FINAL EVENT

NEXTGEN roadfuels

Turning Waste into Fuels: The Results

Amsterdam & Online
4 October 2022
13:30 – 18:00 CEST

Presenting innovations and solutions in the development of HTL, an efficient route to produce high-volume, cost-competitive, drop-in synthetic gasoline and diesel fuels

This project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No 818413

Event Opening & Project Overview

L. Rosendahl, AAU

AALBORG UNIVERSITY

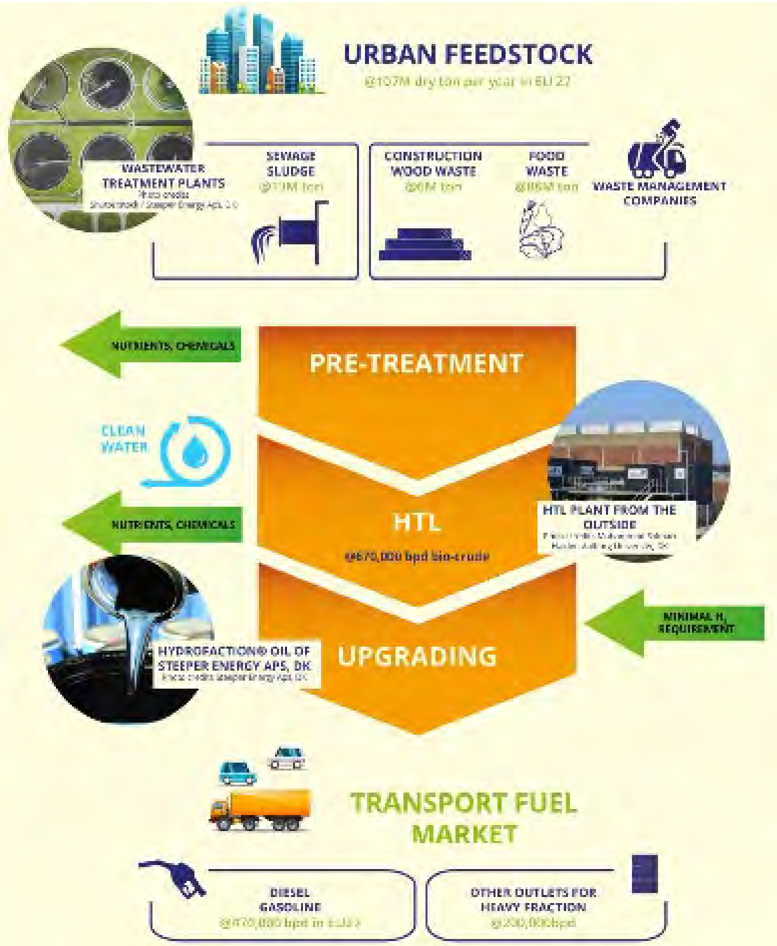
Final Event Agenda

Time	Topic	Affiliation	Presenter
13:30	Event opening and project overview	AAU	L. Rosendahl
13:50	Improving the HTL-value chain from the start: Pre-treatment & wastewater management.	AAU, CENER, KIT	I. Alegría J. Zimmermann
14:10	HTL as core technology for urban waste valorisation - solution for problematic micro plastics.	AAU, CENER, KIT	T. Helmer
14:25	Turning challenging waste-derived biocrude into fuels - Biocrude upgrading - Engine testing results	CERTH, TUM STEEPER, AAU	E. Heracleous K. Rodriguez K. Kohansal
15:00	Related projects: Pacific Northwest National Laboratory – Advancing HTL Technologies Aalborg University - Low Carb Fuels Project: Continuous Hydroprocessing of Nitrogen-rich Biocrudes: Challenges and Achievements. University of Amsterdam - Chemical recycling of waste plastics by HTL	 PNNL AAU UVA	 H. Wang S. Haider S. Raveendran
15:40	Break		
16:00	Market scenarios and commercialization pathway. Minimum selling price. Financial Model – Results & Recommendations. Environmental Impact (LCA).	GoodFuels Steeper SINTEF Steeper CENER	F. Ferrari Ling Li G. Alamo Serrano A. Grenon E. Medina Martos
17:00	Panel discussion – The future of HTL produced biofuels.	Chair: Thomas Helmer, Aalborg University Panel: Lasse Rosendahl, Aalborg University Steen Iversen, Steeper Jostein Gabrielsen, TOPSOE Daniele Bianchi, ENI Johannes Schürmann, Good Fuels Joey van Elswijk, Port of Amsterdam	
17:30	Networking		
18:00	Event close		

NextGenRoadFuels – an (historic) overview …

5 MEUR, 2018-2022 (48 months)

NextGenRoadFuels concept & overall focus



1 **New strategies for collecting and pre-treating urban residues**, building on existing logistics infrastructure while providing a higher added value through HTL processing

2 An **integrated approach along the entire value chain** (at lab- and pilot-scale), to allow in-depth understanding and optimization of process parameters in a holistic approach

3 Different combinations of **pre-treatment, HTL processing, upgrading and integration**

4 Process simulations and associated **techno-economic assessments** to define future industrial-scale implementation for an increased biofuels production capacity

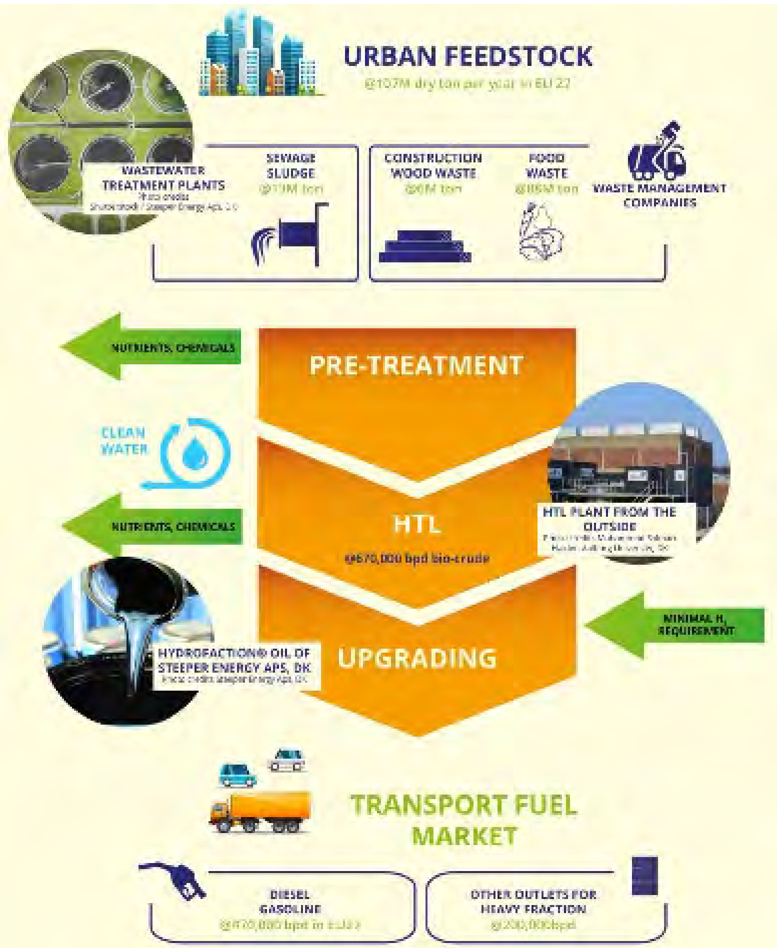
5 **Environmental and sustainability impacts** of the process

6 **Efficient business strategies** for the successful implementation and replication of developed value chains at European/global level

7 **Full risk management strategy** by considering all aspects (technology, economic, business, etc.) to ensure future implementation

8 Promotion of **knowledge-sharing** on HTL pathway and renewable fuels production amongst stakeholders, media and citizens.

NextGenRoadFuels concept & overall focus



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The overall objectives

ECONOMIC

- Potential for direct replacement of **12% fossil fuels** in the EU transport sector
- Production of HTL derived gasoline and diesel fuels cost-competitive with current crude oil prices
- Potential of **more than 1 Billion Euro** per year of direct revenues of biofuels from urban resources
- Enhanced the competitiveness of sector-related industries
- Efficient urban resource management and valorisation

ENVIRONMENTAL

- Valorisation of widely available wastes avoiding their landfilling or incineration.
- Potential of **more than 100 M ton of low-grade degradable feedstock** converted into advanced biofuels
- Enhanced circular economy and recycling of nutrients
- Improvement of the **overall energy efficiency** of biofuel production up to **more than 70%**
- Potential greenhouse gas emission reduction by **75M tons CO_2-eq/year** by replacing fossil fuel, thus contributing to the achievements of the European objectives in terms of GHG emissions reduction

SOCIAL

- Potential of creating **up to 50,000 direct and 300,000 indirect urban job opportunities** for the development, engineering, fabrication, installation and operation of HTL plants
- Increasing **energy security in Europe** by reducing crude oil imports
- Knowledge creation for the scientific community, policy actors, industry and citizens

EU LEADERSHIP

- Leadership in research development and production of **renewable fuels**
- Leadership in **urban resource management valorisation**
- Global opportunities for technology export and licensing for innovative European industries and SMEs

What have we accomplished?

- Investigated possible value-adding pretreatment options
- Operated pilot scale HTL continuously at tonne-scale and for 100s of hours
- Verified that no medicine or microplastic “debris” was present in any effluent stream
- Demonstrated almost complete P recovery
- Established a procedure for turning “raw” HTL biocrude into a hydrotreatable feedstock for refining
- Investigated several approaches to water management
- Hydrotreated HTL biocrude at pilot scale into final fuels for road transport and shipping and investigated novel electrocatalytic pathways
- Created robust and validated high resolution proces data for modelling and TEA
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- Investigated potential first-markets as well as regulatory barriers to implementation

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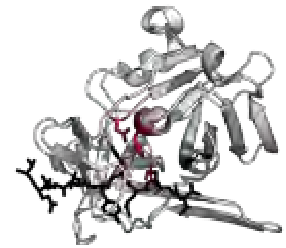
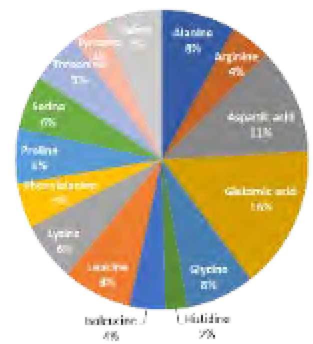


Protease



Yields:
~ 65-70%
Solubilized
Amino acid

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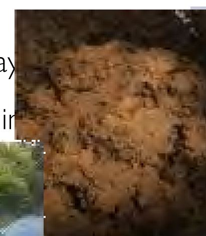

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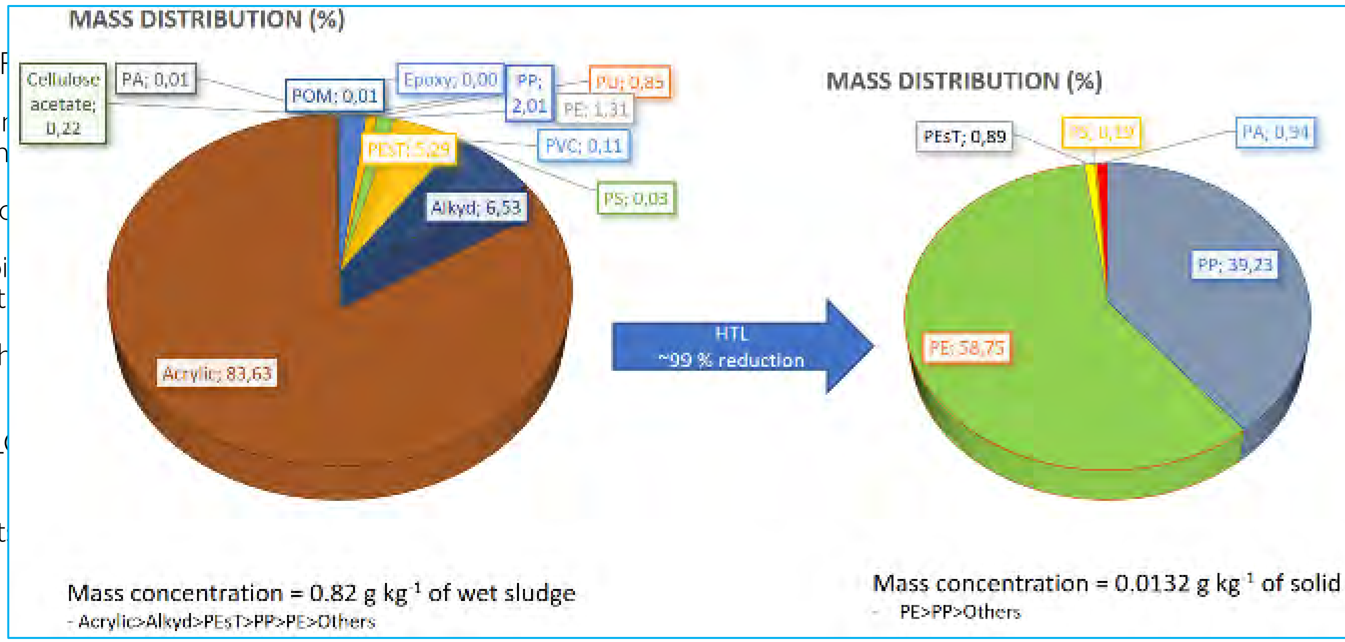
- Investigated potential first-market implementation



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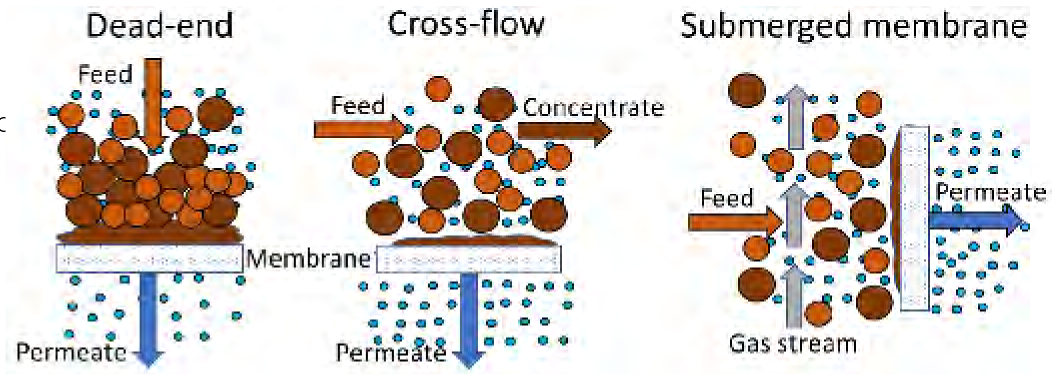

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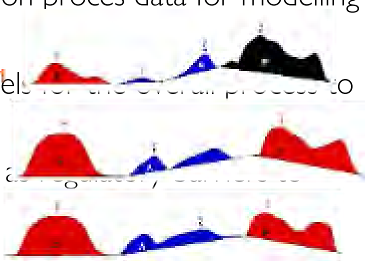
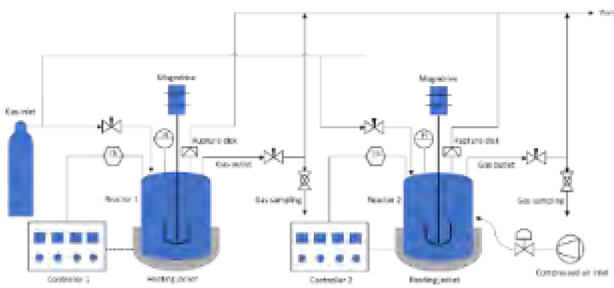
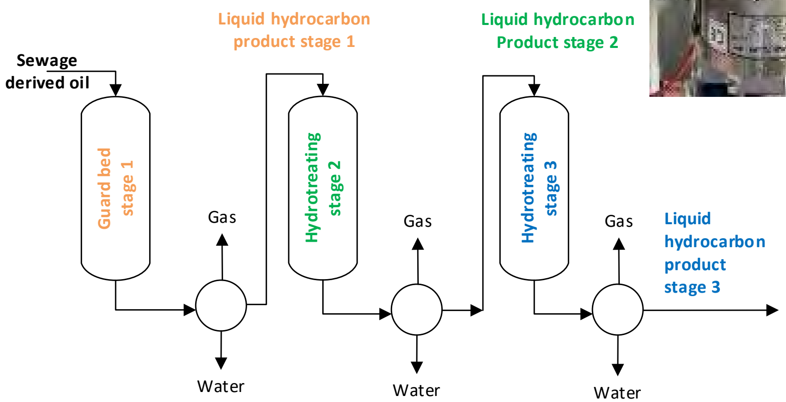




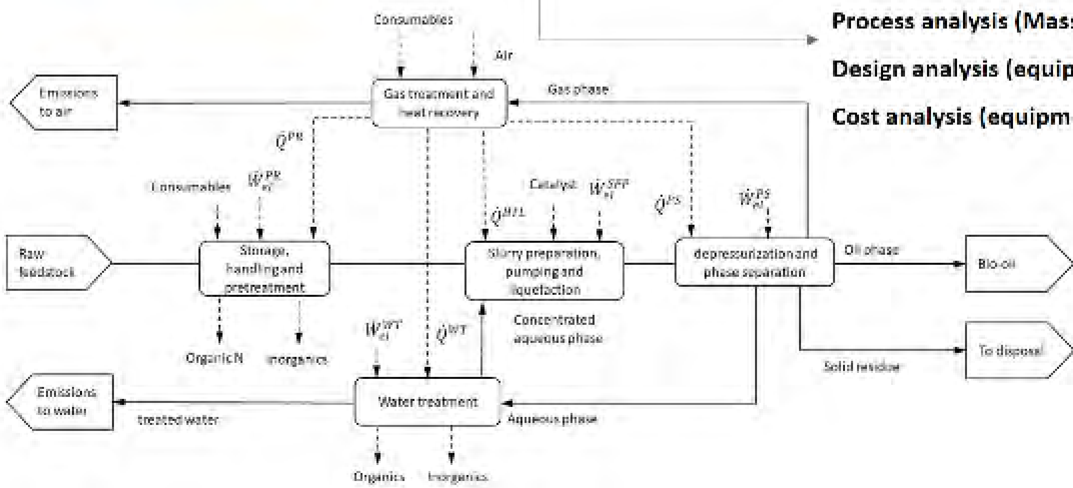


What have we accomplished?

TEA - Methodology

Scale-up models (parametric, uncertainties)

- **Process design - (PBDs / PFDs)**
- **Process analysis (Mass and energy flows, use of experimental results)**
- **Design analysis (equipment specifications)**
- **Cost analysis (equipment installed cost, operating cost)**



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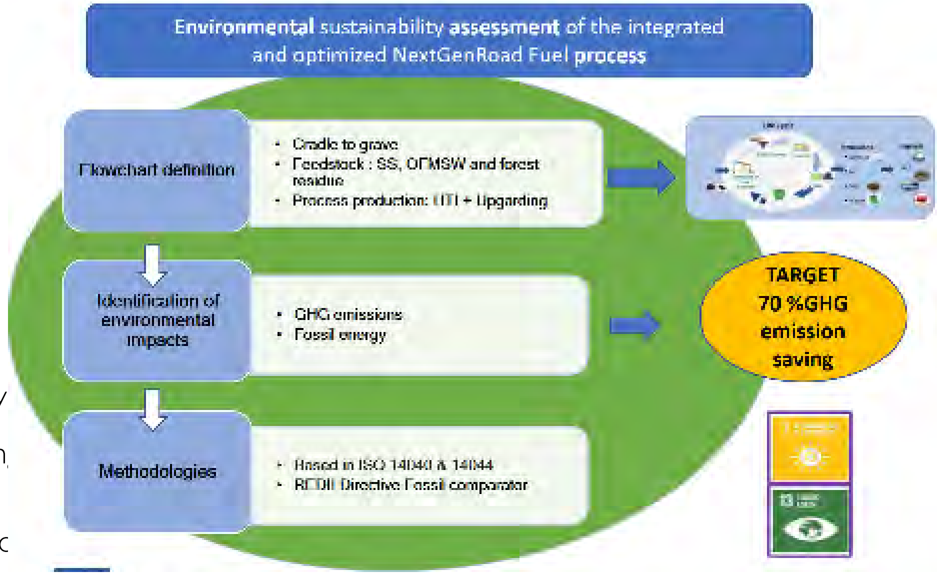

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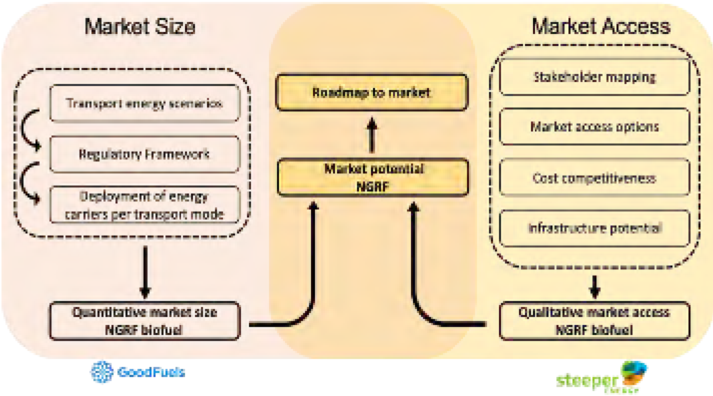
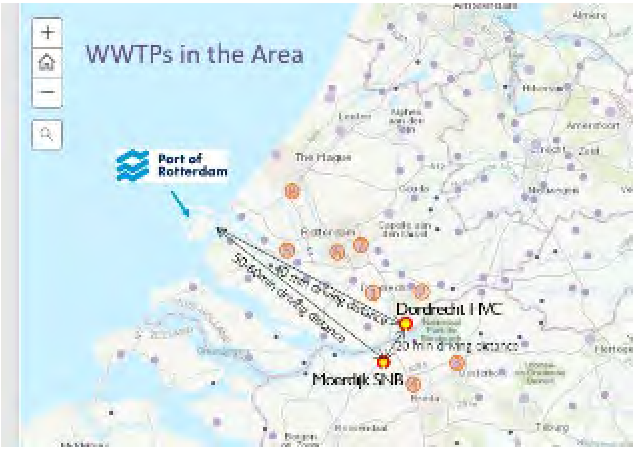




Overall conclusions and results

HTL presents a very attractive technology package for urban waste streams providing

- High energy yield
- Low effluent impact
- High potential for circular use of inorganics

HTL implementation is more than selecting a temperature

- Process design is crucial and must reflect feedstock characteristics

However there are challenges, technical and regulatory

- Phosporous-driven deposits in HTL heating stage poses a problem for continuous operation
  - A workaround could be enzymatic pretreatment
    - Inorganics drastically reduced in HTL feedstocks
    - High carbon loss mitigated by enhanced yield
    - Significantly lower N in biocrude is highly beneficial for hydrotreating into fuels
- Classification of HTL as a disposal technology (low value) rather than an upcycling technology (high value) seriously impacts economics of process

Major results and conclusions

- NextGenRoadFuels has answered several technical, operational and regulatory questions bringing HTL a major step closer to implementation
- NextGenRoadFuels has also identified a number of regulatory barriers to be addressed as well as pointed at new avenues for R&D and optimization of the process
- All in all NextGenRoadFuels has contributed significantly to maturing HTL as a viable technology for urban waste stream utilization, to advance the associated science and to position Europe as no1 in renewables

Improving the HTL-value chain from the start: Pre-treatment & wastewater management

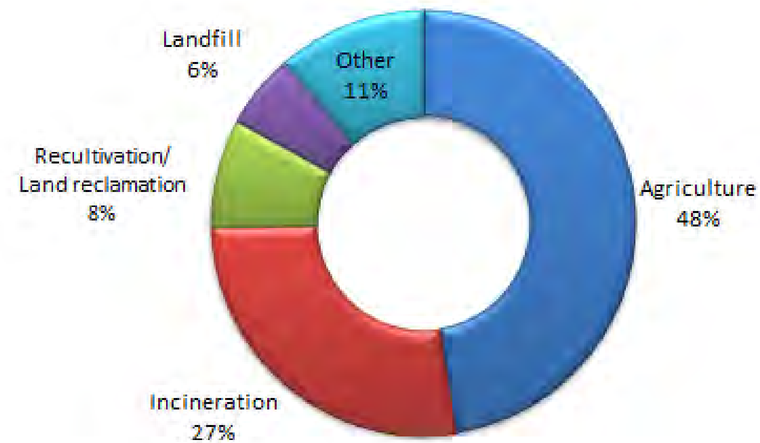
I. Alegría, CENER

J. Zimmermann, KIT

CENER KIT AALBORG UNIVERSITY

Considering that ....

- In Europe (EU-28) **8.7 Mt of dried SS** per year were produced.
- Each one of us generates around 20-25kg of dry solids annually
- What it is used for?



Sewage sludge for biocrude production

Sewage sludge as a feedstock for HTL-biocrude production: the importance of pretreatment

- Different sewage sludge result in different biocrude yields and nitrogen contents (quality)

- Nitrogen is problematic in combustion and need to be removed by upgrading, which can be problematic due to resistant nitrogen compounds.

How to lower nitrogen and inorganic content to improve the HTL-value chain from the start?

Where do the SS come from?

Supply in Denmark:

WWTP of **Aalborg**

- In the form of pellets.
- The content of total solids ≈ 92.46%.
- (large) municipality population of 225,000

Supply in Germany

WWTP of **Karlsruhe:**

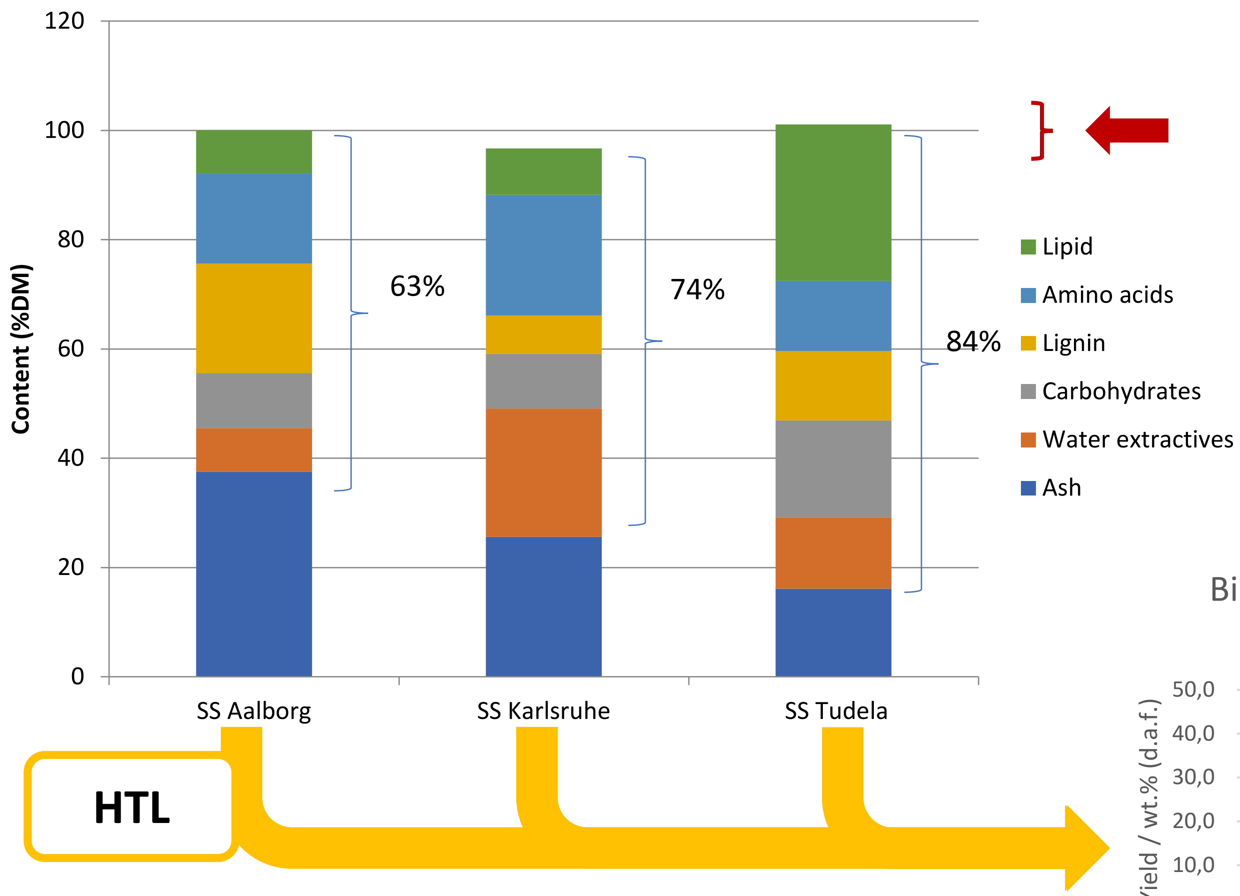
- no AD, primary sludge
- centrifuge to thicken the sludge
- Subsequent incineration of the sludge
- (large) municipality population of 307,750

Supply in SPAIN:

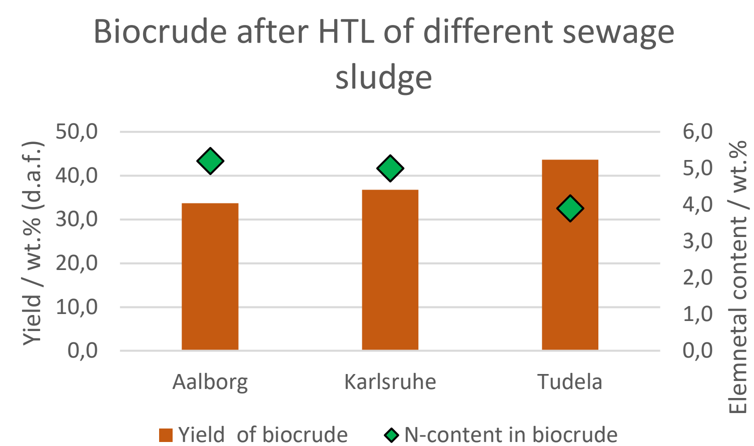
WWTP of **Tudela**:

- trickling filter
- Screw for dewatering;
- (small) municipality population 39,689
- agro food industry

Compositional analysis and the resulting HTL-biocrude_In Summary



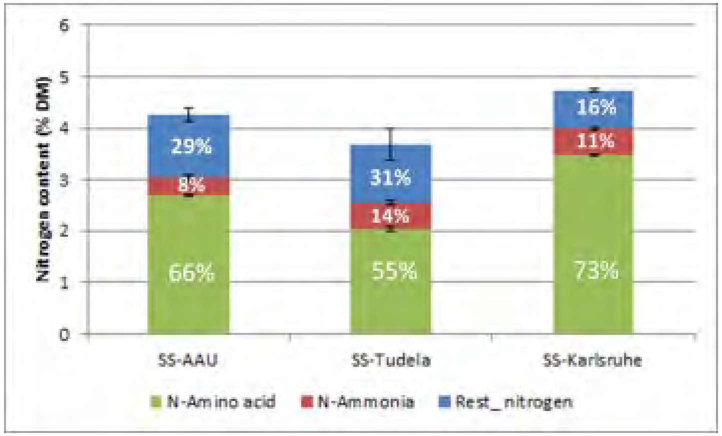
- Mass balance: Adding up these components accounts ~100% by weight
- CH + Lignin + AAC + Lipid + water extractives accounts from 63% up to 84%
- Different sewage sludge result in different biocrude yield and composition



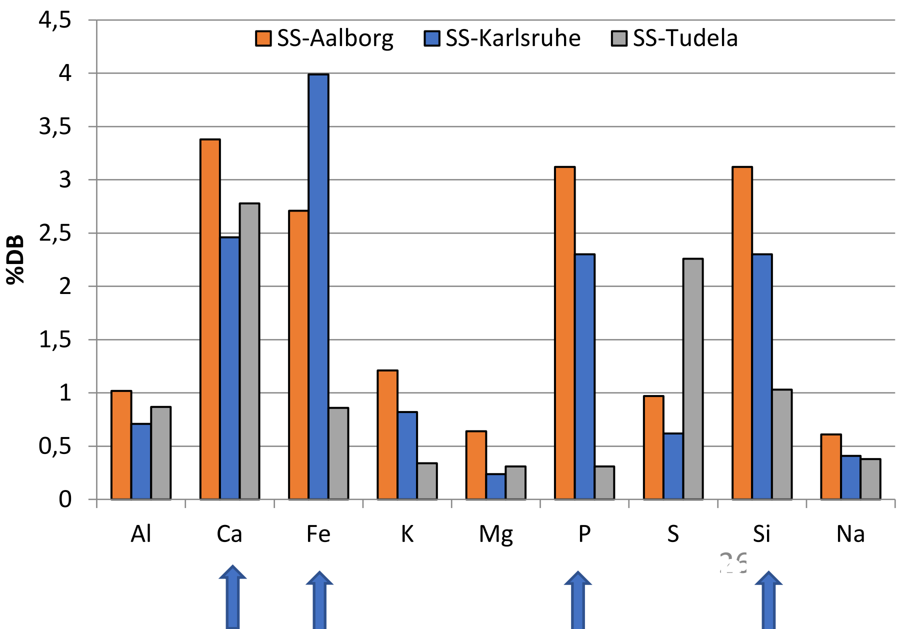
Focusing on composition: What about N and inorganics?

