Linear Models for Optimization of Infrastructure for CO_2 Capture and Storage

Bjorn H. Bakken
SINTEF Energy Research, Norway

Ingrid von Streng Velken
Boston Consulting Group, Norway

bjorn.h.bakken@sintef.no
www.energy.sintef.no
www.sintef.no/etransport

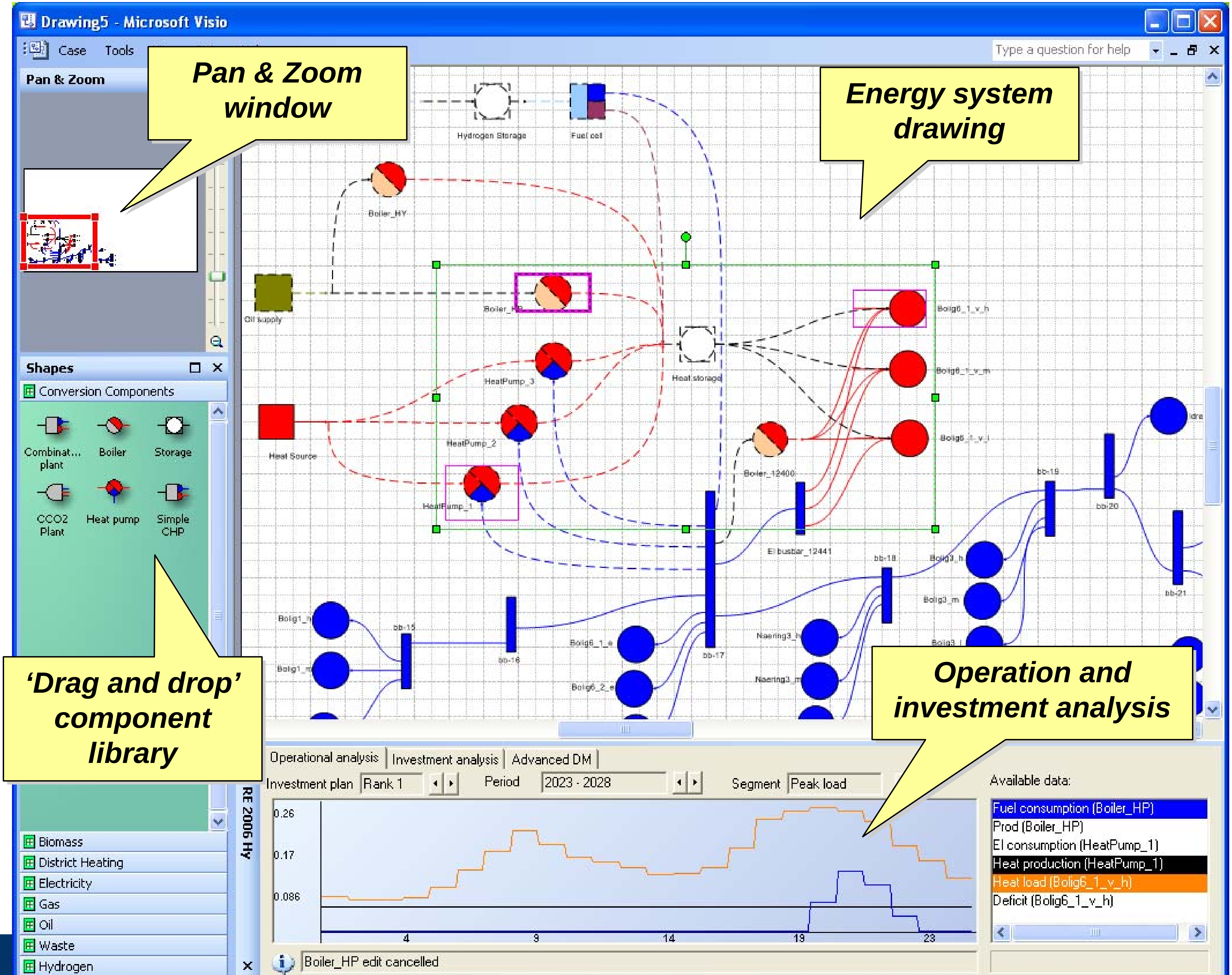
Background and motivation

- **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 CO_2

