

Linear Models for Optimization of Infrastructure for CO₂ 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

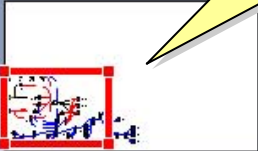
The eTransport model

- **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, CO₂ etc,
 - Road/rail for biomass, waste etc,
 - Ship for LNG, LPG, CO₂ 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**

Pan & Zoom window

Energy system drawing

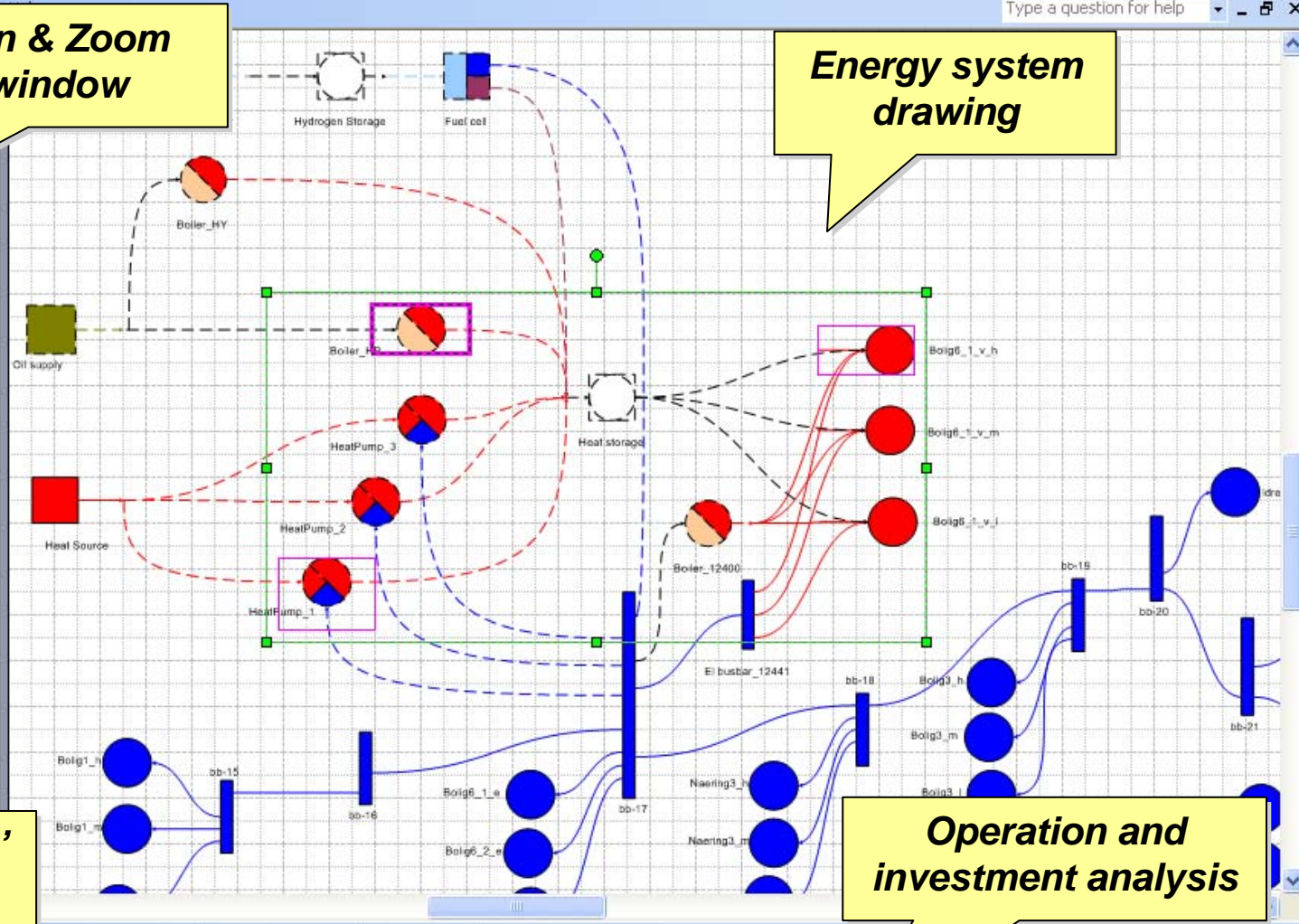
Pan & Zoom



Shapes

Conversion Components

- Combinat... plant
