Modeling energy and climate policy using multihorizon stochastic programming

Workshop: Optimization and Equilibrium in Energy Economics

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Outline

Climate policy modeling and decarbonization studies

- Application of partial-equilibrium or optimization models for analyzing energy system (or individual sectors, e.g. the power sector)
- Usually focus on
  - Cost of a policy
  - Effectiveness
  - Technology selection
  - Cost of electricity (in the case of power system studies)
- Multi-annual, considering both investments and system operation.
- Very often deterministic models are used
- This can be problematic when there is a great deal of uncertainty in the system

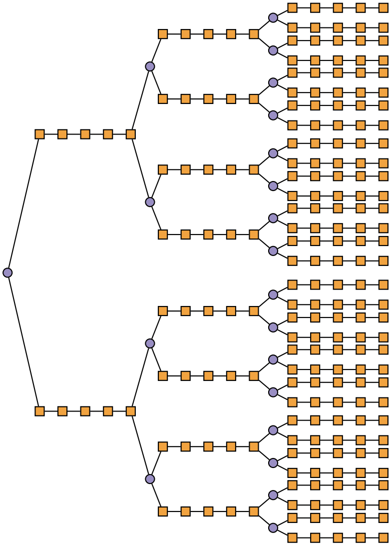
Multi-stage multi-scale stochastic programming

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 ■



What if today's operation doesn't say much about the future?

- Suppose that observing realizations of short-term uncertainty now don't reveal useful information about future strategic uncertainty
  - Example: knowing the wind profile for this year doesn't say much about long-term fuel price development
- What about future short-term uncertainty?
  - Observing this year's wind profile may perhaps say something about the probabilities for observing given future profiles
  - However, if we assume the uncertainty is static it won't necessarily.
- How dependent are future investments and future operational decisions dependent on what you do today?

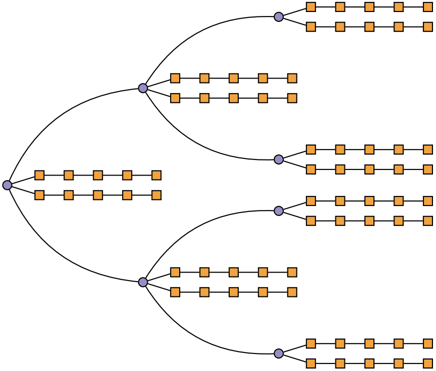
Multi-horizon stochastic programming[1]

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

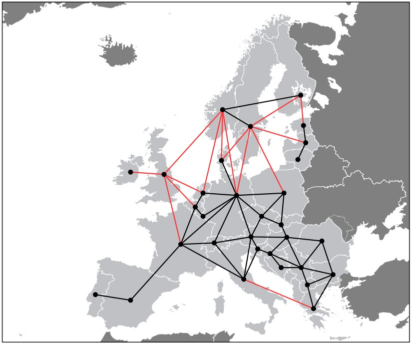


Reduces tree size by a factor of

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

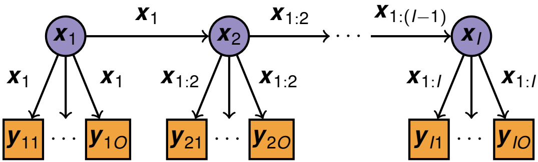
[1] Kaut, M., K. T. Midthun, A. S. Werner, A. Tomasgard, L. Hellemo, and M. Fodstad. 2014. “Multi-horizon stochastic programming.” *Computational Management Science* 11(1–2): 179–193. doi:10.1007/s10287-013-0182-6.

EMPIRE



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

EMPIRE multi-horizon structure



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

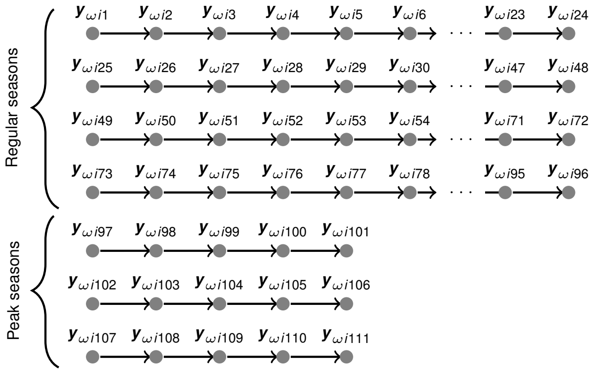
Mathematical formulation of EMPIRE

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

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

EMPIRE: operational modeling $\boxed{\boldsymbol{y}_{\omega i}}$

For a given period i, the elements in $\boldsymbol{y}_{\omega i}$ have the following temporal relation