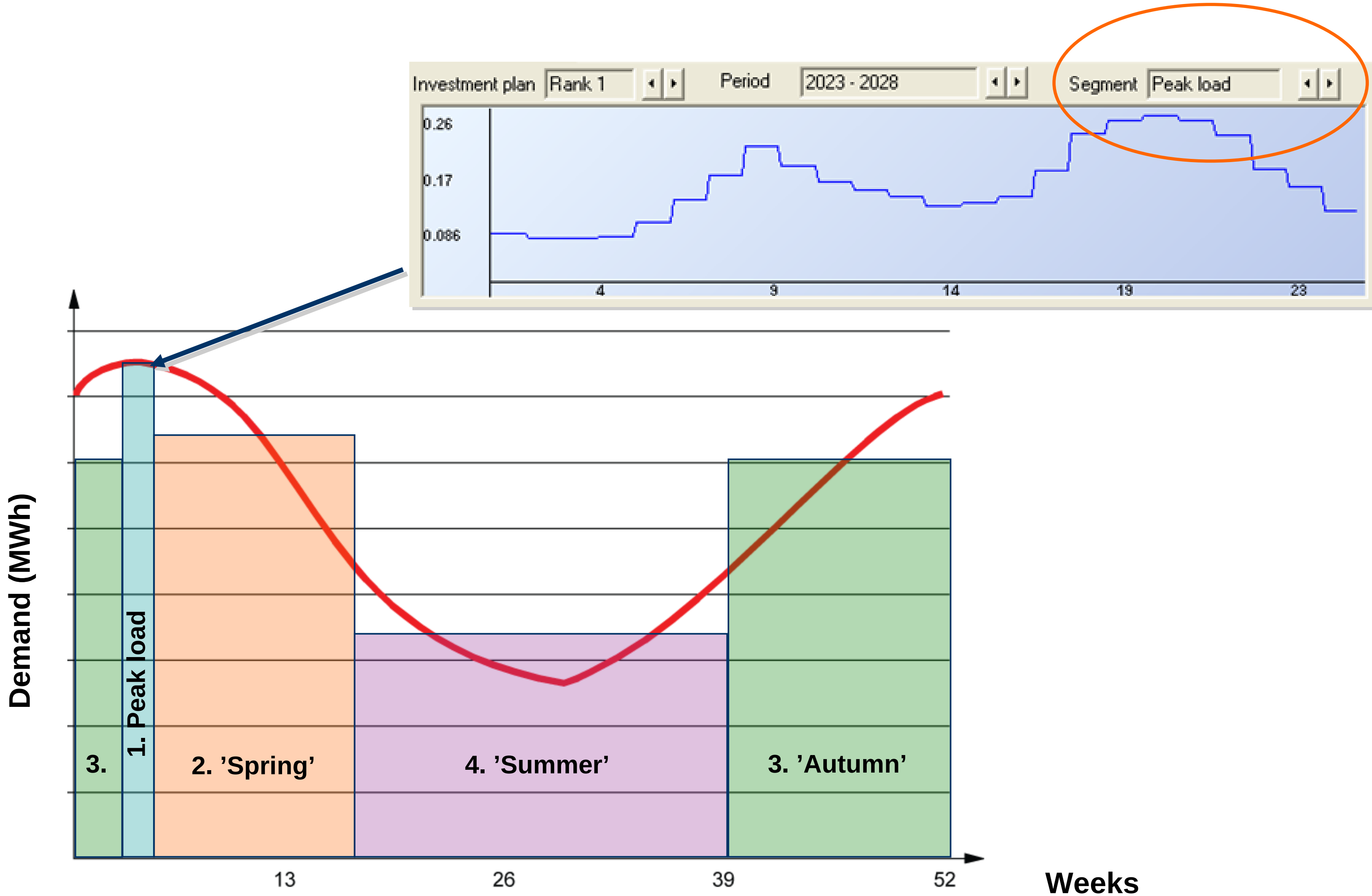
The eTransport model

- **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**

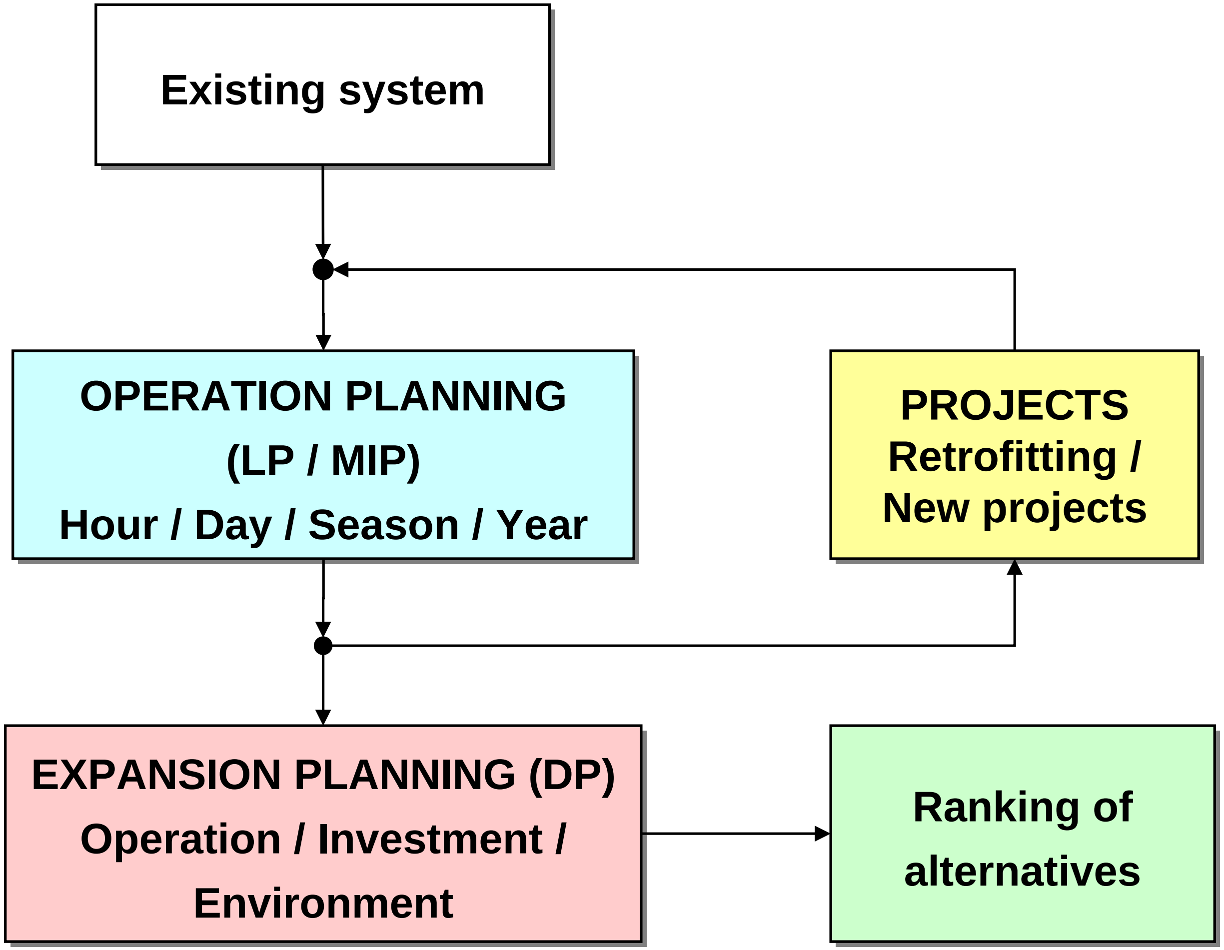


Drawing5 - Microsoft Visio
Pan & Zoom window
Energy system drawing
'Drag and drop' component library
Operation and investment analysis
Pan & Zoom
Shapes
Conversion Components
Combinat... plant
Boiler
Storage
CCO2 Plant
Heat pump
Simple CHP
Biomass