- Boiler
- Storage
- CCO2 Plant
- Heat pump
- Simple CHP

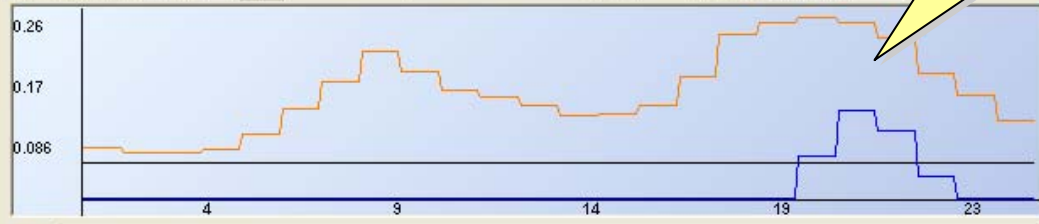


'Drag and drop' component library

Operation and investment analysis

Operational analysis | Investment analysis | Advanced DM

Investment plan Rank 1 | Period 2023 - 2028 | Segment Peak load



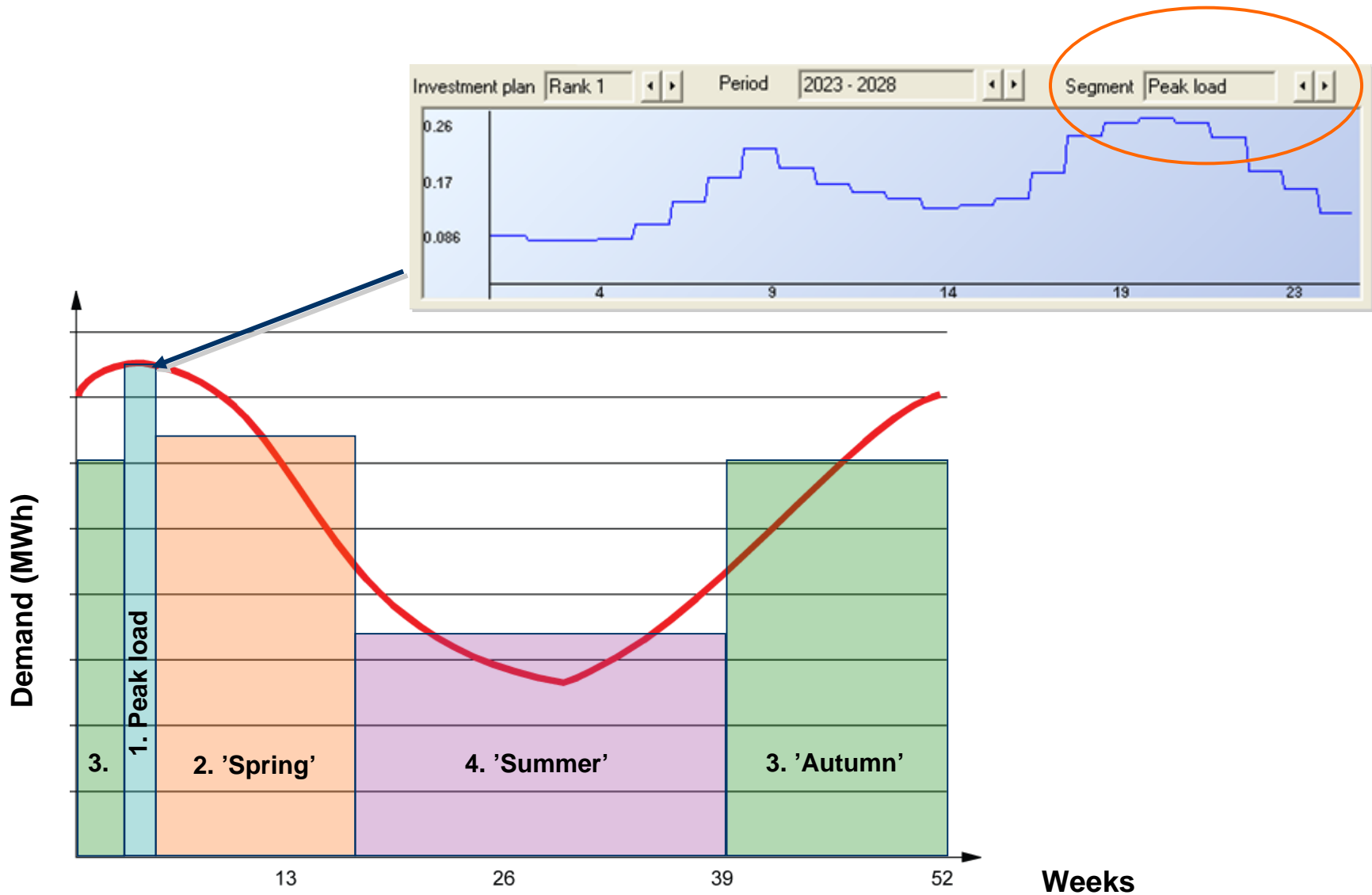
Available data:

- Fuel consumption (Boiler_HP)
- Prod (Boiler_HP)
- El consumption (HeatPump_1)
- Heat production (HeatPump_1)
- Heat load (Boig6_1_v_h)
- Deficit (Boig6_1_v_h)

