Using stochastic programming to analyse demand response in European electricity markets

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Outline

- Transition to near zero emission power systems
- The EMPIRE model
  - Multi-horizon stochastic programming
- European technology mix
  - EMPIRE case 1: passive consumers
- The active consumer
  - Models for scheduling and bidding
- European technology mix
  - EMPIRE case 2: active consumers and demand response
- References

The Zero Emission Power system

What is needed to achieve 90%emission cuts in 2050?

- Transmission versus storage
- How does the role of gas develop
  - With CCS?
  - Or without.
- The “winter package”: Active consumers and demand response. An alternative to transmission?

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Backdrop: European Commission's view of a low-carbon Europe

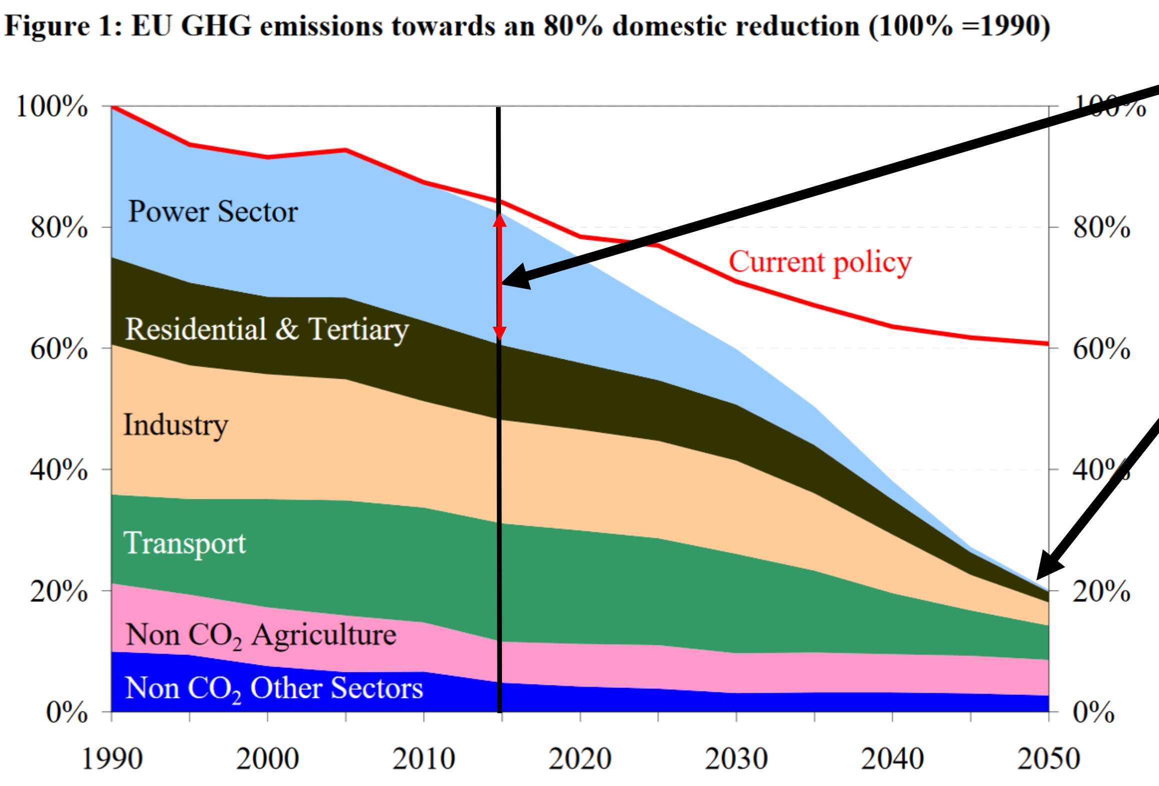
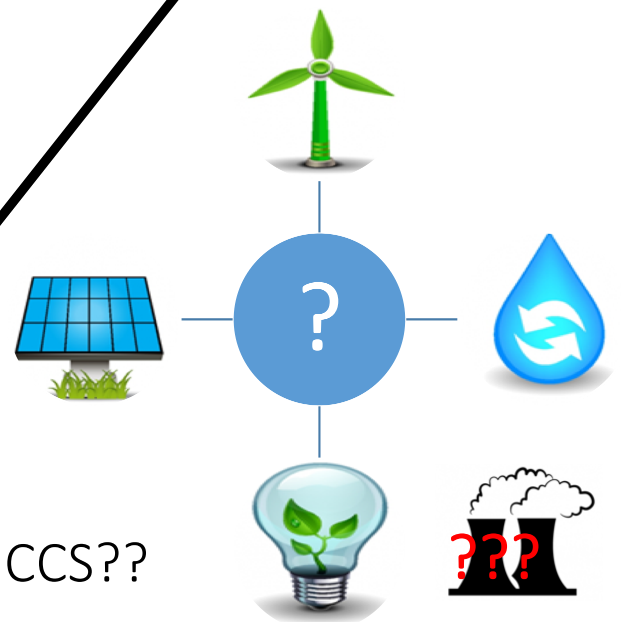


Figure 1: EU GHG emissions towards an 80% domestic reduction (100% =1990)

Today: almost 25 % of total emissions from power generation



Source: European Commission. (2011). A Roadmap for moving to a competitive low carbon economy in 2050. *Communication from The Commission to The European Parliament, The Council, The European Economic and Social Committee and The Committee of The Regions, COM(2011).*

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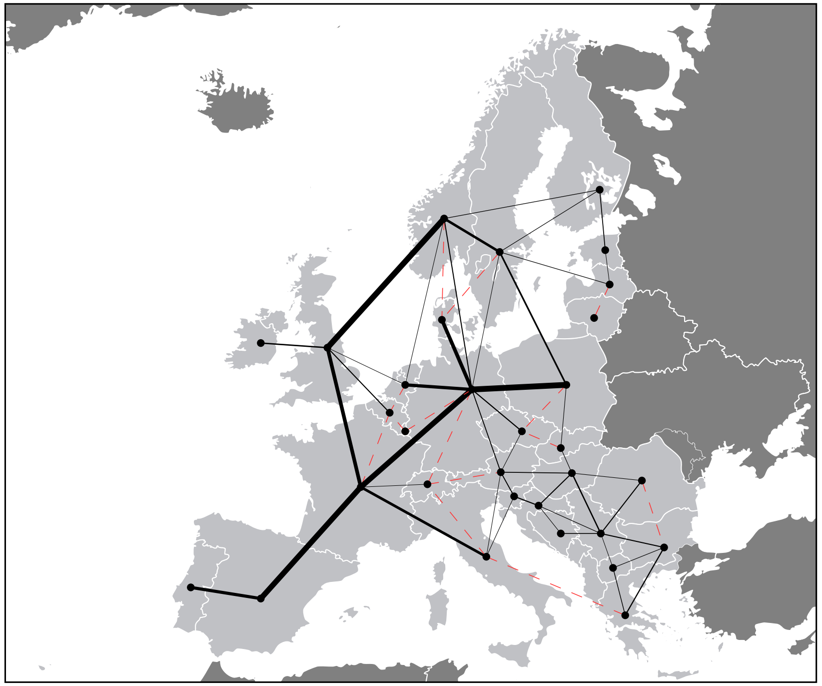
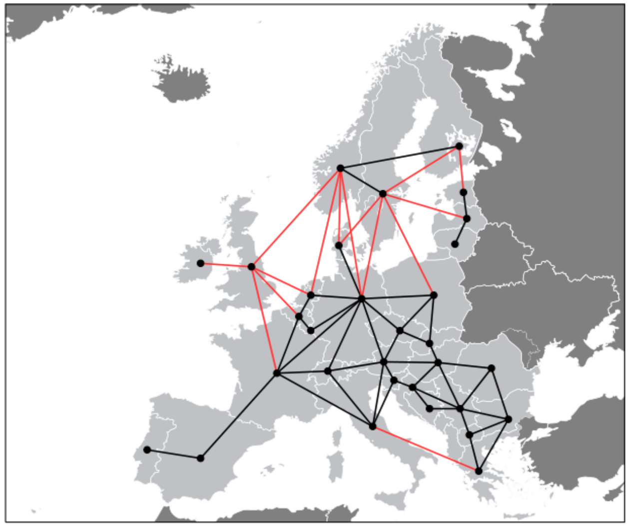
Zero Emission Power systems

FME
FORSKNINGS-SENTER FOR MILJØVENNLIG ENERGI

- Analyses using the EMPIRE model
- Power system design and operation
  - Time horizon until 2050 – investments in 5 year steps
  - Model operational time periods: demand, supply (stochastic wind and solar PV) and optimal dispatch.
- Provides a cost minimization capacity expansion plan for Europe, detailed for each country



EUROPEAN MODEL FOR POWER SYSTEM INVESTMENT WITH RENEWABLE ENERGY (EMPIRE)



Multi-horizon Stochastic Program

- Long-term dynamics (multi-period investments)
- Short-term dynamics (multi-period operation)
- Short-term uncertainty

Modeling assumptions

- Perfect competition (system cost minimization formulation)
- Inelastic demand
- Generation capacity aggregated per technology (i.e. do not model individual plants)
- Investments are continuous
- Lines are independent (i.e. transportation network)
- Perfect foresight about fuel prices, carbon price, and load development.

The challenge for Zero Emission Power Systems
- Intermittent generation and variable load

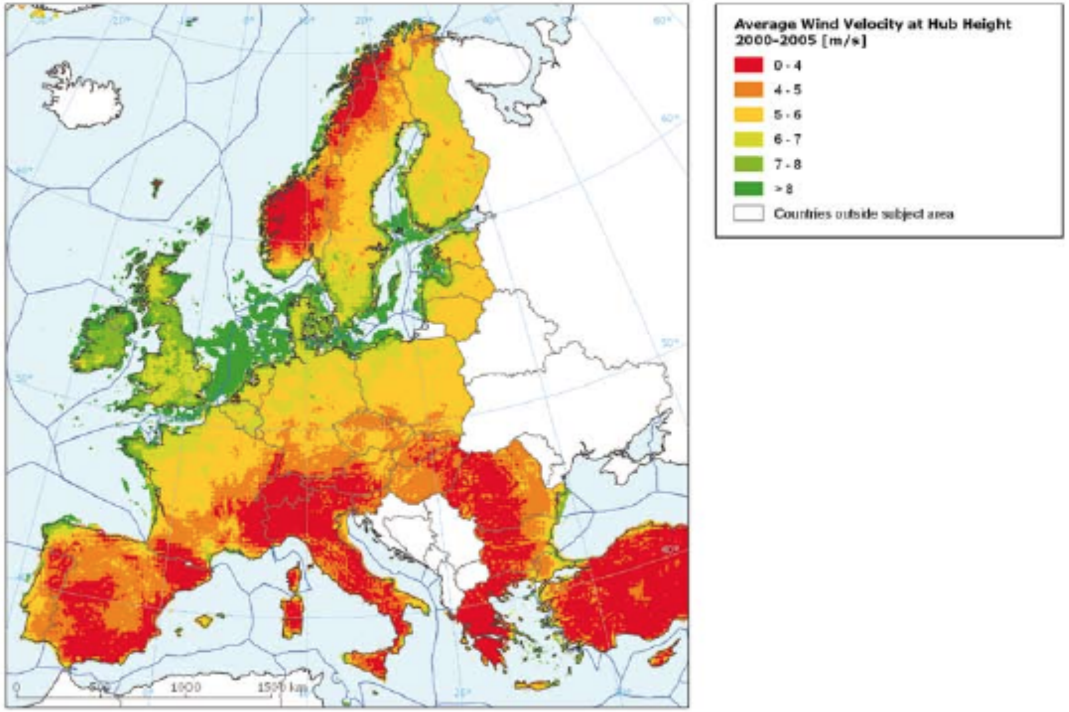


Figure : ECMFW wind field data for Europe (source: European Environment Agency)

We need to model variations in wind, both the intermittent nature and geographically

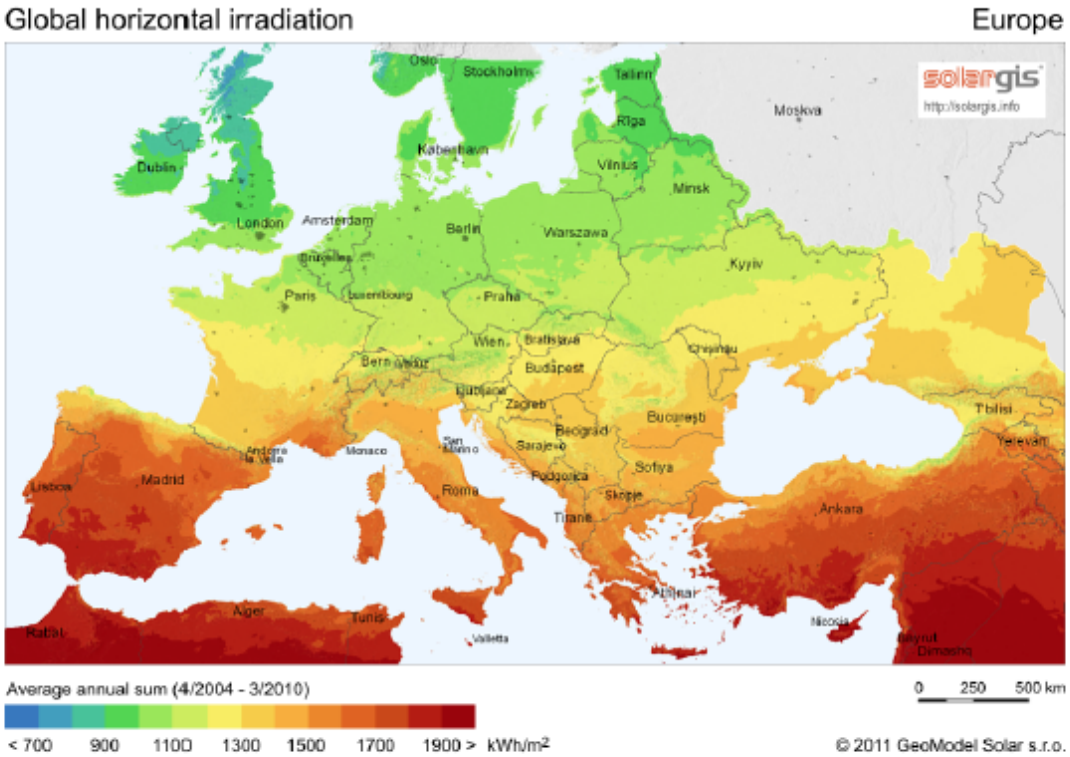


Figure : Average solar irradiation in Continental Europe (source: solargis)

