Impact of CO$_2$ prices on the design of a highly decarbonised coupled electricity and heating system in Europe

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Agenda

Introduction

Methodology

Results

Conclusions

Future work
Introduction
Introduction

- Limit the increase of global average temperature to 2 °C
- CO₂ emissions reduction by 80%-95% in 2050 compared to 1990\(^1\)
- The major future renewable energy: wind and solar energy
- Drastically reduction of CO₂ emissions not only in the electricity sector\(^2\)

\(^1\)European Union, *A Roadmap for moving to a competitive low carbon economy in 2050.*

\(^2\)National emissions reported to the UNFCCC and to the EU Greenhouse Gas Monitoring Mechanism, European Environment Agency.
Research questions

• Is increasing the renewable penetration enough to achieve a low carbon energy system?
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• If not, what is the required CO$_2$ price to ensure the decarbonisation?
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• What are the cost-optimal system configurations under specific CO₂ emission reductions?
Methodology
Methodology: PyPSA Model

Electricity and heating coupled, hourly-resolved one-node-per-country

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Brown, Hörsch, and Schlachtberger, “PyPSA: Python for Power System Analysis”.

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Methodology: Optimisation

- A techno-economical joint optimisation problem
- Technical and physical constraints, assuming perfect competition and foresight
- Renewable self-sufficient for individual country: weakly homogeneous layout

\[
\min_{G_{n,s}, E_{n,s}, F_{\ell}, g_{n,s,t}} \left[ \sum_{n,s} c_{n,s} \cdot G_{n,s} + \sum_{n,s} \hat{c}_{n,s} \cdot E_{n,s} + \sum_{\ell} c_{\ell} \cdot F_{\ell} + \sum_{n,s,t} o_{n,s,t} \cdot g_{n,s,t} \right]
\]

subject to

\[
\sum_s g_{n,s,t} + \sum_{\ell} \alpha_{n,\ell,t} \cdot f_{\ell,t} = d_{n,t} \leftrightarrow \lambda_{n,t} \quad \forall n, t
\]

\[
g_{i,VRES}^{gross} = \gamma_i^{gross} \sum_{t,n \in i} d_{n,t} \quad \forall i
\]
Methodology: Data

- Electricity demand is from ENTSO-e
- Heat demand is modelled by Heating Degree Hour (HDH)
- Heating bus is separated proportionally into rural and urban heat
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- Wind and solar capacity factors are calculated based on reanalysis dataset (CFSR) through REatlas
- The geographical potentials of wind and solar are estimated
Results
Results I: LCOE for configuration sweep

- High VRES penetrations do not necessarily lead to low CO$_2$ emissions
- The CO$_2$ price has limited impact on the cost-optimal wind/solar mix
Results II: Target configuration

- The minimum of LCOE excl. CO\(_2\) tax determines the cost-optimal configuration
- The LCOE shows low sensitivity around the optimum
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- The minimum of LCOE excl. CO₂ tax determines the cost-optimal configuration
- The LCOE shows low sensitivity around the optimum
- A higher CO₂ price curtails less VRES and utilises VRES more efficiently
- The high CO₂ price forces the choice of expensive heat supply
Results III: Germany dispatch time series

5%, 280 €/tCO₂
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5%, 280 €/tCO₂

5%, 380 €/tCO₂
Results IV: Spatial distribution

System cost

Primary energy

5%, 380 €/tCO2

PTH
VRES
gas
hydro
storage

5%, 380 €/tCO2

gas
hydroelectricity
offshore wind
onshore wind
solar PV
Results IV: Spatial distribution

Thermal energy

Thermal capacity

5%, 380 €/tCO₂

- gas
- heat pump
- resistive heater

5%, 380 €/tCO₂

- gas
- heat pump
- hot water storage
- resistive heater
## Results V: Aggregated system configurations

<table>
<thead>
<tr>
<th></th>
<th>Optimal volume</th>
<th>Todays volume</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Transmission volume</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Emission level</td>
<td>20% 10% 5%</td>
<td>20% 10% 5%</td>
</tr>
<tr>
<td>Transmission volume</td>
<td>141 176 196</td>
<td>32 32 32</td>
</tr>
<tr>
<td>CO₂ price</td>
<td>160 260 380</td>
<td>200 320 580</td>
</tr>
<tr>
<td>Penetration</td>
<td>0.46 0.57 0.64</td>
<td>0.5 0.64 0.7</td>
</tr>
<tr>
<td>Wind/solar mix</td>
<td>0.77 0.8 0.8</td>
<td>0.73 0.74 0.79</td>
</tr>
<tr>
<td>LCOE excl. CO₂ tax</td>
<td>43.2 49.8 55.4</td>
<td>45.4 53.9 60.9</td>
</tr>
<tr>
<td>Resistive heater</td>
<td>307 389 464</td>
<td>434 581 673</td>
</tr>
<tr>
<td>Heat pump</td>
<td>69 113 148</td>
<td>67 103 143</td>
</tr>
<tr>
<td>CHP</td>
<td>363 243 165</td>
<td>464 336 268</td>
</tr>
<tr>
<td>Hot water tank</td>
<td>7,768 27,823 91,796</td>
<td>17,232 57,818 156,753</td>
</tr>
</tbody>
</table>
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• Only installing high capacities of renewable is not enough
• A significantly high CO₂ price is required to disincentivise gas usage
• The flatness around cost-optimal CO₂ price allows flexibilities
Future work
Sensitivity

Motivation

Cost optimal scenarios depend on the specific input data.

Potential climate change may change the future demand profile.

Evaluate the robustness of target configurations.

Scenarios

Temperature increase influences the heat and cooling demand.

Retrofitting may lower the heat demand.

Cost parameter.

Possible demand-side management.
Transition pathways

**Motivation**

Seek the robust build-up of renewable capacities

Analyse the required levels of economic instruments

Make sure that the transmission capacities could fulfill the need of expanding renewable

**Methodology**

Logistic growth for renewable capacities

Constrain the CO$_2$ emissions as a function of time

Understand the next feasible investments in decarbonisation
Thanks for your attention.


National emissions reported to the UNFCCC and to the EU Greenhouse Gas Monitoring Mechanism, European Environment Agency. URL: https://www.eea.europa.eu/.