District Heating
Electricity
Gas
Oil
Waste
Hydrogen
Hydrogen Storage
Fuel cell
Boiler_HY
Boiler_HP
Oil supply
HeatPump_3
HeatPump_2
HeatPump_1
Heat Source
Heat storage
Boiler_12400
El busbar_12441
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 (Bolig6_1_v_h)
Deficit (Bolig6_1_v_h)
Boiler_HP edit cancelled

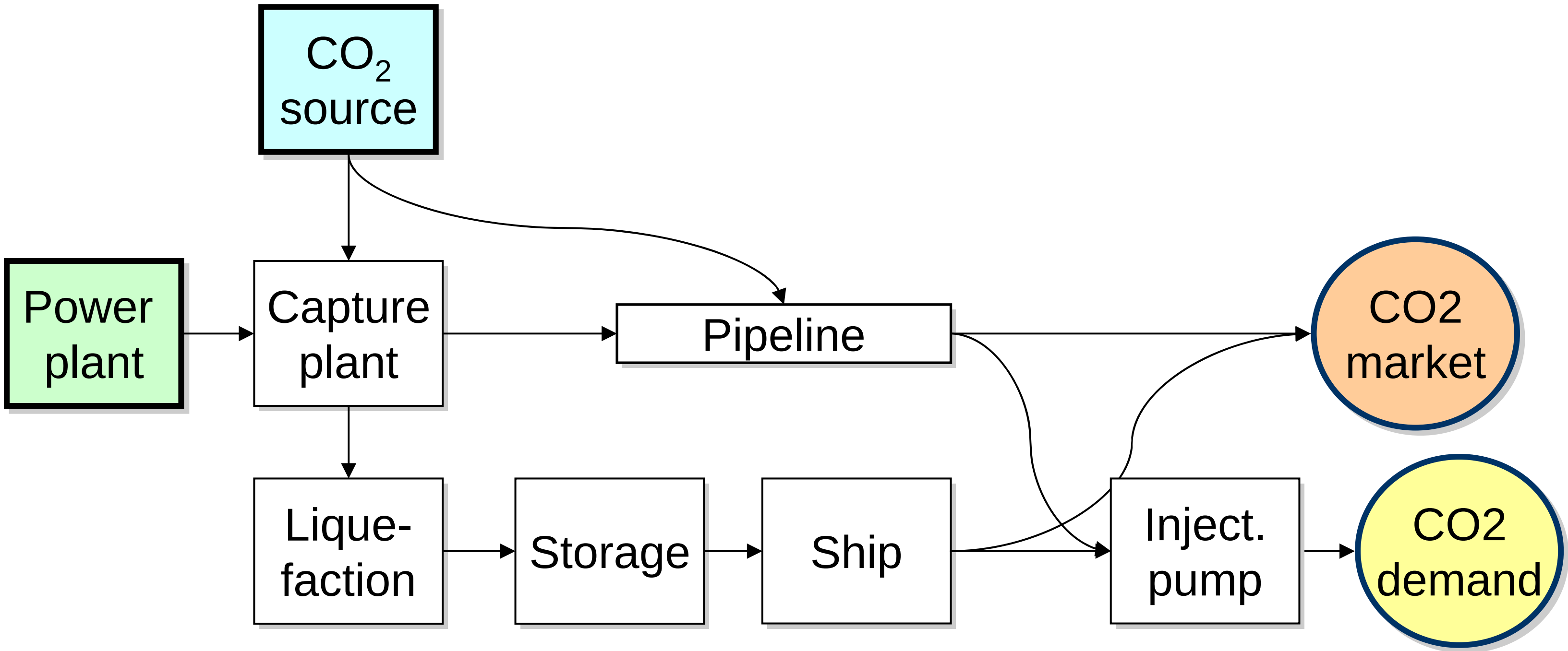
Flexible load segments with hourly time-steps



