Blue hydrogen as an alternative to natural gas

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Acknowledgement of Country

The University of Queensland (UQ) acknowledges the Traditional Owners and their custodianship of the lands on which we meet.

We pay our respects to their Ancestors and their descendants, who continue cultural and spiritual connections to Country.

We recognise their valuable contributions to Australian and global society.

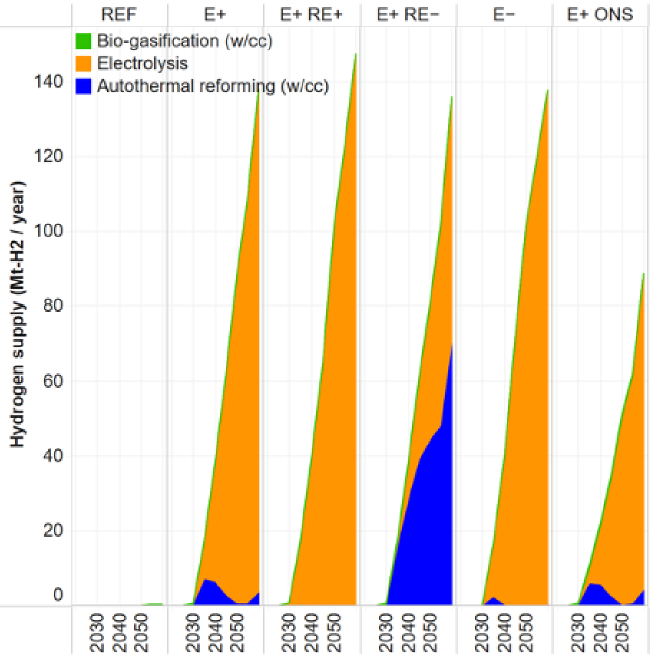
The Brisbane River pattern from *A Guidance Through Time*
by Casey Coolwell and Kyra Mancktelow.

Hydrogen - the molecule of many colours

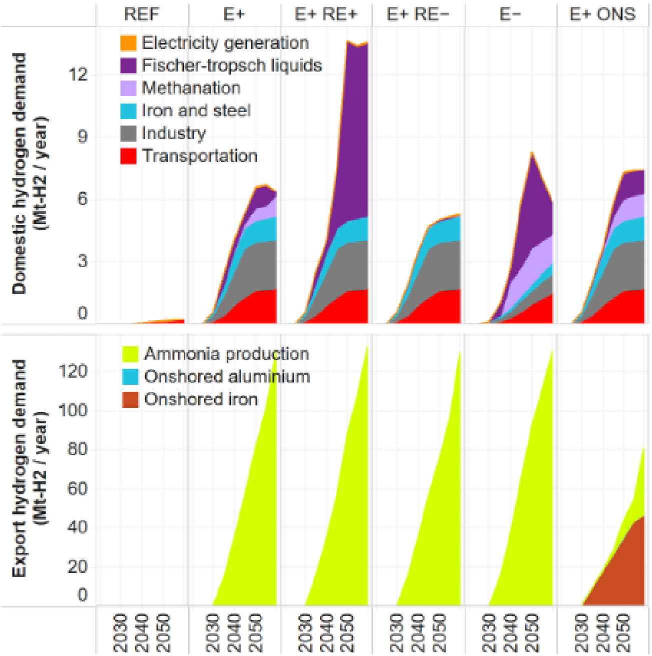
- Coal
- Natural Gas
- Fossil with CCS
- Methane Pyrolysis
- Nuclear
- Electrolysis or Biomass
- Solar

The Australian Hydrogen Opportunity

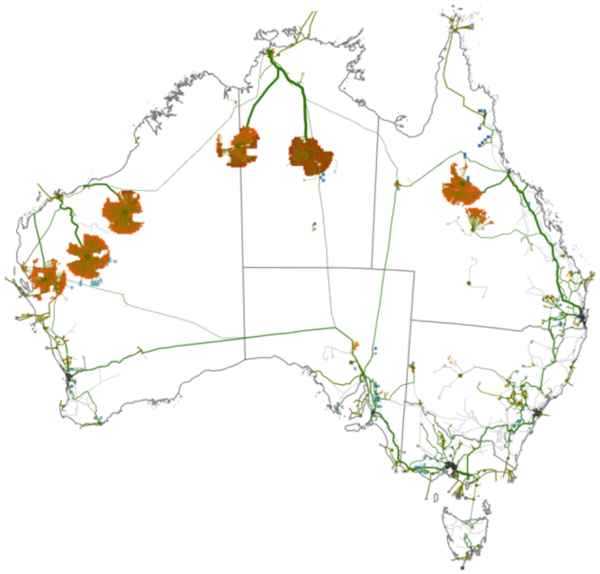
The Net Zero Australia website has more information – visit netzeroaustralia.net.au



130-140 Mt of hydrogen by 2060



6-13 Mt domestically



Green hydrogen dominates unless we can't build RE fast enough

Blue hydrogen from coal

Queensland Black Coal vs Victorian Brown Coal

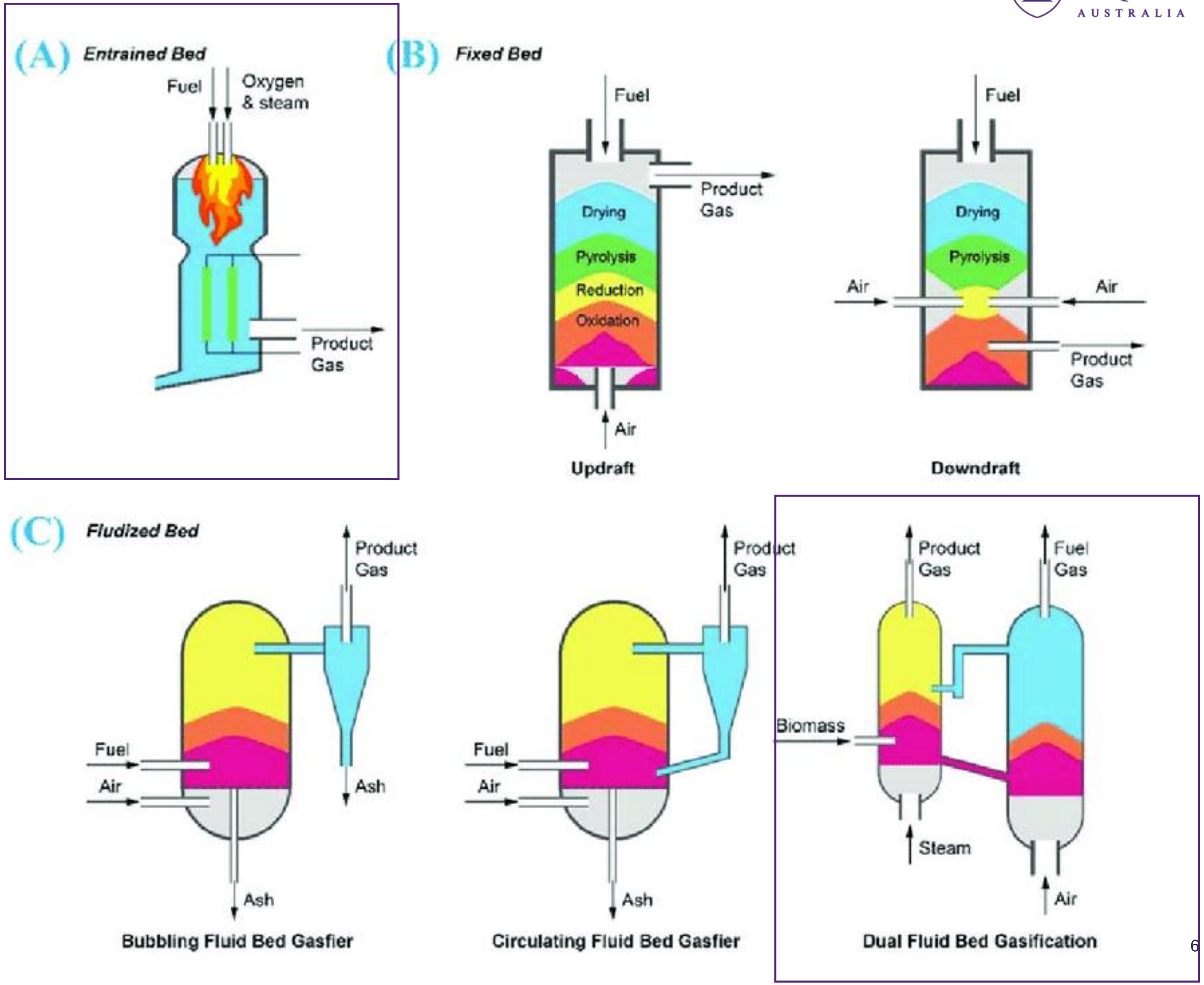
Entrained flow gasifiers (steam) vs fluidized bed (steam / O2)

Acid gas capture vs in-situ carbonisation

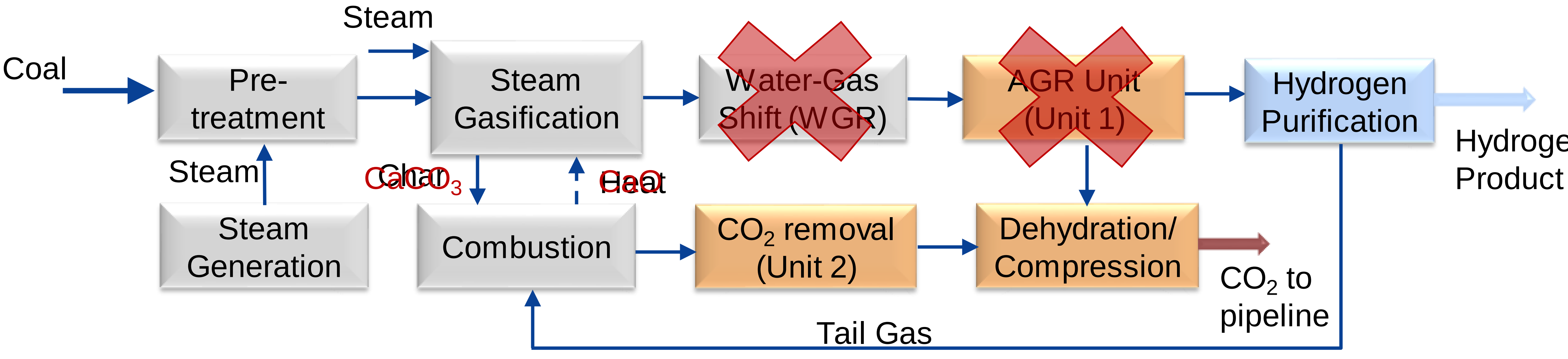
What is gasification?

Addition of heat and oxidant at high temperature and moderate pressures to break coal or biomass down into $H_2/CO/CO_2$

Used to make liquid fuels or chemicals



Steam gasification cases



Steam

Coal

Pre-treatment

Steam Gasification

Water-Gas Shift (WGR)

AGR Unit (Unit 1)

Hydrogen Purification

Hydroge
Product

Steam

Char

$CaCO_3$

Heat

CaO

Steam Generation

Combustion

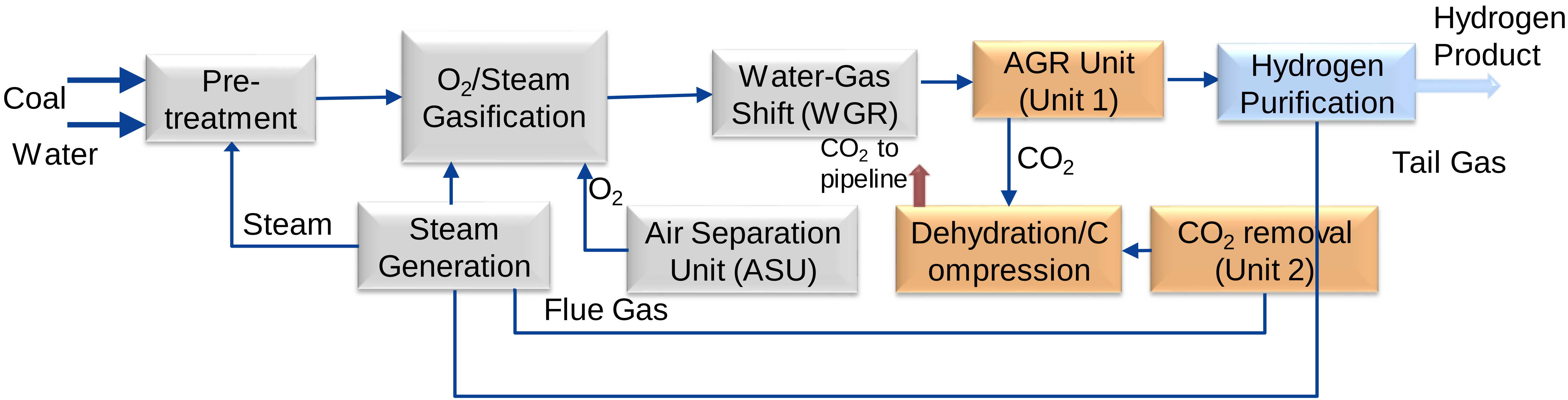
CO_2 removal (Unit 2)

