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Effect of varying electricity and carbon prices on operation and capture levels in flexible post-combustion CCS power plants

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Flexible operation of post-combustion CCS

- Amine post combustion capture technologies - originally developed to **separate acid gases at base-load steady state operation**.
- Post combustion systems in integrated power cycles have a further objective; **generation of power, with low carbon emissions**.
- Responsive real world fossil power plant operations vary power output:
  - Grid balancing
  - Rapid changes in electricity markets
  - Variations in carbon and fuel markets can also influence plant dispatch
- Options for integrated PCC process design to enable flexible operation include:
  1. **Capture plant bypassing**
  2. **Varying carbon capture rates**

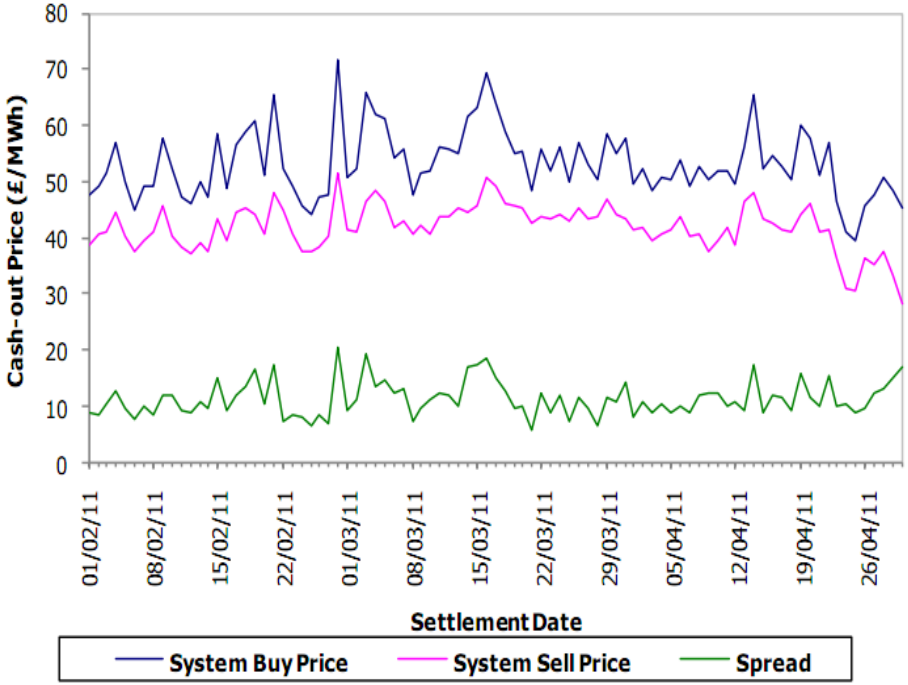
Why operate flexibly?

- Electricity markets
  - Seasonal, daily and hourly fluctuations
  - Ancillary contracts