- Total Nitrogen content distribution:
    - N-Amino acid accounts for 73-55%
    - N-ammonia accounts for 8-14%
    - Other N-compounds accounts for 30-16%: i.e. amines, phospholipids, nucleic acids and nitrogenous glycosides, peptidoglycans

The total nitrogen content varies significantly between samples acquired from different WWTP



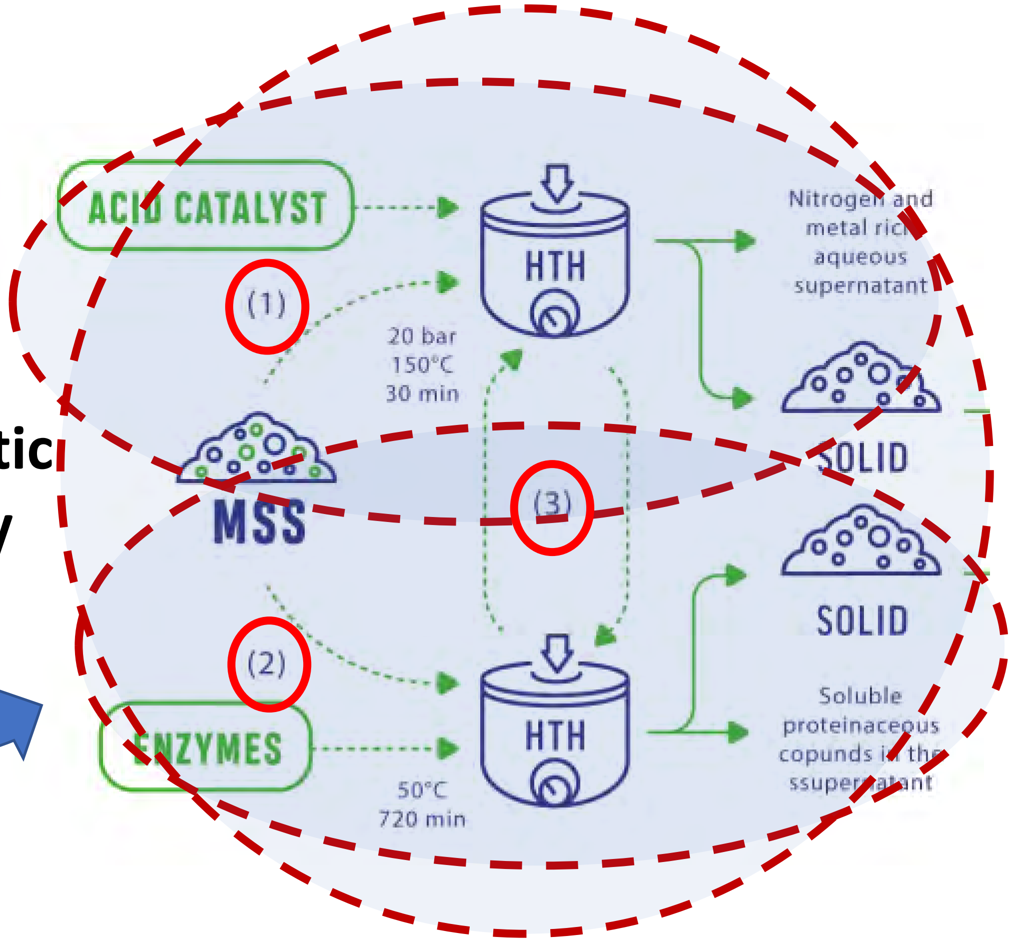
- Inorganics content:
    - Significant differences in ash content and volatile content
    - Importance of Phosphorous and its salts: Calcium apatite
    - Iron vivianite –stengite
    - Silica from sand and minerals



How to lower the nitrogen content in the sludge?

Chemical pathway

Enzymatic pathway



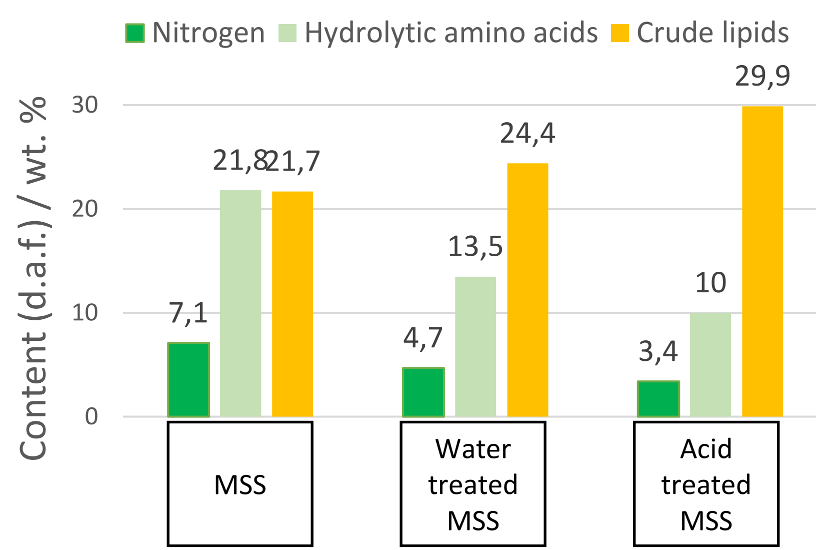
Integration of Enzymatic & chemical pathway

How to lower the nitrogen content in the sludge?

(1) The chemical treatment:

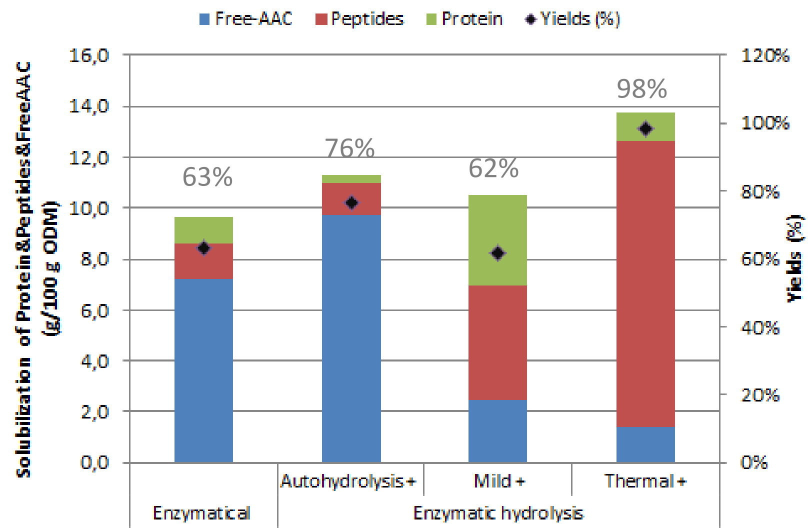
- ➢ enhances the solubilization of more than **70%** of the initial nitrogen fraction
- ➢ changes the biogenic composition of sewage sludge (lipids, carbohydrates proteins)
- ➢ triggers the solubilisation of inorganics, such as calcium, iron, magnesium and phosphorus, **reducing the ash content**.

Composition of raw and pre-treated Sludge



(2) The enzymatic pretreatment:

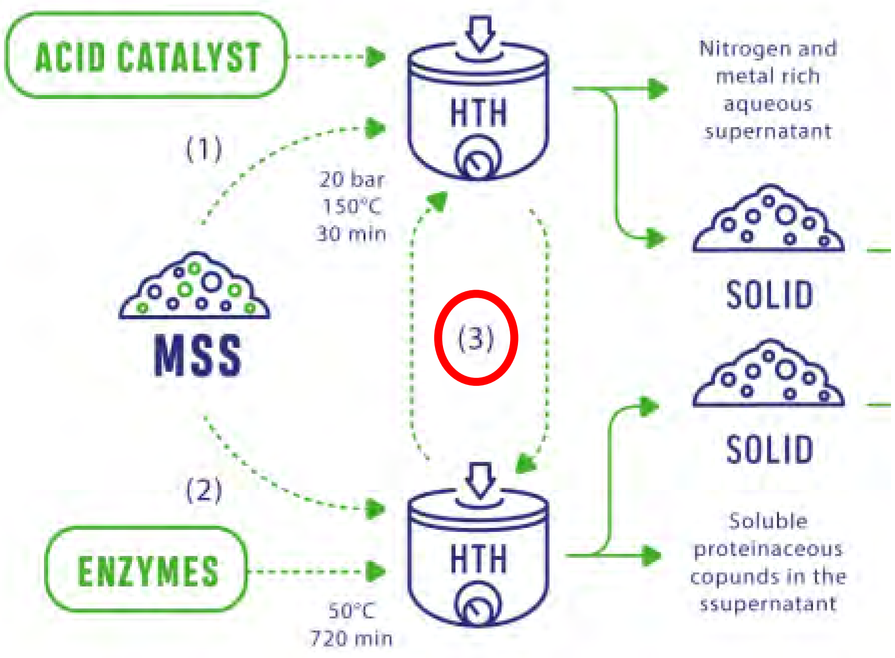
- ➢ Enzymes hydrolyse more than 60% of the proteinaceous fraction, removing more than 70% of the initial Nitrogen content.
- ➢ Mild conditions but it requires longer residence time vs chemical pretreatment
- ➢ The released proteinaceous fraction can be further upgraded

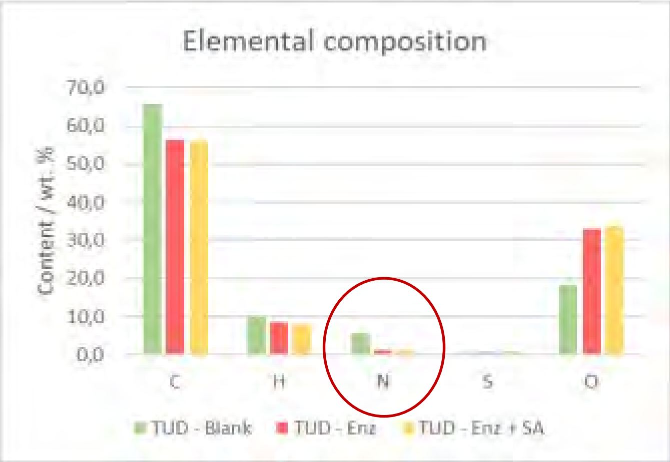


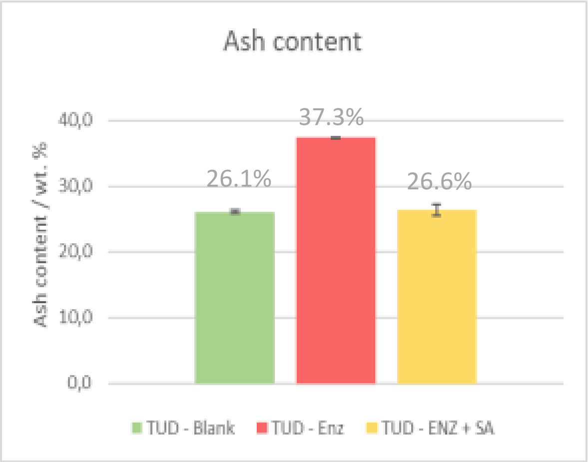
How to lower the nitrogen content in the sludge?

(3) Combination of chemical and biochemical pretreatments :

- The most effective option is to perform first the enzymatic hydrolysis, followed by chemical treatment.
- This combination showed the best performance in terms of nitrogen (↓ 72%) and inorganics removal from SS







Critical issues

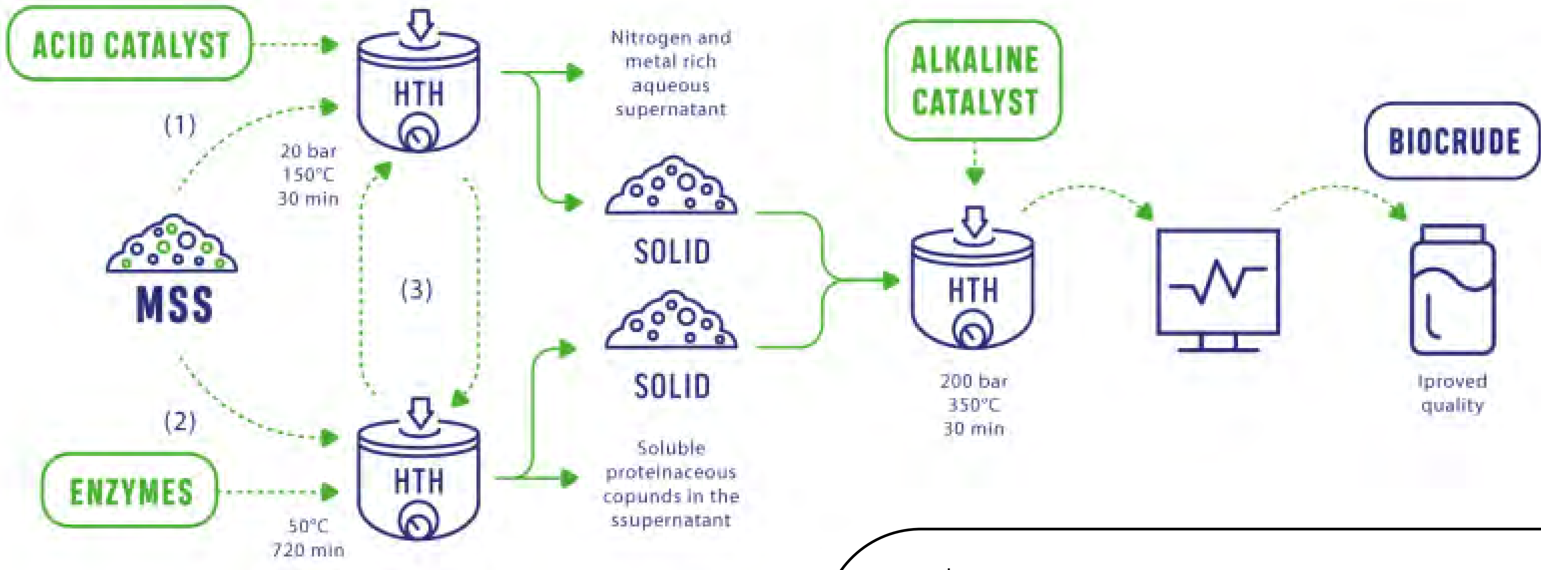
➢ **Carbon loss:**

- Carbon loss is inherent to nitrogen removal: **10-40%,** depending on additive and severity of pre-treatment.
- Production of an additonal wastewater, potential utilization (biostimulant, anerobic digestion)

➢ **Cost:**

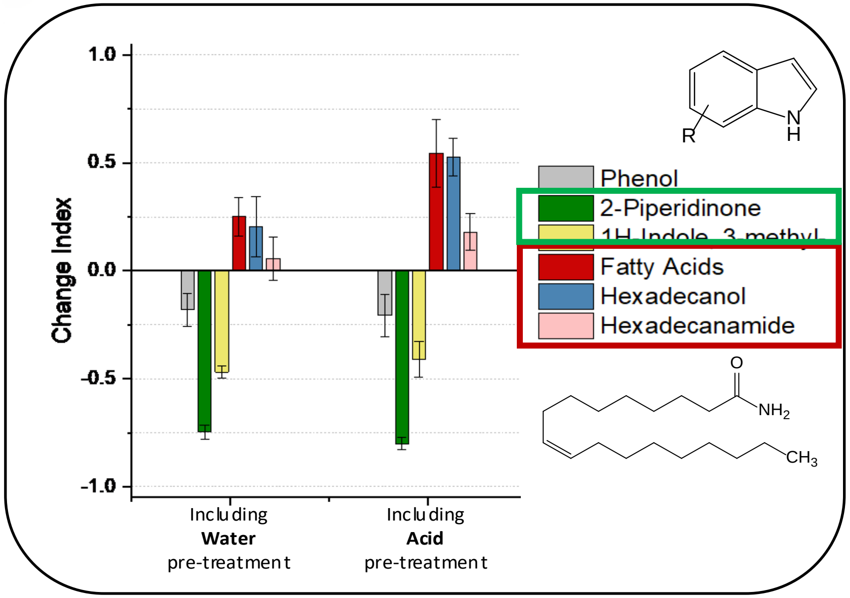
- Overall process cost are increased
- Enzymes is an expensive fungible

How do these pretreatments impact on the HTL process and biocrude quality?



Nitrogen removal improves HTL biocrude :

- **in terms of yield (> 22%)**
- **in terms of quality :**
  - less problematic nitrogen derived compounds (such as N-heterocyclic and N-aromatics)
  - higher content of aliphatic compounds (such as fatty acids, amides)

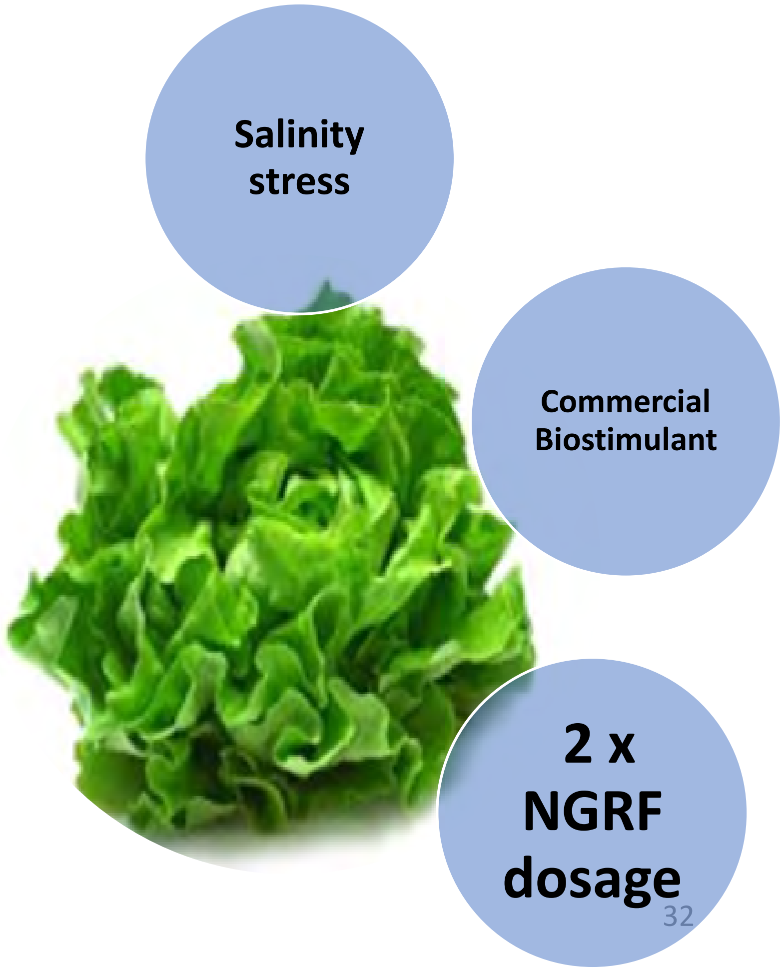


How can the proteinaceous fraction be upgraded?

Protein is a organic form of N, alternative to fossil derived fertilizers:

The results obtained when testing the SS derived biostimulant with lettuce revealed that:

- The generated biomass is similar to the one using commercial biostimulants.
- When plants were subjected to a salinity stress, the amount of nutritional elements (**K, S, Fe, Cu, P, Zn, Ca, Mn, and Mg)** was significantly higher. Also, the bioavailability of cations in soil (**Zn, K** and **Ca)** for the plant was improved.
- Finally, the use of NGRF- product did mobilise in all cases (under saline stress or without stress conditions) more **phosphorus** in the soil.



Conclusion

Pre-treatment improves the HTL of sewage sludge composition by:

… lowering significantly the ash content in the sludge.

… solubilizing 70% of nitrogen from the sludge.

… significantly lowering the nitrogen content in sludge.

… reducing the formation of problematic nitrogen structures in biocrude.

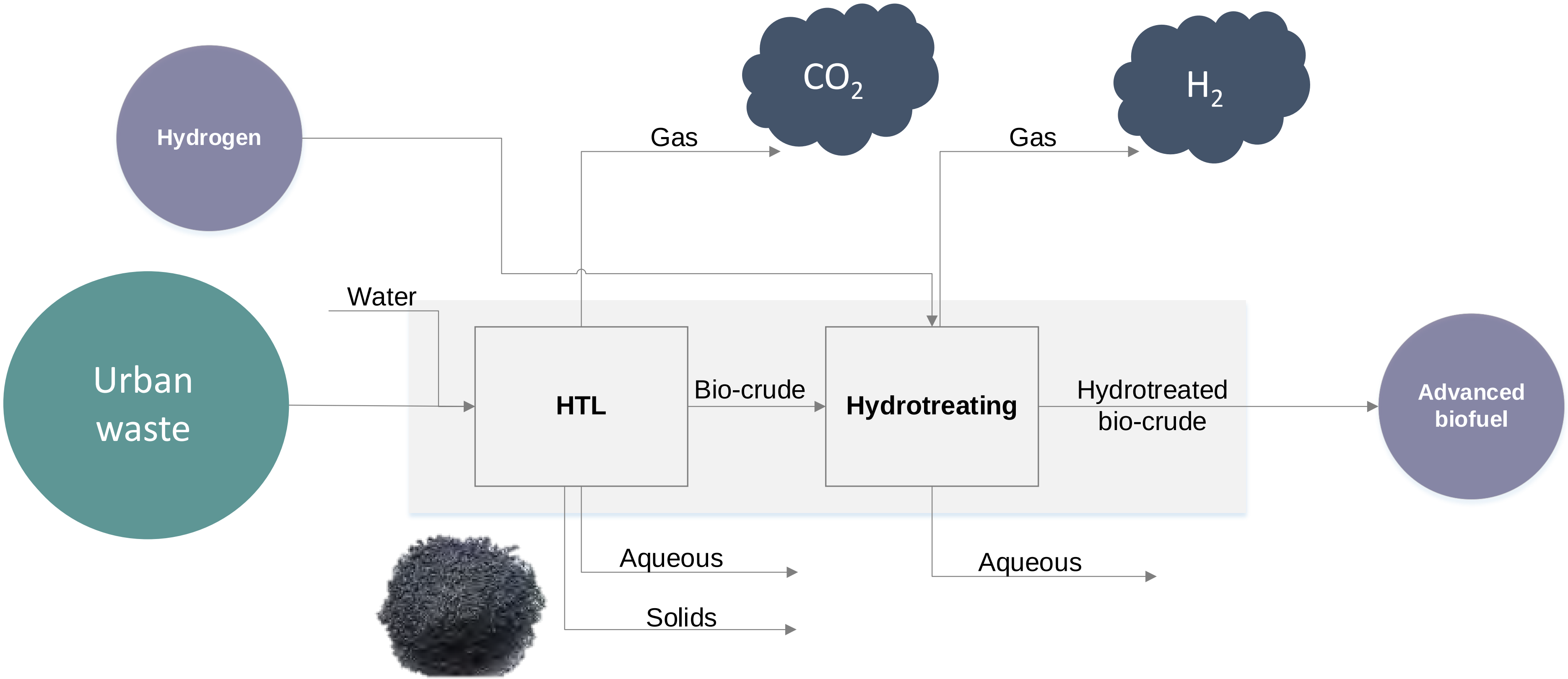
… producing an effective bio-stimulant side product.

HTL as core technology for urban waste valorisation

T. Helmer, AAU

AALBORG UNIVERSITY

HTL and project objectives



Energy recovery: 85 %

Phosphorous recovery: 95 %

Upgradable biocrude

"High ash" feedstock

Effective water management

Major continuous HTL achievements

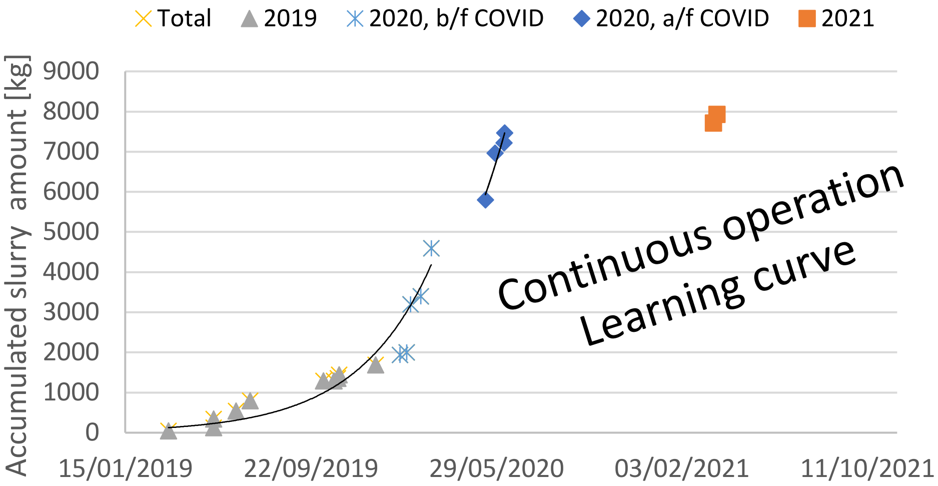
- Approx. 8000 kg of urban waste has been processed.

Dry matter	Up to 35 %
Oxygen	20-40 %
Nitrogen	~0.1 – 8 %
Inorganics (DB)	Up to 31 %

- Designed and installed downstream separation for high quality biocrude.

- Produced more than 100 kilograms of upgradable biocrude

Credit: Steeper Energy



Product recovery – a main challenge

- Biocrude, inorganics, and water form emulsions
  - Biocrude and Phosphorous co-located

- Urgent need to establish a (multi-objective) separation pathway for three phases.