Dehydration/ Compression

CO_2 to pipeline

Tail Gas

Steam/oxygen gasification cases

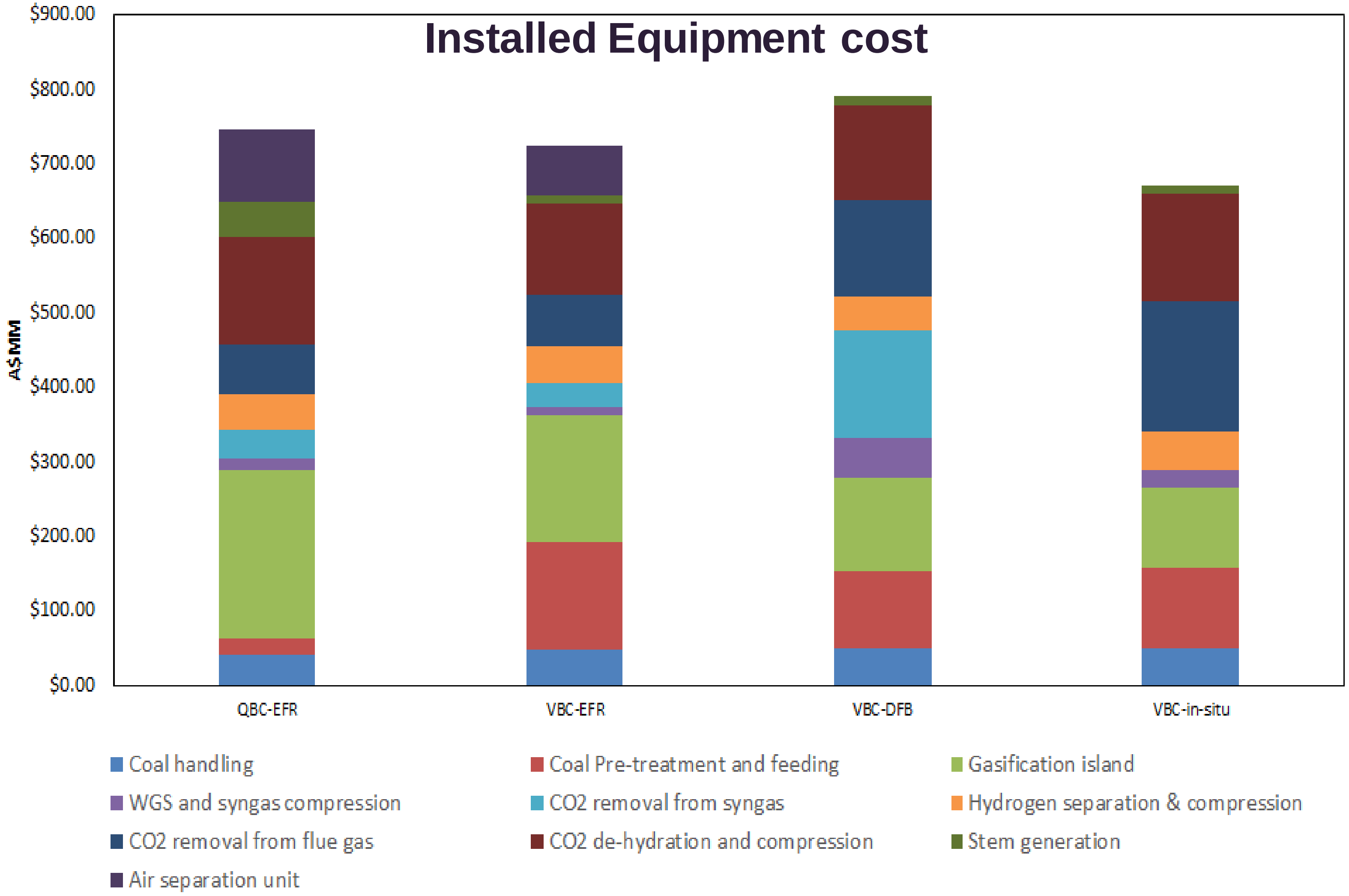


Performance Comparison

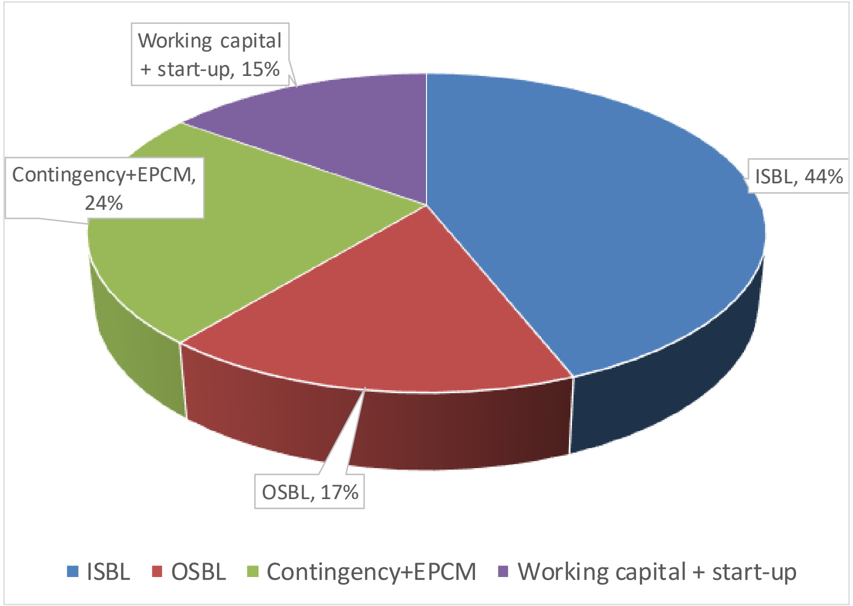
Mass and Energy Balances

Feedstock	Gasification agent	Feed rate (t of coal (daf) / t H_2)	Electricity (MWe / t H_2)	CO_2 Intensity (t CO_2e / t H_2)	CO_2 Captured		Net Energy efficiency (LHV%)
					Syngas	Flue gas	
Qld Black Coal	Steam & Oxygen	6.1	7.9	0.18	☑	☑	57.1
Vic Brown Coal	Steam & Oxygen	6.8	5	0.23	☑	☑	62.2
Vic Brown Coal	Steam	7	7.6	0.68	☑	☑	57.9
Vic Brown Coal	Steam	7.4	6.7	1.09	In-situ capture in the gasifier	☑	56.3

Installed equipment cost and total investment costs

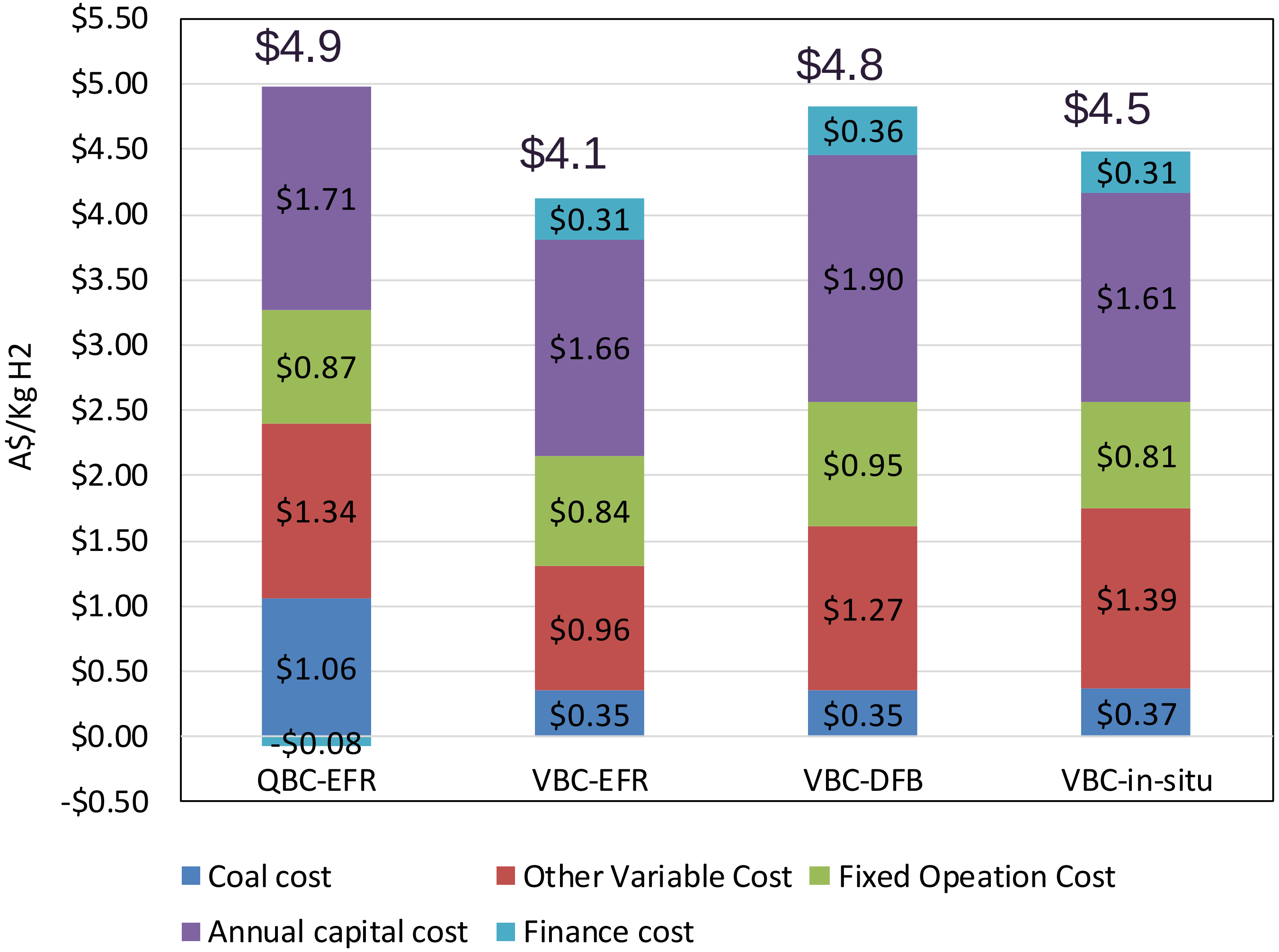


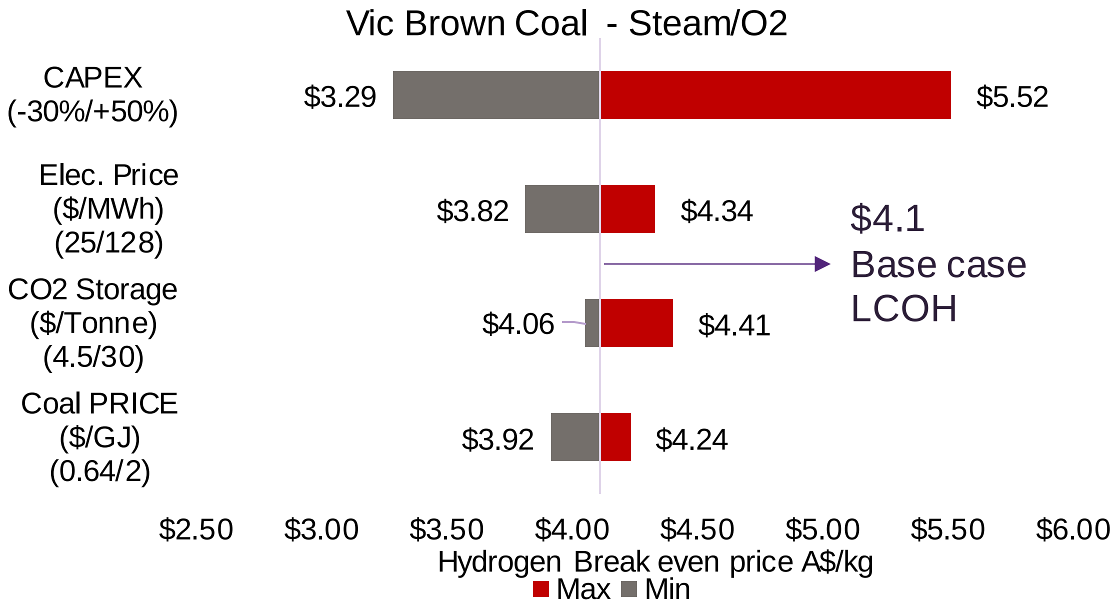
Total investment cost Breakdown



- CO_2 capture, dehydration and storage is ~1/2 installed equipment cost
- In-situ CO_2 capture requires fewer units so lower Capex

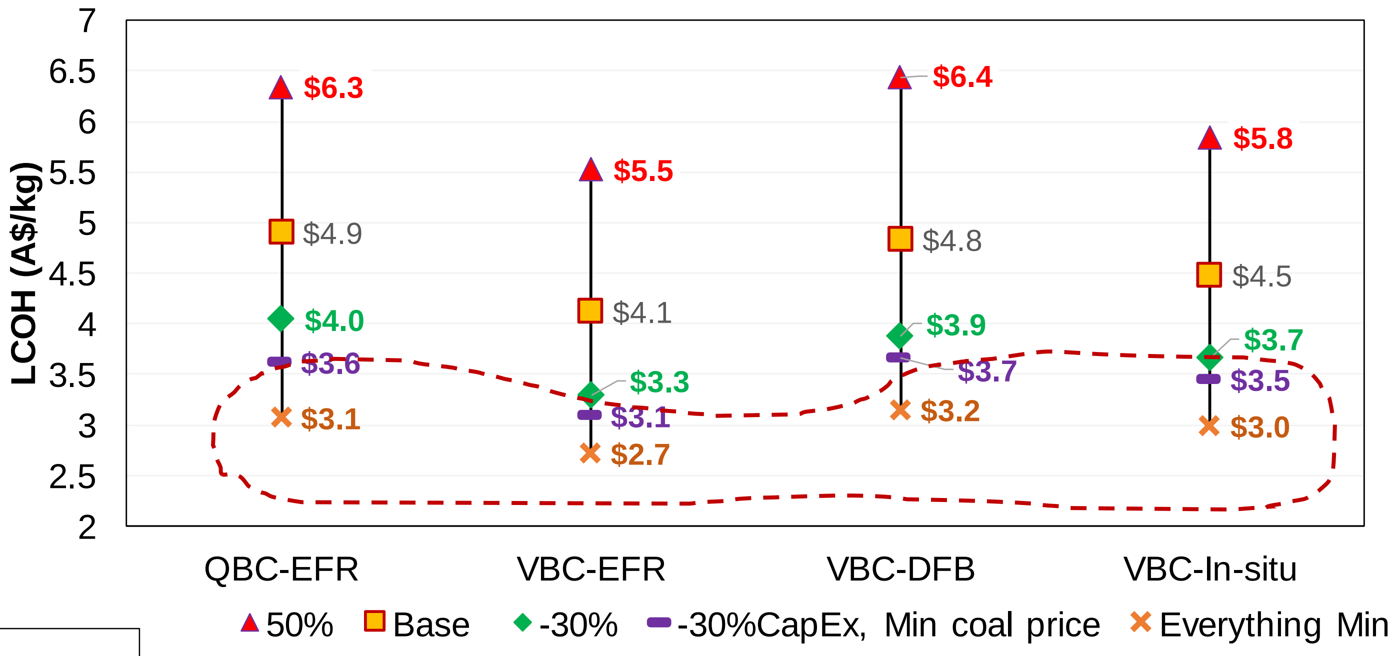
Levelized Cost of Hydrogen (LCOH)





