Scottish Centre for Carbon Storage
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Future-proofing coal plants with post-combustion capture against technology developments

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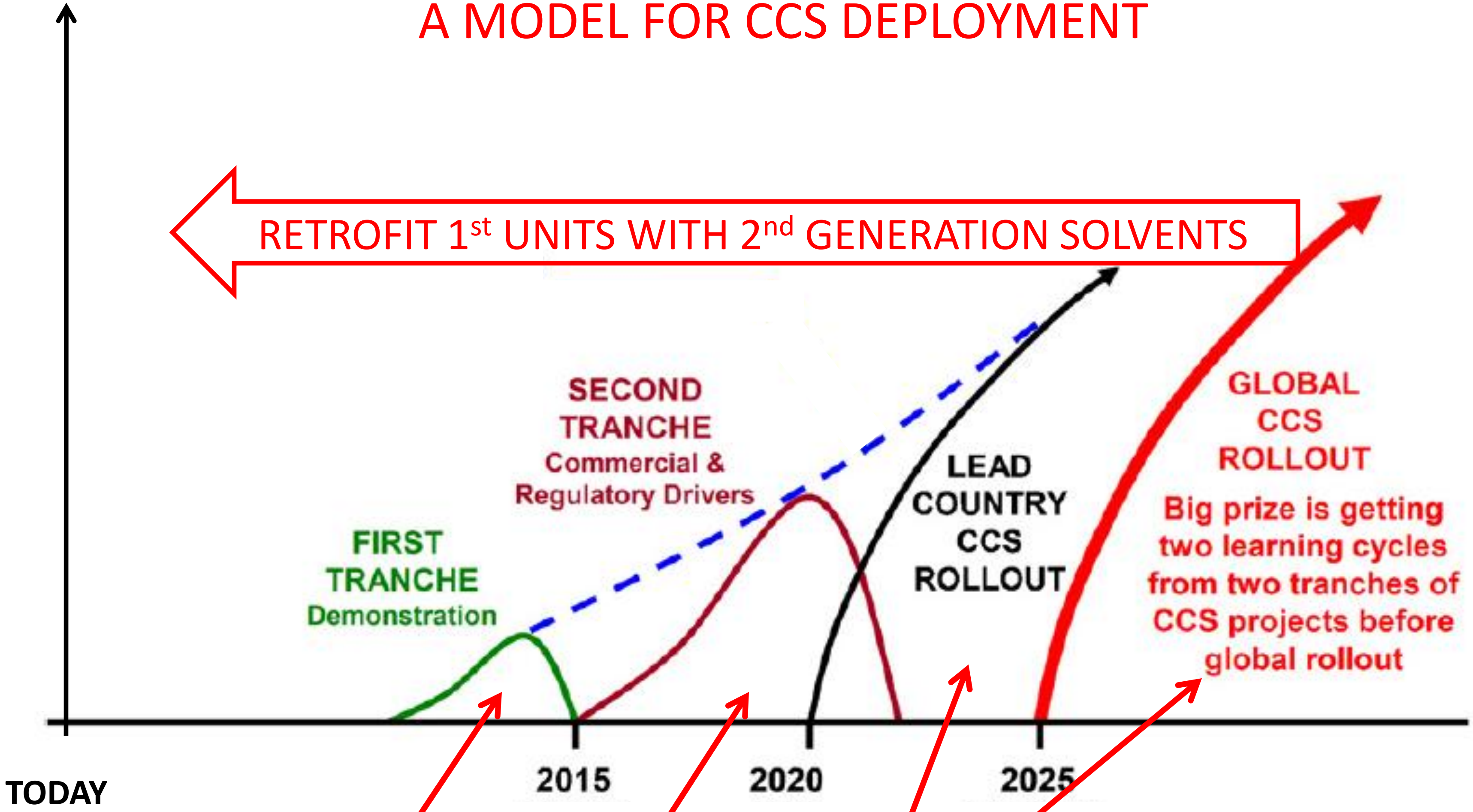
Future-proofing capture plants against technology developments

- ❑ **Capture technology is going to change**

A MODEL FOR CCS DEPLOYMENT



1st generation solvents

1st and 2nd generation solvents

2nd generation solvents and beyond

Future-proofing capture plants against technology developments

- Capture technology is going to change

- **Motivations for future-proofing power generation asset**

- **Keep the plant license to operate by securing compliance with stricter environmental legislation**

New solvent becomes Best Available Technology (e.g. for lower carryover in flue gas)

Level of capture has to be increased beyond ~ 90%

Future-proofing capture plants against technology developments

- ❑Capture technology is going to change

- ❑Motivations for future-proofing power generation asset

- ▪Keep the plant license to operate by securing compliance with stricter environmental legislation

New solvent becomes Best Available Technology (e.g. for lower carryover in flue gas)
Level of capture has to be increased beyond ~ 90%

- ▪**Improve power plant economics**

Increase plant capacity (MW sent out for sale)
Raise efficiency
Reduce exposure to carbon costs
Reduce operating costs
Enhance reliability and availability

Methodology – Step 1

☐ What is a better solvent?