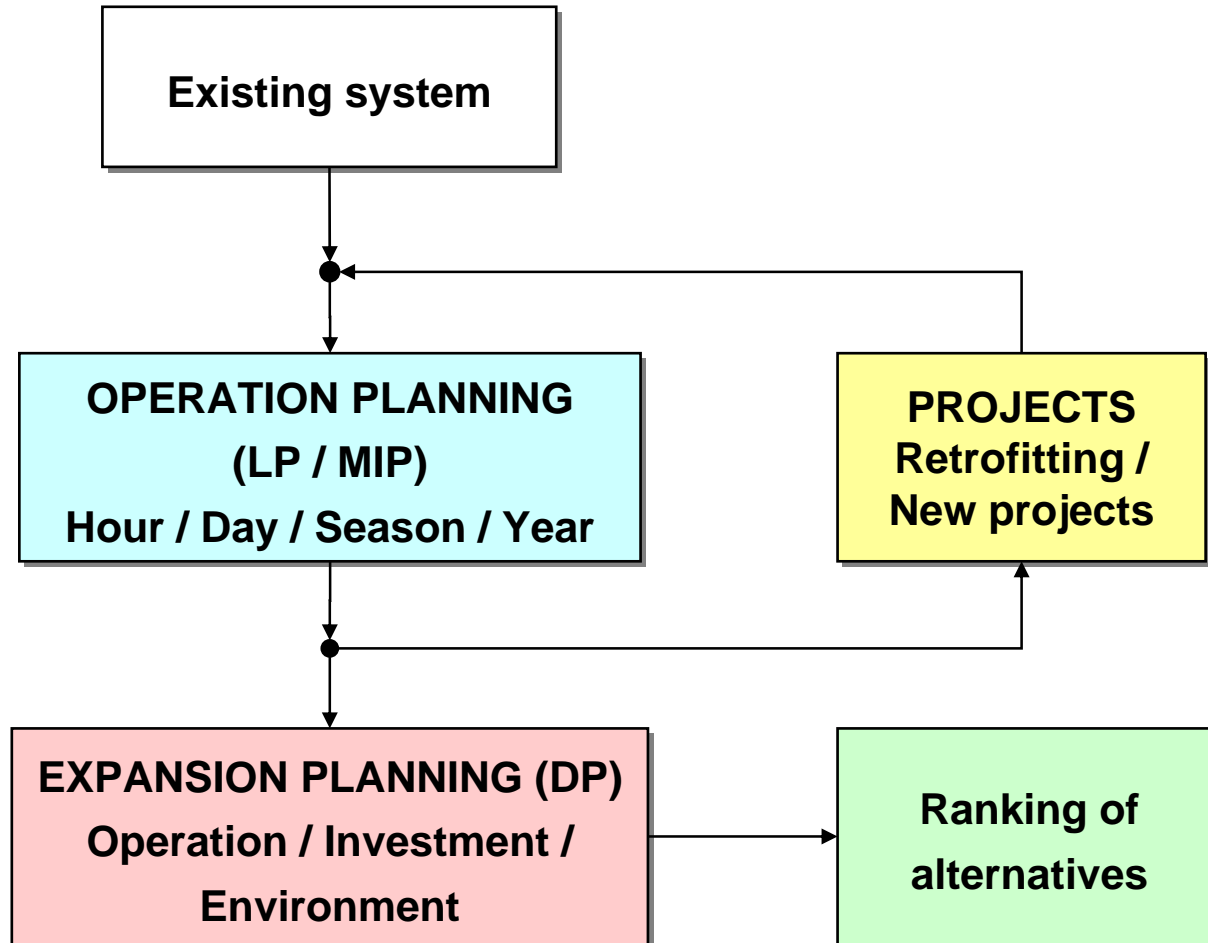
- Biomass
- District Heating
- Electricity
- Gas
- Oil
- Waste
- Hydrogen

Boiler_HP edit cancelled

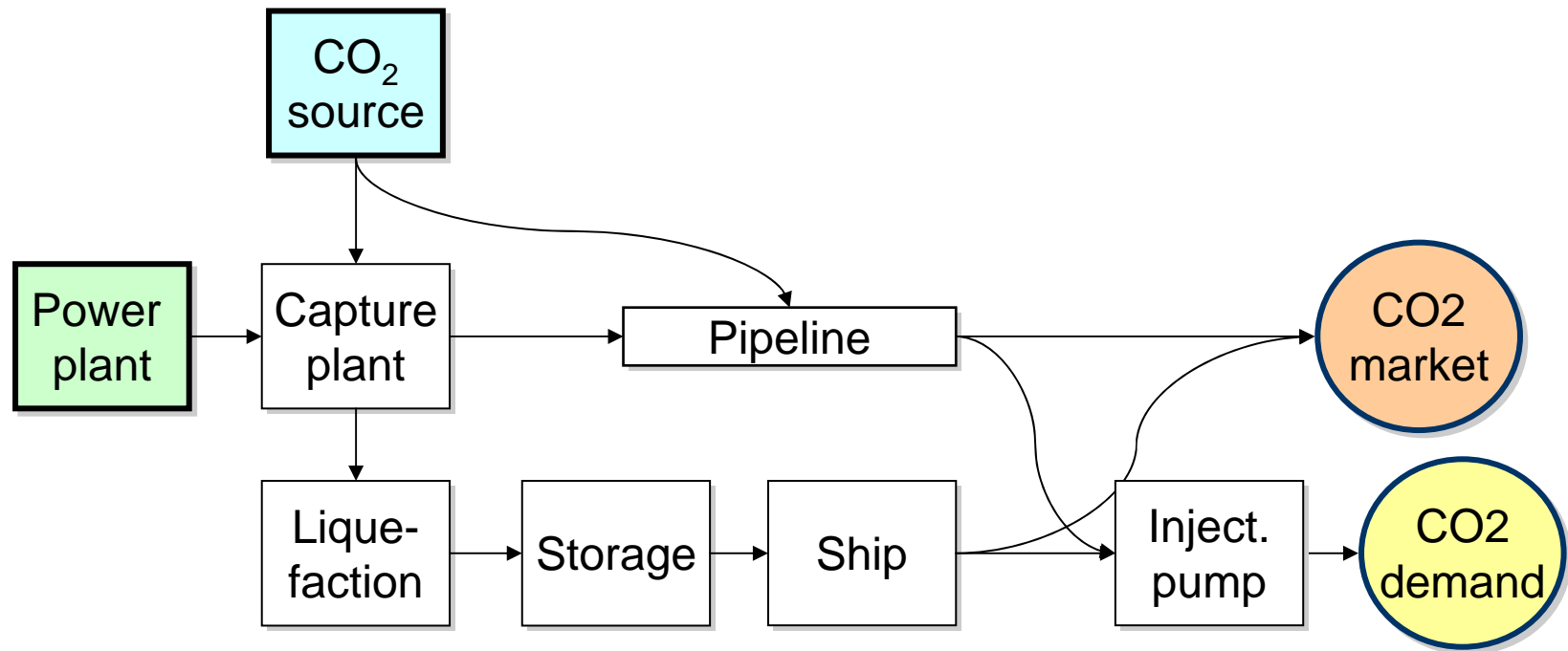
Flexible load segments with hourly time-steps