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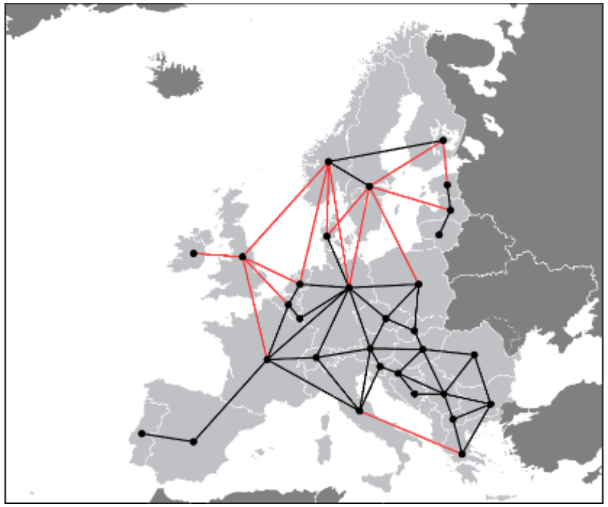
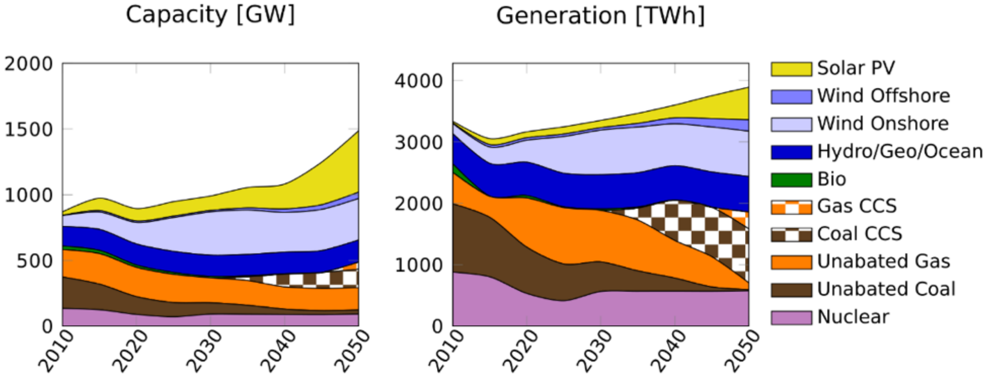
We need to model variations in solar irradiation , both the intermittent nature and geographically

CO-OPTIMIZATION OF STRATEGIC AND OPERATIONAL DECISIONS

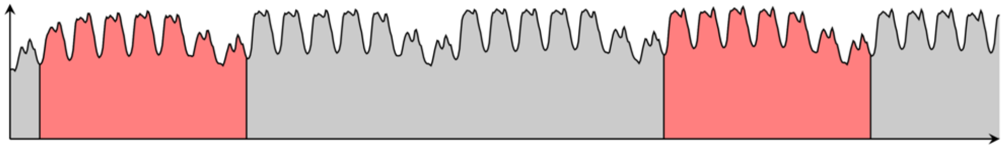


Optimal investment strategy 2010-2015



Coupled optimization problem to minimize total system costs

Optimal dispatch for representative 168-hour blocks



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MULTI-STAGE, MULTI-SCALE STOCHASTIC PROGRAMMING (SP)

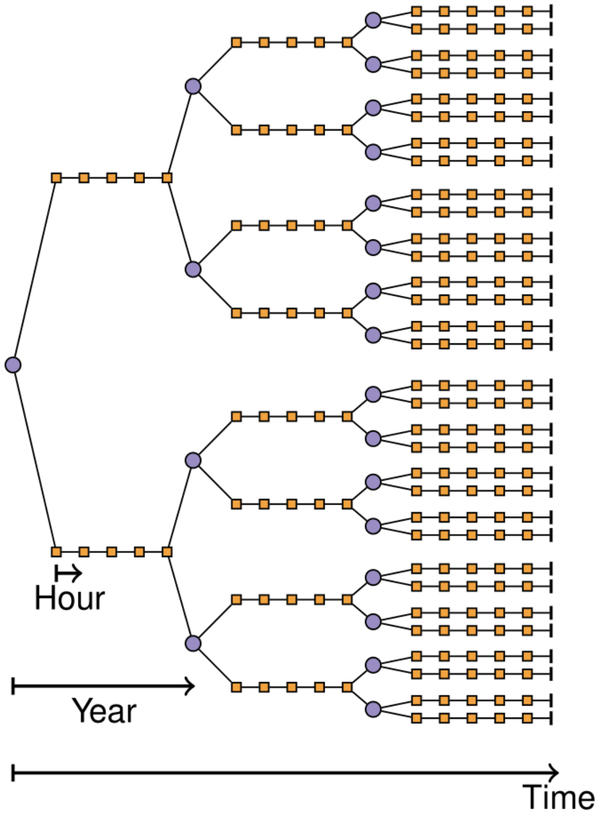
Uncertainty types

- Strategic examples
  - Investment cost
  - Carbon price
  - Fuel price development
- Operational examples
  - Load levels
  - Intermittent RES generation
  - Hydro reservoir inflow

Legend

Investment (strategic) decisions ●

Operational desicions ■



LOOSE COUPLING HERE-AND-NOW OPERATION AND FUTURE DECISIONS

- Future strategic and operational uncertainty independent of current (operational) information
  - Example: observing current wind generation does not give you updated information about future weather

- Future strategic and operational decisions independent of current operational decisions
  - Example: current output from your CCGT does not impact what is optimal to do (investments, operation) in the future

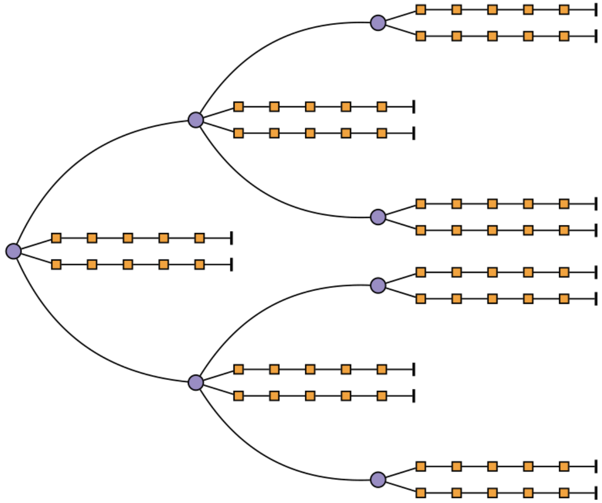
Multi-horizon Stochastic Programming (SP)

Legend

Investment (strategic) decisions ●
Operational desicions 🟧

Important assumptions

- Strategic uncertainty independent of operational uncertainty
- Here-and-now operation does not impact future
  - Strategic decisions
  - Operational decisions



Reduces tree size by a factor of

(# of 🟧 nodes)$^{\text{\# of strategic periods}}$

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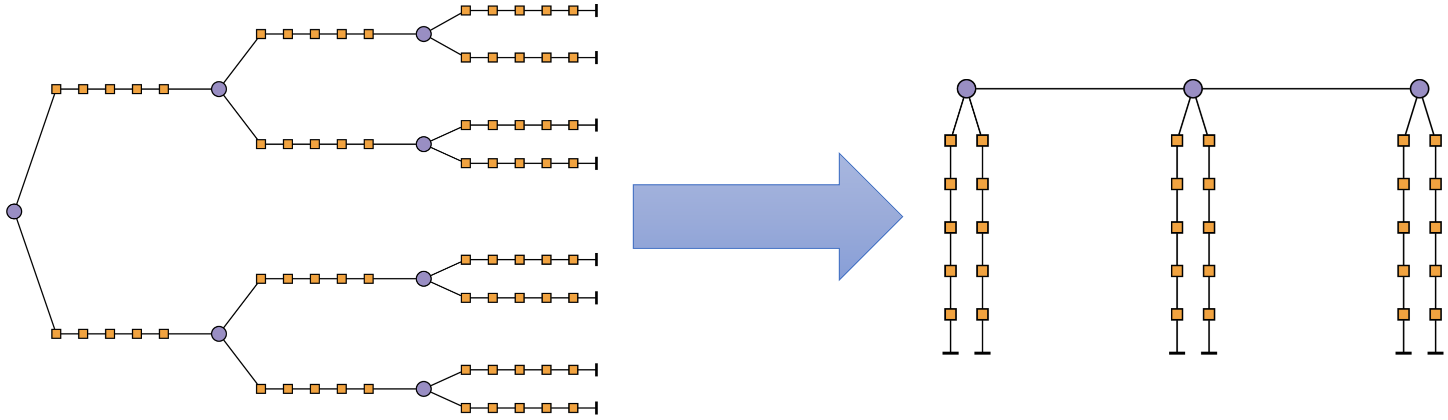
[1] Kaut, M., K. T. Midthun, A. S. Werner, A. Tomasgard, L. Hellemo, and M. Fodstad. 2014. “Multi-horizon stochastic programming.” *Computational Management Science* 11(1–2): 179–193. doi:10.1007/s10287-013-0182-6.

PERFECT FORESIGHT IN THE LONG-TERM

Legend
Investment (strategic) decisions ●
Operational desicions ■

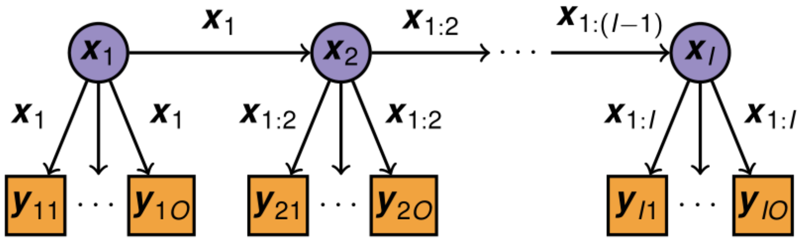
Multi-stage, multi-scale stochastic program

Multi-horizon stochastic program



Common setting if the goal is to analyze system transition for a pathway scenario

EMPIRE STOCHASTIC PROGRAMMING MULTI-HORIZON STRUCTURE



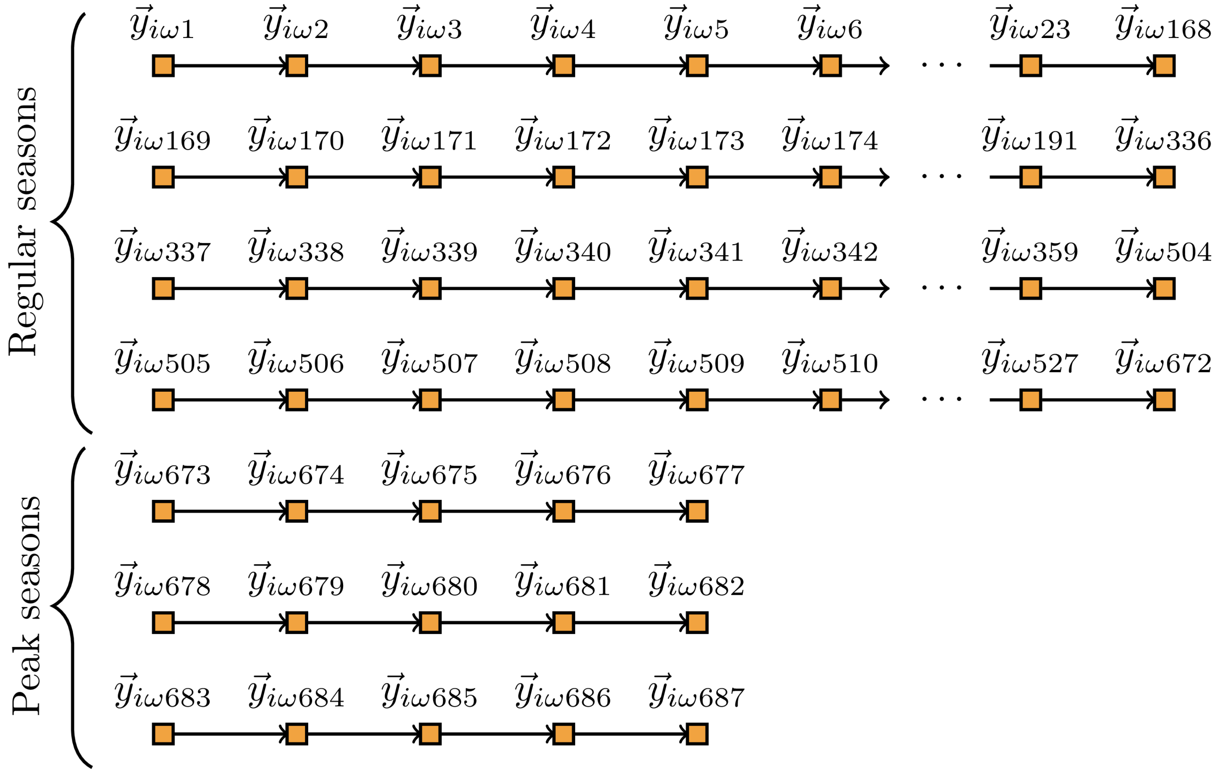
- $\boldsymbol{x}_i$: investments in period i $(2015, 2020, \dots, 2050)$
- $\boldsymbol{y}_{i\omega}$: Operational variables (dispatch, flows, etc.) period i, stochastic scenario ω

