P_{r,u,t,n} + W_{r,u,t,n}\right)\right)$$

seasonal storage

reserve and energy balances

$$\sum_{u} \left(L^{onl}_{r,u,t,n} - P_{r,u,t,n}\right) \ge \varsigma^{res}_{r} \sum_{u} P_{r,u,t,n}$$

spinning reserve

$$\sum_{u} \left(\rho_{u,t} L_{r,u,t} - L^{onl}_{r,u,t,n}\right) \ge L^{res}_{r}$$

standing reserve

$$E_{r\to r',t,n} \le C_{r\to r',t}$$

transmission constraints

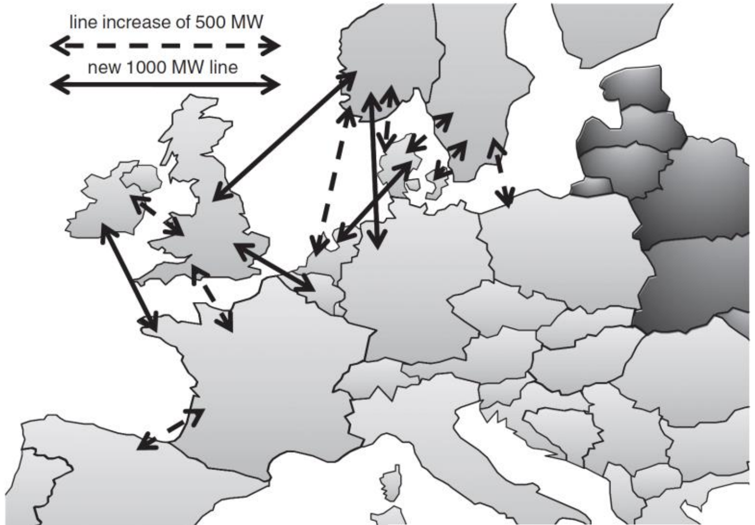
$$\sum_{u} P_{r,u,t,n} + \sum_{r'} (E_{r'\to r,t,n} - E_{r\to r',t,n}) = D_{r,t} + \sum_{u} P^{pum}_{r,u,t,n}$$

energy balance

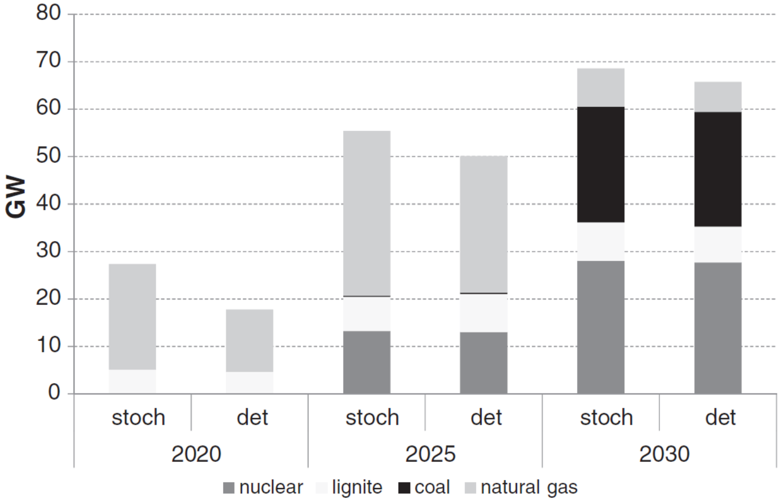
Application of the E2M2s model:
Spiecker, Vogel, Weber (2013): Evaluating interconnector investments in the north European electricity system considering fluctuating wind power penetration

Stochastic optimization

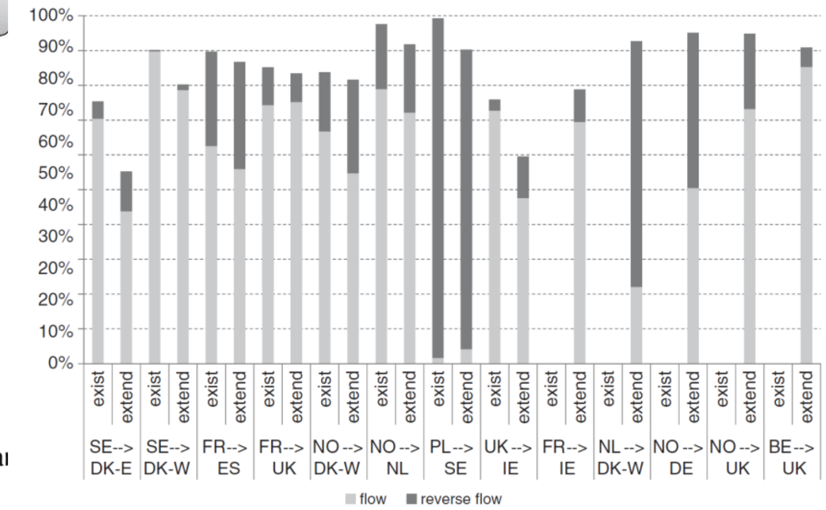
Geographical scope and considered line investments



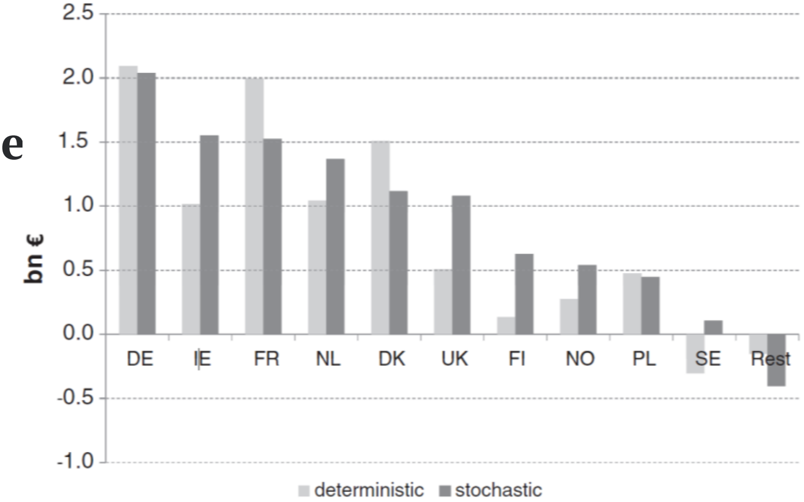
Impact of stochastic modelling on generation investment



Utilization of selected lines – with and without extension in 2020



Discounted welfare gains on a per country basis (base year 2020)



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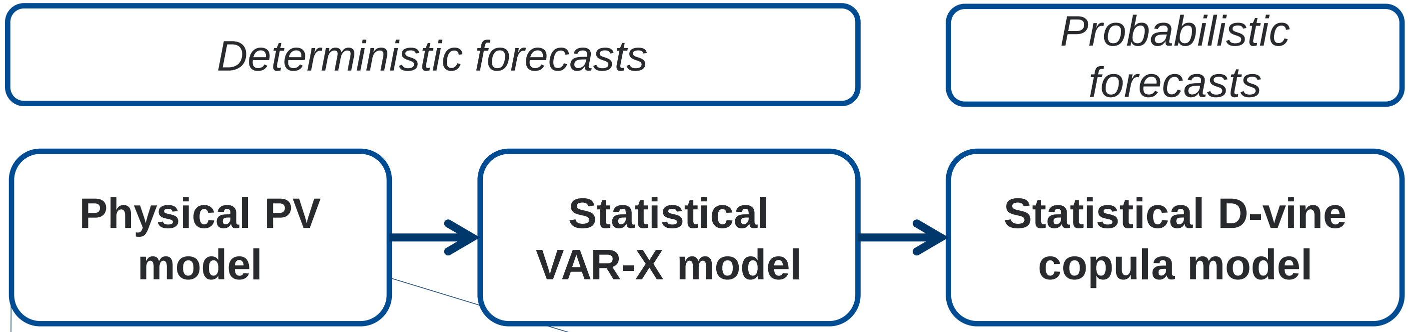
Multivariate stochastic infeed timeseries
Schinke-Nendza et al. (2021): Probabilistic forecasting of photovoltaic power supply

