Linear Models for Optimization of Infrastructure for CO$_2$ Capture and Storage

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Background and motivation

The ‘eTransport’ model

- Formal optimization model with several types of energy carriers, sources, transmission, conversion and demand
  - Expansion planning - optimize infrastructure investments subject to multiple fuels, emissions and energy products
  - Full geographic representation of cables, lines, pipes
  - Identify mutual influence and dependency between alternative energy systems
  - Windows graphical user interface

How will profitability of gas pipelines and power plants change if infrastructure for CCS is included in the investment analysis?

- Challenge #1: Include mass flow [tonne/h] in the network structure, transforming eTransport into a multi-commodity optimization model
- Challenge #2: CCS components need energy supplies to operate in addition to the input and output mass flows of CO₂
The eTransport model

- Combined optimization of operation and investments in multiple energy carrier systems
  - From hourly operation to investment horizon of several decades
  - Energy flow (MWh/h)
  - *Now:* Mass flow (tonne/h)

- Physical infrastructure and geographic distance included
  - Lines/cables for electricity, pipes for gas, district heating, CO$_2$ etc,
  - Road/rail for biomass, waste etc,
  - Ship for LNG, LPG, CO$_2$ etc

- Full graphical user interface in Windows
  - "Drag and drop" model building
  - User dialogs
  - Graphical display of results

- Modular design enables easy replacement and addition of technologies
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'Drag and drop' component library

Energy system drawing

Pan & Zoom window

‘Drag and drop’ component library

Operation and investment analysis
Flexible load segments with hourly time-steps
Operation and expansion planning

Existing system

OPERATION PLANNING (LP / MIP)
Hour / Day / Season / Year

PROJECTS
Retrofitting / New projects

EXPANSION PLANNING (DP)
Operation / Investment / Environment

Ranking of alternatives
Relevant technology modules in the CO$_2$ Value Chain

- Any number and combination of modules is possible
Power plant with exhaust outlet

- Base load CCGT power station
- The fuel is converted to electricity and heat (optional)
- Exhaust gas with a certain CO$_2$-concentration is produced
- The optimal amount of el. and heat is produced according to demand and market price
Generic CO$_2$ (or exhaust) source

- Pure CO$_2$ supplied from outside the system boundary at a given price
  - The price can be negative if someone is willing to pay for disposal of CO$_2$
- Can also represent an exhaust gas from industry with a certain concentration of CO$_2$. The supply is then connected to a capture plant where the CO$_2$ is separated from the exhaust gases
CO₂ capture plant

- Post combustion module independent of power plant and source(s)
- **Absorber**: MEA. Requires mechanical energy (el/gas). Size and cost depend on the total amount of flue gas and the CO₂ concentration
- **Stripper**: Regeneration of MEA by increasing the temperature. Low quality heat can be used; steam 150ºC
- Chemicals are required to reduce water, SOx, NOx and other pollutants than might influence the capture process
- Producing a highly concentrated CO₂ stream (>99%)
**CO₂ pipeline**

- Module includes both compressor, pump and pipeline
- The user specifies required inlet pressure, outlet pressure, diameter and length
- Increasing the pressure to ~80 bar (liquid CO₂) using compressors
- Further compression is done by pumps
- Energy supplied can be electricity or gas, the efficiency is adjusted according to the energy carrier
- Cannot be used as intermediate storage
Large scale transport of CO₂ by ships favours operating conditions close to CO₂’s triple point where the density is fairly high, approx. 70 bar.

The liquefaction is done by compression in several steps followed by expansion and cooling.

Energy supplied can be electricity or gas, the efficiency is adjusted according to the energy carrier.
**CO₂ ship transport**

- Similar to LPG transport
- Liquid CO₂
  - \( P = 5.2 \text{ bar} \)
  - \( T = -50 \degree C \)
- Currently, a simplified approach using continuous transport module with average flows of CO₂ and energy
- Required energy is calculated using the transportation length, speed and the hours needed for loading etc
- Energy supplied can be oil, gas or electricity
- If investment costs are very uncertain, the user can lease the ship for an hourly/daily rate
Intermediate storage capacity may be needed at several stages in the transport chain.

In particular, ship transportation as a discrete process requires storage.

- $1.5 \times \text{capacity of ship}$

Energy supplied can be electricity or gas; the efficiency is adjusted according to the energy carrier.
CO₂ injection pump

- Pump for injection of CO₂ into oil wells or other underground storage
- The energy requirement is a function of the well head pressure
- Can be used after transportation by ships or pipelines
- The energy requirement is higher after ship transport than after pipelines
- Investment cost of offshore modifications can be included
If there is a given demand of CO₂ this is represented by a CO₂ load module.