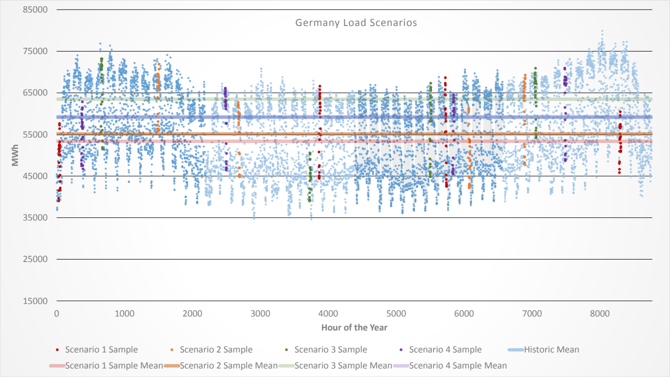
In the objective function:

$$\boldsymbol{q}_i^\top \boldsymbol{y}_{\omega i} = \sum_{s \in \mathcal{S}} \alpha_s \Big\{ \sum_{h \in \mathcal{H}_s} \boldsymbol{q}_i^\top \boldsymbol{y}_{\omega i h} \Big\}$$

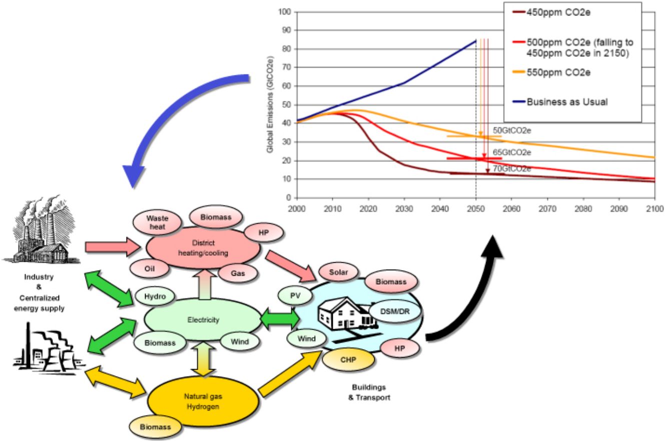
Uncertainty modeled in EMPIRE

- Wind profiles
- Solar profiles
- Load
- Hydro power energy limits

Scenarios generated by a simple moment matching scheme sampling time-segments from multi-annual time series.

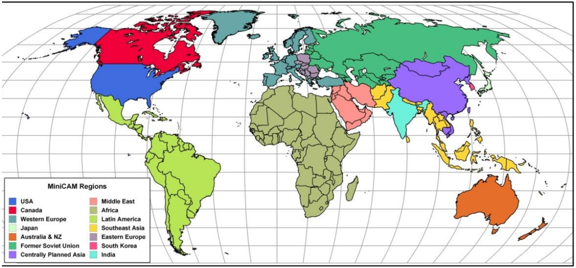


Study: Linking Global and Regional Energy Strategies

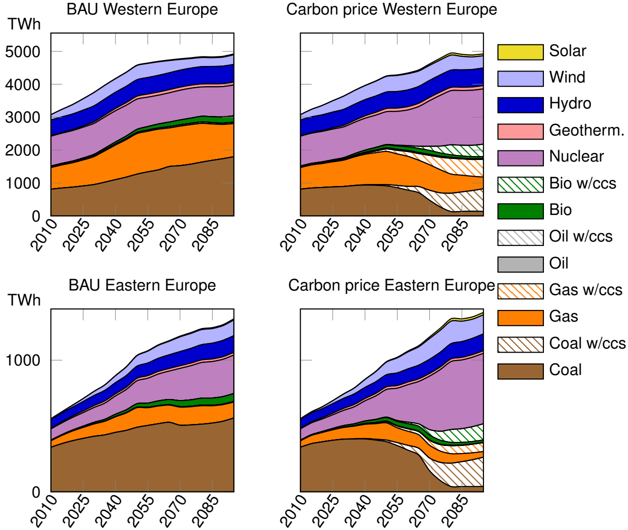


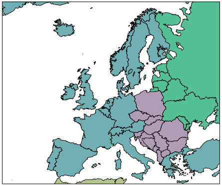
Global Change Assessment Model (GCAM)

