ASTRI
AUSTRALIAN SOLAR THERMAL RESEARCH INITIATIVE

Creating new CST markets through solar fuels

ASTRI Symposium on The Future of Concentrating Solar Thermal Technology

Graham 'Gus' Nathan, Wojceich Lipinski, Jim Hinkley and the team

3 May 2016

Drivers for solar fuels

Electricity

- Steam turbine
- Gas turbine
- Future cycles

Wholesale ~$12/GJ

$\eta_{heat\text{-}power} \sim 35\%$

"Non" Exportable

Growing role in light vehicle transport

Possible role in heavy freight

Source: CSIRO.au

Liquid transport fuels

- Gasification: Biomass &/or coal
- Reforming: Natural gas
- Splitting: CO_2 & H_2O

Wholesale ~ $26/GJ

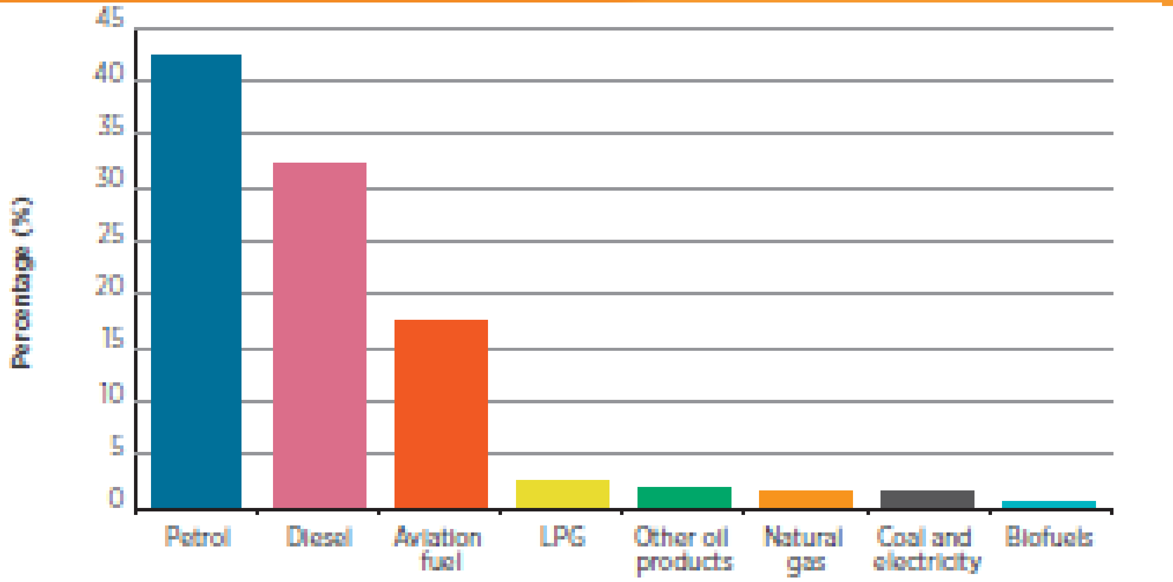
$\eta_{heat\text{-}fuel} \sim 20\text{-}60\%$

Exportable commodity

Vital for heavy transport

Essential for air transport

Fractional demand for oil products



Source: BREE (2014)

	2013–14		*Average annual growth*	
	PJ	Share (per cent)	2013–14 (per cent)	10 years (per cent)
Road	1156.9	72.8	-0.1	1.3
Air	303.0	19.1	4.9	4.6
Rail	52.0	3.3	-0.1	4.4
Water	53.0	3.3	6.2	-2.5
Other	24.3	1.5	-3.4	-0.1
Total transport	**1589.2**	**100.0**	**1.1**	**1.8**

Source: Aus Energy Update (2015)

Comparing feed-stock and technologies

Feedstock	Efficiency solar to feed-stock	LHV feed-stock (MJ/kg)	Feed-stock present cost ($/tonne)	Feed-stock future cost trend	Resource sustainable capacity	Comment
Oil-rich crops (Gen I)	~3%	~18	~ $60	stable	zero	Unsustainable because it competes with food crops
Agricultural residues	~3%	~15	$10-40	stable	Significant niche	CST ↑ output by ~30% - 40% from limited, valuable resource
Woody biomass (Gen II)	~3%	~15	$150-$250	stable	Significant niche	CST ↑ output by ~30% - 40% from limited additional resource
Macro & Micro algae (Gen III)	~20%	~15	$180-450	down	Large (sea-water)	CST ↓ cost of more larger, more expensive, sustainable resource
CO_2 from flue-gas	-	0	~ $60	down	Large	Challenging cost targets, but may be necessary
CO_2 from air	-	0	~ $600	down	“Infinite”	Likely to be the most expensive of all CST options

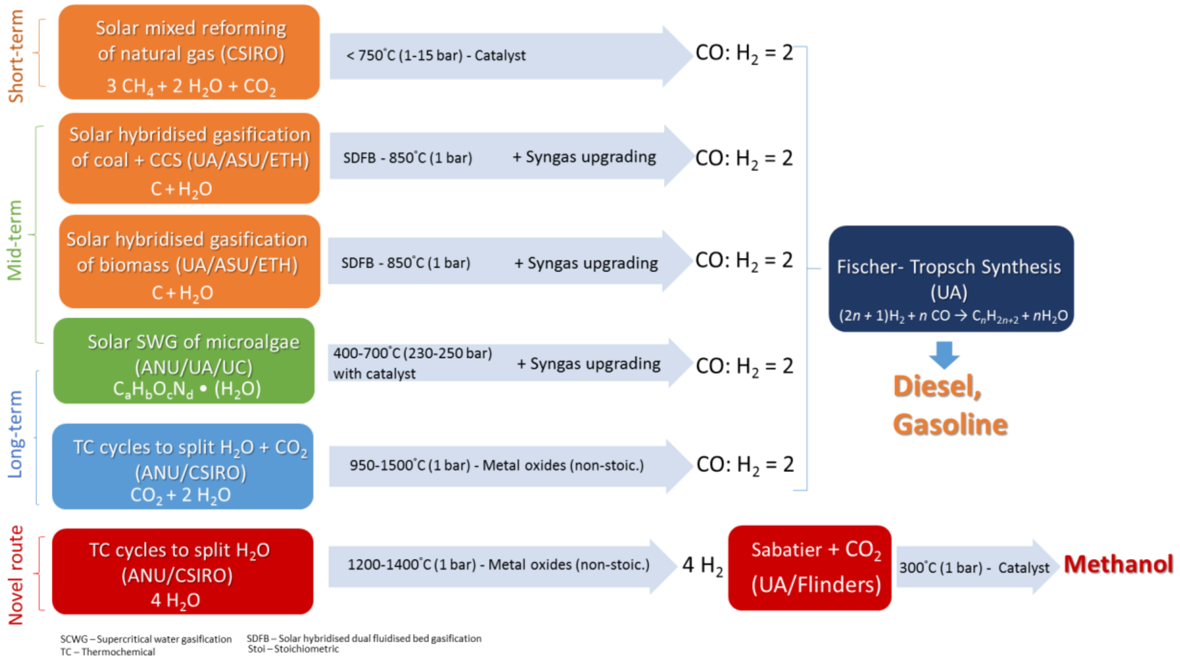
Targets and path to market

- **Original targets for synthetic diesel by Fischer-Tropsch**
  - $1:20/L with 10% reduction in CO_2 re mineral crude
  - $2:50/L with sustainable feed-stock and 50% reduction in CO_2
- **Path-way to market**
  - Establish market with high value biomass co-products / fossil bends
  - Lower cost & de-risk technology for long-term sustainable feed-stock