Operation and expansion planning

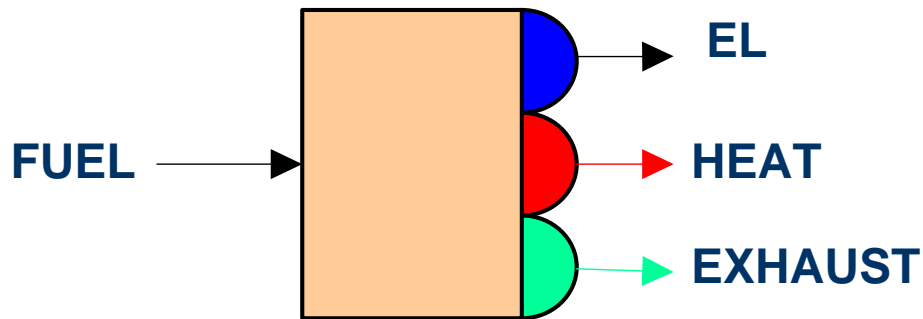


Relevant technology modules in the CO₂ Value Chain



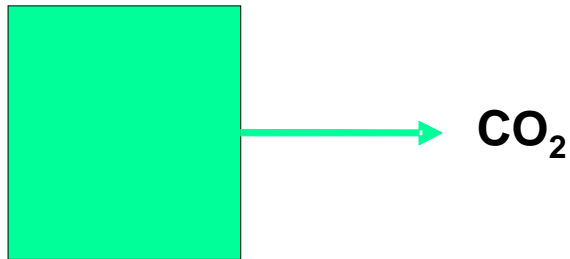
- Any number and combination of modules is possible

Power plant with exhaust outlet



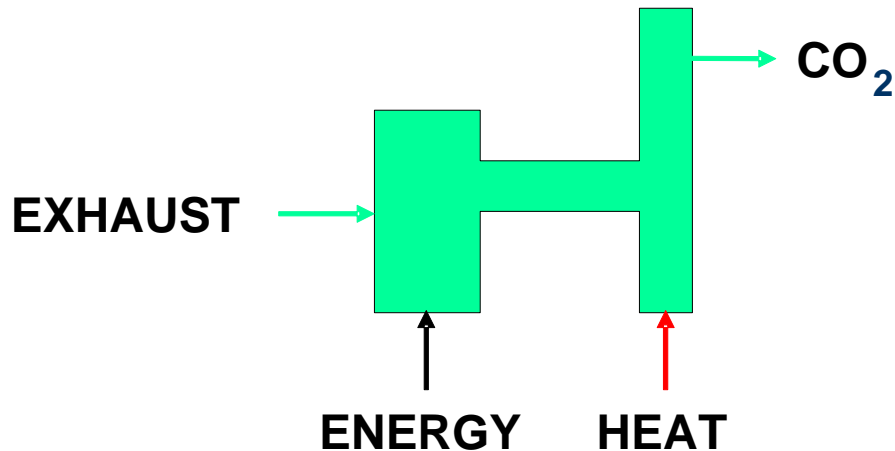
- Base load CCGT power station
- The fuel is converted to electricity and heat (optional)
- Exhaust gas with a certain CO₂-concentration is produced
- The optimal amount of el. and heat is produced according to demand and market price

Generic CO₂ (or exhaust) source



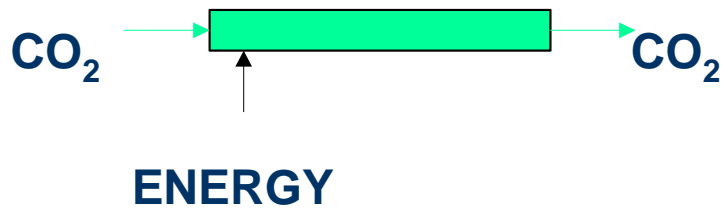
- Pure CO₂ supplied from outside the system boundary at a given price
 - The price can be negative if someone is willing to pay for disposal of CO₂
- Can also represent an **exhaust gas from industry** with a certain concentration of CO₂. The supply is then connected to a **capture plant** where the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

CO₂ capture plant

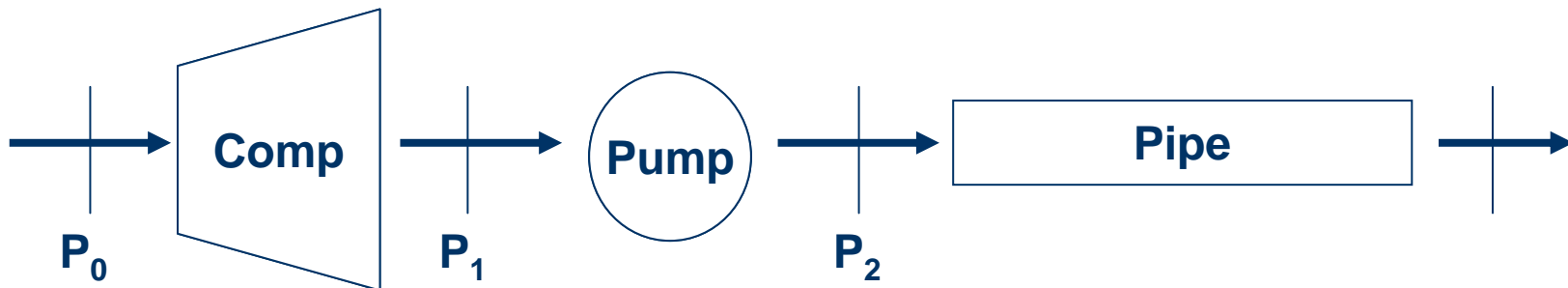


- Post combustion module independent of power plant and source(s)
- **Absorber:** MEA. Requires mechanical energy (el/gas). Size and cost depend on the total amount of flue gas and the CO₂ concentration
- **Stripper:** Regeneration of MEA by increasing the temperature. Low quality heat can be used; steam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