Method: Hybrid model for multivariate probabilistic forecasts



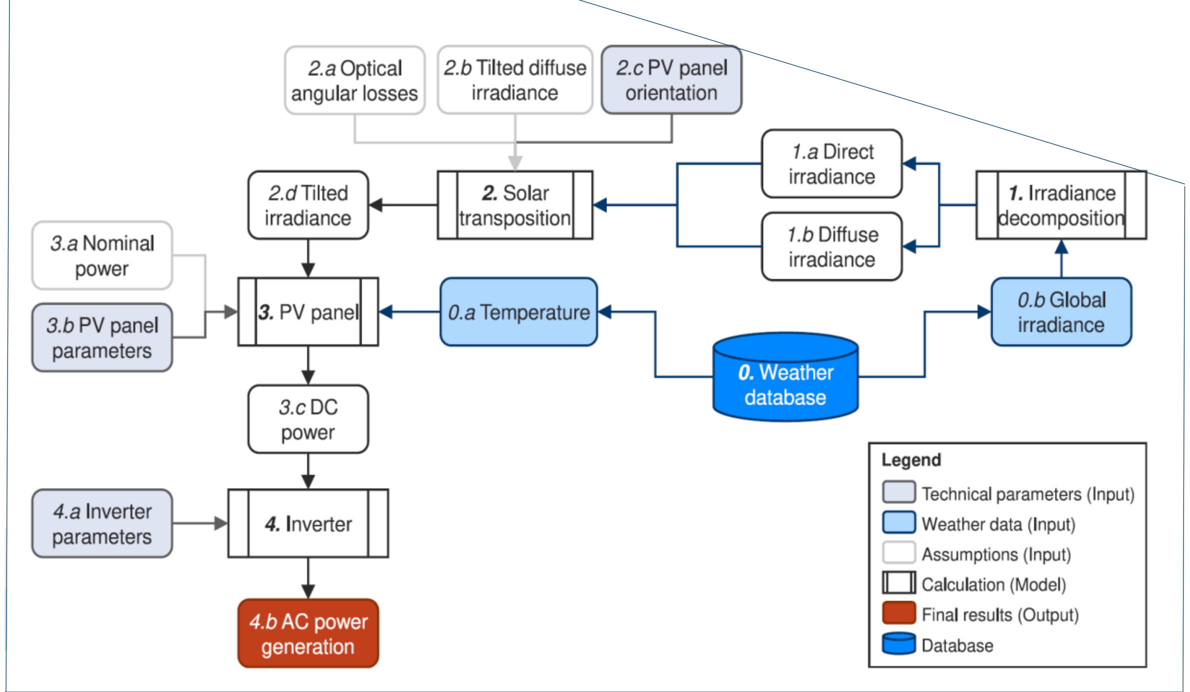
Deterministic forecasts

Probabilistic forecasts

Physical PV model

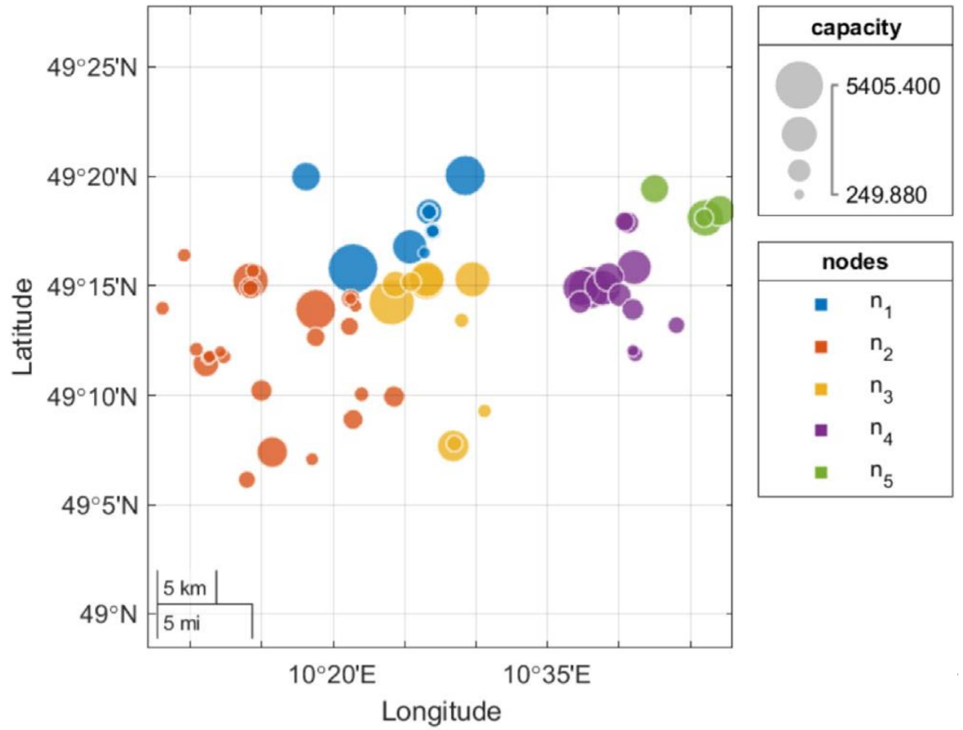
Statistical VAR-X model

Statistical D-vine copula model



Application study

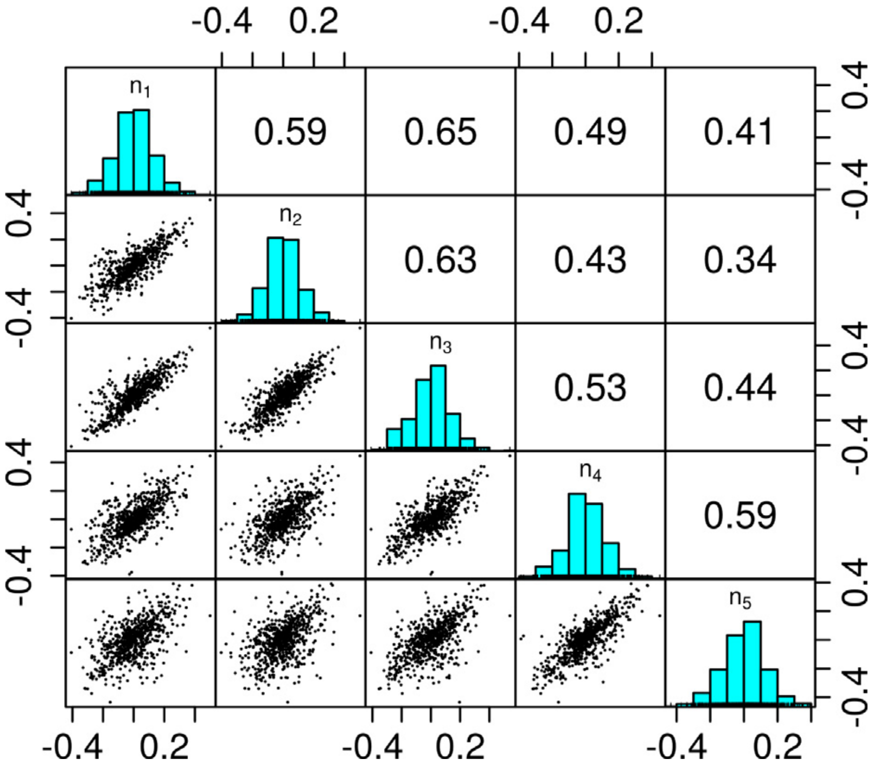
- high voltage power system of N-ERGIE Netz GmbH in the south of Germany
- 53 utility-scale PV units selected
- connected to five nodes



Multivariate stochastic infeed timeseries

Schinke-Nendza et al. (2021):
Probabilistic forecasting of photovoltaic power supply - Results

Forecasts errors physical model (PM-B):
histogram (diag.), scatter plots (bottom left),
Kendall's tau (top right)



Overall model performance:
Energy score (ES) and variogram-based scores (VS1 and VS2) of intraday forecasts

Deterministic model	Probabilistic m.	ES	VS1	VS2
PM-VARX	D-vine	2.04	3.06	2.76
PM-VARX	MVN	2.09	3.11	2.80
PM-VARX	UVN	2.15	3.56	3.22
VARX-B	D-vine	2.10	3.08	2.78
VARX-B	MVN	2.18	3.12	2.81
VARX-B	UVN	2.23	3.62	3.28
PM-B	D-vine	2.22	3.59	3.25
PM-B	MVN	2.38	3.86	3.49
PM-B	UVN	2.39	4.01	3.62

Key insights regarding stochastic optimization

- Uncertainty is almost ubiquitous in energy and climate modelling
- Stochastic optimization is a conceptually attractive option to cope with uncertainties

But:

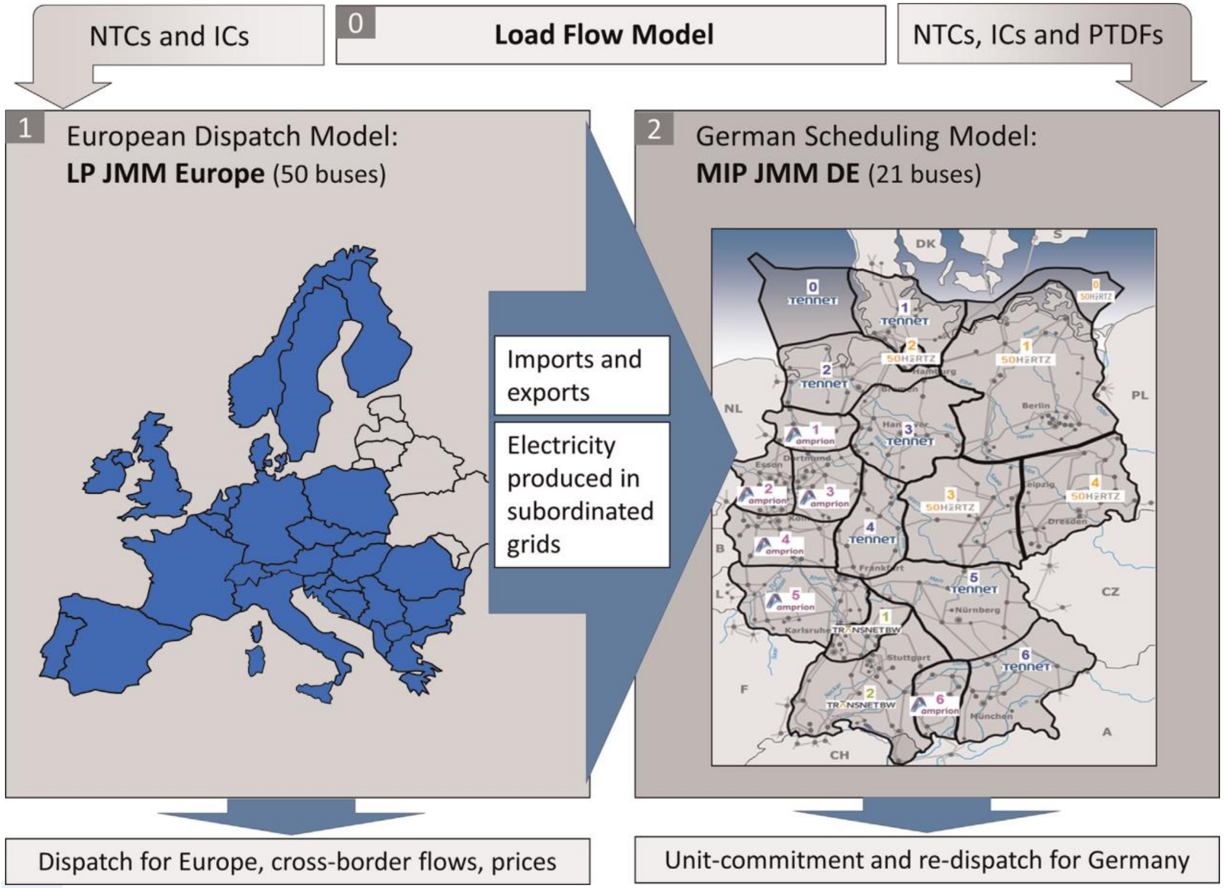
- There are too many uncertainties to put them into one model
- Computational complexity increases exponentially both in the number of stochastic factors and the stages (timesteps) in the stochastic program
- Modelling and parametrizing uncertainties is by itself challenging

