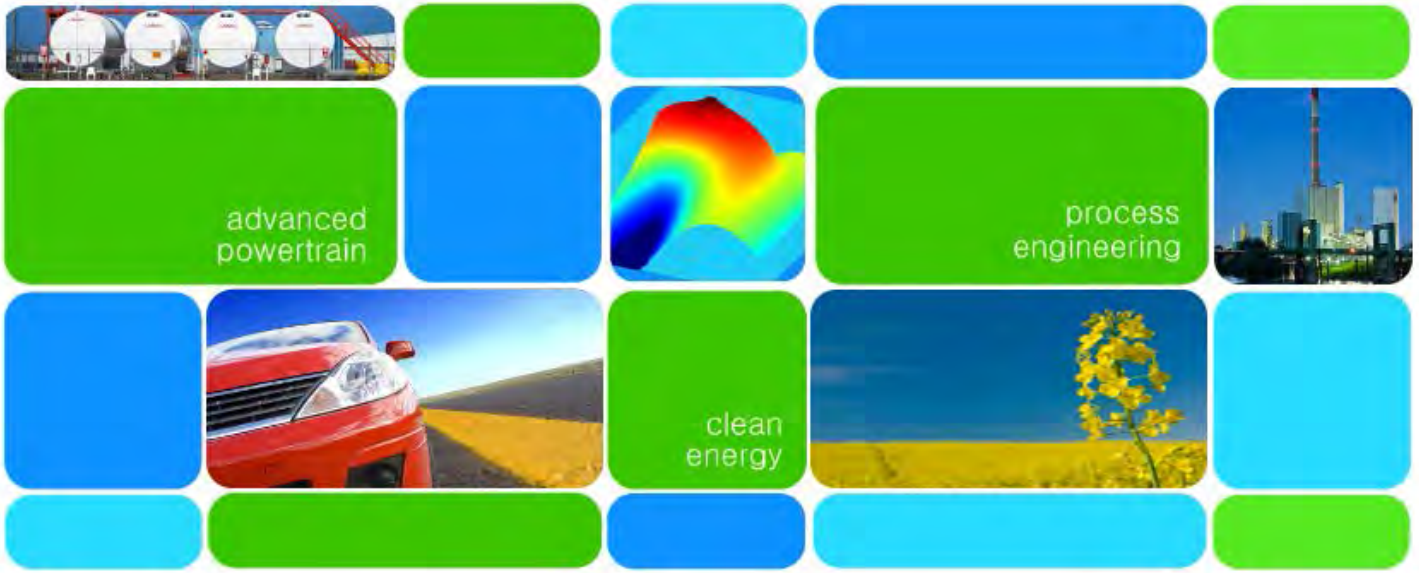

Techno-economic assessment and global sensitivity analysis for biomass-based CO_2 capture storage and utilisation (CCSU) technologies

Maria Botero, Peter Man, Andrew Smallbone & Amit Bhave

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MoDS

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SAE Industry Innovator 2010

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Biomass based CCS and CCU

IPCC WGIII, IEA, ZEP reports and roadmaps in the last 3-4 years:

- Unprecedented emphasis on development and deployment of technologies with **negative CO_2 footprint**
- Dearth of data and detailed analyses of such technologies

- Project **TESBiC**:
  - Biomass to Power with CCS (Biopower CCS)
  - Rapid and large carbon-negative

- Project **C-FAST**: Fuels and chemicals from biomass based CCU

- **Approach:** Process engineering combined with machine learning algorithms
  - Process engineering: PFDs, mass and energy balances, CAPEX, OPEX, costs of CO_2 captured estimation
  - Machine learning: Data-driven surrogates, uncertainty analysis, process optimisation

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MoDS: model development suite

MODS is a unique software tool which can be “wrapped around” any process, system or software, enabling:

(a) Rapid multi-objective optimisation of processes, systems, technologies

(b) The generation of surrogate (fast response) models derived from more complex systems/processes. e.g. Polynomial fits, High dimensional model representation (HDMR)