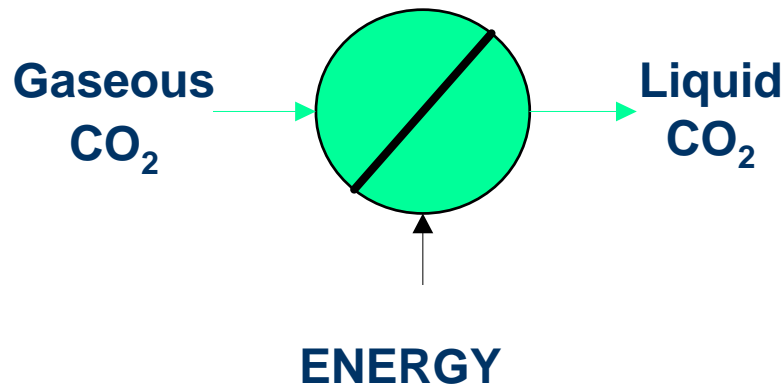
CO₂ pipeline



- 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

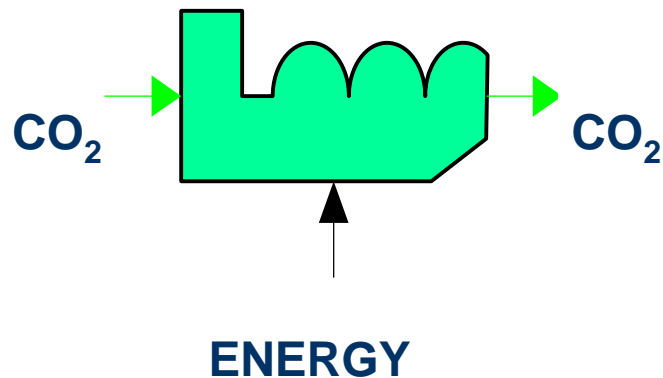


CO₂ liquefaction plant



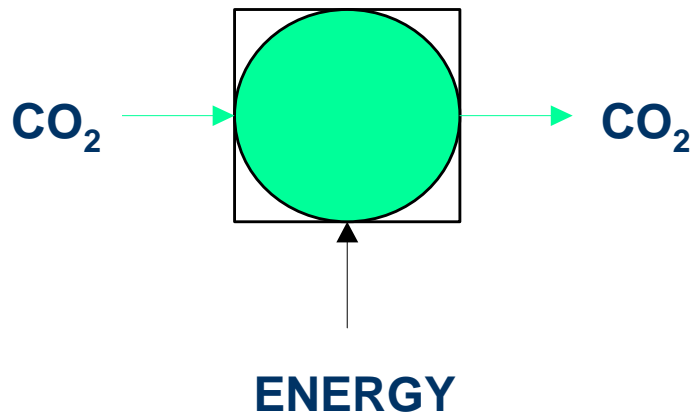
- Large scale transport of CO₂ by ships favours operating conditions close to CO₂'s triple point where the density is fairly high, approx. 70 bar
- The liquefaction is done by compression in several steps followed by expansion and cooling
- Energy supplied can be electricity or gas, the efficiency is adjusted according to the energy carrier

CO₂ ship transport



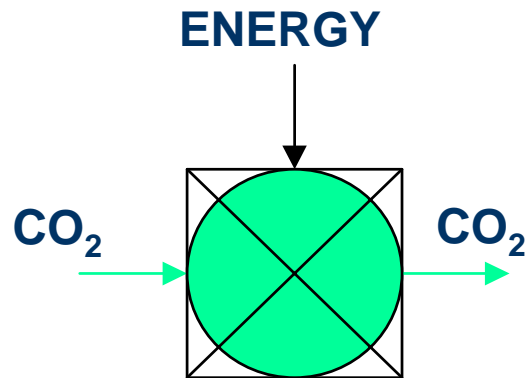
- Similar to LPG transport
- Liquid CO₂
 - P = 5,2 bar
 - T = - 50 °C
- Currently, a simplified approach using continuous transport module with average flows of CO₂ and energy
- Required energy is calculated using the transportation length, speed and the hours needed for loading etc
- Energy supplied can be oil, gas or electricity
- If investment costs are very uncertain, the user can lease the ship for an hourly/daily rate

CO₂ intermediate storage



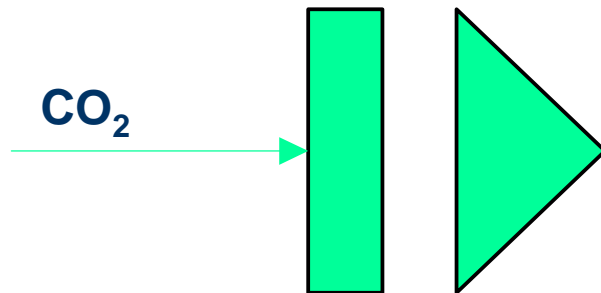
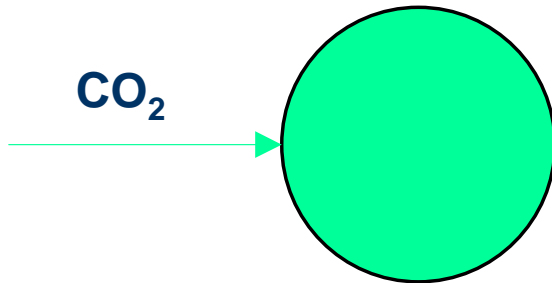
- Intermediate storage capacity may be needed at several stages in the transport chain
- In particular, ship transportation as a discrete process requires storage
- 1,5 *capacity of ship
- Energy supplied can be electricity or gas; the efficiency is adjusted according to the energy carrier

