Influence of CO₂ taxation and hydrogen utilization on the cost-optimal development of the German power system by 2050

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Outline

1. Motivation for the study

2. Methodological overview

3. Model analyses
   a) CO$_2$ tax-instead-of-limit
   b) Hydrogen utilization scenarios for electricity supply

4. Conclusions
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1. Motivation of the study

German energy system to become **carbon-neutral** by 2045 (German climate protection law 2021)

Decarbonization instruments include:
- carbon trading schemes (**volume-driven**) or
- direct CO$_2$ taxation (**price-driven**)

Utilization of H$_2$ in electricity sector offers options for tackling the intermittency of renewables
- **in-land generation** by surplus renewable production
- **import** from abroad

**Goal of the study:** an assessment of options via optimization of a simplified electricity system model of Germany with sensitivities on the $CO_2$ price, electricity demand and import price of hydrogen
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Energy system modelling framework *urbs*

**Energy system modelling**

Representation of an energy system of a given scale/resolution as a mathematical optimization model

\[
\begin{align*}
\min_{x} & \quad f(x) \quad \rightarrow \text{total system costs} \\
\text{s.t.} & \quad g(x) \leq 0 \quad \rightarrow \text{system operation constraints} \\
& \quad h(x) = 0 \quad \rightarrow \text{system operation/investment decisions}
\end{align*}
\]

Determination of the cost-optimal evolution of the energy system s.t.:
- sum of costs is minimized
- while ensuring that energy balances are met at all times

**urbs framework**

Open-source\(^1\) energy system modelling framework developed by TUM ENS

**Temporal scale:** single-year or intertemporal (for expansion pathways)

**Temporal resolution:** variable (typically 1h)

**Regional scale:** user-defined model regions (countries, counties, cities…)

[1] [https://github.com/tum-ens/urbs](https://github.com/tum-ens/urbs)
2. Methodological overview

Model overview for the study

Model basics

+ Single node (Germany + offshore),
+ Single year (snapshot 2050), hourly resolution
+ Coal and nuclear phase-out
+ 95% emission reduction in electricity sector compared to 1990
+ „Almost“ greenfield: PV/wind replaced, rest decommissioned

The reference energy system

- Biomass, Biogas
- Gas
- Wind
- Solar
- Deep geothermal
- Heat
- Electricity
- CO₂

H₂ import (with prices: 1 to 5 €/kg)

H₂ storage

Drilling facility

Thermal storage

Onshore WT

Offshore WT

PV

Biomass PP

Biogas PP

Geothermal PP

CCGT (H₂ or NG fired)

Electrolyser

Demand (up to double the 2017 value)

Limitation 95% wrt 1990

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CO2 tax-instead-of-limit, approach

<table>
<thead>
<tr>
<th>Goal</th>
<th>Scenario generation</th>
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<tbody>
<tr>
<td>+ Investigate the reaction of the cost-optimal electricity system to varying CO2 prices</td>
<td>1. Under a given electricity demand and H₂ import price, solve the system model with 95% CO₂ reduction constraint. Cost-optimal solution that satisfies the CO₂ goal</td>
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<tr>
<td>+ Quantify the tax “revenues” which could in practice be excluded from the system costs (by distribution back to the society as dividends: example „Energiegeld“)</td>
<td>2. Read the dual variable associated with the total CO₂ limitation constraint. = the shadow price (or the marginal abatement cost) of CO₂</td>
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<tr>
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<td>3. Solve the same system model, now without the CO₂ constraint but with 10% increments of the shadow price</td>
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3. Model analyses

**CO₂ tax-instead-of-limit, results**

Presented case: H₂ import price: 90€/MWh_th (~3€/kg), electricity demand: ~800 TWh

-> **marginal abatement cost: 211€/ton** (for reference: price corridor 55-65€/ton in 2026 in DE)

**Emission pathway**

a. 70% emission reduction achieved without CO₂ pricing

**Capacities**

b. PV and wind (onshore + offshore) among the cheapest options even at a zero price on CO₂

c. Back-up capacity for dispatchable CCGT (min. 50 GW) always necessary

d. Electrolyser build-up after CO₂ price of 84€/ton

e. Biomass starts replacing gas at >126.6€/ton (break-even of marginal costs)

- Electricity production by deep geothermal not economical
3. Model analyses

**CO₂ tax-instead-of-limit, results**

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**Electricity balance**

- No hydrogen import for electricity supply

![Electricity balance chart]

- Curtailment
- Retrieved storage
- Electrolysis
- In-land H₂
- Biogas
- Solid biomass
- PV
- Onshore wind
- Offshore wind
- Natural gas
3. Model analyses

CO₂ tax-instead-of-limit, results

Presented case: H₂ import price: 90€/MWhₜₜ (~3€/kg), electricity demand: ~800 TWh

- marginal abatement cost: 211€/ton (for reference: price corridor 55-65€/ton in 2026 in DE)

System costs

As the CO₂ price increases:

- Fuel costs reduce (a) (reduced use of natural gas) and then slightly increase (b) (increased use of biomass)

- Then the fixed and investment costs increase (as the PV, wind, battery capacities increase) (c)

- Very minimal increase in the „physical“ costs (total costs minus CO₂ tax payments) for CO₂ prices up to 84€/ton (d)

- Emission reduction from 70% to 95% is achieved with
  - +30% total costs,
  - of which +20% „physical“ costs
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Hydrogen utilization scenarios for electricity supply

Research question

+ Where should the hydrogen be sourced for the utilization in the cost-optimal power system? (import or locally produced)

Method

+ Set CO₂ target to 95%,
+ Parameter sweep on
  + the electricity demand (100% to 200% of the annual demand in 2017), and
  + the hydrogen import price (30 to 150€/MWh, or 1 to 5€/kg)
3. Model analyses

Hydrogen utilization scenarios for electricity supply, results
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Summary

+ System costs to the society and consumer may be overestimated with carbon taxation

+ Feasibility of the imported and locally produced hydrogen observed to be an open topic (co-presence possible also at realistic ranges of demand and price assumptions)

Remarks

+ Simplified model (one-node, linear representations of technologies…), the actual numbers mentioned should always be taken with a grain of salt (as with any energy system model)

+ Sector coupling has been ignored; hydrogen has high potential in other sectors such as direct use in industry and long-range mobility