Sensitivity Analyses

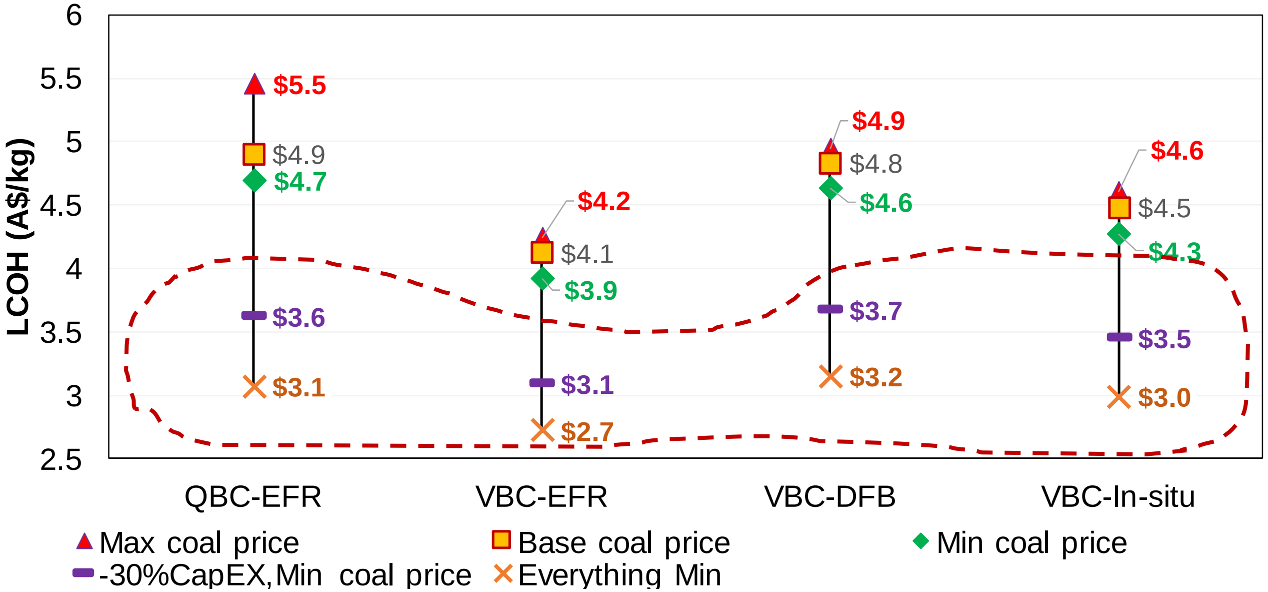
Effect of CAPEX on coal gasification



The LCOH shows highest sensitivity to the CAPEX variation

- The lowest LCOH ($3.3) is achievable upon 30% reduction for the VBC in an entrained flow gasifier

Effect of Coal Price on coal gasification



Coal price influences Qld Black Coal case much more significantly than Vic Brown Coal

Blue Hydrogen from Natural Gas

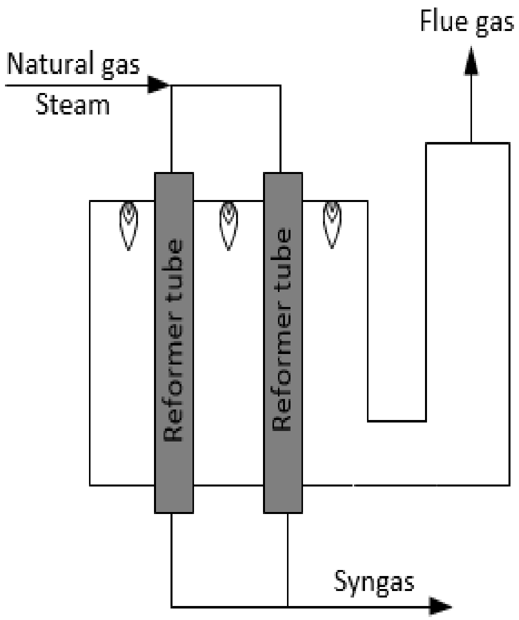
SMR vs ATR

Process efficiency vs max CCS

Traditional Grey Hydrogen

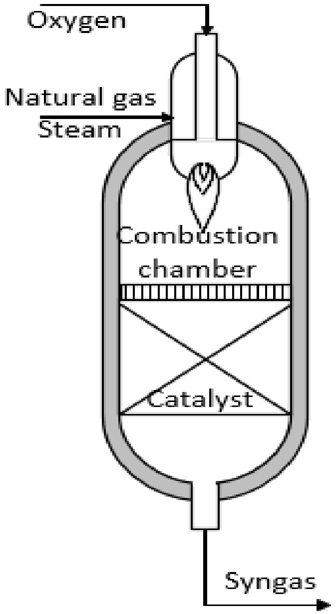
Let's examine the integration of these technologies with CCS

- Selected Technologies
  - Steam Methane Reforming(SMR)
  - Combined SMR
  - Auto-thermal Reforming
- Currently these technologies are used (without CCS) to produce:
  - Hydrogen & Chemical via SMR
  - Chemical via C-SMR
  - Gas to Liquids via ATR



SMR furnace

- Catalytic steam reforming in the catalyst
- Indirect heating

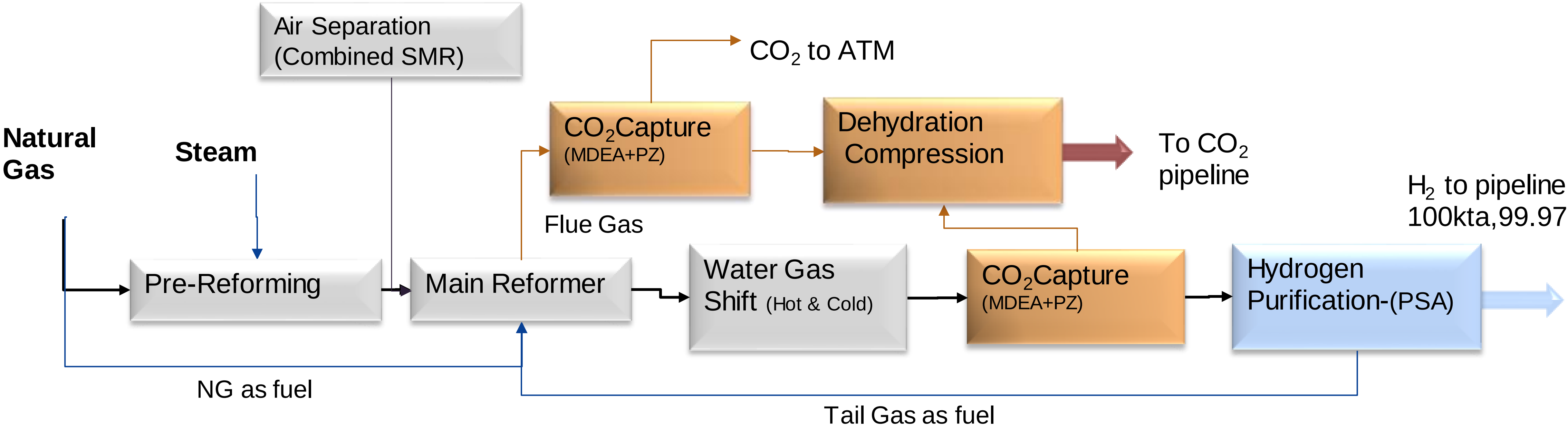


Auto-thermal Reactor

- Partial oxidation in the combustion chamber
- Catalytic steam reforming in the catalyst
- Direct heating

SMR + CCS

Steam Methane Reforming(SMR) & Combined SMR Reforming



Air Separation (Combined SMR)

Natural Gas

Steam

Pre-Reforming

Main Reformer

Flue Gas

CO_2 Capture (MDEA+PZ)

CO_2 to ATM

Dehydration Compression

To CO_2 pipeline

Water Gas Shift (Hot & Cold)

CO_2 Capture (MDEA+PZ)

Hydrogen Purification-(PSA)

H_2 to pipeline 100kta,99.97%

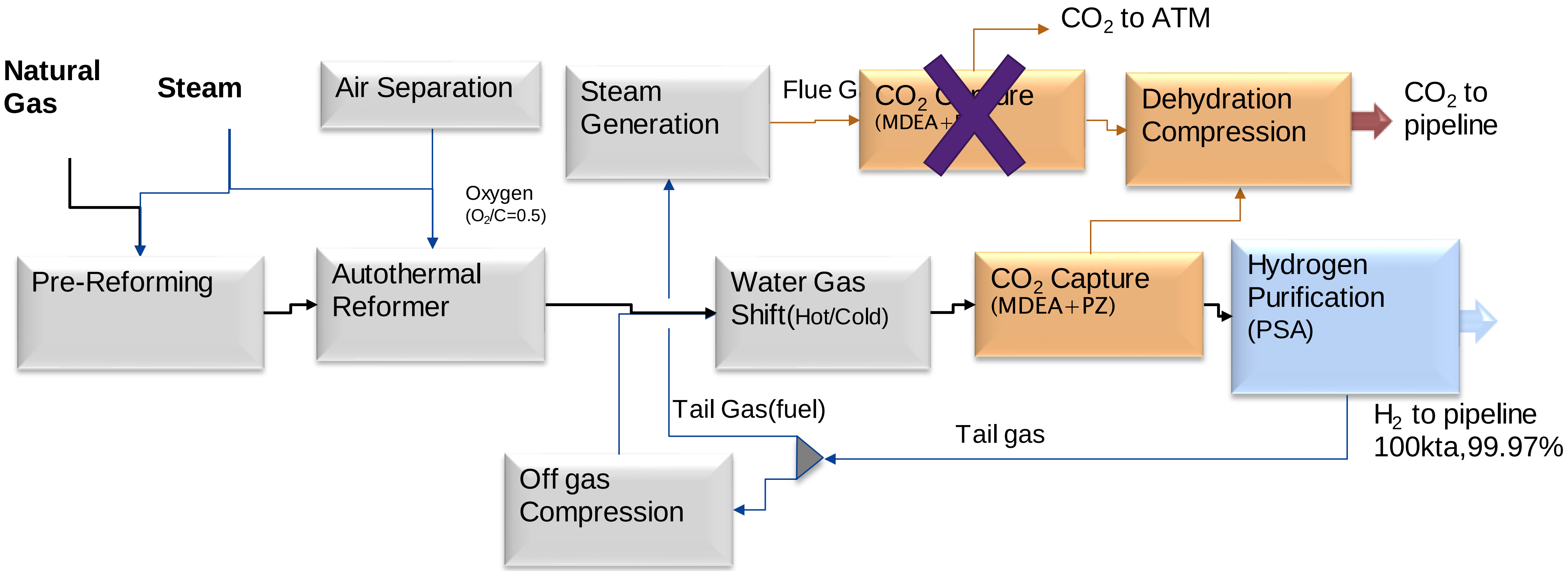
NG as fuel

Tail Gas as fuel

ATR + CCS

Auto-Thermal Reformer (ATR)

ATR-Optimum Energy Efficency (ATR-OP)-CO$_2$ Capture from Reformer ONLY



CO$_2$ to ATM

Natural Gas

Steam

Air Separation

Steam Generation

Flue G

~~CO$_2$ C ure (MDEA+~~

Dehydration Compression

CO$_2$ to pipeline

Oxygen (O$_2$/C=0.5)

Pre-Reforming

Autothermal Reformer

Water Gas Shift(Hot/Cold)

CO$_2$ Capture (MDEA+PZ)

Hydrogen Purification (PSA)

Tail Gas(fuel)