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

CO₂ demand (given quantity) and market (given price)

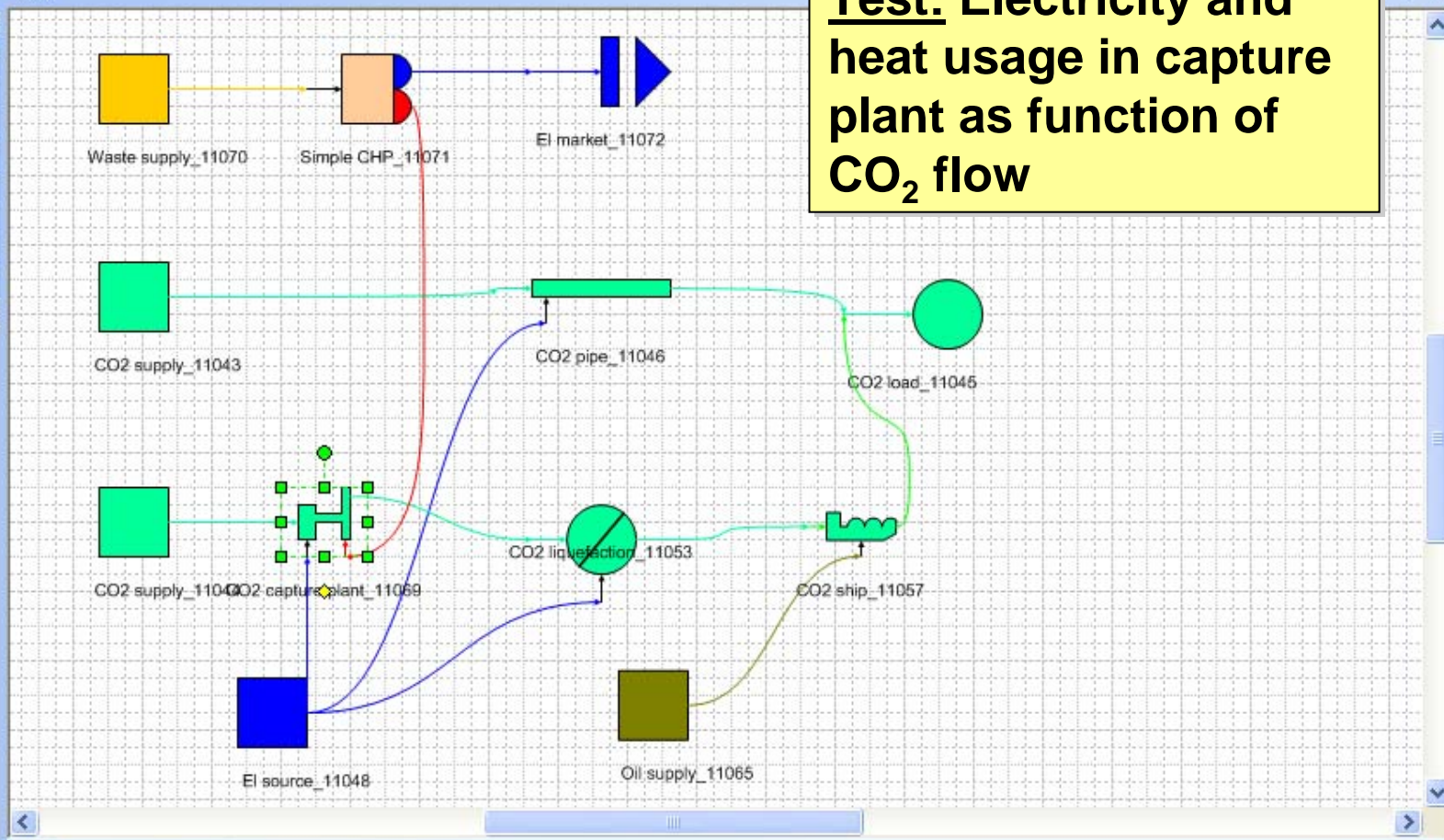


- If there is a given demand of CO₂ this is represented by a **CO₂ load** module.
- The load requires a certain quantity of CO₂ [tonne/h] - e.g. an oil field that needs CO₂ for Enhanced Oil Recovery
- Penalty cost for non-delivery