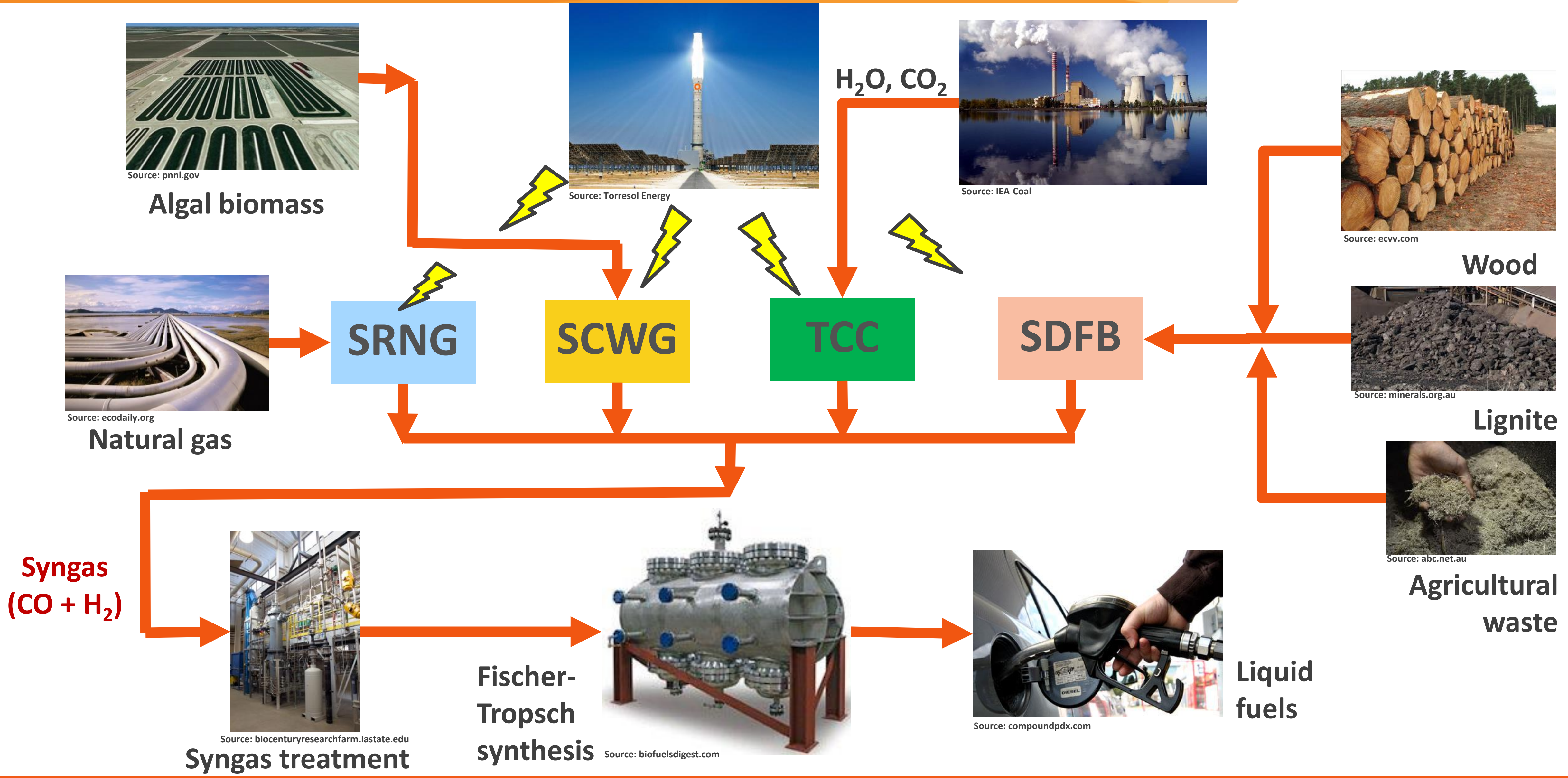
Source: CSIRO.au

ASTRI: Establishing a pathway

- Common path to CST liquid fuels via syngas
  - Leveraging parallel developments in Fischer-Tropsch Liquids (FTL)
- Advance pathway - near to long-term feedstock
  - Fossil fuels: Coal and natural gas
  - Low cost biomass: Agricultural residues
  - Future biomass: Micro- and macro-algae
  - Future CO_2: Thermo-chemical cycles
- Targeted development of selected components
  - Solar hybridised dual fluidised bed (DFB) gasification
  - Super-critical water gasification of algae
  - Reactors for splitting CO_2 and H_2O into CO and H_2



ASTRI solar-to-liquid-fuel program



Complementary technologies being developed by ASTRI

Technology	Feed-stock	Temperature	Pressure	Key advantages
Solar hybridised dual fluidised bed gasification	Reactive, dry: Wood, macro-algae, residues, lignite	~ 850 °C	Atmospheric	• Accommodates solar variability upstream of gasifier • Heats inert bed material • Readily hybridised
Solar super-critical water gasification	Wet: Micro-algae	~400 – 700 °C	230-250 bar	• Low reactor temperature • Handles wet feed-stock • No particles in syngas
Thermo-chemical cycles	CO_2, H_2O	900 – 1500 °C	Atmospheric	• Realistic path to CO_2 regeneration • LCOF $2.00/L if 25% efficiency can be obtained
Liquid synthesis catalysts	CO, CO_2 & H_2	200 – 380 °C	2 – 5 bar	• Higher value products • Lower operating temperature • More efficient use of precious metal catalysts

