Lessons learned from building an EMPIRE

Christian Skar[1], Gerard Doorman[1] and Asgeir Tomasgard[2]

NTNU – Trondheim
Norwegian University of
Science and Technology

CenSES

Department of Electric Power Engineering[1]
Department of Industrial Economics and Technology Management[2]

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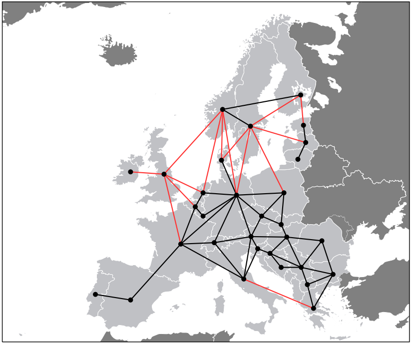
Outline

European **M**odel for **P**ower system **I**nvestments with (high shares of) **R**enewable **E**nergy

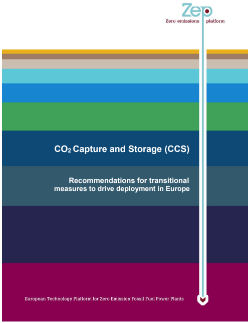
- EMPIRE is a dynamic capacity expansion model for the European power system
- Formulated as a two-stage stochastic linear program
  - Capacity investments made subject to uncertainty about operating conditions such as load and intermittent generation
  - Hourly optimal dispatch for selected seasons solved as the second stage problem
- Results at national levels for five year time steps
- Developed at the Norwegian University of Science and Technology (NTNU)

EMPIRE modeling assumptions

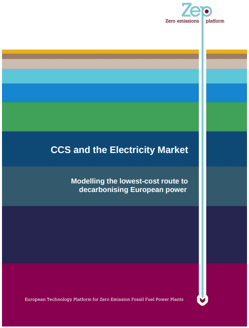


- Perfect competition
- Generation capacity aggregated per technology (i.e. do not model individual plants)
- Investments are continuous
- Lines are independent (i.e. transportation network)
- Inelastic demand
- Perfect foresight about fuel prices, carbon price, and load development.

Use of EMPIRE in Zero Emissions Platform (ZEP)

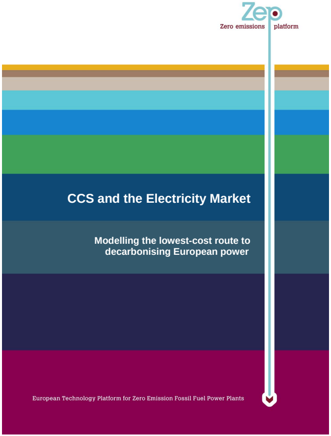


- Published November 2013
- Transitional measures for demonstration CCS

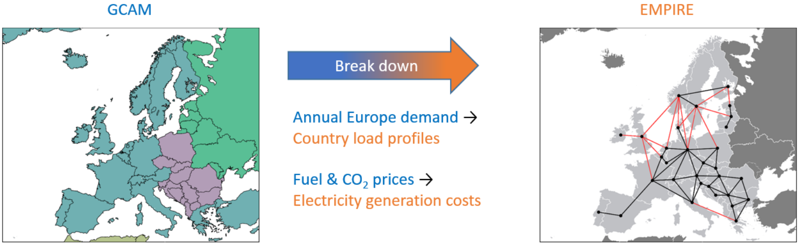


- Published November 2014
- Decarbonization scenarios for the European power system