Mathematical formulation of EMPIRE

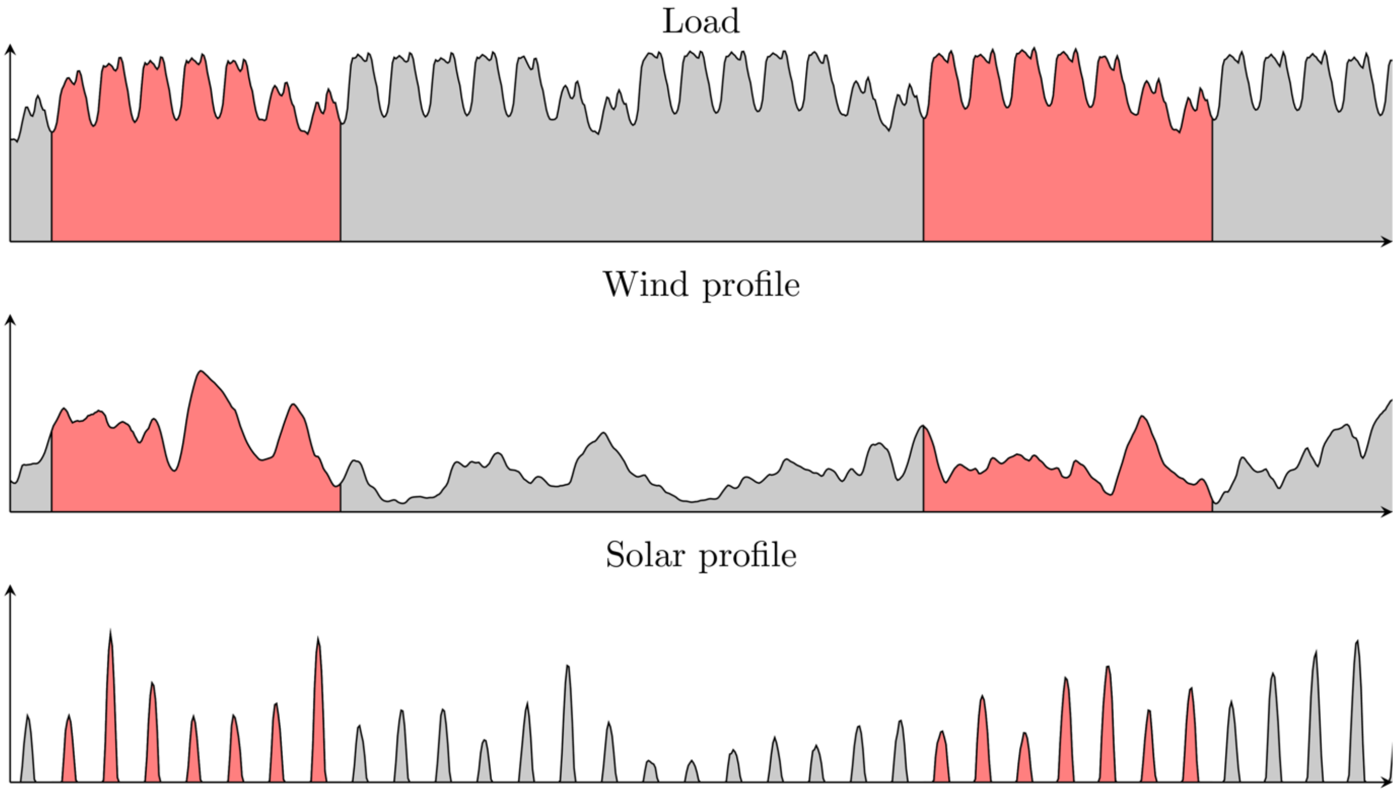
$$\min_{\boldsymbol{x}\in\mathbb{R}^n} \mathcal{Q}(\boldsymbol{x}) = \sum_{i=1}^{I} \delta_i \left\{ \boldsymbol{c}_i^\top \boldsymbol{x}_i + \sum_{\omega\in\Omega_i} p_{\omega i} Q_{\omega i}(\boldsymbol{x}_{1:i}) \right\}, \text{ s.t. } A\boldsymbol{x} = \boldsymbol{b},\ \boldsymbol{x} \geq 0,$$

$$Q_{\omega i}(\boldsymbol{x}_{1:i}) = \min_{\boldsymbol{y}_{\omega i}\in\mathbb{R}^m} \{\vartheta \boldsymbol{q}_i^\top \boldsymbol{y}_{\omega i} \mid W_i \boldsymbol{y}_{\omega i} = \boldsymbol{h}_{\omega i} - T_{\omega i}\boldsymbol{x}_{1:i},\ \boldsymbol{y}_{\omega i} \geq 0\}.$$

OPERATIONAL OPTIMIZATION – TEMPORAL STRUCTURE



OPERATIONAL DATA – SLICING



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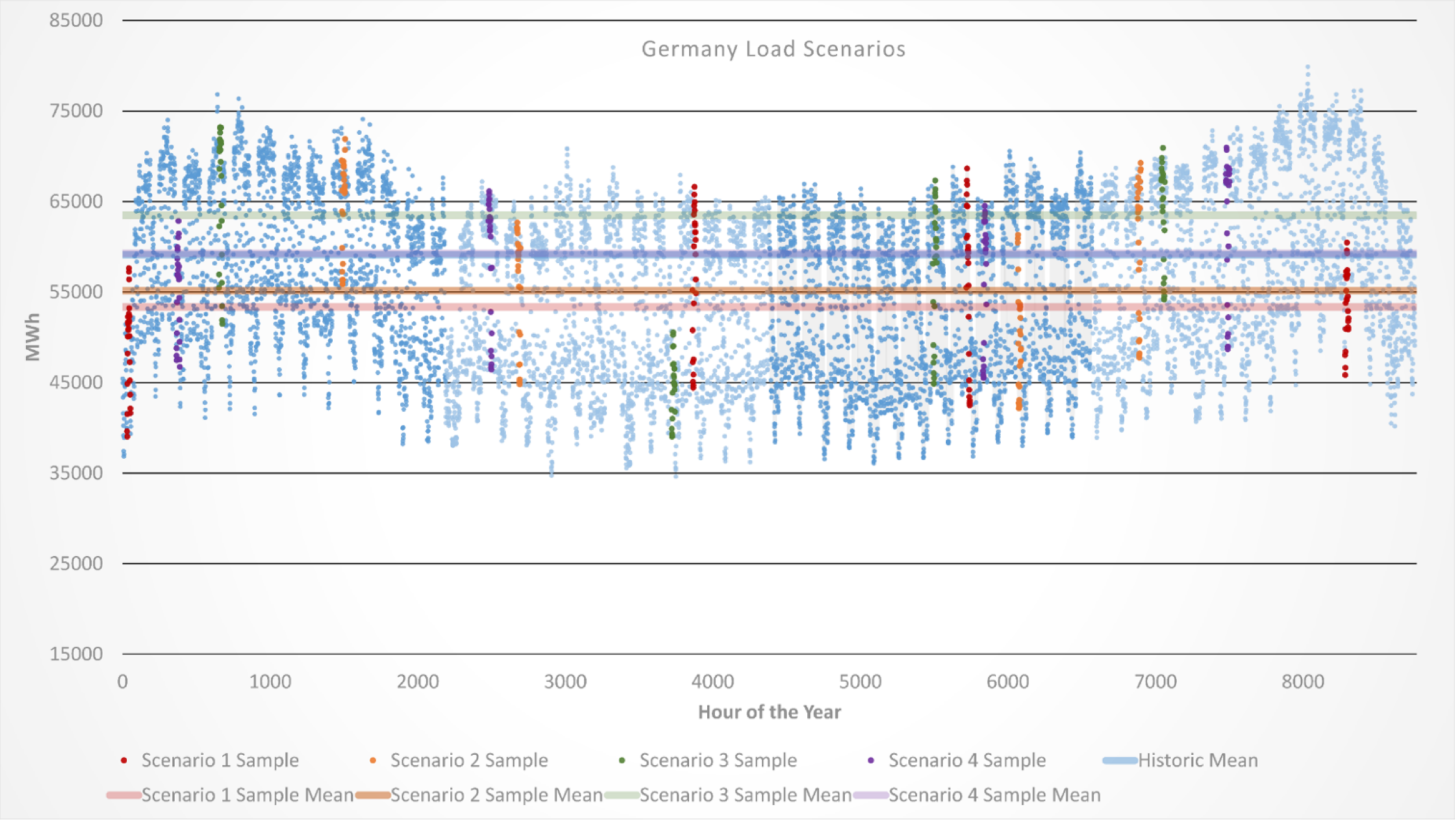
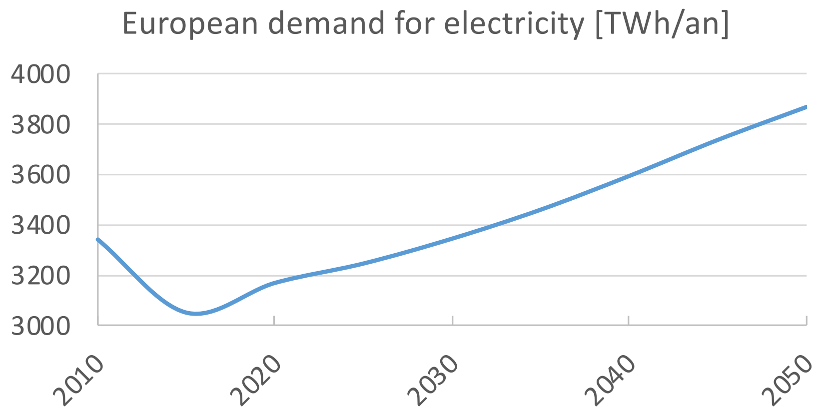
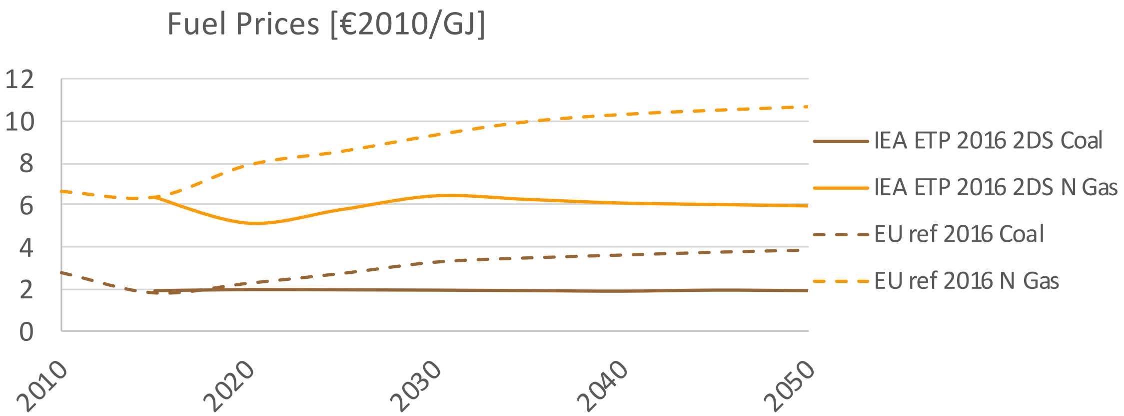
SAMPLE SCENARIOS



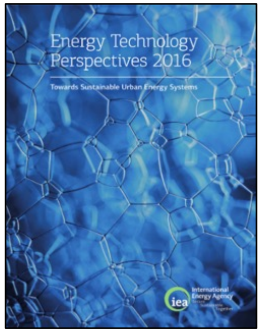
Background





EU reference
scenario 2016

IEA Energy
Technology
Perspective
2016



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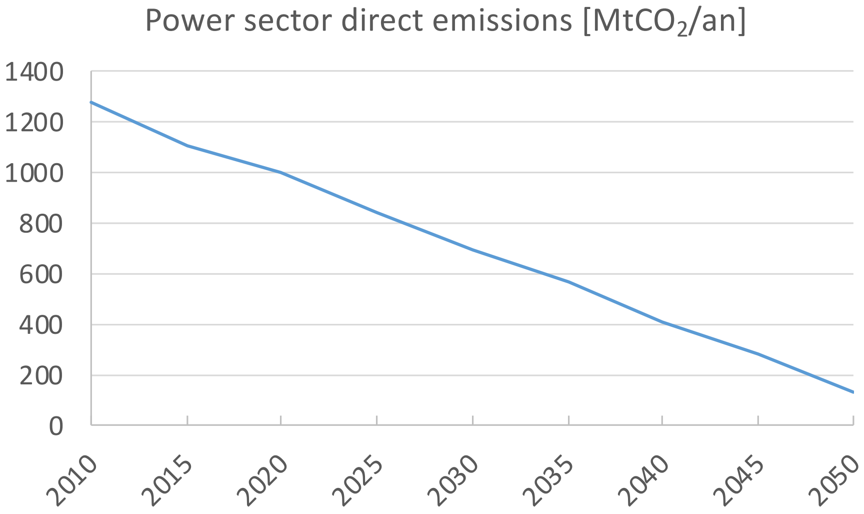
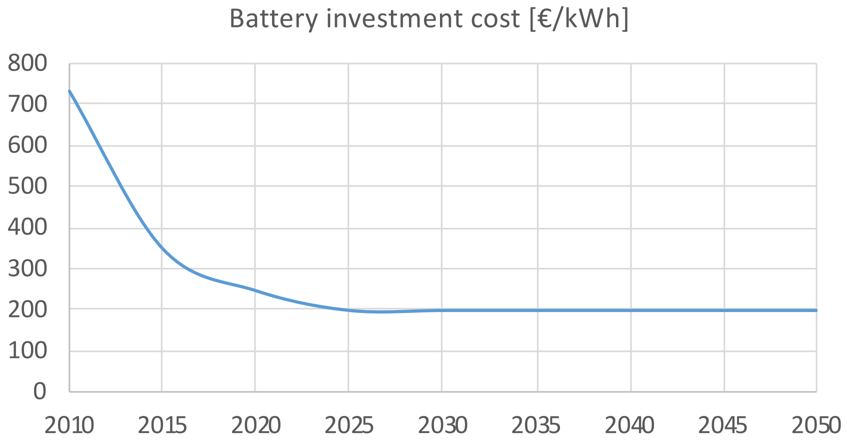
Scenario assumptions

1. Baseline decarbonization: **90 % emission reduction from 2010 to 2050**
    - i. Grid expansion towards 2020 fixed to ENTSO-E's 2016 TYDP reference capacities.
        - i. Beyond 2020: expansion limit of 4 GW for each interconnector every five year period
    - ii. Capacity limits for selected technologies
        - i. Wind onshore capacity potential from IEA's NETP 2016.
        - ii. Solar limited to cover no more than 14% of a country's area (assuming 150 W/m^2)
        - iii. Nuclear capacities limited
    - iii. RES targets defined for Germany, France, Great Britain and Spain
    - iv. Development of Norwegian hydro power predefined

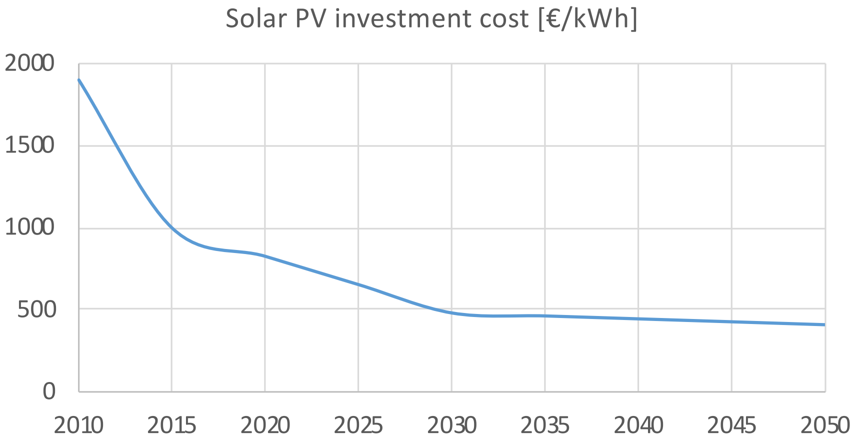
2. Alternative scenario NoCCS: same as baseline but no carbon capture and storage available



Medium optimistic assumptions for “decentral” technologies



Source: Cole, W. J., Marcy, C., Krishnan, V. K., & Margolis, R. (2016). Utility-scale lithium-ion storage cost projections for use in capacity expansion models. DOI:doi.org/10.1109/NAPS.2016.7747866



Source: PV: Fraunhofer ISE. (2015). Current and Future Cost of Photovoltaics. Long-term Scenarios for Market Development, System Prices and LCOE of Utility-Scale PV Systems. Agora Energiewende.