Top priority: *Make an upgradable Biocrude*

- Up to 93 % of the Phosphorous is concentrated in the emulsion → Recoverable in a mineral product

- Remaining P is in the aqueous phase → 95 % recovery has been demonstrated

- Mineral product is:
  - High in P (7-9 wt.%)
  - Low in Heavy Metals
  - Low in organics pollutants (LAS, PAH, NPE, DEHP, pharma)
  - Low in microplastics

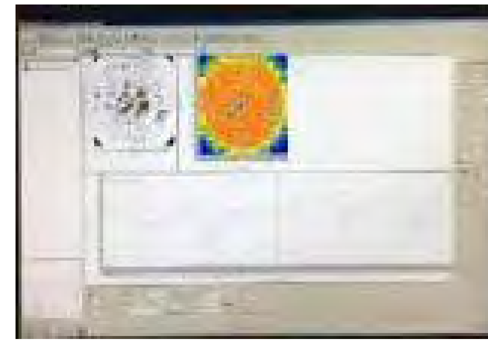
Credit: Steeper Energy

Destruction of Microplastics

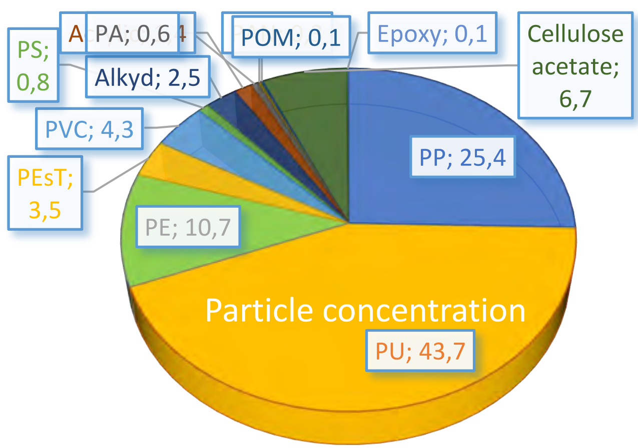
- Developed of an analytical method for quantifying microplastics

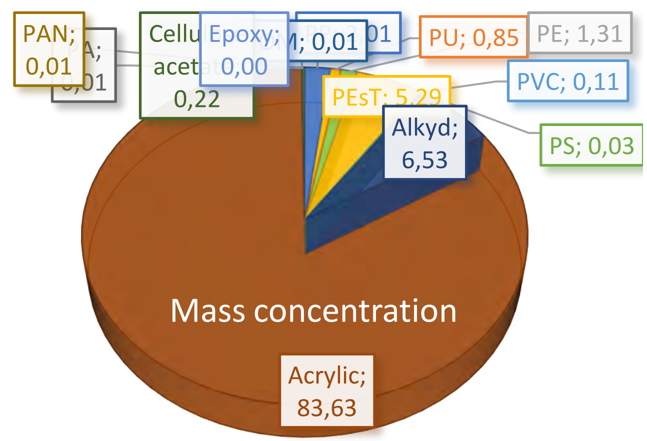
Imaging with µ-FTIR:
Acquisition Imaging – Transmission mode with 15x

FPA Size - 128 x 128,
Pixel size - 5.5 µm
Instrumental Resolution: 8 cm^{-1}
Wavenumber Range collected: 850-3750 cm^{-1}
Substrate type: ZnSe Window, 2mm thick



Mass, number of particles, and size distribution can be determined





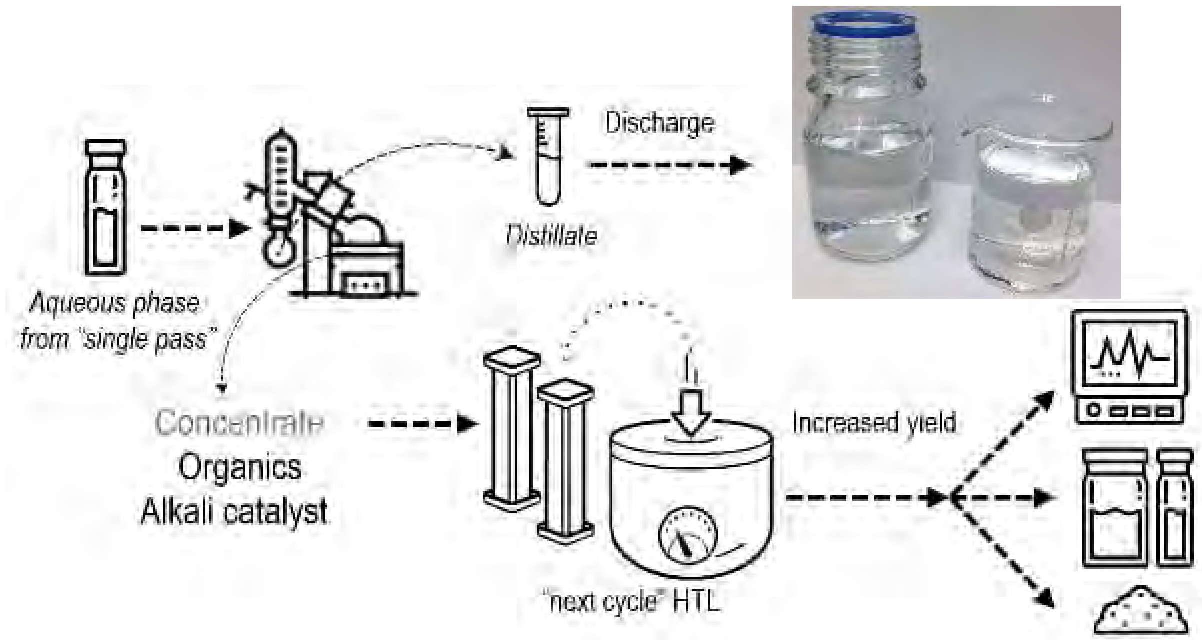
The overarching result:

Micro-plastics mass reduction in HTL = 98.97 %

*Chand et al., 2022,*10.1016/j.jclepro.2022.130383

HTL performance

- *”Single-pass”* vs. recirculation of organics in HTL
  - ”Single pass” → Process penalty → Loss of organics and alkalis



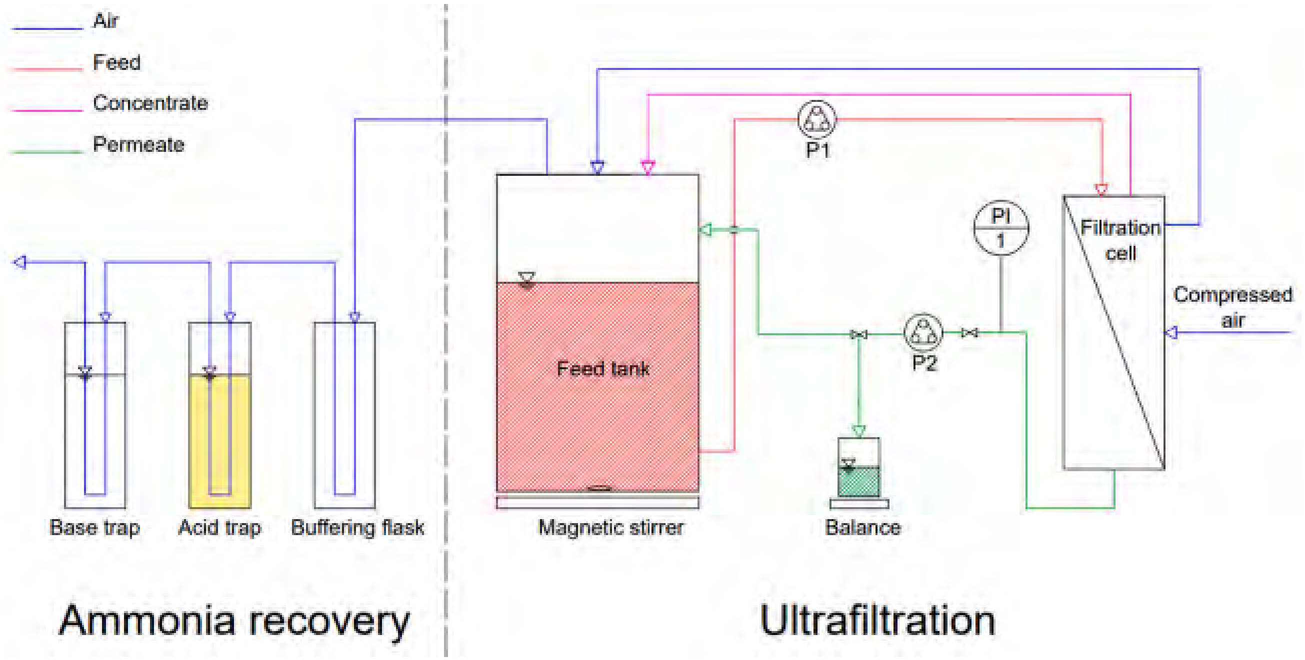
- Continuous pilot testing, *”single pass”* operation → 79 % Energy recovery
- Lab scale testing, *”Recirculation of organics”* → 85 % Energy recovery
- Identification of ways to produce ”low N” biocrudes → N vs. C

doi.org/10.3390/pr9030491 doi.org/10.1016/j.biombioe.2021.106032

Credit: Komeil Kohansal

Effective water management

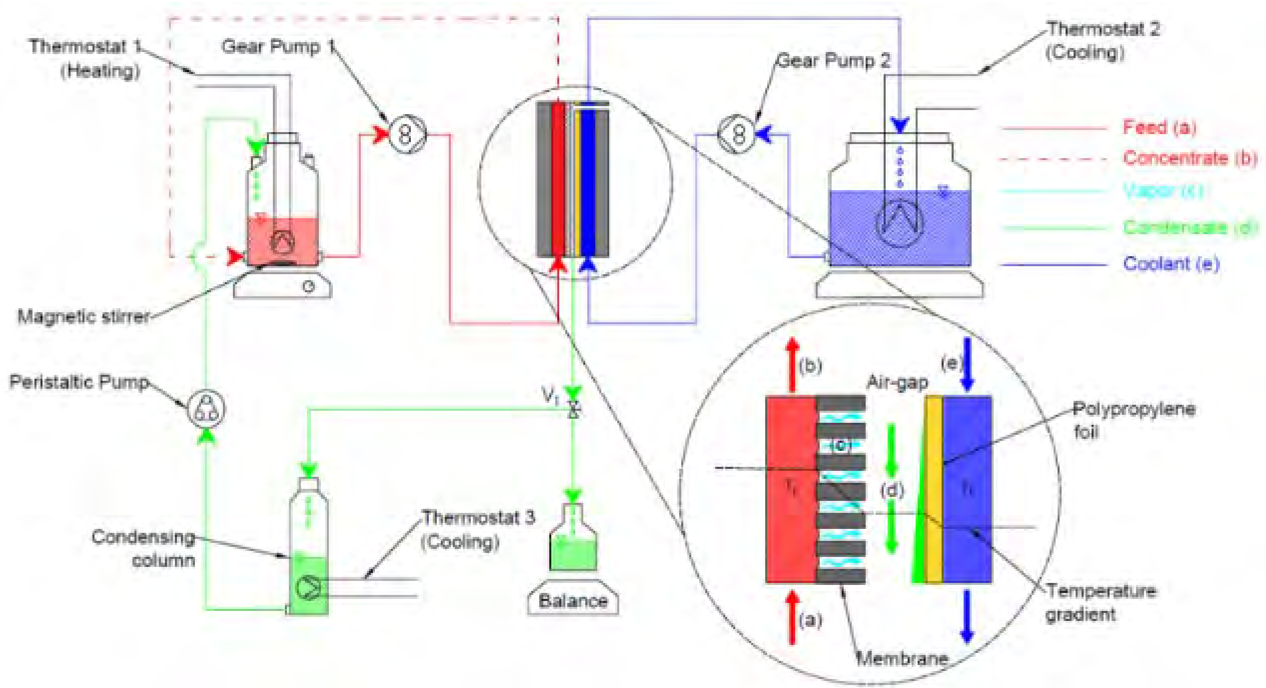
- Novel submerged ultrafiltration as a ”first stage” aqueous phase purification.
- The membrane effectively retained suspended particles and emulsified biocrude.
- High permeability could be maintained by relaxation and backwash cycles.
- Aeration of the membrane provided shear forces to mitigate fouling and further provided an opportunity for ammonia recovery (+90 %).

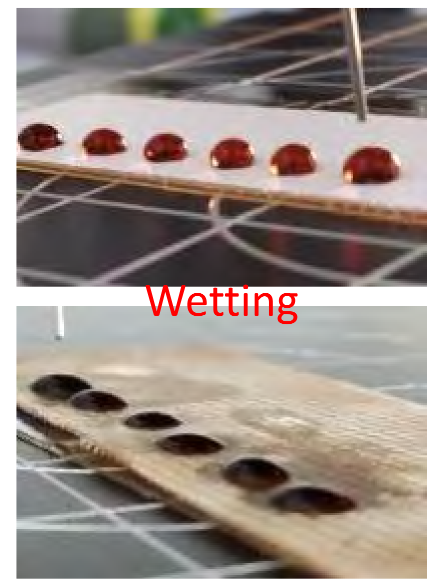


Credit: Ali Sayegh

Effective water management

- Membrane distillation as a ”second stage” aqueous phase purification/concentration.
- 60 % recovery was optimal, 70 % was achievable.
- Fouling was reversible with 100 % flux recovery at 60 % recovery and below.





Credit: Ali Sayegh

Conclusions

- Gained lot of experimental experience with pilot HTL and urban wastes
- Urban wastes can be processed in HTL with high performance
- Biocrude can be made *upgradable*
- > 90 % of Nitrogen and > 95 % of Phosphorous can be recovered from "urban waste" (N and P containing feedstock)
- HTL can be terminal technology for micropollutants (micro-plastics, pharmaceutical etc.)
- Effective water management pathways identified and tested

Turning challenging waste-derived biocrude into fuels: Biocrude upgrading

E. Heracleous, CERTH

K. Rodriguez, STEEPER

K. Kohansal, AAU

Sewage sludge-derived HTL oil

Hydrothermal Liquefaction is a great process for converting a “nasty” feedstock into a flowing liquid, with high energy content

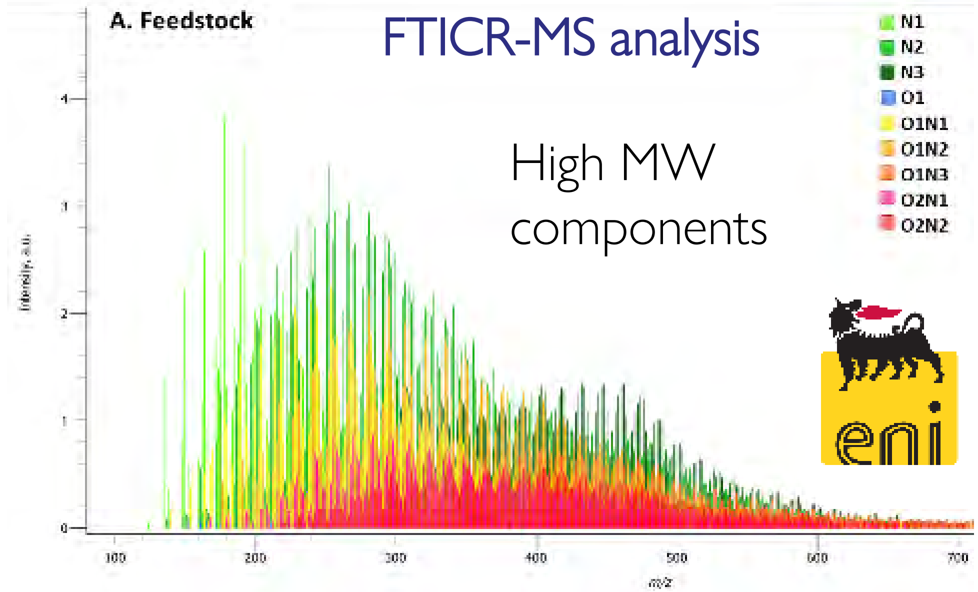
Still, HTL oil is a complex mixture with some unfavourable properties for direct use in fuel applications:

- High inorganics content
- High levels of nitrogen and oxygen (up to 10%)
- High acidity
- High viscosity
- High coke-forming tendency (MCR)

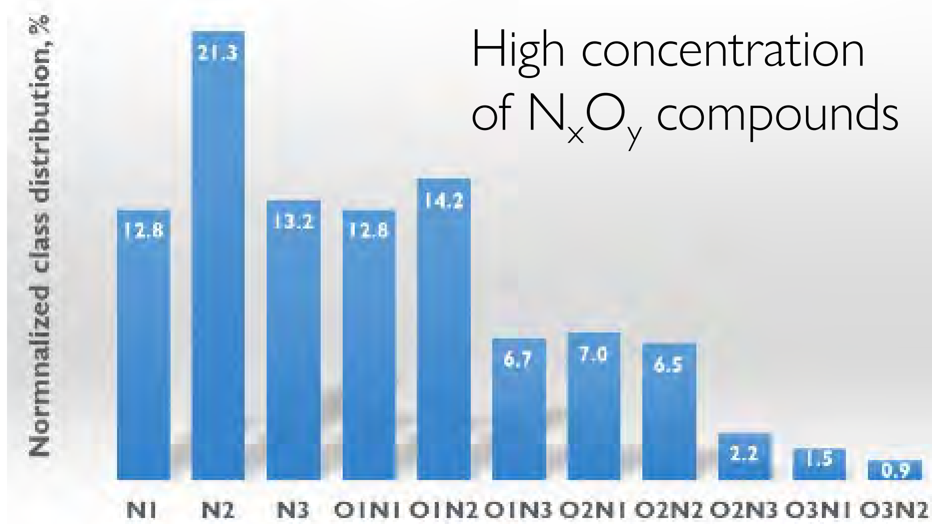
Properties of sewage sludge-derived HTL oil

Property	Feedstock
Density 60 °C, g/cm^3	0.97
Heating value, MJ/kg	37.3
MCRT, wt.%	12.1
TAN, mg KOH/g	103.7
Total ash, ppm	1000
Fe, ppm	665
H_2O content, wt.%	1.0
Elemental analysis, wt.% d.b.	
C	77.7
H	9.7
N	2.3
S	0.7
O (by difference)	9.6

FTICR-MS analysis



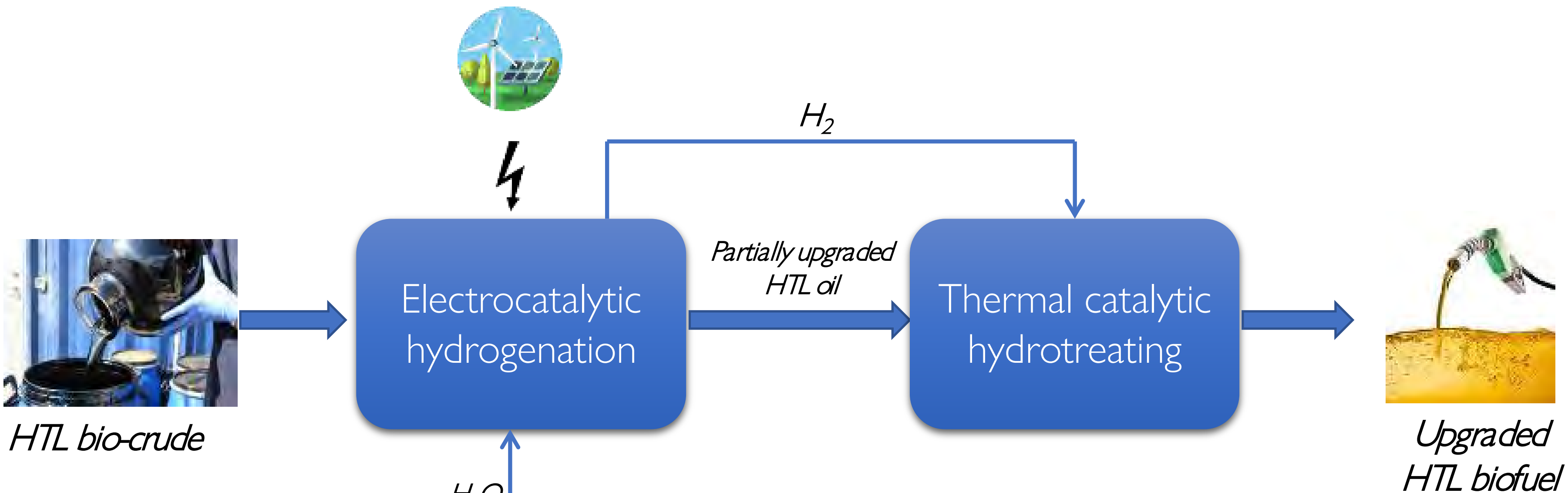
High MW components



High concentration of N_xO_y compounds

HTL bio-crude upgrading in NextGenRoadFuels

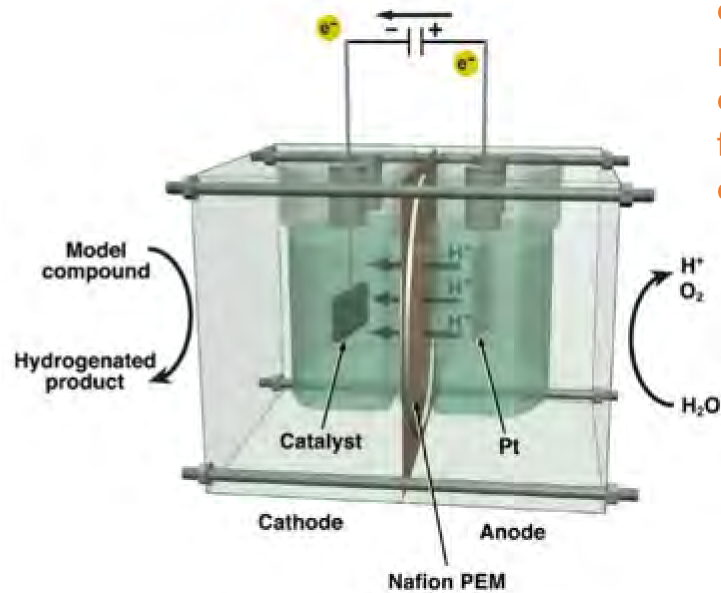
Combined electro-thermal catalytic hydrotreating process with in situ hydrogen generation at mild operating conditions



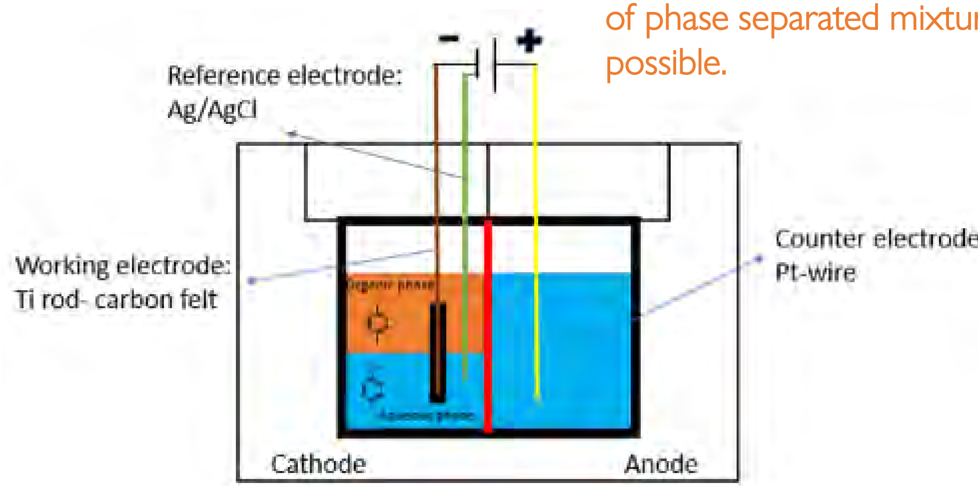
Electrocatalytic hydrogenation	Thermal catalytic hydrotreating
	Continuous slurry reactor
T = 25 – 100 °C P = 1 – 30 bar	T = 350 – 400 °C P = 30 - 80 bar
Base (Ni, Co, Fe and alloys) and noble (Rh, Ru and alloys)/C- based catalysts	Supported Mo nitrides

Electrocatalytic hydrogenation of HTL bio-crude

- Direct hydrogen addition to organic substrates and hydrogen evolution demonstrated at moderate current densities and elevated pressures.
- Operation at high pressures (direct hydrogenation with evolved H_2) and in biphasic mixtures has been successfully demonstrated.
- Working at temperatures above 70°C leads to less ideal operating conditions and decreases specific catalytic activity.
- Working under high concentrations (ionic strengths) is beneficial for the system efficiency.



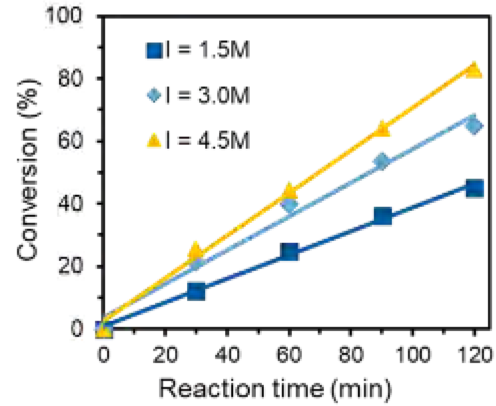
High pressure titanium cell with Nafion membrane allows conversion without fouling and in a continuous mode.

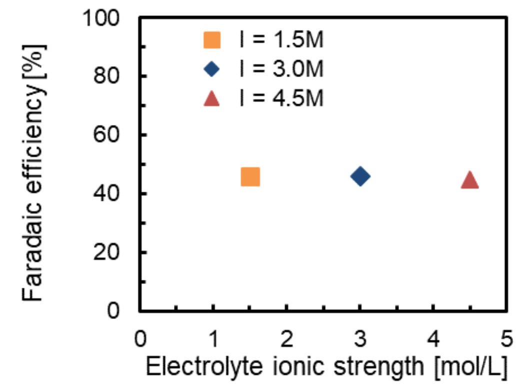


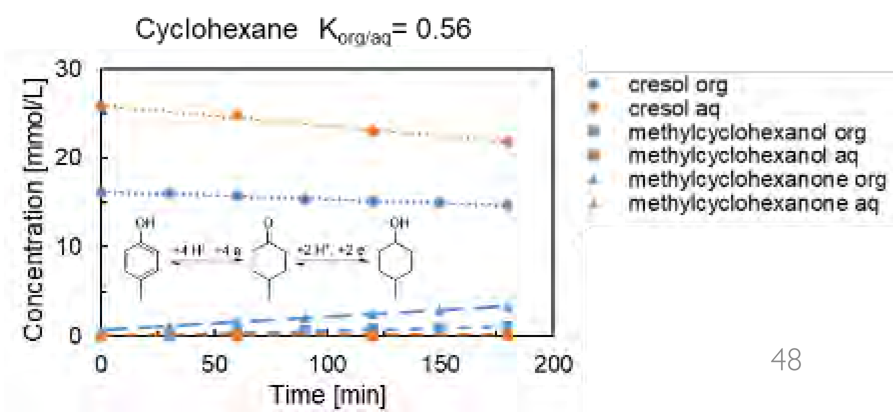
Biphasic configuration for electrocatalytic hydrogenation of phase separated mixtures is possible.

Electrocatalysis offers a scalable decentralized route to hydrogen addition

- Electrocatalytic hydrogen addition allows to partly hydrogenate typical organic feedstock at electric potentials below 1.5 eV against standard hydrogen electrode.
  - Electrocatalysis will be suitable for loading liquid organic hydrogen carriers, but will not be able to replace hydrotreating.
- High ionic strength (high concentration of electrolyte) increases rates without influencing the selectivity to hydrogen addition vs. H_2 evolution.
- Biphasic operation occurs only in the aqueous phase and depends on the solubility of organic substrates, phase transfer rates (suspension beneficial) and the excess chemical potential of the organic substrate in aqueous phase.

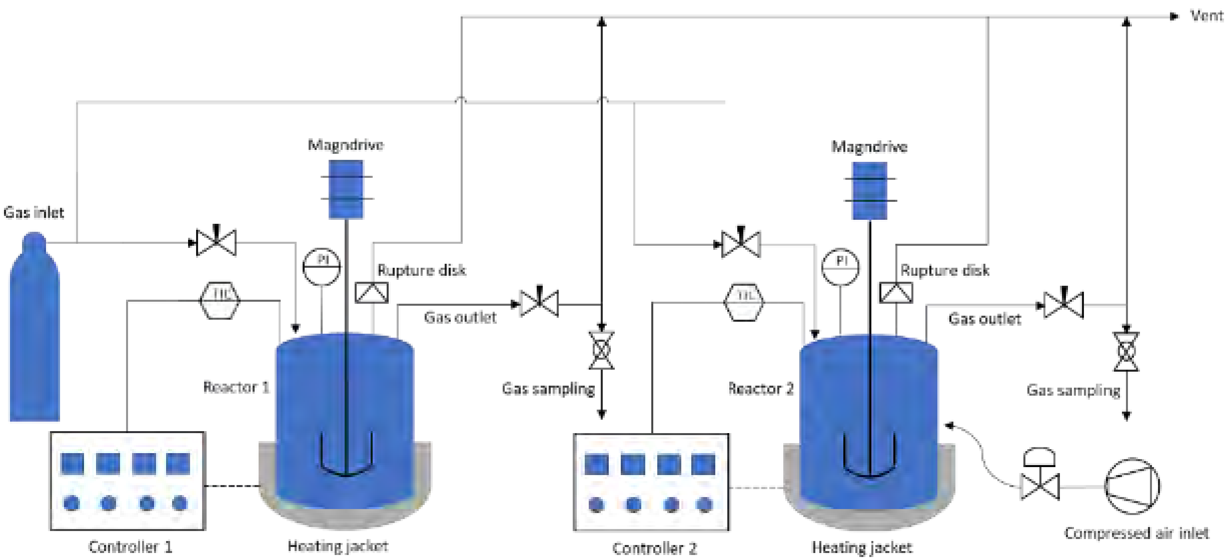




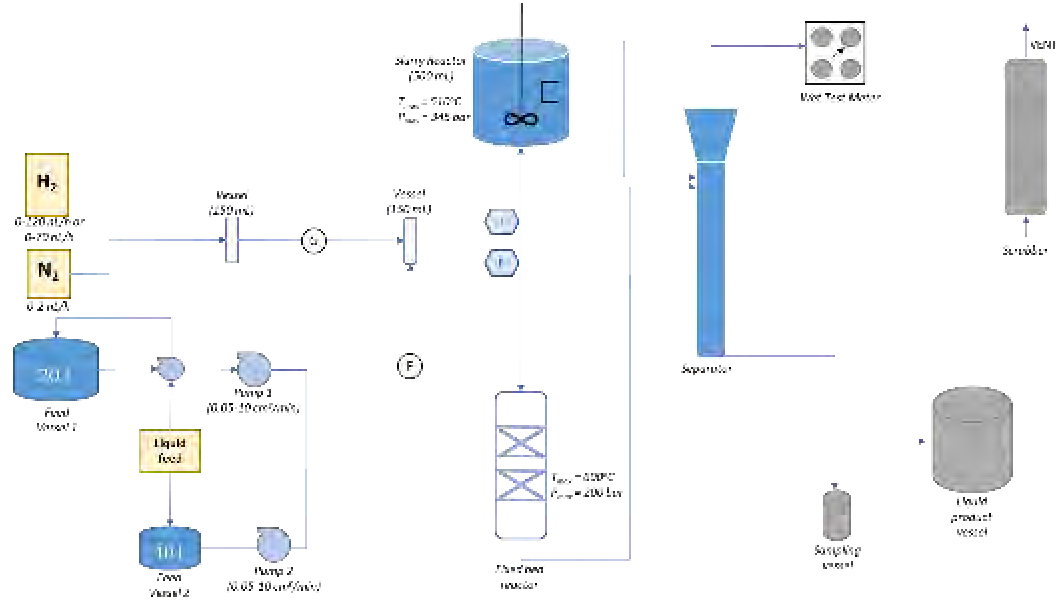


Thermocatalytic hydrotreatment of HTL bio-crude

- Synthesis and characterization of a series of Mo_2N-based catalysts: Unsupported **Mo_2N** and **Mo_2N on ZrO_2, CeO_2, SBA-15, MCM-41 and C**
- **Lab-scale testing** of and Mo_2N-based catalysts and commercial Haldor Topsøe catalyst in batch experiments with model compounds (**p-cresol, pyridine, octanamide**) and **HTL biocrude** in batch experiments at various conditions to investigate the effect of **temperature**, process **configuration** and **thermal** reactions



Demonstration of the optimized process in continuous mode in CPERI's pilot plant unit