➢ There is still **plenty to be researched** regarding **tailored approaches** to cope with **key uncertainties**

First application example
Trepper, Bucksteeg, Weber (2015): Market splitting in Germany – New evidence from a three-stage numerical model of Europe

Policy Advice

Overall approach



NTCs and ICs

0 **Load Flow Model**

NTCs, ICs and PTDFs

1 European Dispatch Model:
LP JMM Europe (50 buses)

Imports and exports

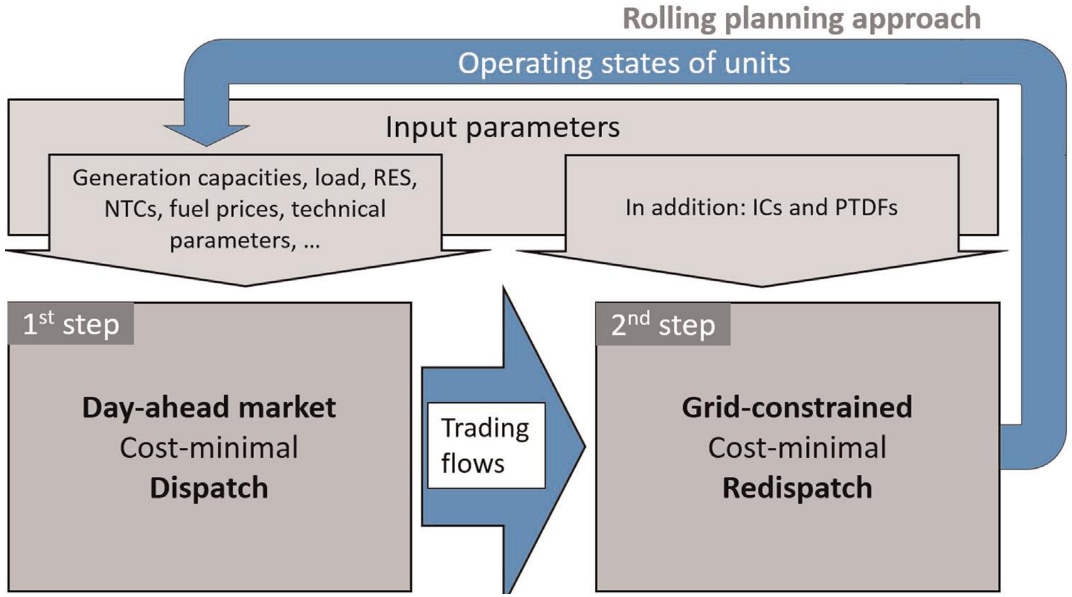
Electricity produced in subordinated grids

2 German Scheduling Model:
MIP JMM DE (21 buses)

Dispatch for Europe, cross-border flows, prices

Unit-commitment and re-dispatch for Germany

Two-stage optimization with rolling planning for German scheduling and redispatch



Rolling planning approach

Operating states of units

Input parameters

Generation capacities, load, RES, NTCs, fuel prices, technical parameters, …

In addition: ICs and PTDFs

1st step

Day-ahead market
Cost-minimal
Dispatch

Trading flows

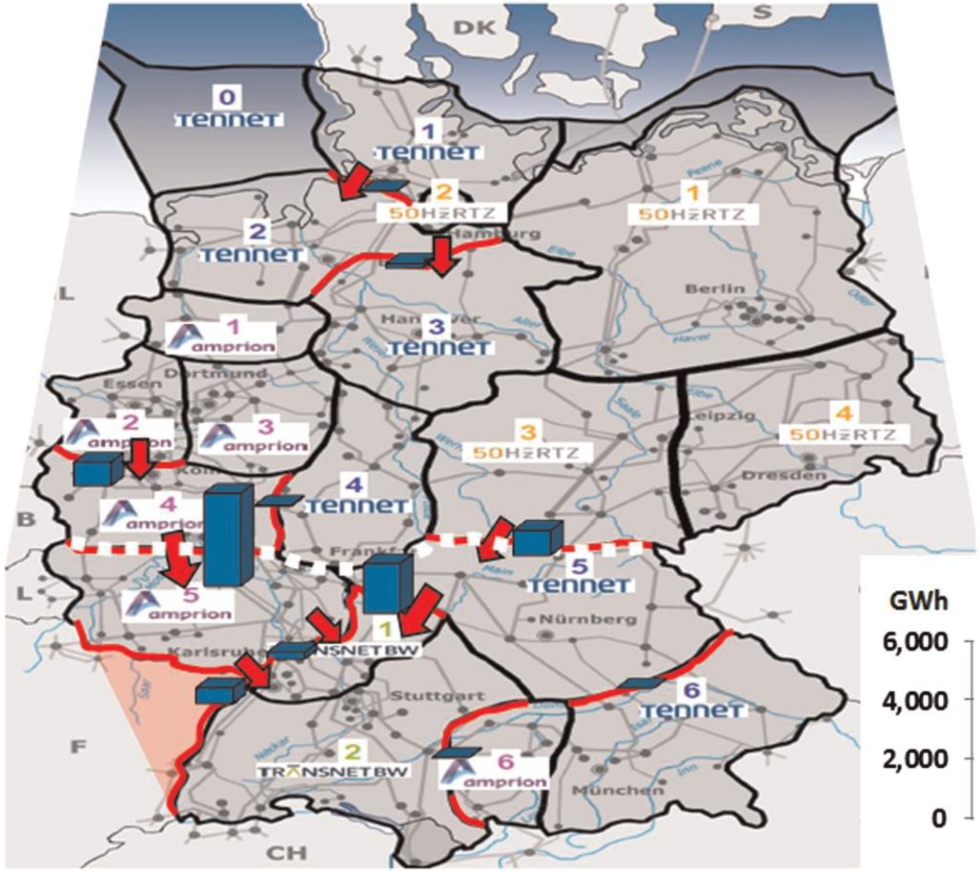
2nd step

Grid-constrained
Cost-minimal
Redispatch

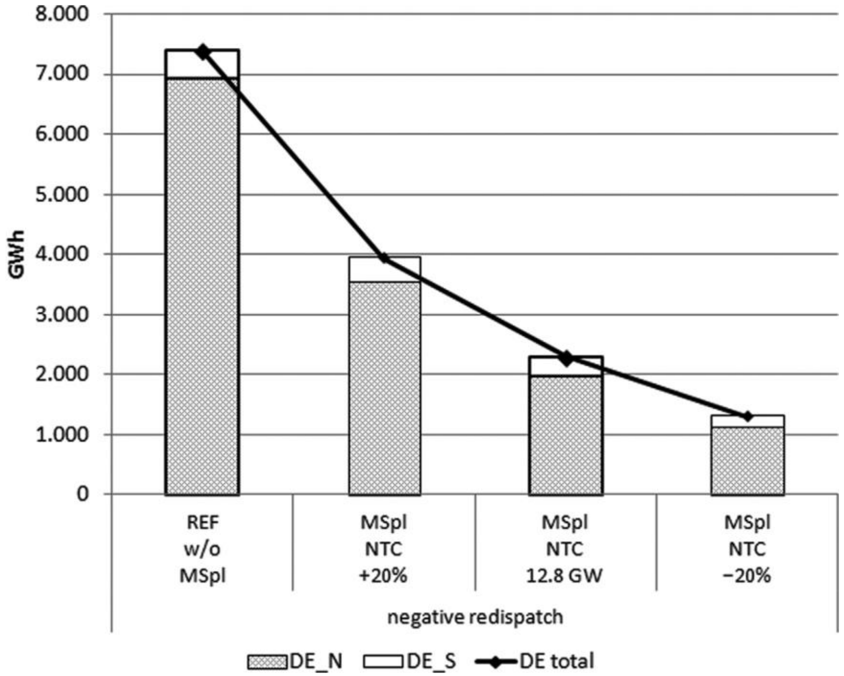
- Overall problem split into three subproblems to limit computation time
- Later (e.g. Felling et al. 2023) scheduling and redispatch implemented at European scale
- Further changes include e.g., nodal power flows and flow-based market coupling (FBMC)