Electricity market price volatility

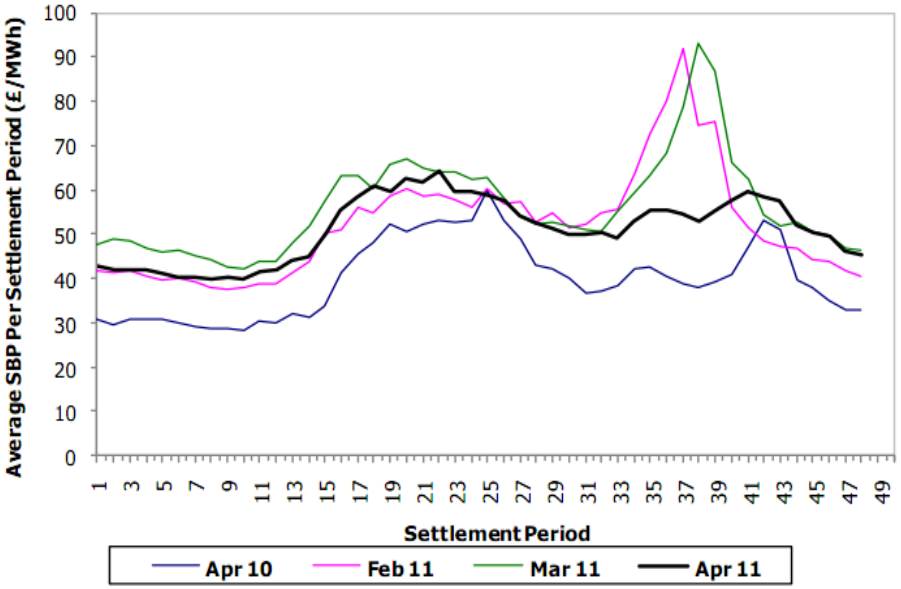
Daily

Daily average system prices £/MWh



Hourly

Daily average system buying prices per ½ hour settlement period £/MWh

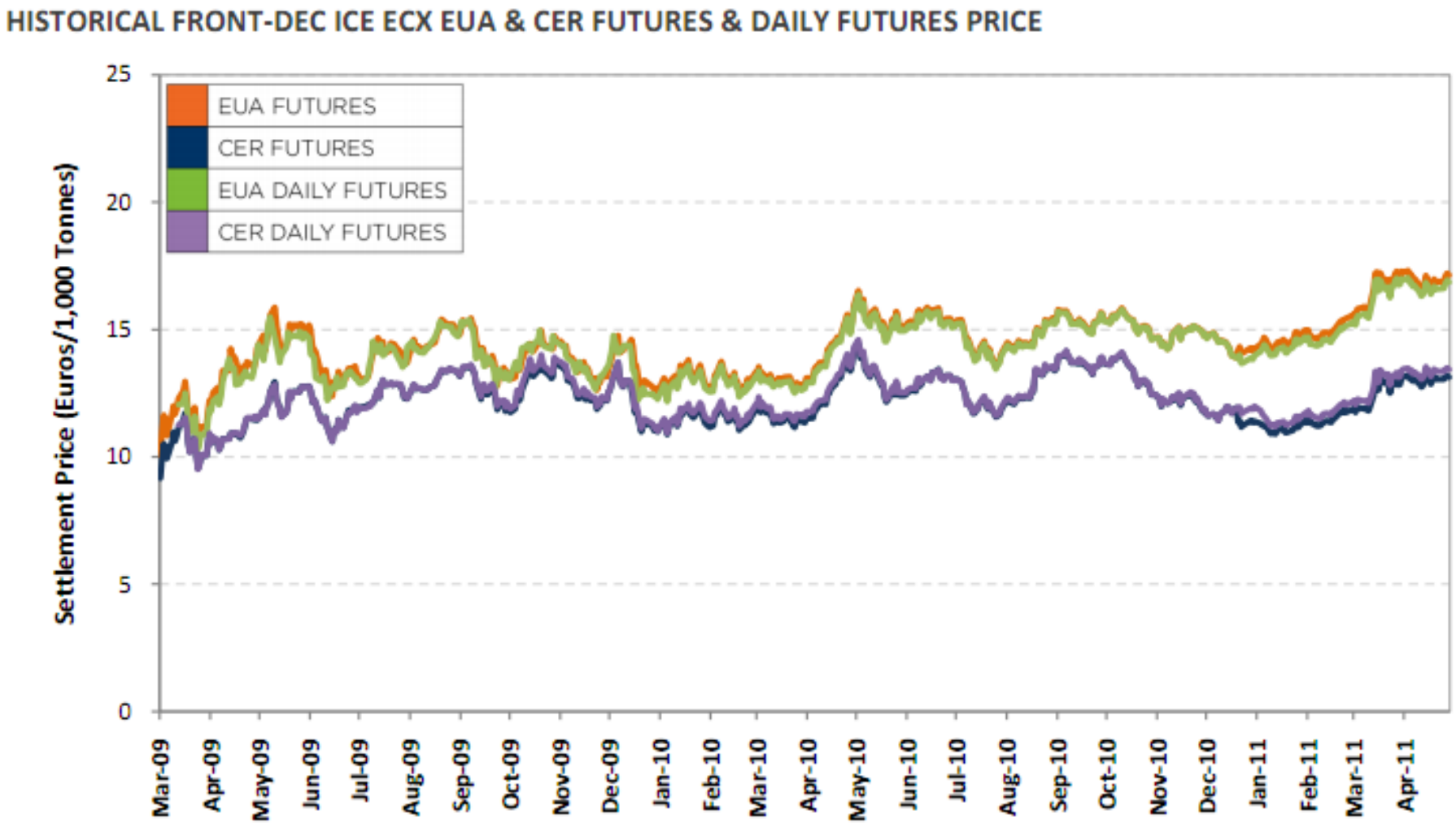


Source: Elexon Trading Operations Report April 2011

Why operate flexibly?

- Electricity markets
  - Seasonal, daily and hourly fluctuations
  - Ancillary contracts
- Carbon markets
  - Mid-long term and daily variation