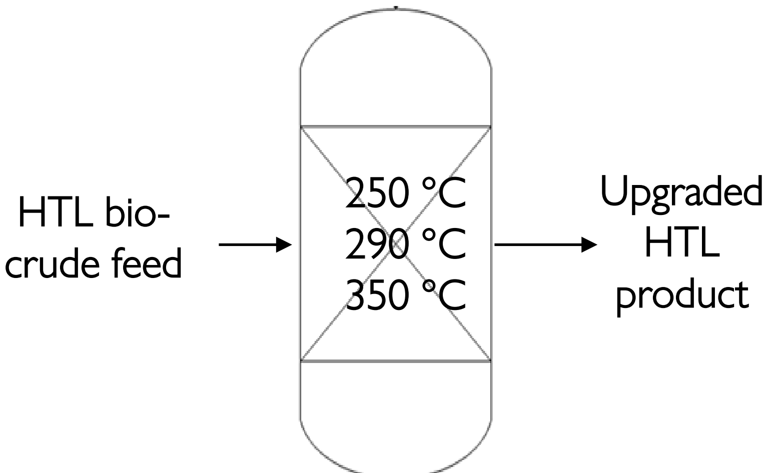
Flexible operation

Ability to operate with fixed-bed or slurry reactor

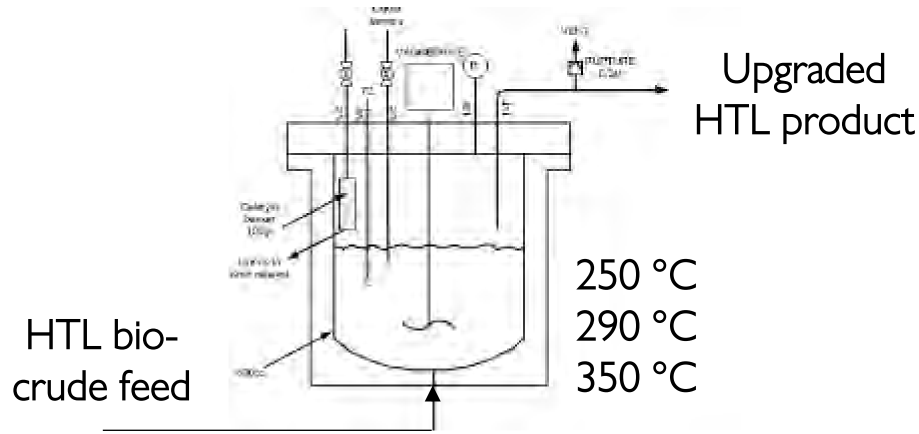
Demonstration of the optimized process in continuous mode in CPERI's pilot plant unit

Effect of reactor type: fixed-bed vs slurry reactor

1-stage fixed-bed reactor



1-stage slurry reactor



Operating conditions

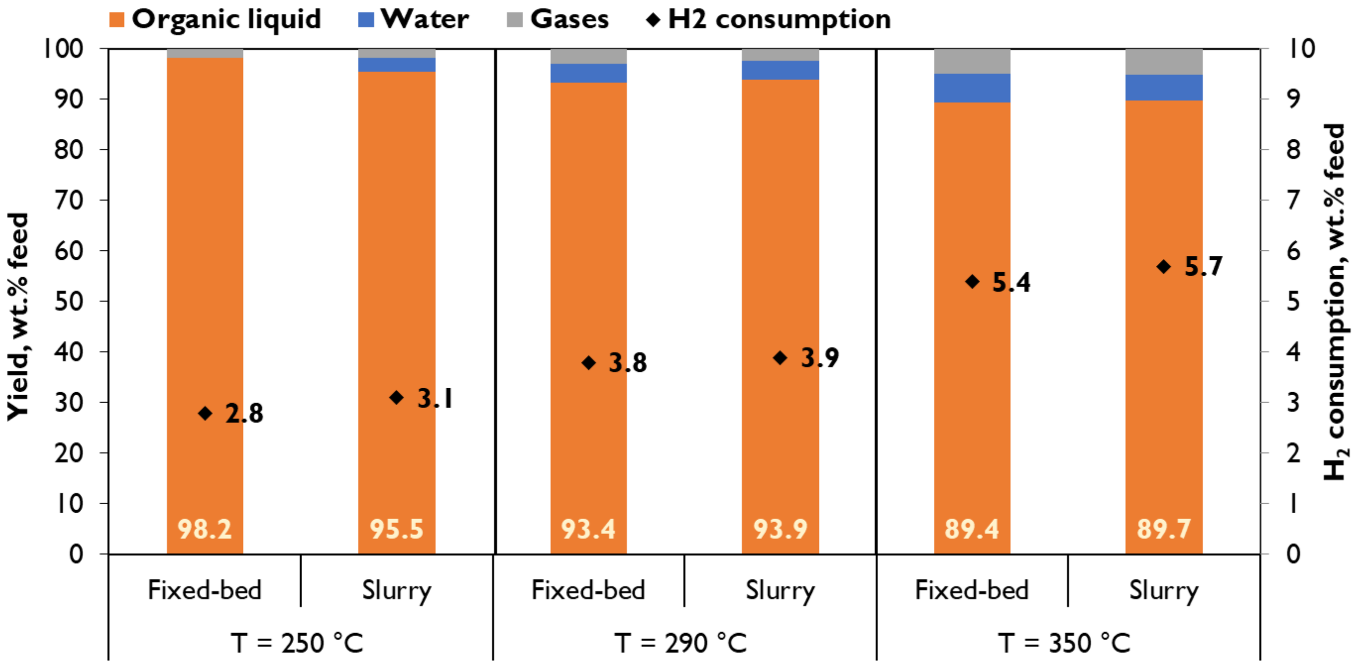
T = 250 °C – 290 °C - 350 °C

P = 100 bar H_2, WHSV = 0.5 h^{-1}

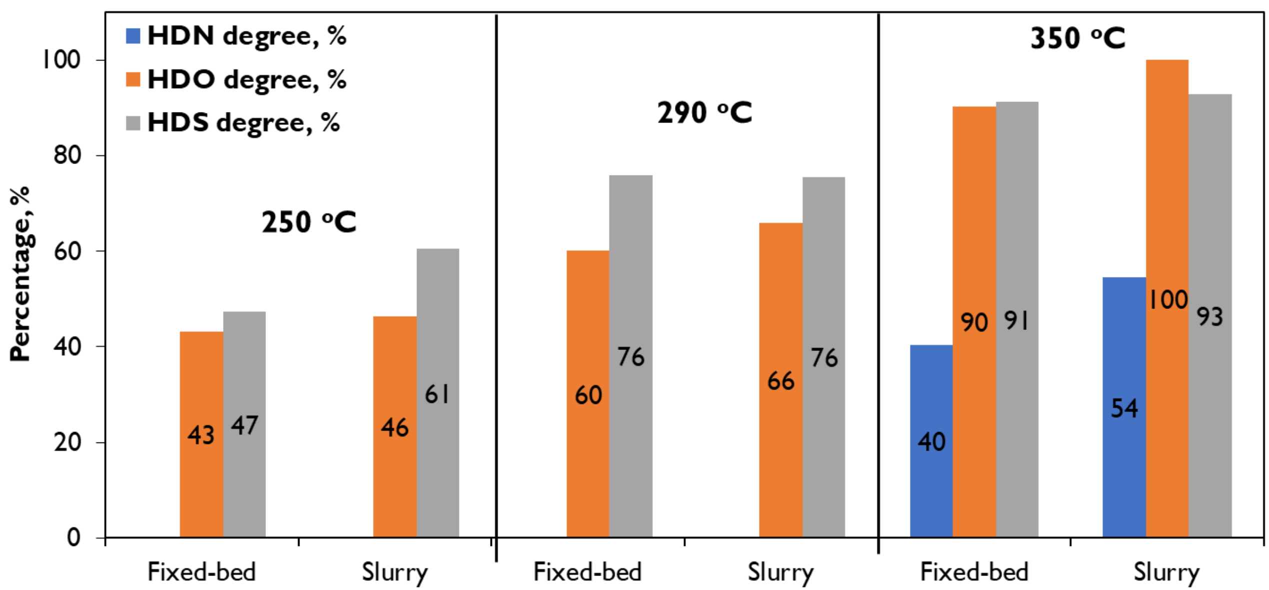
H_2/oil (vol) = 1000

Catalyst: Haldor Topsøe catalyst

Effect of temperature/reactor type



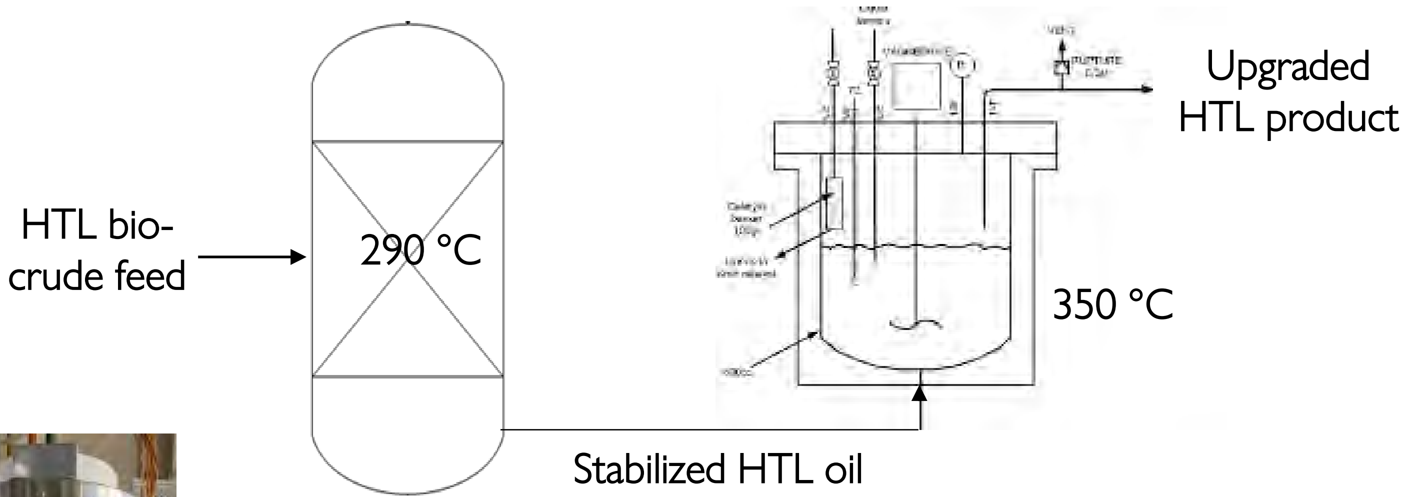
- High oil yields in the range of 90 – 98 wt.%
- Yield mainly determined by temperature
- Subtle differences attributed to reactor type



- 90 - 100% O and S removal
- > 50% N removal in one stage
- Slurry reactor exhibits systematically higher heteroatom removal degree compared to fixed bed

Demonstration of the optimized process in continuous mode in CPERI's pilot plant unit

2-stage fixed-bed/slurry reactor



Operating conditions

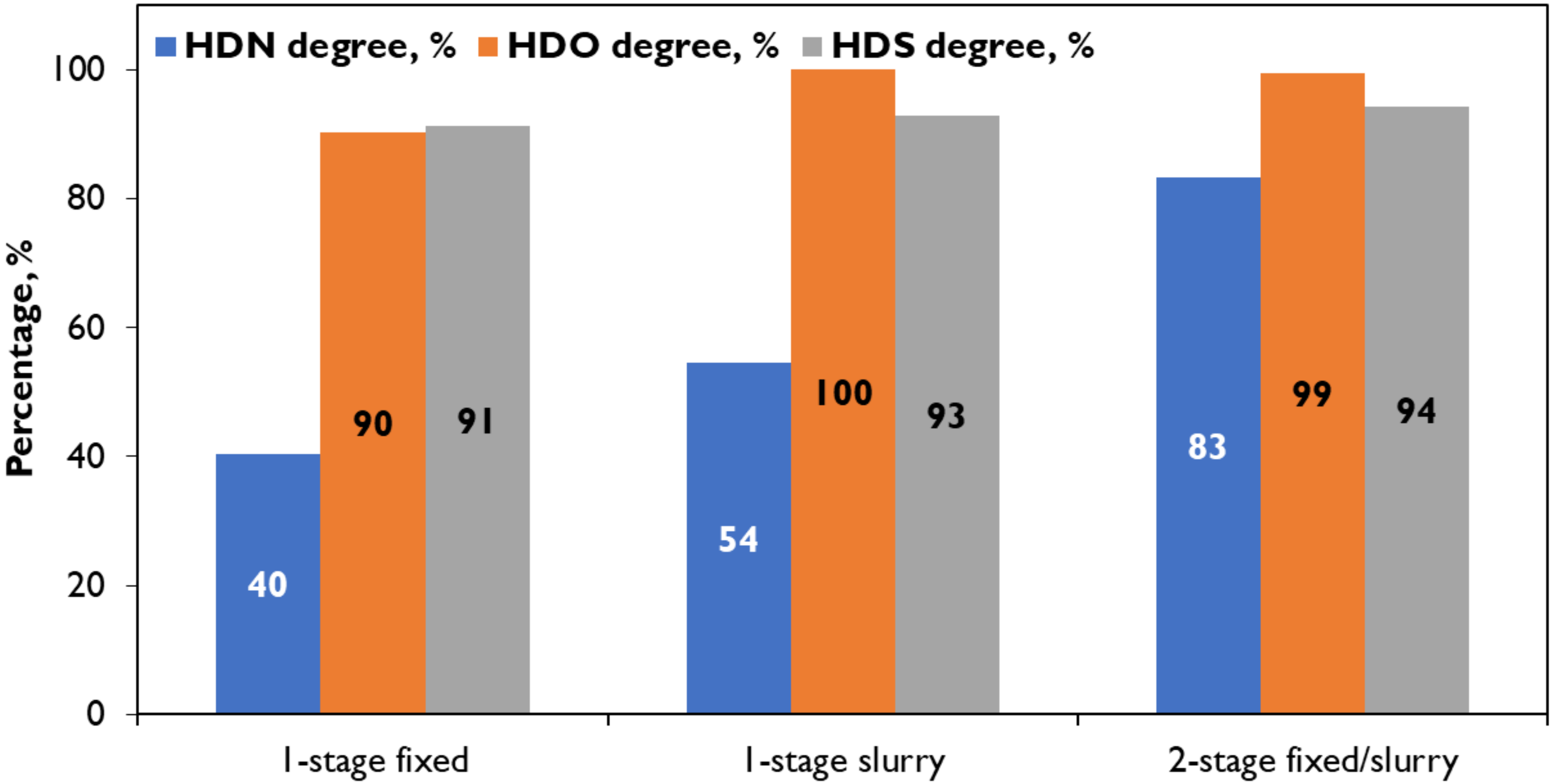
T = 250 °C – 290 °C - 350 °C

P = 100 bar H_2, WHSV = 0.5 h^{-1}

H_2/oil (vol) = 1000

Catalyst: Haldor Topsøe catalyst

Effect of process configuration at 350 °C



- Highest heteroatom removal achieved by 2-stage fixed/slurry configuration
- Achieved ~ 100% oxygen and sulfur removal and > 80% nitrogen removal

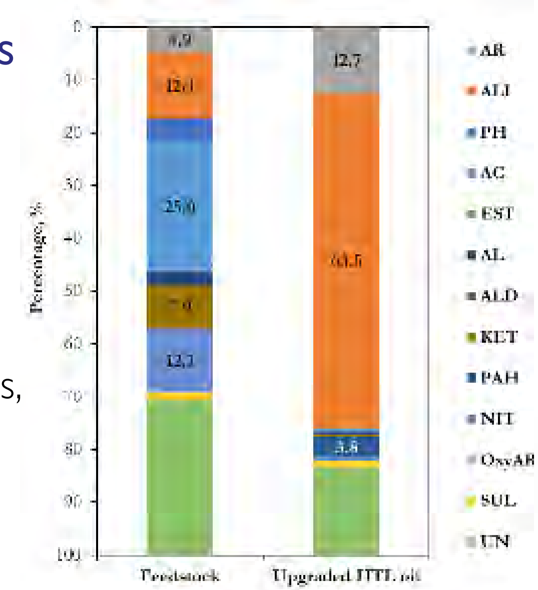
Upgraded HTL oil properties

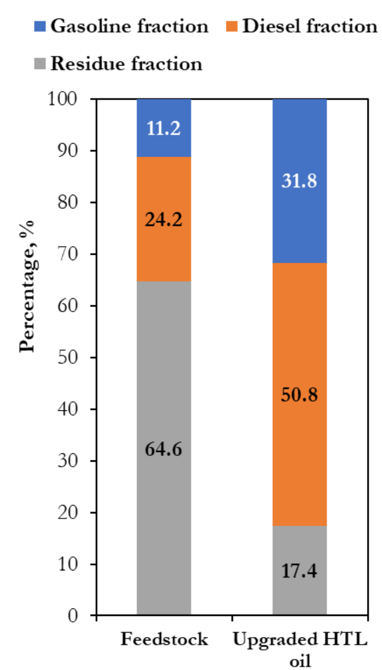
Property	Feedstock	1st stage fixed-bed - 290 °C 2nd stage slurry – 350 °C	
Density 60 °C, g/cm^3	0.97	0.79	-18.6%
Heating value, MJ/kg	37.3	44.6	+20.1%
MCRT, wt.%	12.1	< 0.1	-100%
TAN, mg KOH/g	103.7	< 0.1	-100%
Fe content, ppm	665	1.7	-99.7%
H_2O content, wt.%	1.0	0.04	-96.0%
Elemental analysis, wt.% d.b.			
C	77.7	86.1	
H	9.7	13.5	
N	2.3	0.4	-82.6%
S	0.7	0.0	-100%
O (difference)	9.6	0.0	-100%

GC-MS analysis

Significant production of aliphatic and aromatic compounds

$C_{10} – C_{18}$ alkanes, BTX, alkyl-benzenes





~ 82% gasoline- and diesel-fractions

Steeper's Advanced Biofuels Centre

Defining the value of Hydrofaction® Oil

- Advancing biocrude stability, blending, and compatibility
- Utilizing in-situ renewable H_2
- Demonstrating refinery integration
- Developing techno-economic pathways to renewable fuels
- Delivering flexibility in commercial design for Hydrofaction® licensees

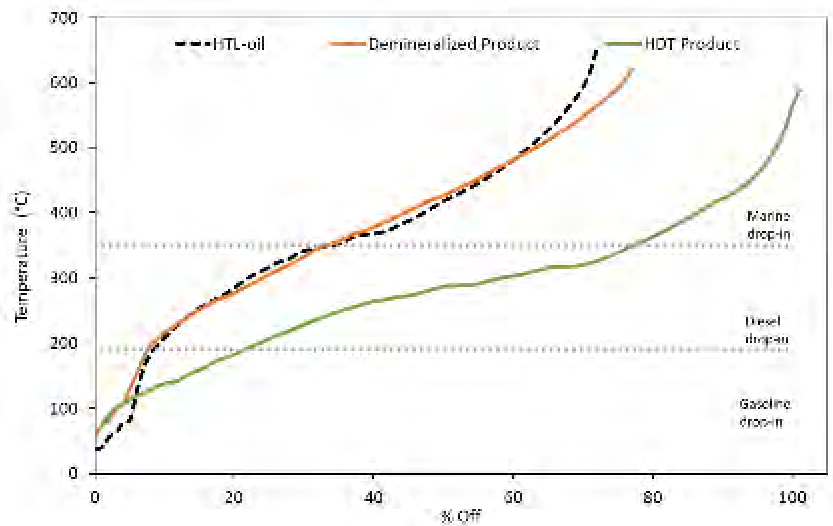
This highly specialized laboratory is enhancing Steeper's upgrading and refinery co-processing capabilities

Hydrofaction® oil Upgrading

Continuous pilot-scale upgrading tests at Steeper Energy

- Processing of HTL oil using novel catalyst for demineralization and commercial catalysts for hydrotreating
- **> 400 hours of stable operation were achieved** when using commercial catalyst at the tested process conditions

Test	Method	HTL oil	Demineralized oil	Upgraded oil
Hydrotreating results				
Water yield [wt.%]	-	-	3.2	7.5
Gas yield [wt.%]	-	-	5.2	11.2
Liquid hydrocarbon yield [wt.%]	-	-	91.6	81.3
Hydrogen consumption [wt.%]	-	-	0.49	2.97
Product characterization				
Nitrogen [wt.%, dry basis]	ASTM D5291	3.81	3.46	1.01
Sulfur [wt.%, dry basis]	ASTM D1552	0.75	0.41	0.01
Oxygen [wt.%, dry basis]	by difference	9.28	6.38	1.35
H/C Molar Ratio	ASTM D5291, calculated	1.51	1.58	1.80
HHV - daf [MJ/kg]	ASTM D240	36.99	39.26	44.67
Ash [ppm]	ASTM D482 (Mod)	2873	1482	11
Iron - Fe [ppm]	ASTM D5708B	926	387	BDL
Micro carbon residue [wt.%]	ASTM D4530	12.70	8.34	0.46
Water Content [wt.%]	ASTM D4377 (Mod)	0.54	0.44	0.11
Density @ 25 °C [kg/m³]	ASTM D4052/D5002	997	969	847
Viscosity @ 25 °C [cP]	ASTM D445	879	247	2.23
TAN [mg KOH/g oil]	ASTM D664A	78	22.34	<1
Flash Point [°C]		36	-	<20



Processes conditions

Demineralization stage: 100 bar; 290 °C; 0.5h^{-1}, 1000 H_2/oil

Hydrotreating stage: 100 bar; 400 °C; 0.5h^{-1}, 1000 H_2/oil

Summary and Next steps

✓Proof of concept: sewage-derived HTL oil upgraded via conventional hydrotreating

✓Iron removal was achieved after hydrotreating tests.

✓The physicochemical properties of the Hydrofaction® oil were significantly improved during hydrotreating:

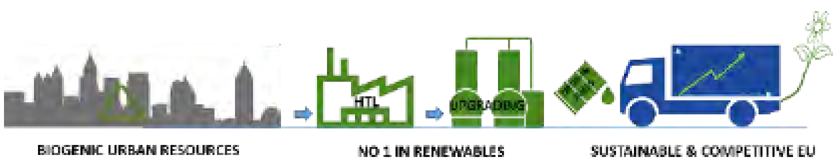
- 86% of oxygen reduction;
- 98% sulfur reduction;
- 73% of nitrogen reduction
- 96% of MCR reduction
- TAN elimination

✓Diesel drop-in fraction (150 - 350 °C) doubled after hydrotreating.

- *In progress: Product distillation and blending for drop-in fuels application*

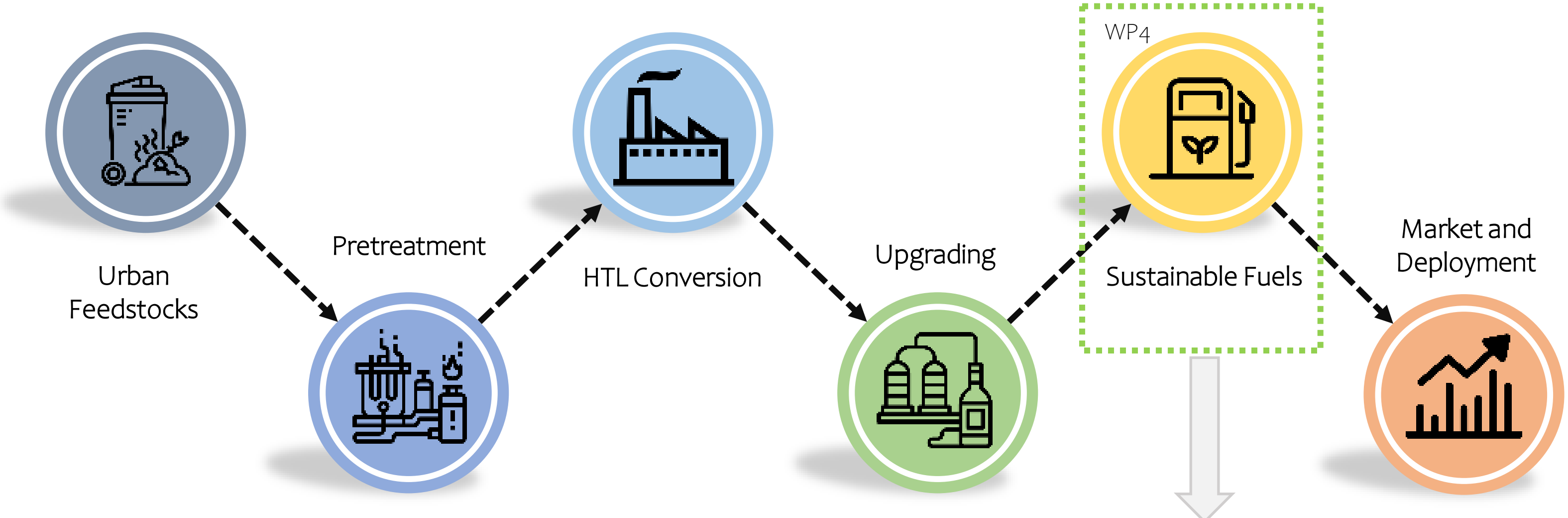
Biodiesel Blendstock production and Engine Tesing Results

K. Kohansal, AAU



Overview of NGRF and WP4

Contributors: *AAU*, GF, SEA



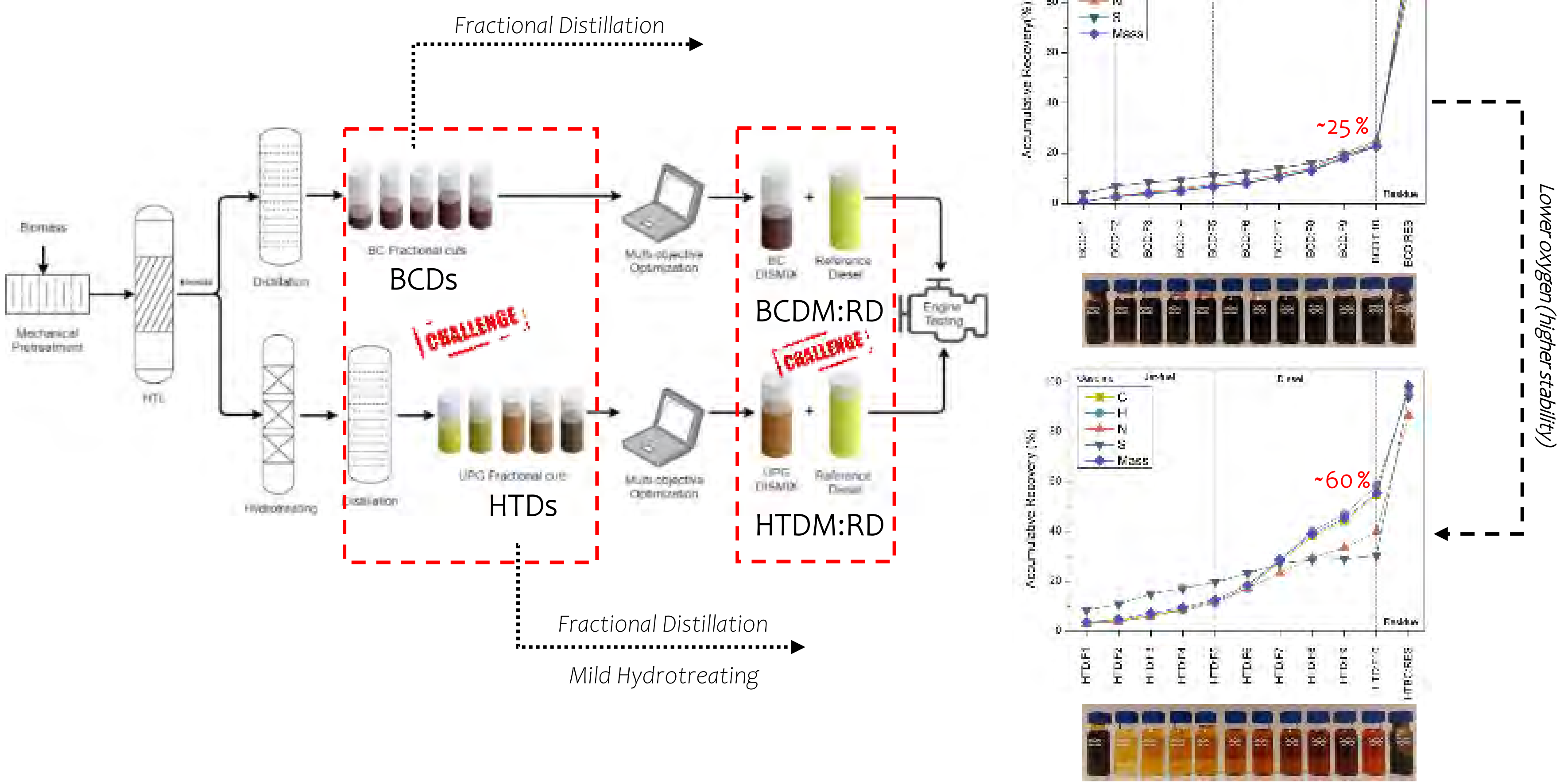
By AAU: Sustainable diesel blendstock production, stability, miscibility, and combustion

Objective 4.1. Miscibility and compatibility of produced drop-in fuels

Objective 4.2. Miscibility and compatibility of produced oxygenate blendstocks

Objective 4.3. Testing of emissions of produced drop-in fuels and oxygenate blendstocks