Distinctive features of ASTRI projects

- Assess whole of plant performance including downstream plant
  - Downstream processing is ~ 45% capex
- Consider solar resource variability in evaluating performance
  - This is a first-order influence
- Establish common framework for techno-economics and LCA CO_2 emissions
  - Compare different technology options for target feed-stock on same basis
- Integrated with, and leveraged from, the other ASTRI projects
  - Heliostats (P11), Receivers (P12) and Energy storage systems (P21)
  - ASTRI 25 - 100MW scale is well suited to solar fuels
- Integrated national and international program
  - Four Australian and three international institutions

THE UNIVERSITY of ADELAIDE

Australian National University

CSIRO

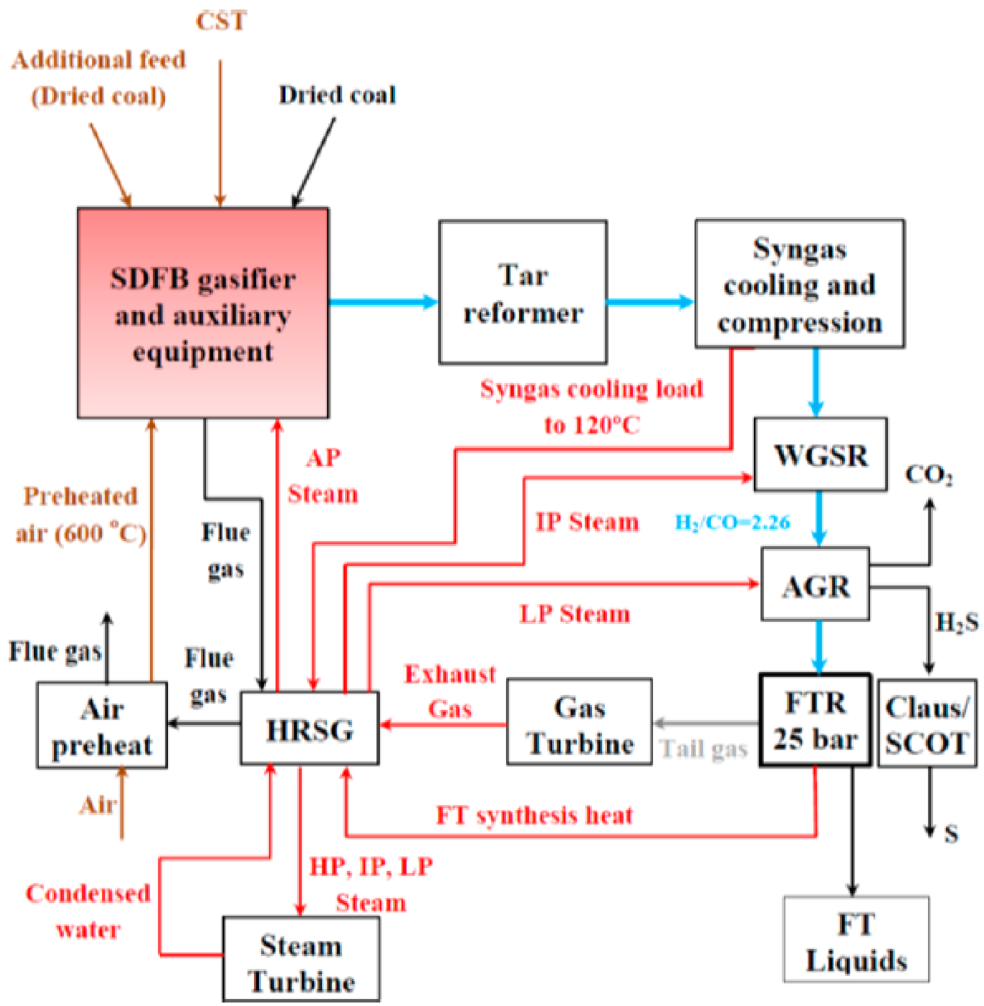
Flinders UNIVERSITY

ARIZONA STATE UNIVERSITY

University of Colorado Boulder

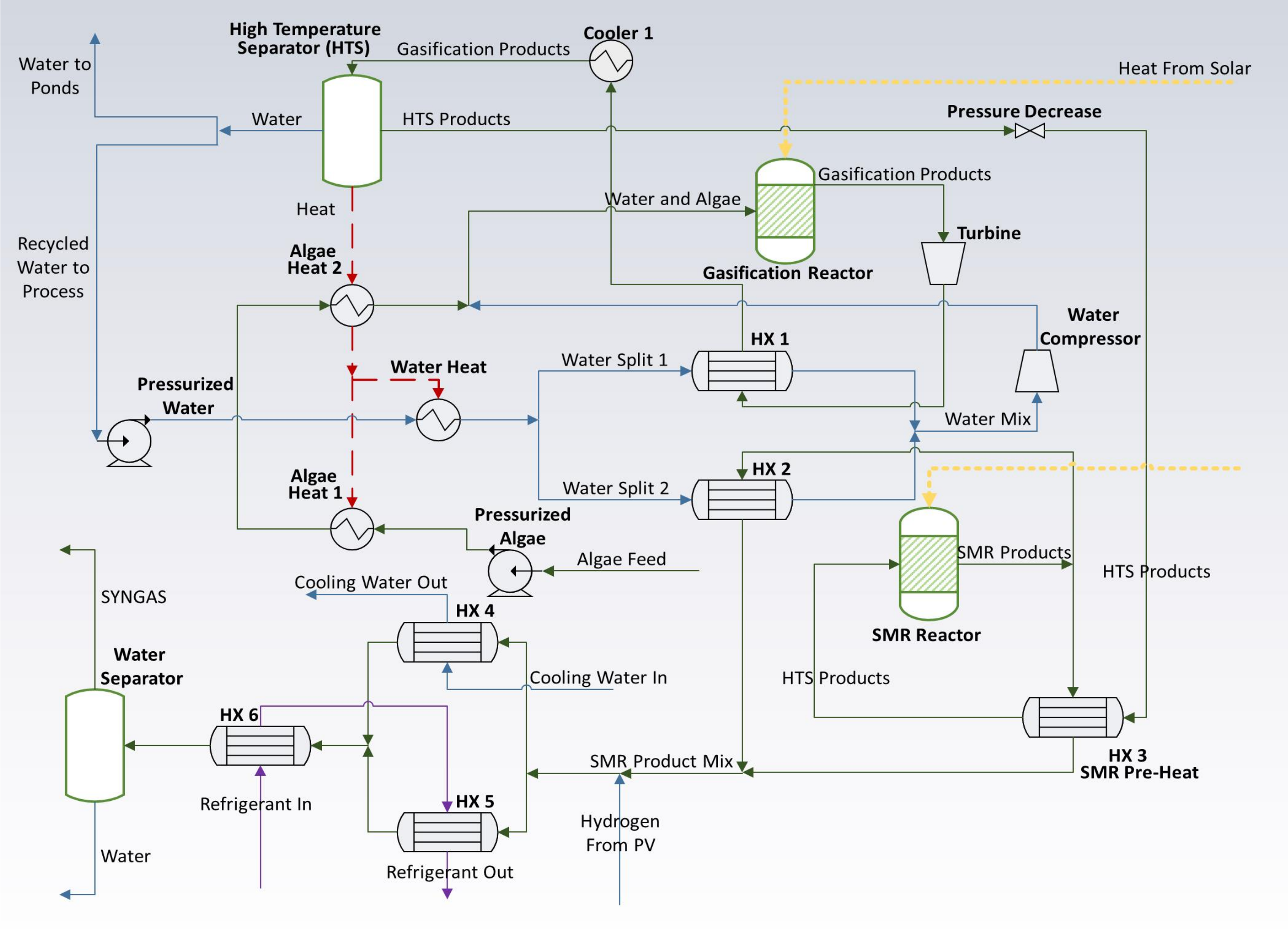
ETH Swiss Federal Institute of Technology Zurich