More recent daily fluctuations in carbon price

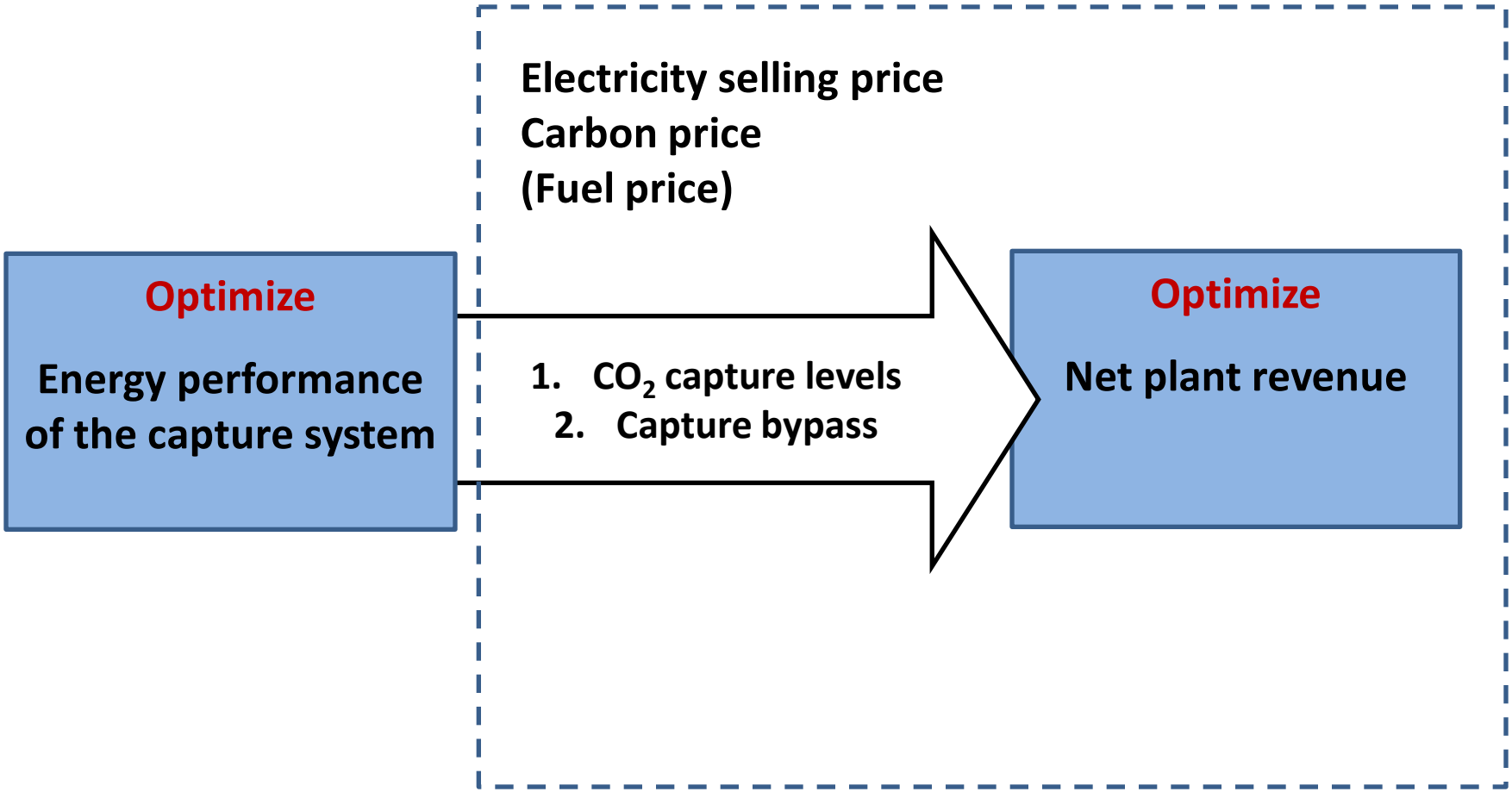


https://www.theice.com/publicdocs/futures/ICE_Monthly_Utility_Report.pdf

Why operate flexibly?

- Electricity markets
  - Seasonal, daily and hourly fluctuations
  - Ancillary contracts
- Carbon markets
  - Mid-long term and daily variation
- Increase in grid intermittency with growing contribution from renewable sources
  - Enhance market price signals

Objective of this work:
Maximise net revenue for a range of scenarios



Implications and options for CCS plant operation

Design beyond base load operations:

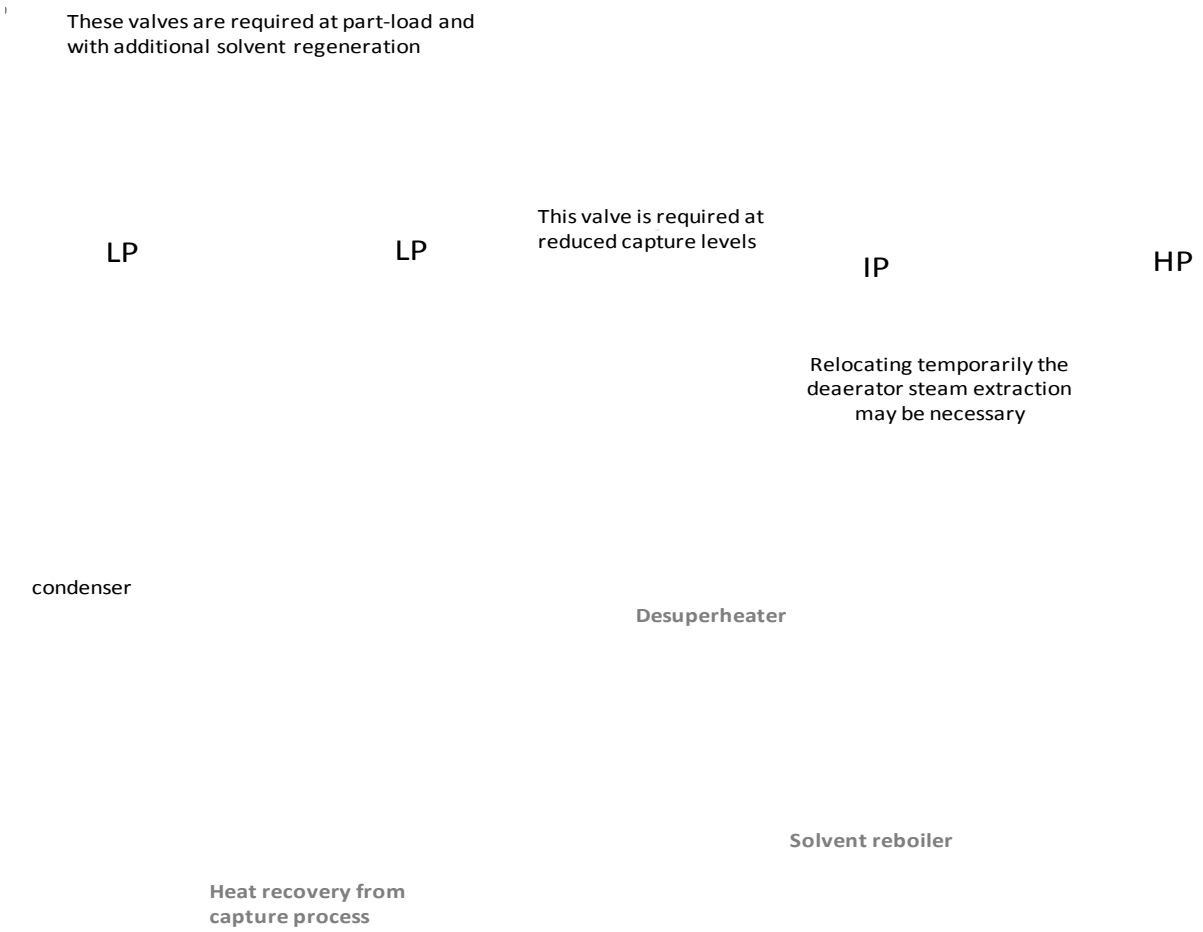
1. Steam cycles with flexible steam turbine operations
   - varying capture levels
   - Capacity to reduce steam extraction thereby reducing the total carbon captured and increasing the energy output for a maintained period
2. Bypass
   - Assumption of rapid "shutting off" of capture wing liberating extra MW capacity