Production: Different strategies, different fuel properties

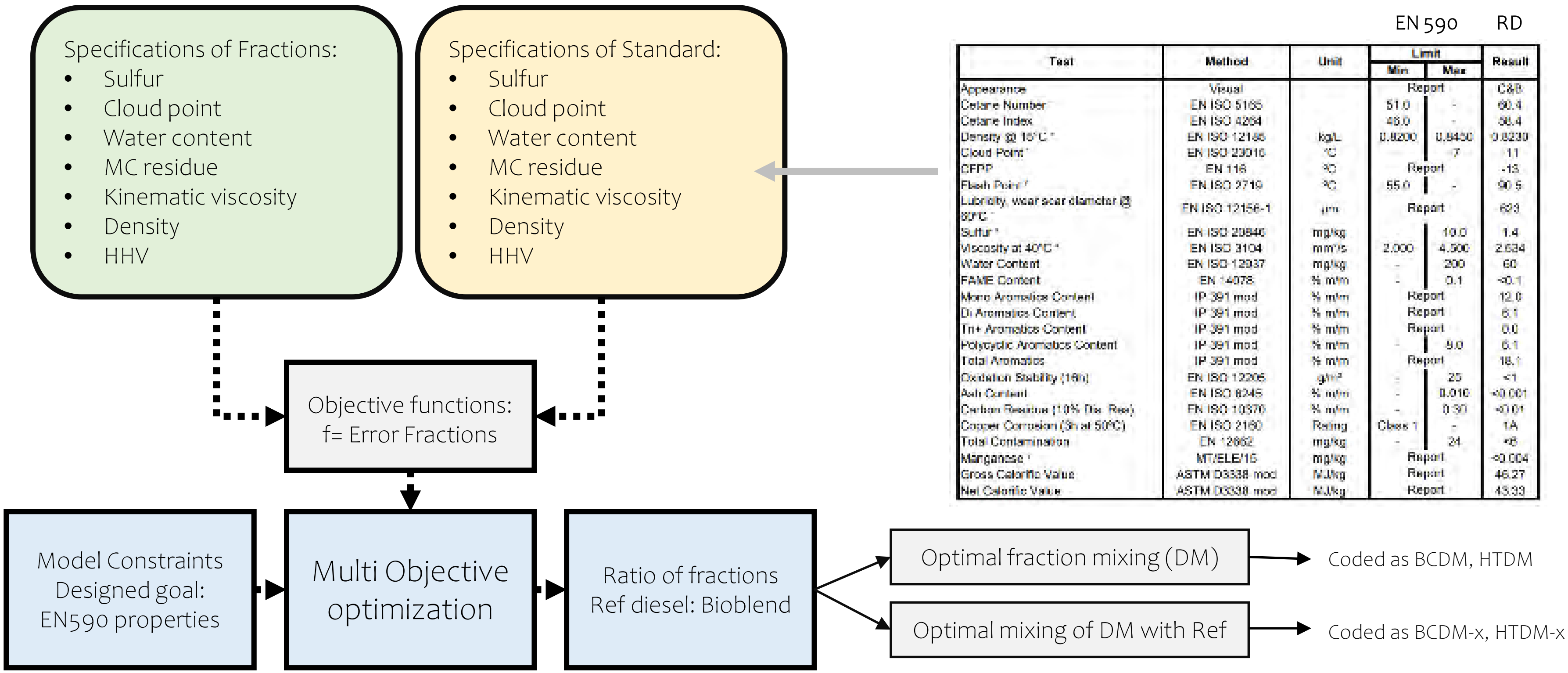


Fuel Blending and Blendstock considerations

”Coryton” ref. diesel for EN590

EN 590 — RD

Test	Method	Unit	Limit Min	Limit Max	Result
Appearance	Visual		Report		C&B
Cetane Number	EN ISO 5165		51.0	-	60.4
Cetane Index	EN ISO 4264		46.0	-	58.4
Density @ 15°C *	EN ISO 12185	kg/L	0.8200	0.8450	0.8230
Cloud Point *	EN ISO 23015	°C	-	-7	-11
CFPP	EN 116	°C	Report		-13
Flash Point *	EN ISO 2719	°C	55.0	-	90.5
Lubricity, wear scar diameter @ 60°C *	EN ISO 12156-1	μm	Report		623
Sulfur *	EN ISO 20846	mg/kg	-	10.0	1.4
Viscosity at 40°C *	EN ISO 3104	mm²/s	2.000	4.500	2.634
Water Content	EN ISO 12937	mg/kg	-	200	60
FAME Content	EN 14078	% m/m	-	0.1	<0.1
Mono Aromatics Content	IP 391 mod	% m/m	Report		12.0
Di Aromatics Content	IP 391 mod	% m/m	Report		6.1
Tri+ Aromatics Content	IP 391 mod	% m/m	Report		0.0
Polycyclic Aromatics Content	IP 391 mod	% m/m	-	8.0	6.1
Total Aromatics	IP 391 mod	% m/m	Report		18.1
Oxidation Stability (16h)	EN ISO 12205	g/m³	-	25	<1
Ash Content	EN ISO 6245	% m/m	-	0.010	<0.001
Carbon Residue (10% Dis. Res)	EN ISO 10370	% m/m	-	0.30	<0.01
Copper Corrosion (3h at 50°C)	EN ISO 2160	Rating	Class 1	-	1A
Total Contamination	EN 12662	mg/kg	-	24	<6
Manganese *	MT/ELE/16	mg/kg	Report		<0.004
Gross Calorific Value	ASTM D3338 mod	MJ/kg	Report		46.27
Net Calorific Value	ASTM D3338 mod	MJ/kg	Report		43.33



Blending considerations – Bio-crude distmix (BCDM) as blendstock

❑ Observation

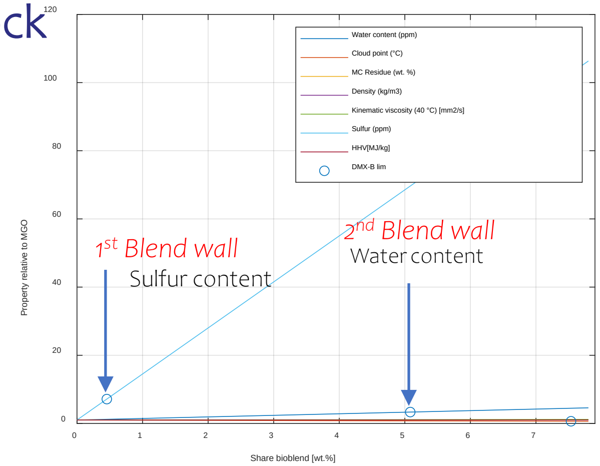
- Biocrude distillate mixture is soluble in hydrocarbons (50-50 mixture approved).
- 1st Blend wall: Sulfur at 0.5 %, 2nd blend wall is water content content at 5 %.

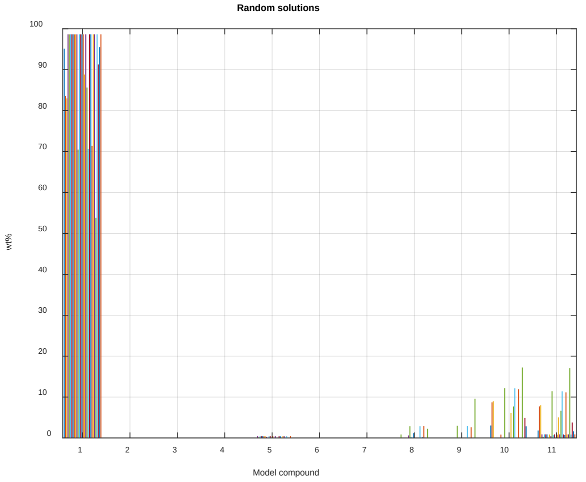
❑ Conclusion

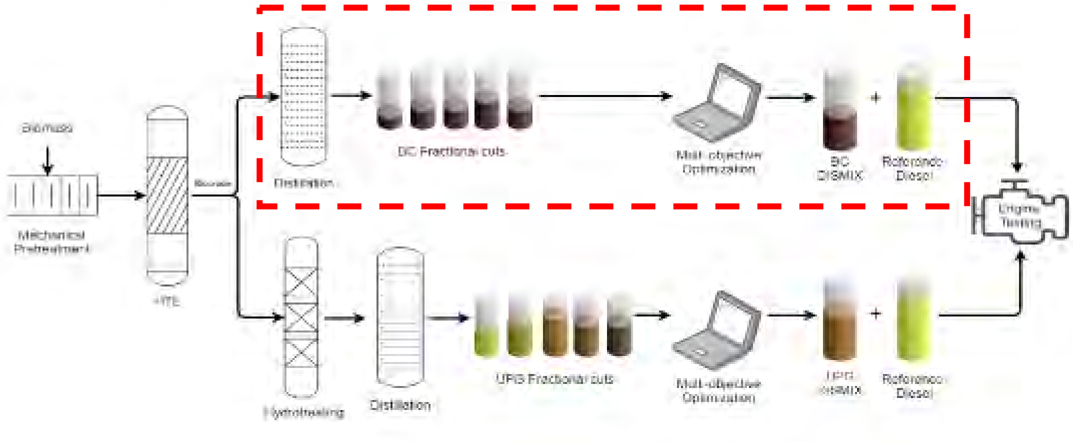
- No physical blend wall.
- Highly limiting Physicochemical blend walls.

❑ Action

- On-spec fuel (0.5 % bio-blendstock) was not considered as an option for engine testing.
- A 10 % bio-crude distmix in Ref. Diesel: (#BCDM10) was tested in Engine for Comparison.





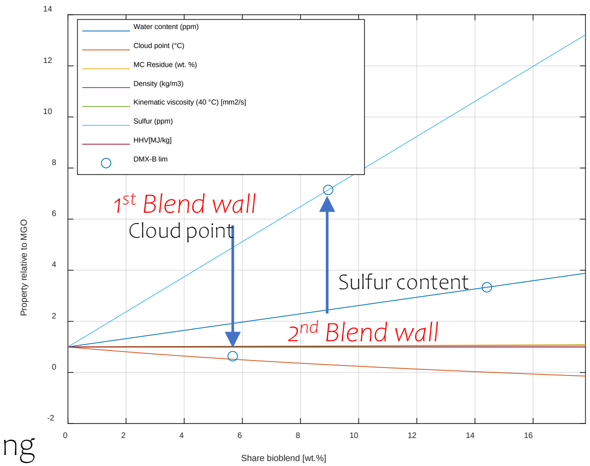


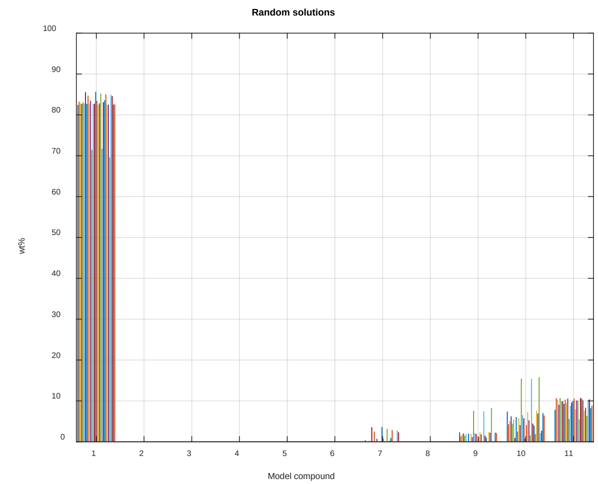
Blending considerations – Upgraded dist.mix as blendstock

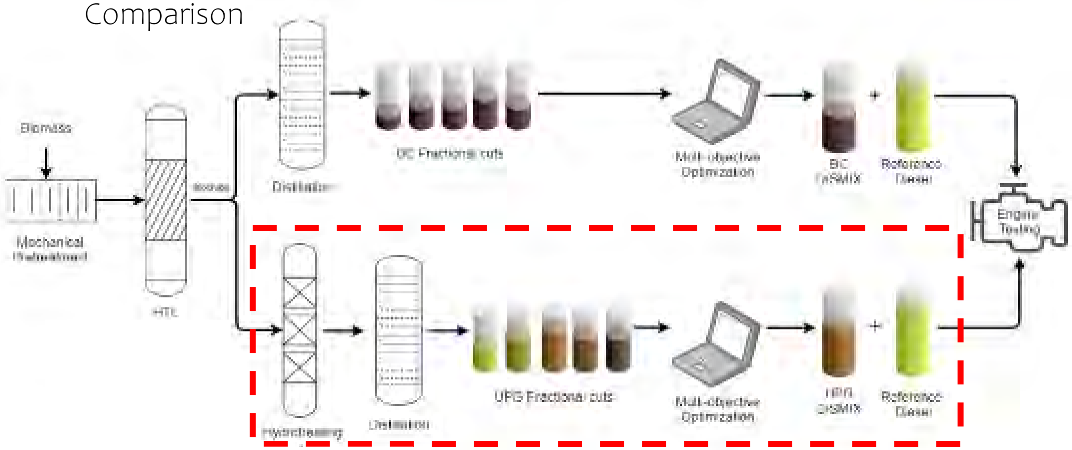
- ❑ Observation
- Hydrotreated biocrude distillate mixture is soluble in hydrocarbons.
- 1st Blend wall: Cloud point at 5.5 %, 2nd blend wall is sulfur content at 10.5 %

- ❑ Conclusion
- No physical blending wall
- Less limiting Physicochemical blend walls

- ❑ Action
- On-spec fuel (5 % bio-blendstock (#HTDM-5) was considered as an option for engine testing
- A 10 % hydrotreated bio-crude distmix in Ref. Diesel: (#HTDM-10) was tested in Engine for Comparison

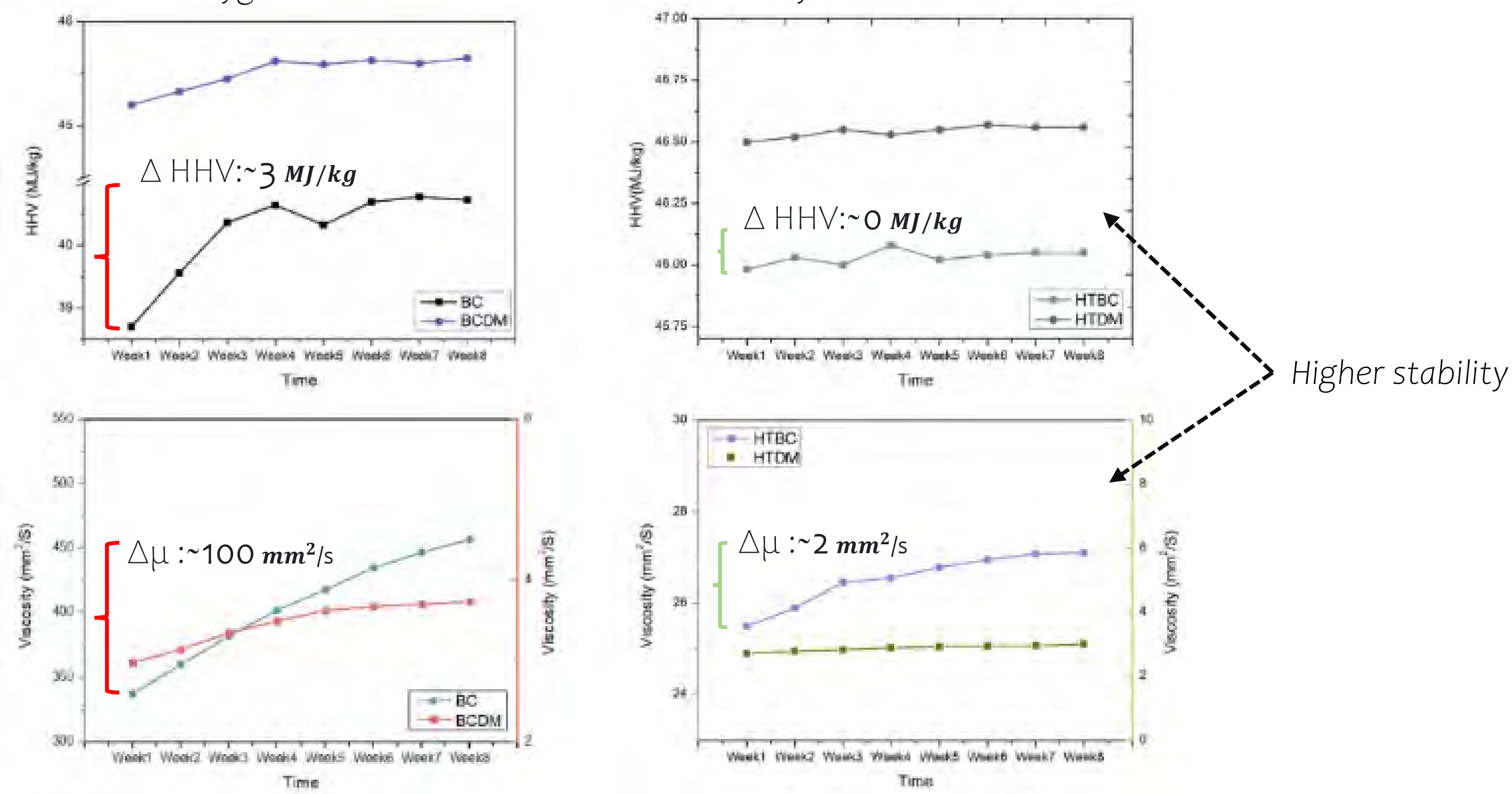






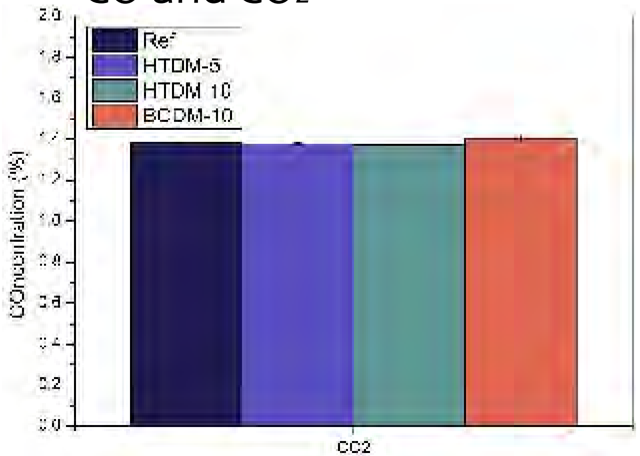
Aging and Stability

Oxygenated fuels | Hydrotreated fuels



Fuel Combustion- Emissions

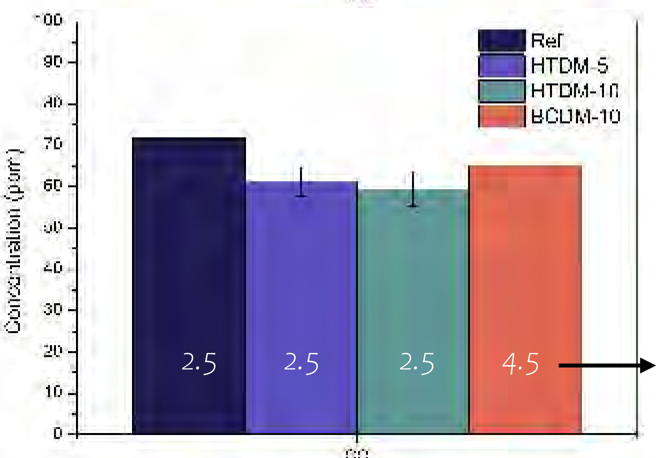
CO and CO_2



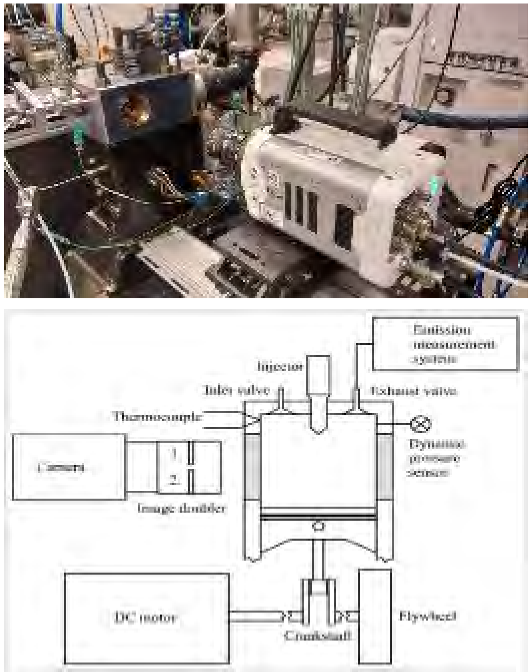
$$C_xH_y + zO_2 \longrightarrow xCO_2 + \frac{y}{2}H_2O$$

mass of fuel burnt ∝ CO_2 emission

Higher CO_2 reduction: Higher C-neutral Bioblend incorporation



Viscosity



- *OACIC engine setup*

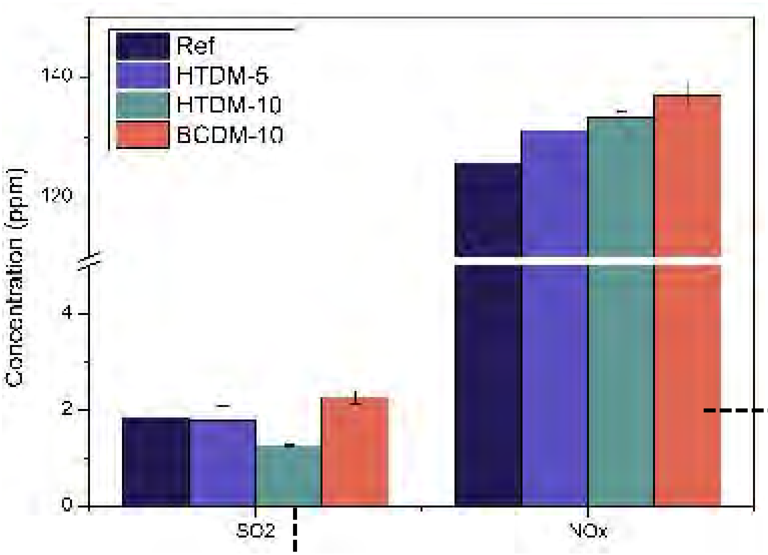
$$\underset{\text{fuel}}{C_xH_y} + \underset{\text{oxygen}}{zO_2} \longrightarrow \underset{\text{carbon dioxide}}{aCO_2} + \underset{\text{carbon monoxide}}{bCO} + \underset{\text{water}}{cH_2O} + \underset{\text{hydrogen}}{dH_2}$$

Higher O content in fuel ∝ lower incomplete combustion ∝ lower CO

Higher viscosity ∝ lower atomization ∝ Higher CO

Fuel Combustion- Emissions

SO_2 and NO_x



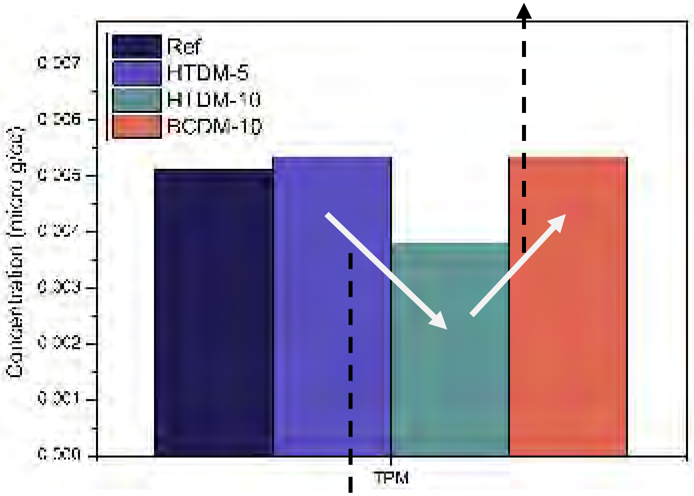
NOx emission follows a same sequence as fuel's Nitrogen content
The in-situ nitrogen content follows the sequence of:
BCDM-10> HTDM-10> HTDM-5>RD
Higher N in fuel ∝ Higher NOx
Higher O in fuel ∝ Higher NOx

Higher SO2 in HTBC-10 than Ref
Low viscosity of fuel ∝ Higher fuel premixing ∝ higher conversion of SO2 to SO3

Fuel Combustion- Emissions

TPM and THC

Higher degree of unsaturation∝ Higher soot formation

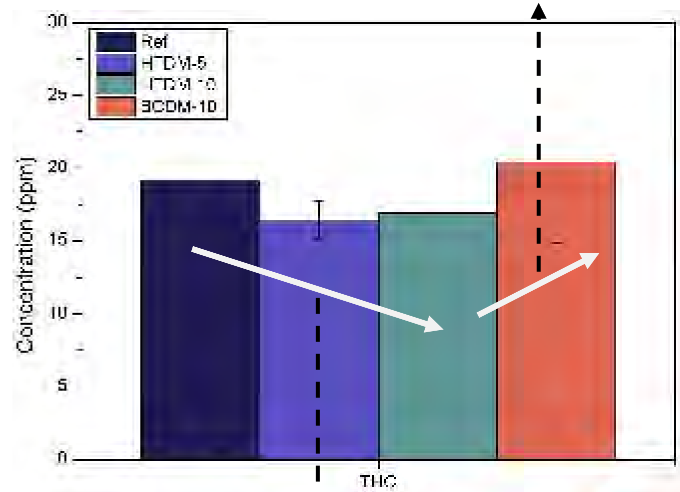


Higher oxygenates in HTDM-10 than HTDM-5

Higher oxygen in fuel ∝ Higher soot oxidation ∝ lower TPM

Lower Cetane index ∝

Higher viscosity ∝ Higher THC



Higher Cetane index ∝ lower ignition delay ∝ lower THC

Cetane index: BCDM-10>HTDM-10>HTDM-5 >REF

Conclusion

- Biocrude stabilization is a key step prior to any further Upgrading.
- The physicochemical properties of the Distillates can be tuned by hydrotreating, so the share of Bioblend feedstock in the final fuel will be increased.
- The de-oxygenated distillates and biocrude were considerably more stable than their O-containing counterparts.
- The HTDM-5 and HTDM-10 revealed on par viscosity and HHV than the reference diesel (Fuel performance).
- The on spec-blends emitted comparable emissions to the ULS reference diesel.

Guest Speaker: Pacific Northwest National Laboratory

H. Wang, PNNL

Hydrothermal Liquefaction R&D at PNNL: Biocrude Coprocessing

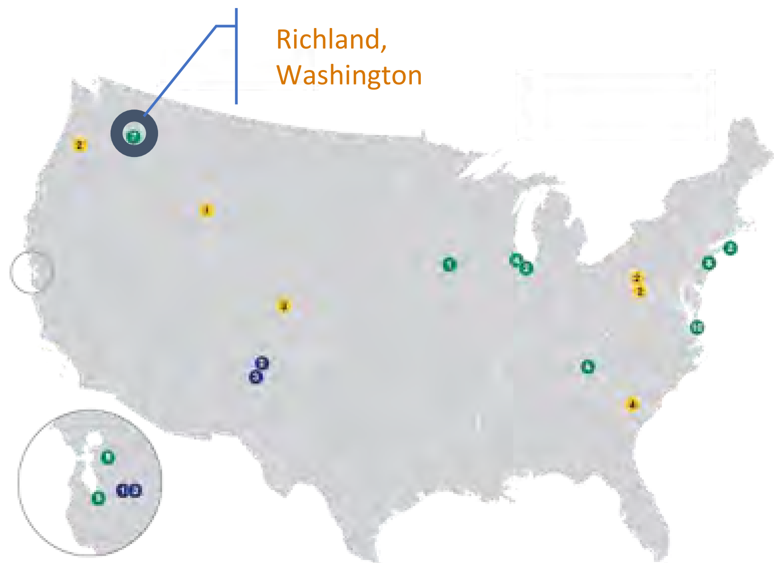
Huamin Wang
Pacific Northwest National Laboratory

October 4th, 2022

Pacific Northwest National Laboratory

	5,314	Staff
	$1.24B	Spending
	1,755	Peer-reviewed publications
	247	Inventions
	204	Companies with PNNL roots

Fiscal Year (FY) 2021



Chemical and Materials Science

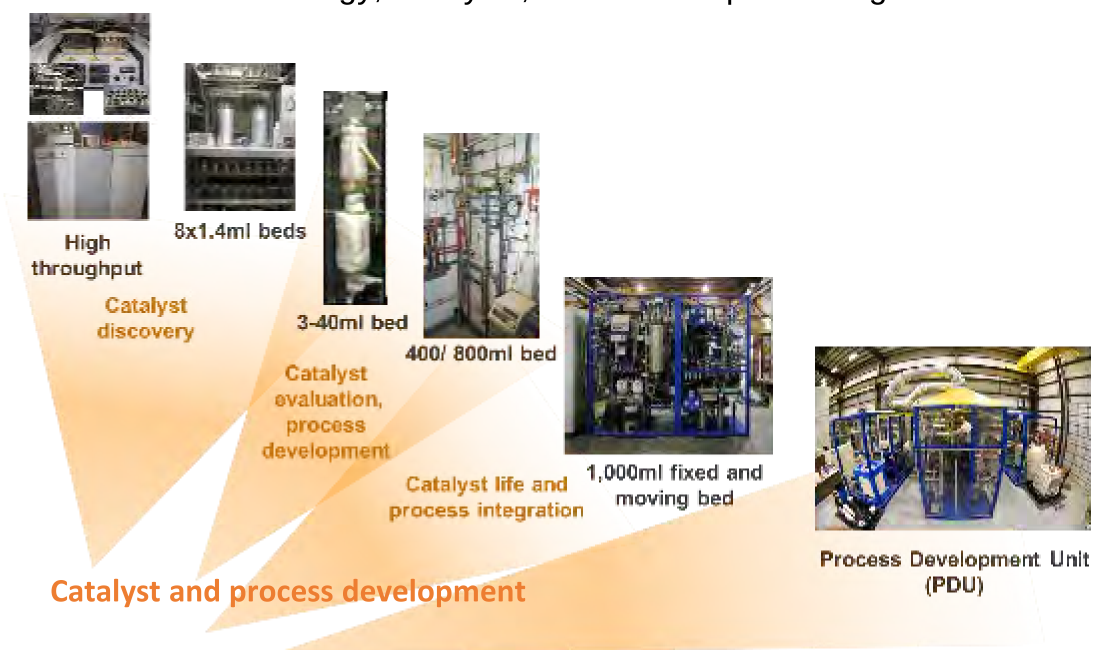
Biological and Earth Sciences

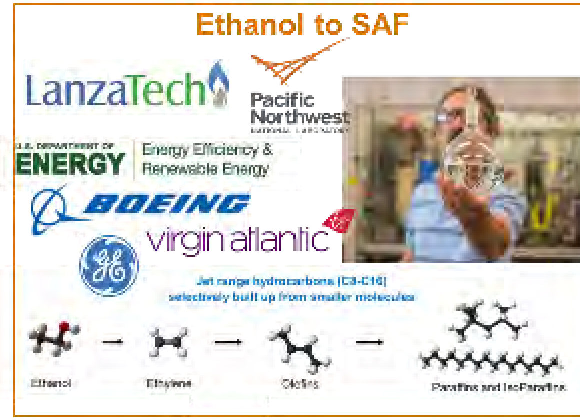
Engineering

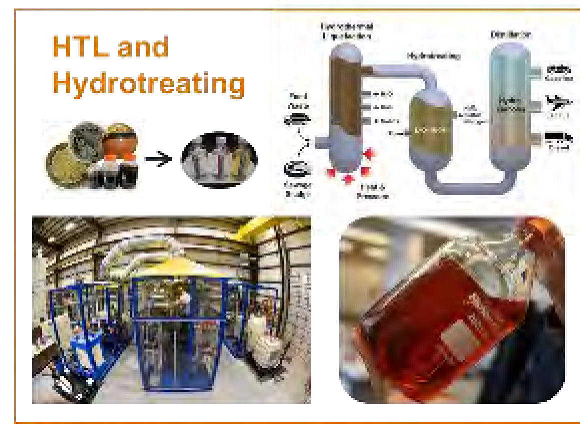
Computational and Mathematical Sciences

Bioenergy Technology R&D at PNNL

- Focuses on processes that convert biomass and wastes into chemicals and biofuels that are infrastructure ready (e.g., gasoline, diesel and jet fuel).
- Researchers with technical expertise in advanced biotechnology, catalysis, and thermal processing