- **Focus on electricity output penalty**

Electricity output penalty = Efficiency penalty / Fuel specific emissions

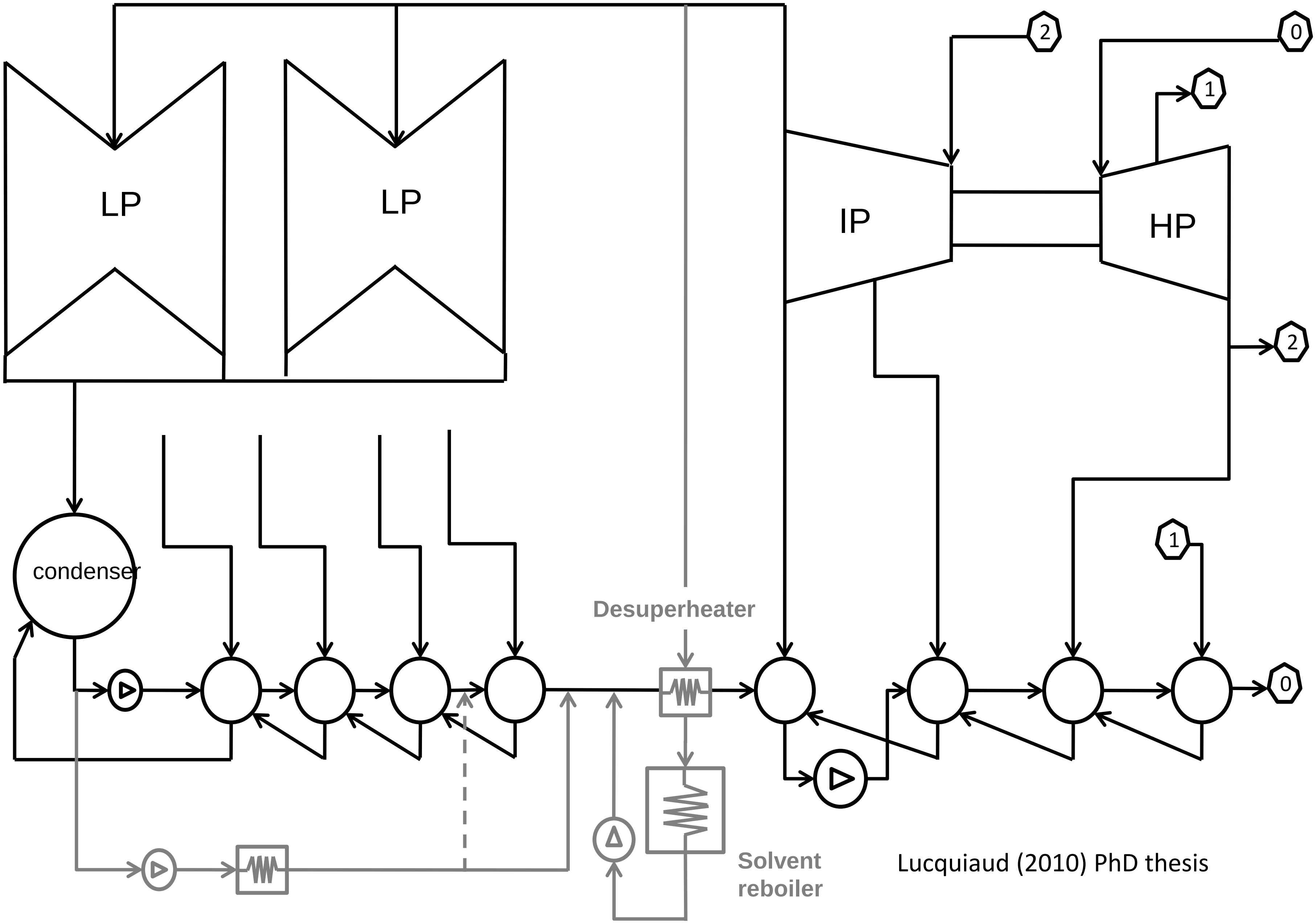
Electricity output penalty	(kWh_e/tCO_2)
Efficiency penalty	(kWh_e/kWh_{th} or % point LHV)
Fuel specific emissions	(tCO_2/kWh_{th})

- **Overall process assessment required**

Electricity output penalty =

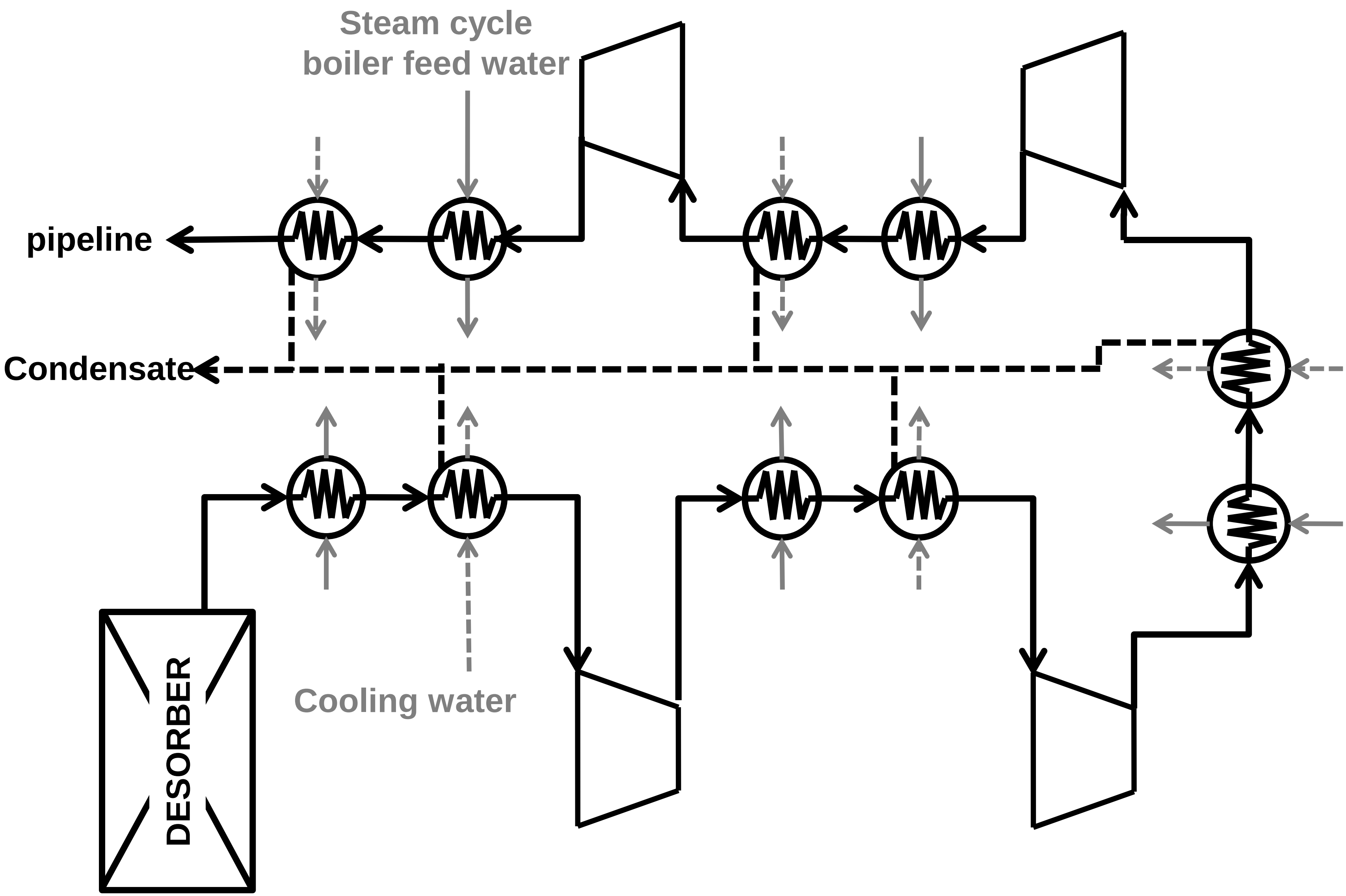
(loss of generator output + compression power + ancillary power) / CO2 mass flow