Modelling the whole process:
Here for solar hybridised DFB gasification



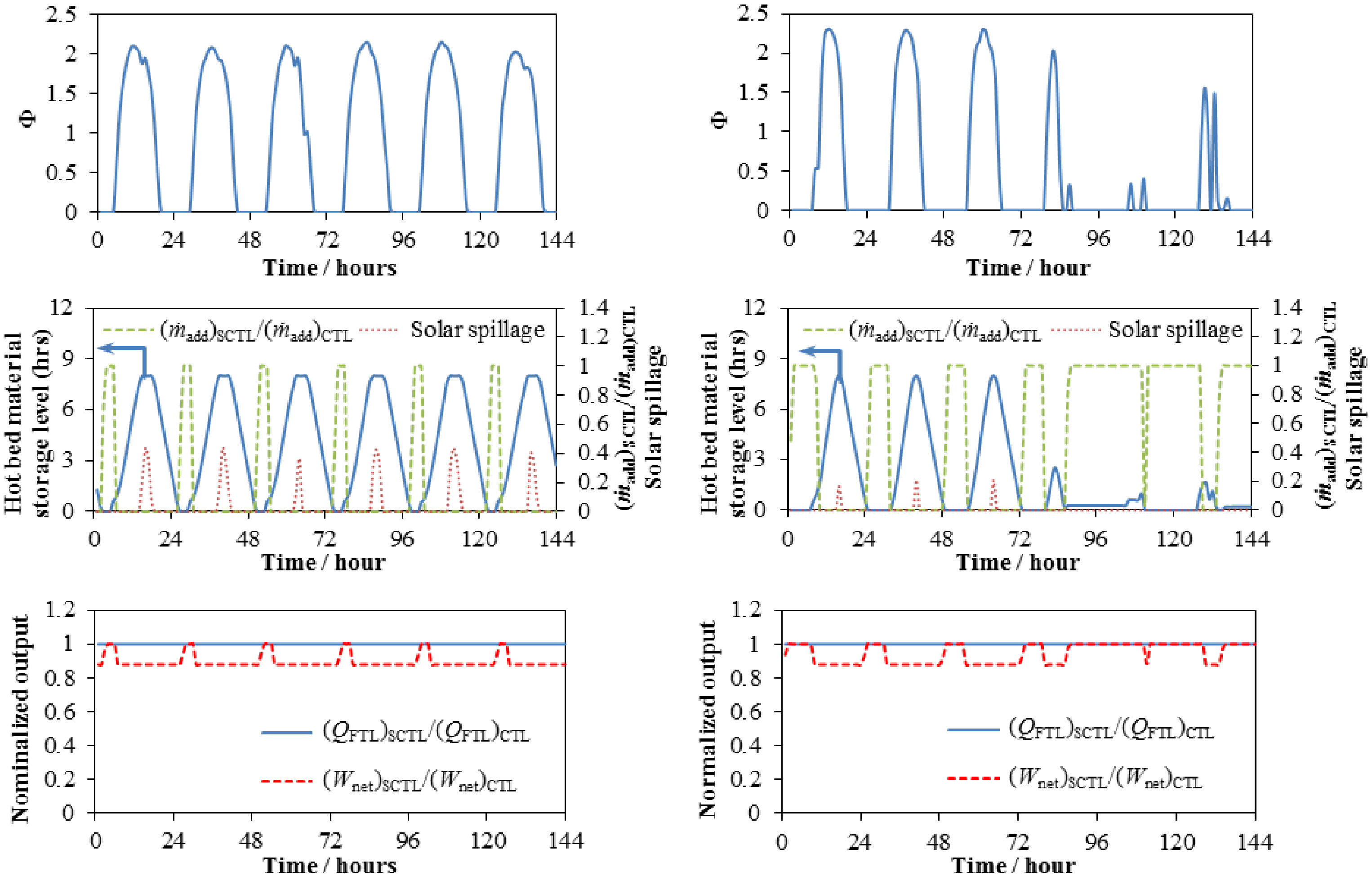
Source: P. Guo, P. J. van Eyk, W. L. Saw, P. J. Ashman, G. J. Nathan and E. B. Stechel, Energy Fuels 2015, 29, 2738-2751

Process model:
Solar super-critical water gasification of algae



Accounting for solar resource variability six days in 1 year time-series

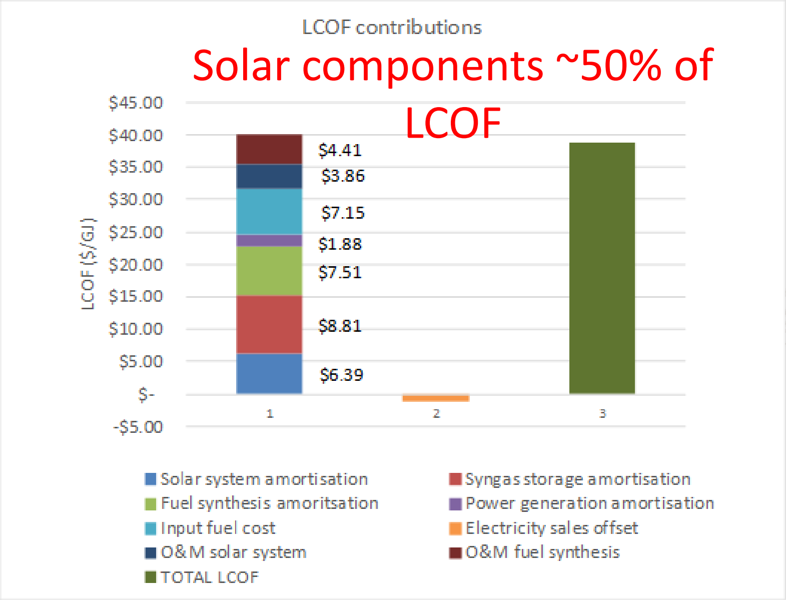
Solar hybridised dual fluidised bed gasification