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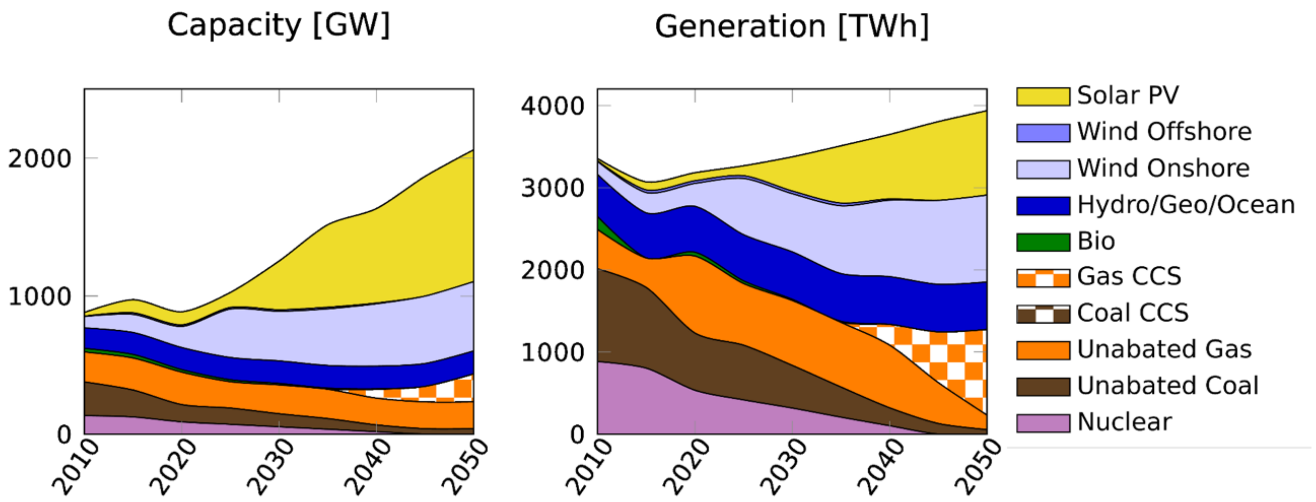
Baseline scenario: 90 % emission reduction



Technology/fuel (2050)	Capacity [GW]	Generation [TWh]
Solar	954 (46%)	1026 (26%)
Wind	503 (24%)	1057 (27%)
Gas CCS	204 (10%)	1043 (26%)
Coal CCS	0 (0%)	0 (0%)
Fossil unabated	233 (11%)	231 (5%)
Others	166 (8%)	578 (15%)

Battery energy storage by 2050: 99 GWh

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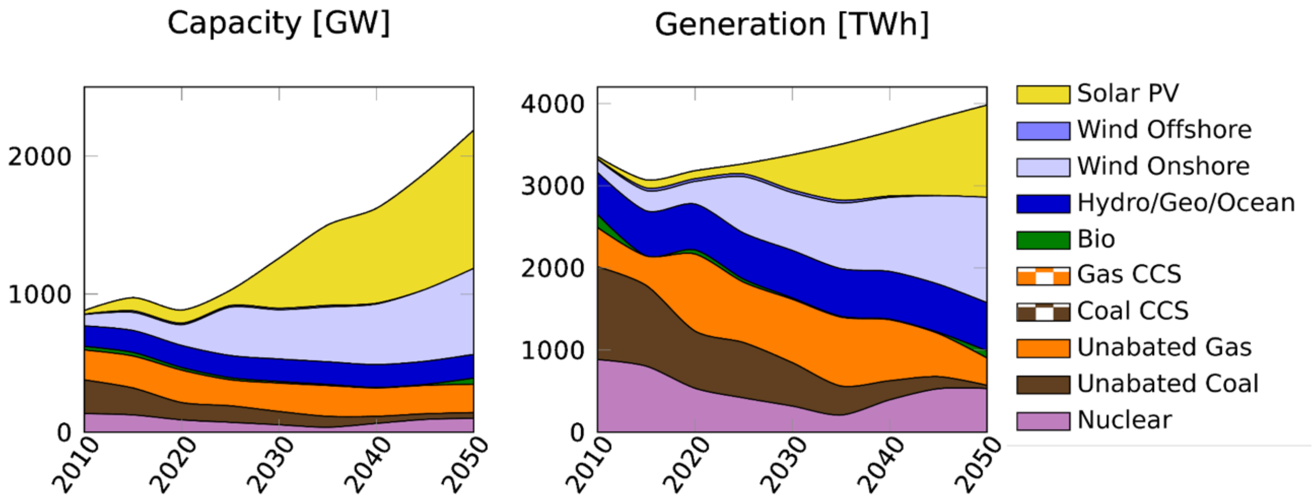
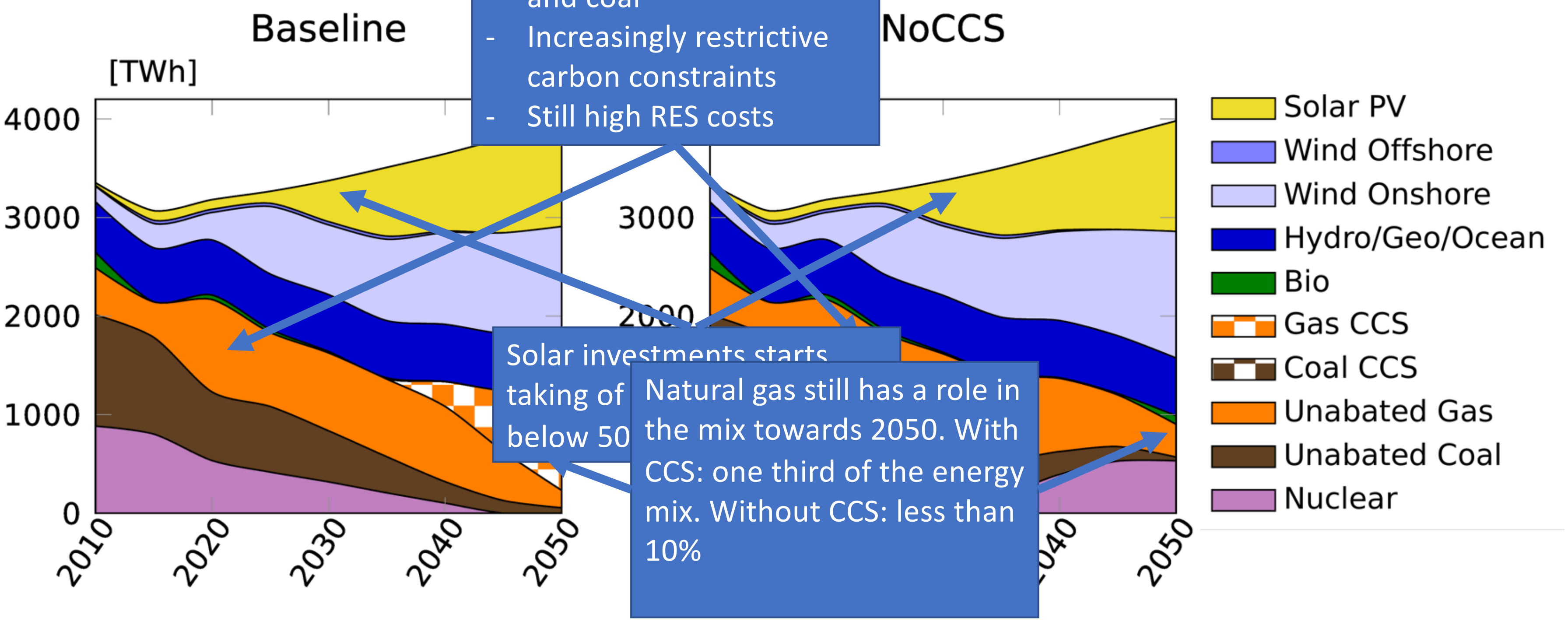
NoCCS scenario: 90 % emission reduction



Technology/fuel (2050)	Capacity [GW]	Generation [TWh]
Solar	1001 (46%)	1120 (28%)
Wind	623 (28%)	1284 (32%)
Gas CCS	0 (0%)	0 (0%)
Coal CCS	0 (0%)	0 (0%)
Fossil unabated	247 (11%)	371 (9%)
Others	316 (15%)	1204 (30%)

Battery energy storage by 2050: 339 GWh

Transition to a low- n power sector



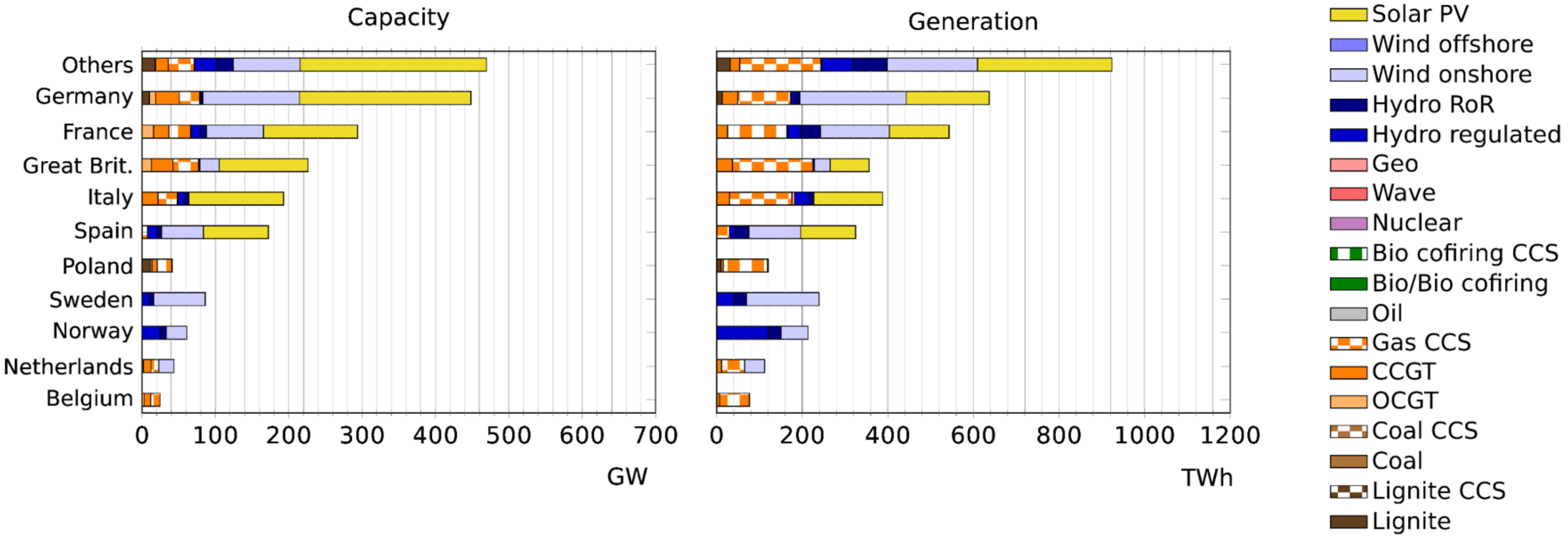
Increased shared of unabated natural gas in the medium term. Due to

- Retirement of nuclear and coal
- Increasingly restrictive carbon constraints
- Still high RES costs

Solar investments starts taking of below 50

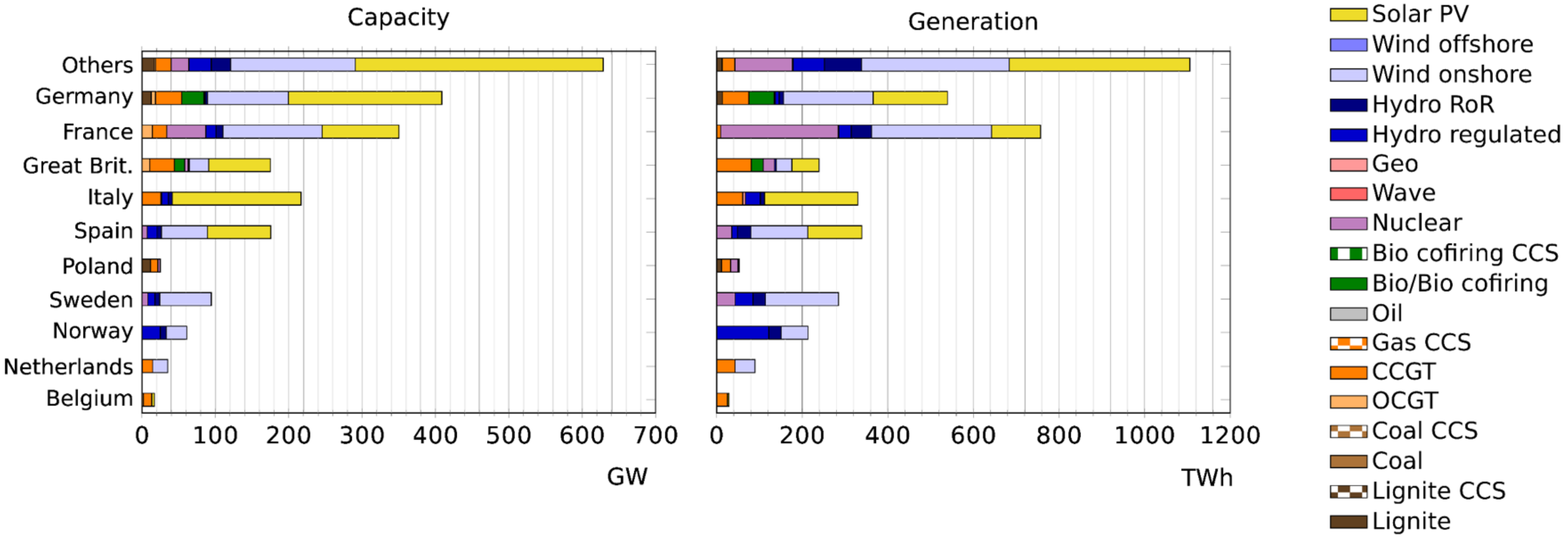
Natural gas still has a role in the mix towards 2050. With CCS: one third of the energy mix. Without CCS: less than 10%