Steam cycle



Lucquiaud (2010) PhD thesis

Compression



Lucquiaud (2010) PhD thesis

Methodology – Step 1

☐ Dedicated steam cycle and compression model

Relate electricity output penalty of new-build plants to key amine process parameters

- Solvent energy of regeneration G, GJ/tCO_2
- Solvent temperature of regeneration T, ºC
- Desorber and delivery pressure, P_0 and P_1, bar
- Ancillary power, EOPa, kWh/tCO_2

▪ Electricity output penalty of steam extraction

$$EOPx = (G * a_0 + a_1) * T^3 + (G * a_2 + a_3) * T^2 + (G * a_4 + a_5) * T + G * a_6 + a_7$$

▪ Electricity output penalty of compression

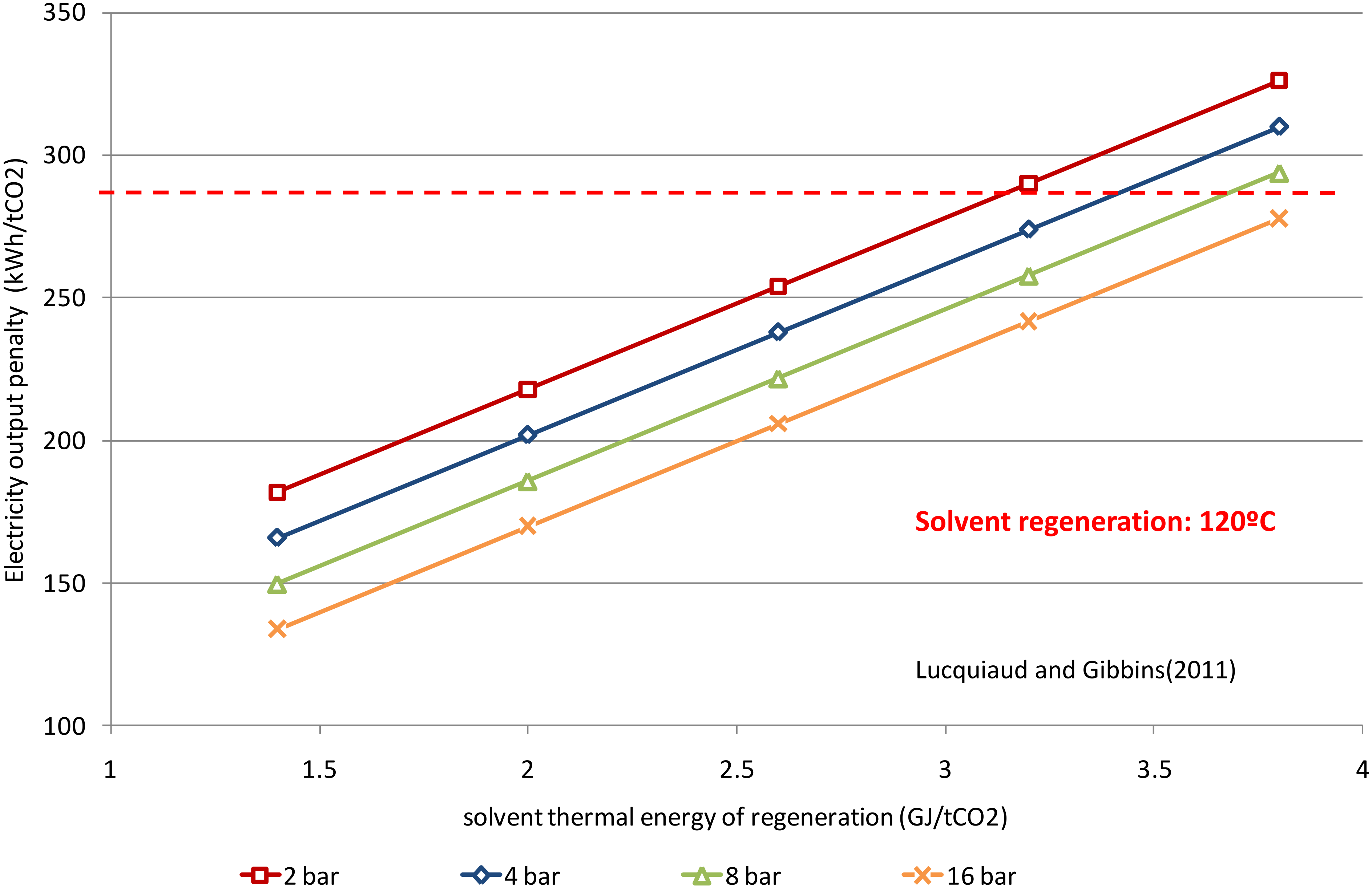
$$EOPc = b_0 * \ln(P_0) + b_1 * P_1^2 + b_2 * P_1 + b_3$$

▪ Overall electricity output penalty for new-build units

$$EOP = EOPx + EOPc + EOPa$$

Parameter values available in Lucquiaud, M., Gibbins, J. (2011), Chem Eng Res Des, In press, doi:10.1016/j.cherd.2011.03.003

Illustration of trade-offs between key amine process parameters



Solvent regeneration: 120ºC

Lucquiaud and Gibbins(2011)

Reference line: EOP of 290 kWh/tCO2, desorber pressure of 2 bar, solvent energy of regeneration of 3.2 GJ/tCO2 and ancillary power for the amine plant of 20 kWh/tCO2.