- An integrated assessment model
- Developed and maintained by Joint Global Change Research Institution in Maryland.
- Used for analyzing climate change mitigation policies
- 14 (energy) regions
- Annual demand and energy mix available in 5 year intervals
- Horizon: 2100



GCAM power sector results Europe

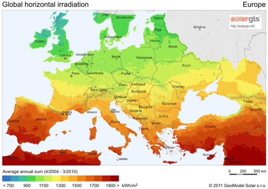




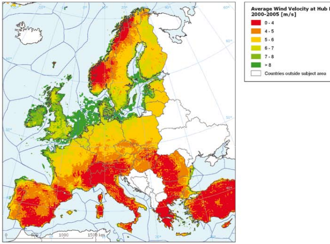
- Annual results
- No explicit generation capacities
- No transmission system

Spatial variability of electricity

(a) Electricity consumption (source: ENTSO-E)

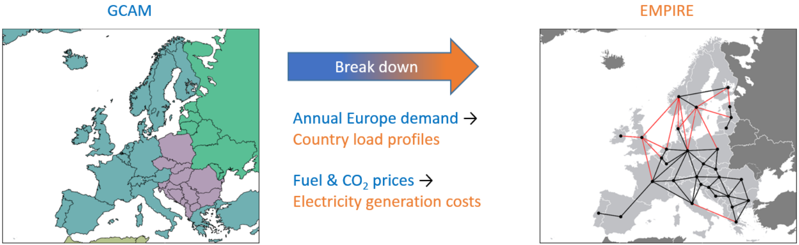


(b) Average solar irradiation (source: solargis)



(c) Wind field data (source: EEA)