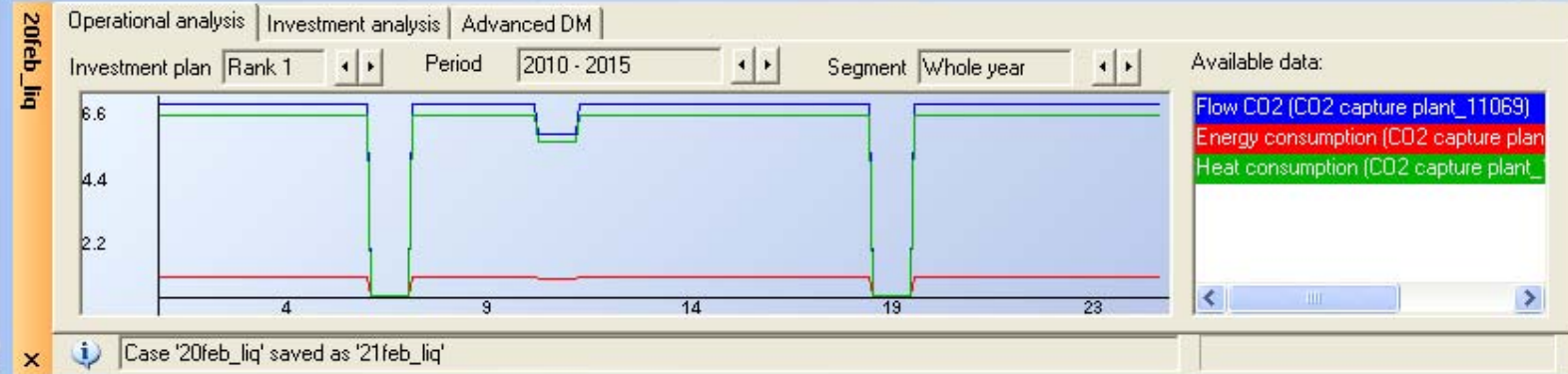
- A **CO₂ market** can be industry or an oil field willing to pay for CO₂-delivery
- An aquifer for storage of CO₂ can be modeled as a market with a negative price to cover the injection costs
- No obligation to deliver

Shapes

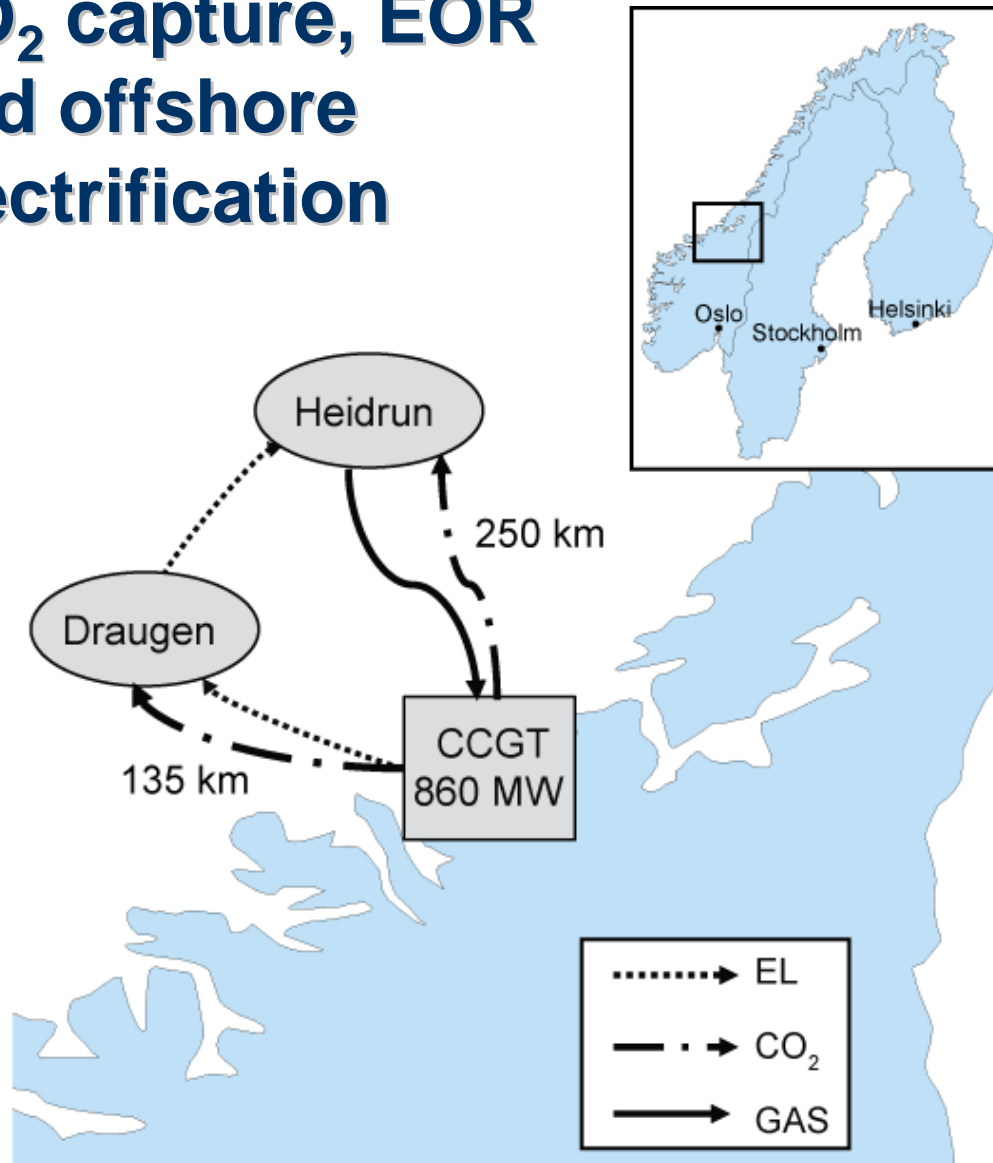
- Conversion Components
 - Biomass
 - District Heating
 - Electricity
 - Gas
 - Oil
 - Waste
 - CO2
- CO2 supply
 - CO2 load
 - CO2 market
 - CO2 storage
 - CO2 Pipe
 - CO2 Liquefaction
 - CO2 Ship
 - CO2 Capture