Tail gas

H$_2$ to pipeline 100kta,99.97%

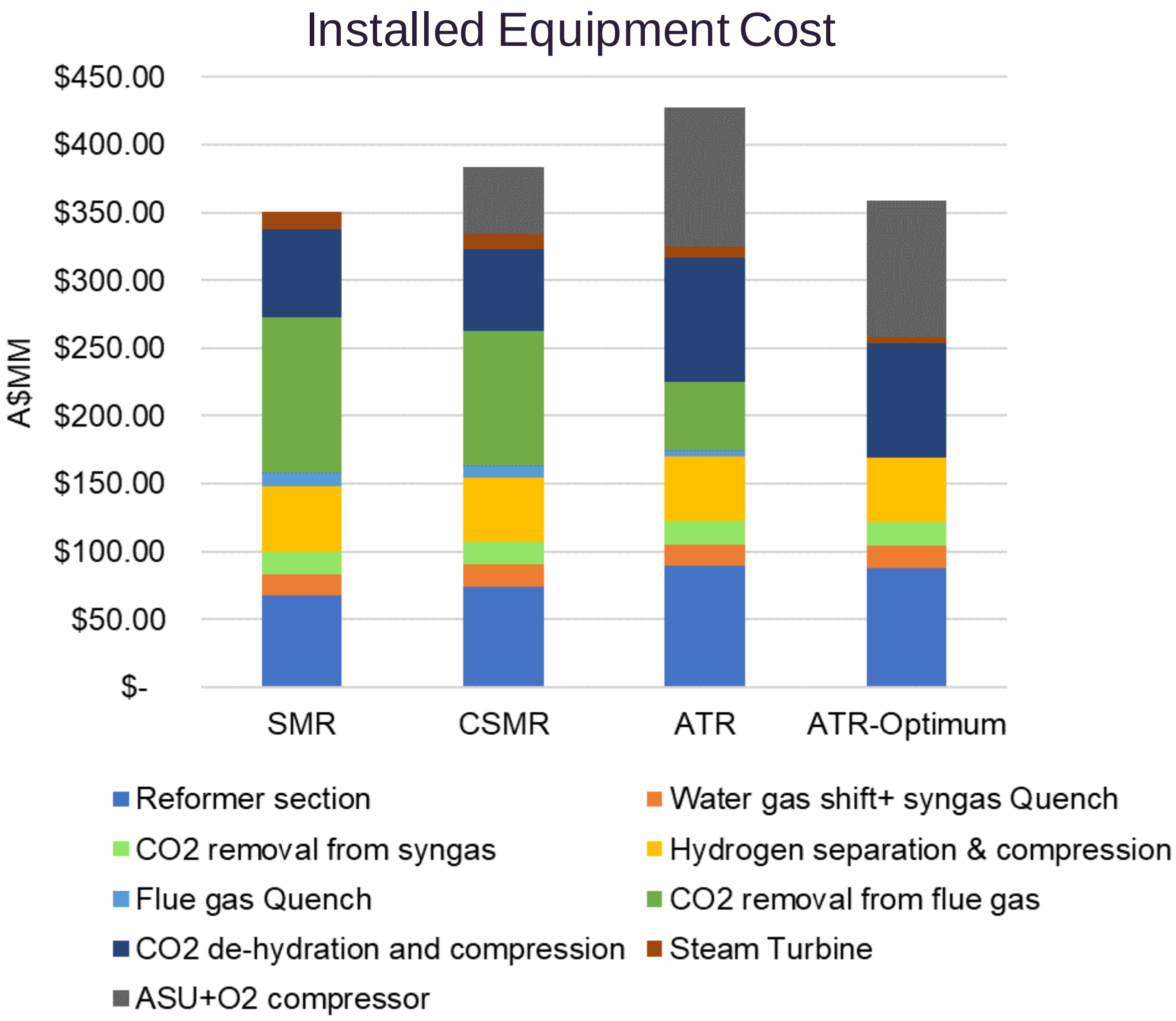
Off gas Compression

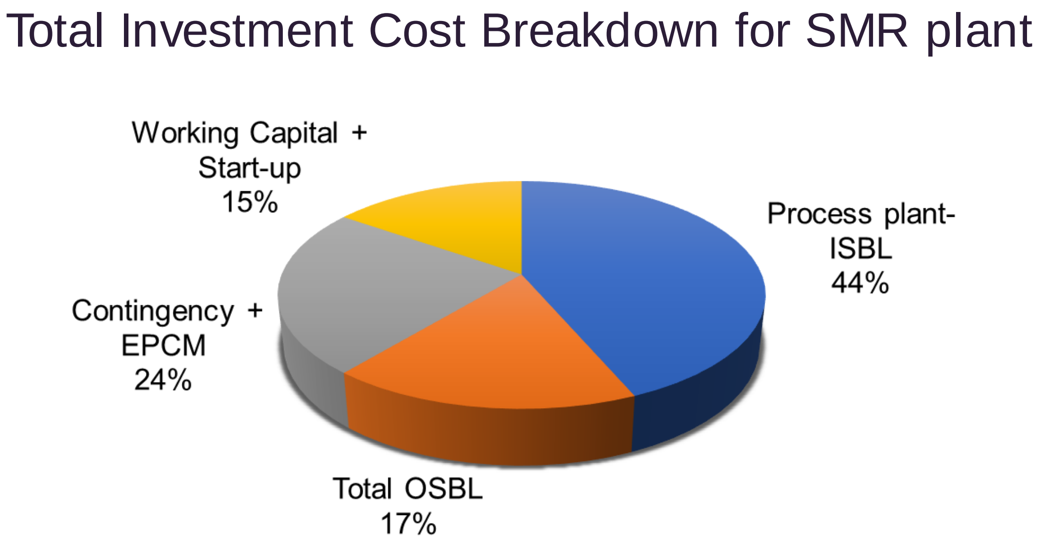
Blue Hydrogen from Natural Gas-TRL09

Mass and Energy Balances

Technolgy	Reforming agent	Natural Gas t NG / tH_2	Total Steam t H_2O/t H_2	CO_2 Intensity tCO_2 / t H_2	CO_2 Captured		Net Energy efficiency LHV%
					Syngas	Flue gas	
Standalone SMR	Steam	3.9	21.8	0.93	☑	☑	69.5
Combined SMR	Steam & Oxygen	3.79	18.6	0.92	☑	☑	70.97
ATR	Steam & Oxygen	3.59	16.6	0.75	☑	☑	73.4
ATR-Partial capture	Steam & Oxygen	3.47	14.3	1.4	☑	✕	75.7

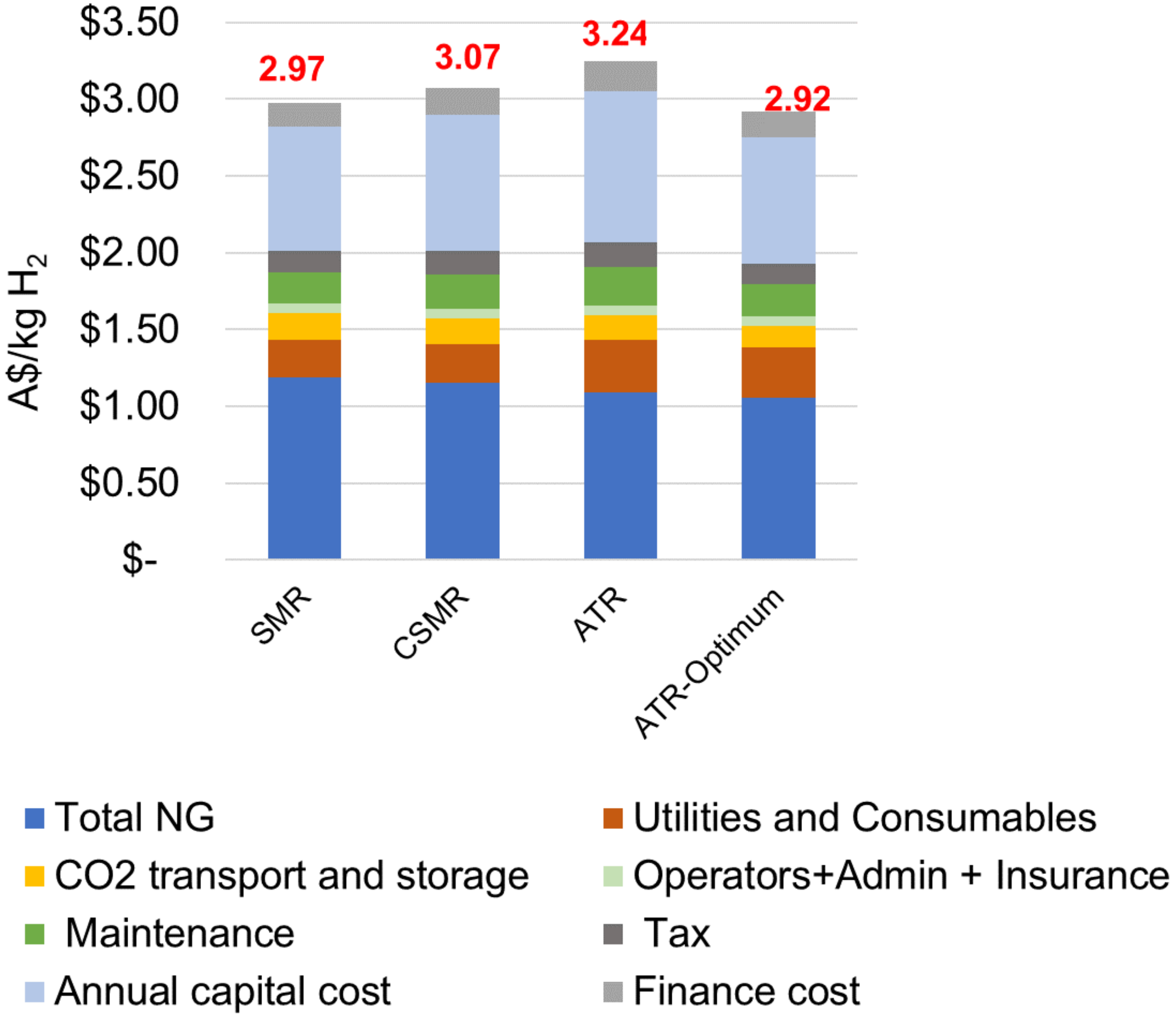
Installed equipment cost and total investment costs

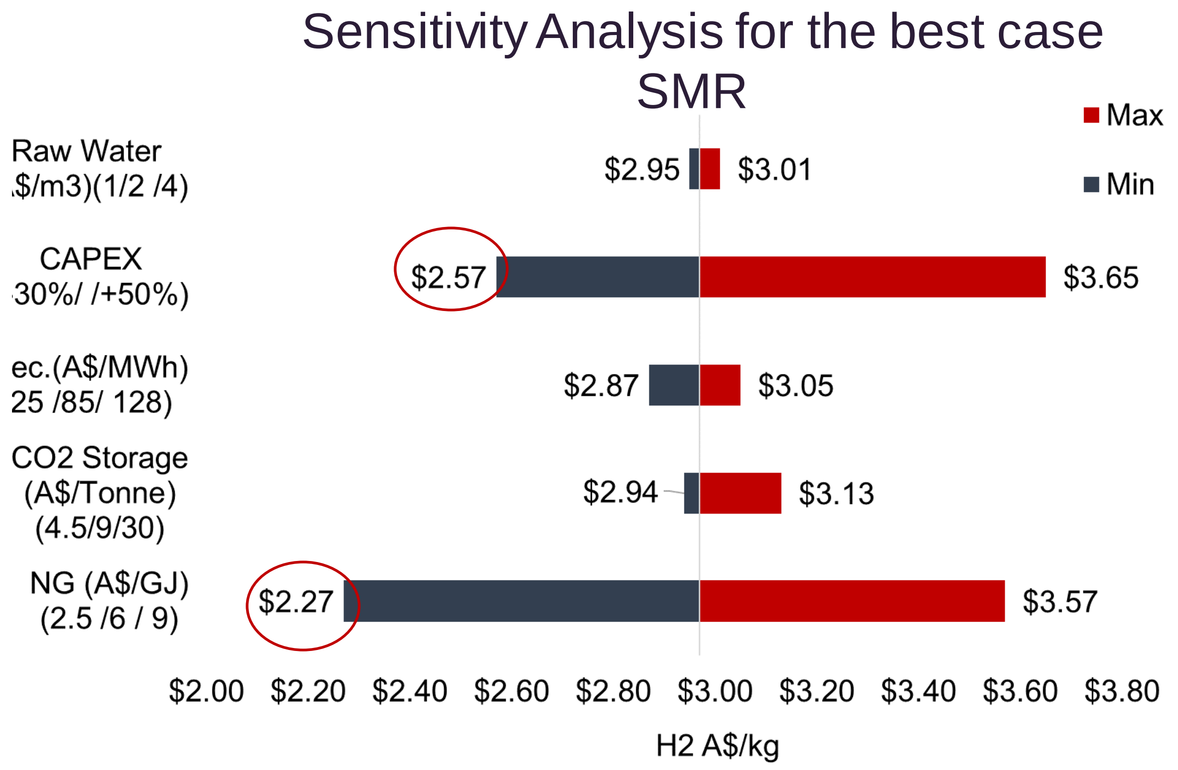




CapEx significantly increases with high CO_2 capture rate
ATR technology has the lowest CO_2 capture cost
ATR at optimum energy efficiency competes with SMR at this scale

Levelised Cost of Hydrogen (LCOH)