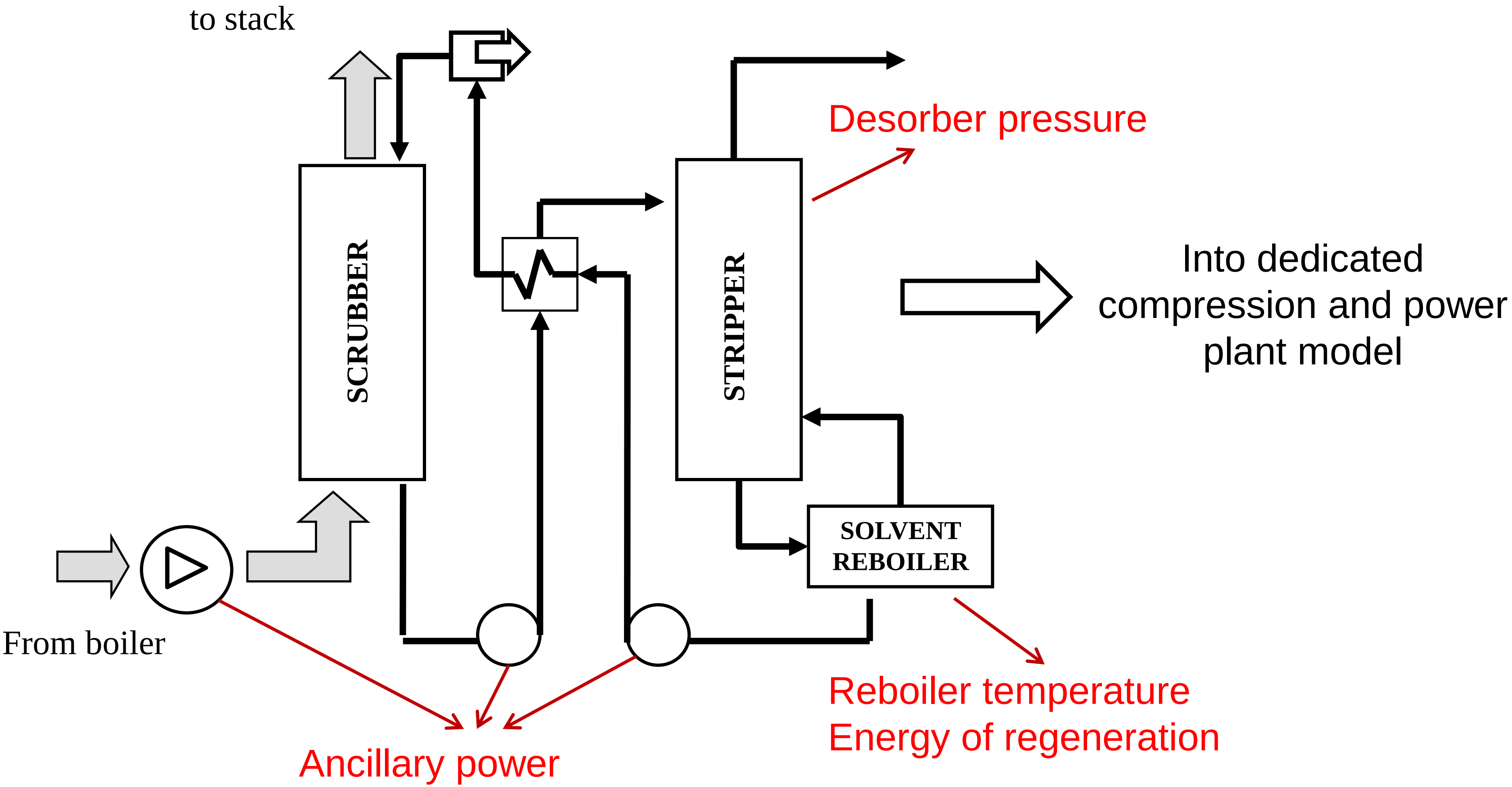
Methodology – Step 2

- **Sensitivity of electricity output penalty to key solvent parameters**
  - Specific heat capacity
  - Thermal stability
  - Enthalpy of absorption
  - Mass transfer

- **Reference plant:** New-build unit with post-combustion capture
- **Reference solvent:** 30%wt MEA

- **Objectives of methodology:**
  - Generate a range of hypothetical solvents, i.e. normally related key solvent parameters are now artificially independent
  - Assess performance for dedicated new-build plants for each solvent
  - Identify pieces of equipment leading to performance lock -in