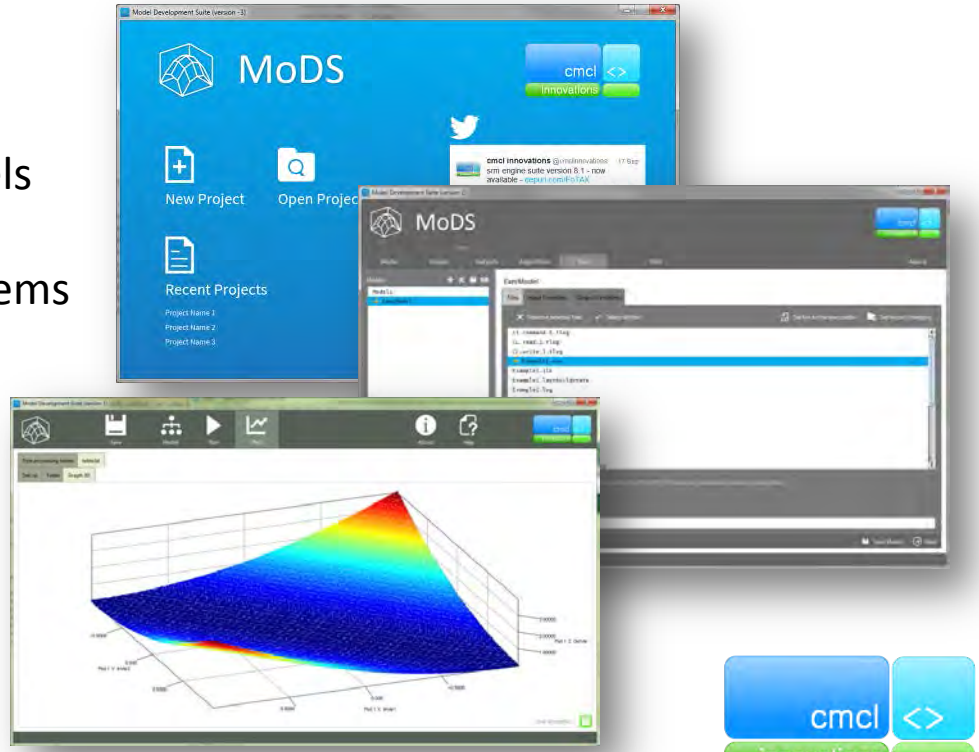
(c) Data-driven modelling

(d) Global parameter estimation for all models

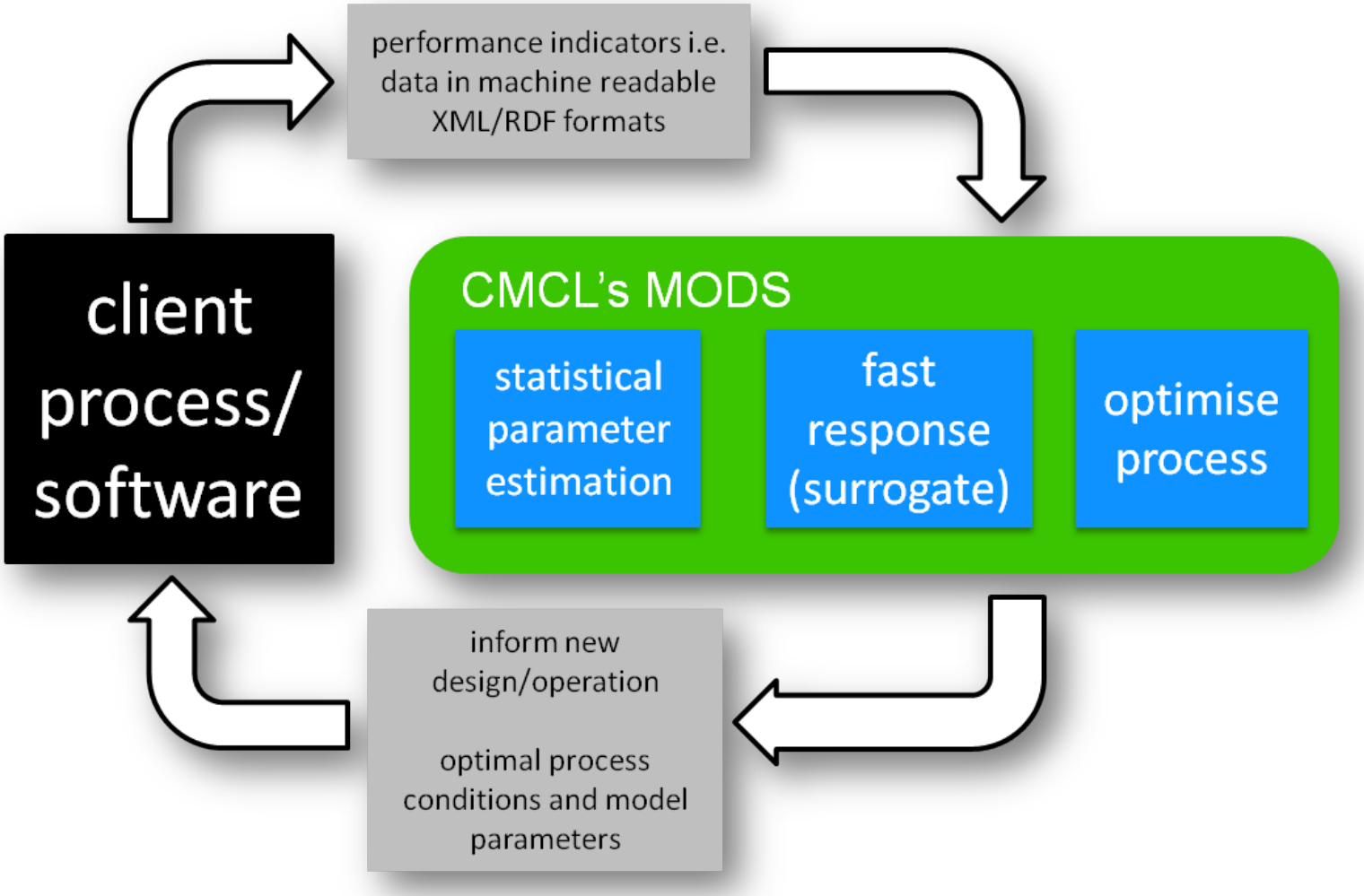
(e) Uncertainty propagation throughout systems

(f) Global and local sensitivity analysis

(g) Intelligent design of experiments



model development suite (MoDS)



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Application 1 – Biopower CCS analysis approach