EMPIRE linked to GCAM

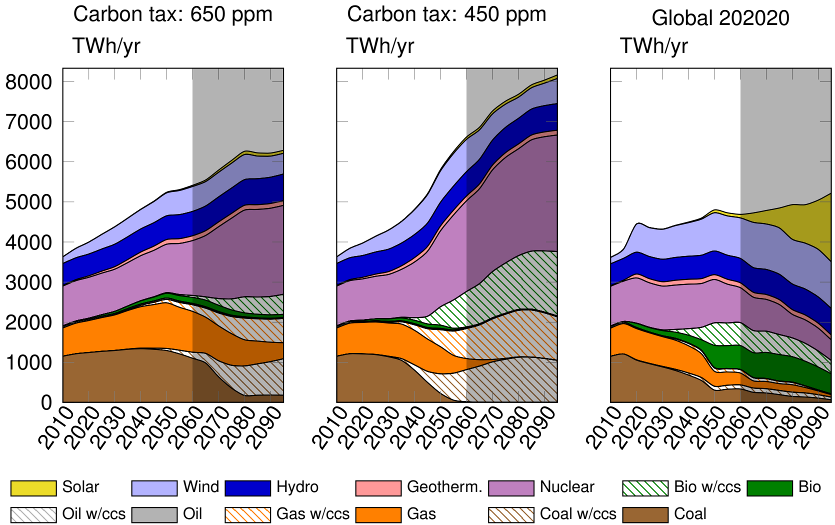


- Constrain the annual European generation mix to match GCAM

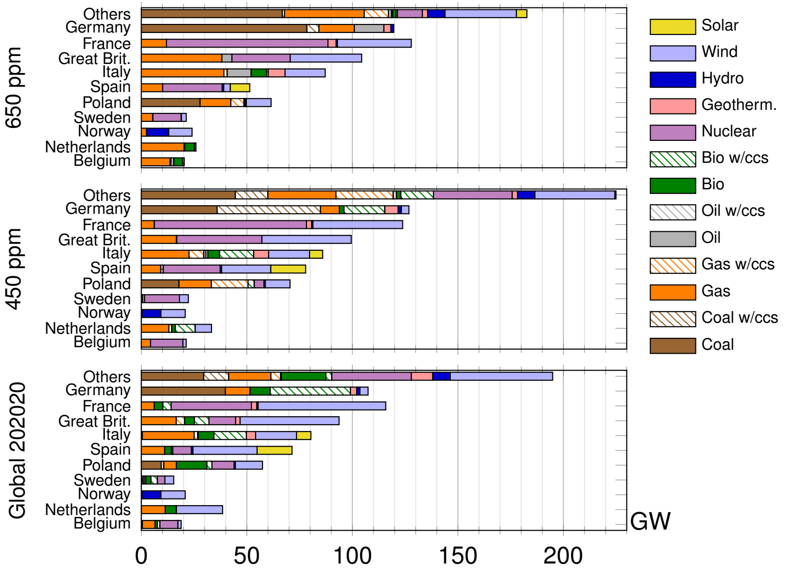
Top-level GCAM scenarios

- 450/650 ppm stabilization scenario (EMF-22)
  - A policy scenario where the atmospheric concentration of greenhouse gases is limited to 450 ppm CO2-eq by the end of the century. Emission reduction is achieved by implementing a carbon price
- Global 202020 scenario
  - A policy scenario inspired by the European 20-20-20 targets.Renewable portfolio standards, energy efficiency improvements and share of bio fuel in the transportation sector are set for different regions across the world.

GCAM electricity mix for Europe



Investments generation by 2050 from EMPIRE



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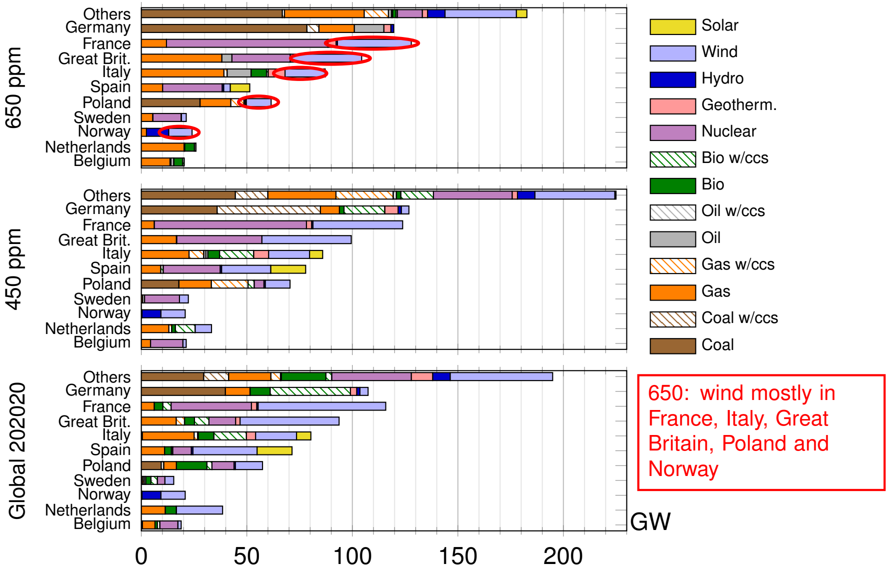
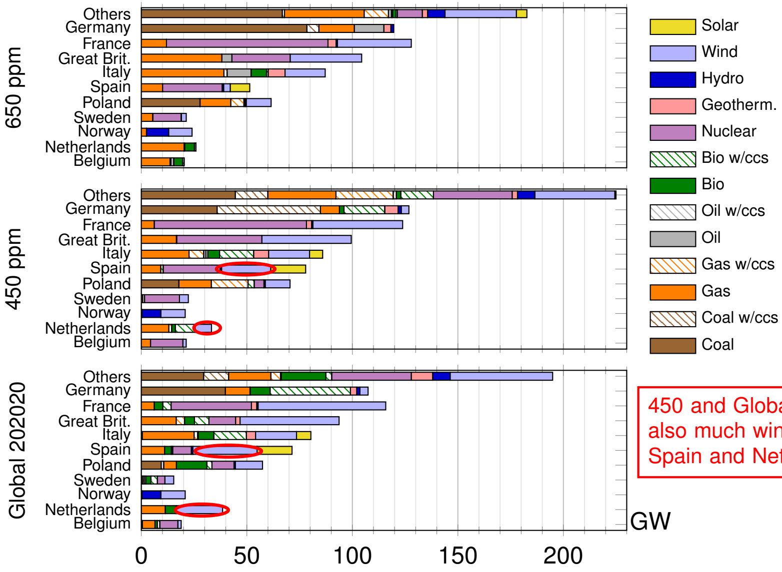