Baseline country results 2050



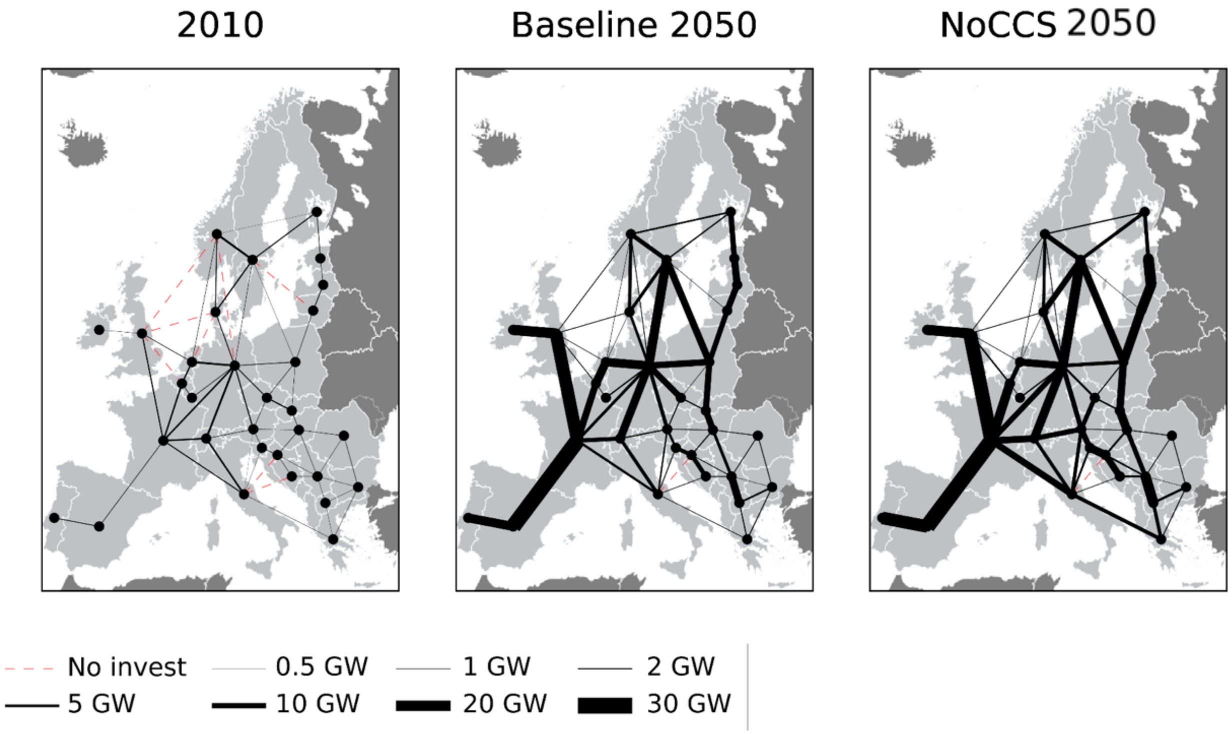
Source: CenSES position paper Norway as a flexibility provider to Europe, in preparation.

NoCCS country results 2050



Source: CenSES position paper Norway as a flexibility provider to Europe,
in preparation.

Transmission



Baseline
European cross-boarder interconnector expansion: capacity increases by 644 % from 2010 to 2050

NoCCS
Capacity increases by 826 % from 2010 to 2050

Selection of flexibility options 2050

Scenario	Baseline			NoCCS		
	Gas (GW)	Trans. (GW)	Battery (GWh)	Gas (GW)	Trans. (GW)	Battery (GWh)
With transmission exp.	398	416	99	206	533	339
Limited transmission exp.	442	121	86	247	121	646

Scenario	Baseline		NoCCS	
	Curtail energy (TWh/an)	Avg. elec. Cost (€/MWh)	Curtail energy (TWh/an)	Avg. elec. Cost (€/MWh)
With transmission exp.	60	51	74	56
Limited transmission exp.	83	54	104	64

Alternatives to transmission

FIRST CONCLUSION:

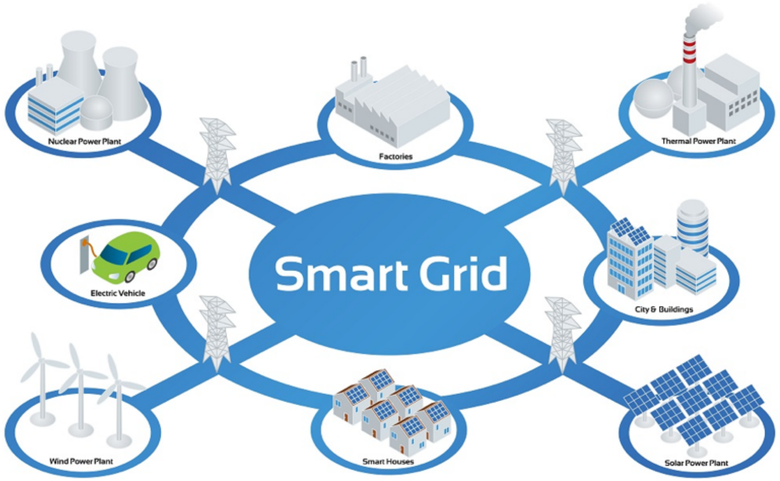
There is a high need for flexibility in the future system

In the studies I have shown, transmission investment seems to be the solution.

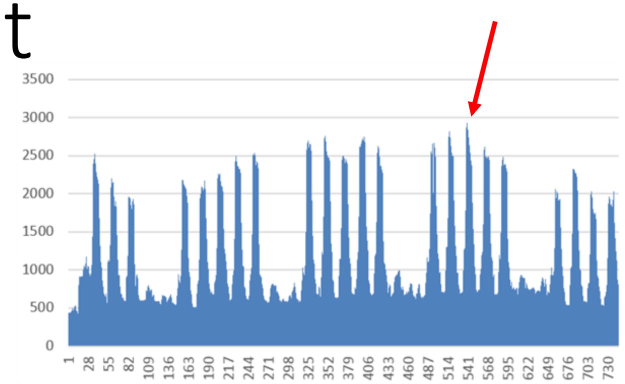
NEW DRIVERS:

- Demand side flexibility
- The merger of the power system and ICT

How will this affect the transition to a near zero emission power system?

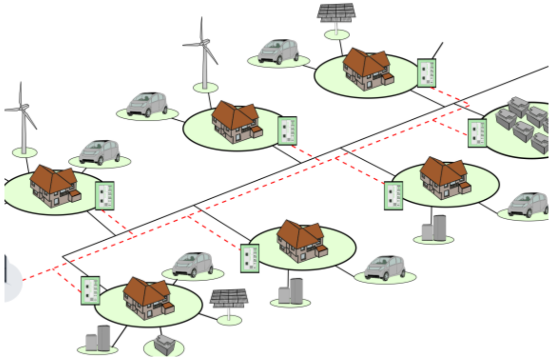


Changes in the electricity market



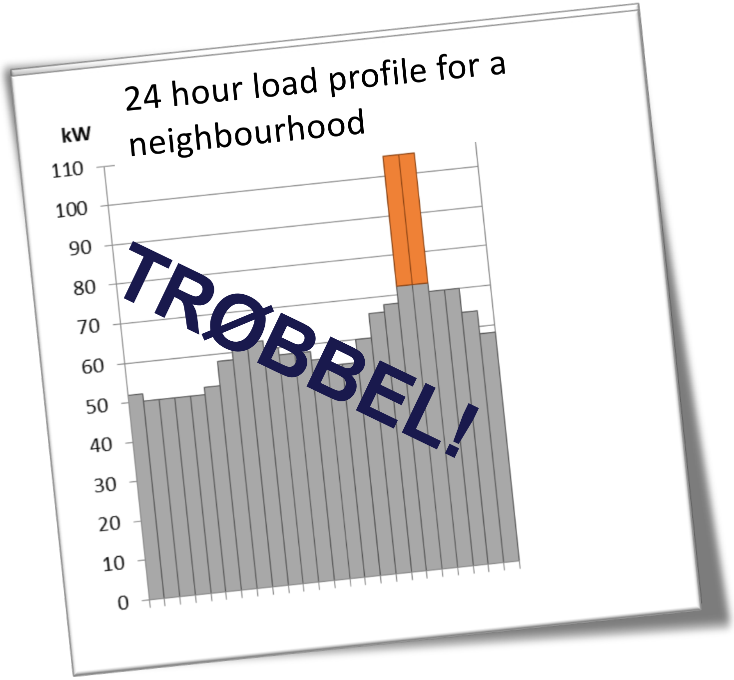
- New contract types and business models
  - Complex and dynamic price models
  - Penalization for peaks (demand charges)
  - Reward from providing flexibility

- Market participant changes
  - Passive consumer => flexible prosumer
  - New-comers: Energy Service Companies (ESCo), Aggregators ++



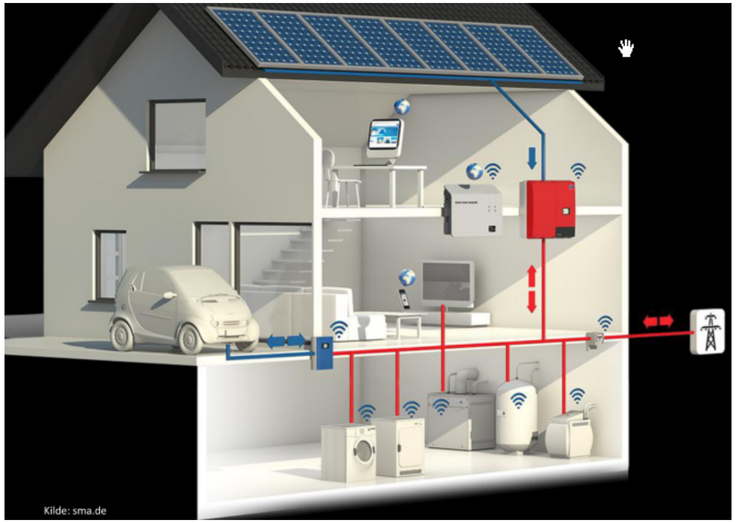
- New markets and changes in market rules
  - More focus on (close to) real time
  - Local markets

Challenge: ”Trouble in the neighbourhood”



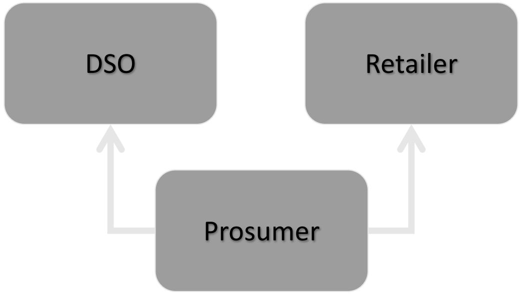
SmartGrid

- Active interaction between smart end users and the energy system/market to create benefits in the value chain

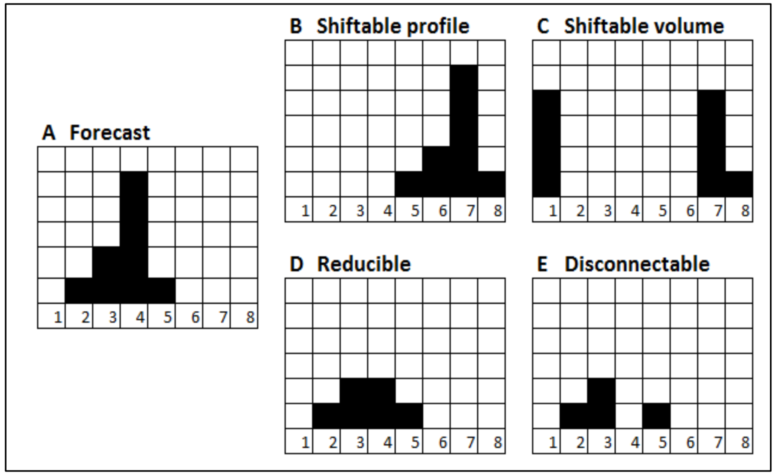

Kilde: sma.de

- Demand side flexibility
- Why this flexibility has an increasing value
  - New distributed renewable energy generation
  - Electric vehicles creating peak problems
- Local challenges must be met by local solutions
- Need proper decision models

A stochastic model for scheduling energy flexibility in buildings



- Context: A prosumer in the end-user market
- Problem: *How to schedule flexible units to minimize total energy-related costs*?
- Develop a basic model for demand side flexibility used throughout the thesis
  - Load units classified according to their flexibility properties:
    - Shiftable (in time)
      - Profile: Start time can be changed, but profile must be kept
      - Volume: Profile can be altered
    - Curtailable
      - Reducible: Load can be reduced without disconnection
      - Disconnectable: On or off
    - Inflexible