Assumptions

- Capability to export greater levels of carbon dioxide, at variable rates
- Capability to produce more power than design specification
- Retrofitted or pre-investment in larger or secondary turbines and generator capacity plant
- Retrofitted plant designed to operate variable IP/LP crossover steam extraction

Steam turbines with flexible capture

COP (and EOP) varies with steam extraction. The ratio of the mass flow of steam entering the solvent reboiler to the mass flow of steam entering the low pressure turbine before capture is added.



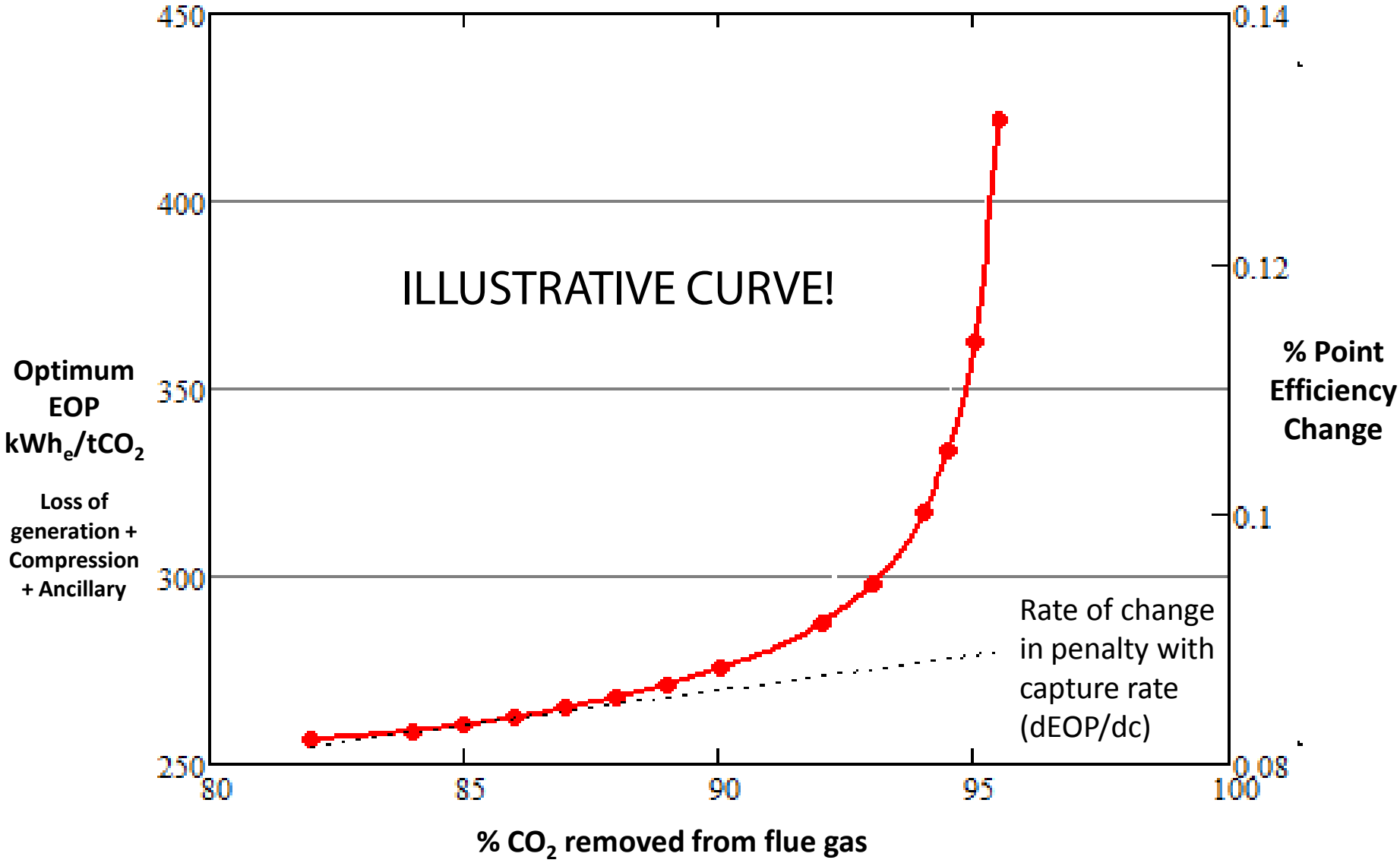
M. Lucquiaud 2010

Plant model

- In-house gPROMS model of post combustion coal power plant
  - Integrated supercritical steam cycle, amine plant, power plant compression system and associated heat recovery equipment
- Optimization of electricity output penalty of capture system: thermodynamic integration and solvent lean:rich loading
- Aqueous solvent capture system: 30%wt MEA.
- Base plant efficiency: 44% LHV
- Carbon intensity of coal: 0.327 tonne/MWh_{th} (0.091 tonne/GJ)
- Constant fuel input

Electricity output penalty at optimum lean loading

Indicative electrical output penalties (EOP) for 25m absorber



Optimum capture level for plant net revenue

Once the plant in built, net operating revenue that can be varied by operating decisions does not include any fixed costs by definition. Capital costs considerations are important at investment decision level only.