Rate-base absorber model within a generic amine flowsheet



to stack

SCRUBBER

STRIPPER

Desorber pressure

Into dedicated compression and power plant model

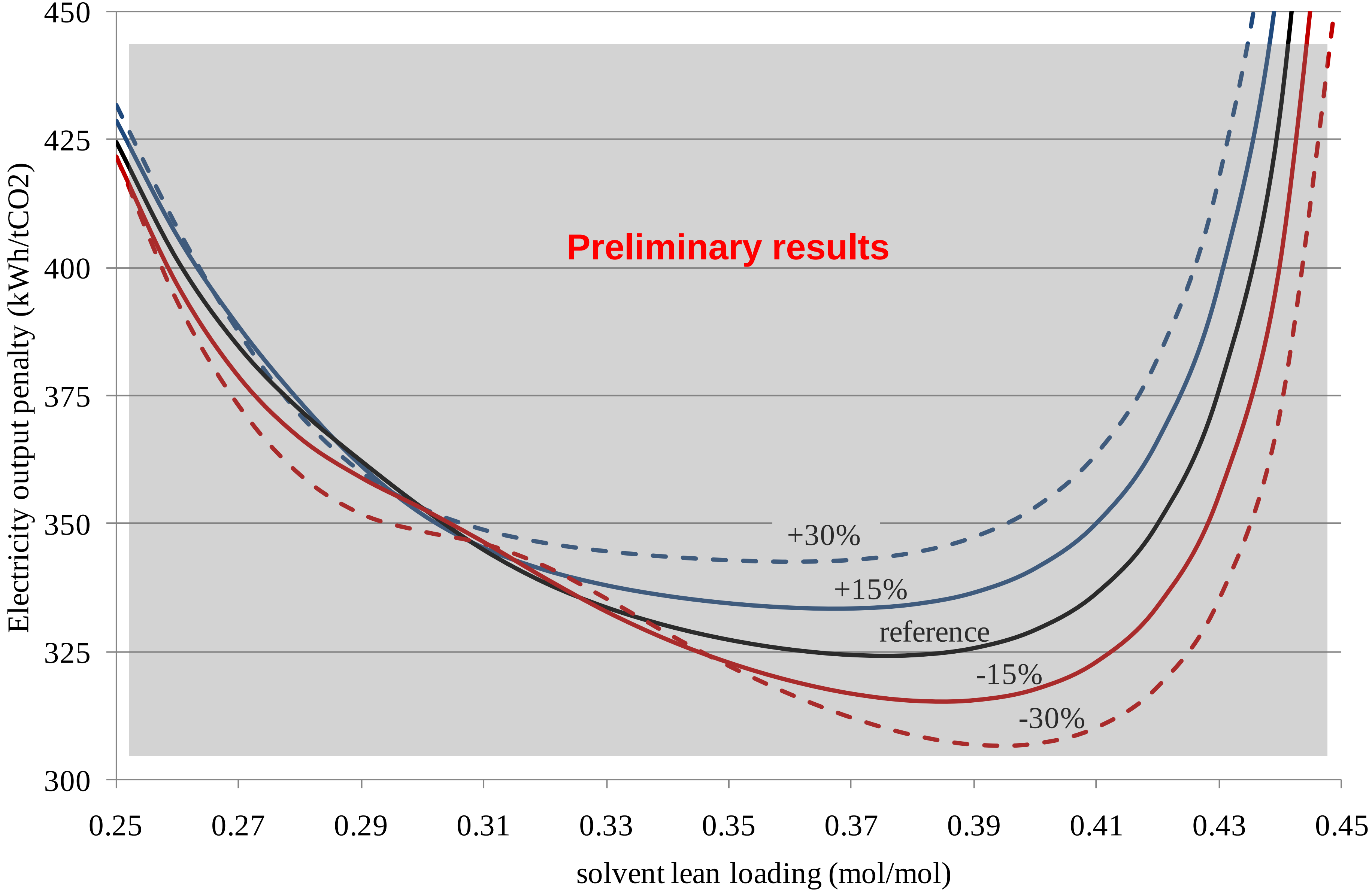
SOLVENT REBOILER

From boiler

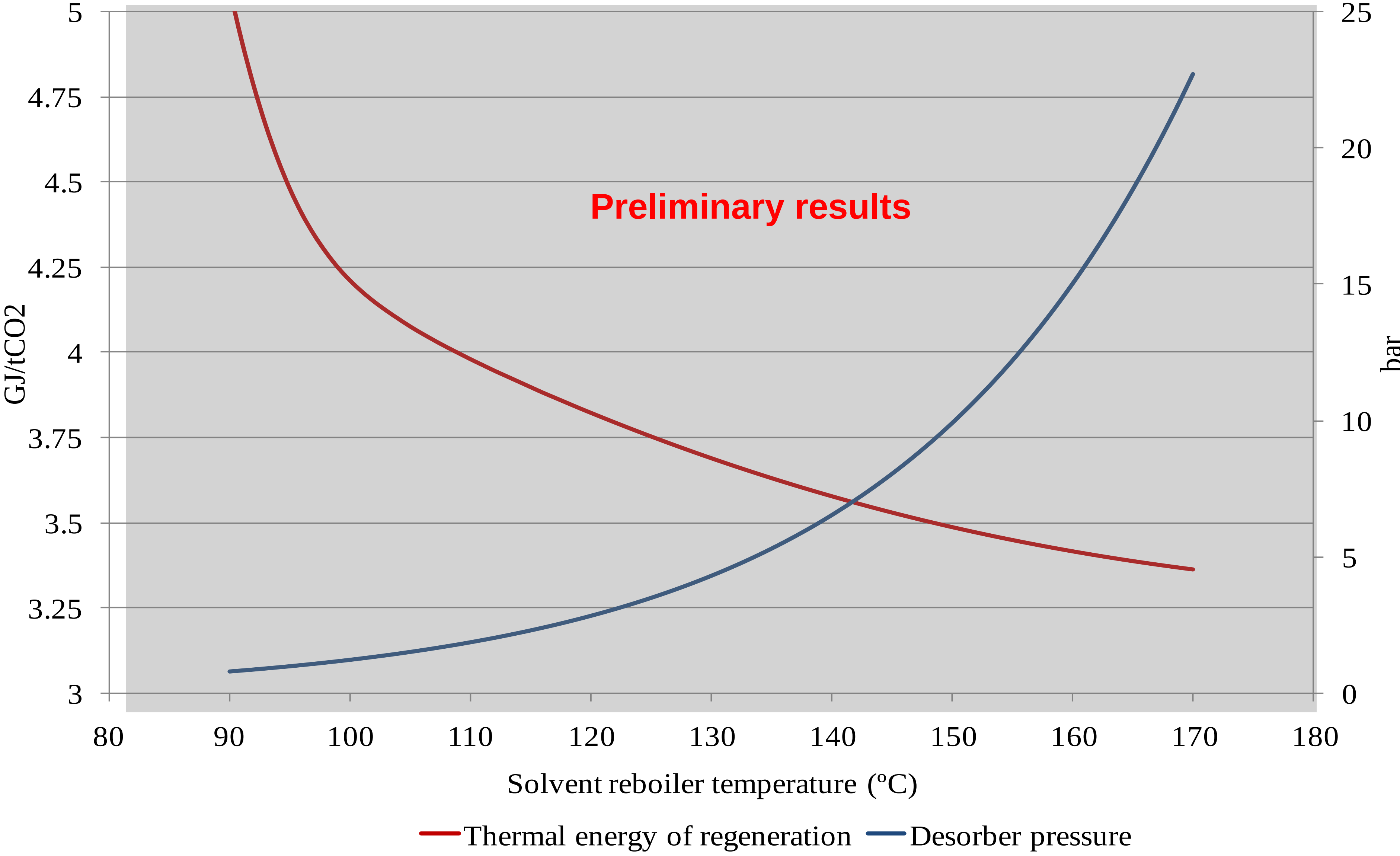
Reboiler temperature
Energy of regeneration