Operation and expansion planning

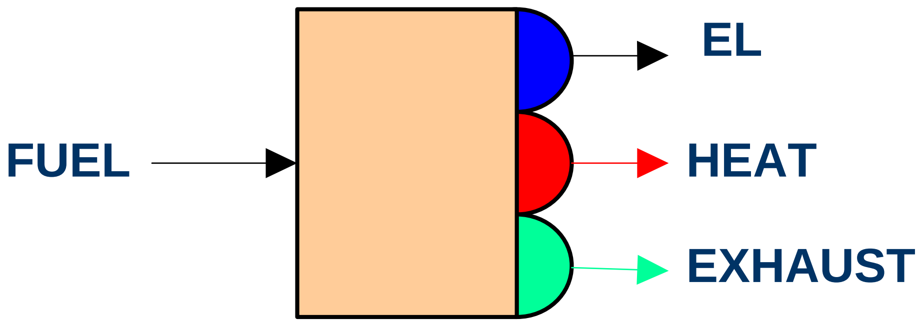


Relevant technology modules in the CO_2 Value Chain



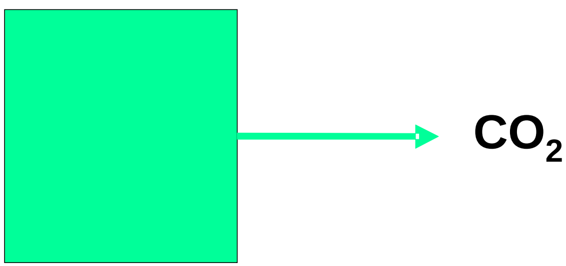
- Any number and combination of modules is possible

Power plant with exhaust outlet



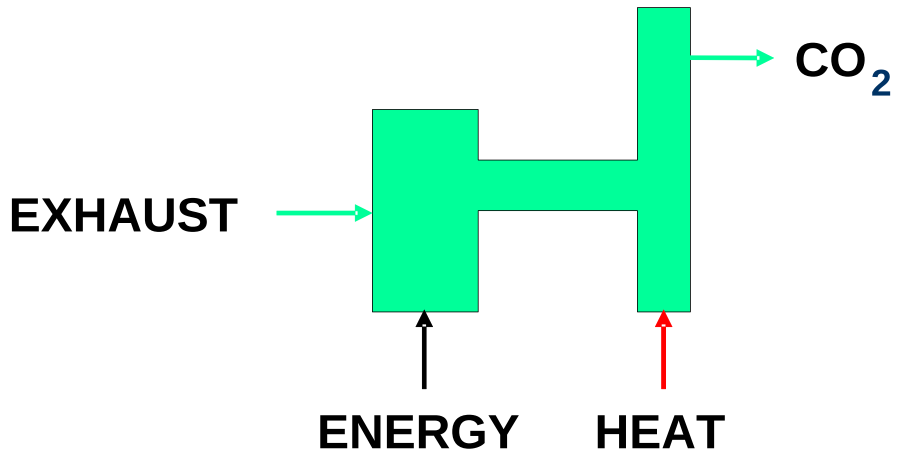
- Base load CCGT power station
- The fuel is converted to electricity and heat (optional)
- Exhaust gas with a certain CO_2-concentration is produced
- The optimal amount of el. and heat is produced according to demand and market price

Generic CO_2 (or exhaust) source



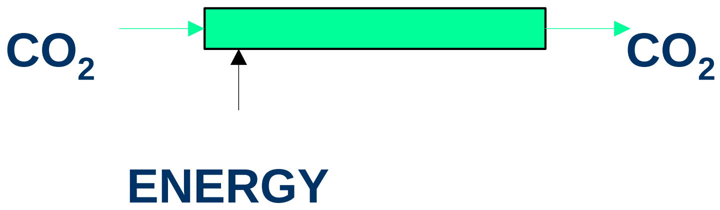
- Pure CO_2 supplied from outside the system boundary at a given price
  - The price can be negative if someone is willing to pay for disposal of CO_2
- Can also represent an exhaust gas from industry with a certain concentration of CO_2. The supply is then connected to a **capture plant** where the CO_2 is separated from the exhaust gases