Optimization model

- Objective: Minimize expected total costs

$$\min z = \sum_{s\in S} R_s \cdot \left[\begin{array}{l} \sum_{a\in A}\sum_{t\in T} P^{energy}_{a,t,s}\,\chi^{net-in}_{a,t,s} + \sum_{a\in A} P^{cap}_{a}\,\chi^{cap}_{a,s} + \sum_{y\in Y}\sum_{o\in O}\sum_{t\in T}\alpha^{start}_{o,y,t,s}\,G^{startup}_{y,o} + \\ \sum_{d\in D^C}\sum_{y\in Y}\sum_{t\in T} X_{d,y}\,\varphi_{d,y,t,s} - \sum_{a\in A}\sum_{t\in T} P^{sales}_{a,t}\,\chi^{net-out}_{a,t,s} \end{array} \right]$$

- Subject to:
  - Energy source constraints
  - Converter constraints
  - Storage constraints
  - Load constraints
  - Energy system balances
- Stochastisk mixed integer problem (SMIP)

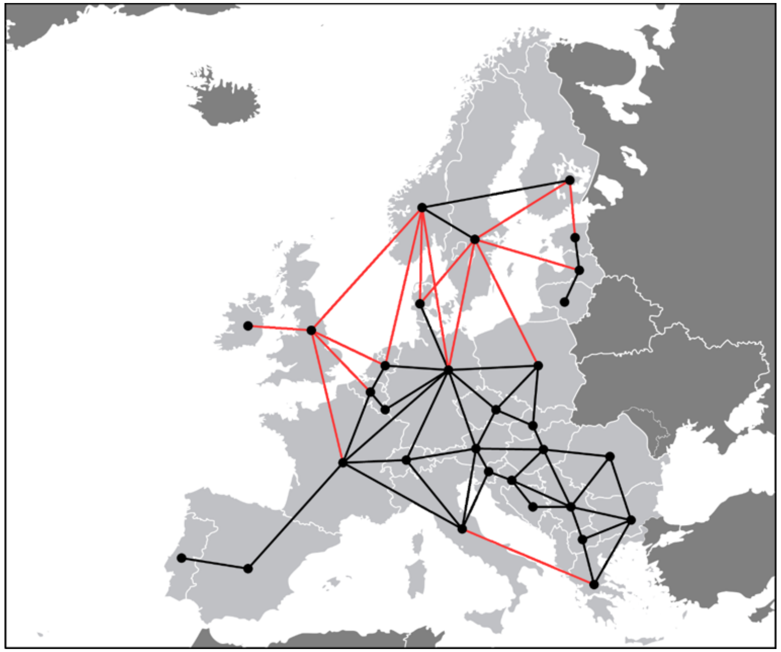
Demand response as a technology in EMPIRE

Demand Response module in EMPIRE : in testing now

Multiscale geographical representation

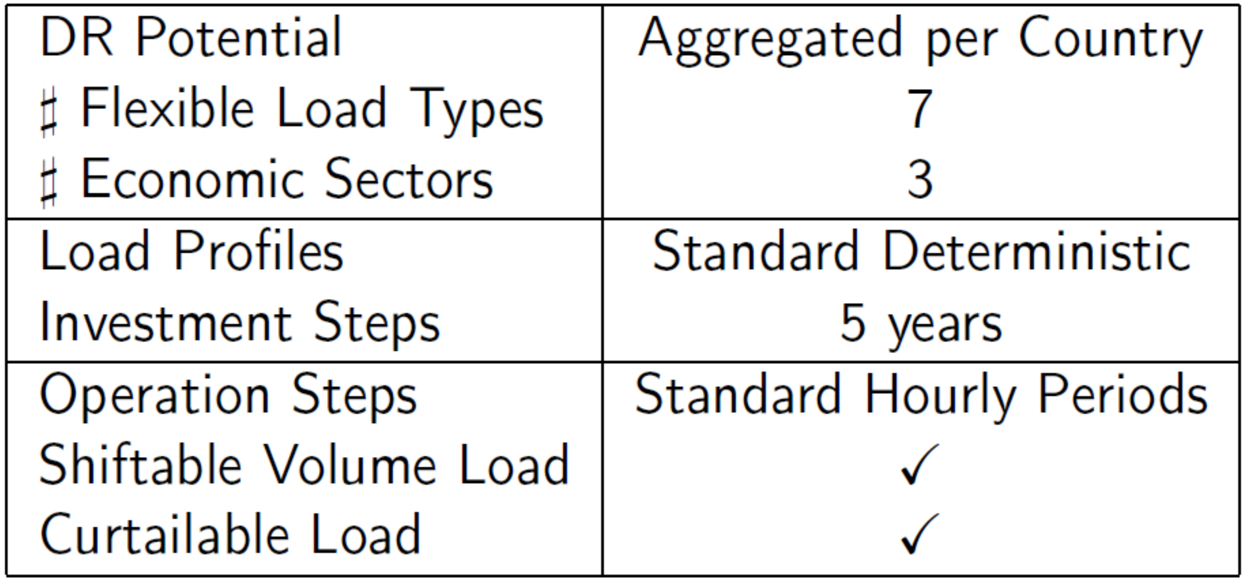
- Countries
- Regions
- Neigbourhoods

Kilde: 3M, Smart Grid: http://solutions.3m.com/wps/portal/3M/en_EU/SmartGrid/EU-Smart-Grid/



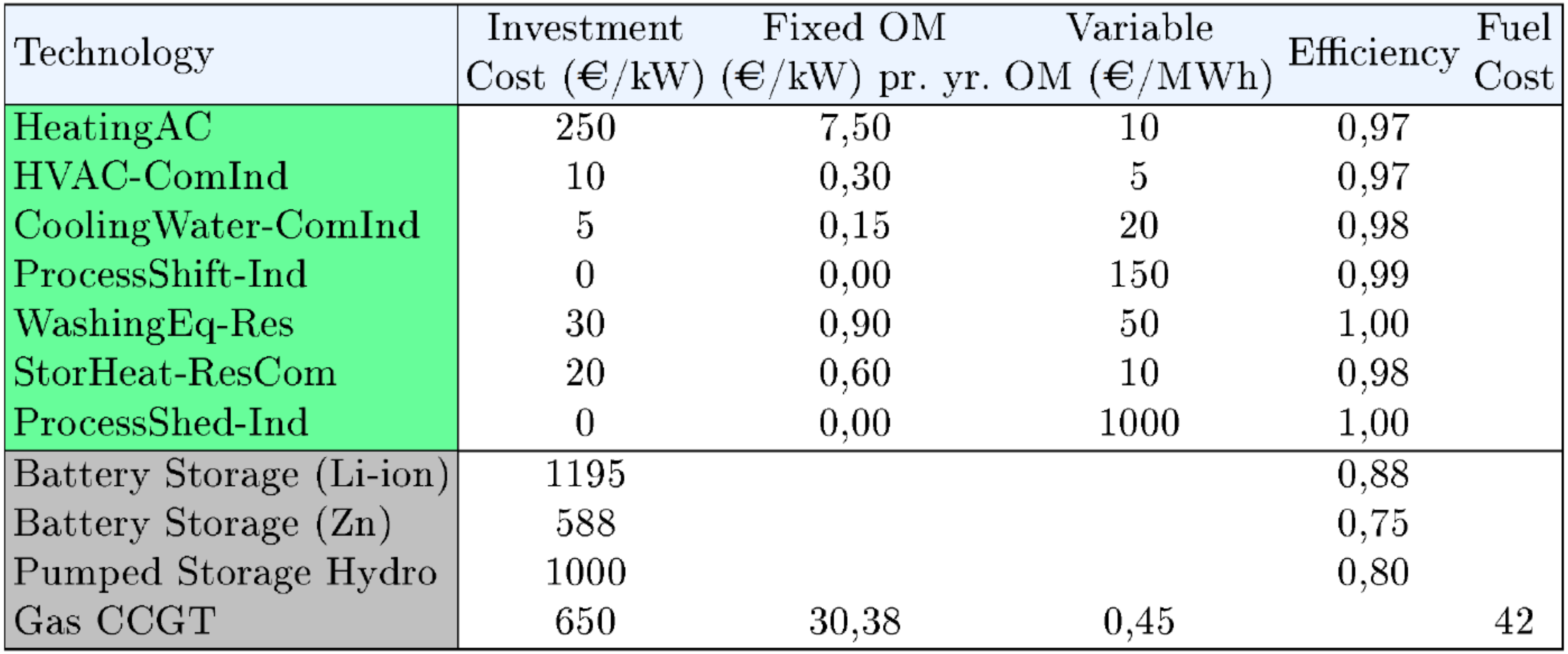
How does it change the technology mix?

Demand Response (DR) module



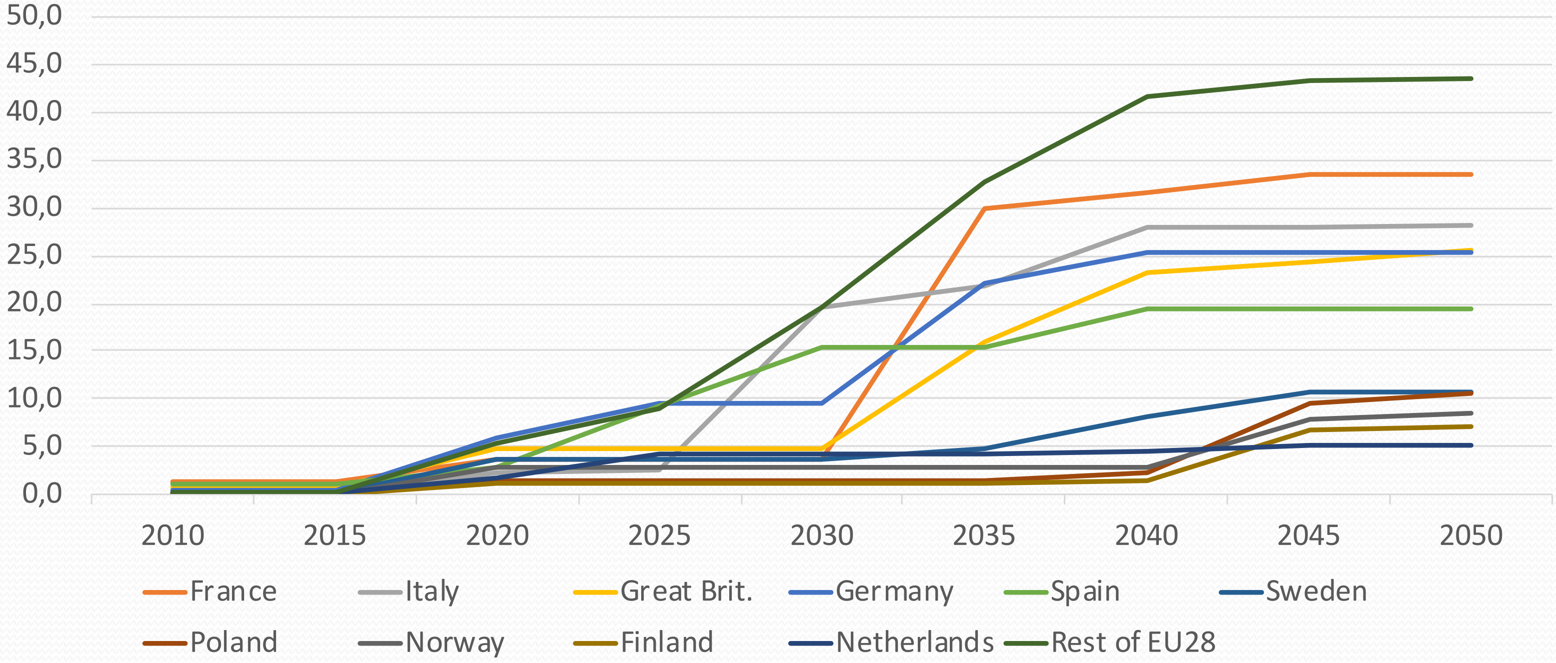
DR Potential	Aggregated per Country
♯ Flexible Load Types	7
♯ Economic Sectors	3
Load Profiles	Standard Deterministic
Investment Steps	5 years
Operation Steps	Standard Hourly Periods
Shiftable Volume Load	✓
Curtailable Load	✓

DR costs characteristics



Technology	Investment Cost (€/kW)	Fixed OM (€/kW) pr. yr.	Variable OM (€/MWh)	Efficiency	Fuel Cost
HeatingAC	250	7,50	10	0,97	
HVAC-ComInd	10	0,30	5	0,97	
CoolingWater-ComInd	5	0,15	20	0,98	
ProcessShift-Ind	0	0,00	150	0,99	
WashingEq-Res	30	0,90	50	1,00	
StorHeat-ResCom	20	0,60	10	0,98	
ProcessShed-Ind	0	0,00	1000	1,00	
Battery Storage (Li-ion)	1195			0,88	
Battery Storage (Zn)	588			0,75	
Pumped Storage Hydro	1000			0,80	
Gas CCGT	650	30,38	0,45		42

DR capacity evolution (GW)