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

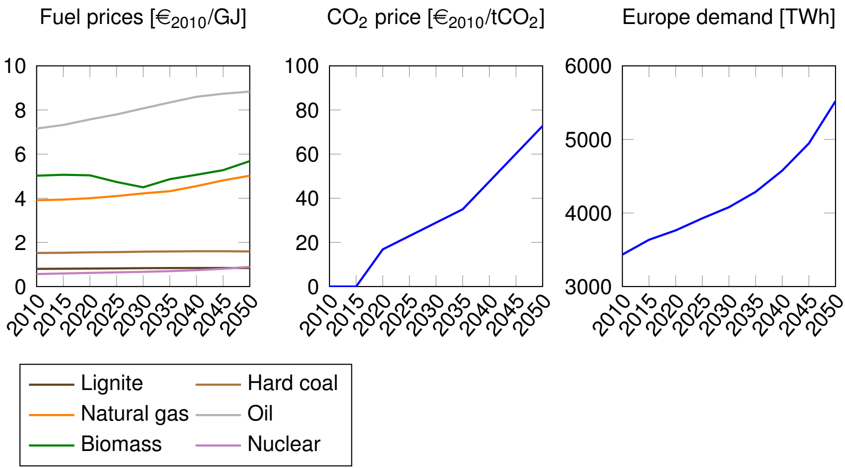


ZEP studies: EMPIRE linked to the integrated assessment model GCAM



- GCAM: Global Climate Assessment Model
- Developed by Joint Global Change Research Institute in Maryland, USA.
- Extensively used for climate mitigation studies
    - Example: The contribution of Working Group III for the fifth assessment report of the IPCC

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

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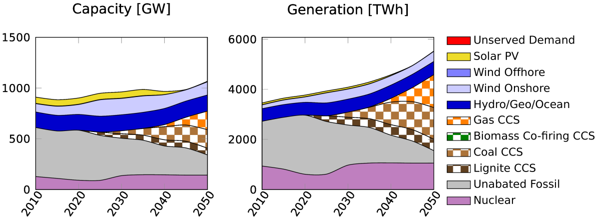
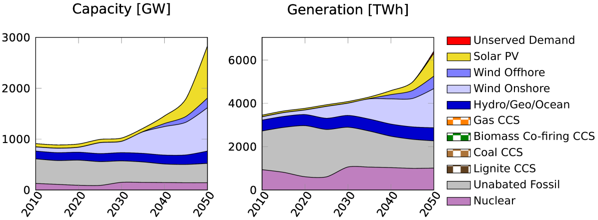
Europe electricity sector: Baseline vs no CCS variant

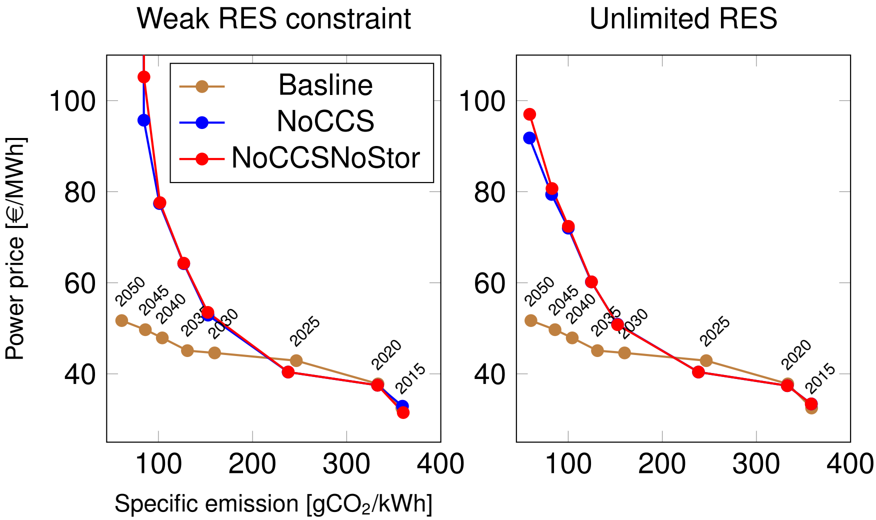
Baseline



No CCS



Price (LRMC) vs specific emission: Weak constraints, high PV cost



Key figures

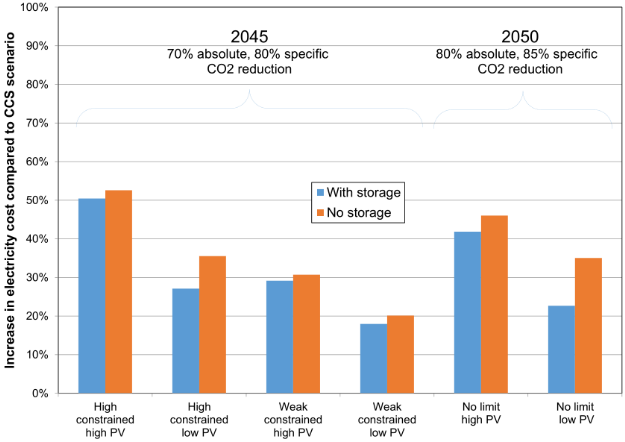
Table: Key figures from analysis 2050: Weak constraints