Over an operating period where the electricity selling price and the cost of carbon are constant, the net operating revenue balance per hour, R_{net}, is:

Income — Short run marginal costs

$$R_{net} = \{POE * fuelin * \eta_{cap}\} - \left\{\left(\frac{\$\,fuel}{\eta_{cap}} + COC * (1-c) * \frac{e}{\eta_{cap}} + vc_{CCS} * c * \frac{e}{\eta_{cap}}\right) * fuelin * \eta_{cap}\right\} - \{vc_{base} * fuelin * \eta_{base}\}$$

Electricity selling price — Plant MW output with capture — Fuel costs — Carbon cost — Capture plant operating costs — Base plant operating costs — Base plant MW output

$$\bullet_{cap} = \bullet_{base} - \%point\ capture\ penalty$$

$$R_{net} = \{POE * fuelin * (\eta_{base} - (EOP * e * c))\} - \{(\$\,fuel + COC * (1-c) * e + vc_{CCS} * c * e) * fuelin\} - \{vc_{base} * fuelin * \eta_{base}\}$$

R_{net} ($/hr)	Net operating revenue	***fuelin*** (MWh_{th}/hr)	Rate of energetic input
POE ($/$MWh_e$)	Time averaged price for electricity	***vc_{base}*** ($/$MWh_e$)	Specific variable costs for power plant
EOP (MWh_e/tCO_2)	Electricity output penalty	***vc_{CCS}*** ($/$tCO_2$)	Specific variable costs for capture plant
e (tCO_2/MWh_{th})	Specific emissions factor for plant	***$fuel*** ($/MWh_{th})	Fuel costs
c (-)	Fraction of CO_2 captured from flue gas	***η_{cap}*** (MWh_e /MWh_{th})	Power plant efficiency with CO_2 capture
COC ($/$tCO_2$)	Cost of carbon emissions	***η_{base}*** (MWh_e /MWh_{th})	Base plant efficiency excluding capture wing

Optimum capture level for plant net revenue

To determine optimum net revenue at a specific carbon price we can differentiate revenue with respect to capture and find the optimum where there is no further increase in revenue with a change in capture rate: $\frac{dR_{net}}{dc} = 0$

$$\frac{dR_{net}}{dc} = \left\{ -POE * fuelin * e * \left(\frac{dEOP * c}{dc} \right) \right\} - \left\{ \left(-COC * e + vc_{CCS} * e \right) * fuelin \right\} = 0$$

$$c_{opt} = \left(\frac{COC - vc_{CCS}}{POE} - EOP \right) * \frac{dc_{opt}}{dEOP}$$

This optimum is specific to a given carbon emission cost and electricity selling price

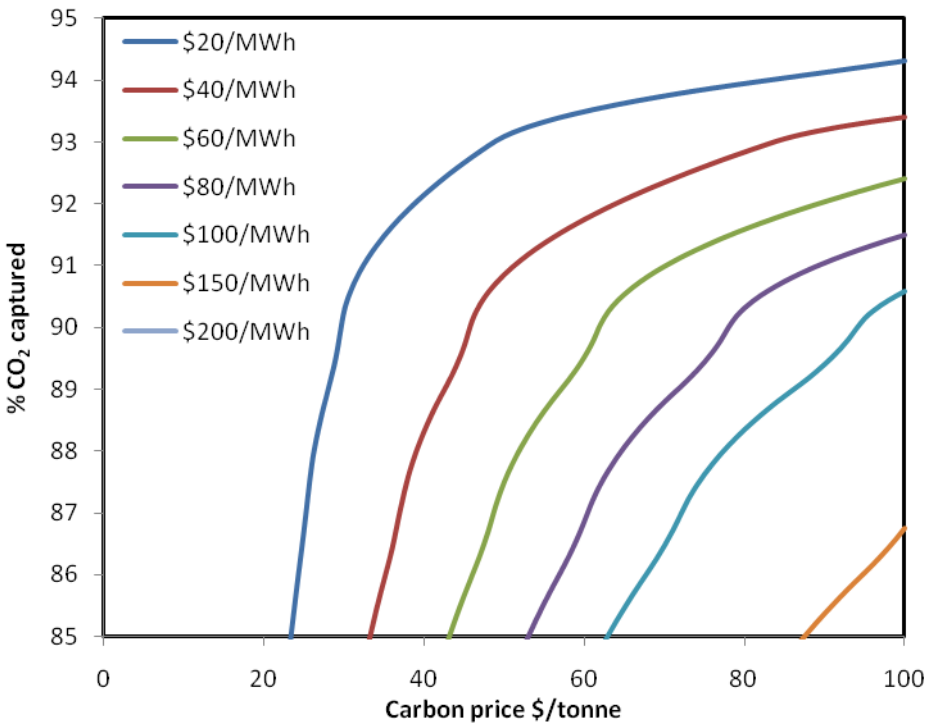
R_{net} ($/hr)	Net operating revenue	***fuelin*** (MWh_{th}/hr)	Rate of energetic input
POE ($/$MWh_e$)	Time averaged price for electricity	***vc_{CCS}*** ($/$tCO_2$)	Specific variable costs for capture plant
EOP (MWh_e/tCO_2)	Electricity output penalty	***c_{opt}*** (-)	Optimal fraction of CO_2 captured
e (tCO_2/MWh_{th})	Specific emissions factor for plant		
c (-)	Fraction of CO_2 captured from flue gas		
COC ($/$tCO_2$)	Cost of carbon emissions		