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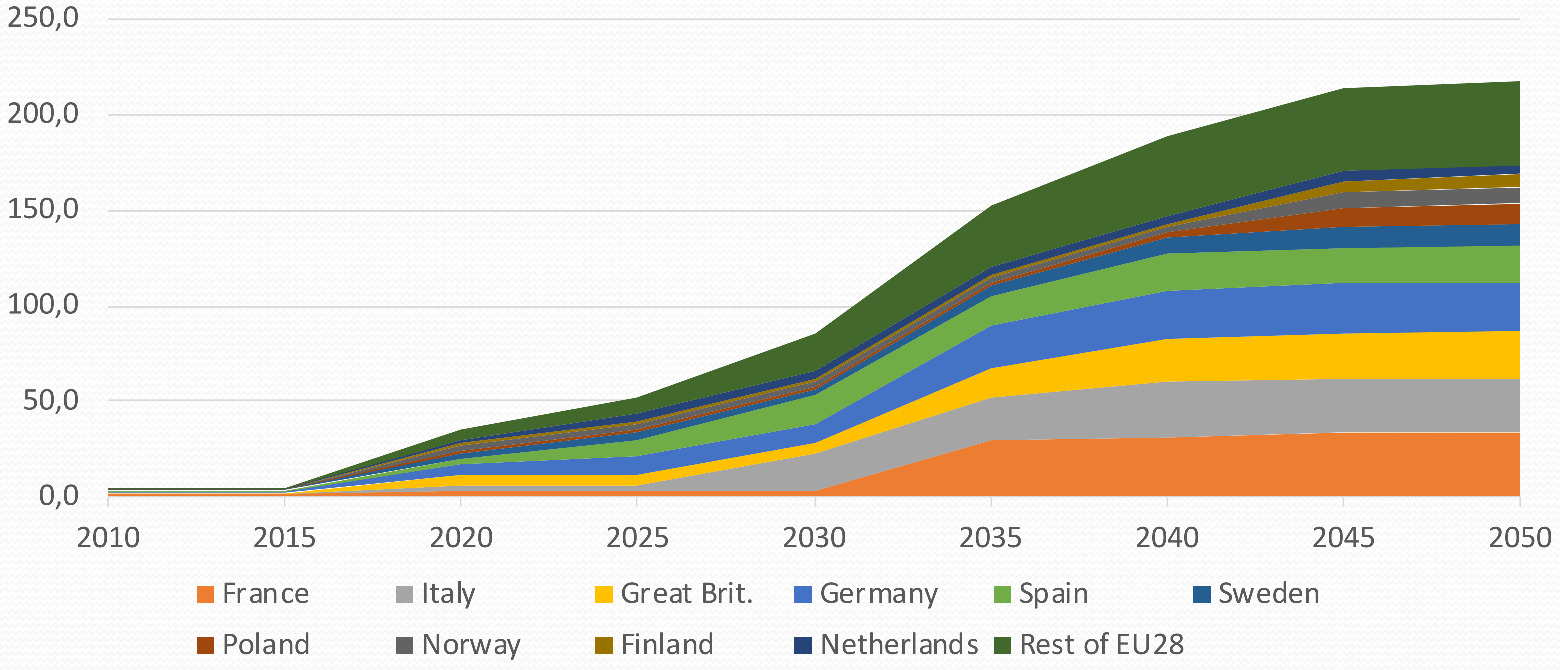
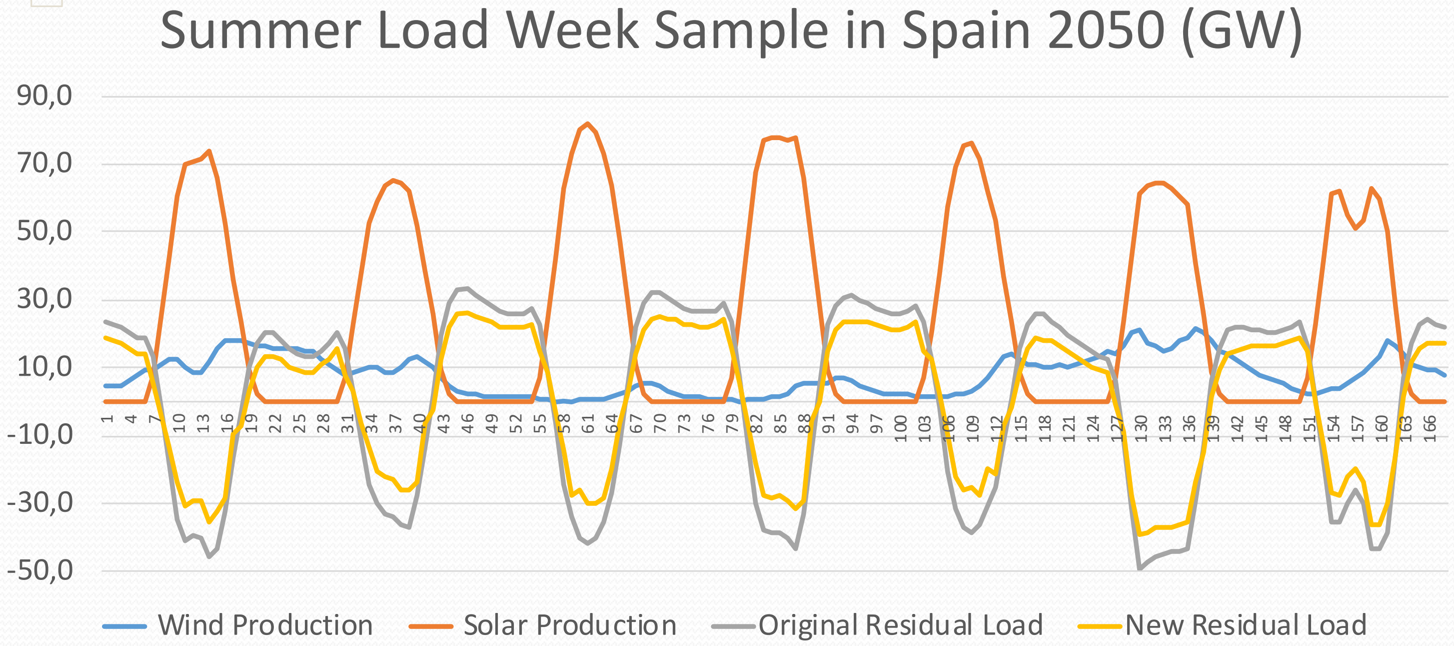
DR capacity evolution in Europe (GW)





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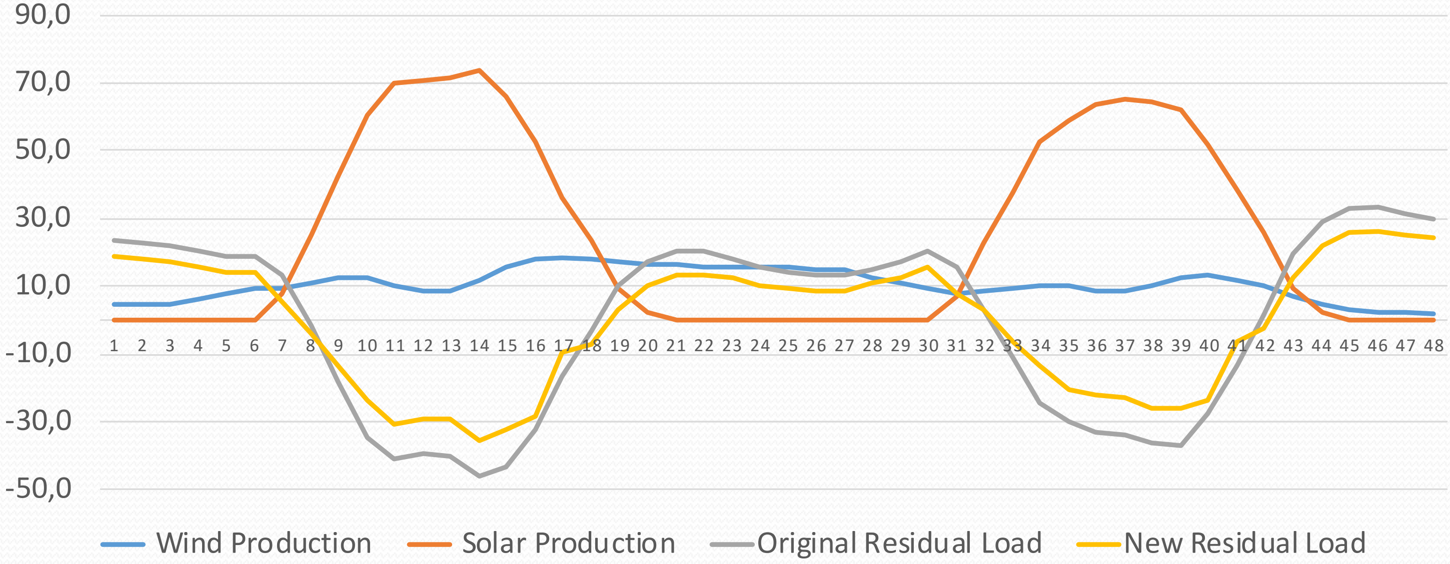
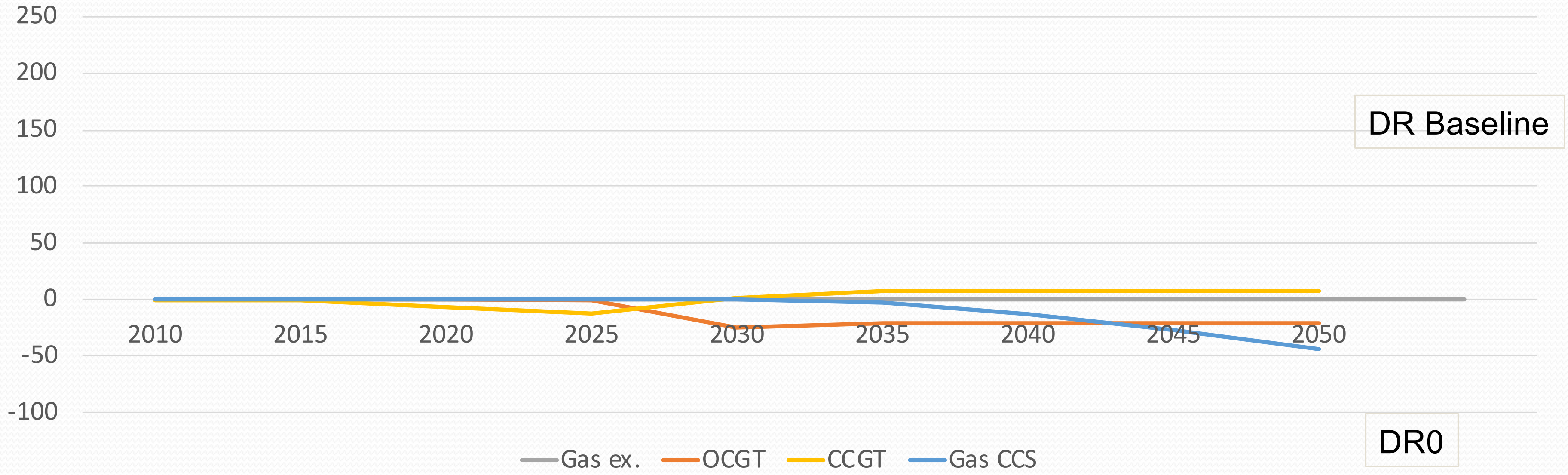
Summer Load 2-day Sample in Spain 2050 (GW)



Capacities comparison between DR2 and DR0

- The following bar graphs show the main differences in technology capacities in the case with DR (case DRB) and without (case DR0) between year 1 (2010) and year 9 (2050).
- The positive y-axis indicate larger capacity in DRB than in DR0 and viceversa

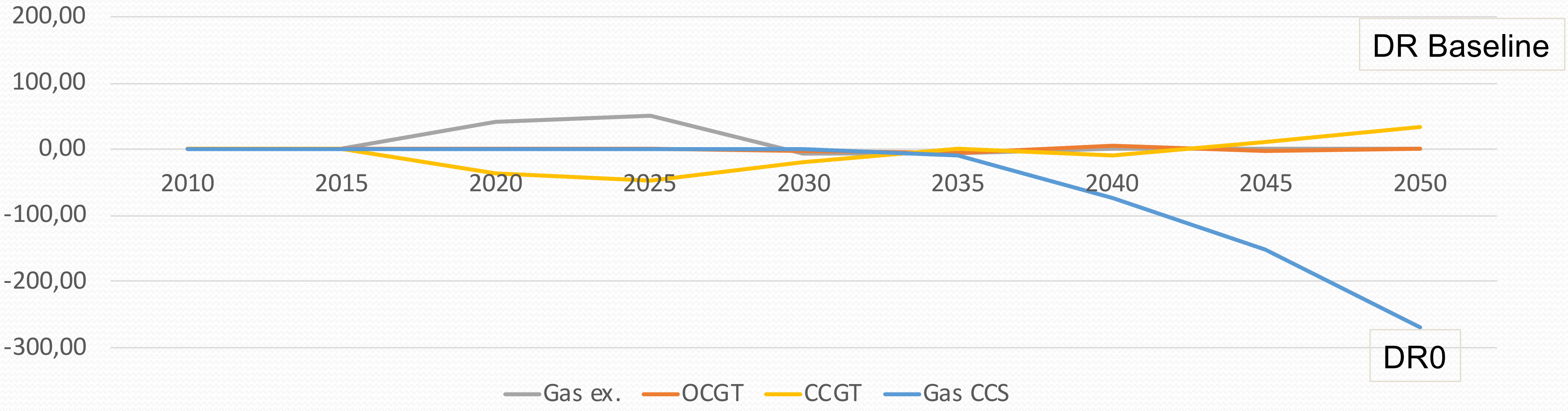
Europe's peak plants capacity differences (GW)