Source: P. Guo, P. J. van Eyk, W. L. Saw, P. J. Ashman, G. J. Nathan and E. B. Stechel, Energy Fuels 2015, 29, 2738-2751

Levelised cost of fuel (LCOF) – Year 2020

Pathway	Process conditions	Product / LCOF
Low sulphur diesel (LSD) Australian Institute of Petroleum		**LSD** \$1.1/L (TGP[b])
Short-term: Solar mixed reforming of natural gas (CSIRO) $3\ CH_4 + 2\ H_2O + CO_2$	< 750˚C (1-15 bar) – Catalyst + FTS	**Diesel/Gasoline** \$1.0/L
Mid-term: Solar hybridised gasification of coal + CCS (UA/ASU/ETH) $C + H_2O$	SDFB - 850˚C (1 bar) + Syngas upgrading + FTS	**Diesel/Gasoline** \$0.9/L
Mid-term: Solar hybridised gasification of biomass (UA/ASU/ETH) $C + H_2O$	SDFB - 850˚C (1 bar) + Syngas upgrading + FTS	**Diesel/Gasoline** \$1.4/L
Long-term: Solar SCWG of microalgae (ANU/UC/UA) $C_aH_bO_cN_d \bullet (H_2O)$	400-700˚C (230-250 bar) with catalyst + Syngas upgrading + FTS	**Diesel/Gasoline** \$3.0/L
Long-term: TC cycles to split $H_2O + CO_2$ (ANU/CSIRO) $CO_2 + 2\ H_2O$	900-1500˚C (1 bar) - Metal oxides (non-stoic.)	**Diesel/Gasoline** \$2.0/L



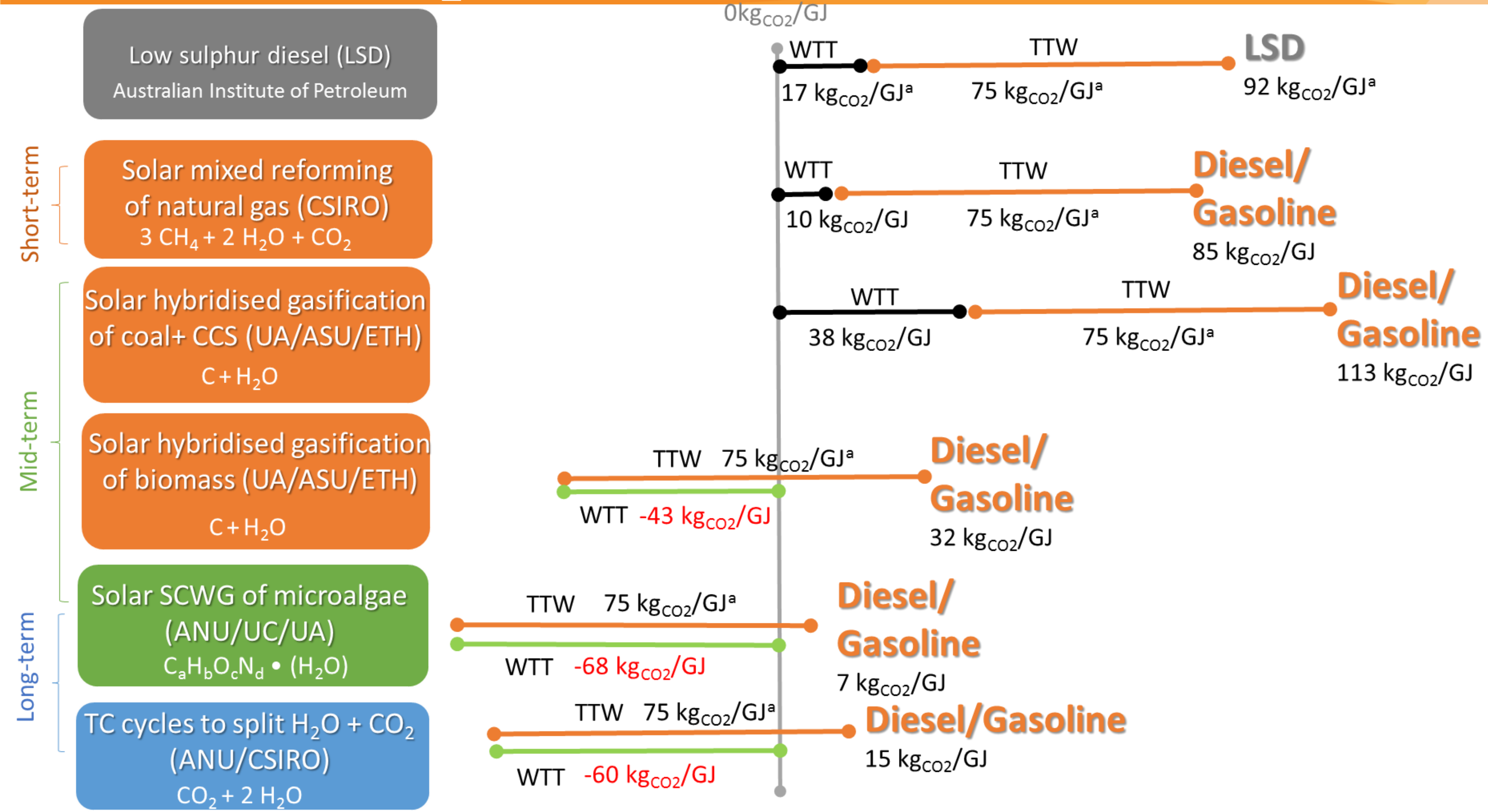
E.g. Distribution of LCOF contributions for SRNG

THE UNIVERSITY of ADELAIDE
Australian National University
CSIRO
Flinders UNIVERSITY
ASU ARIZONA STATE UNIVERSITY
University of Colorado Boulder
ETH Swiss Federal Institute of Technology Zurich

SDFB – Solar hybridised dual fluidised bed gasification
SCWG – Supercritical water gasification
TC – Thermochemical
Stoi – Stoichiometric

a- Mui, S., Tonachel, L., McEnaney, B. and Shope, E., GHG Emission Factors for High Carbon Intensity Crude Oils. Natural Resources Defense Council, 2010.
b- http://www.aip.com.au/ October 2015, Terminal Gate Price

Life cycle CO_2 emissions – Year 2020



THE UNIVERSITY of ADELAIDE
Australian National University
CSIRO
Flinders UNIVERSITY
ASU Arizona State University
University of Colorado Boulder
ETH Swiss Federal Institute of Technology Zurich

SDFB – Solar hybridised dual fluidised bed gasification
SCWG – Supercritical water gasification
TC – Thermochemical
Stoi – Stoichiometric
WTT – Well-to-Tank
TTW – Tank-to-Wheel

a- Mui, S., Tonachel, L., McEnaney, B. and Shope, E., GHG Emission Factors for High Carbon Intensity Crude Oils. Natural Resources Defense Council, 2010.