Dedicated biomass
Chemical looping combustion

Landscape review

Screening 28→ 8

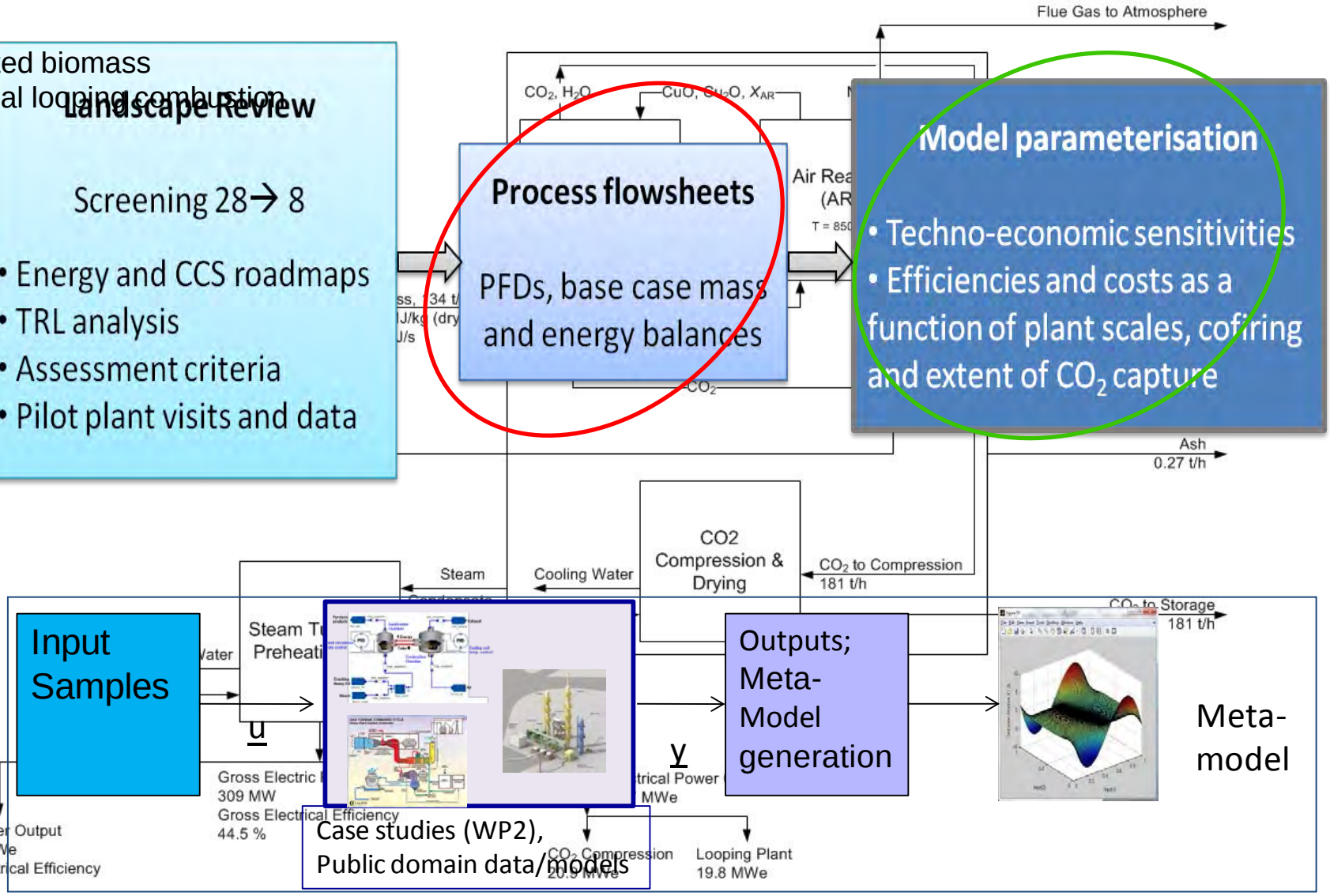
- Energy and CCS roadmaps
- TRL analysis
- Assessment criteria
- Pilot plant visits and data

Process flowsheets

PFDs, base case mass and energy balances

Model parameterisation

- Techno-economic sensitivities
- Efficiencies and costs as a function of plant scales, co-firing and extent of CO_2 capture



BioPower CCS technology landscape

		Post-combustion						Oxy-combustion			Pre-combustion				
		Solvent scrubbing, e.g. MEA, chilled ammonia	Low-temp solid sorbents, e.g. supported amines	Ionic liquids	Enzymes	Membrane separation of CO_2 from flue gas	High-temp solid sorbents, e.g. carbonate looping	Oxy-fuel boiler with cryogenic O2 separation	Oxy-fuel boiler with membrane O2 separation	Chemical-looping-combustion using solid oxygen carriers	IGCC with physical absorption e.g. Rectisol, Selexol	Membrane separation of H_2 from synthesis gases	Membrane production of syngas	Sorbent enhanced reforming using carbonate looping	ZECA concept
Coal IGCC gasification	Direct cofiring Conversion to 100% biomass	Not feasible						Not feasible			15	17	19	21	23
Pulverised coal combustion	Direct cofiring Conversion to 100% biomass	1	3	5	5a	7	9	11	11a	13	Not feasible				
Dedicated biomass combustion	Fixed grate Bubbling fluidised bed Circulating fluidised bed	2	4	6	6a	8	10	12	12a	14					
Dedicated biomass gasification	Bubbling fluidised bed Circulating fluidised bed Dual fluidised bed Entrained flow	Not feasible						Not feasible			16	18	20	22	24

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BioPower CCS – screening for 2050 deployment