Trepper, Bucksteeg, Weber (2015): Market splitting in Germany – New evidence from a three-stage numerical model of Europe
Key results

Regional distribution of congestion



Impact of market splitting on redispatch quantities



- ➢ Total redispatch cost decrease by 64 %
- ➢ **Impact on overall system costs** depends on **efficiency losses in redispatch** vs. market clearing
- ➢ But also **incentive effects** – cf. next example

Second application example
Breder, Meurer, Bucksteeg, Weber (2023): Spatial Incentives for Power-to-hydrogen through Market Splitting

Policy Advice

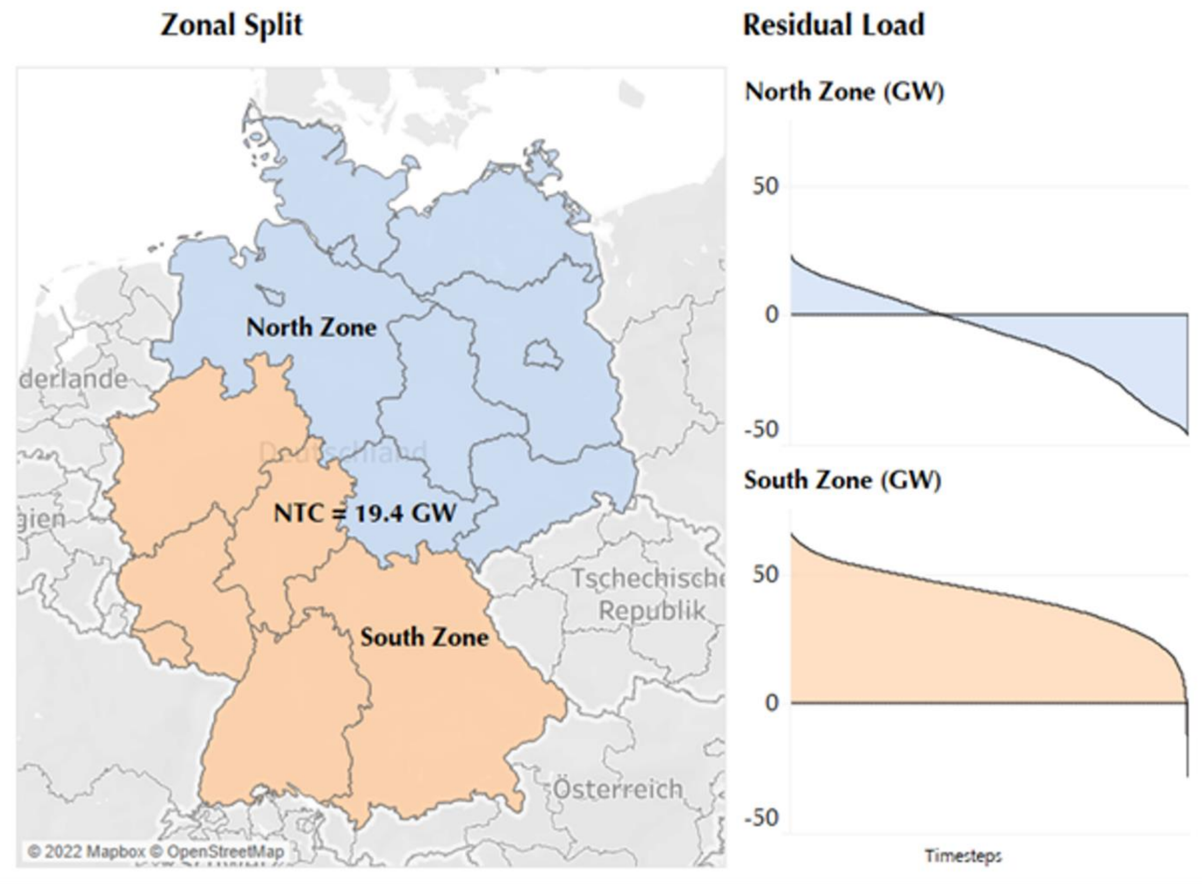
- Analysis of **incentive effects for electrolyzers** through **market splitting**
- Use of **JMM** with an extension for **endogenous investments**

  IDILES: based on **Benders decomposition**

Investigated configurations

Driver for use value →		**Steam reforming**	**Green hydrogen imports**
Bidding zone configuration ↓	*Reference run*	*SMRdom*	*GreenImp*
Status quo *SQ*	*SQ_0*	*SQ_SMRdom*	*SQ_GreenImp*
Market split *MS*	*MS_0*	*MS_ SMRdom*	*MS_ GreenImp*

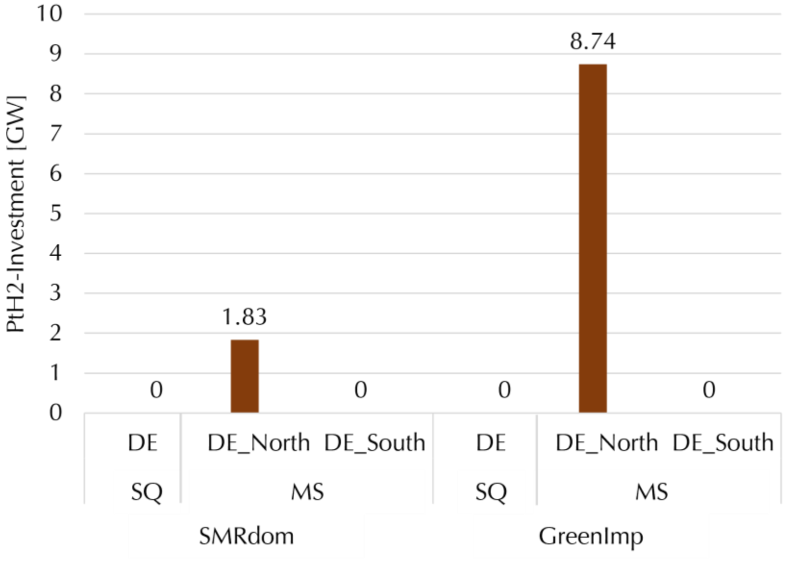
Considered zonal split



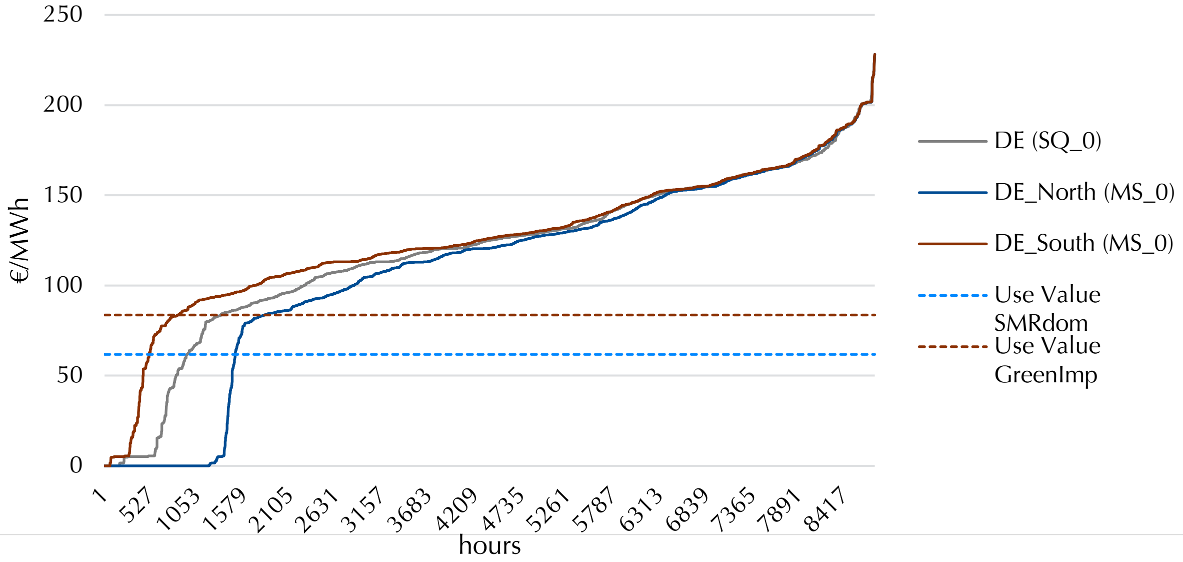
Breder, Meurer, Bucksteeg, Weber (2023):
Spatial Incentives for Power-to-hydrogen through Market Splitting
Key results