CO_2 capture plant

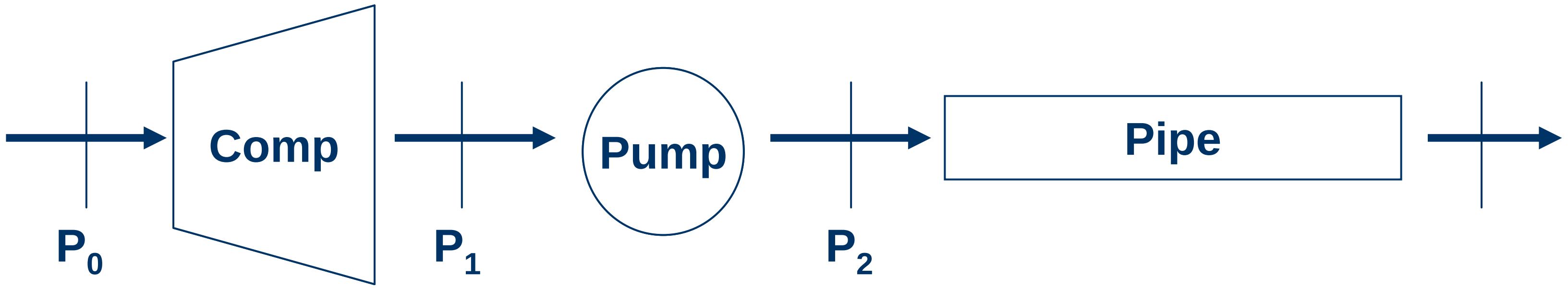


- Post combustion module independent of power plant and source(s)
- **Absorber:** MEA. Requires mechanical energy (el/gas). Size and cost depend on the total amount of flue gas and the CO_2 concentration
- **Stripper**: Regeneration of MEA by increasing the temperature. Low quality heat can be used; steam 150ºC
- Chemicals are required to reduce water, SOx, NOx and other pollutants than might influence the capture process
- Producing a highly concentrated CO_2-stream (>99%)

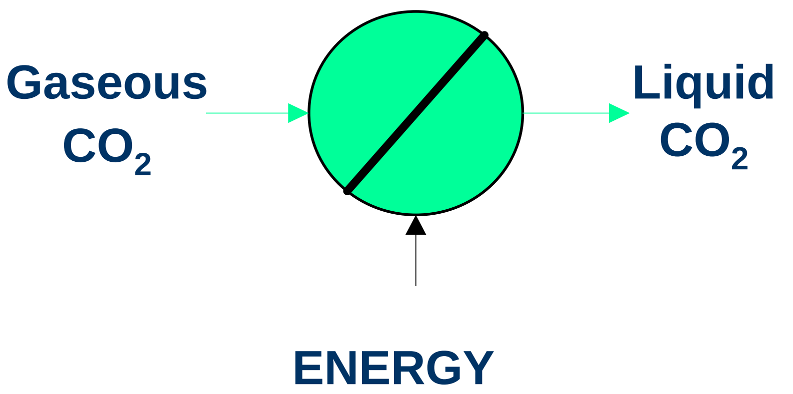
CO_2 pipeline



- 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 CO_2) 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

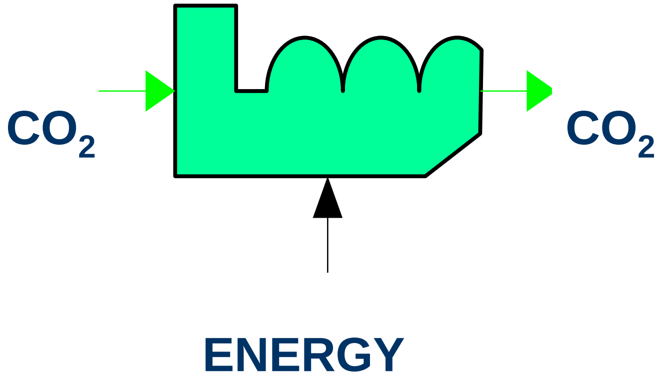


CO_2 liquefaction plant



- Large scale transport of CO_2 by ships favours operating conditions close to CO_2'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