Ancillary power

Future-proofing coal plants
Sensitivity of performance to solvent heat capacity

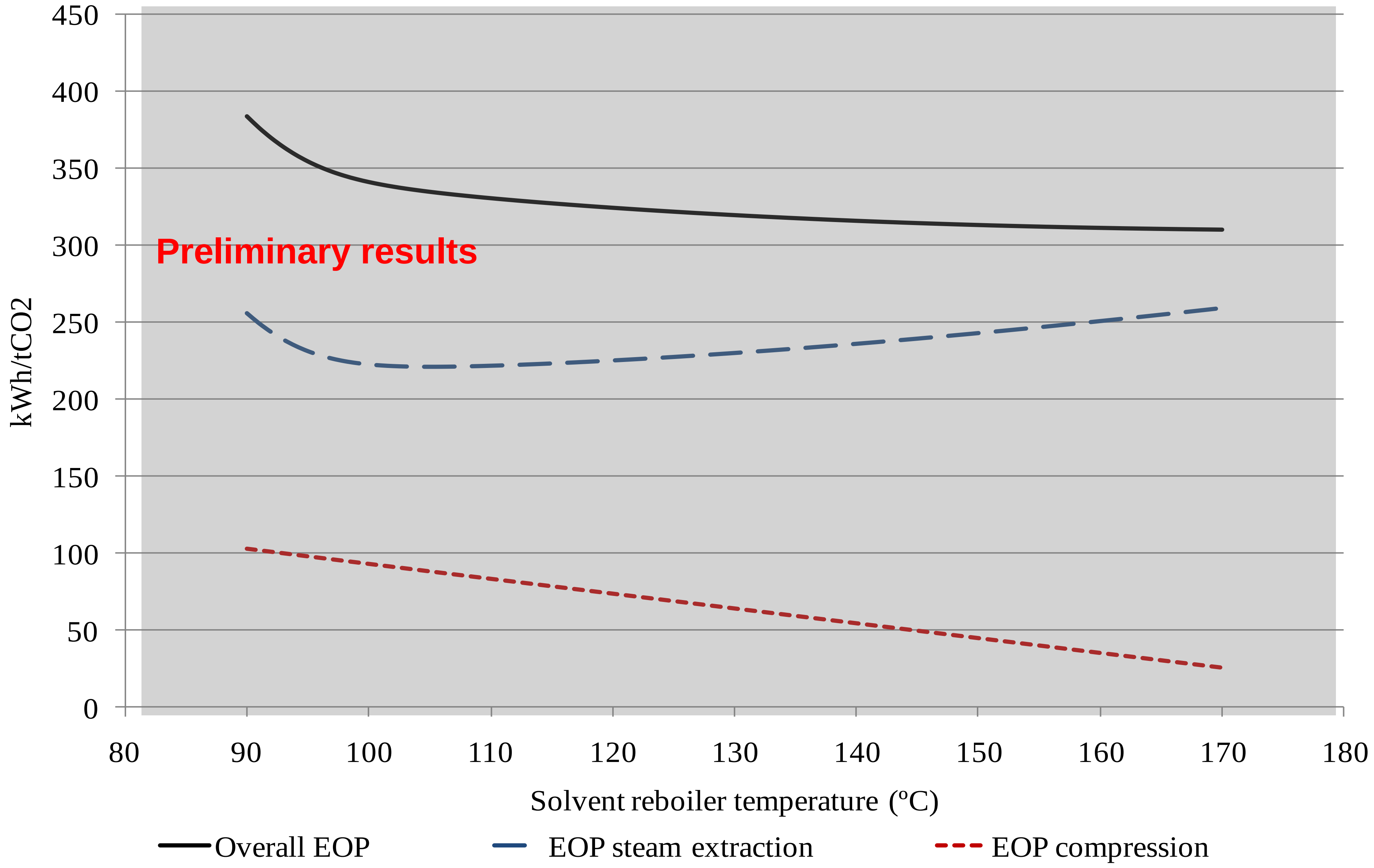


Future-proofing coal plants
Sensitivity of performance to solvent thermal stability



Preliminary results

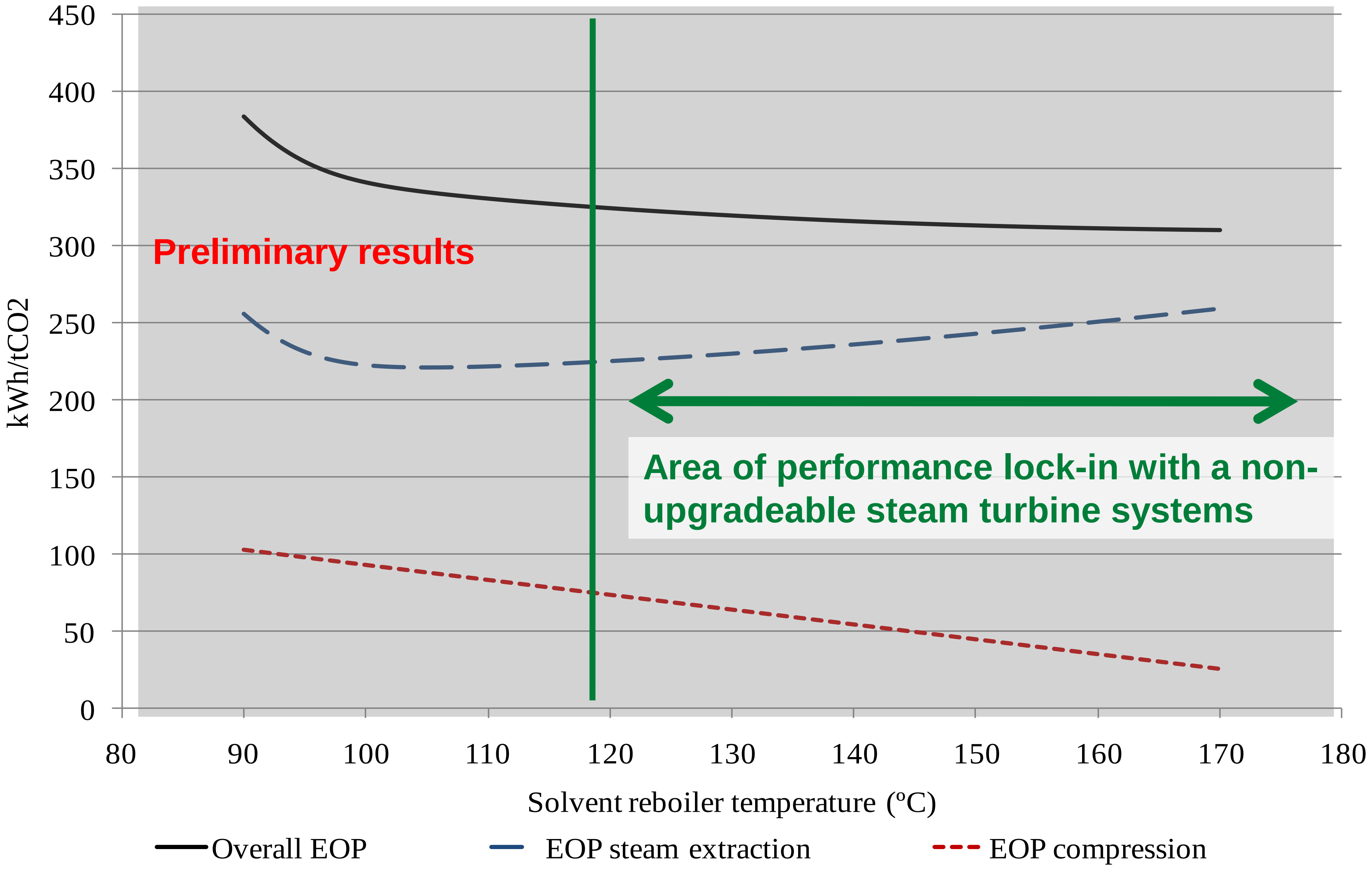
Sensitivity of performance to solvent thermal stability
Example of performance lock-in