Current status of assessment matrix

Process	Technical feasibility (22%)	Solar share (10%)	Economic feasibility (33%)	Sustainability (20%)	Stage of development (15%)	Overall	Priority
Solar mixed reforming of methane	7.8	3.0	6.8	2.5	6.5	**5.7**	**1**
Solar hybridized coal gasification via vortex flow reactor	6.3	3.0	5.3	1.0	4.5	**4.3**	**2**
Solar hybridized coal gasification via dual fluidised bed gasifier	7.5	3.0	7.1	1.0	6.0	**5.4**	**1**
Solar hybridized biomass gasification via dual fluidised bed gasifier	7.0	3.0	4.5	9.0	6.0	**6.0**	**1**
Supercritical water gasification of Algae	5.8	5.0	2.3	9.0	6.5	**5.3**	**1**
Thermochemical cycles	5.0	10.0	2.3	7.8	7.0	**5.4**	**1**

Technology development:
Solar hybridised DFB gasification (UA/ASU/ETH)

An economic process that delivers a constant production rate of liquid fuels despite solar variability

Leverages existing/parallel technology:

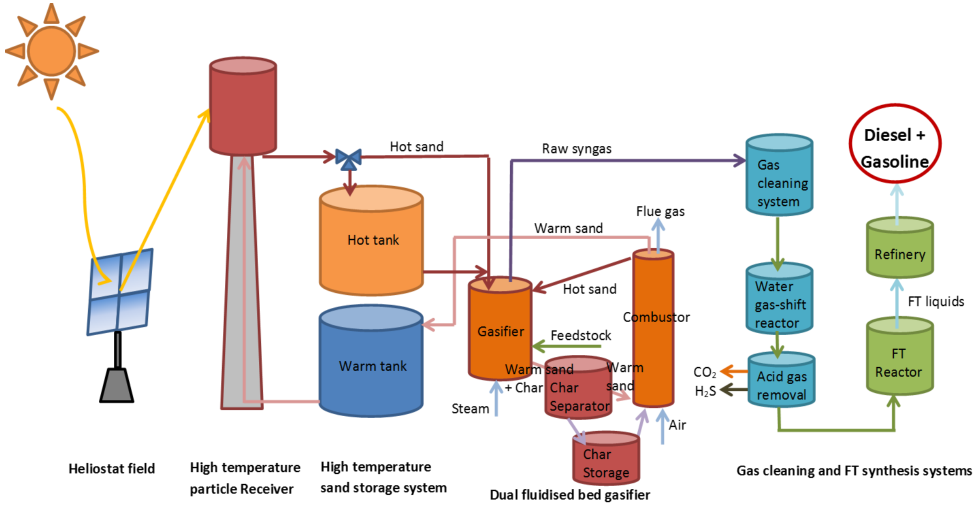
- Fluidised bed gasification technology has been demonstrated
- Other ASTRI projects

New understanding for target feedstocks/bed material:

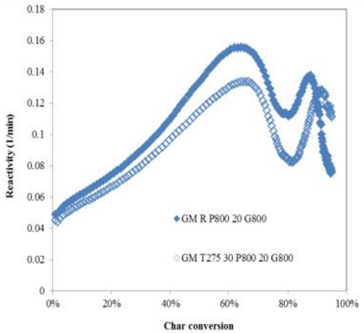
- Bed material (physical/thermal/catalytic properties)
- Torrefaction of agricultural residues and algae
- Char reactivity of biomass under gasification environment
- Increases viability for gasification

Future research activities:

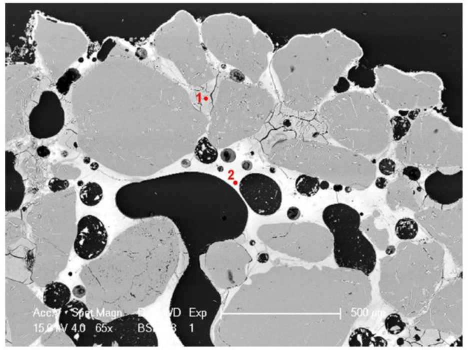
- Interaction between solar radiation and fuel ash/bed material
- Planning toward pilot-scale testing