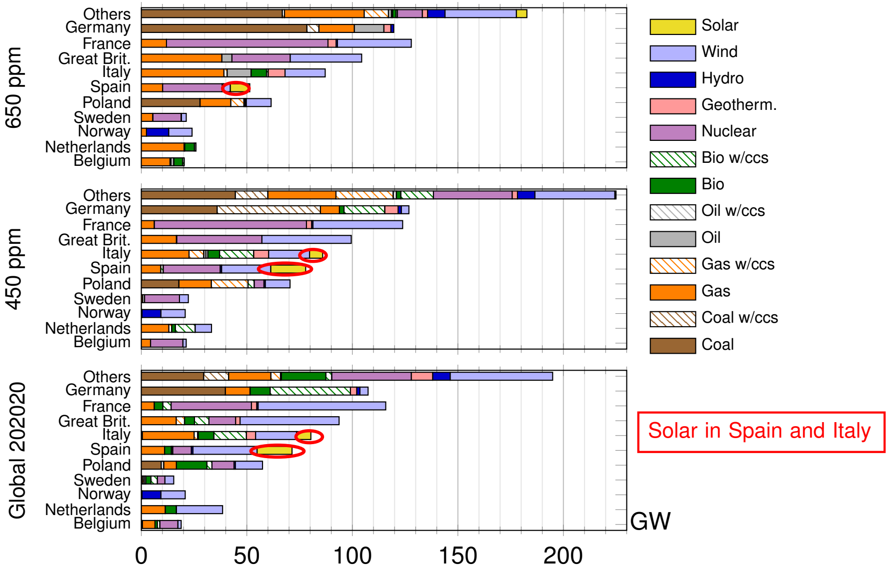
650: wind mostly in France, Italy, Great Britain, Poland and Norway

Investments generation by 2050 from EMPIRE



450 and Global202020: also much wind in Spain and Netherlands

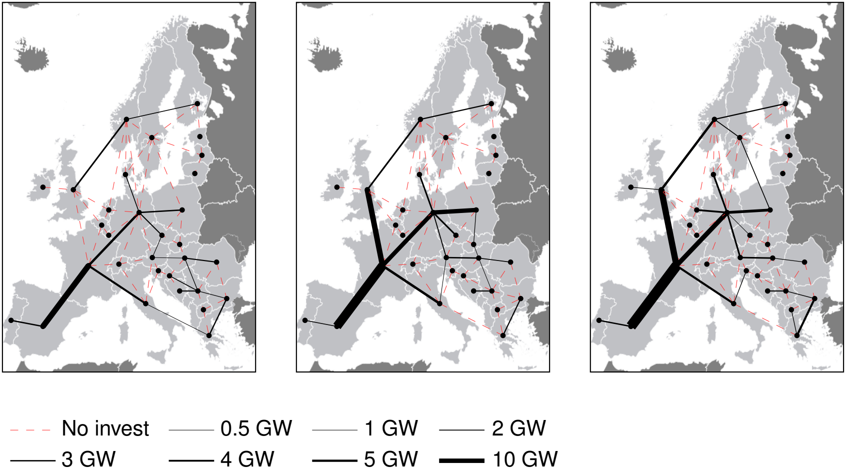
Investments generation by 2050 from EMPIRE



Solar in Spain and Italy

Investments transmission by 2050 from EMPIRE

650 ppm | 450 ppm | Global 202020



Summary

Table: Key figures from analysis 2050

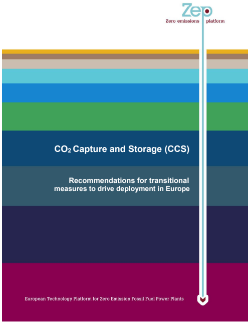
Scenario	iRES share [%]	iRES Cap. [GW]	Line inv. [GW]	Tot. Energy [TWh]
650 ppm	11	250	60	5000
450 ppm	15	375	96	5500
Global 202020	21	431	108	4600

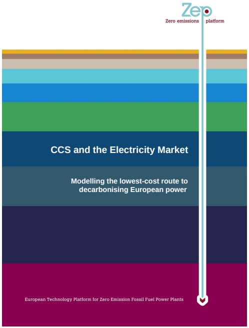
iRes = Intermittent renewables, i.e. wind (onshore and offshore) and solar