Preliminary findings

- **Critical pieces of equipment and related solvent properties**
  - Steam turbine – solvent temperature and energy of regeneration
  - Absorber – kinetics and mass transfer
  - Compression - enthalpy of absorption, solvent temperature of regeneration
  - Desorber - enthalpy of absorption, solvent temperature of regeneration
  - Pipeline (if increased capture levels)

Sensitivity of performance to solvent thermal stability
Example of performance lock-in



Methodology – Step 3

- ❑ **Economic assessment of upgrading CCS plants**
- ❑ Two key research questions:
  - What is the financial value of the option of being able to upgrade a CCS plant? The financial value of the option is the maximum cost for pre-investment for future-proofing the plant and for the cost of the upgrade that will break-even under the assumptions made in this study.
  - What are the potential strategies to inform an investment decision, i.e. whether and when to exercise a possible upgradability option?

Methodology – Step 3

- **Methodology Summary:**
  - Real option approach with a stochastic cash flow model.
  - Long run marginal costs of electricity are used to justify the upgrade decision

Methodology – Step 3

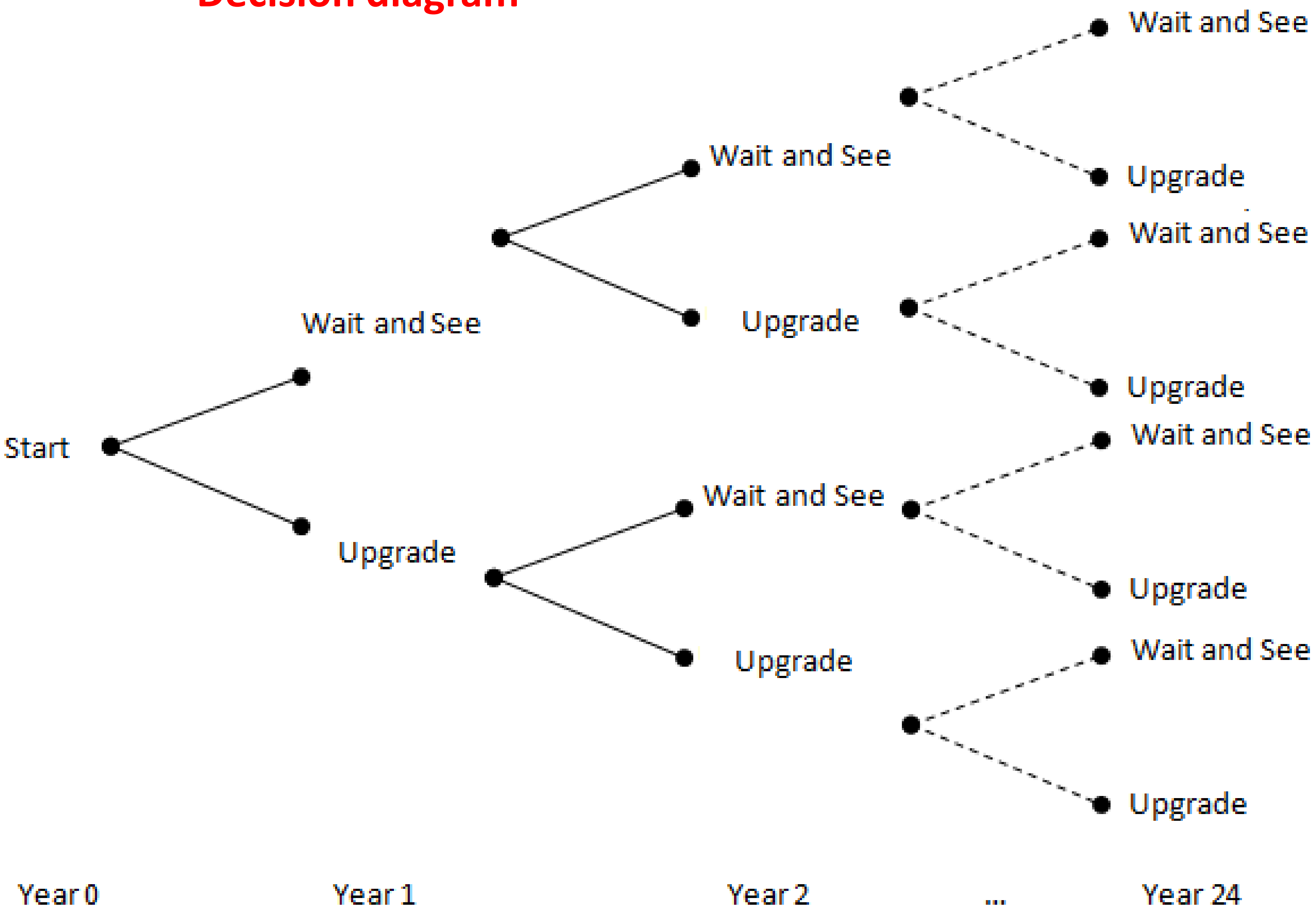
☐ Methodology Summary:

- Real option approach with a stochastic cash flow model.
- Long run marginal costs are used to justify the upgrade decision

- Variables selected
  - Additional investment for future proofing the plant
  - Fuel price
  - Carbon price
  - Technology progress ratio:
    Reduction of the electricity output penalty occurs per doubling of the global installed capacity

- The deployment rate follows the IEA Blue Map Scenario.

Decision diagram



Start

Wait and See

Upgrade

Wait and See

Upgrade

Wait and See

Upgrade

Wait and See

Upgrade

Wait and See

Upgrade

Wait and See

Upgrade

Wait and See

Upgrade

Year 0

Year 1

Year 2

...