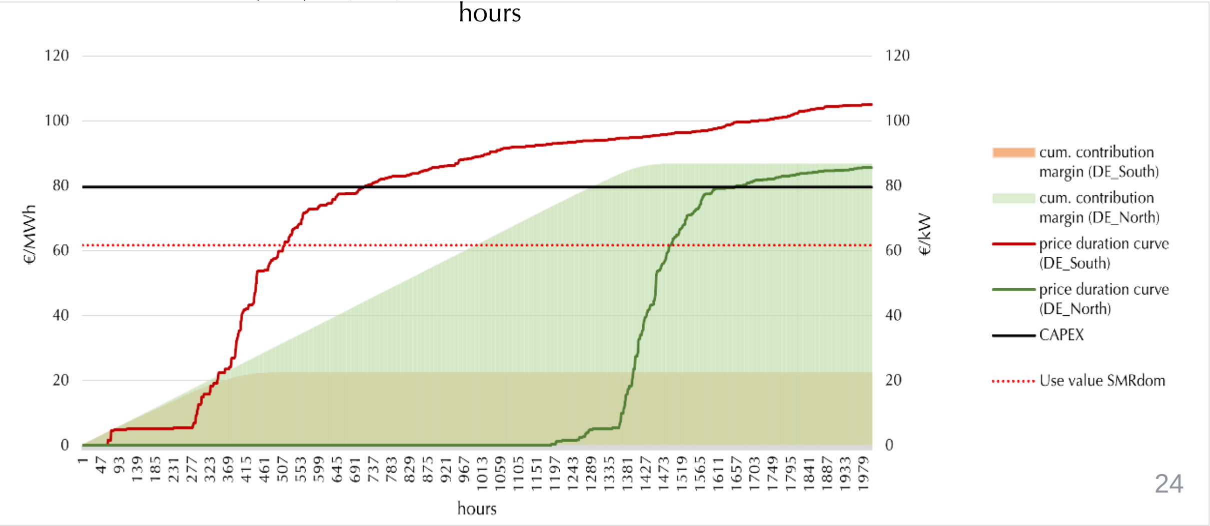
Policy Advice

Installed capacities



Price duration curves





- **Electrolyser investments only** under **market splitting**
  - lower prices in DE_North
  - relevant: hours with prices below use value
- Higher **investments** if competition to green hydrogen

Bottom right figure: details of the price duration curves and profitability of electrolyzers

scenario *MS_SMRdom,* initial run *MS_0*

Third application example

Weber, Vogel (2014): Contingent certificate allocation rules and incentives for power plant investment and disinvestment

Policy Advice

Free CO_2 certificate allocation:

- Example of policy instrument defying the logic of a simple optimization problem
- Other examples: renewable infeed tariffs & standard retail contracts applied to prosumers

- Solution here: **mixed complementarity problem (MCP)**,

8 comlementarity cond. derived from first order cond. for **profit maximizing agents** and **market clearing** conditions

Supply – demand equilibrium	$\sum_i Q_{i,s} \geq D_s\left(1-\alpha(P_s-P)\right)$	$\perp$	$P_s^{Elec} \geq 0$	$\forall s$	(1)
Capacity Constraint	$K_i \cdot \phi_i - Q_{i,s} \geq 0$	$\perp$	$\Pi_{i,s}^0 \geq 0$	$\forall s, \forall i$	(2)
Capacity balance	$K_i^{old} + K_i^{new} - K_i \geq 0$	$\perp$	$\Pi_i^1 \geq 0$	$\forall i$	(3)
Contribution margin $\Pi_{i,s}^0$	$C_i^{misc,var} + \frac{1}{\eta_i}\left(C_{f(i)} + e_{f(i)} P^{CO2}\right) + \Pi_{i,s}^0 \geq 0$	$\perp$	$Q_{i,s} \geq 0$	$\forall s, \forall i$	(4)
Operating profits Π_i^1	$C_i^{fix} + \Pi_i^1 \geq \sum_s \Pi_{i,s}^0 t_s + (1-r) H_i \cdot B_i \cdot P^{CO_2}$	$\perp$	$K_i \geq 0$	$\forall i$	(5)
Investment cost recovery	$C_i^{inv} \cdot a_i \geq \Pi_i^1$	$\perp$	$K_i^{new} \geq 0$	$\forall i \in I^{Invest}$	(6)
CO_2 cap	$L^{CO2} \geq \sum_i \sum_s (\sum_{f \in F^i} \frac{1}{\eta_i} E_f) Q_{i,s} t_s$	$\perp$	$P^{CO_2} \geq 0$		(7)
CO_2 certificate allocation	$L^{CO2} \geq (1-r) \sum_i (H_i \cdot B_i \cdot K_i)$	$\perp$	$r \geq 0$		(8)

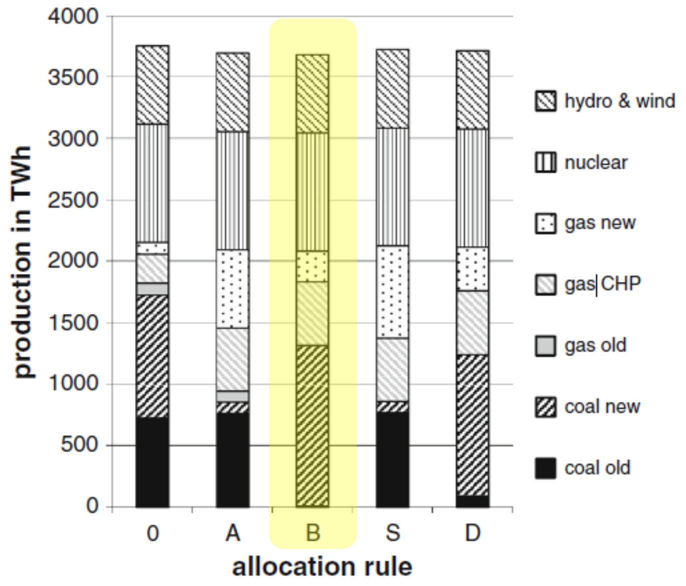
Weber, Vogel (2014): Contingent certificate allocation rules and incentives for power plant investment and disinvestment
Key results

Policy Advice

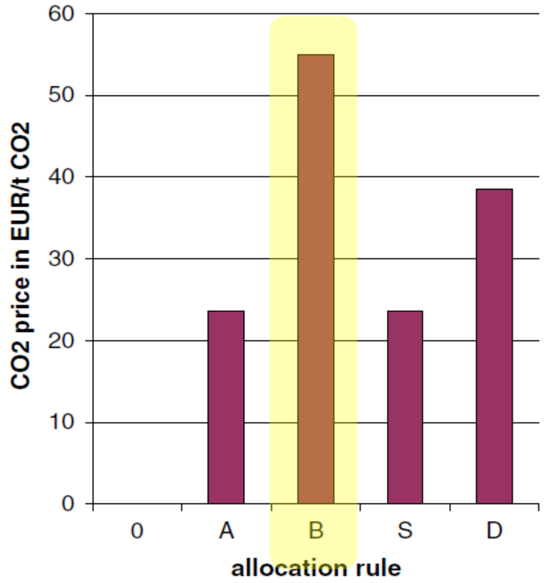
Allocation rules considered

Rule name	Allocation policy	Considered Specifications (for new plants)
0	No emission cap	-
A	Auctioning	-
B	Benchmark based on specific plant needs	Specific fuel benchmarks Specific operation time
S	Standard benchmark	standard fuel benchmark standard operation time
D	Fuel specific benchmark	Specific fuel benchmark Standard operation time

Electricity generation by technology



CO$_2$ price



Initial German policy choice for 2nd ETS period

- Strong **distorting effect** of chosen allocation rule
- Due to contingent allocation: **distribution** of certificates **dependent** on **technology** choice
- Ongoing work: distorting effect of retail tariffs on prosumers with PV-Battery systems

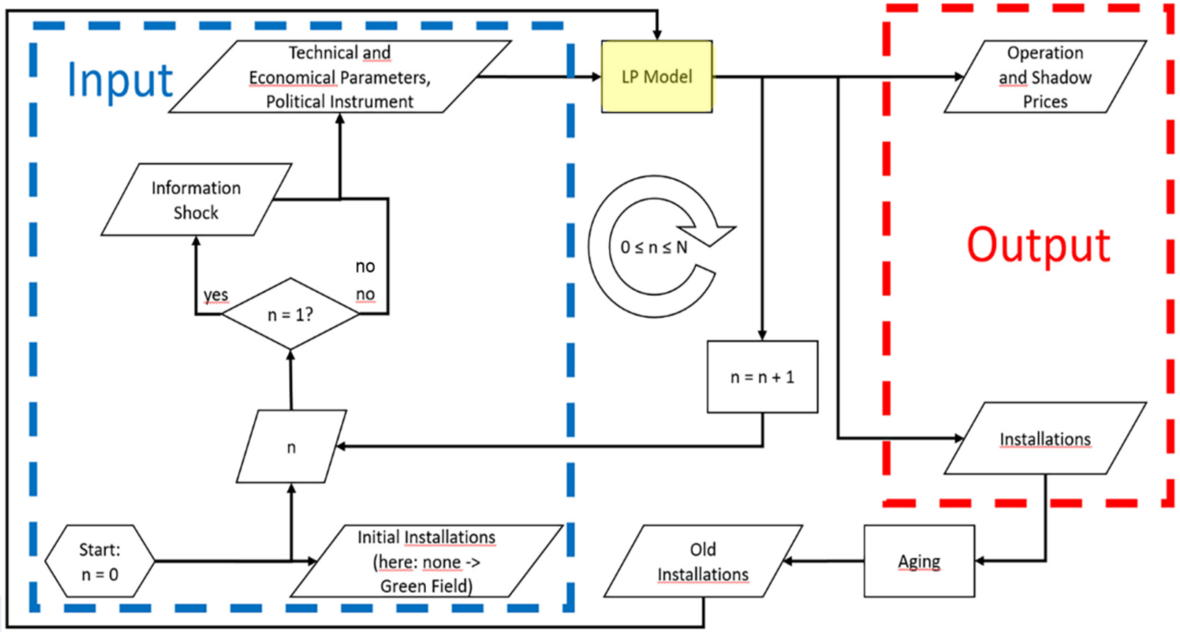
(first findings cf. Thomsen, Weber 2021)