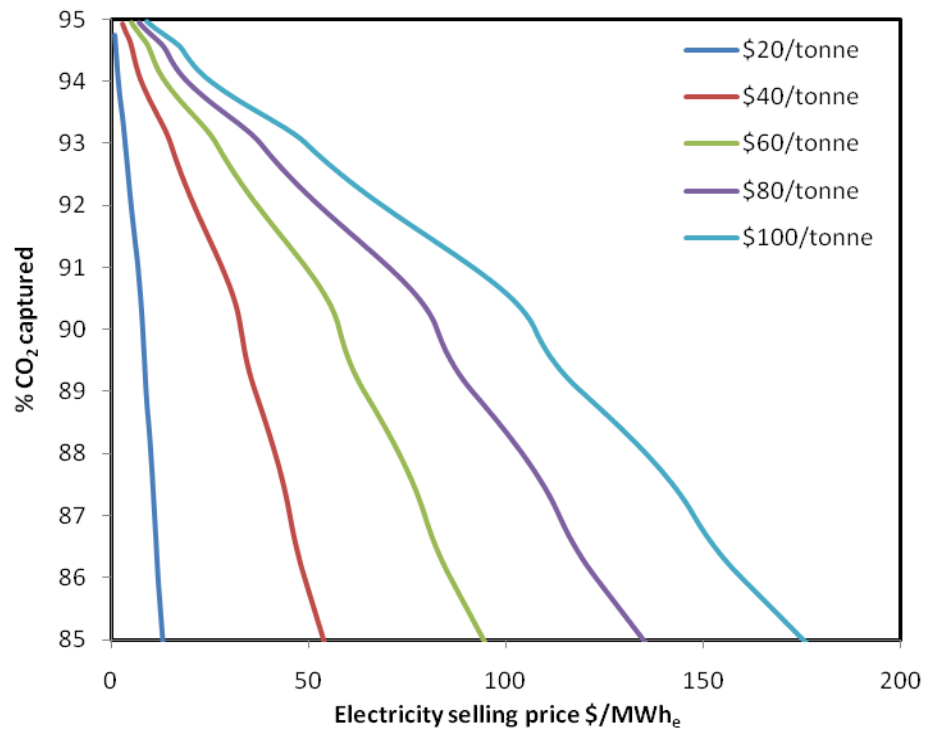
Optimum capture level for maximum plant net revenue

Optimum net revenue: $\frac{dR_{net}}{dc_{opt}} = 0$ for a given carbon emission cost and electricity selling price

Optimum capture level for a range of carbon and electricity prices:

$$c_{opt} = \left(\frac{COC - vc_{CCS}}{POE} - EOP \right) * \frac{dc}{dEOP}$$





R_{net} ($/hr) net operating revenue
POE ($/MWh$_e$) time averaged price for electricity
EOP (MWh$_e$/tCO2) electricity output penalty associated with capture level

c_{opt} (-) optimum fraction of CO_2 captured from flue gas
COC ($/tCO2) cost of carbon emissions
vc_{CCS} ($/tCO2) specific variable costs for capture plant

Capture plant bypass

When bypass is an option, it will be financially beneficial to fully bypass the capture wing at specific carbon and electricity price scenarios. The point at which it is profitable to bypass the plant rather operate the capture plant will vary depending on the capture level being operated in each scenario. These crossover points can be found when the net revenue for capture is equal to net revenue for bypass for a specific carbon/electricity price scenario:

$$R_{net\,(capture)} = R_{net\,(bypass)}$$

From the previous R_{net} equation, the above can simplified with electricity selling price as the subject to:

$$POE = \frac{e*(c_{bypass} - c_{capture})*(COC - vc_{CCS})}{(\eta_{base} - (\boxed{EOP*c_{capture}*e})) - (\eta_{base} - (\boxed{EOP*c_{bypass}*e}))} \Rightarrow POE = \frac{(c_{bypass} - c_{capture})*(COC - vc_{CCS})}{(EOP*c_{bypass}) - (EOP*c_{capture})}$$

%point capture penalty *%point bypass penalty*

Assumptions: $EOP*c = c*[EOP_x + EOP_{comp}] + EOP_{ancillary}$

At bypass, c, EOP_x and EOP_{comp} (EOPs for steam extraction and compression respectively) = 0.