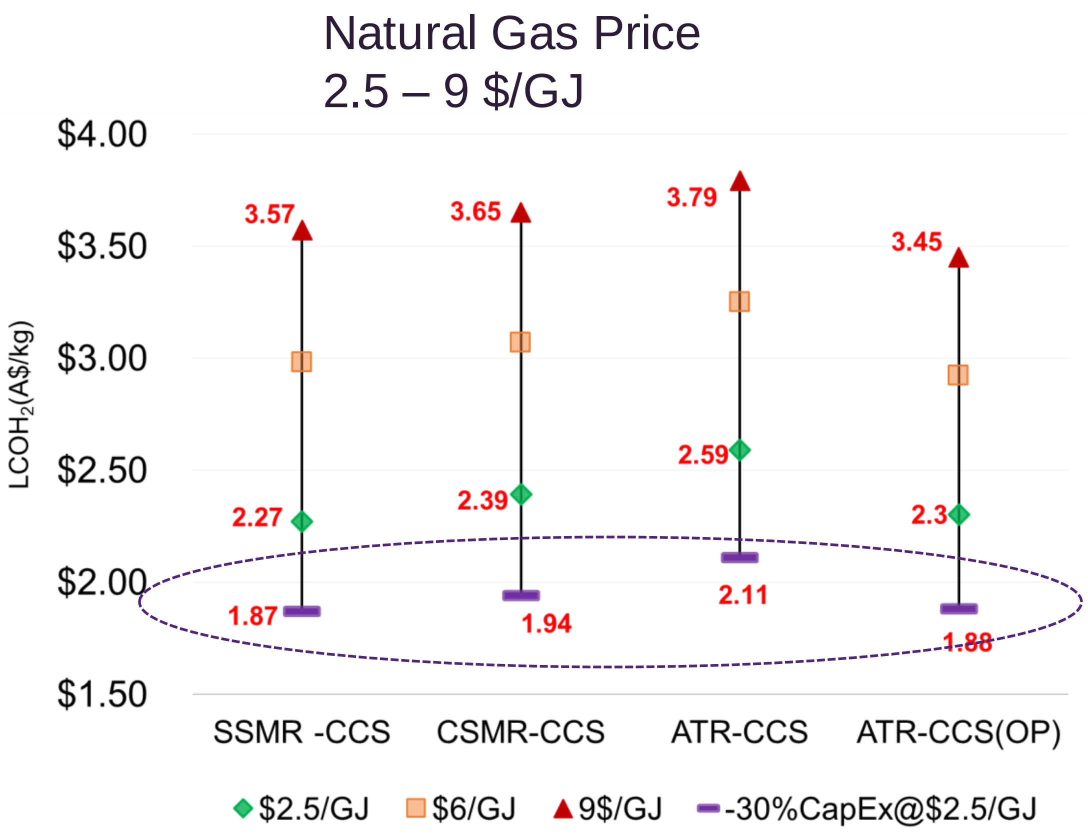


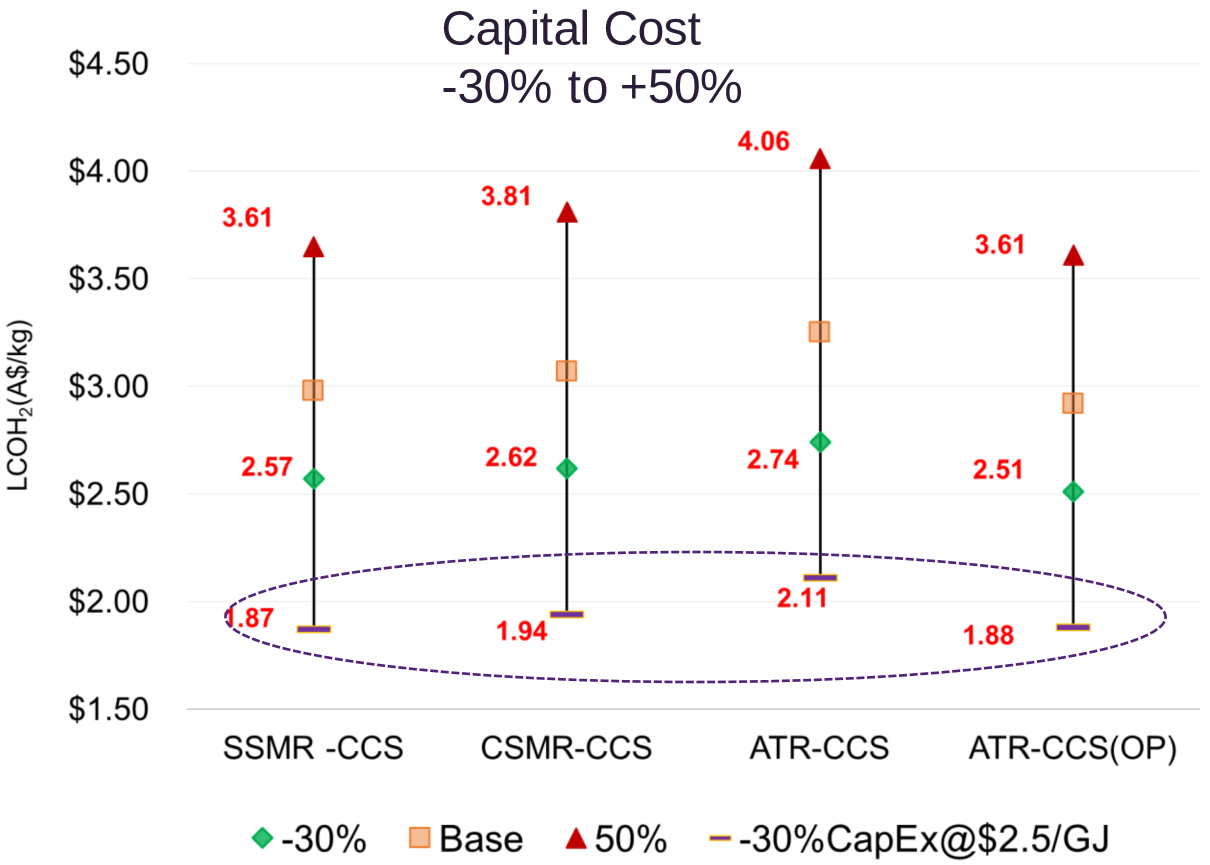


$2 H_2/kg is probably achievable at lower natural gas price

CapEx is the second largest influence on the process economics

Sensitivity analysis results





To achieve the \$2/kg H_2 target both low natural gas prices and substantial CapEx reductions are required. At larger scales we know from experience that ATR will become more competitive than SMR+CCS

Turquoise Hydrogen from Methane Pyrolysis

Molten liquids vs fluidized bed

Indirect heating vs direct heating vs renewable energy integration

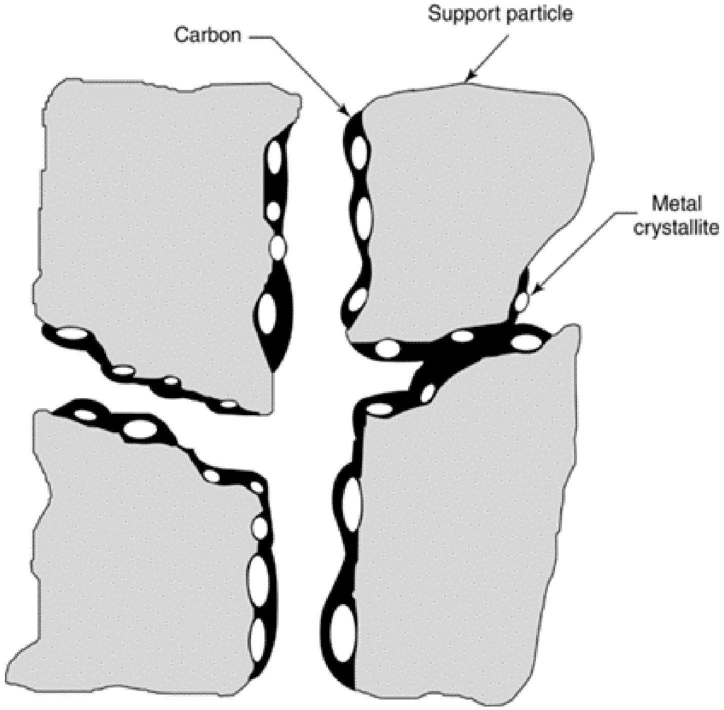
Emerging technology - Pyrolysis of Methane

Thermal dehydrogenation of methane produces hydrogen and carbon

$$CH_4 \rightleftarrows C + 2\,H_2$$

CO_2 free hydrogen production from CH_4

- Carbon is a by-product but can also be a problem:
  - Deactivates catalytic surfaces
  - Restricts gas flow through reactors
  - Is removed by combustion, producing CO_2

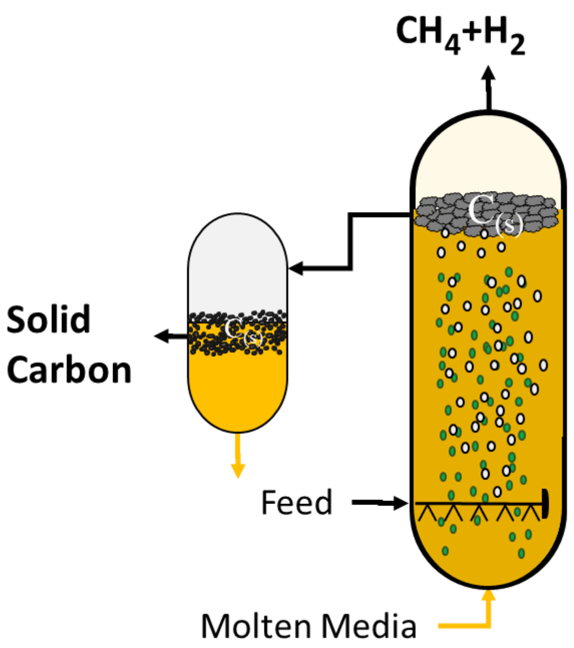


Emerging technology - Pyrolysis of Methane

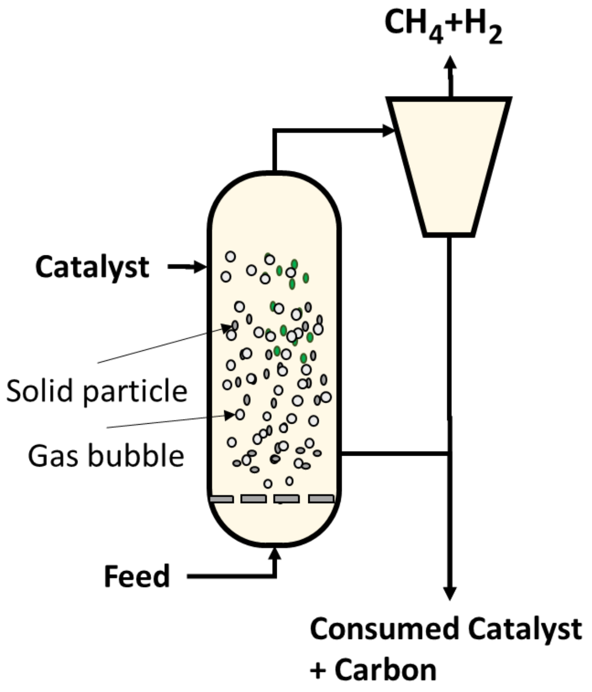
Two pyrolysis technologies-with proven concept

- **Solid Catalyst-** Pilot plant TRL 5-6
  - Carbon is removed through reaction with catalyst
- **Molten Media-** Pilot plant under investigation TRL 3-4
  - Molten Media facilitate to remove the by-product carbon

Selected technologies remove carbon continuously



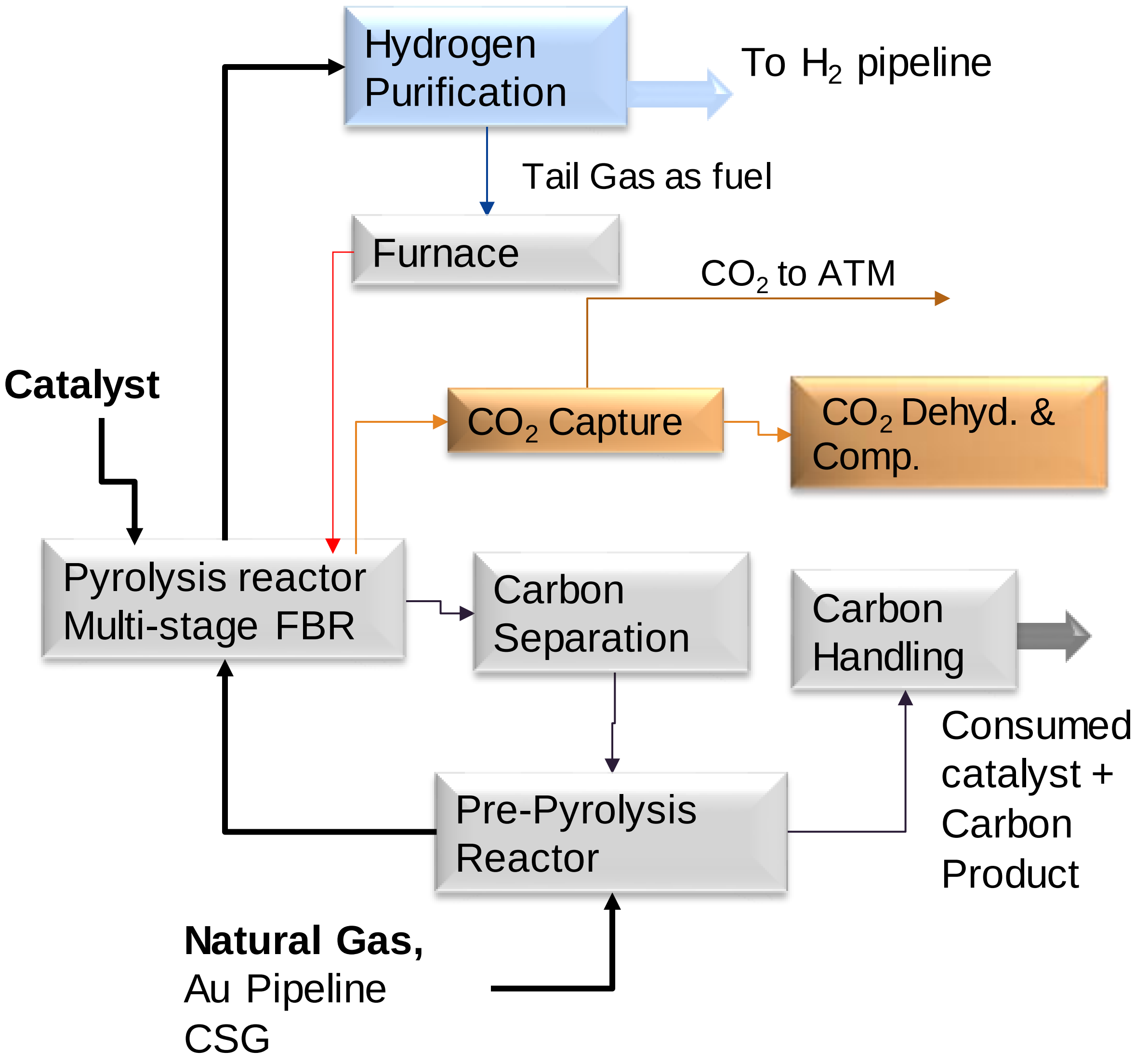
Molten Media



Solid Catalyst

Natural Gas Pyrolysis- Solid Catalyst

Indirect Heating



Hydrogen Purification

To H_2 pipeline

Tail Gas as fuel

Furnace

CO_2 to ATM

Catalyst

CO_2 Capture

CO_2 Dehyd. & Comp.