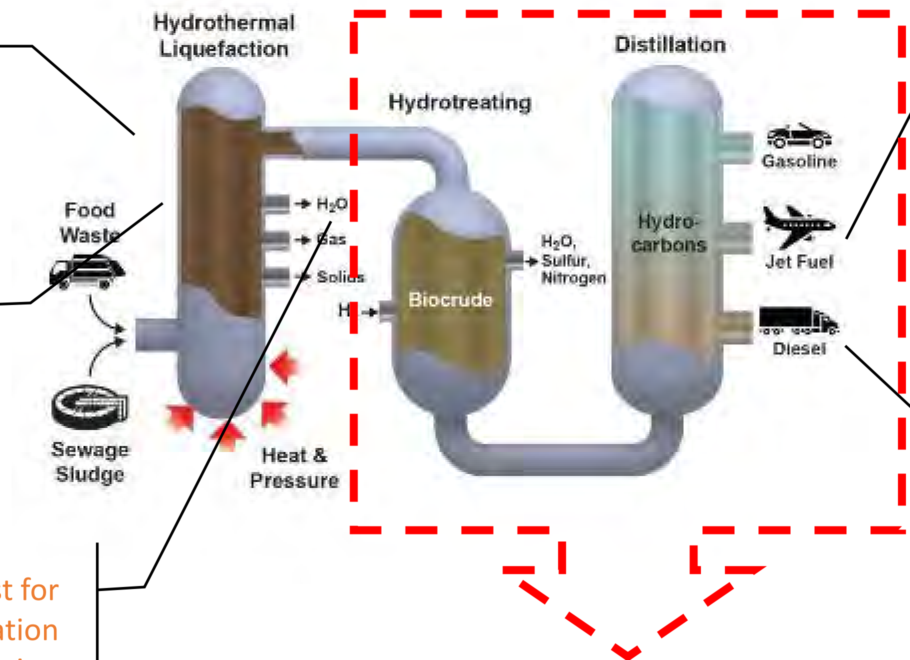


PNNL continues advancing HTL technologies

Significant reductions in modeled SOT (State of Technologies) costs

Reducing the modeled heat exchanger cost and increasing its robustness

Robust sulfur resistant catalyst for catalytic hydrothermal gasification (CHG) of HTL aqueous fraction

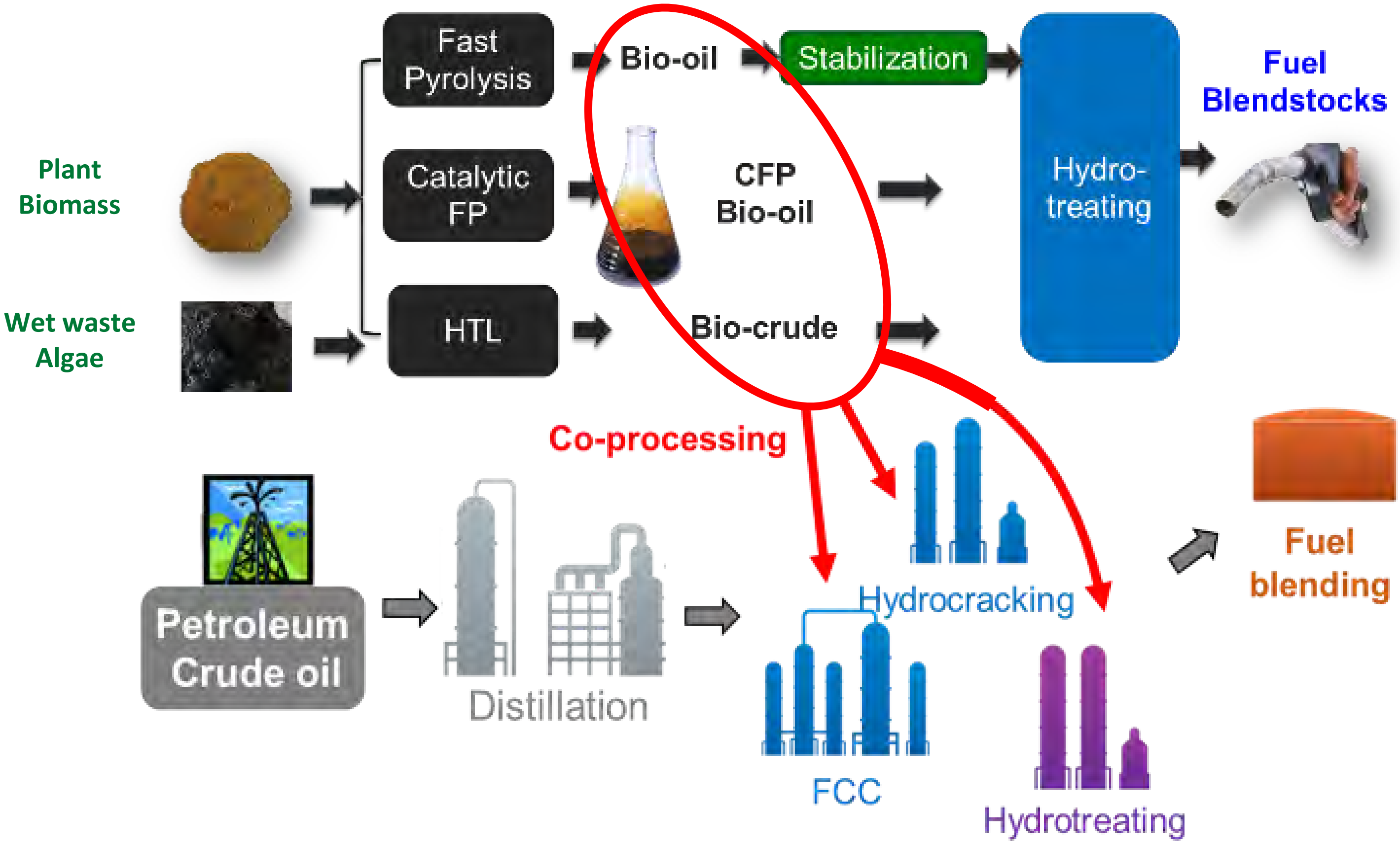


Improved deep N removal in jet fuel application

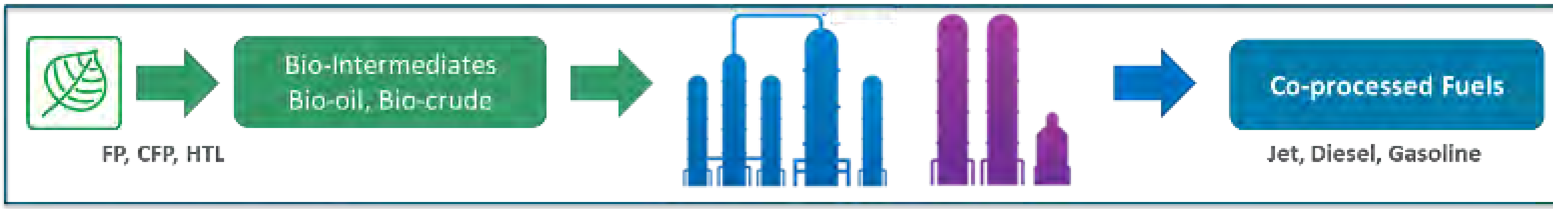
Diesel cold point properties improvement

Coprocessing biocrudes in refinery

We can leverage existing refining infrastructures to leverage billions of US$

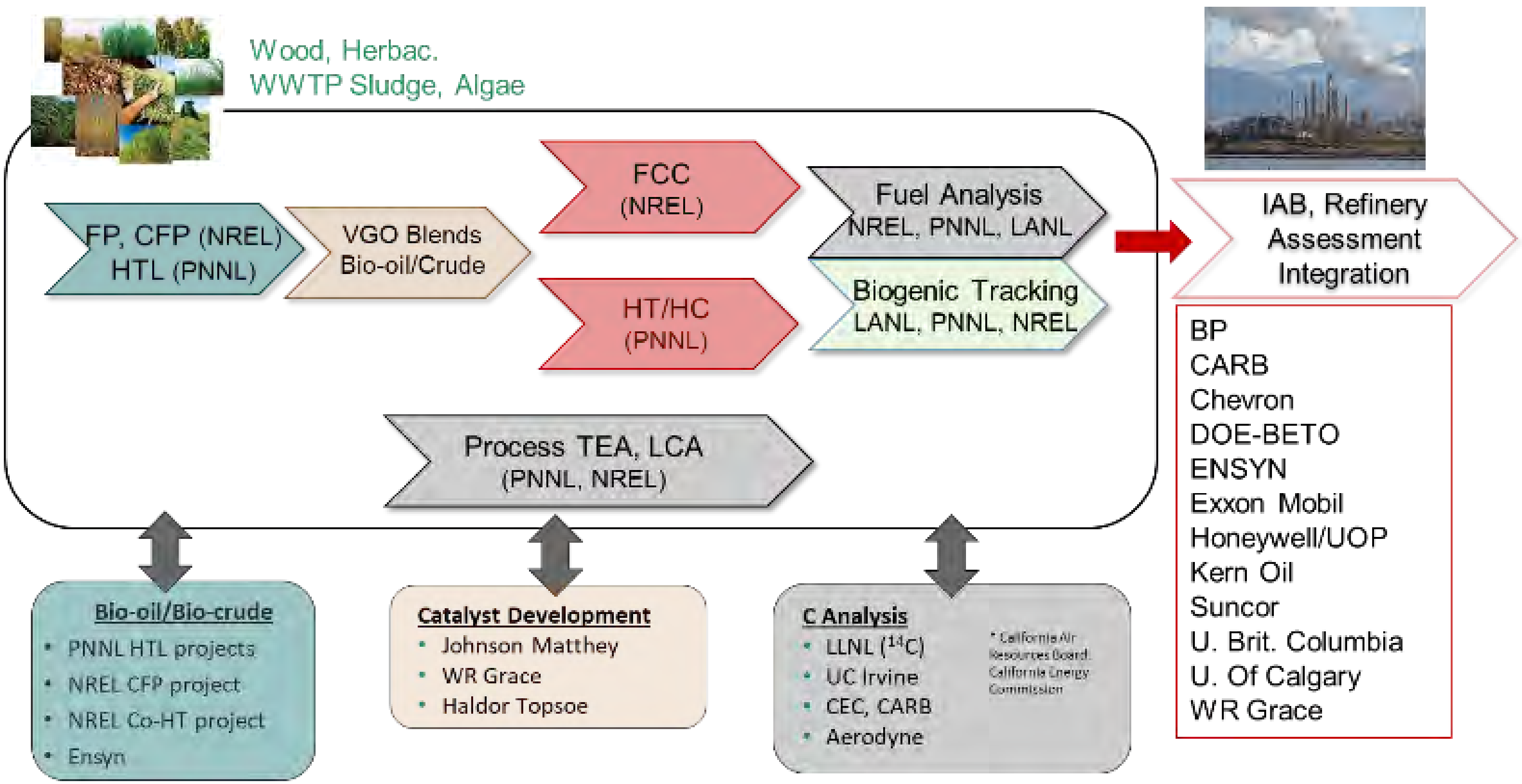


De-risking co-processing requires extensive R&D



Knowledge Gaps	Our approach
Feed quality consistency	Varied feed and feed pretreatment
Maximize biogenic C incorporation	FCC and HT/HC with industrial relevant catalyst/processing tunning
Impact to refinery (chemistry, catalyst, reactor, and fuel quality)	Kinetics/reactor model, catalyst deactivation, fuel quality
Track and measure biogenic carbon	Evaluate and improve low-cost and fast isotope methods
Economic and environmental benefits to refineries and bio-refineries	TEA and refinery impact analysis

An interdisciplinary and collaborative effort to de-risk co-processing in refinery



A comprehensive study of co-processing in hydrotreating and hydrocracking

H$_2$

VGO / SR Diesel / Kerosene / Fuel oil

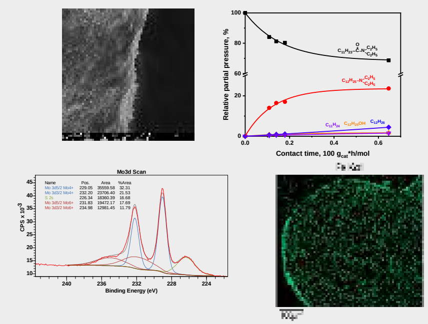
Woody FP bio-oil, Woody CFP bio-oil
Sewage sludge/food waste HTL bio-crude
2-20% blending

Commercial catalyst extrudates

Feed analysis

- Chemical composition
- Heteroatoms and contaminants

Catalyst Characterization



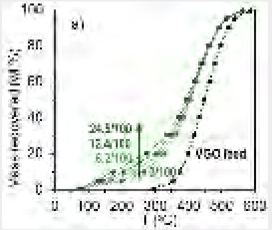
Hydrotreating performance

- >300 h TOS with steady state operation
- HT/HC performance
  - Fuel/gas/water yield
  - Heteroatom removal (N, S, O)
  - Hydrocracking (diesel yield)
- H$_2$ consumption

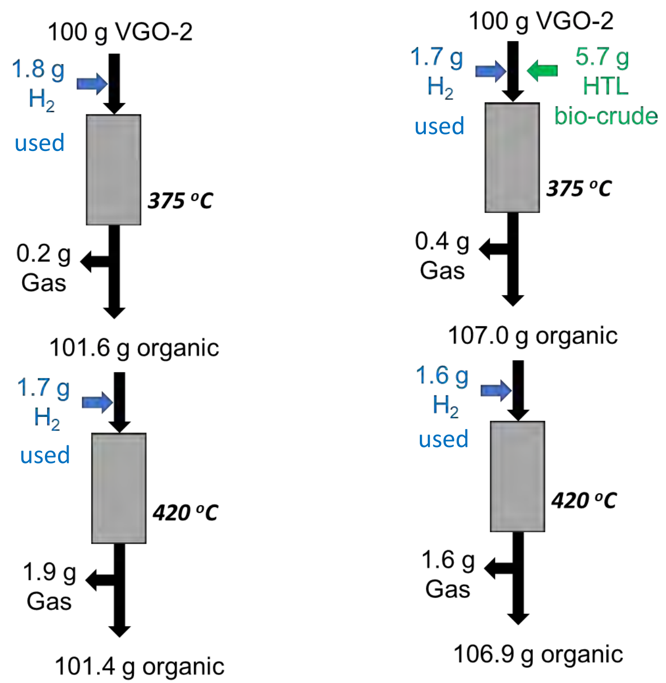
Fuel
Gas
Water

Fuel analysis

- Gas and liquid product composition
- Diesel/Jet quality
- Biogenic carbon content



High biogenic carbon incorporation demonstrated for the HTL bio-crude co-processing



Organic yield, g/g dry bio-crude	96%
Organic carbon yield	97%

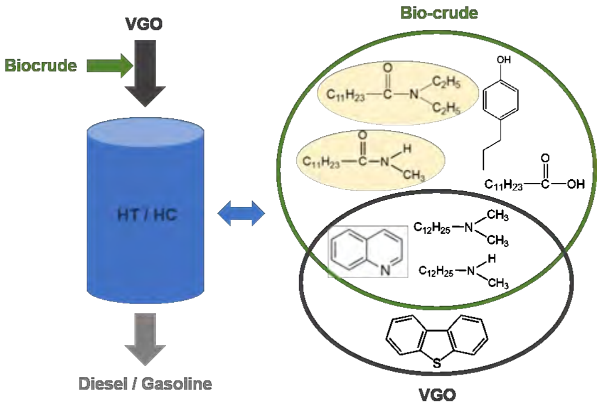
Diesel fraction

	VGO only	5.7/100 HTL/VGO
Cetane Number	42	47
S, ppm	<15	<15
N, ppm	30	93
S. g. at 20°C	0.883	0.881
T90, °C	353	358
pMC, %, by AMS	0.2±0	7.3±0.1

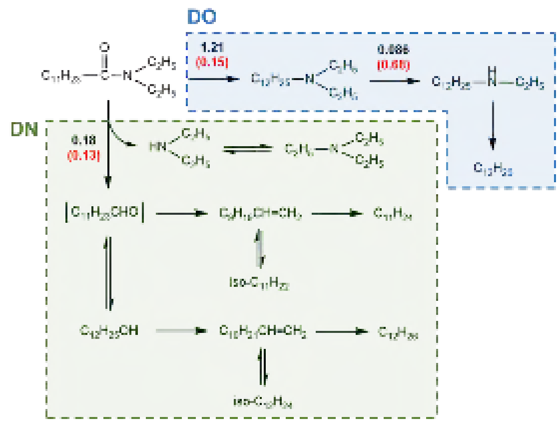
- Competition between heteroatom (S, N, O) removal is critical during co-processing in hydrotreating
- Demonstrated HT pretreatment to mitigate N issues of bio-crude and enable co-processing in HC

Kinetic measurement of HDN/HDO/HDS of bio-crude/VGO guides catalyst selection and supports reactor model development

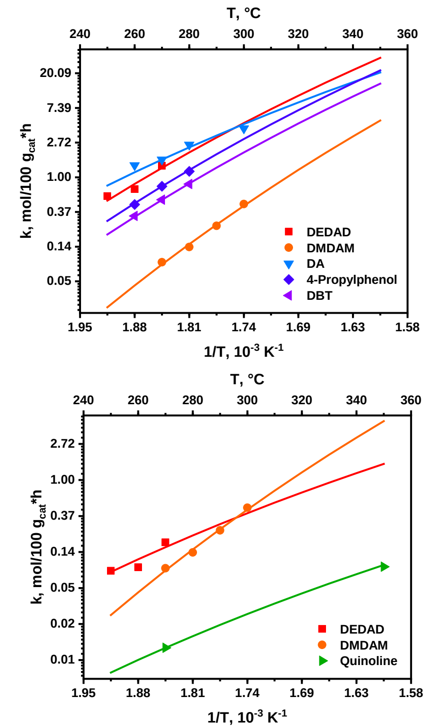
Representative molecules



Reaction network of fatty acid amide



Reaction kinetics and energy measurement

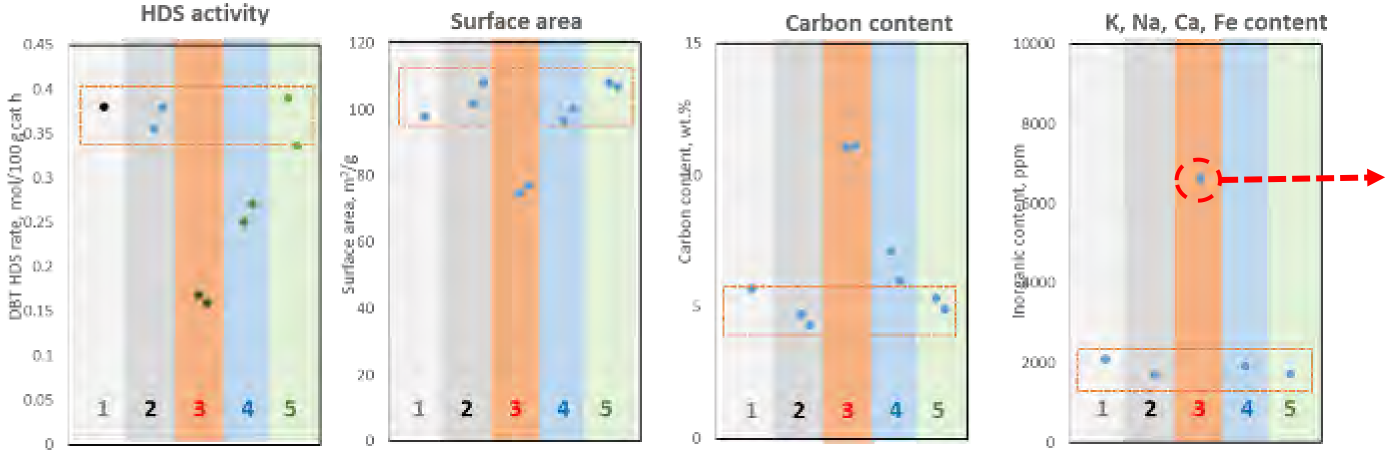


- Hydrodenitrogenation is critical for bio-crude co-processing
- Development of kinetic-based reactor model for co-processing
    - Aspen HYSYS Refinery Models

C. Zhu,… H, Wang, Applied Catalysis B: Environmental, 2022, 307, 121197

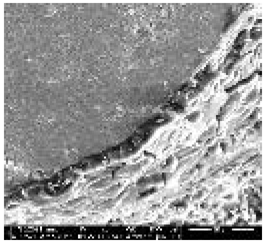
Mitigation of catalyst deactivation by co-processing suggested

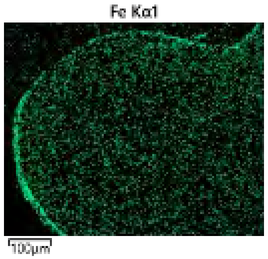
After ~300 h test



1. Fresh 2. Diesel only 3. Diesel with raw bio-crude
4. Diesel with pretreated bio-crude 5. Diesel with pretreated bio-crude and catalyst guard bed

Fouled catalyst after co-processing raw bio-crude





- Bio-crude pretreatment and guard bed use mitigate catalyst deactivation

C. Zhu,… H. Wang, Energy and Fuels, 2022, 36, 9133

Preliminary analysis showed co-processing has potential to reduce biomass conversion cost for biorefinery and benefit refinery by profitable feedstock and renewable carbon in fuel product

Effect of various factors on the upgrading cost of wet waste HTL biocrude with co-processing

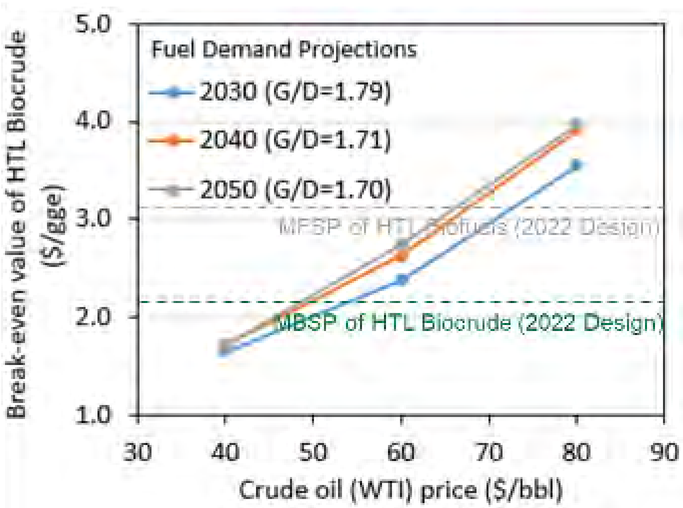
ID	Scenarios	Catalyst and Operating Assumptions				Upgrading Capital Cost Assumptions			Upgrading Cost
		Catalyst Life (yr)	Catalyst Price ($/lb)	WHSV (Hr^{-1})	Change in P_{H2} (%)	Feeding system	H_2 Compressor and PSA	Wastewater Treatment	($/gge)*
1	Without Impacts	2	16.5	0.8	0	No	No	No	0.26
2	Lower Catalyst Life	1.5	16.5	1	0	No	No	No	0.26
3	Higher Catalyst Price	2	32.9	1	0	No	No	No	0.27
4	New Feed System	2	16.5	0.8	0	Yes	No	No	0.27
5	Additional Waste Treatment	2	16.5	0.8	0	No	No	Yes	0.28
6	2, 4 & 5 Combined	1.5	16.5	1	0	Yes	No	Yes	0.28
7	3, 4 & 5 Combined	2	32.9	1	0	Yes	No	Yes	0.29
8	Higher Partial H2 Pressure	2	16.5	0.8	10	No	Yes	No	0.32
9	4, 5, 8 Combined with Higher WHSV	2	16.5	1	10	Yes	Yes	Yes	0.33
10	Conservative (2, 3, 9 Combined)	1.5	32.9	1	10	Yes	Yes	Yes	0.34

$0.26 - 0.34 /gge

Upgrading cost at a standalone bio-refinery = $0.91/gge.

Refinery Impact Analysis of Co-Processing Bio-Oil/Bio-crude and VGO at Mild Hydrocracking Unit

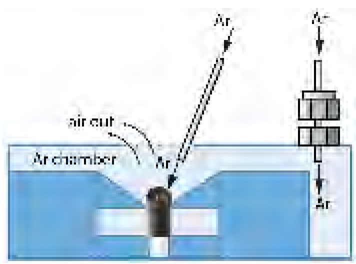
HTL Biocrude

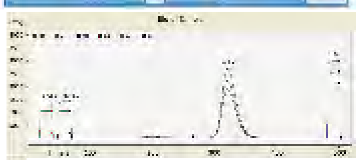


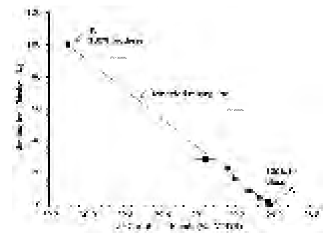
- Increase in operating severities and new capital investment will lead to higher biocrude upgrading cost to some extent
- With on-going R&Ds, the modeled break-even value of CFP bio-oil and HTL biocrude will be greater than their modeled MBSPs at 2022 design cases

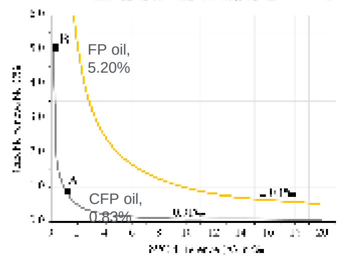
Combing two inexpensive and deployable isotope methods could potentially meet refinery's biogenic carbon analysis requirements

$^{13}C/^{12}C$ Ratio Analysis







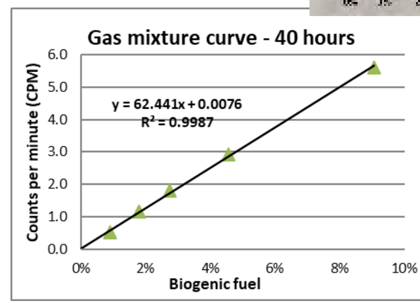


- Developed analytical protocol and algorithm for high-precision analysis of $\delta^{13}C$ and biogenic carbon content
- $\delta^{13}C$ analysis can be used for **online tracking biogenic C** in the co-processing

C^{13}/C^{12}: *ACS Sustainable Chemistry and Engineering*, 2020, 8, 47, 17565
Fuel, 2020, 275, 117770.
Energy & Fuels, 2022, 34, 9, 11134–11142

^{14}C LSC (Liquid Scintillation counting)

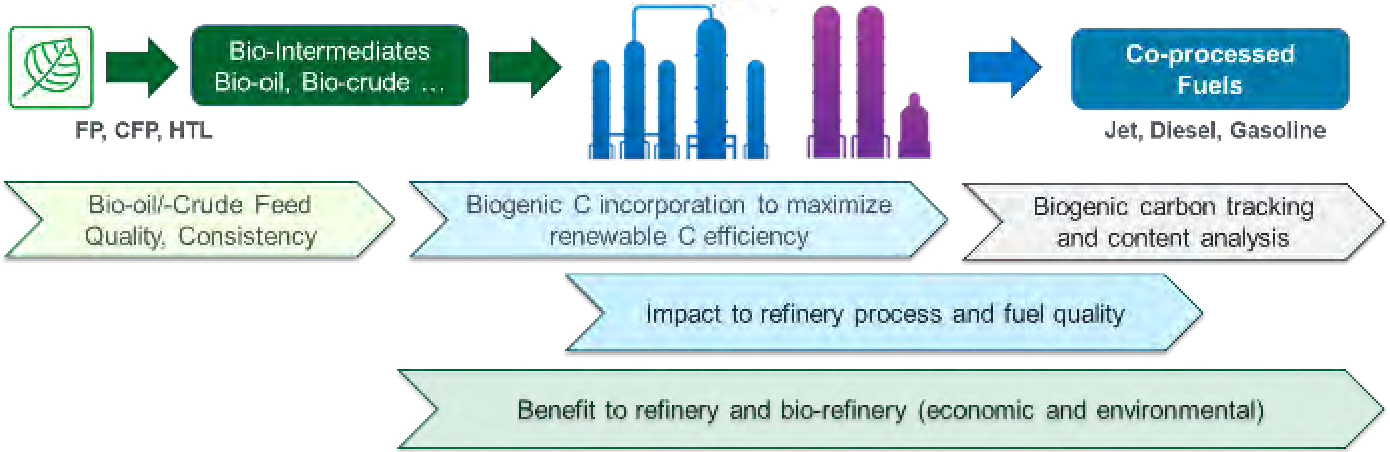
- Direct LSC method
- Compared over three instruments



- Feasible to accurately determine 1% biogenic carbon in fuel
- Direct LSC could be an option for **quality assurance at co-processing facilities**

^{14}C LSC: *Energy & Fuels*, 2022, 36, 7592
Fuel, 2022, 315, 122859
Fuel, 2021, 291, 120084

We can leverage existing refining infrastructures to leverage billions of US$



- High biogenic carbon incorporation by co-processing bio-crudes in HT/HC
- For co-hydrotreating, competition of heteroatom removal is critical. Specifically, for HTL bio-crude with high N content, HDN is the key to enable co-processing in hydrocracking
- Catalyst deactivation by co-processing can be mitigated
- Co-processing can be beneficial to both biorefinery and refinery
- Combing two inexpensive and deployable isotope methods could potentially meet refinery's biogenic carbon analysis requirements

Acknowledgement

Huamin Wang: Huamin.Wang@pnnl.gov
Mike Thorson: Mike.Thorson@pnnl.gov

Pacific Northwest
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Miki Santosa
Igor Kutnyakov
Cheng Zhu
Oliver Gutierrez
Yuan Jiang
Charlie Doll
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Corinne Drennan

Mike Thorson
Andy Schmidt
Justin Billing
Todd R Hart
Samuel P Fox
Dylan Cronin
Karthikeyan Ramasamy,
Daniel B Anderson,
Lesley J Snowden-Swan
Shuyun Li

NREL

Bob Baldwin
Earl Christensen
Kristiina Iisa
Rebecca Jackson
Calvin Mukarakate
Jessica Olstad
Yves Parent
Brady Peterson
Glenn Powell
Reinhard Seiser
Mike Sprague
Anne Starace

Los Alamos
NATIONAL LABORATORY

Zhenghua Li
James Lee
Douglas Ware
Thomas Geeza
Oleg Maltseve
Jacob Helper

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy
BIOENERGY TECHNOLOGIES OFFICE

SDI Program: Beau Hoffman, Mark Shmorhun, Josh Messner, Jim Spaeth

Thank you!