CO_2 ship transport

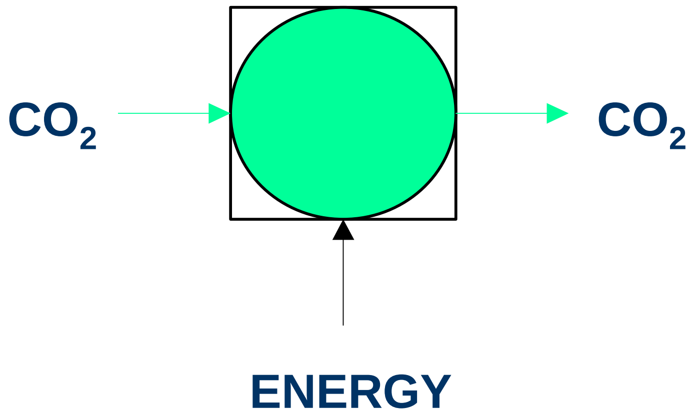


- Similar to LPG transport
- Liquid CO_2

  P = 5,2 bar

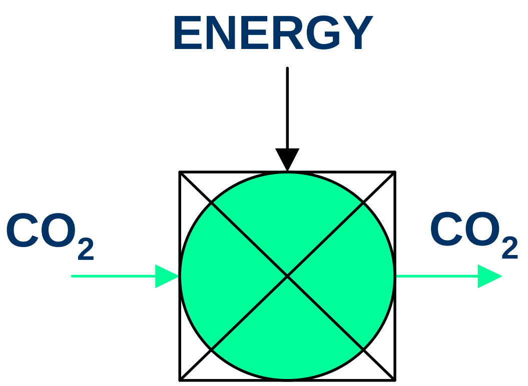
  T = – 50 ^oC
- Currently, a simplified approach using continuous transport module with average flows of CO_2 and energy
- Required energy is calculated using the transportation length, speed and the hours needed for loading etc
- Energy supplied can be oil, gas or electricity
- If investment costs are very uncertain, the user can lease the ship for an hourly/daily rate

CO_2 intermediate storage



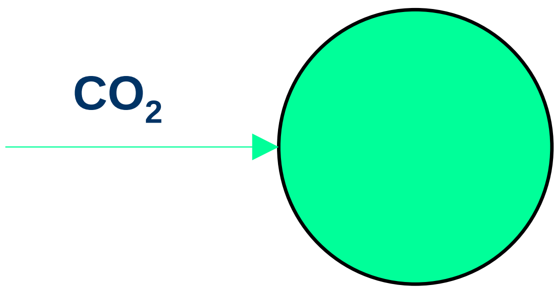
- Intermediate storage capacity may be needed at several stages in the transport chain
- In particular, ship transportation as a discrete process requires storage
- 1,5 *capacity of ship
- Energy supplied can be electricity or gas; the efficiency is adjusted according to the energy carrier

CO_2 injection pump

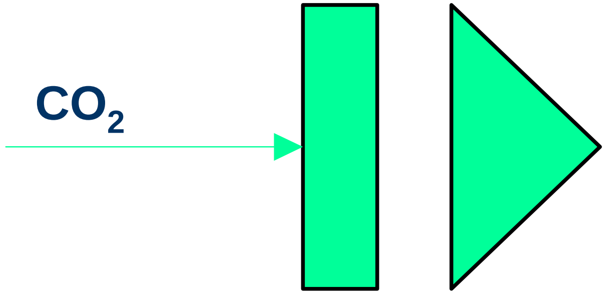


- Pump for injection of CO_2 into oil wells or other underground storage
- The energy requirement is a function of the well head pressure
- Can be used after transportation by ships or pipelines
- The energy requirement is higher after ship transport than after pipelines
- Investment cost of offshore modifications can be included

CO_2 demand (given quantity) and market (given price)