Conclusions

- Based on the EMPIRE model we see that
  - Siting renewables where the resource potential is high and reinforcing the transmission system is preferable to more distributed solution
  - Reinforcing transmission corridors along the Spain – Germany axis makes sense regardless of scenario
  - In high RES scenarios it is economical to have a strong link between the UK and Norway, and the UK and France
  - Without any support mechanisms intermittent renewables are not preferred in Germany
  - Investments in transmission should happen sooner rather than later

Use of EMPIRE in Zero Emissions Platform (ZEP)

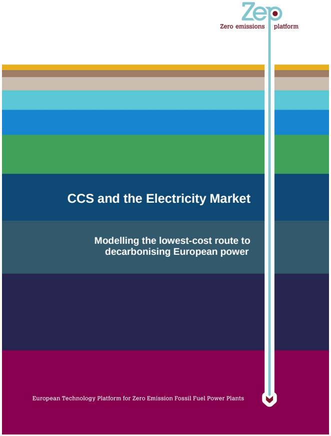




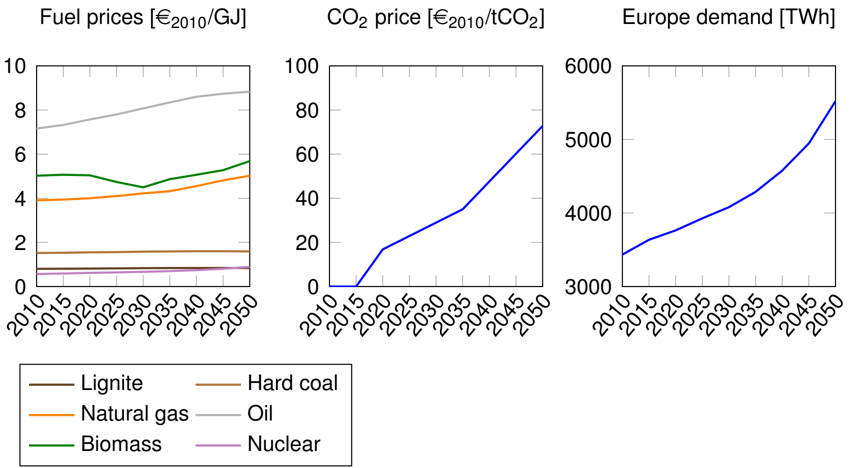
- Published November 2013
- Transitional measures for demonstration CCS

- Published November 2014
- Decarbonization scenarios for the European power system

Selected results from the study *CCS and the Electricity Market*



Using GCAM 450 ppm stabilization scenario data



Analysis setup

Six ZEP scenarios

- Constraints on RES potential in Europe
  - Stringent constraints: 270 GW wind, 1000 GW PV
  - Weak constraints: 850 GW wind, 1000 GW PV
  - Unlimited
- PV cost development (current cost assumed to be $\sim 1700 - 1900$ €/kW)
  - High cost: 1000 €/kW in 2050
  - Low cost: 200 €/kW in 2050

Three variants

A Baseline: with CCS and storage

B No CCS and same specific emissions (gCO_2/kWh) as in A

C No CCS, no storage, and same specific emissions as in A

Analysis setup

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Three variants

A Baseline: with CCS and storage

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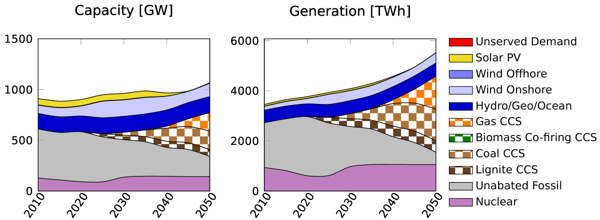
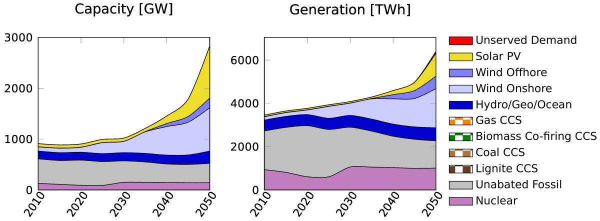
Europe electricity sector: Baseline vs no CCS variant