Variant	Spec. Em [g/kWh]	LRMC. [€/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]	LRMC. [€/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

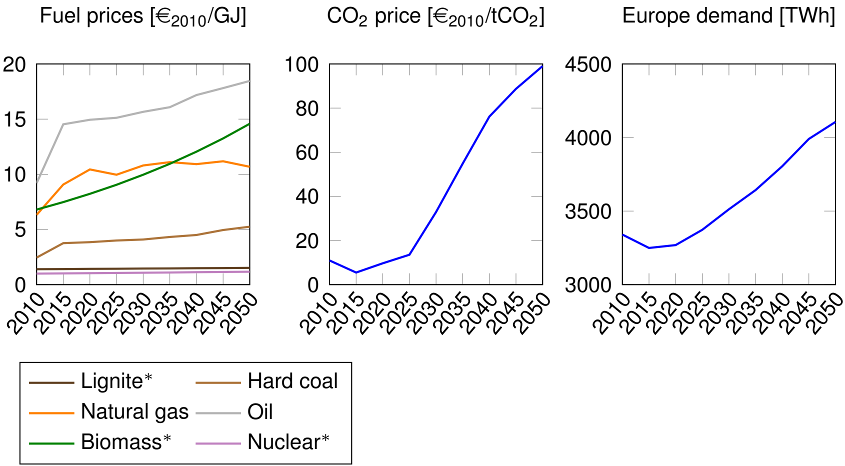
Selected results from recent NTNU study

- 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.

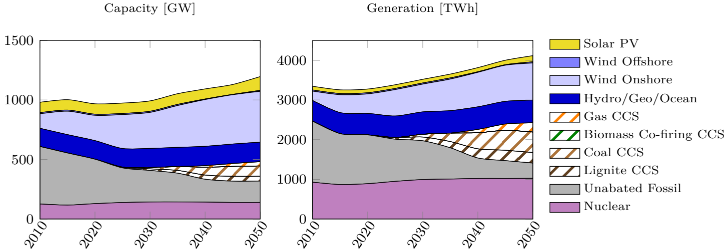
EU reference scenario 2013 data



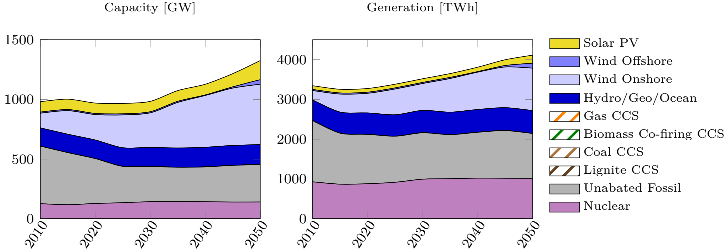
*Price not available from EU reference scenario. Different source used.

Generation and capacity mix in Europe

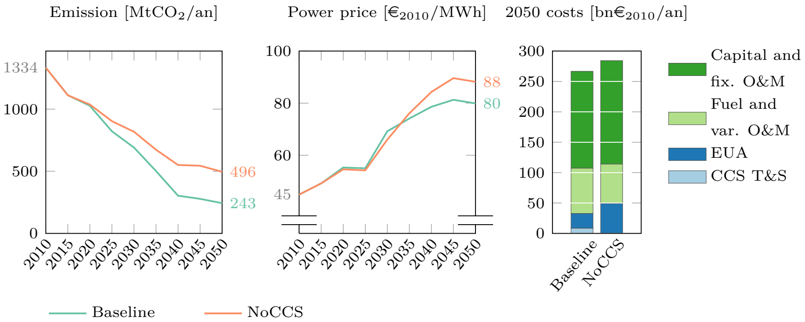
Baseline (CCS available)



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 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?