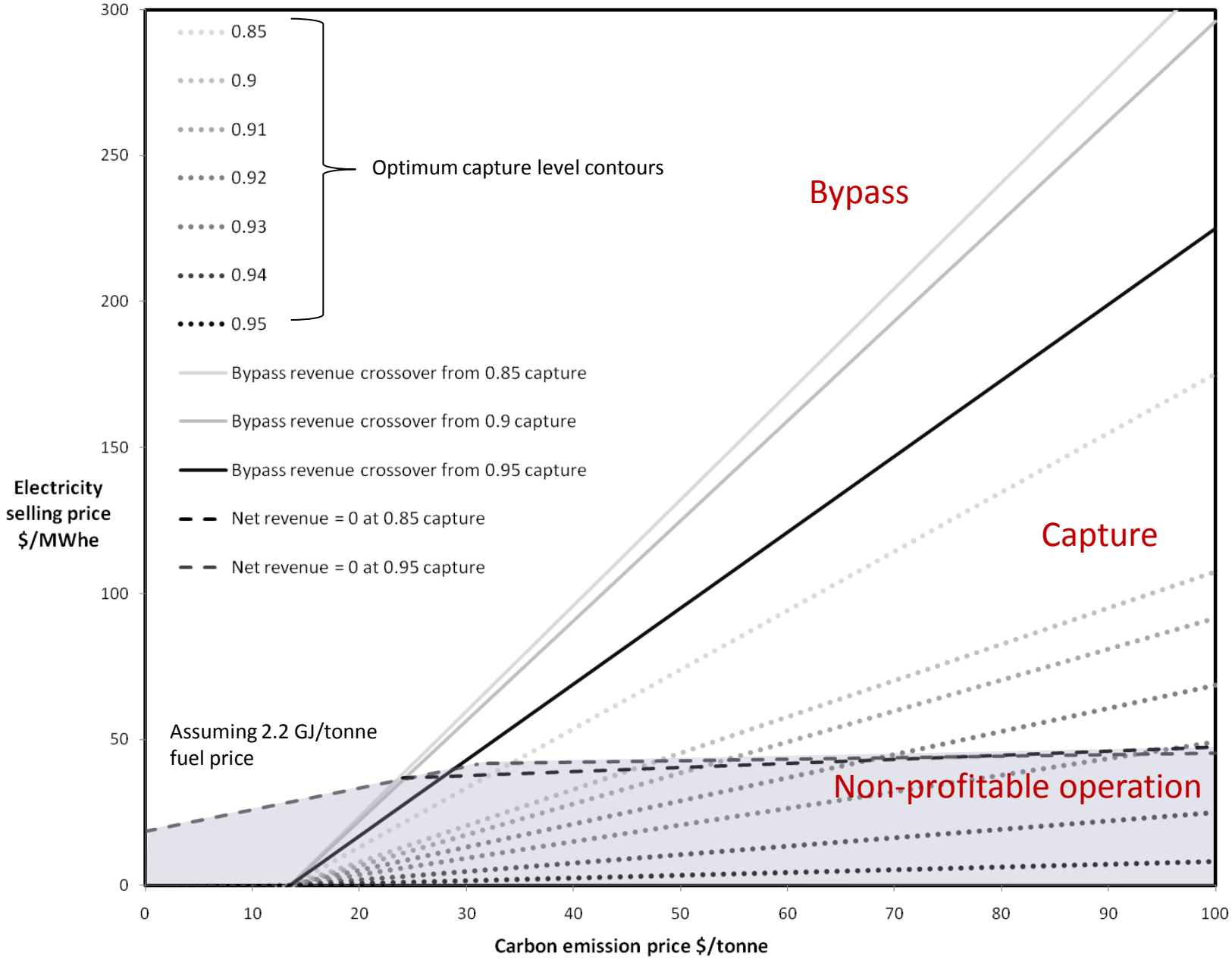
$EOP_{ancillary}$ at bypass remains constant at the capture level bypassed (ancillary equipment on 'stand-by')

Using the above assumptions and simplifying again, the electricity selling price when the bypass becomes financially preferential (for a specific carbon price and capture level) is defined as:

$$POE = \frac{COC - vc_{CCS}}{EOP_x + EOP_{comp}}$$

R_{net} ($\$/h_r$)	Net operating revenue	***e*** (tCO_2/MWh_{th})	Specific emissions factor for plant
POE ($\$/MWh_e$)	Time averaged price for electricity	***c*** (-)	Fraction of CO_2 captured from flue gas
EOP (MWh_e/tCO_2)	Total electricity output penalty	***COC*** ($\$/tCO_2$)	Cost of carbon emissions
EOP_x (MWh_e/tCO_2)	EOP from steam extraction	***vc_{CCS}*** ($\$/tCO_2$)	Specific variable costs for capture plant
EOP_{comp} (MWh_e/tCO_2)	EOP from CO_2 compression	***η_{base}*** (MWh_e/MWh_{th})	Base plant efficiency excluding capture wing
$EOP_{ancillary}$ (MWh_e/tCO_2)	EOP from capture wing ancillary		