Guest Speaker: Low Carb Fuels Project. Continuous Hydroprocessing of Nitrogen-rich Biocrudes: Challenges and Achievements.

S. Haider, AAU

Continuous Hydroprocessing of Nitrogen-rich Biocrudes: Challenges and Achievements

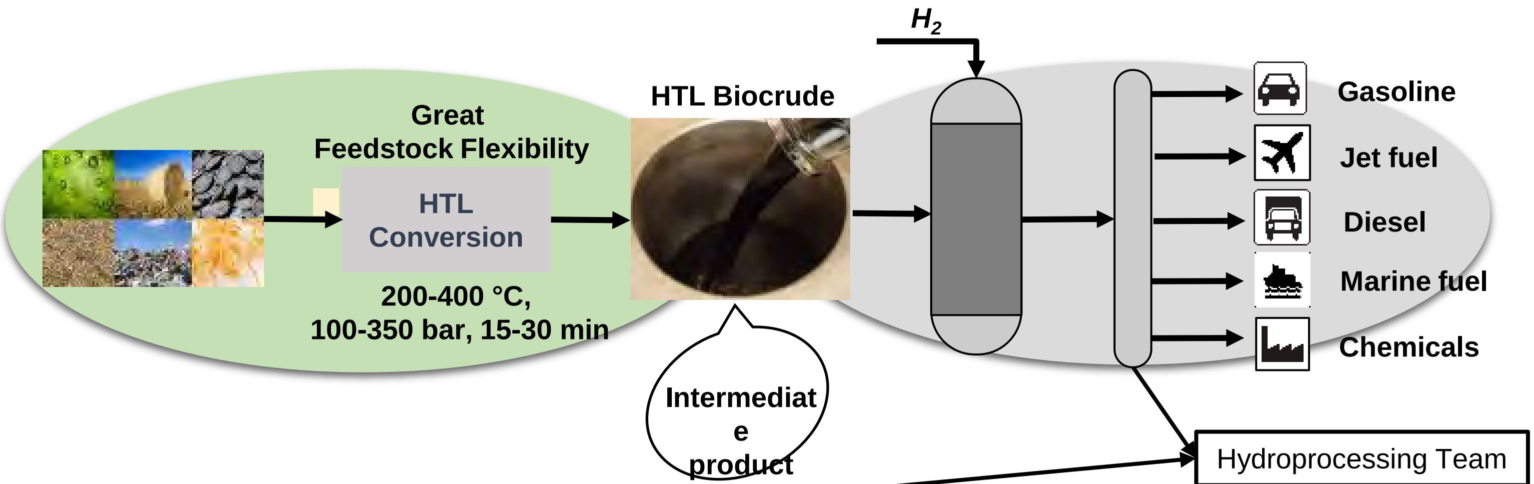
MUHAMMAD SALMAN HAIDER,

DANIELE CASTELLO & LASSE ROSENDAHL

AAU ENERGY, AALBORG UNIVERSITY

AALBORG UNIVERSITY
DENMARK

The Advanced Biofuel Group – Aalborg University

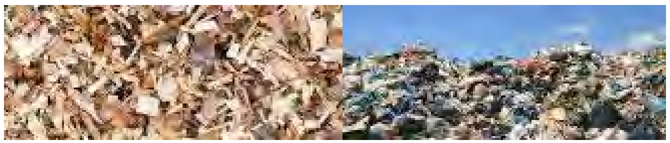


- Removing **heteroatoms** (O, N, S) & metals
- **Saturating** hydrocarbons (increase H/C)
- **Drop-in** sustainable diesel and jet fuel

- Muhammad Salman Haider
- Daniele Castello
- Lasse Rosendahl

AAU ENERGY

Renewable Biomass Feedstocks - Revised EU-RED II (Annex IX part A)



Solid Wastes

Agricultural residue

Forestry residue

Sewage sludge

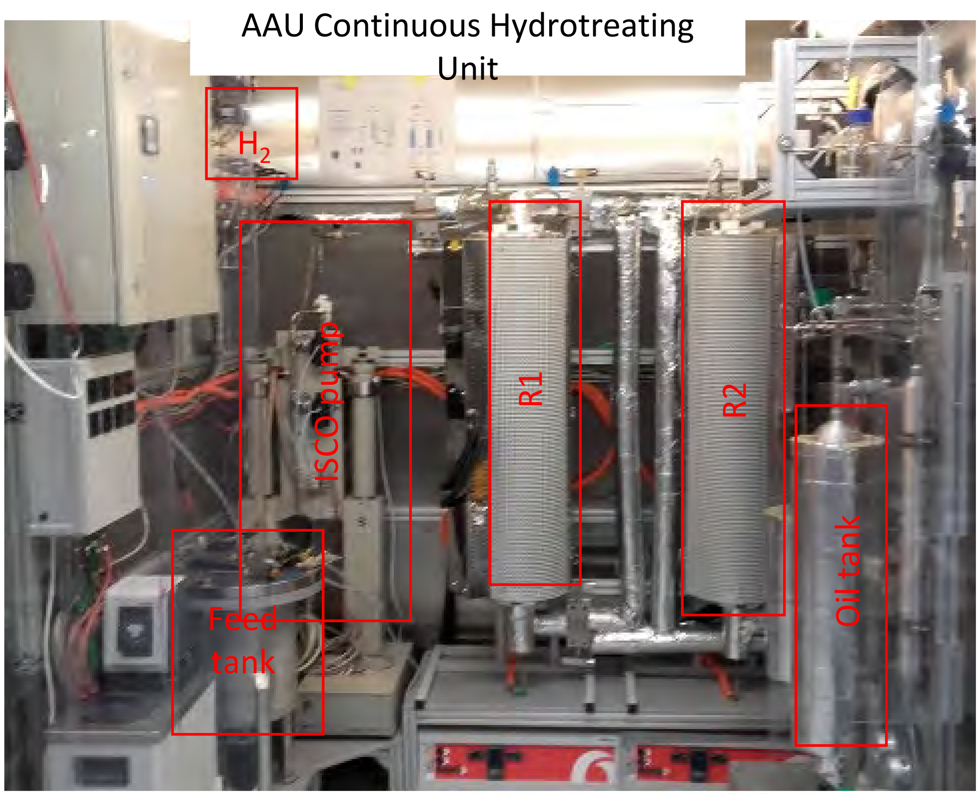
Organic fraction of MSW

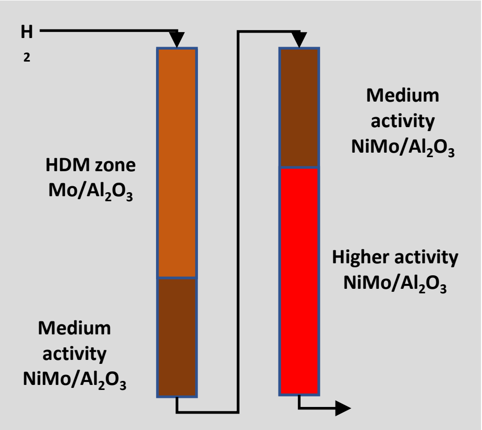
Low ILUC/rotational crops

Micro/macro algae

Miscanthus

Hydrotreating Unit at AAU





No. of Reactors	2
Reactor Volume	150 cm^3 (each)
Operating mode	Independent / series
Reactor type	Tubular, packed-bed
Flow mode	Down -flow
Usual throughput	~ 80 mL/h
Heating	3-zone tubular furnace
Max. Operating P	150 bar

Hydroprocessing Activities at AAU

4refinery

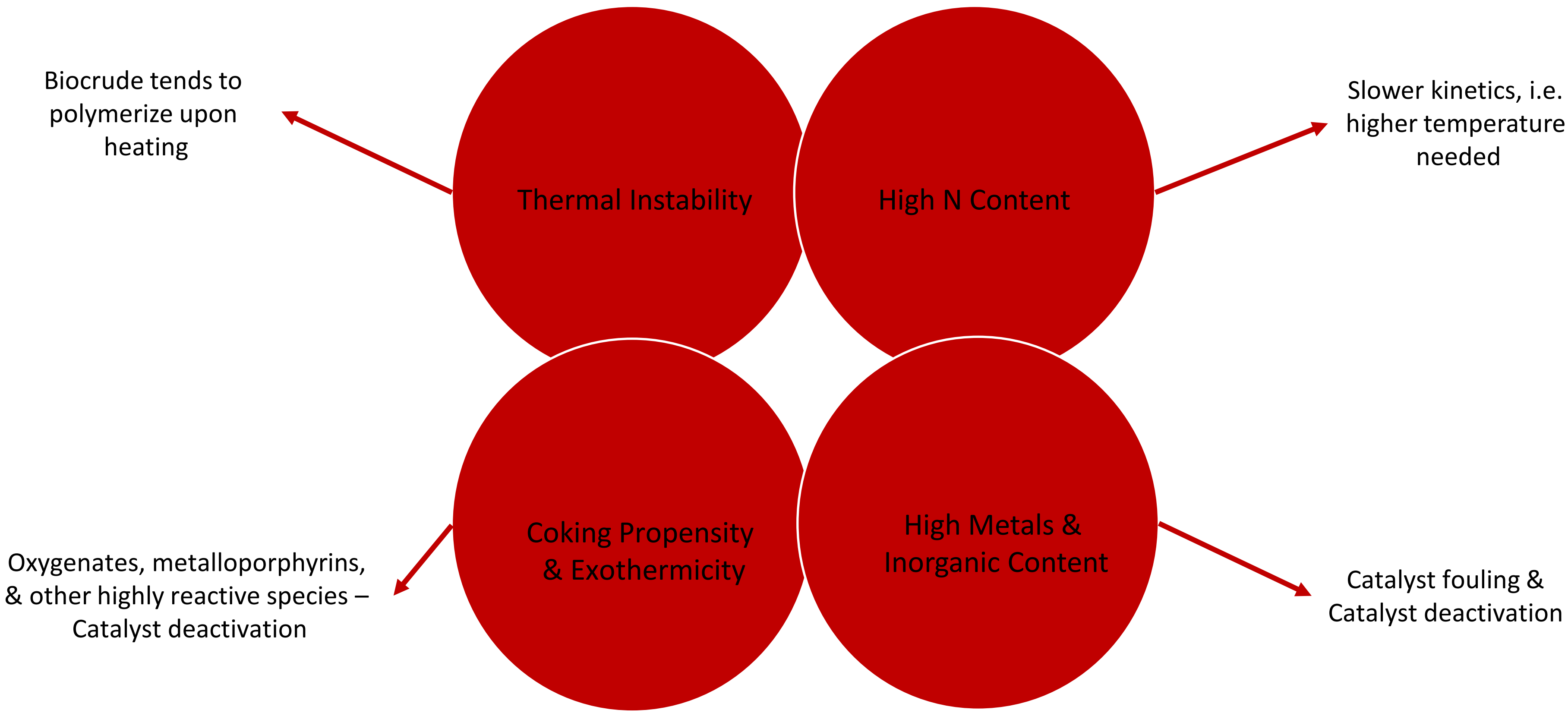
HyFlexFuel

NEXTGEN roadfuels

Low Carb Fuels

AAU ENERGY

Main Challenges during biocrudes Hydroprocessing

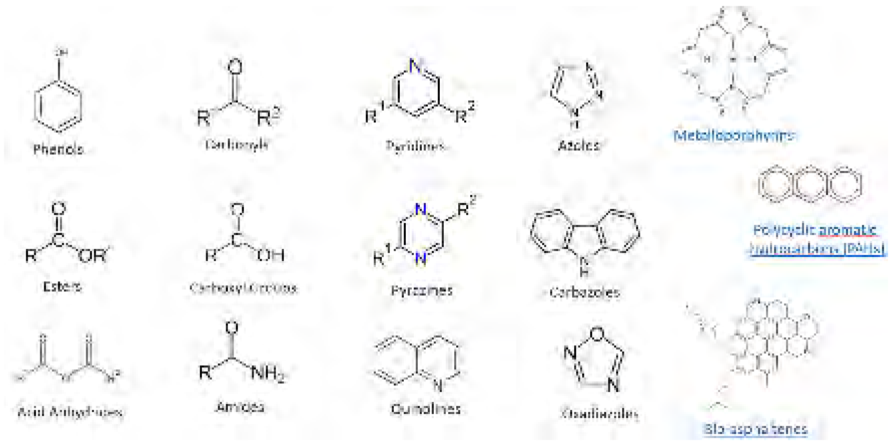


Hydroprocessing Activities at AAU – Early 2019

4refinery

- **Pine Wood HTL biocrude**
- **3 failed hydrotreating campaigns in 5 months**
- **Immediate and severe plugging with both CoMo and NiMo**
- **No more than 10 hours of continuous hydrotreating was achieved**
- **Entire work carried-out by following the data reported in literature (biocrudes cont. hydroprocessing)**

Rethinking the Hydroprocessing of Biocrudes

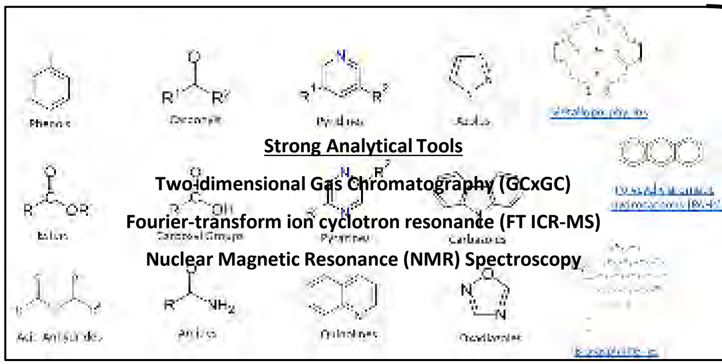


- Complexity of biocrudes

- Thermal Instability of Biocrudes

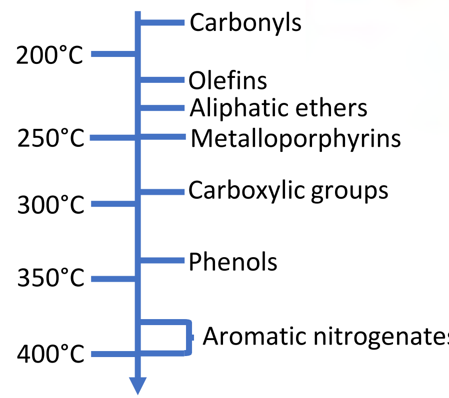
Biocrudes Hydroprocessing - What is to keep in mind?

1.
Molecular-Level Understanding of Biocrudes



2.
Thermal Instability of Biocrudes

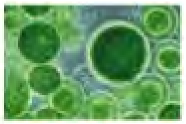
different molecules have different reactivity



3.
Comprehension of Catalysis and Reaction Chemistry

Hydroprocessing Activities at AAU – End 2019 to Early 2021

HyFlexFuel



Spirulina

Stabilization (330-350 °C) → Upgrading (330-400 °C)

335 hours

Sewage sludge

Pre-stabilization (260 °C) → Stabilization (330-350 °C) → Upgrading (330-400 °C)

165 hours

Wheat straw

Stabilization (260-340 °C) → Upgrading (300-380 °C)

215 hours

Nitrogen Removal – A Challenge during Biocrudes Hydroprocessing

Nitrogen limit

Nitrogen in Fuels (i.e. SAF's) lowers the

- Storage Stability
- Thermal Stability

	N (ppm)
ASTM SAF's Current limit *(for other approved SAF's from biofuels)*	**2**

Distribution of "N" after biocrudes hydroprocessing

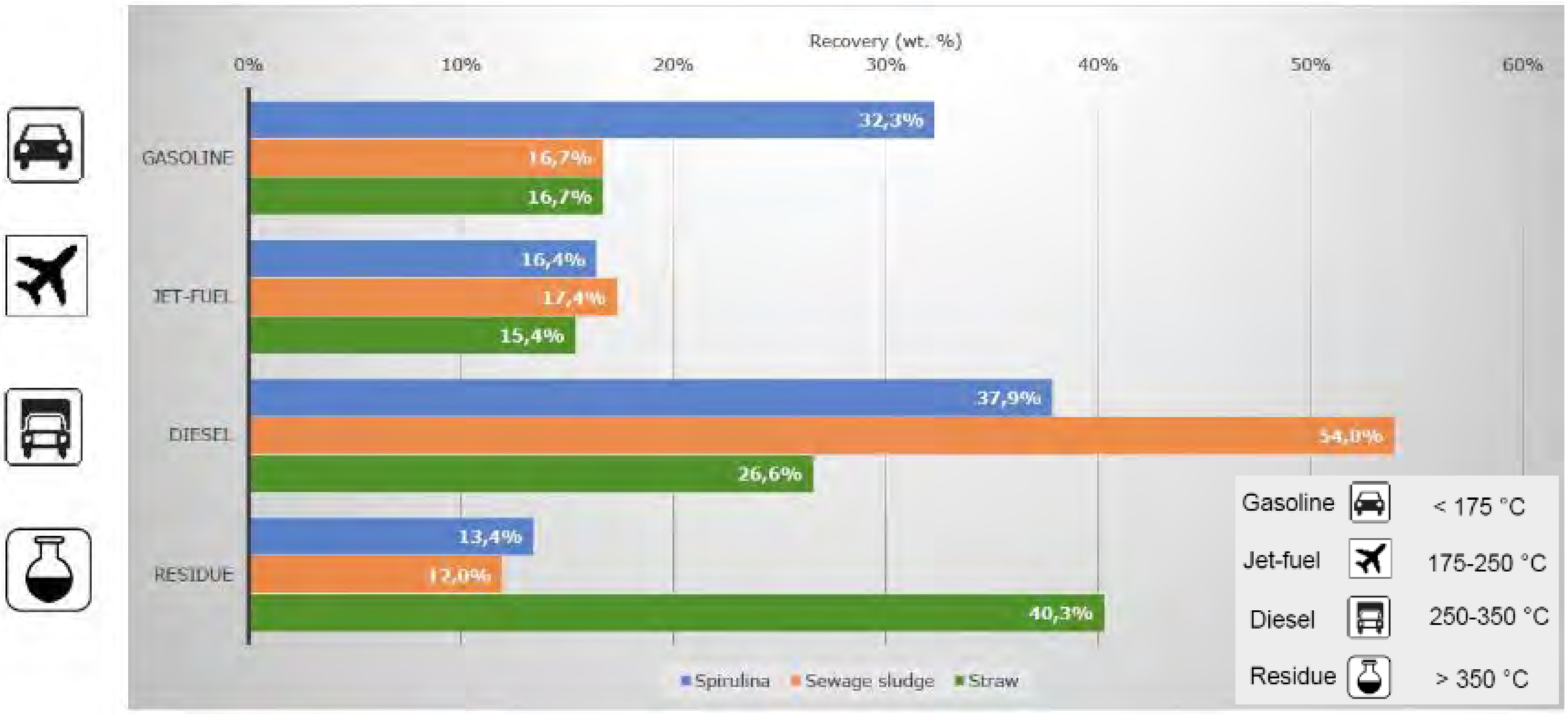
Nitrogen Removal – not a challenge anymore!

- **<u>Complete HDN</u> – achieved by re-thinking/re-evaluating the entire biocrude hydroprocessing**
  - with lower catalyst loading or high WHSV/LHSV

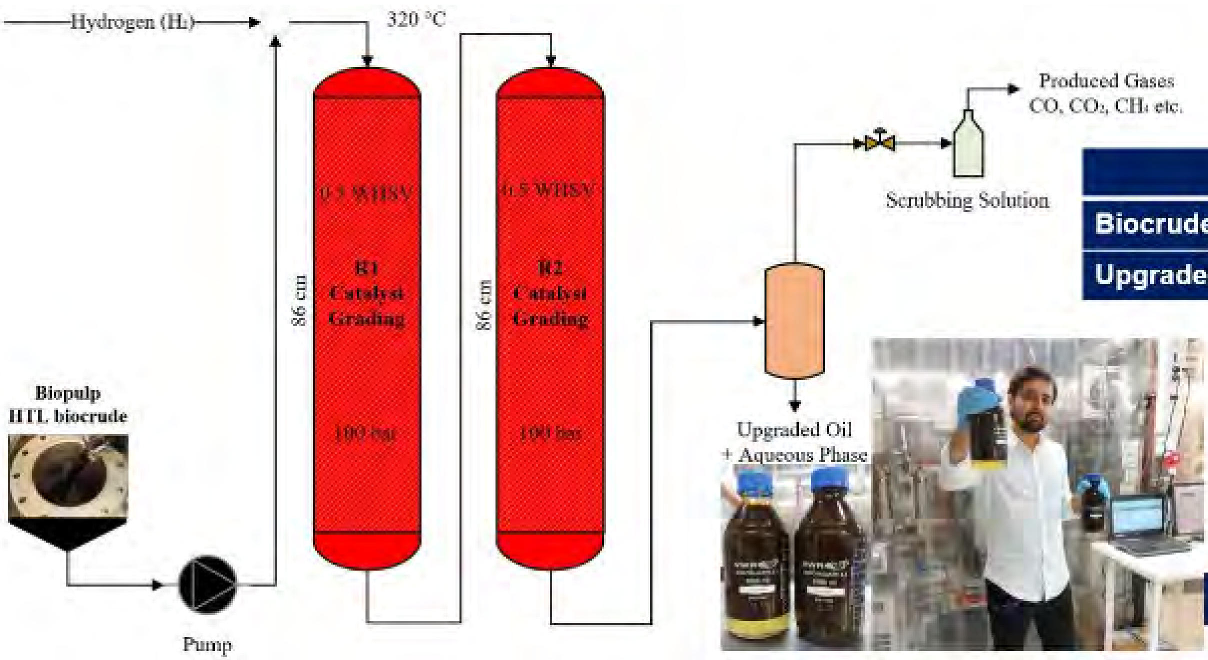
ASTM D4629 → <7.4 ppm N

ASTM D5453 → 9 ppm S

Distillation and Yields - Hydroprocessing Activities at AAU



Hydroprocessing Activities at AAU – End of 2021



	O	S	N	H/C
Biocrude	8.9	0.30	3.4	1.58
Upgraded	0.2	0.07	3.2	1.90

AAU ENERGY

Hydroprocessing Activities at AAU – Early 2022 to present day

Low Carb Fuels

Deutsches Zentrum für Luft- und Raumfahrt German Aerospace Center (DLR)

AALBORG LUFTHAVN | AIRPORT

IFP Energies nouvelles

Billund Airport

AARHUS AIRPORT

SKYNRG

DCC | Shell

steeper ENERGY

COWI

energy CLUSTER DENMARK

PORT OF AALBORG

MAERSK

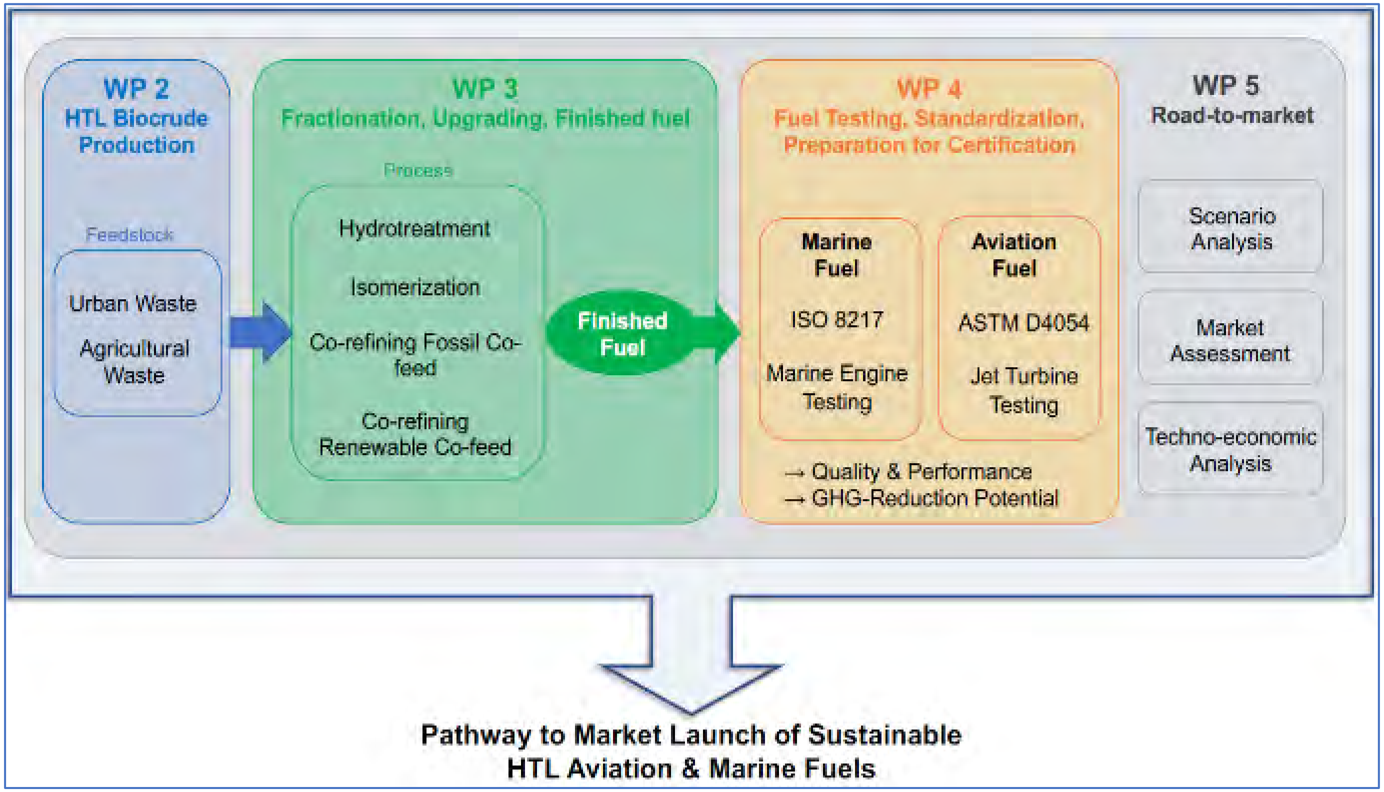
AARHUS HAVN PORT OF AARHUS

ALFA LAVAL

GREENFUELHUB

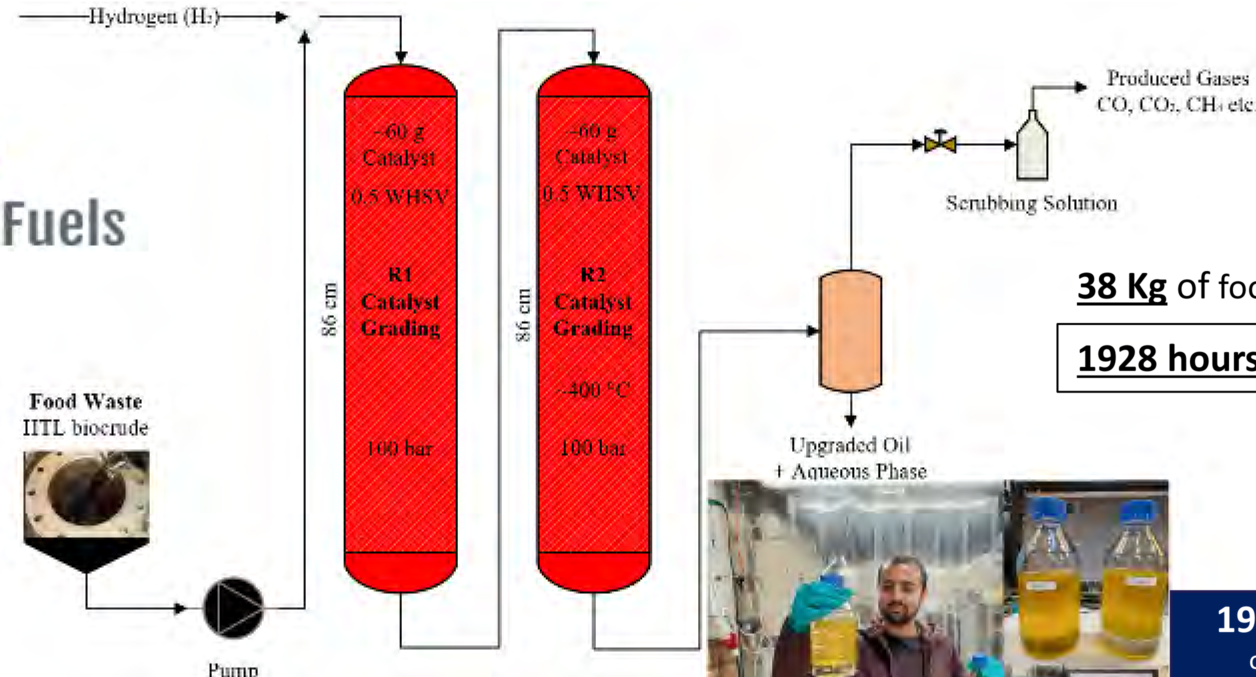
AAU ENERGY

Hydroprocessing Activities at AAU – Early 2022 to present day



Hydroprocessing Activities at AAU – Early 2022 to present day

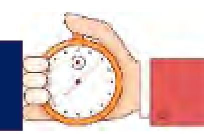
Low Carb Fuels



38 Kg of food waste HTL biocrude

1928 hours on-stream in-one-go

1928 hours on-stream



AAU ENERGY

Conclusion

- Comprehensive knowledge about molecular structure of HTL biocrudes and catalyst is vital
- Catalyst deactivation due to coking is suppressed by identifying biocrude thermal instability & highly reactive organic species
- HTL + optimized longer continuous hydrotreating runs are possible and can produce promising drop-in biofuels (SAF’s & diesel)
- Complete denitrogenation (in nitrogen-rich HTL biocrudes) and nitrogen chemistry is a topic of on-going research