Fourth application example
Botor, Böcker, Kallabis, Weber (2021): Information shocks and profitability risks for power plant investments – impacts of policy instruments

Optimization results of a **capacity expansion** model often interpreted as **competitive long-term equilibrium**

- In **reality**, repeatedly **shocks** occur – i.e. **unexpected developments**, e.g., the **energy crisis of 2022**
- Rational **investors anticipate** possible **shocks** and the resulting **risks** for investments – deterrent effect in case of **risk aversion**

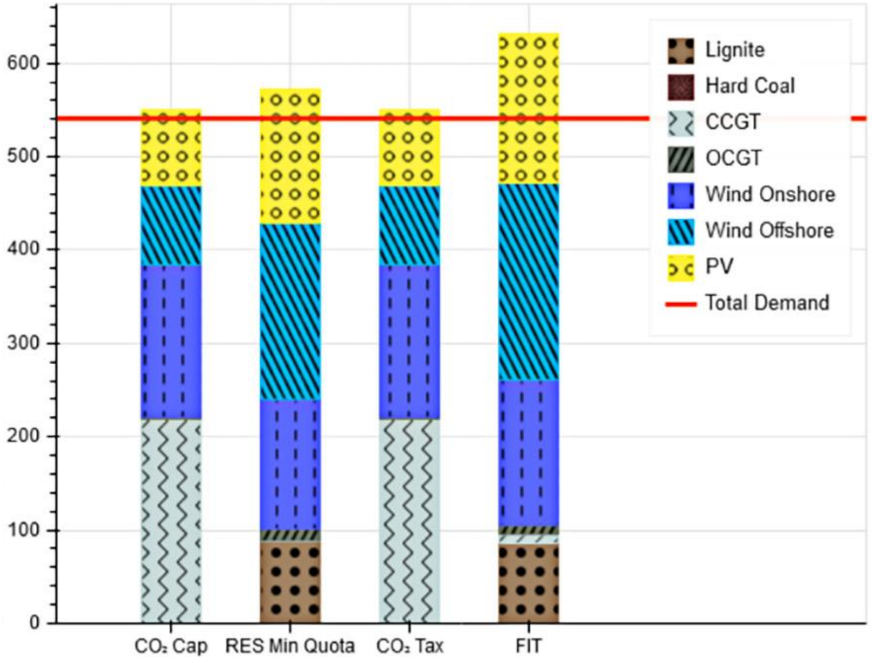
- **Assessment of risks** under **different** decarbonization **instruments** in a stylized setting
  - **Single shock** and resulting **impacts over 20 years** – similar to **impulse-response function** in **control theory**



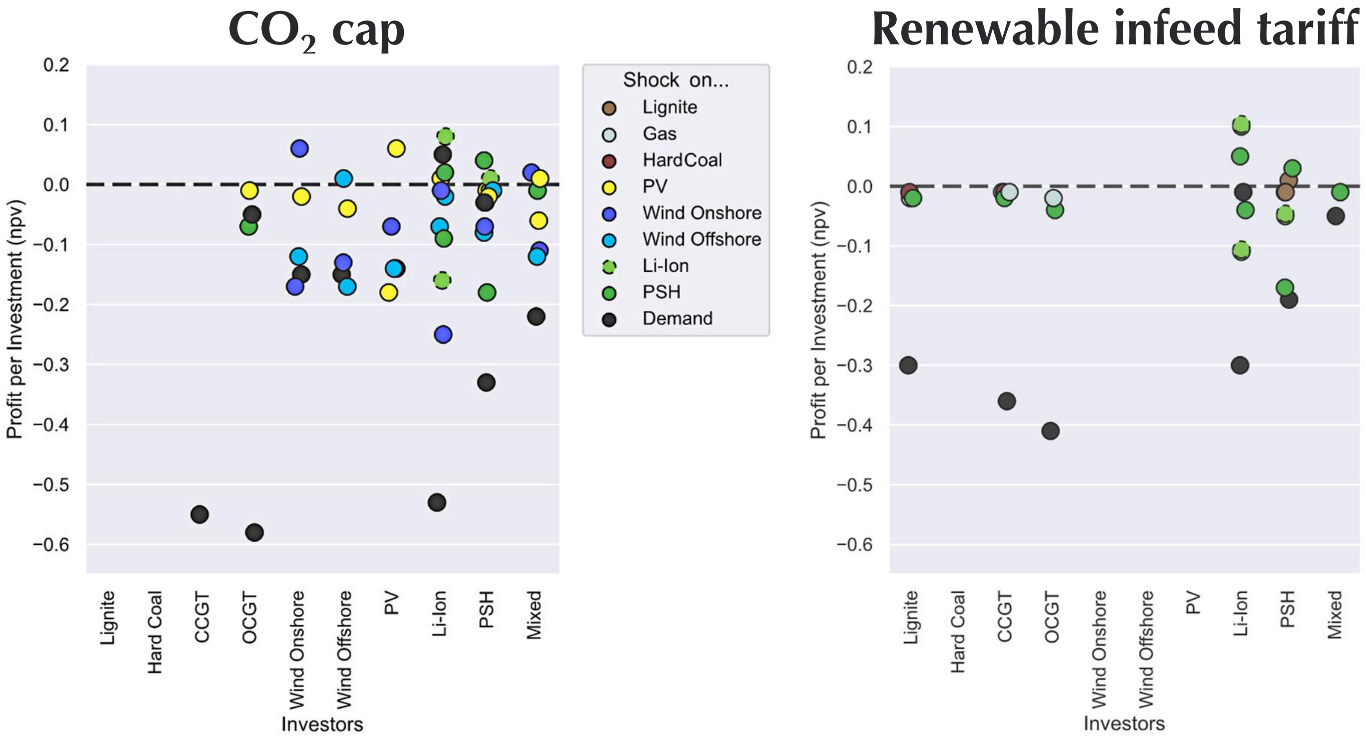
Instrument (Abbreviation)	Price or Quantity	First -best	Background
CO_2 Cap	Quantity	Yes	Limits CO_2 emissions by implementing a **certificate** regime
CO_2 Tax	Price	Yes	**Fixed charge** per emitted unit of CO_2
Renewable Minimum Quota (RES Min Quota)	Quantity	No	Obligation for suppliers to provide **green (RE) certificates** for a certain percentage of their sales
Fixed Feed-in Tariff (FIT) / Procurement auction	Price/ Quantity	No	Renewable generation support via a **guaranteed fixed remuneration** per kWh (also for curtailed volumes), regarding shocks equivalent to auctions for renewable capacity

Botor, Böcker, Kallabis, Weber (2021): Information shocks and profitability risks for power plant investments – impacts of policy instruments
Selected results

Equilibrium generation mix



Impact of shocks for


CO$_2$ cap

Renewable infeed tariff

- ➢ Decarbonization **instruments** affect **equilibrium generation mix**

  CO$_2$ price drives coal out of the (greenfield) generation mix, **renewable support** mechanisms do **not**

- ➢ **Demand shocks** have **highest impacts** (at same relative size)
- ➢ **No risk** for **renewables** under **infeed tariff**
- ➢ **Other technologies** affected by technology **cost risk** of **RE**

  Impact under FIT smaller – if FIT level is immediately adjusted

- ➢ **CO$_2$ tax** and **quota** induce **intermediary risk profiles**

Key insights regarding policy advice

- Optimization provides important insights for policy making in the energy and climate field
- Notably optimization enables the investigation of trade-offs

But:

- Overconfidence in optimization results is dangerous
- Optimization results depend on input parameters
  – which are in turn subject to considerable uncertainty
- Typical policy problems are more complicated than classical optimization problems
  - Multiple stakeholders and levels of governance
  - Multiple objectives which are partly not easy to operationalize