P11 P12 P21 P42 Commercially available



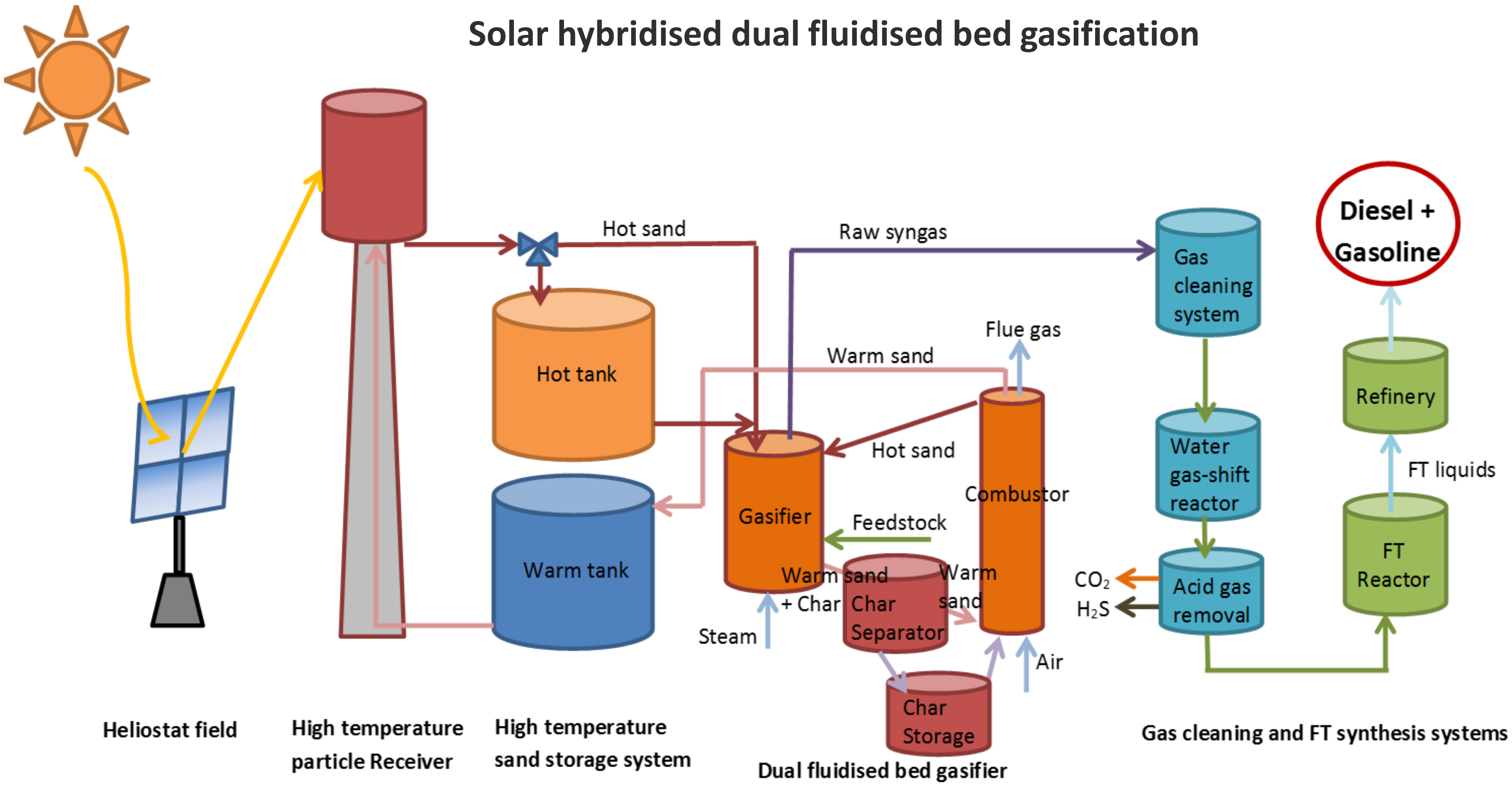
Char reactivity- Grape marc



Cross section of an agglomerate

Linkages across ASTRI projects

Solar hybridised dual fluidised bed gasification



P11 P12 P21 P42 Commercially available

Technology development: Solar SCWG (ANU/UC/UA)

Leverages existing/parallel technology:

- H_2 and CH_4 as targets, not liquid fuels
- Leverages understanding of tubular receivers from P12

New understanding for reactor/target feedstock:

- Reaction kinetics for micro-algae under SCWG
- Heat and mass transfer of the reactor

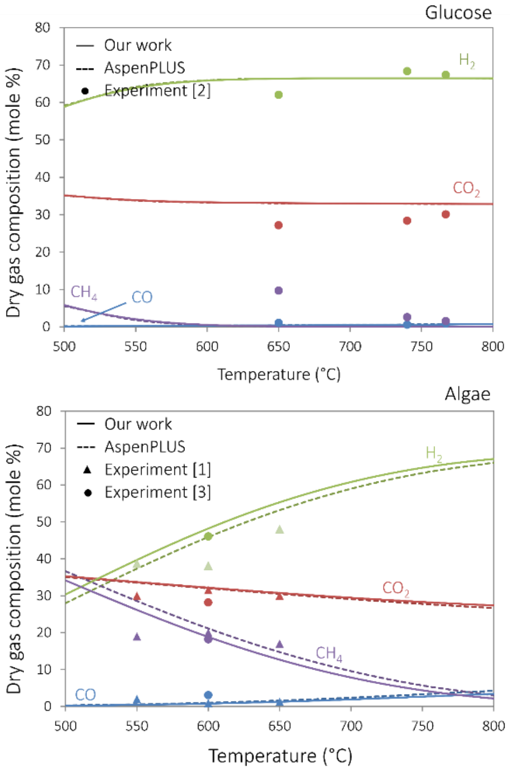
Provision of new design data:

- Materials selection, stress analysis
- System integration

Future research activities:

- Experimental/modelling assessment of transients
- Detailed techno-economic assessment
- Planning toward pilot-scale testing

New rig under construction



Developing validated models of reactions

Technology development: Thermo-chemical cycles (ANU/CSIRO)

Complements international R&D:

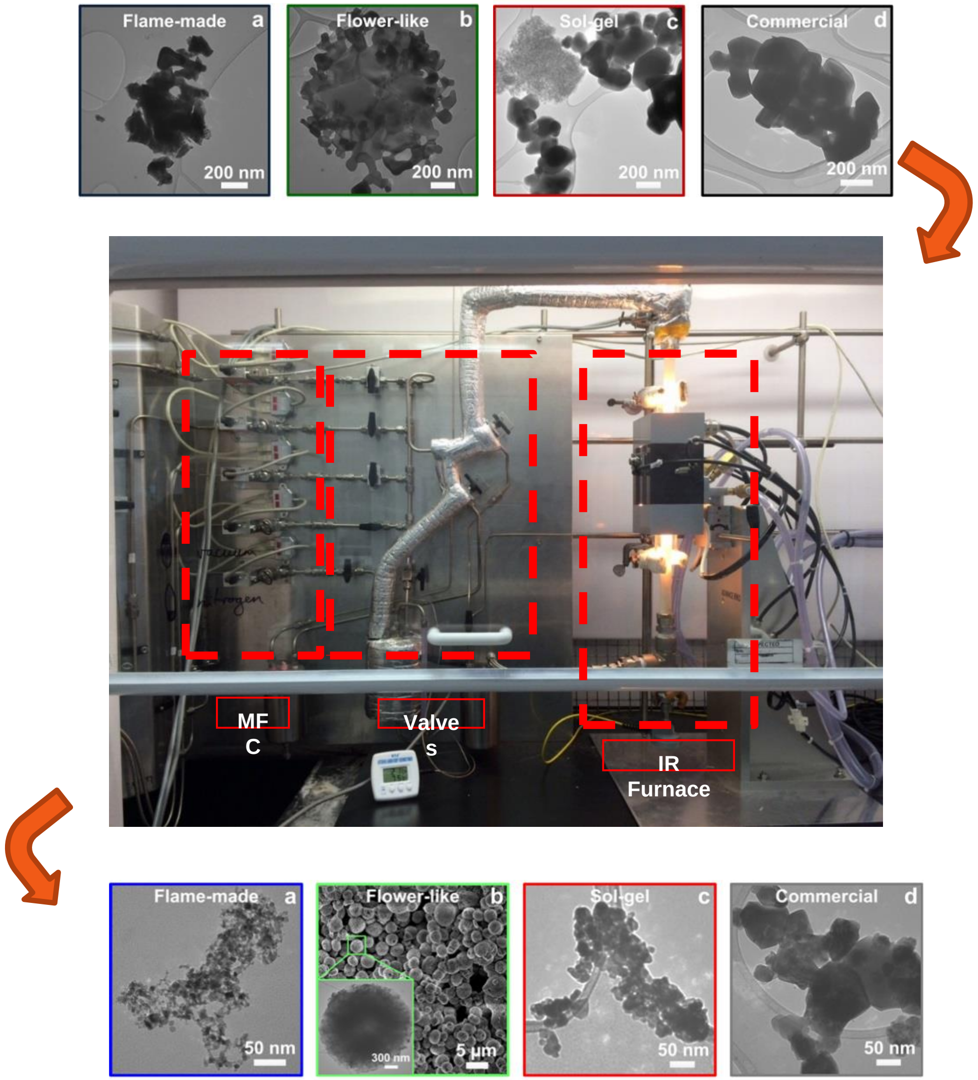
- Through novel nano-structured metal oxides
  - Efficient redox material with improved $\delta/\Delta T/P_{O2}$