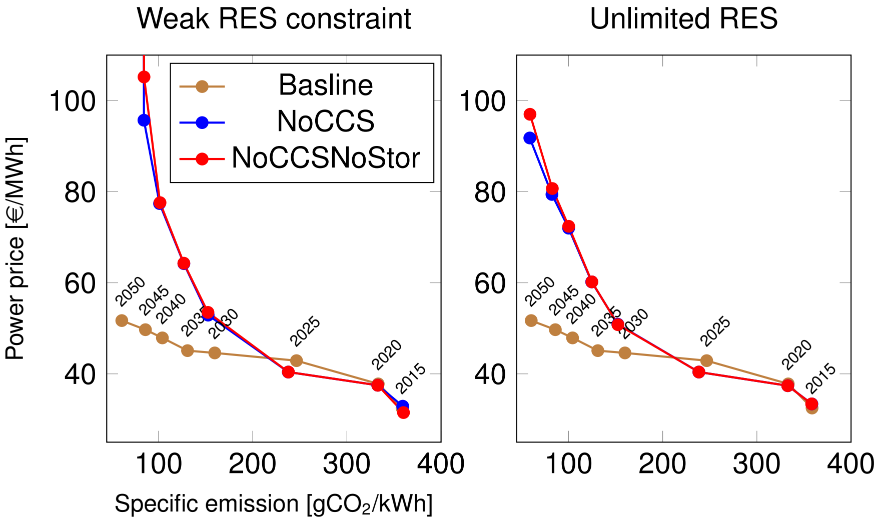
Baseline



No CCS



Price vs specific emission: Weak constraints, high PV cost



Key figures

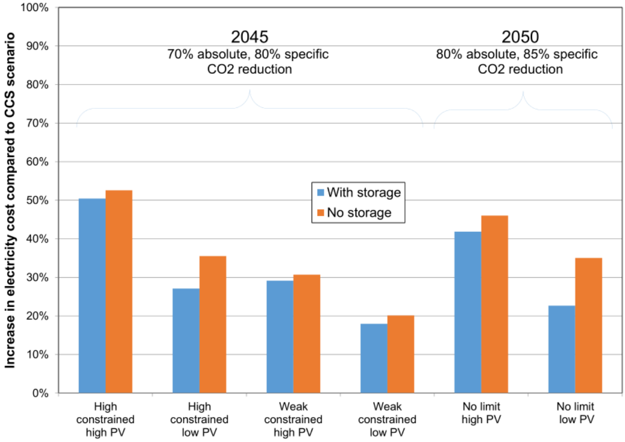
Table: Key figures from analysis 2050: Weak constraints

Variant	Spec. Em [g/kWh]	Price [€/MWh]	Stor cap [GW]	Stor en [GWh]	New RES [GW]	Res Gen [TWh]
Baseline	61	51.7	5	21	151	412
NoCCS	61	N.A.	1056	5410	2083	3450
NoCCSNoStor	61	N.A.	0	0	2083	2759

Table: Key figures from analysis 2050: Unlimited

Variant	Spec. Em [g/kWh]	Price [€/MWh]	Stor cap [GW]	Stor en [GWh]	New RES [GW]	Res Gen [TWh]
Baseline	60	51.7	5.8	22	166	453
NoCCS	60	91.8	110	1062	1774	3051
NoCCSNoStor	60	97.0	0	0	1848	3049

Increase in electricity cost compared to Baseline



Conclusions

- The most cost-efficient way of meeting future electricity demand while have an aggressive reduction of emissions includes significant use of CCS
- According our simulation results the price of electricity doubles in the non-CCS cases. Cumulative costs are 20–50% higher without CCS.
- Use of storage does reduce costs, but only slightly