Year 24

Assumptions of the Reference Plant

Parameters (USD)	**Input**	**Notes**
Project Life	25 years	From Operation
Risk-free Rate	2%	real
Base Year	2004 Price Level	
Gross Output (MW)	827MW	IEA GHG PH4/33 Study (Net Ouput 666MW)
Fixed Capital (Capex)	1249 million	at year 0
Working Capital	9 million	IEA GHG PH4/33 Study
Upfront Capex for Upgrade	5% of Original Fixed Capital	Sensitivity analysis with ±1% and ±2%
EOP without Upgrade	257	kWh/tonne
Net Supply Efficiency (LHV)	44%	At full load (degrading by 1.5%)
Load Factor	85%	For 2-25 years; year 1: 60%
Coal Price	4	$/GJ with 2% real growth 10% std dev
CO_2 **Emissions Cost**	start 25euro/t	with a real growth of 4% and 20% std dev
Emissions Factor Baseline	743	gram/kWh
Emissions Factor with CO_2 **Capture**	117	gram/kWh
Coal Feed Rate	0.00817	GJ/kWh
Fixed O&M	85 million/year	
Fixed O&M after Upgrade	unchanged	
Learning Rate of EOP	0.92	with sensitivity analysis
Financing Cash Flow	not considered	

Methodology – Step 3

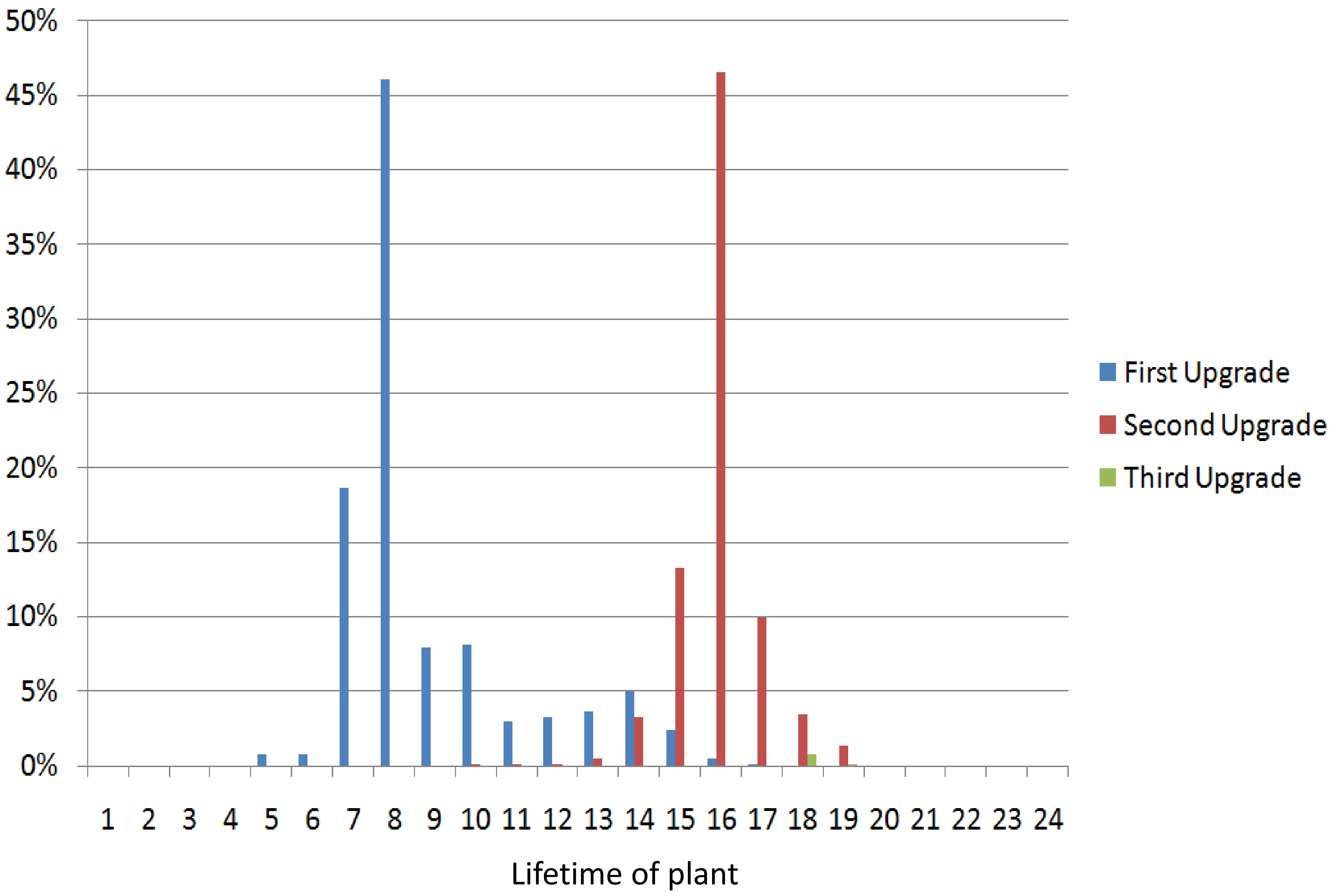
❑ Methodology Summary:

- Least square regression with Monte-Carlo simulation is used to model the financial value at each option decision node

- Uncertainties on coal price, carbon price and technology improvement rates are the drivers for the options value

- The main driver for the upgrade is a possible reduction of the electricity output penalty as new technologies enter the market.

Probability of Upgrades in the Lifetime



Value of the upgradability option: 92% progress ratio

(Million:US$)	Option Value (Only One Upgrade Option)	Option Value (Multiple Options)	Δ COE with Multiple Options
Average	117.5	**126.7**	-1.92
Std Dev	32.1	33.2	0.45
Std Err	0.3345	0.3672	0.002844
Max	249.4	279.3	-0.52
Min	19.2	19.5	-2.79

Sensitivity analysis

1. Change in Progress Ratio	90%	91%	92%	93%	94%
Option Value (US$:million)	165.3	145.4	126.7	104.3	85.5
Impact on COE (US$/MWh)	-2.4	-2.16	-1.92	-1.71	-1.53

2. Change in additional CAPEX for future-proofing and the upgrade	3%	4%	5%	6%	7%
Multiple Options (US$)	167.4	148.5	126.7	108.9	94.3
Impact on COE (US$/MWh)	-2.04	-1.99	-1.92	-1.83	-1.76
Chance of Second Upgrade	99.92%	98.45%	79.32%	36.58%	12.01%

Conclusions

- Technology upgrades may be driven by future policies and/or technology developments
- Future-proofing power plants need to include the overall CCS process
- Given that future technology developments are by nature uncertain and potential savings are uncertain too (Energy savings, timing for upgrade, Fuel and carbon cost, Capital cost): Only low-cost options with high return can be justified.

- Limited additional upfront capital costs to future-proof CCS plants may be justified. The value of a future-proofing option is, however, strongly dependent on technology learning rate assumed.
- A first upgrade is very likely to take plant 7 to 10 years after the plant has been commissioned.
- A second upgrade during the plant lifetime is also very likely

- **Forthcoming report commissioned by IEAGHG**
  Incorporating future technological improvements in existing CO_2 capture plants

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