Novel reactor development:

- Reduce radiation losses
- Increase heat recovery

Future research activities:

- Further development of Red-Ox materials
- Testing of reactor with Red-Ox materials
- Planning toward pilot-scale testing



Reactor & particles

Technology development: Advanced Sabatier (UA/Flinders)

Complements international R&D:

- Demonstrated use of novel metal cluster catalysts deposited on titania (TiO_2)
  - ➢ Very efficient use of every metal atom

Reactor development:

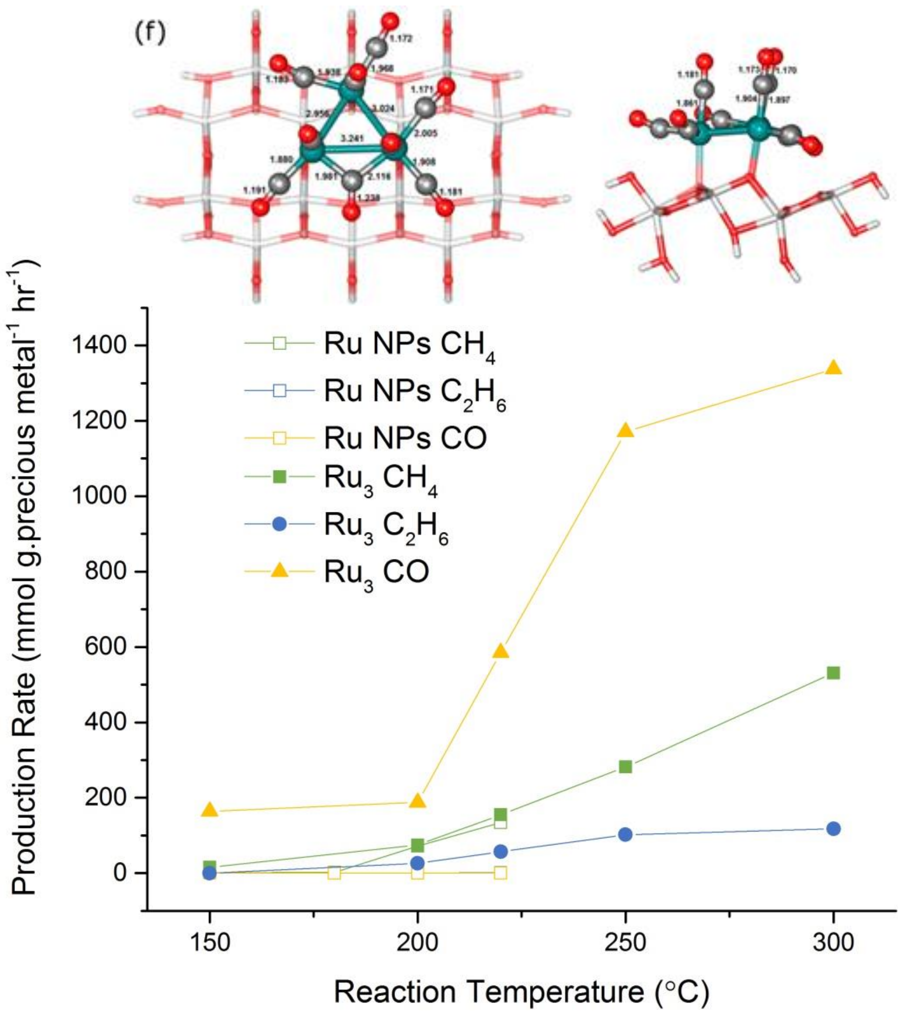
- Small cell volume reactors
- Batch and continuous flow

Calculations:

- Cluster allows for exact calculations
- Identified energy of ligand removal

Future research activities:

- Further testing of other clusters
- Reactivity calculations
- Optimising for longer hydrocarbons



Ru_3 cluster vs RuNPs on anatase, rxn at 250 °C

Concluding comments (1)

- **Sustainable liquid fuels: Important component of Australia's future energy mix (& global)**
  - Vital in air-transport, important in heavy freight, agriculture, mining, hybrid vehicles
- **ASTRI has established a common-platform for comparing different technology pathways**
  - Identified technologies with realistic potential for $0.8/L < LCOE < $1.4/L
  - Plan to broaden framework into common international platform
- **CST expected to play a vital role in the lowest cost path to sustainable fuels**
  - **Biomass co-products:** CST increases output by ~ 30-40% of lowest cost, limited resource
  - **Algal feed-stock:** CST expected to lower cost of "Gen III bio-fuels" to form "bio-solar-fuels"
  - **CO_2 feed-stock:** CST offers plausible path to CO_2 regeneration, which may be necessary
- **ASTRI is driving low-cost technology development for each core feed-stock**
  - Solar hybridised DFB gasification: Novel platform with low technical risk, suits biomass co-products
  - Solar super-critical gasification: Well suited to wet feed-stock (micro-algae) – novel path to lower cost
  - CO_2 Regeneration: Targeting novel materials and reactors to lower the cost in the longer-term

Future plans

- **Expand international partnerships to better coordinate efforts**
  - Expand common platform to allow cross comparison of different feed-stocks and technologies
  - Explore benefit of complementary components in a system
- **Expand industry partnership**
  - End-users, including agricultural and mining sectors
  - Technology providers, including CST, feed-stock providers, fuels processors
- **Drive high value technology options through scale-up and development**
  - Access international facilities for scale-up
  - Using international partnerships to attract additional resources

Acknowledgements

The Australian Solar Thermal Research Initiative (ASTRI) Program is supported by the Australian Government through the Australian Renewable Energy Agency (ARENA).

Thank you

Market Barriers

- **Higher capital cost of syngas processing plant**
  - Cost depends on solar reactor performance
  - Costs sensitive to intermittent operation
  - Economics challenging to estimate
- **Solar fuels reactors are pre-commercial**
  - Reactor design sensitive to feed-stock
- **Need a path-way to market**
  - Establish with high value, niche products
  - Develop capacity for long-term feed-stock

Source: CSIRO.au