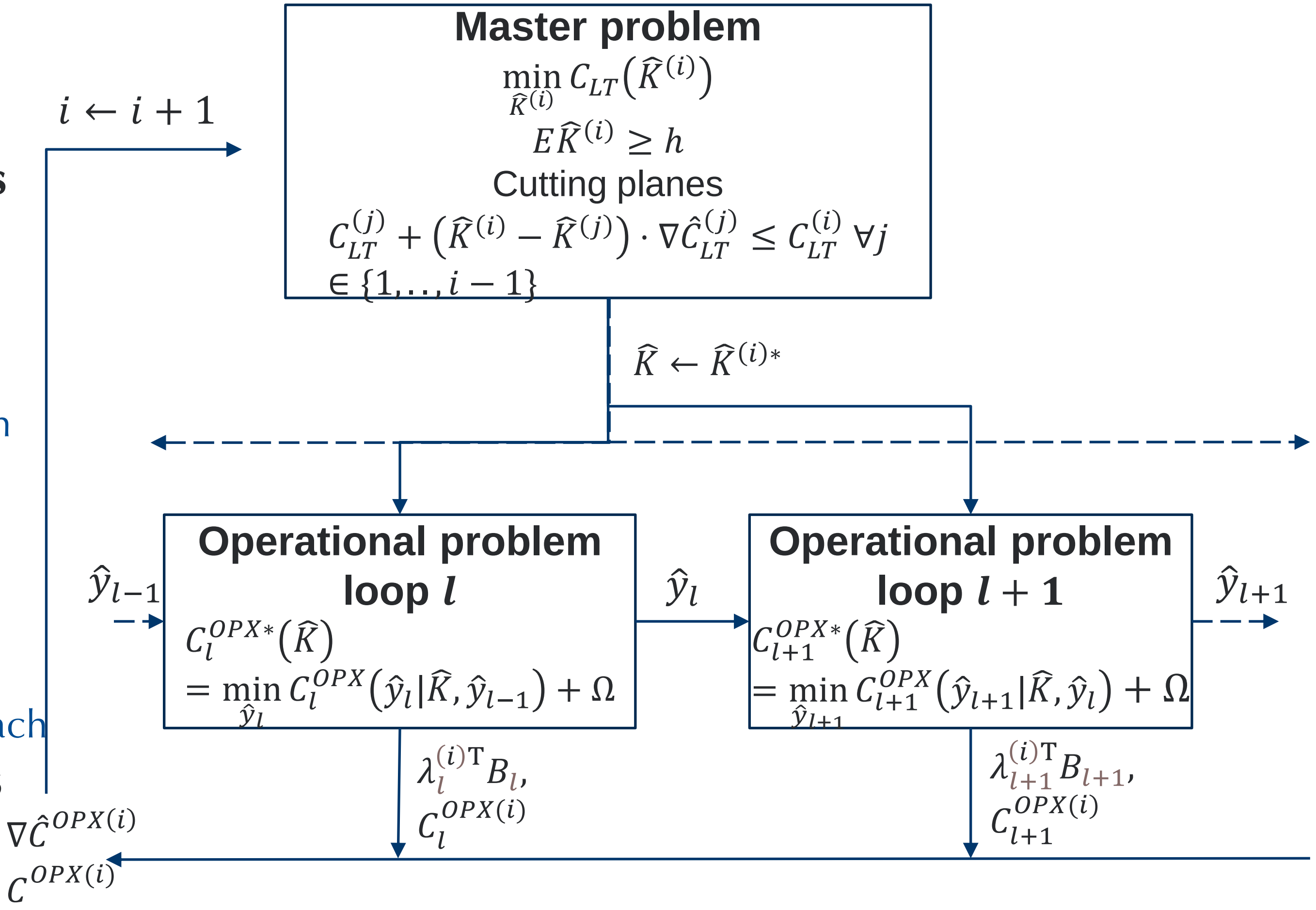
➢ For **good policy advice**, the **optimization tools** are important,
yet the **process** and the **political discourse** are equally relevant

Weber, Leisen, Böcker (2022): Combining rolling planning and Benders decomposition to solve large scale-electricity system models
Motivation & general approach

Ongoing Work

- **Increasing shares of renewables**
  - ➢ More distributed generation, especially rooftop PV
  - ➢ Also distributed flexibilities, esp. electric vehicles and heat pumps
- ➢ **Increasing requirements regarding temporal, spatial and technology details in capacity expansion models**
  - ➢ Detailed modelling of operations required for an adequate model of optimal generation (and transmission) expansion
  - ➢ Large interconnected systems (e.g. entire Europe) to be considered
  - ➢ Ordering of time steps to be maintained for storage operation
- ➢ **Standard energy system models reach their limits**
  - ➢ Huge storage requirements and long run times despite progress in computing performance
  - ➢ Aggregation of time steps, areas or technologies is one possibility, yet induces aggregation errors
  - ➢ Decomposition of optimization problems alternative approach
- ➢ **Objective: scalable approach to combine operations modelling based on rolling planning with long-term capacity adjustments**

➢ **General approach IDILES**



Master problem

$$\min_{\widehat{K}^{(i)}} C_{LT}\left(\widehat{K}^{(i)}\right)$$

$$E\widehat{K}^{(i)} \geq h$$

Cutting planes

$$C_{LT}^{(j)} + \left(\widehat{K}^{(i)} - \widehat{K}^{(j)}\right) \cdot \nabla\hat{C}_{LT}^{(j)} \leq C_{LT}^{(i)} \ \forall j \in \{1,\ldots,i-1\}$$

$i \leftarrow i+1$

$\widehat{K} \leftarrow \widehat{K}^{(i)*}$

Operational problem loop l

$$C_l^{OPX*}\left(\widehat{K}\right) = \min_{\hat{y}_l} C_l^{OPX}\left(\hat{y}_l | \widehat{K}, \hat{y}_{l-1}\right) + \Omega$$

Operational problem loop $l+1$

$$C_{l+1}^{OPX*}\left(\widehat{K}\right) = \min_{\hat{y}_{l+1}} C_{l+1}^{OPX}\left(\hat{y}_{l+1} | \widehat{K}, \hat{y}_l\right) + \Omega$$

$\hat{y}_{l-1}$

$\hat{y}_l$

$\hat{y}_{l+1}$

$\lambda_l^{(i)\mathrm{T}} B_l$, $C_l^{OPX(i)}$

$\lambda_{l+1}^{(i)\mathrm{T}} B_{l+1}$, $C_{l+1}^{OPX(i)}$

$\nabla\hat{C}^{OPX(i)}$

$C^{OPX(i)}$

➢ Benders + Rolling Planning may be reformulated into a two-stage ordinary optimization problem

House of Energy Markets & Finance

Weber, Leisen, Böcker (2022): Combining rolling planning and Benders decomposition to solve large scale-electricity system models
Early application and results

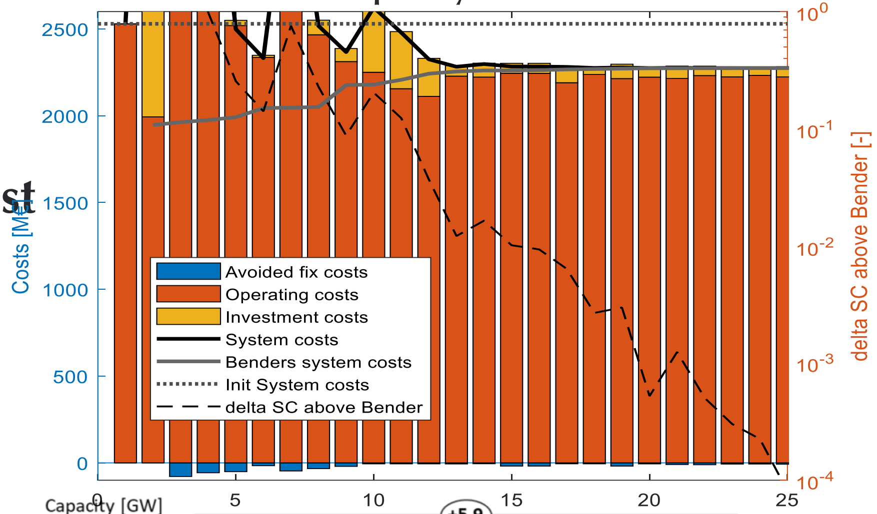
Ongoing Work

Key methodological findings

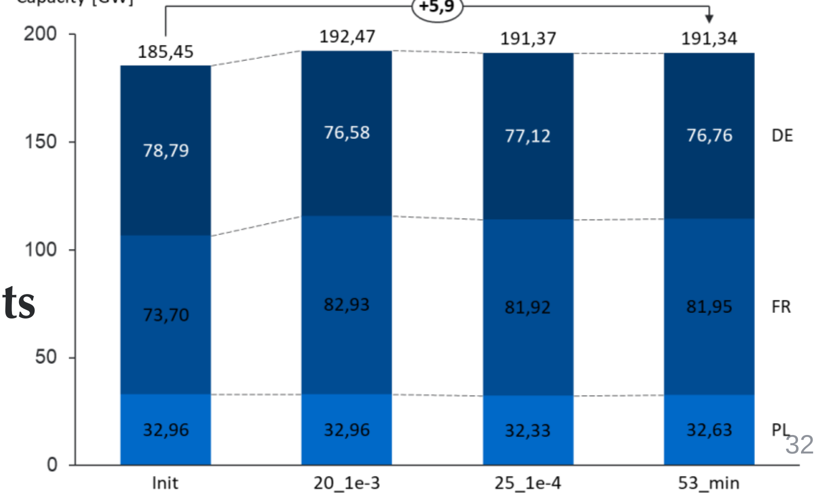
- In the lower level, the sum of the objective functions of the rolling planning are applied
- At given starting points for each loop, the lower problems are linear and standard duality theory applies
- Yet a correction term is needed to eliminate the opportunity cost for reservoir filling, as these are no actual costs
- The correction term may be computed ex post yet not ex ante.
- The correction term is a convex function of capacity under the following conditions:
  1. Hydro-based generation in each loop is monotonously decreasing in capacities
  2. Terminal filling levels in each loop are correspondingly monotonously increasing in capacities
  3. The correction term is monotonously converging to zero with increasing capacities

First small scale application:

- DE, FR and PL for one exemplary month
- **System cost over iterations**



- **Capacity adjustmenets**



Weber (2022): Heterogenous investors in energy system models
Motivation & general approach