Criteria	Co-firing amine scrubbing	Dedicated biomass with amine scrubbing	Co-firing oxy-fuel	Dedicated biomass oxy-fuel	Co-firing carbonate looping	Dedicated biomass chemical looping	Co-firing IGCC	Dedicated biomass BIGCC
Likely TRL in 2020	7 to 8	6 to 7	7	6	5 to 6	5 to 6	7	5 to 6
Key technical issues	Scale-up, amine degradation,	Scale-up, amine degradation,	O_2 energy costs, slow response	O_2 energy costs, slow response	Calciner firing, solid degradation, large purge of CaO	Loss in activity, reaction rates, dual bed operation	Complex operation, slow response, tar cleaning, retrofit impractical	Complex operation, slow response, tar cleaning, retrofit impractical
Suitability for small scale	Low	High	Low	High	Low	High	Low	High
Plant efficiency with capture	OK	Low	OK	Low	Good	Good	High,	Good
Capital costs with capture	OK	Expensive	OK	High ASU costs	OK	OK	OK	Expensive,
UK deployment potential	Immediate capture retrofit opportunities ,	retrofit opportunities high long-term potential	retrofit opportunities , long-term doubtful	retrofit opportunities , high long-term potential	capture retrofit opportunities, cement integration	Likely first demos in Europe, UK in ~2020. High long term potential	No current UK plants, several demos by 2020 Long-term doubt	No current UK plants, demo unlikely by 2020. High long-term potential

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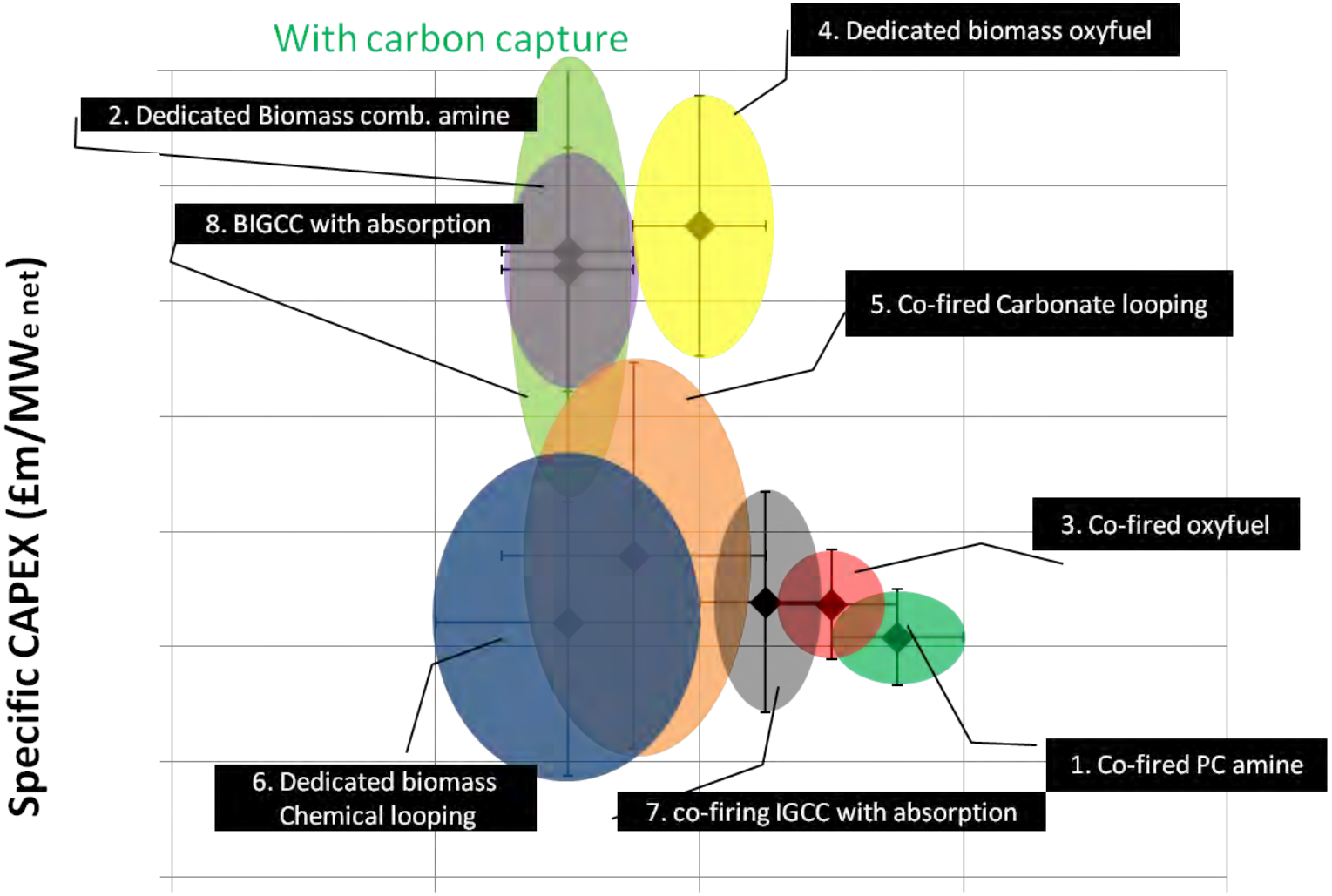
Process engineering calculations at base scales