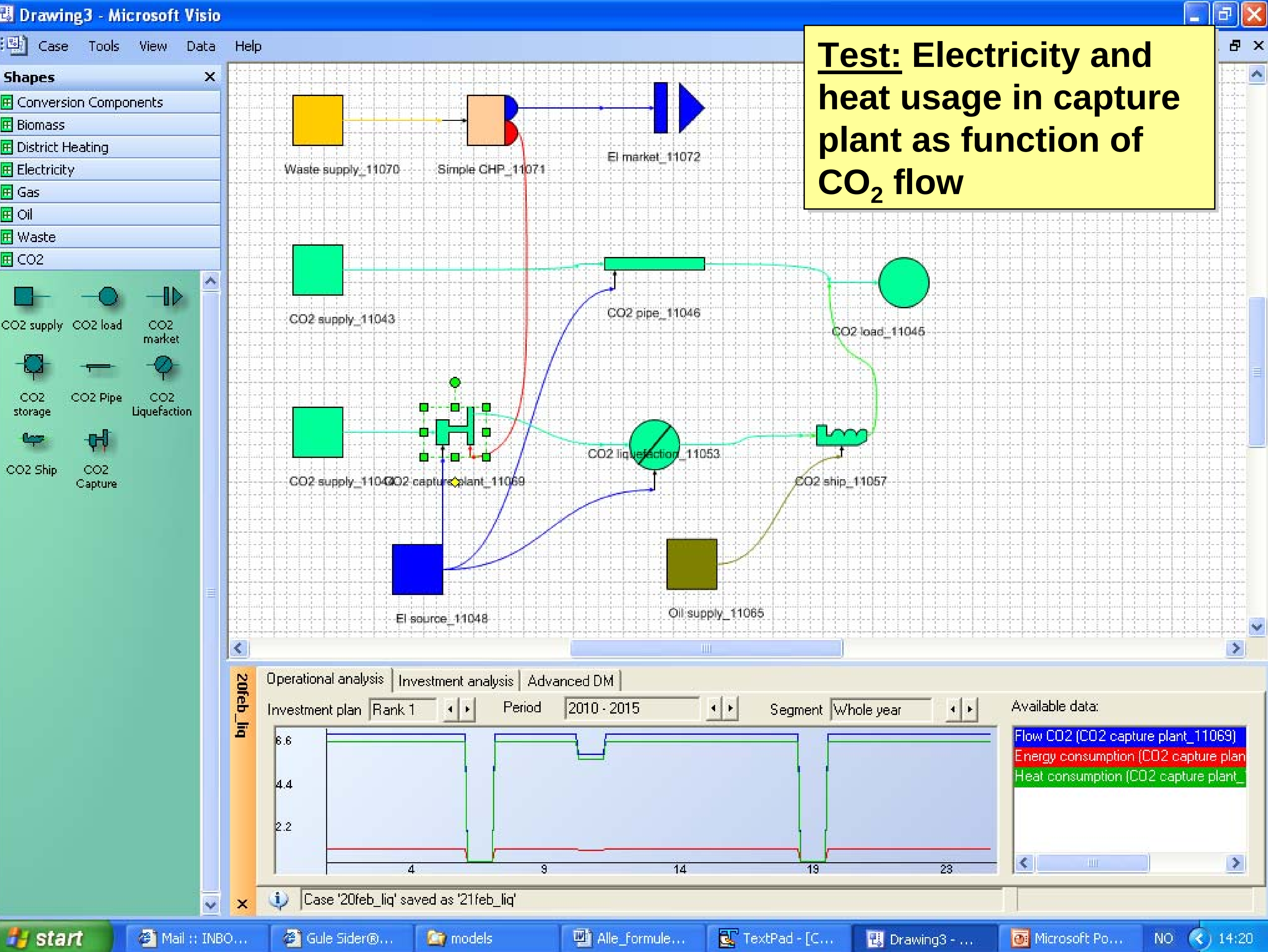


- If there is a given demand of CO_2 this is represented by a **CO_2 load** module.
- The load requires a certain quantity of CO_2 [tonne/h] - e.g. an oil field that needs CO_2 for Enhanced Oil Recovery
- Penalty cost for non-delivery

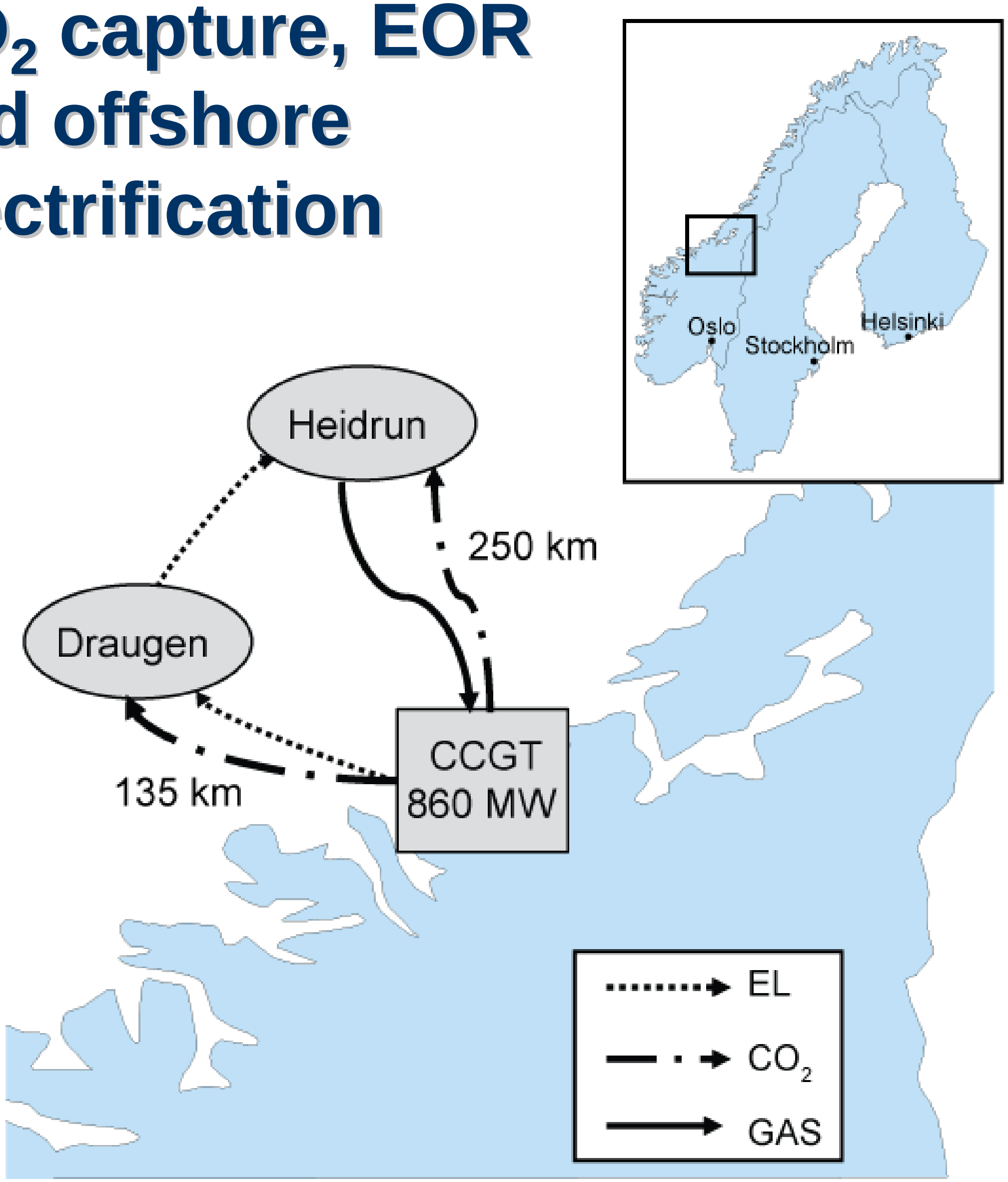


- A **CO_2 market** can be industry or an oil field willing to pay for CO_2-delivery
- An aquifer for storage of CO_2 can be modeled as a market with a negative price to cover the injection costs
- No obligation to deliver