Ongoing Work

- **Increasing shares of renewables**
  - More distributed generation, especially rooftop PV
  - Also distributed flexibilities, esp. electric vehicles and heat pumps
- **Heterogenous investments and investors**
  - Heterogeneity of preferences and technology availabilities
  - Also limited knowledge of planners/modellers
- **Standard energy system models do not cope with these investors**
  - Linear programs subject to penny switching
  - Differentiation by investment sites and technology types possible, yet yields large models and still unsatisfactory
- **Objective: develop an alternative approach to cope with heterogenous investments**

- **Discrete choice models**:
  - Describe **optimal choices** under stochastic utility
  - **Logit** specification enables **analytical formulations**
- Standard stochastic utility formulation

$$U_i = V_i + \varepsilon_i$$

- Corresponding choice probability

$$Prob_i = \frac{\exp(V_i)}{\exp(V_i)+1} = 1 - \frac{1}{\exp(V_i)+1}$$

- **Expected** (indirect) **utility function: LogExpSum** (cf. Small & Rosen 1981)

$$\mathrm{E}[U_i] = \ln(\exp(V_i) + 1)$$

  - **convex function**
  - **mathematically tractable yet less supported by commercial solvers**

Weber (2022): Heterogenous investors in energy system models
Very early application and results

Ongoing Work

First implementation:

- Based on data from Poestges et al. (2019), publically available under zenodo: https://zenodo.org/record/3674005
  - CO_2 price 100 €/t CO_2
- Aggregation to five regions in Germany
- Investments in the following technologies:
  - CCGT
  - OCGT
  - PV
  - Wind onshore
- No grid restrictions
- Five randomly selected hours

First results:

Capacity PV						
	Total	**R_50**	**R_AM**	**R_EN**	**R_TB**	**R_TN**
Convex optimization	199.8	28.0	48.4	48.3	42.3	32.9
Linear program	174.3	0	74.3	100.0	0	0
Capacity wind						
		R_50	**R_AM**	**R_EN**	**R_TB**	**R_TN**
Convex optimization	104.2	63.3	5.7	0.7	0.2	34.3
Linear program	102.2	100.0	0	0	0	2.2
Capacity CCGT						
Convex optimization	55.1					
Linear program	54.3					

Final remarks

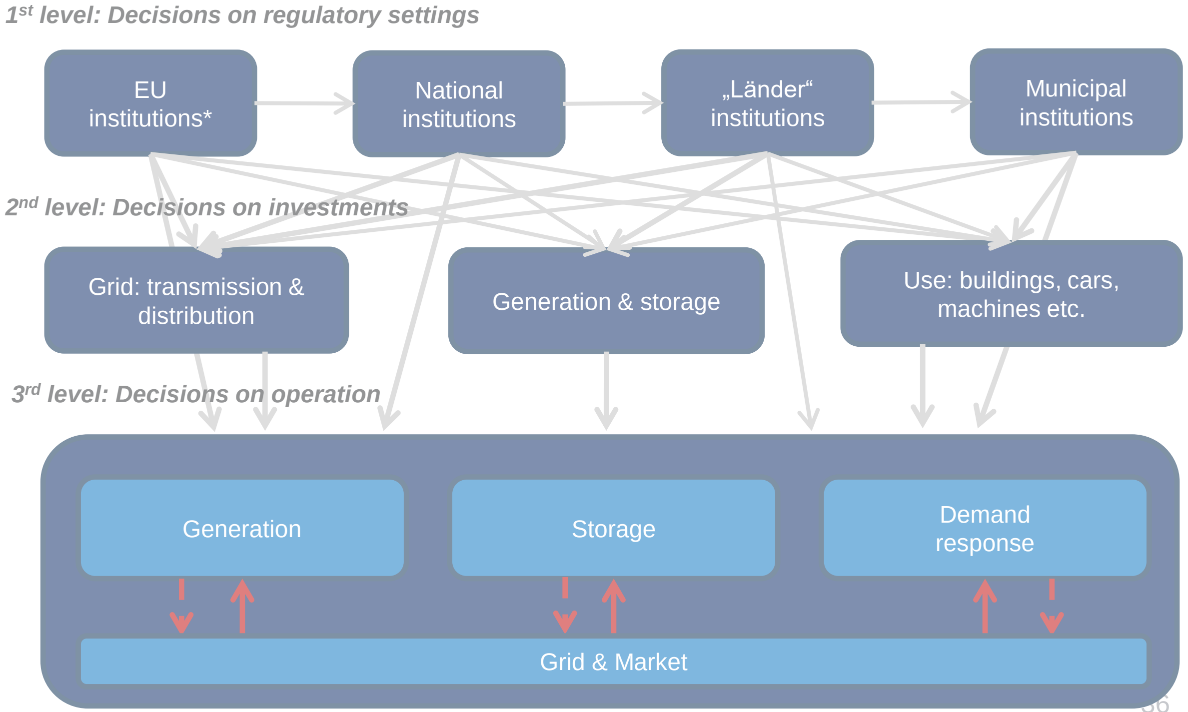
Veritas adequatio rei et intellectus

(attributed to) Aristote

An informal translation: Truth is the matching of things and thinking.

An important addition for OR:

… and reflection on intertwined human decision making



This is getting even **more important** in a world with simultaneously **increasing complexity and knowledge**.

A tentative list of **hot topics in climate and energy for applied research** in that vein:

- Global and local hydrogen networks
- Decarbonization of heating
- Distributed flexibilities in electricity demand
- …

Thank you for your attention!

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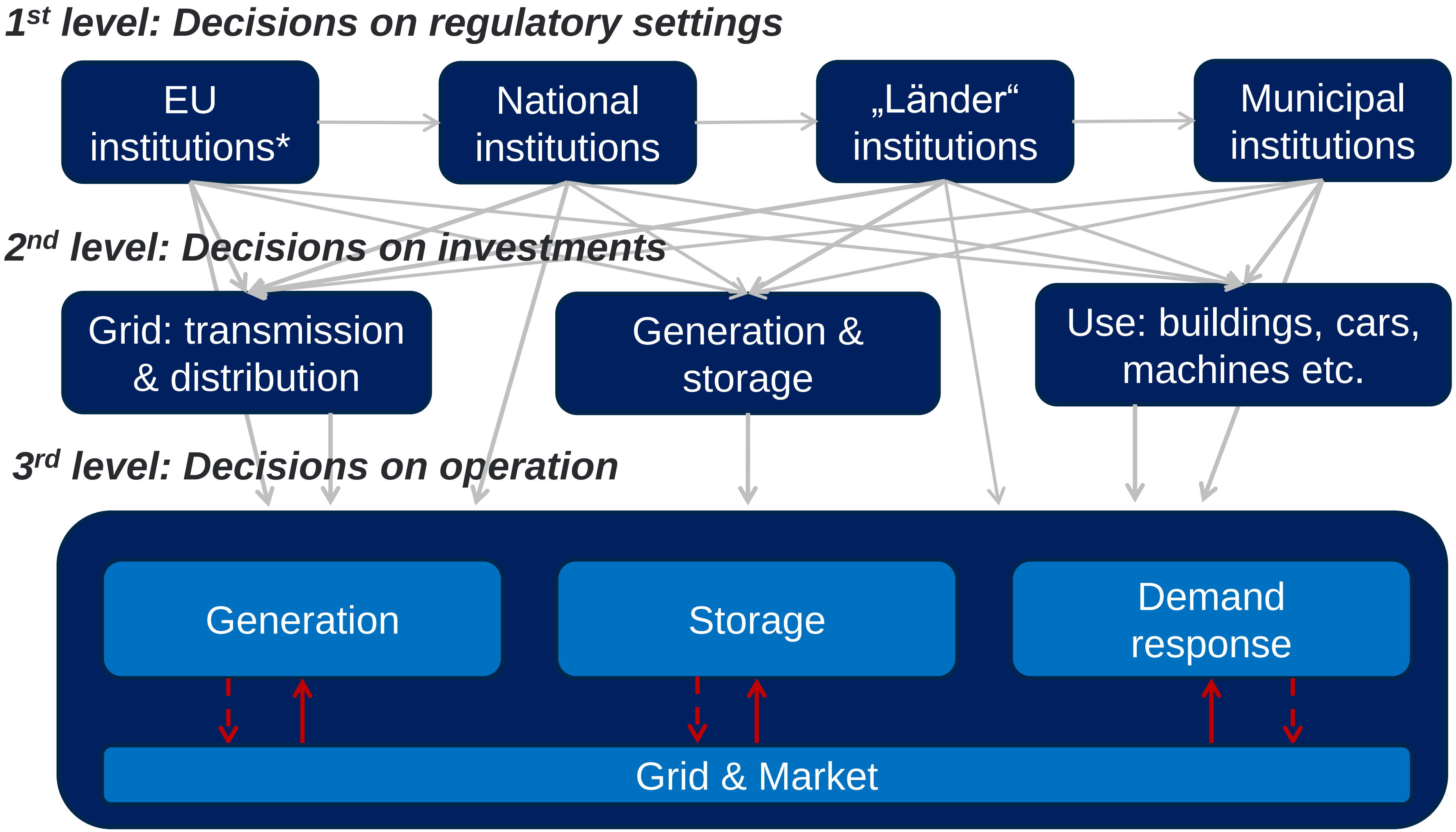

1st level: Decisions on regulatory settings

EU institutions*

National institutions

„Länder“ institutions

Municipal institutions

2nd level: Decisions on investments

Grid: transmission & distribution

Generation & storage

Use: buildings, cars, machines etc.

3rd level: Decisions on operation

Generation

Storage

Demand response

Grid & Market