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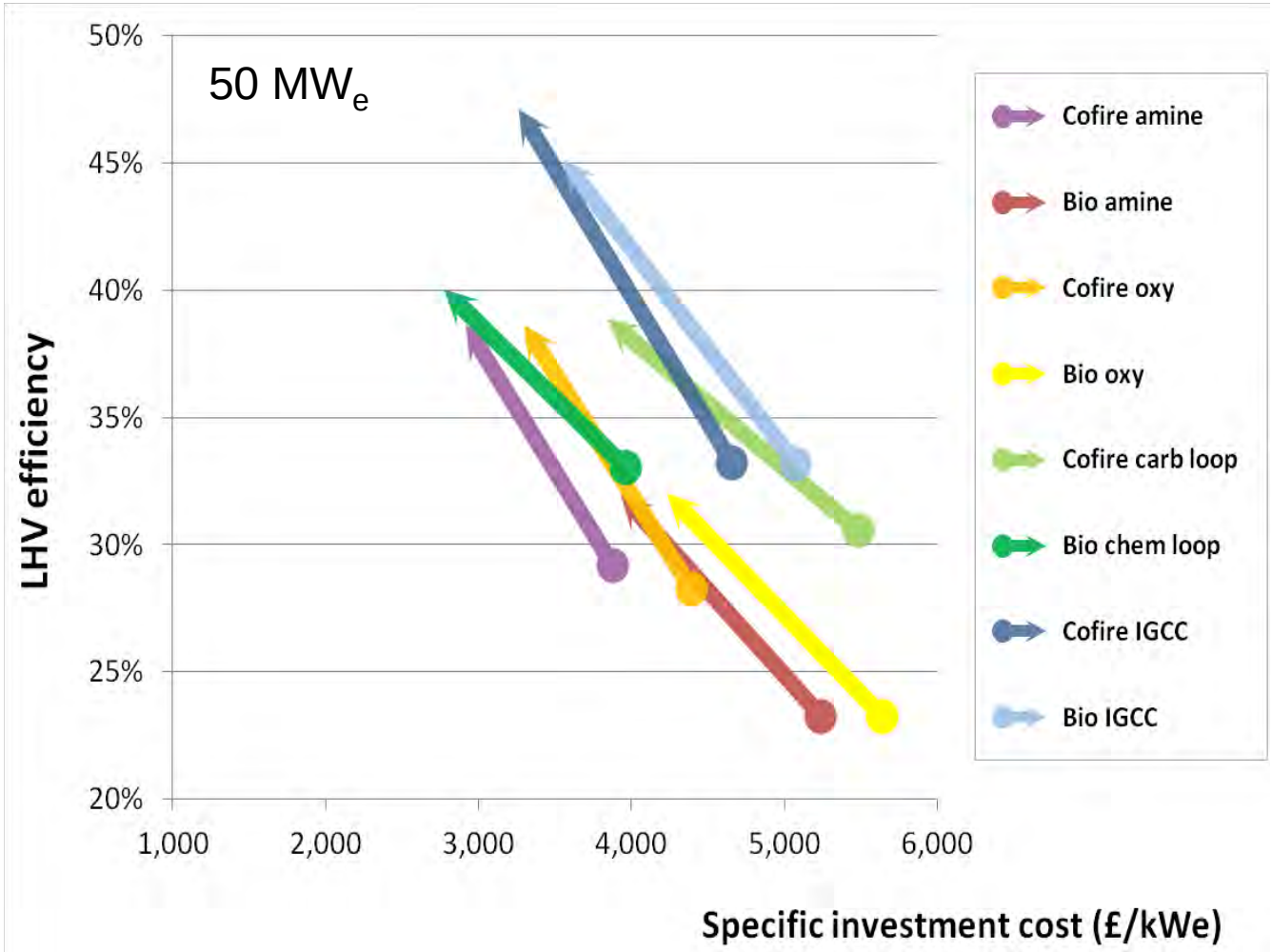
Bayesian parameter estimation

Plant-wide techno-economic model parameter estimation: CAPEX, OPEX, LHV efficiency and emissions as a function of scale, co-firing and extent of capture



Application – 1: summary–i

- To date**, little activity at industrial scale** on the application of CO_2 capture technologies to co-fired or dedicated biomass power plants. This dearth of practical data increases the complexity and uncertainties associated with the estimation and roadmapping of biomass CCS technologies.

- The industry's progression to the large fossil-based CCS demonstration projects is slow due to **high costs** and **requirement of significant government subsidies.**

- **Dependency on fossil based CCS:** Recent setbacks and cancellations of the coal-based CCS projects will further delay the development of biomass CCS. This, however, also presents **an opportunity for lower TRL** biomass CCS technologies.

- **Incentivising negative CO_2** emissions via the capture and storage of biogenic CO_2 under the EU emissions trading scheme (ETS) is highly important.