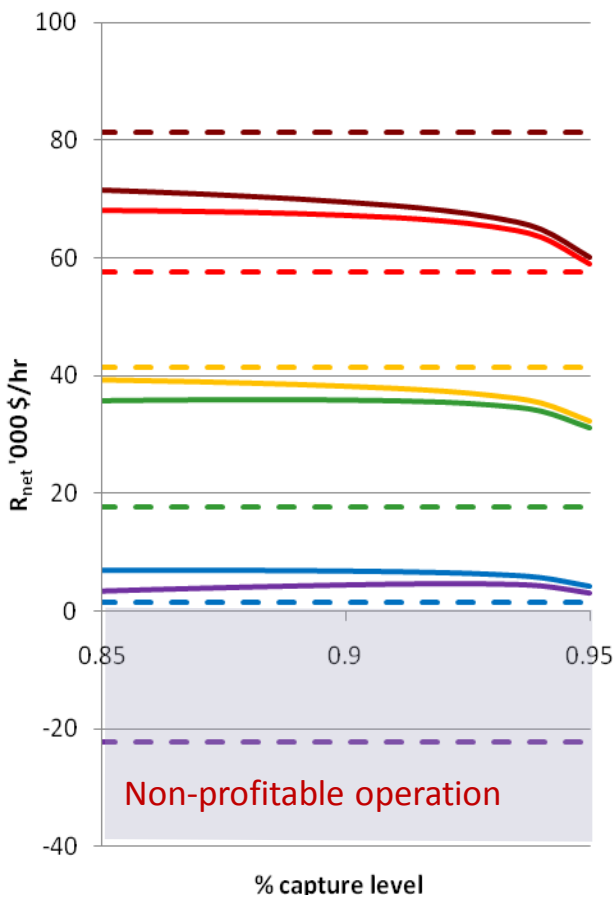
Optimum capture levels in variable price scenarios

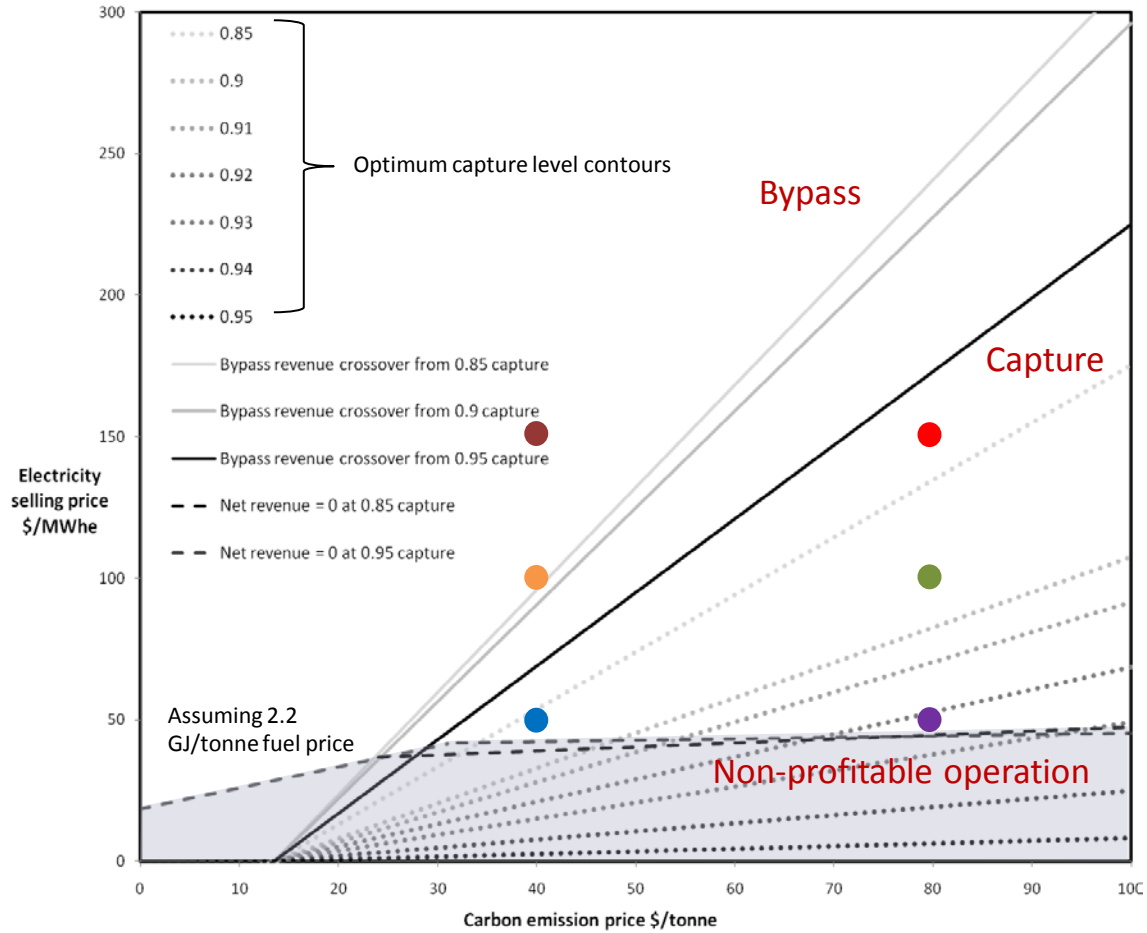


Short run net cash flow revenue options for different market scenarios

The left hand chart shows cash flows in different market scenarios (corresponding to the colours on the right hand chart scenarios) under different capture level operating regimes.

Solid lines refer to revenue with capture.
Dashed lines refer to revenue with bypass.





Summary

- Post combustion carbon capture plants will exist in dynamic markets
- Higher electricity output penalties at higher capture levels
- Revenue can be maximised by operating variable capture rates and bypass systems where allowable
- Variable capture rates offer higher relative increases in revenue at higher electricity prices
- With a system which is not optimised for higher capture levels, it will not be possible to generate revenue at higher capture levels even with high carbon prices
- Market scenarios exist where CCS generates revenue compared with bypass
- CCS operation will be more sensitive to electricity prices than carbon prices

Thank you

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