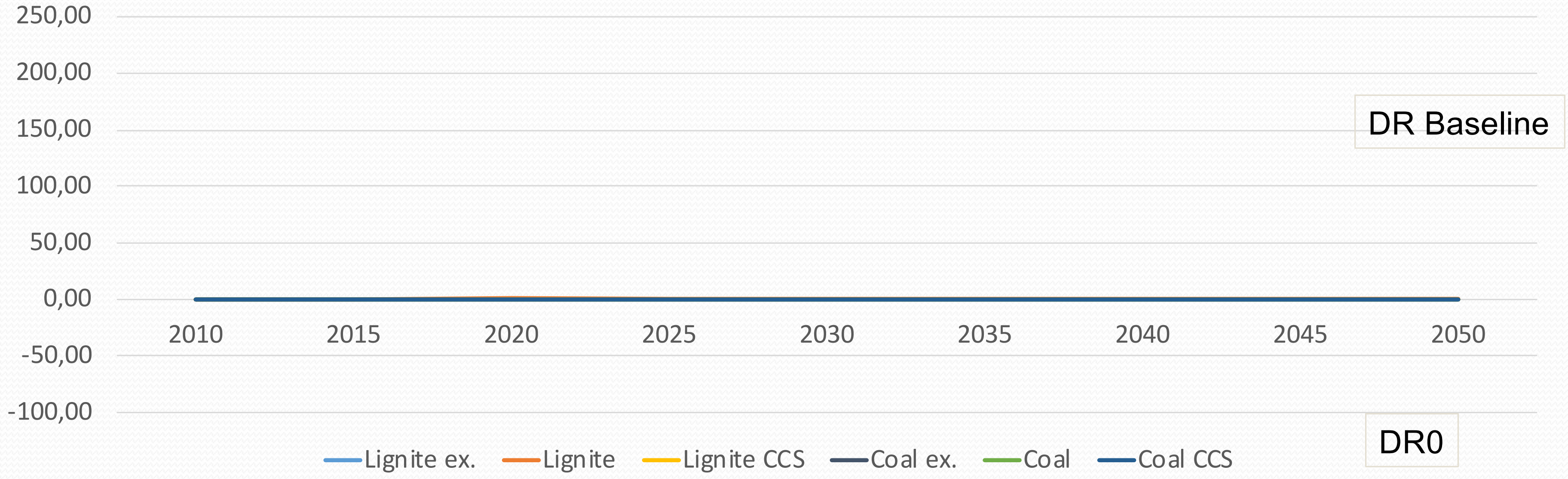
DR Baseline

DR0

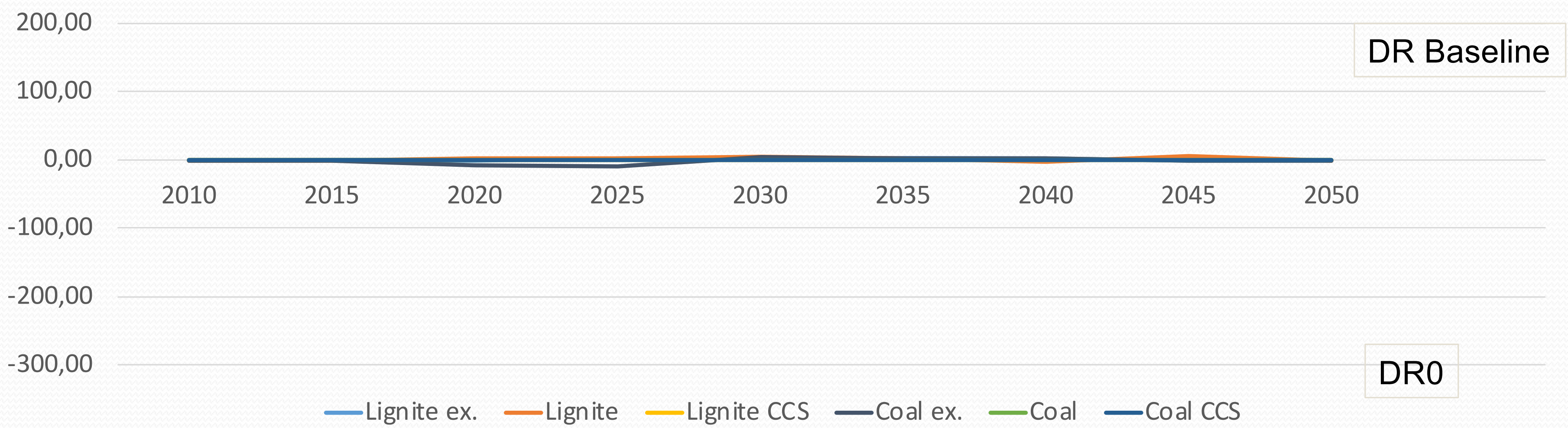
Europe's peak plants generation differences (TWh)



Europe's coal capacity differences (GW)



Europe's coal generation differences (TWh)



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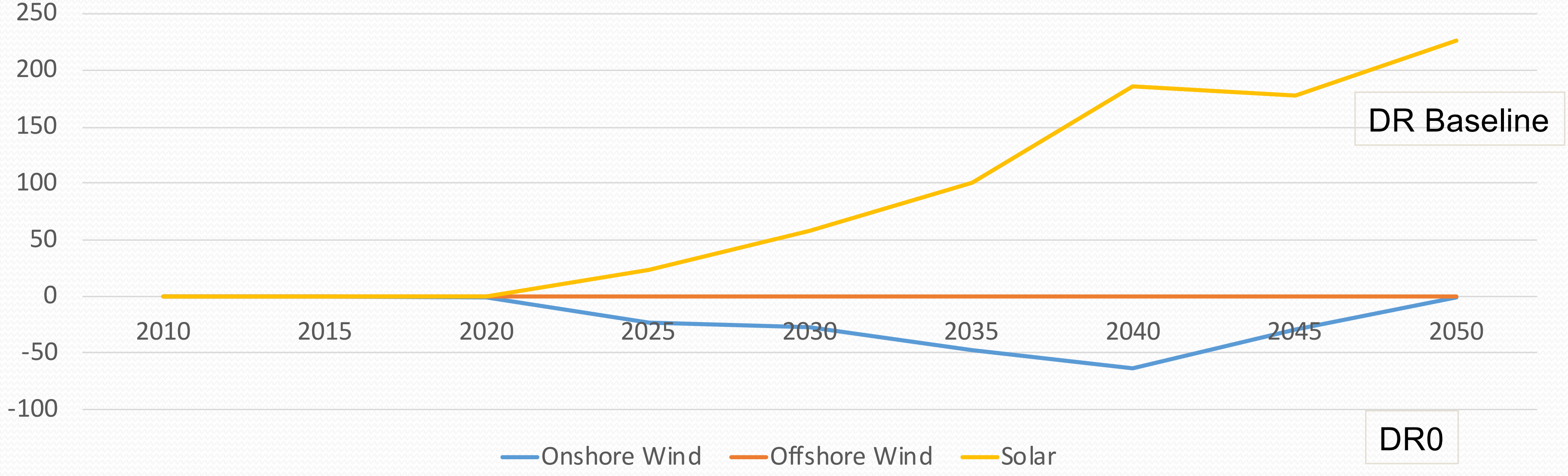
Europe's IRES capacity differences (GW)



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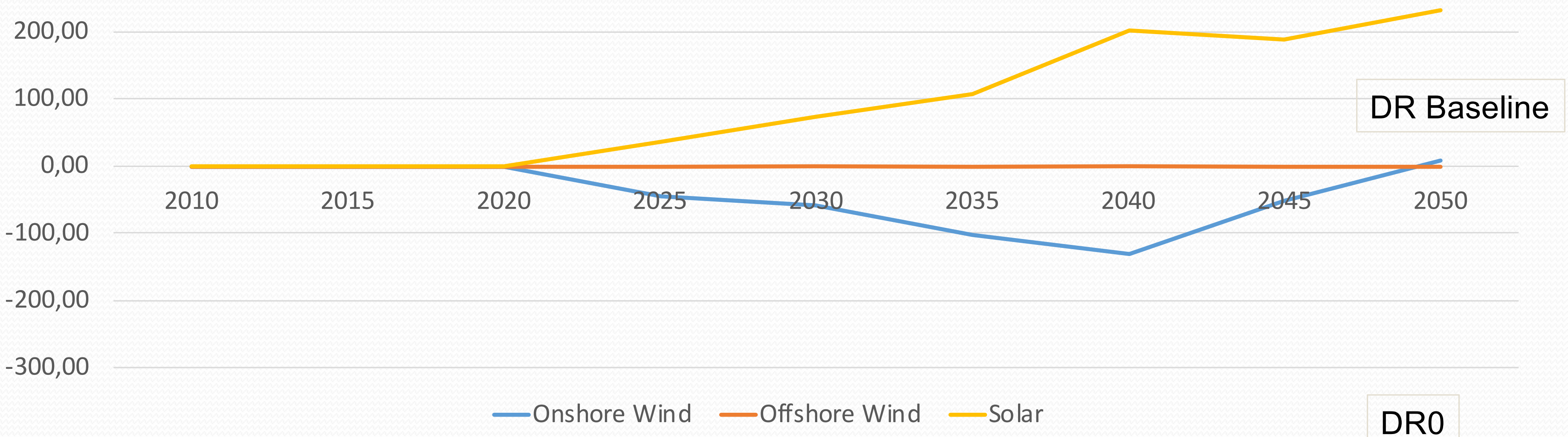
Europe's IRES generation differences (TWh)



DR Baseline

DR0

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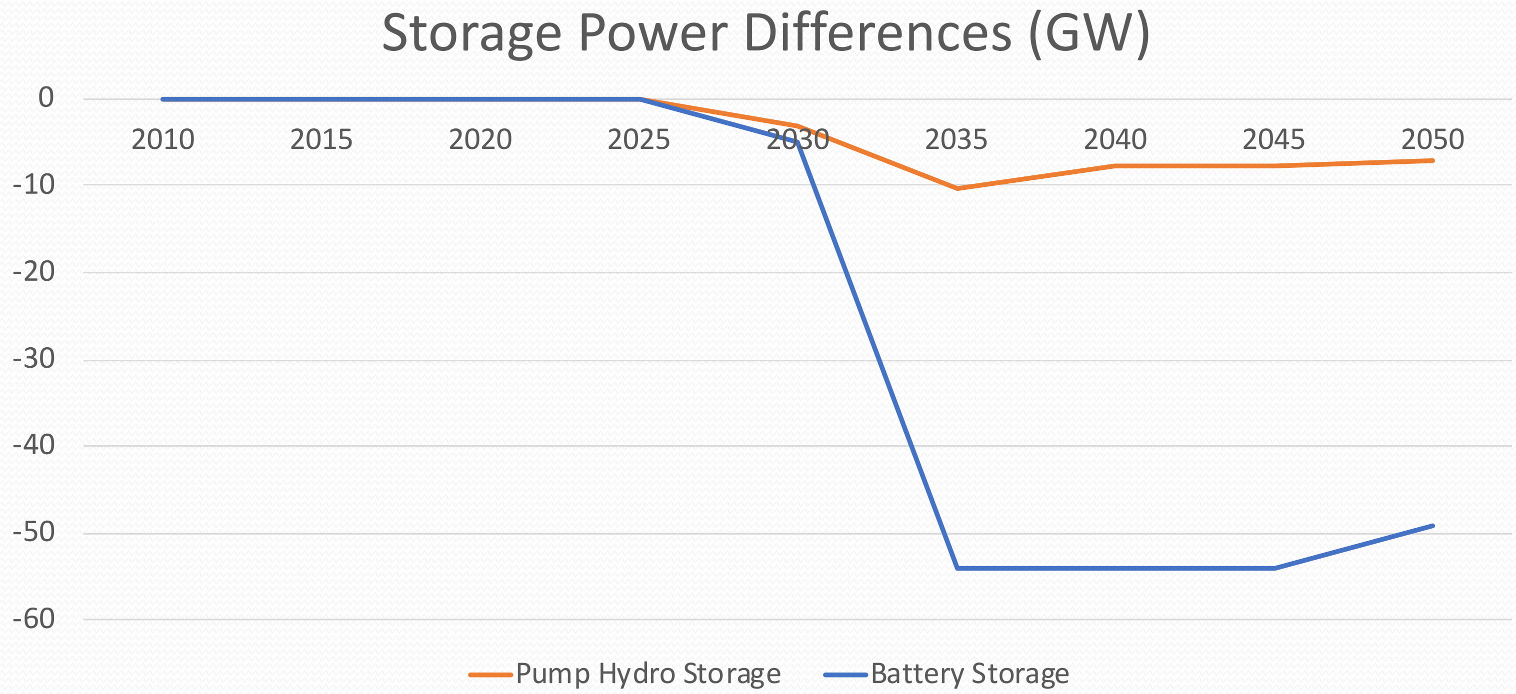
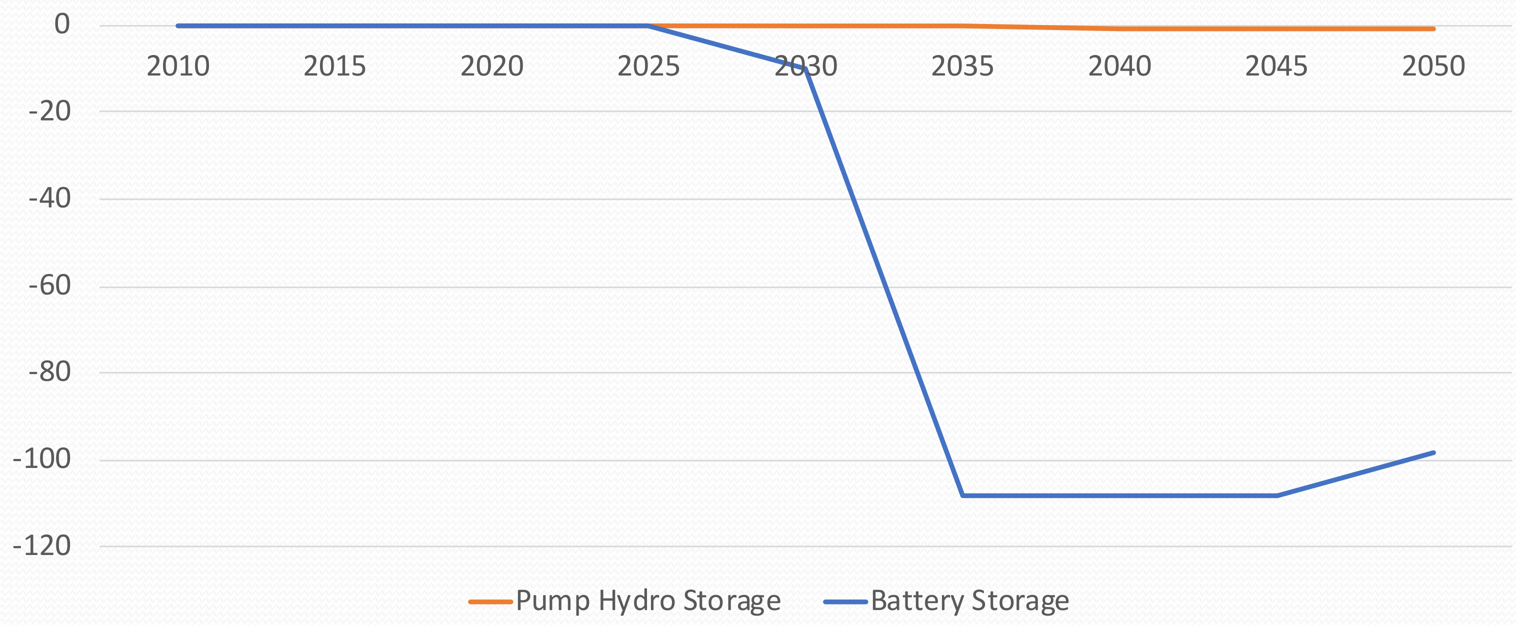
DR Baseline

DR0



Storage Energy Differences (GWh)



DR Baseline

DR0

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Summary

- New technologies increase the need for flexibility at different levels
- New technologies increase the potential for flexibility provision from demand side
- Flexibility can create values at different levels (prosumer, DSO, TSO…)
- Aggregation needed
- The aggregator’s decision problem is a complex task
- Demand response will put pressure on other technologies, both transmission and other flexibility sources.

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TACEMM winter school Energy market modelling March 3-8 Kvitfjell, Norway

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- **July 27 and 28: Pre-conference tutorials**
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