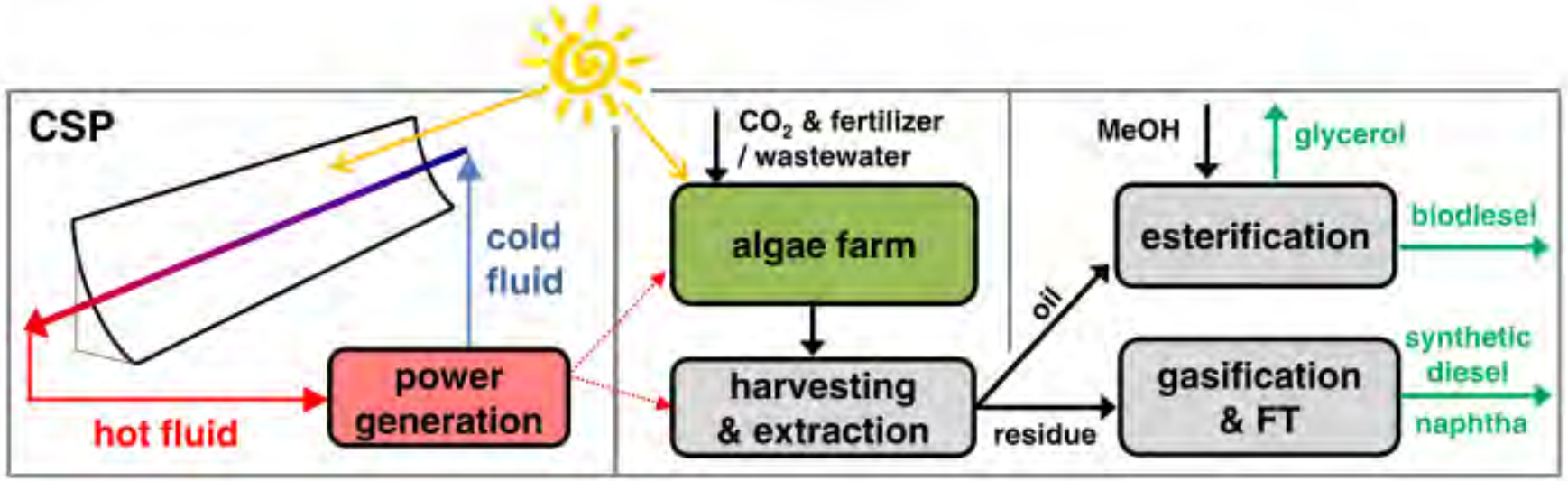
Application – 1: summary–ii

- Biomass CCS attractive for small (50 MW_e), intermediate (250 MW_e) and large (~600 MW_e) scales. At large scales, the issue of "sustainable biomass procurement" also needs careful consideration.

- For the eight biomass-based power generation combined with carbon capture technologies varying over a wide range of TRLs, from **TRL 3 to TRL 8,** the range of **techno-economic parameters** are the following:
    - ~ 5% to 15% : Range of the efficiency drop
    - ~ 45% to 130%: Range of the increase in specific CAPEX (£/MW_e) with CO_2 capture
    - ~ 4% to 36%: Range of increase in OPEX (£/yr) with carbon capture

- CAPEX, LCOE: Generation scales and fuel costs the main drivers

Application 2: C-FAST biorefinery



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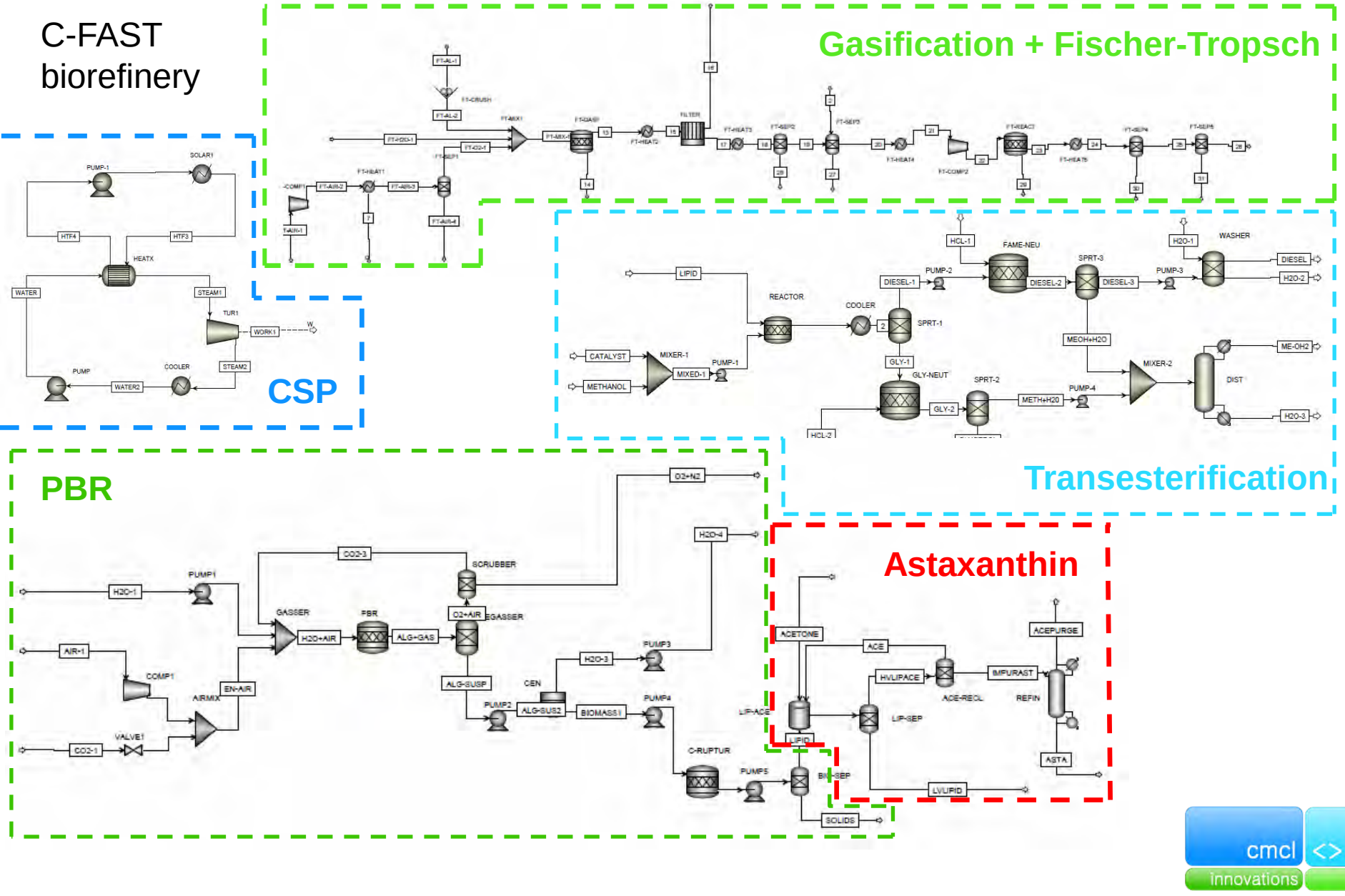
Application 2: C-FAST process engineering