The load requires a certain quantity of CO₂ [tonne/h] - e.g. an oil field that needs CO₂ for Enhanced Oil Recovery

Penalty cost for non-delivery

A CO₂ market can be industry or an oil field willing to pay for CO₂-delivery

An aquifer for storage of CO₂ can be modeled as a market with a negative price to cover the injection costs

No obligation to deliver
Test: Electricity and heat usage in capture plant as function of \( \text{CO}_2 \) flow
Regional case with CO₂ capture, EOR and offshore electrification

Case objectives
- Compare gas fired power plants with and without CCS
- Taxes and emission penalties
- Market price of CO₂ delivered to platform
- Ship transport versus pipelines
- Optimal pressure in pipelines
### Case parameters

<table>
<thead>
<tr>
<th>Investment [mUSD]</th>
<th>Operation [mUSD/year]</th>
<th>Lifetime [years]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power plant 860 MW</td>
<td>409</td>
<td>62</td>
</tr>
<tr>
<td>Capture plant</td>
<td>240</td>
<td>37</td>
</tr>
<tr>
<td><strong>CO2 pipeline</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>to Draugen (135 km)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Low pressure</td>
<td>162</td>
<td>3.2</td>
</tr>
<tr>
<td>- High pressure</td>
<td>180</td>
<td>3.6</td>
</tr>
<tr>
<td>to Heidrun (250 km)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Low pressure</td>
<td>233</td>
<td>4.6</td>
</tr>
<tr>
<td>- High pressure</td>
<td>261</td>
<td>5.2</td>
</tr>
<tr>
<td>Ship (15 000m³)</td>
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<td>2.3</td>
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<tr>
<td>Liquefaction</td>
<td>76</td>
<td>3.8</td>
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<tr>
<td>Storage (24 000 m³)</td>
<td>60</td>
<td>1.2</td>
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<tr>
<td><strong>Injection-pumps + equipment offshore</strong></td>
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<tr>
<td>- gas turbines</td>
<td>-</td>
<td>20</td>
</tr>
<tr>
<td>- after pipelines</td>
<td>8</td>
<td>0.2</td>
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<tr>
<td>- after ship transport</td>
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<td><strong>Electricity cable</strong></td>
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<tr>
<td>- to Draugen</td>
<td>46</td>
<td>0.7</td>
</tr>
<tr>
<td>- Draugen-Heidrun</td>
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<td>0.5</td>
</tr>
</tbody>
</table>
Sample drawing in eTransport
Initial results and sensitivities

- Power plant with CCS not competitive with conventional power plant with initial assumptions
- Overall CO$_2$ tax has to exceed 69 USD/tonne CO$_2$ to make investments in CCS competitive with a conventional power plant (today 15.4 USD/tonne CO$_2$)
- The price of pressurized CO$_2$ delivered to Draugen must exceed 90 USD/tonne to make CCS competitive with conventional power plant
- Average electricity price below 52 USD/MWh makes offshore electrification competitive
- Transportation: High pressure pipeline is best, closely followed by low pressure pipe including gas fuelled injection pump and finally ship transport
More complicated case

Additional assumptions
- EOR possible both at Draugen and Heidrun, but in different time windows
- Demand for CO₂ for EOR at Draugen lasts only from 2010 to 2020, replaced by a demand at Heidrun the same year
- Oil production at Draugen is expected to end in 2025, leading to zero energy demand at Draugen after 2025
- EOR is expected to prolong the production at Heidrun to 2030

Main results
- Due to the reduced lifetime of Draugen field, investments in electrification are not competitive. The electricity is sold to the Nordic market instead
- The best solutions are to build CO₂ pipelines to Draugen in 2010 and to Heidrun in 2020
- Low pressure pipelines are chosen before high pressure pipelines; injection pumps get energy from offshore gas turbines
- Intermediate solution with no CO₂ pipeline to Heidrun
- Less competitive solution with one CO₂ ship operating first to Draugen, then to Heidrun
**Summary**

- Energy planning model ‘eTransport’ optimizes infrastructure investments subject to multiple fuels and energy products.

- To be able to include infrastructure for CCS in the investment analysis, mass flow [tonne/h] is introduced in the network structure, and each component receives external energy supply to operate.

- Relevant technology modules in the CCS value chain implemented in a mathematical framework consistent with models for gas, electricity and heat.

- The purpose of the framework is comparison of different design options – not a detailed system design.

- Tested on fictive case studies with best available data.

- Further work and better data needed to test the models and include more technologies.
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