Test: Electricity and heat usage in capture plant as function of CO_2 flow



Regional case with CO_2 capture, EOR and offshore electrification



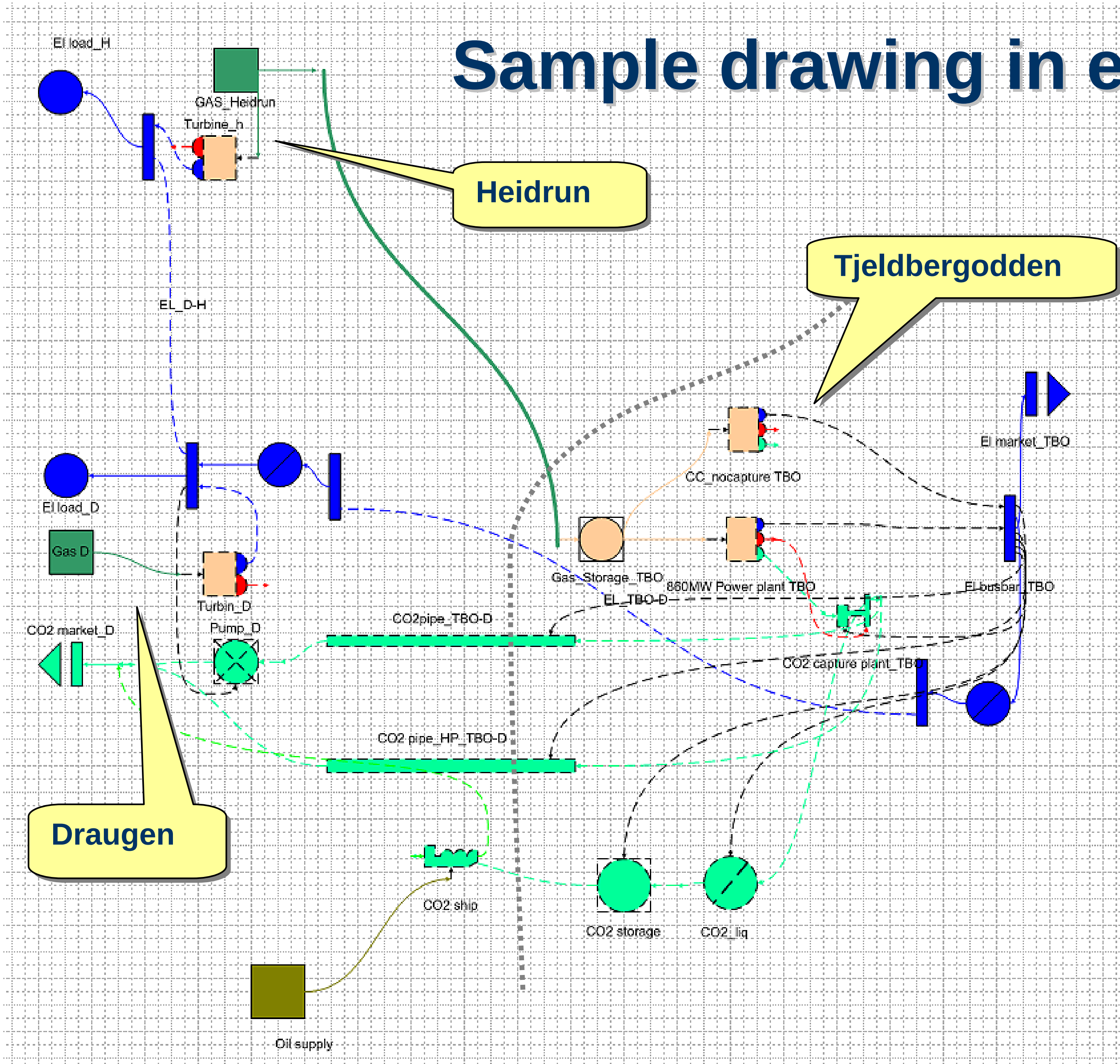
Case objectives

- Compare gas fired power plants with and without CCS
- Taxes and emission penalties
- Market price of CO_2 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 - High pressure	 162 180	 3.2 3.6	 30 30
to Heidrun (250 km) - Low pressure - High pressure	 233 261	 4.6 5.2	 30 30
Ship (15 000m³)	46	2.3	30
Liquefaction	76	3.8	30
Storage (24 000 m³)	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 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 CO_2 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 CO_2 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 CO_2 pipeline to Heidrun
  - Less competitive solution with one CO_2 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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Bjorn H. Bakken
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Boston Consulting Group, Norway

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