C-FAST biorefinery

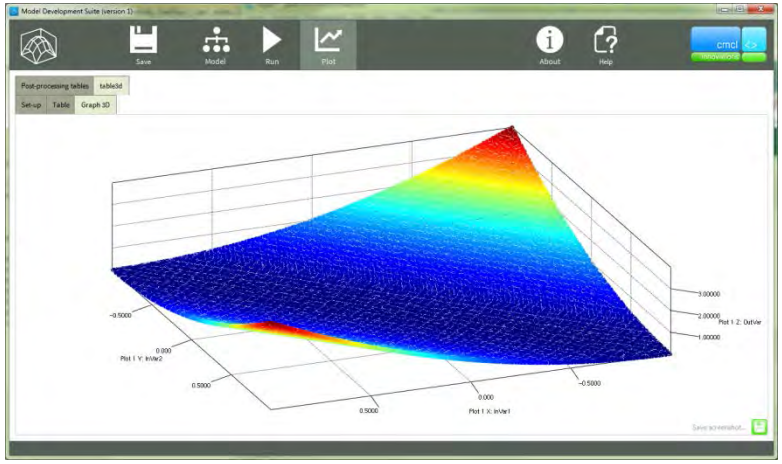


Surrogate models and sensitivity

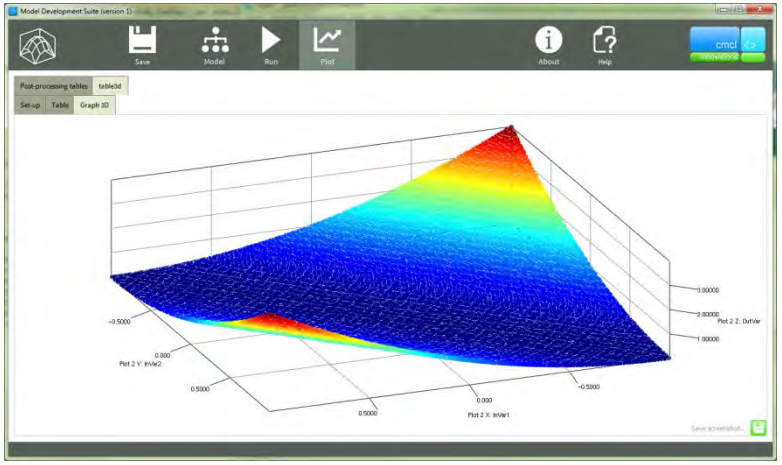
HDMR: High Dimensional Model Representation

Surrogate model that offers global and local sensitivities

Influence of process parameters on the variance of the output



True function $f(x,y) = x^2 + 2xy + y^2$



HDMR surrogate results

R-square value = 0.999978

f_1 sensitivity = 0.0837123

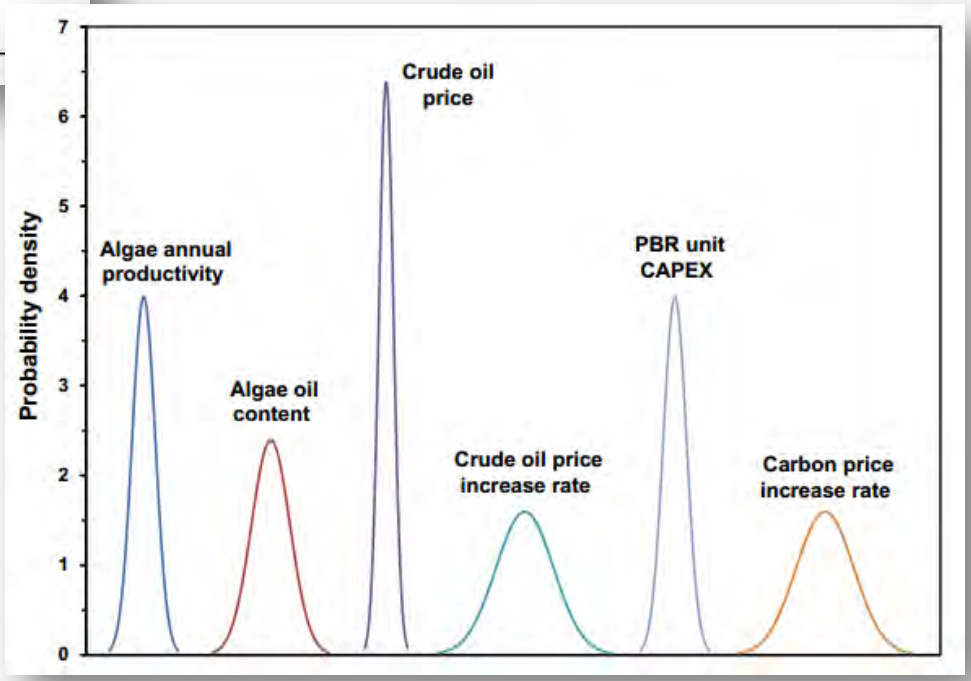
f_2 sensitivity = 0.0837129

f_{12} sensitivity = 0.832575

Uncertainty: process conditions

Parameter	Lower bound	Upper bound	Unit
Production capacity	1,000	100,000	tonne/year
Algae productivity	80	120	tonne/ha/year
Algae oil content	20	40	wt%
Crude oil price	0.53	0.68	£/kg
Carbon price	0.013	0.028	£/kg
Fertiliser price	0.47	0.57	£/kg
Crude oil price increase rate	1	3	%/year
Carbon price increase	0.003	0.009	£/kg/year
Fertiliser price increase	1	3	%/year
CAPEX	-10	+10	%