Pyrolysis reactor Multi-stage FBR

Carbon Separation

Carbon Handling

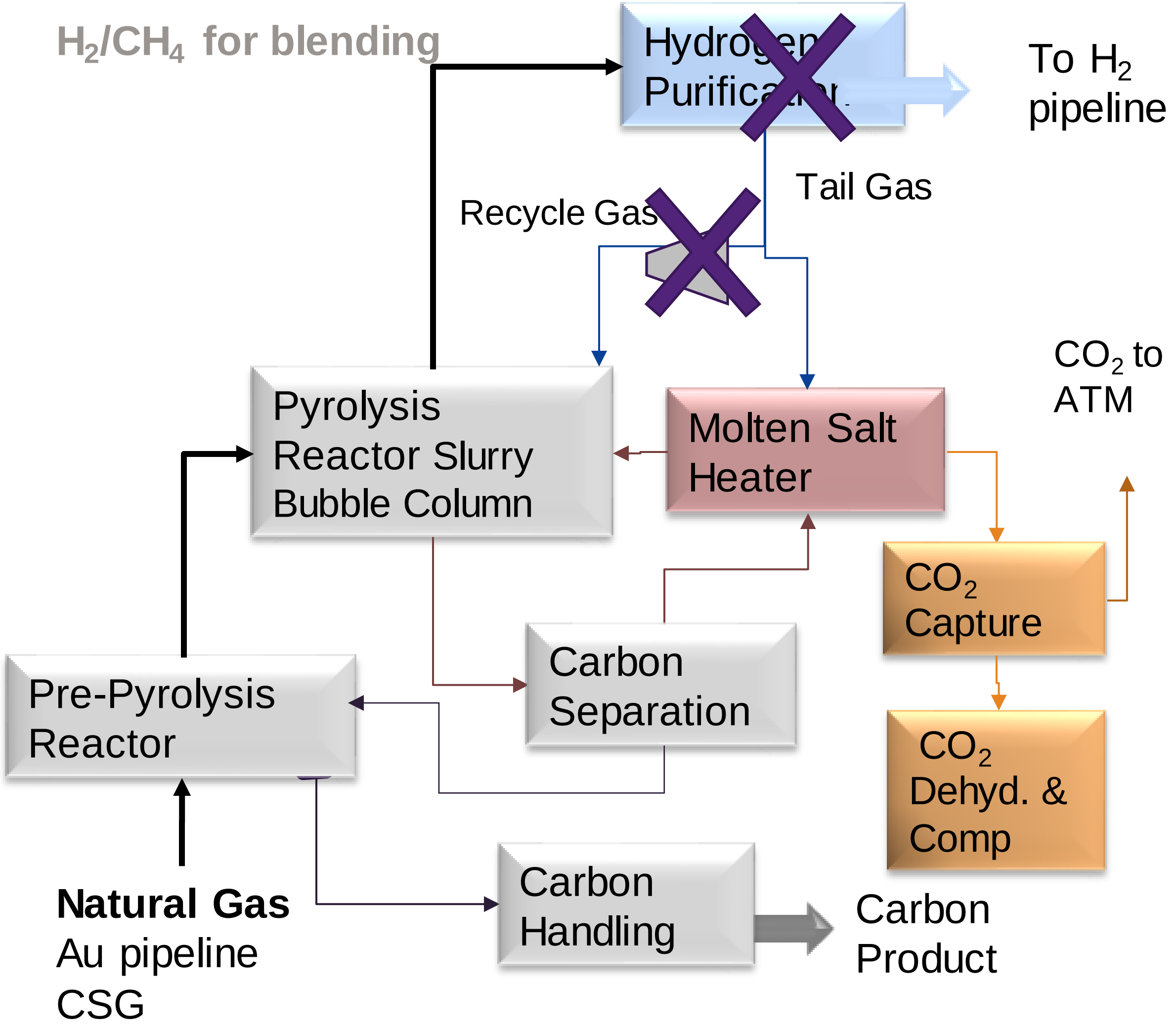
Consumed catalyst + Carbon Product

Pre-Pyrolysis Reactor

Natural Gas,
Au Pipeline
CSG

Natural Gas Pyrolysis- Molten Media

Direct Heating via Molten Media



H_2/CH_4 for blending

Hydrogen Purification

To H_2 pipeline

Tail Gas

Recycle Gas

CO_2 to ATM

Pyrolysis Reactor Slurry Bubble Column

Molten Salt Heater

CO_2 Capture

Carbon Separation

Pre-Pyrolysis Reactor

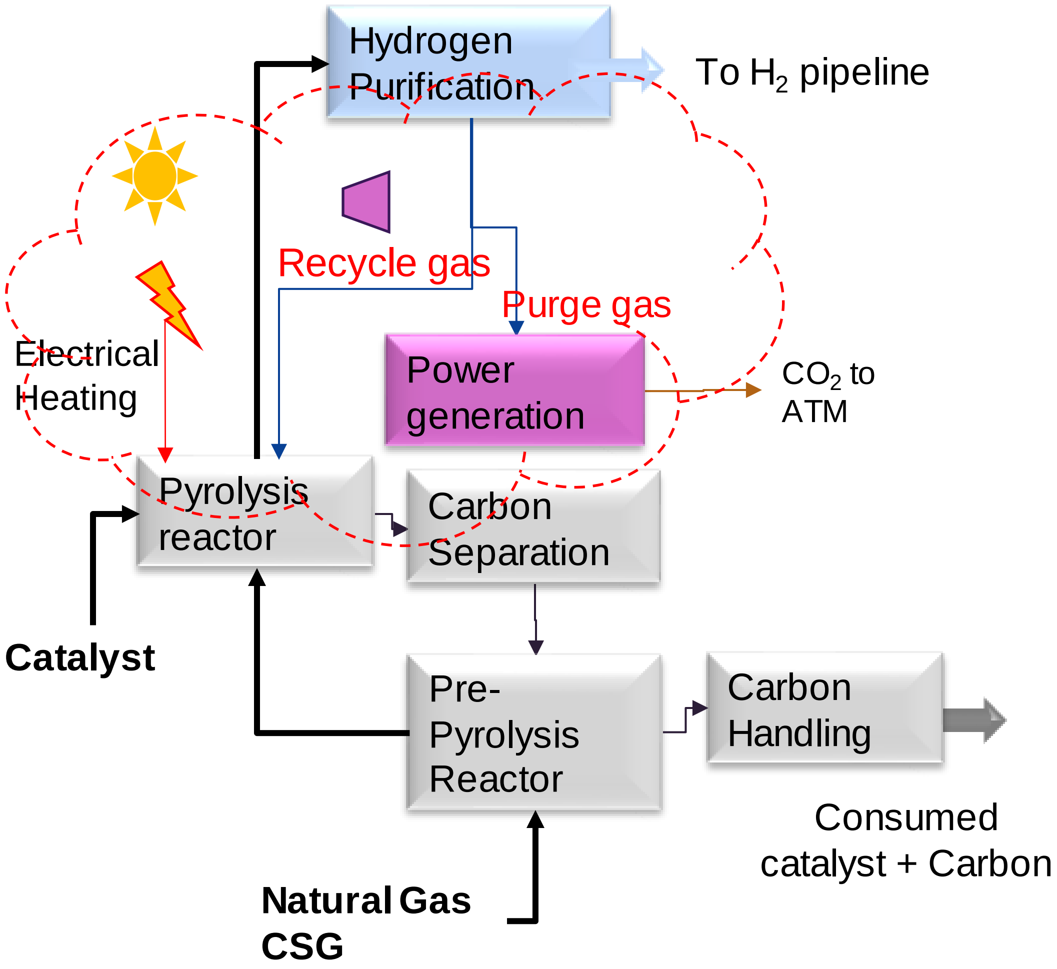
CO_2 Dehyd. & Comp

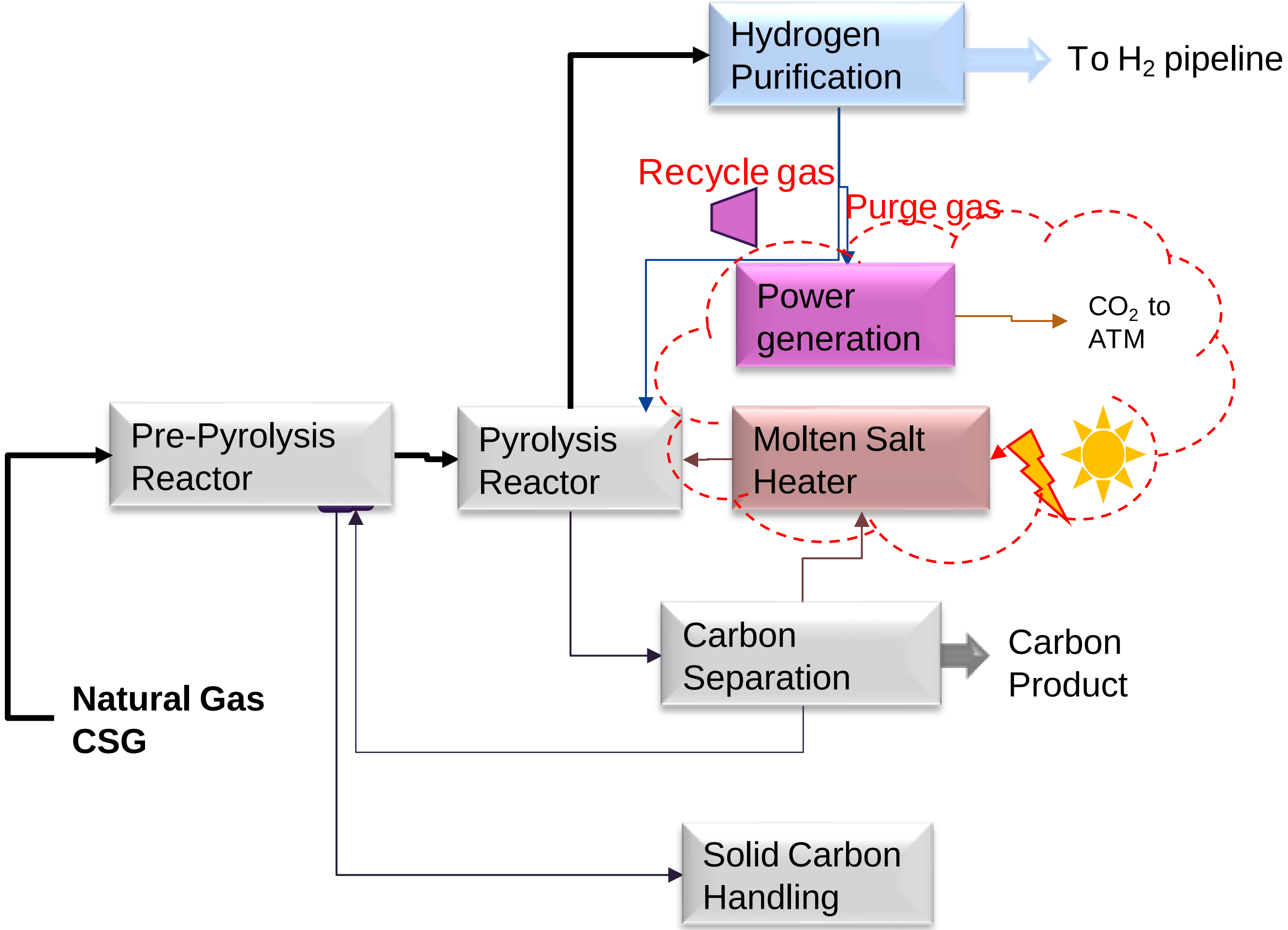
Carbon Handling

Carbon Product

Natural Gas
Au pipeline
CSG

Integration with Renewable Energy





Methane Pyrolysis – Mass and Energy Balances

Pyrolysis Tech.	Energy source	Natural Gas t NG /tH_2	By-Product Carbon t C /tH_2	CO_2 Intensity tCO_2 /t H_2	CO2 Captured (>90%) Flue gas	Net Energy efficiency %
Solid catalyst NG-pipeline	NG+ Electricity	5.76	3.57	0.23	☑	46.9
Solid catalyst CSG	NG+ Electricity	5.33	3.47	0.23	☑	47.4
Solid Catalyst CSG	Renewable electricity	4.38	3.28	0.60	✗	51.6
Molten Media NG-pipeline	NG+ Electricity	5.95	3.27	0.32	☑	46.5
Molten Media NG-pipeline	NG+ Electricity	2.67	1.29	0.05	☑	74.4
Molten Media CSG	NG+ Electricity	5.5	3.27	0.30	☑	47.2
Molten Media CSG	Renewable electricity	4.58	3.05	1.13	✗	58.37

Emerging Technologies vs Conventional Technologies

Conventional – Reforming

$CH_4 + H_2O$ (+ heat) → $CO + 3H_2$

$CO + H_2O \rightarrow CO_2 + H_2$

- Emerging – Pyrolysis

CH_4 (+ heat) → $C + 2H_2$

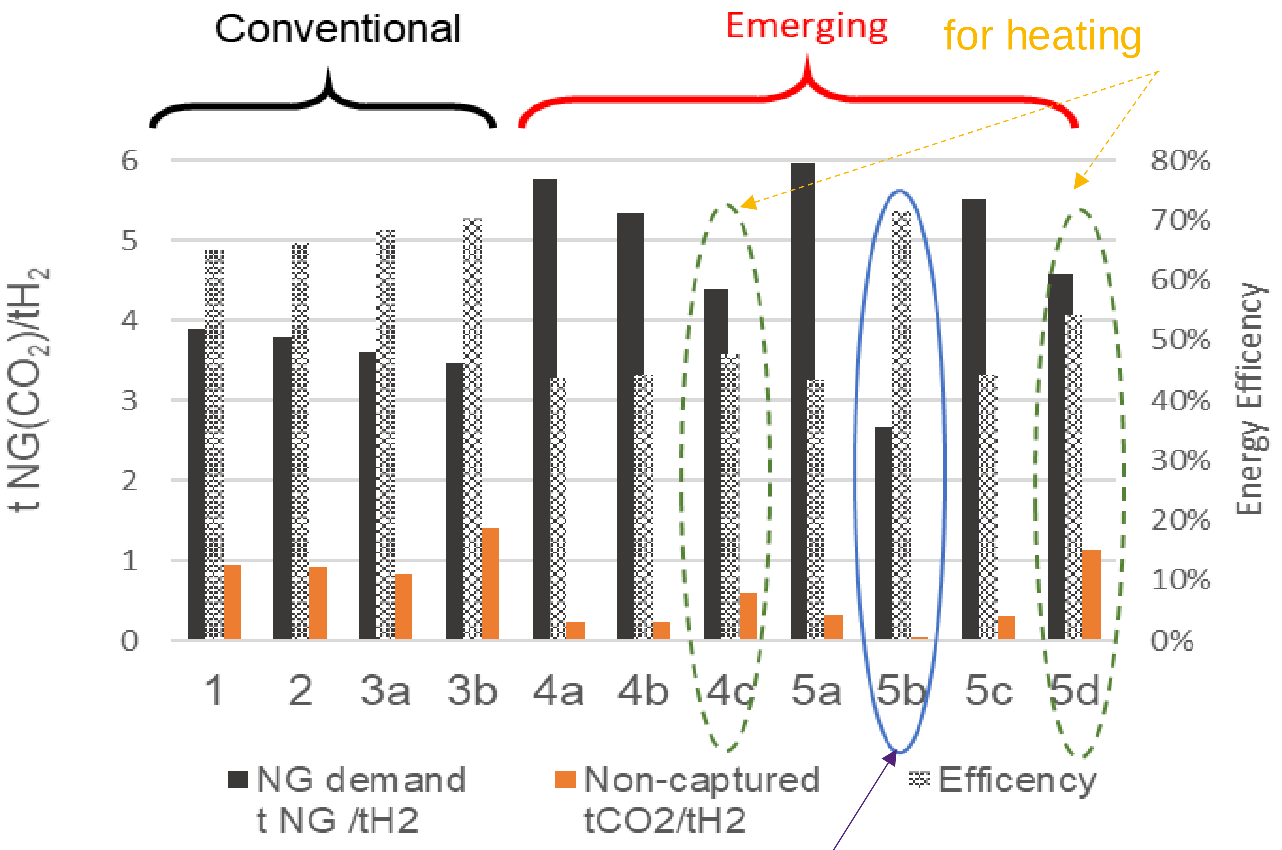
Emerging technologies have:

Significantly lower CO_2 emission and able to be independent to CCS

Higher natural gas demand

Lower process efficiency due to the higher NG consumption

Able to utilise renewable electricity for heating rather than NG or H_2



Renewable electricity for heating

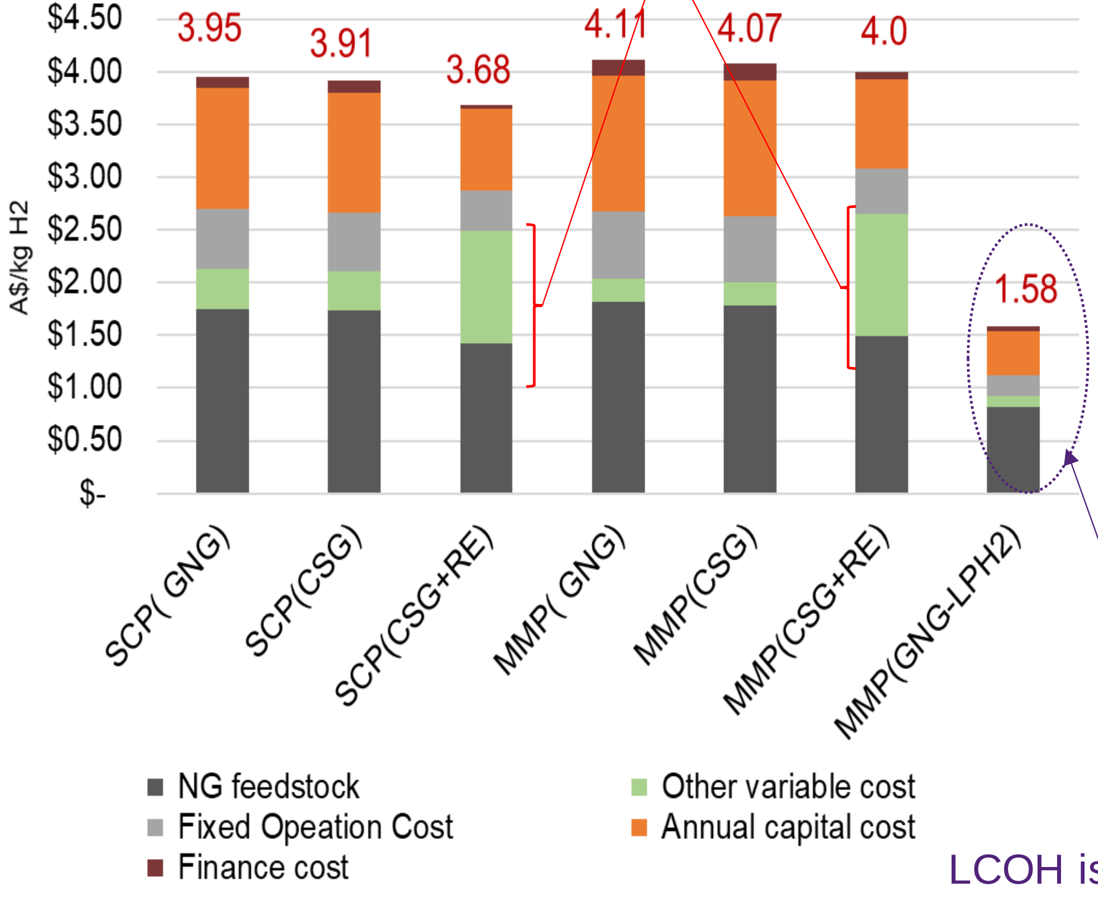
H_2/CH_4 mix product

Net energy eff: Including the electricity demand

H_2 / CH_4 Mix: H_2(79 mol%) and CH_4(18 mol%)

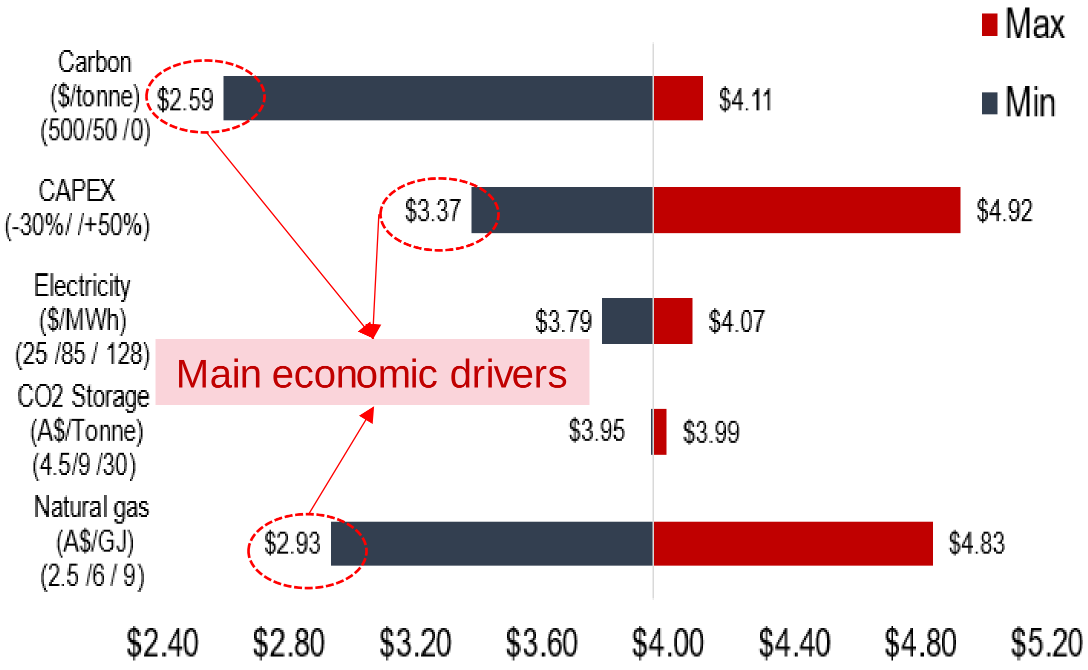
Levelised Cost of Hydrogen

Impact of electricity price



LCOH is based on mixed CH_4+H_2
79 mol% of H_2

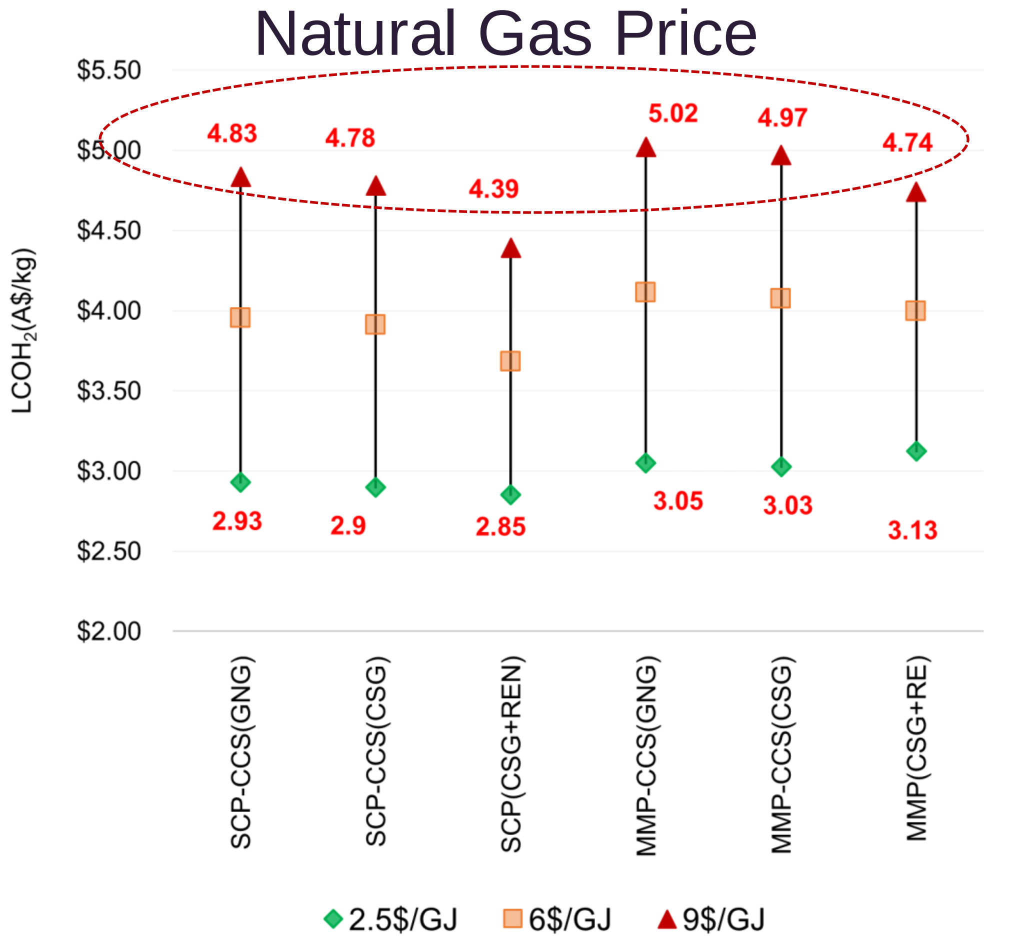
Sensitivity Analysis

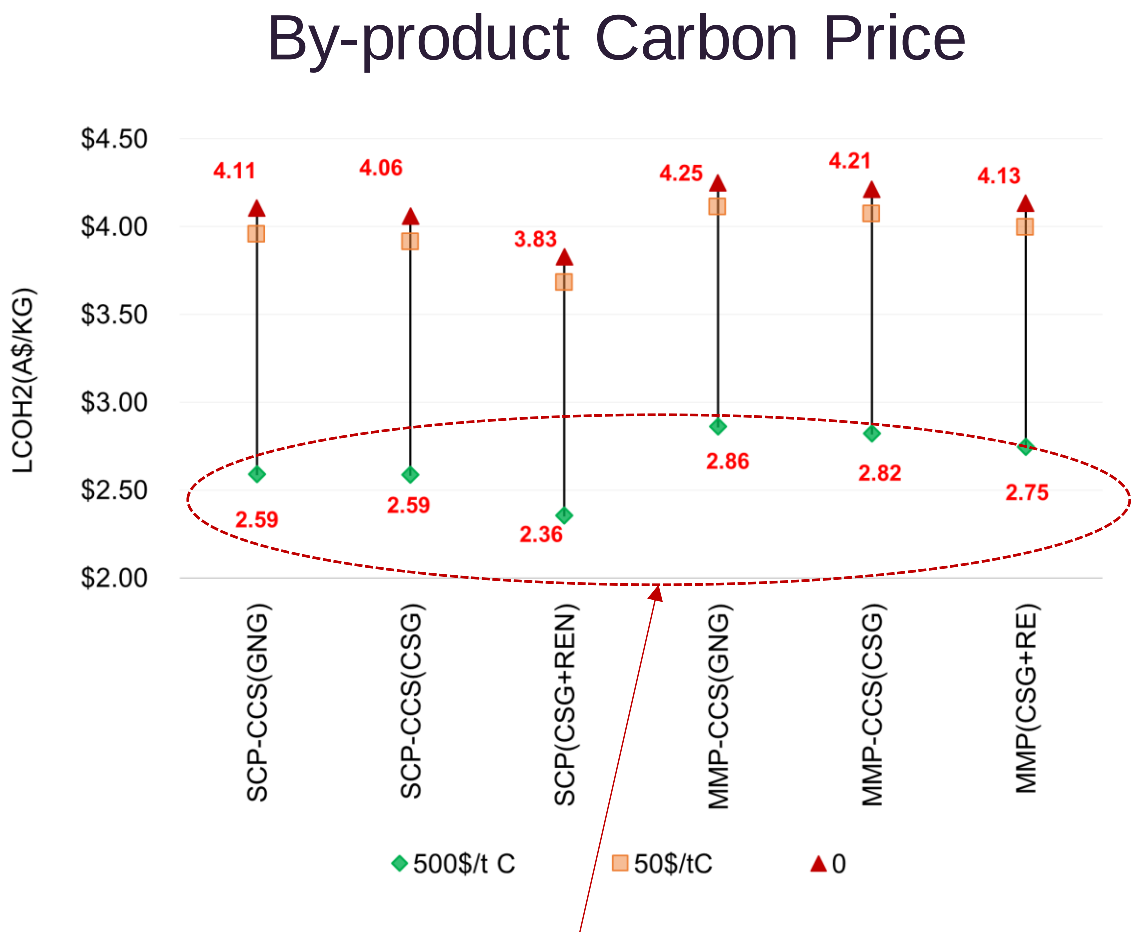


Main economic drivers

High quality carbon is a game changer

Sensitivity analysis results


Natural Gas Price


By-product Carbon Price

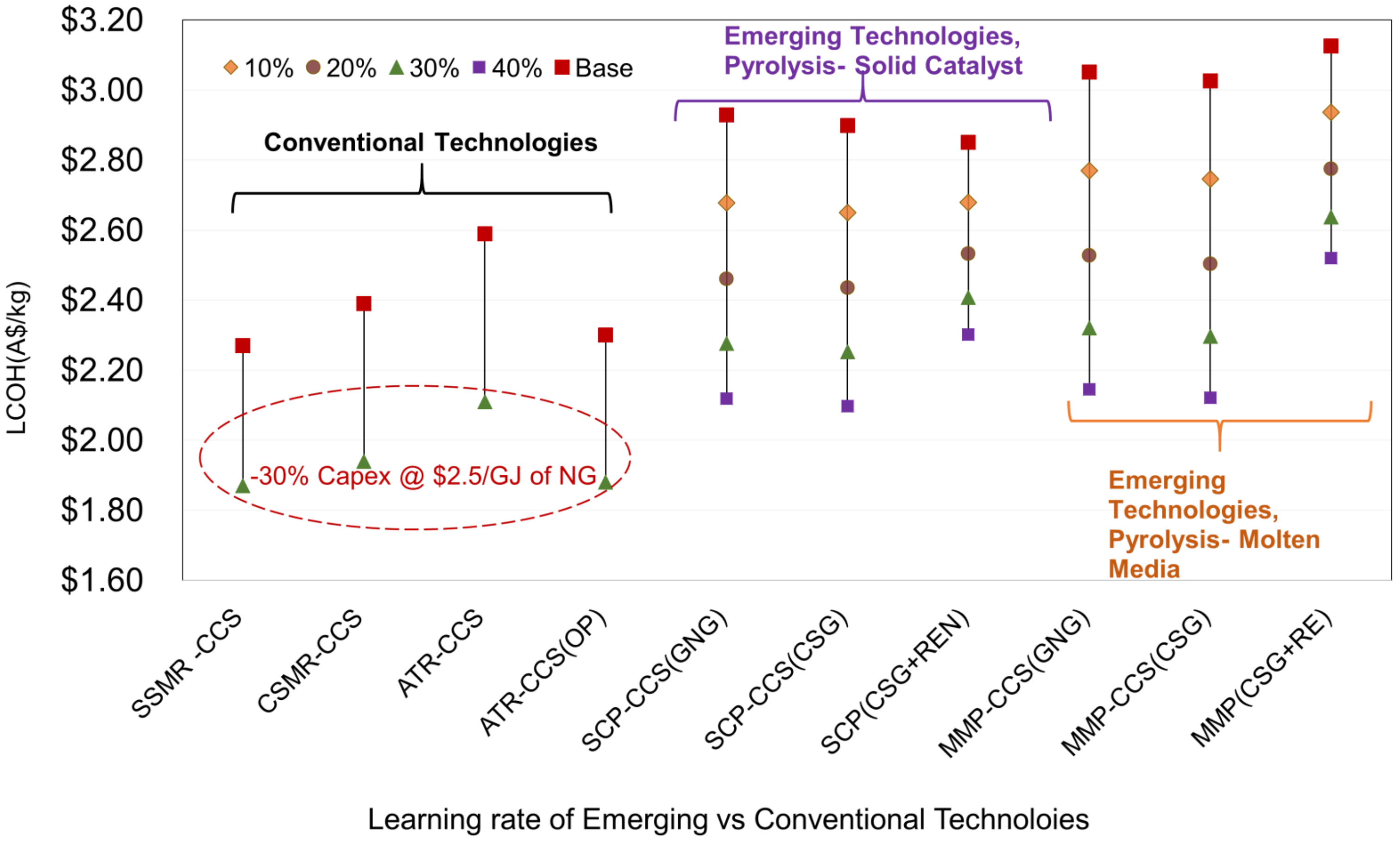
Process economics are less plausible under higher NG price due to higher NG consumption compared to conventional technologies