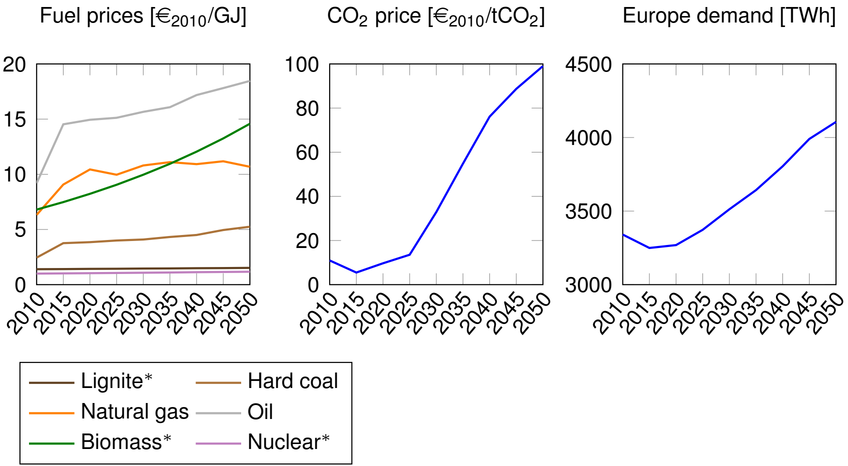
Selected results from recent NTNU study

- Using fuel prices, electricity demand and CO_2 prices from the EU 2013 reference scenario
- The generation technology parameter data is the same as used for the previous ZEP studies.
- Recent study done at NTNU

Disclaimer

This is not a ZEP study. Members of ZEP have not yet had the opportunity to comment on the analysis, nor the results, and the following part of the presentation is solely the responsibility of the authors.

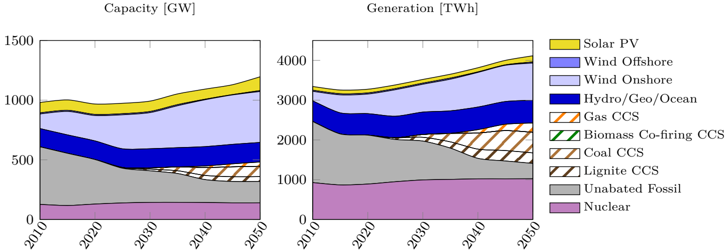
EU reference scenario 2013 data



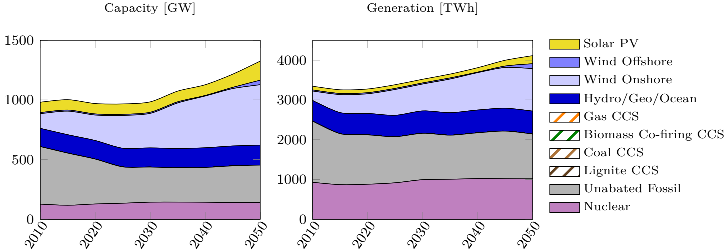
*Price not available from EU reference scenario. Different source used.

Generation and capacity mix in Europe

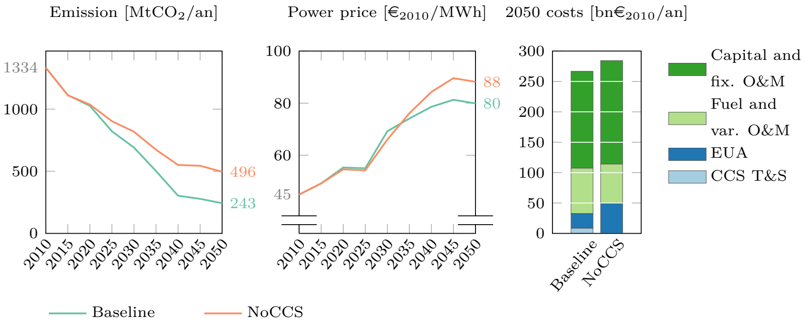
Baseline (CCS available)



No CCS available (no additional emission constraints)



Emission reduction, prices and cost



Key figures

Table: Key figures from analysis 2050

Variant	2050 spec em [g/kWh]	CCS cap [GW]	CCS gen [TWh]	iRES [GW]	iRes gen [TWh]
Baseline	59	163	1014	551	1119
NoCCS	121	0	0	704	1396

Conclusions

- The recent NTNU study reaffirms ZEP findings using the EU 2013 reference scenario data
  - CCS is an important technology in a least cost decarbonization of European power
- Without CCS an EUA price of 100 €/tCO_2 not sufficient to reach a 80 % reduction in emissions
- The No CCS case shows higher costs, higher prices and twice the emissions as the Baseline.
- The study shows less CCS and more intermittent renewables than the previous ZEP studies
  - Caused by higher fuel prices in the EU reference scenario

Thank you for your attention

Questions?