Test: Electricity and heat usage in capture plant as function of CO₂ flow



Regional case with CO₂ capture, EOR and offshore electrification



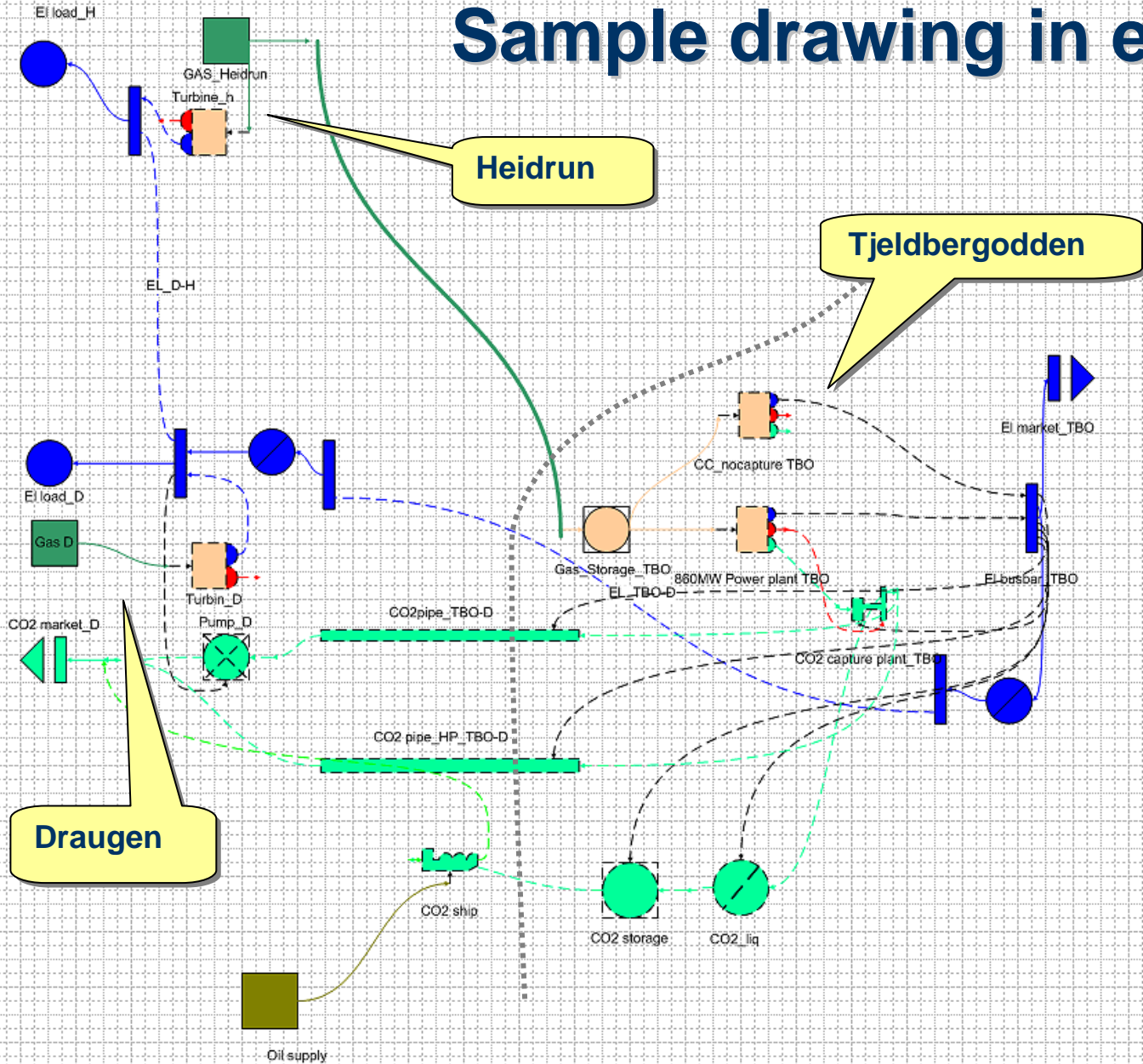
Case objectives

- 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
- *NB: Highly fictive case using best available data (2006)*

Case parameters

| | Investment [mUSD] | Operation [mUSD/year] | Lifetime [years] |
|---|----------------------|--------------------------|---------------------|
| Power plant 860 MW | 409 | 62 | 25 |
| Capture plant | 240 | 37 | 25 |
| CO2 pipeline | | | |
| to Draugen (135 km) | | | |
| - Low pressure | 162 | 3.2 | 30 |
| - High pressure | 180 | 3.6 | 30 |
| to Heidrun (250 km) | | | |
| - Low pressure | 233 | 4.6 | 30 |
| - High pressure | 261 | 5.2 | 30 |
| Ship (15 000m ³) | 46 | 2.3 | 30 |
| Liquefaction | 76 | 3.8 | 30 |
| Storage (24 000 m ³) | 60 | 1.2 | 30 |
| Injection-pumps + equipment offshore | | | |
| - gas turbines | - | 20 | - |
| - after pipelines | 8 | 0.2 | 30 |
| - after ship transport | 33 | 0.6 | 30 |
| Electricity cable | | | |
| - to Draugen | 46 | 0.7 | 30 |
| - Draugen-Heidrun | 34 | 0.5 | 30 |

Sample drawing in eTransport



Initial results and sensitivities

- Power plant with CCS not competitive with conventional power plant with initial assumptions
- Overall CO₂ tax has to exceed **69 USD/tonne CO₂** to make investments in CCS competitive with a conventional power plant (today 15.4 USD/tonne CO₂)
- The price of pressurized CO₂ 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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- *IEEE Trans. on Energy Conversion*, Vol. 23, No.3, Sept. 2008 -

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