High quality by-product carbon drives the process economics towards the target price of $2/kg H_2

Final Thoughts

Impact of Technology Learning Curves on LCOH

Learning Rate	Low	Medium	High	Highest	Base
Emerging Technologies	10%	20%	30%	40%	NG Price: $2.5/GJ & Min feed price & Max ACCU



Natural gas is the most promising pathway towards blue hydrogen for both conventional and emerging technologies

BUT only at low natural gas prices

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CRICOS 00025B

Process development (General Concept & Assumptions)

- Plant capacity -100kta H_2
- Targeted Product
    - High purity Hydrogen -99.97%
    - High Pressure H_2 Gas-80 bar
- Plant battery limit (BL) is the physical interface
- Carbon Capture Utilization and storage
    - Compressed Dehydrated CO_2 -150 bar
    - Maximum of 90% CO_2 capturing efficiency
    - No limit for CO_2 storage
- Maximized the energy recovery from inlet fossil fuel feedstock as energy source (heat, steam and surplus to electricity)
- The required fuel, electricity and raw water are available at the Plant BL
- No additional infrastructure are included
- Other required utilities (such as steam, CW, treated water,..) will cost as energy base
- The hydrogen will cost at the Plant BL

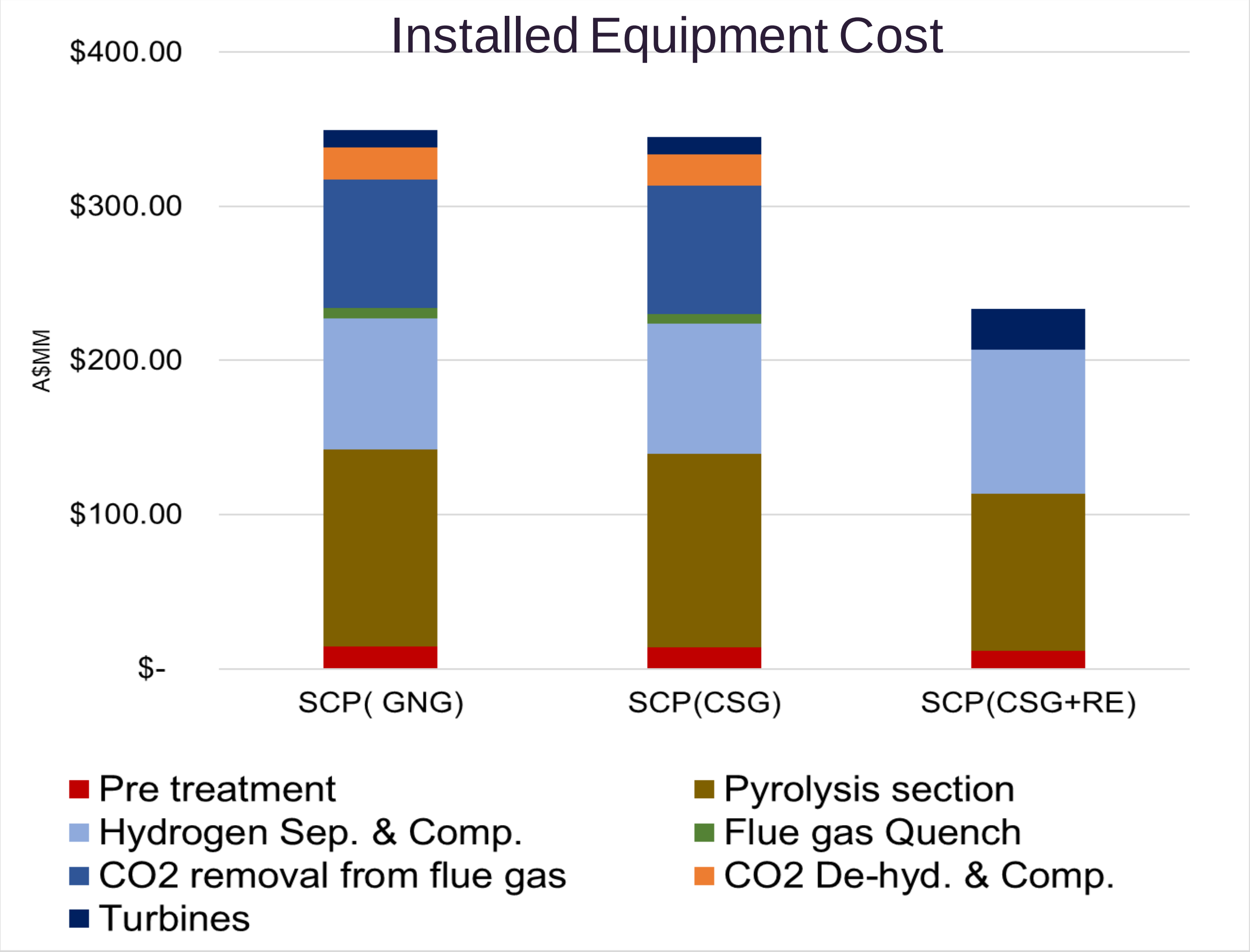
Sensitivity Analyses approach

Parameter	Upper bound	Base	Lower bound	Note
Capex	+50%	-	-30%	Class 5 estimation guideline
Natural gas price (A$/GJ)	9	6	2.5	min and max potential prices for domestic consumption
Electricity price(A$/MWh)	128	85	25	min and max in different states
Sugar cane bagasse price (A$/GJ)	0	0.1	0.2	Min (if the biomass waste could be collected for free)
Black Coal Price (A$/GJ)	5.3	3.5	2.8	Historical coal price over the past 10 years and projection to next 10 years
Brown Coal Price (A$/GJ)	2	1.5	0.64	
CO_2 Transport +Storage	+50%	-	-20%	
CO_2 credit for green CO2 capture (A$/t of CO_2)	100	25	0	

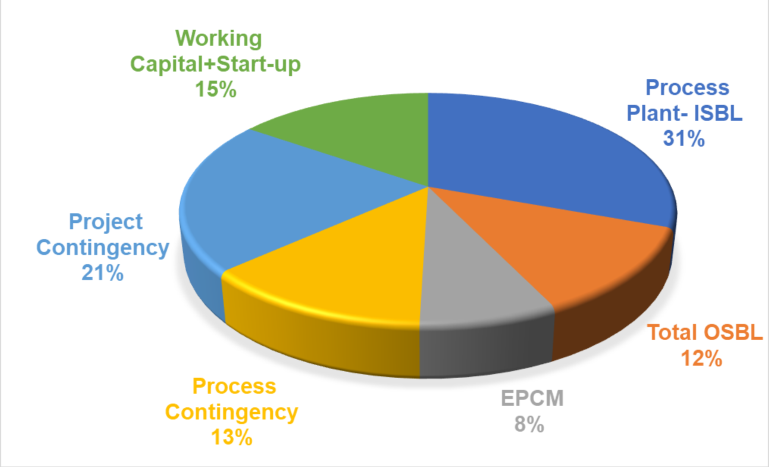
Capex and the main feedstock prices were considered as a sensitivity analysis parameters

CO_2 Storage and transportation cost is also another parameter considered for sensitivity analyses

Installed equipment cost and total investment costs

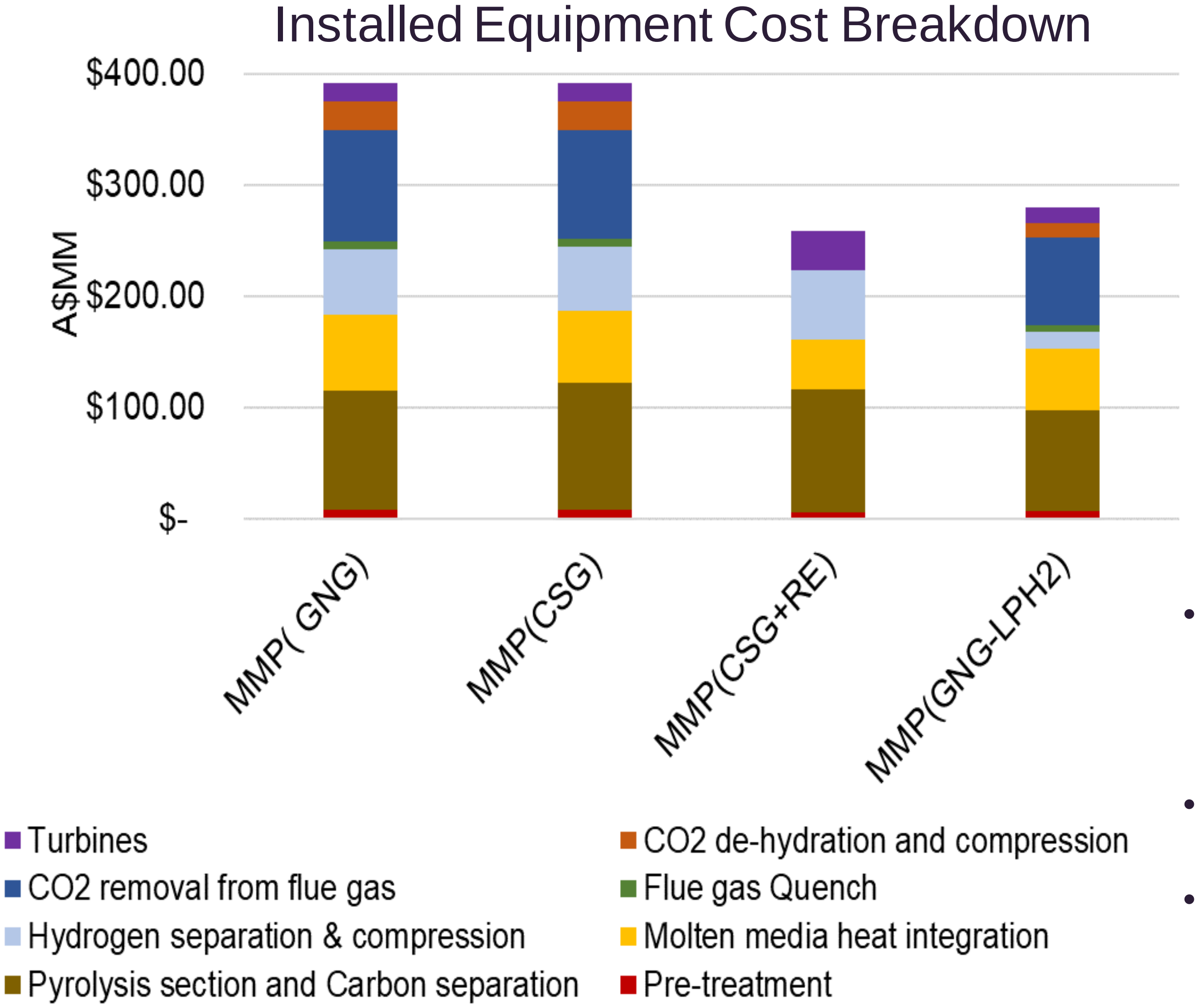


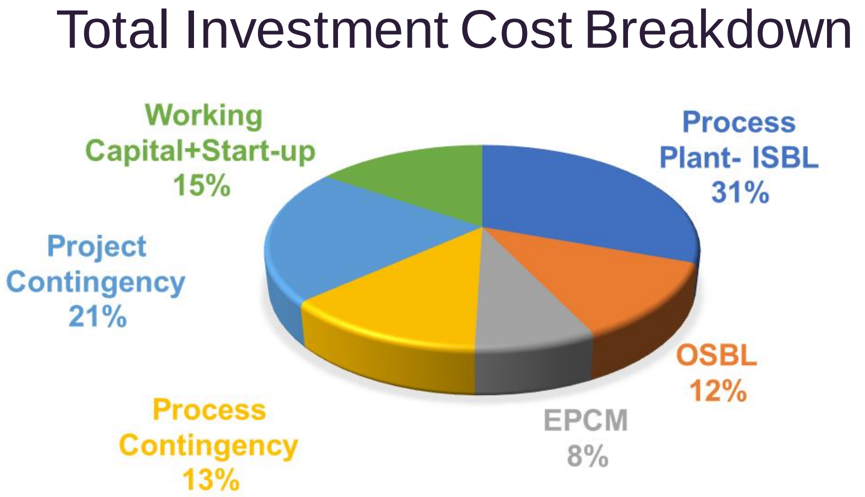
Total Investment Cost Breakdown



- Pyrolysis reactor is single largest contribution to CapEx
- Hydrogen purification cost increases due to low process pressures
- Changing heat provision to renewable electricity can reduce CapEx due to absence of CO_2 capture unit
- High contingency has a major impact on the total investment cost of emerging technologies

Installed equipment cost and total investment costs





- Hydrogen purification contributes less to overall CapEx compared to solid consumable catalyst
  - Blending hydrogen into NG pipelines offers the opportunity to reduce CapEx here
- Changing heat provision to renewable electricity can reduce CapEx substantially due to the absence of CO_2 capture unit
- Compared to solid consumable catalyst process the overall CapEx is higher