- e.g., Fluctuations in the algal production capacity (tonne/ha) on outputs (biodiesel production, ROI)



MoDS accounts for uncertainty in data propagating through to the **plant** and **unit operation** models

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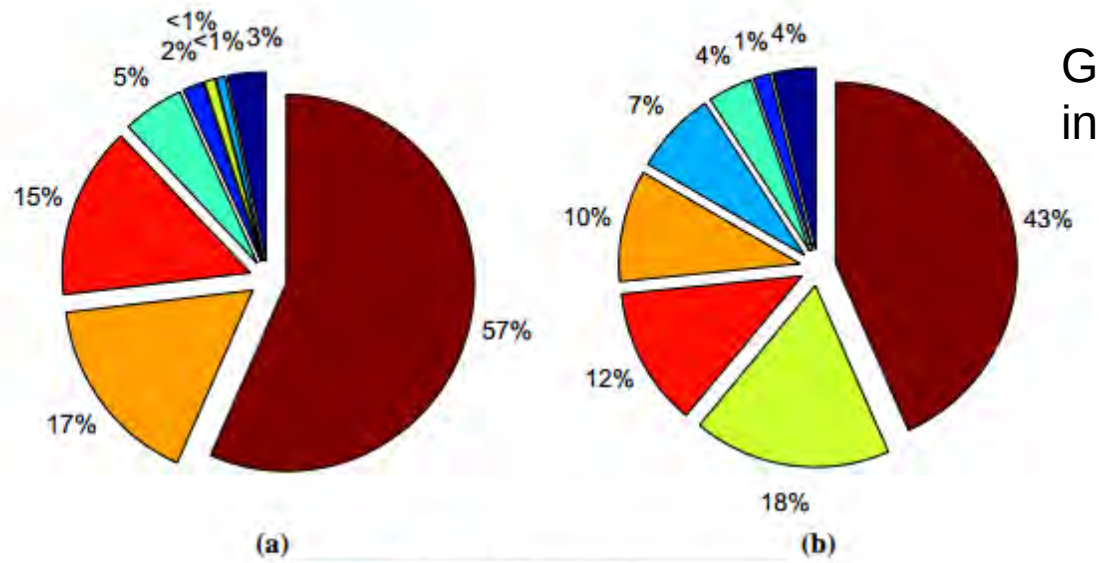
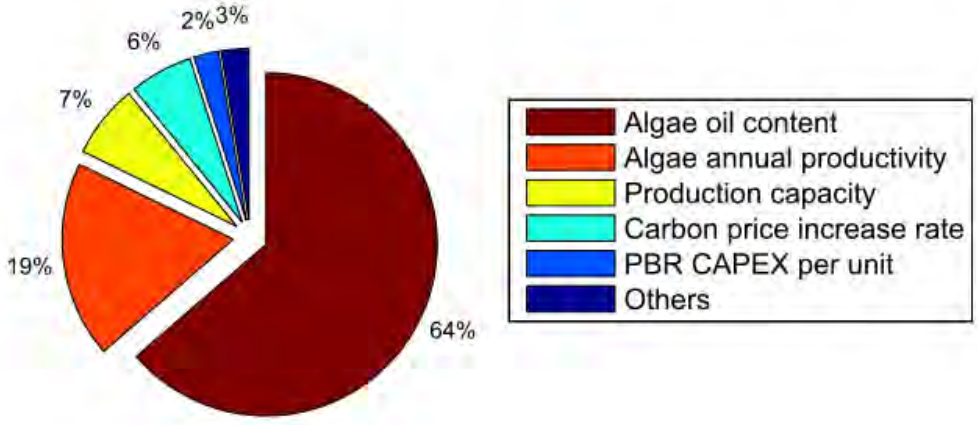
Surrogate-driven sensitivities



Global sensitivity of ROI to inputs, (a) 5 and (b) 30 years



Global sensitivity of algal diesel production cost

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Application – 2: Summary

1. Global sensitivities take into account the input parameter variation range

2. Sensitivity of the production cost of algal-derived Diesel decreases in the following order:
   algal oil content
   > algal specific annual productivity
   > plant capcity
   > Carbon price increase rate
   > PBR unit CAPEX

3. Crude oil and carbon price increase rates influence long term ROI substantially, as compared to the negligible impact on short-term ROI.

4. Plant solely producing algal biodiesel not commercially feasible; needs supplementary revenue from producing additional value-added products.

Application 3: ACUTEC project: work–in–progress

- **ACUTEC**: Assessing CO_2 utilisation technologies in the European Context

- **Objective 1 - CCU TRL review and model formulation:**
- To develop and validate process flow models for the five (**Methanol, urea, formic acid, polyurethanes, and mineralisation**) CO_2 utilisation options
- To analyse operational, cost and environmental performance parameters including the identification of bottlenecks for technology scale-up.

- **Objective 2 – CCU product pricing, demand and impact:**
- To analyse current and future (up to 2030) estimates for prices, demand and corresponding elasticities for the CCU products and
- To assess the impact of CCU deployment on the current and future market penetration and the EU energy system.

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