Guest Speaker: Chemical recycling of waste plastics by HTL

S. Raveendran, UVA

UNIVERSITY OF AMSTERDAM

Chemical recycling of plastics by HTL

Dr. Shiju Raveendran

Associate Professor

Catalysis Engineering group

Van't Hoff Institute for Molecular Sciences,

University of Amsterdam

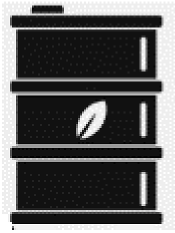
Hydrothermal Liquefaction

Waste collection and processing

Solvothermal liquefaction

Biocrude

Catalytic upgrading



Renewable fuel

Annual volumes of organic waste:
- -Amsterdam Households (872.380 consumers): 100kton.
- -Current: burning Meerlanden, Attero, Renewi: Costs:119€/ ton
- -Food industry: 142kton organic waste per annum.
- -MRA: 138kton (incl. Amsterdam)

Booking.com

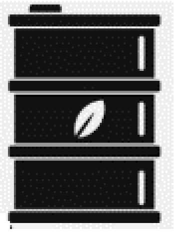
Q8 Research

Hydrothermal Liquefaction

Waste collection → Feed processing → HTL → Catalytic upgrading

HTL ↓ Recovery of Carbs, Proteins

Catalytic upgrading ↓



Renewable fuel

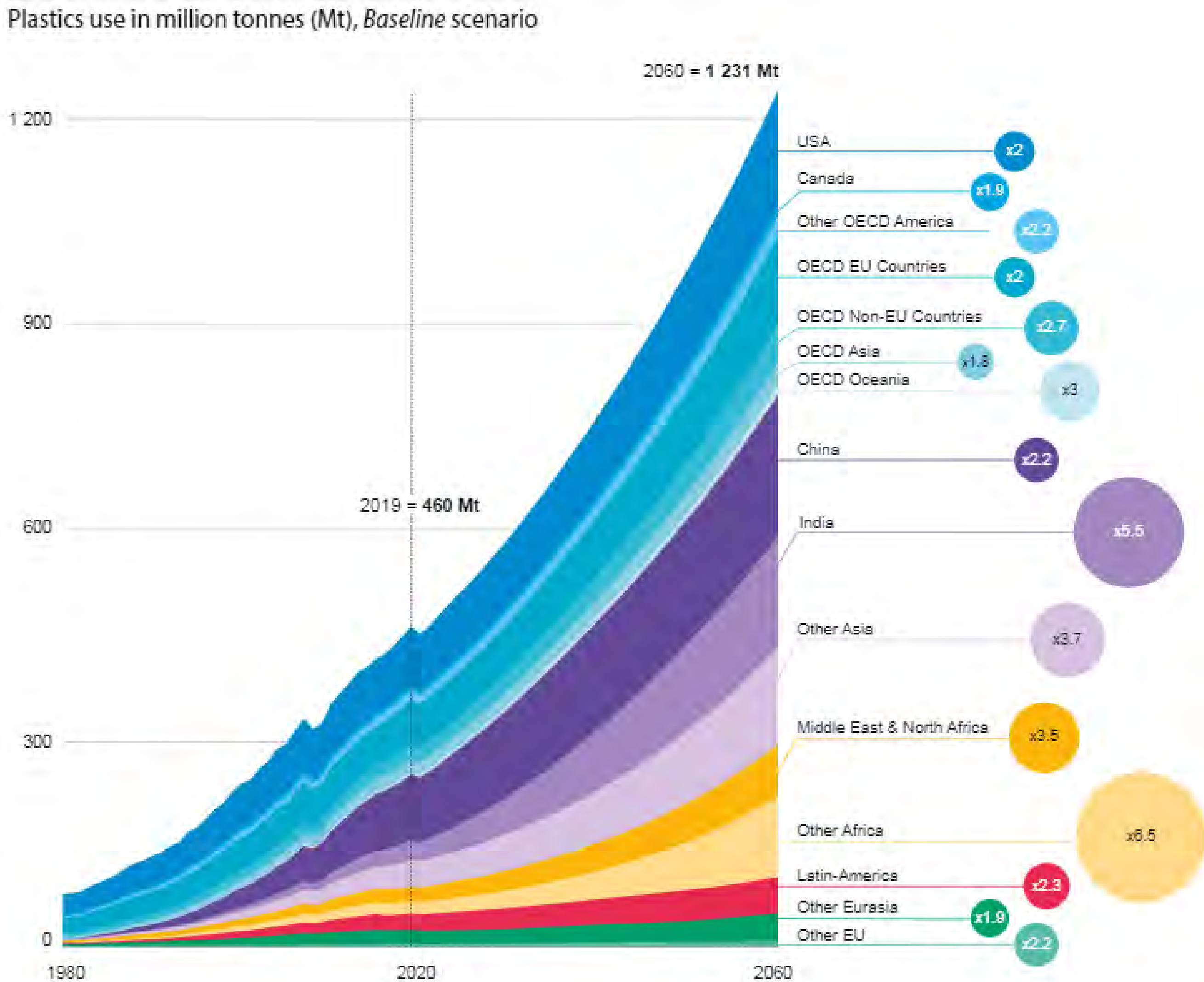
Handles any organic waste - Feed –flexible Technology *(food waste, food processing waste, Agro waste, manure, industrial waste, mixed non-recyclable plastics)*

Energy efficient*: Uses water in waste as a reactant and recovers mineral-rich water. No need of drying wet waste*

Drop-in renewable crude as product: *Energy-dense liquid crude, compatible with petroleum crude. Can be processed in existing refining infrastructure. No change required in engine technology.*

US EPA
https://www.epa.gov › plastics-material-specific-data

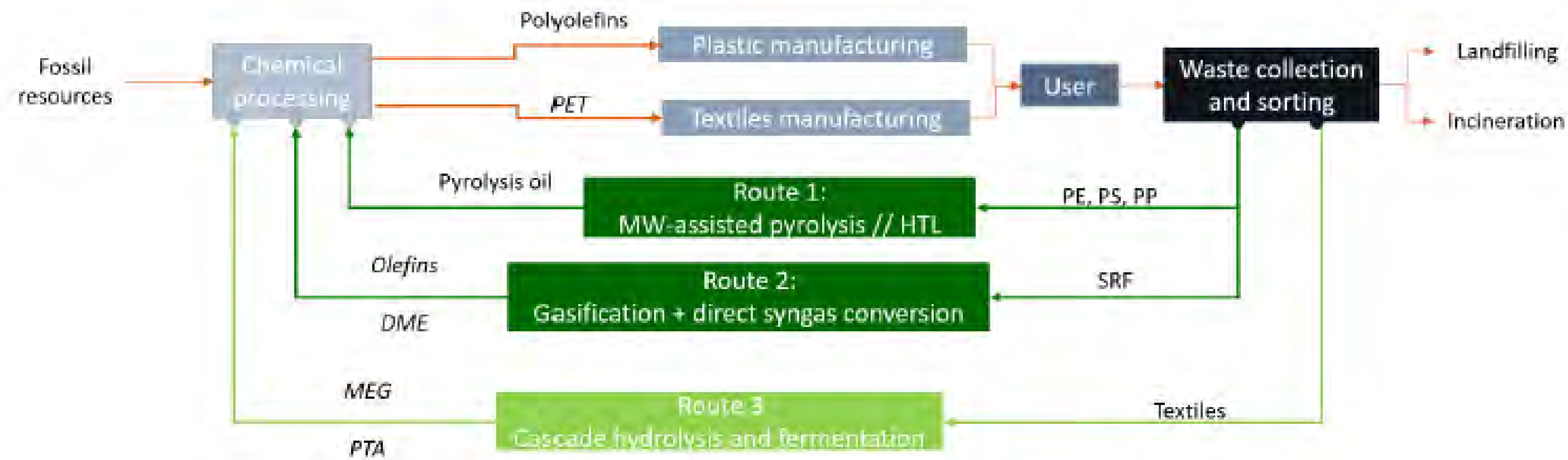
Projected growth in plastics



OECD, Global Plastics Outlook: Policy Scenarios to 2060, 2022, https://www.oecd.org/environment/plastics/

Plastice-Closing the loop in the plastic lifecycle

To valorize a wide range of unsorted plastic and textile waste



Overall: 20 million Euros
HTL: 1.6 million Euros

European Commission

PLASTICE

https://plastice.eu/

Horizon Europe

Plastice-consortium

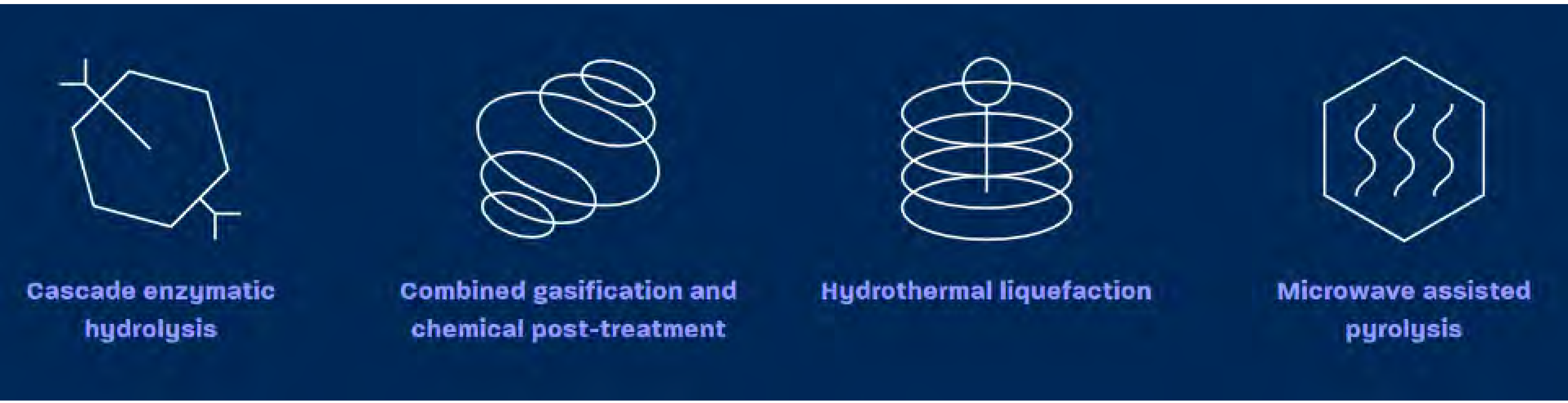
Consortium

circe FUNDACIÓN CIRCE – CENTRO DE INVESTIGACIÓN DE RECURSOS Y CONSUMOS ENERGÉTICOS Project Coordinator	urbaser URBASER	AZCATEC TECNOLOGIA E INGENIERIA AZCATEC TECNOLOGÍA E INGENIERÍA	UNIVERSITY OF AMSTERDAM Van 't Hoff Institute for Molecular Sciences UNIVERSITEIT VAN AMSTERDAM
COGERSA COGERSA SAU	RINA RINA CONSULTING	Consiglio Nazionale delle Ricerche CNR-ITAE – CONSIGLIO NAZIONALE DELLE RICERCHE	P.R.T. S.R.L. POLYURETHAN RECYCLING TECHNOLOGY
CE.ECO CHEMICAL EMPOWERING	TotalEnergies TOTALENERGIES	ALBÉA ALBÉA SERVICES	CENTEXBEL CENTRE SCIENTIFIQUE & TECHNIQUE DE L'INDUSTRIE TEXTILE BELGE ASBL

Plastice-consortium

TRANSFERCENTER FÜR KUNSTSTOFFTECHNIK	DE KRINGWINKEL ANTWERPEN	AUSTROCEL HALLEIN	KORTEKS
SUN TEKSTIL	LA FUNDACIÓN CTIC – CENTRO TECNOLÓGICO PARA EL DESARROLLO EN ASTURIAS DE LAS TECNOLOGÍAS DE LA INFORMACIÓN	INSTITUTE OF COMMUNICATION AND COMPUTER SYSTEMS	RINA CONSULTING – CENTRO SVILUPPO MATERIALI
JUSTB2B – B2B CONSULTING GROUP	POLYMERIS	FONDAZIONE ICONS Communication and dissemination leader	

Plastice-Closing the loop in the plastic lifecycle



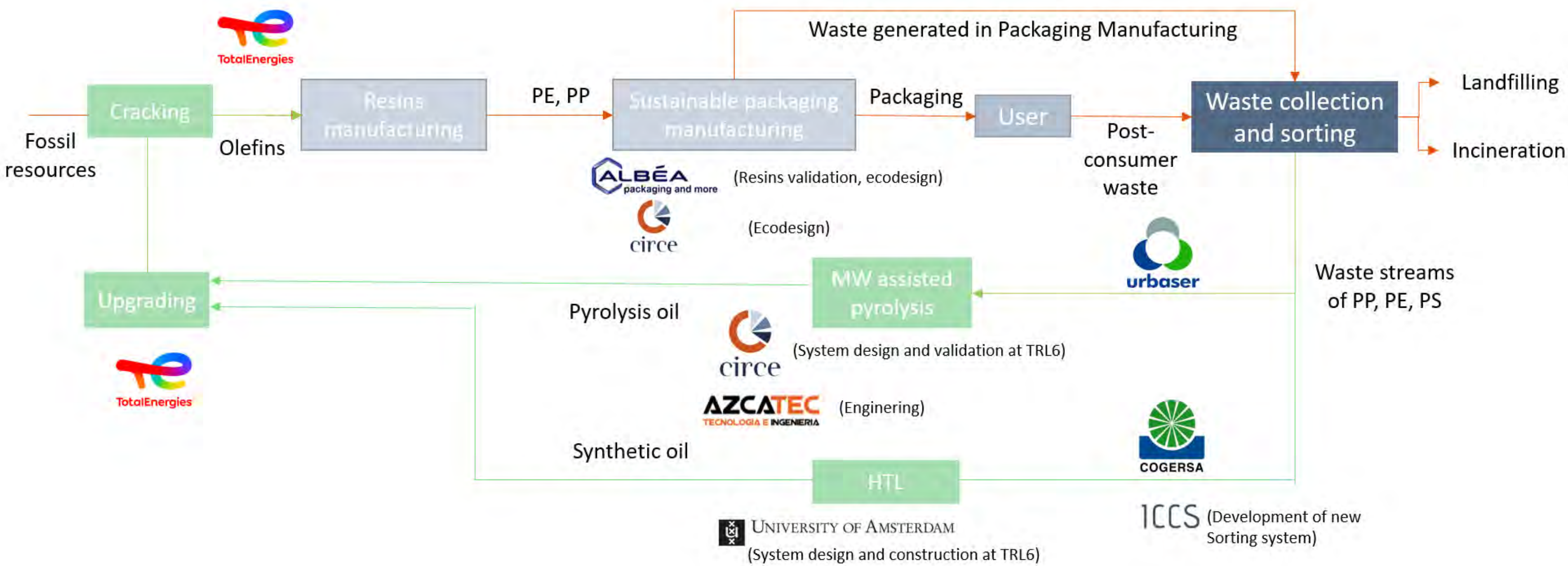
European Commission

PLASTICE

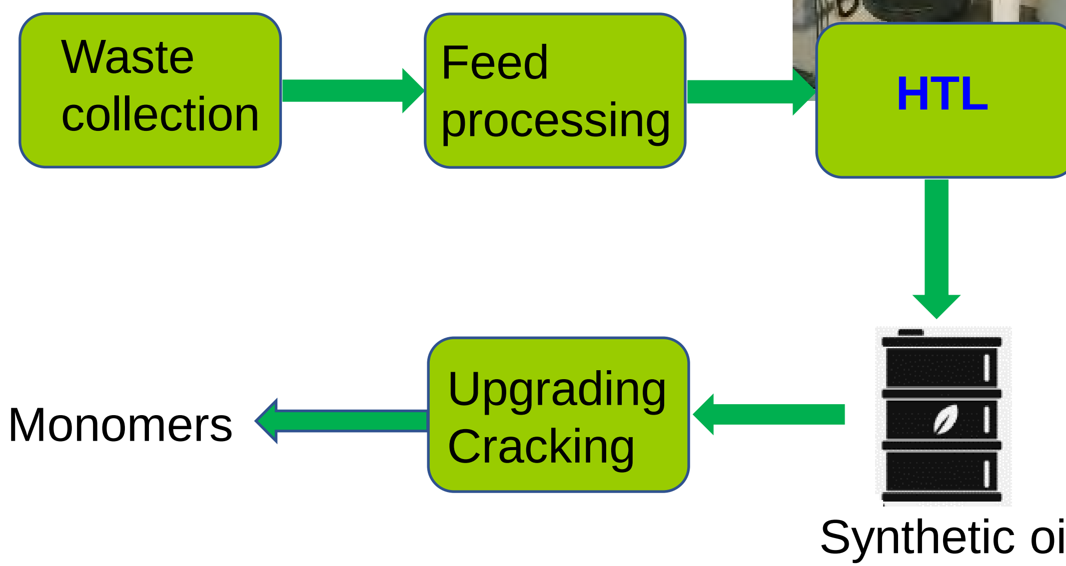
https://plastice.eu/

Horizon Europe

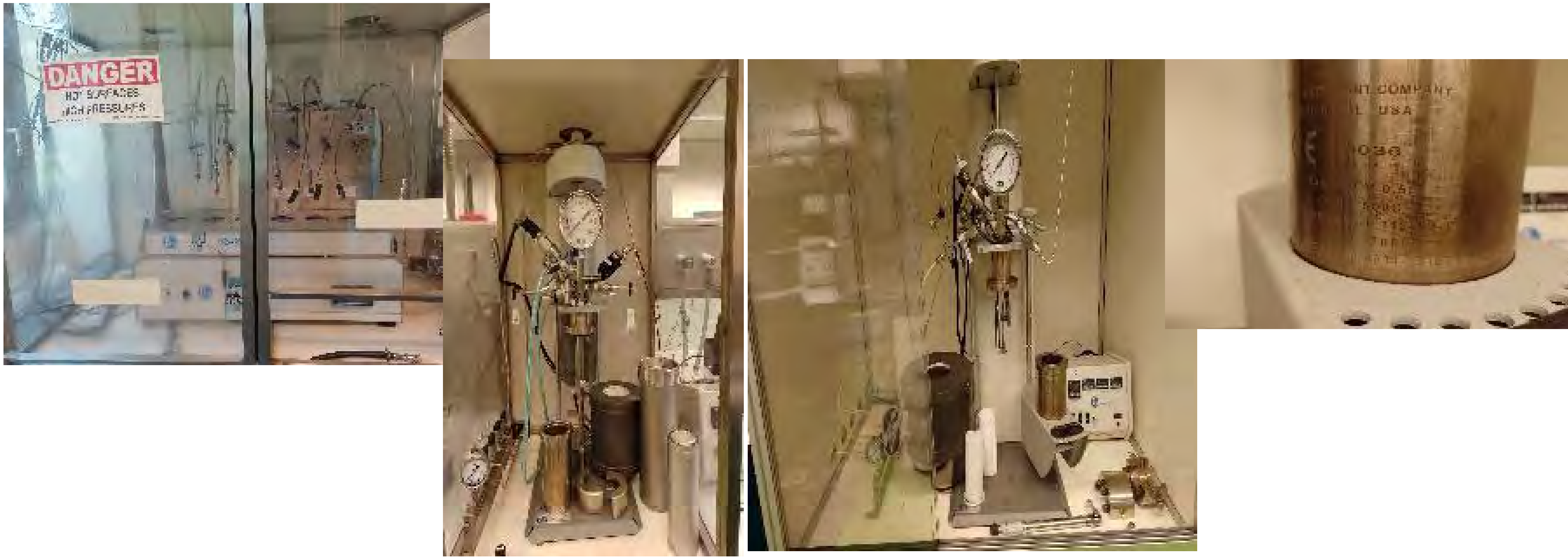
Plastics recycling by HTL



Plastics recycling by HTL



Plastics recycling by HTL



1. A parallel reactor of six reactors, each with a volume of 50 ml. Quick screening of catalysts and conditions.
2. A reactor of 450 ml, max. temp and pressure = 300 deg C and 200 bar
3. A reactor of 500 ml, max. temp and pressure = 500 deg C and 345 bar
4. A reactor of 2000 ml, max. temp and pressure = 400 deg C and 160 bar

Plastics recycling by HTL

Plastics extrusion (first step)

Mix plastic with water and pump with a flow rate of 6 ml/min

Reactor
Operation temp 620 °C and 220 bar

Months	6	12	18	24	30	36	42	48
Labscale study and optimization								
Numerical simulation								
Basic engineering								
Validation, testing, demonstration trials								

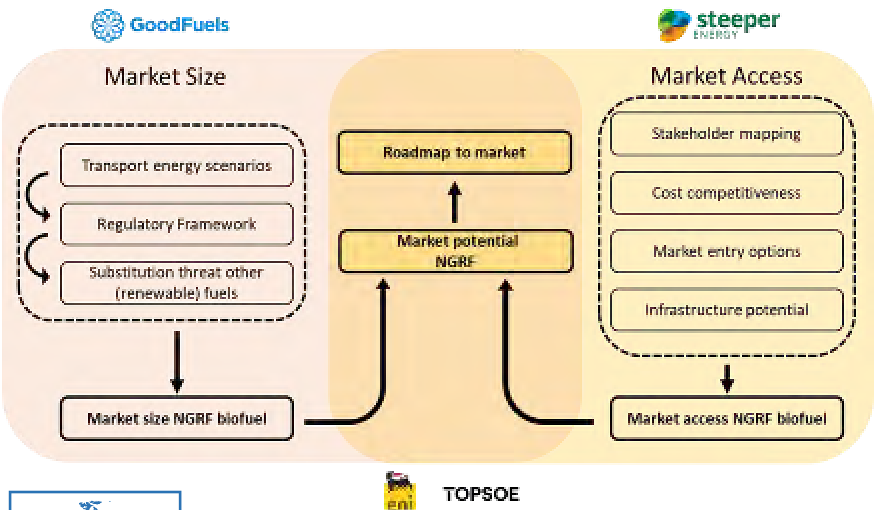
This project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No 818413

Market Scenarios and Commercial Pathway

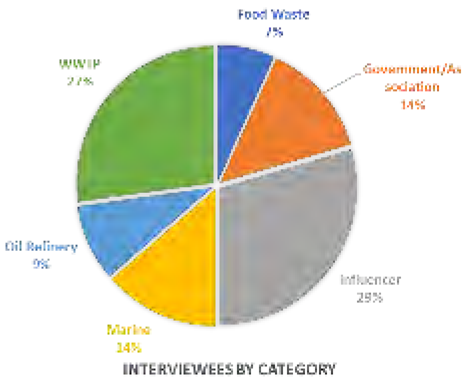
F. Ferrari, GoodFuels

Ling Li, Steeper Energy

Fuel Market Go-to-Market Strategy



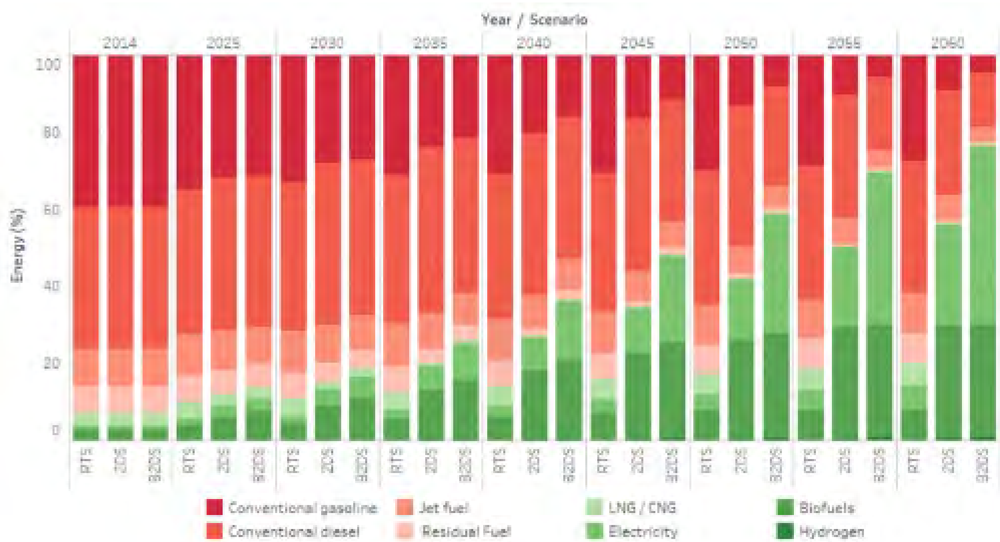
CONDUCTED **MCA** AMONG **7** COUNTRIES
THE **NETHERLANDS**, **SWEDEN**, FRANCE, **GERMANY**, UNITED KINGDOM, GREECE, DENMARK



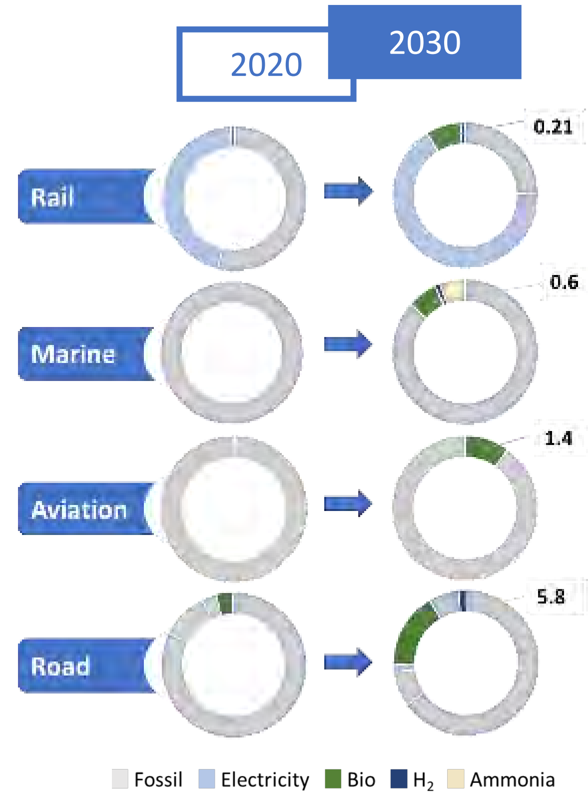
45+ INTERVIEWEES FROM
THE NETHERLANDS, GERMANY, SWEDEN. ITALY, NORWAY, DENMARK, SWITZERLAND

Market Size HTL Biofuel-Transport Energy Scenarios

- Quantify future energy consumption in the European and global transport sector
- Forecast of what is likely to happen in the future under certain conditions (assumptions).



Consumption world per fuel type for IEA scenarios



Market Size HTL Biofuel-Regulatory Frameworks & Targets

- Targets and Policies by government institutions that can promote/influence the uptake of biofuels

- Fuel Quality Directive
- Transport Biofuels Directive
- Renewable Energy Directive (expected RED III)
- EU Green Deal – Fit for 55

- Renewable Fuel Standard Program
- Chinese demonstration programs
- Indian ethanol/ biodiesel blending program

- International Convention for the Prevention of Pollution from Ships

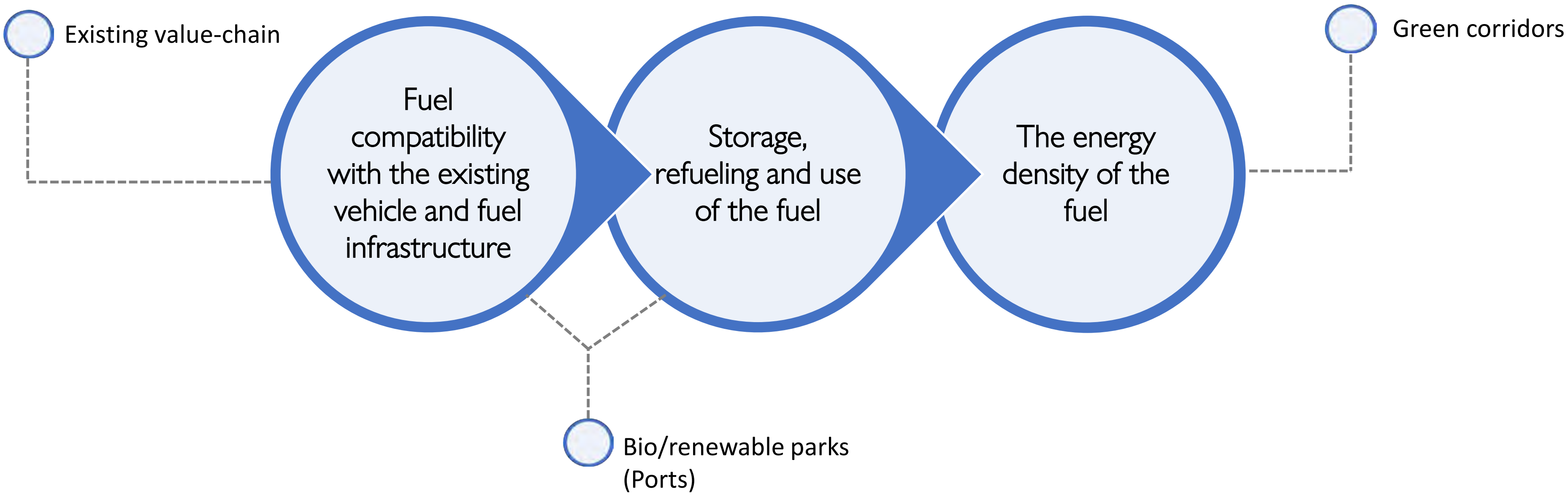
- Carbon Offsetting and Reduction Scheme for International Aviation

European countries with a ticket system regarding biofuel

Market Size HTL Biofuel-Substitution threat (other fuels)

No single fuel solution for the future of low-carbon mobility.

Factors that influence the suitability of the fuel for a specific transport mode are:



Market Access HTL Biofuel-Stakeholder Mapping

Feedstock Suppliers

- **SS:** limited due to increasing build-out capacity from mono-incineration
- **Biowaste:** EU WFD amendment mandates to separate collect biowaste by 2023

Challenges & Opportunies by country

- **NL:** all 21 waterboards towards energy neutrality by 2030 and circular by 2050; 16 of them are vested in mono-incineration
- **DE:** P recovery mandate by 2029; 22 mono-incineration plants by 2018 with more under construction; opportunity in states with land-spreading or co-incineration at coal-fired plants (exit by 2035)
- **SE:** mainly land-application; policy uncertainty

Design HTL plant to process both sewage sludge and biowaste

Fuel Offtake

- **Oil refineries:** obligated to meet national blending mandates; advanced biofuels with low CI preferred; price tolerance: not exceed the non-compliance penalty
- **Marine sector:** no international policy or incentives; carbon neutral target 2040/2050; believes advanced biofuels the most economically feasible zero-emission alternative for short- to mid-term; premium 15%; competing with road & aviation

Challenges & Opportunies by country

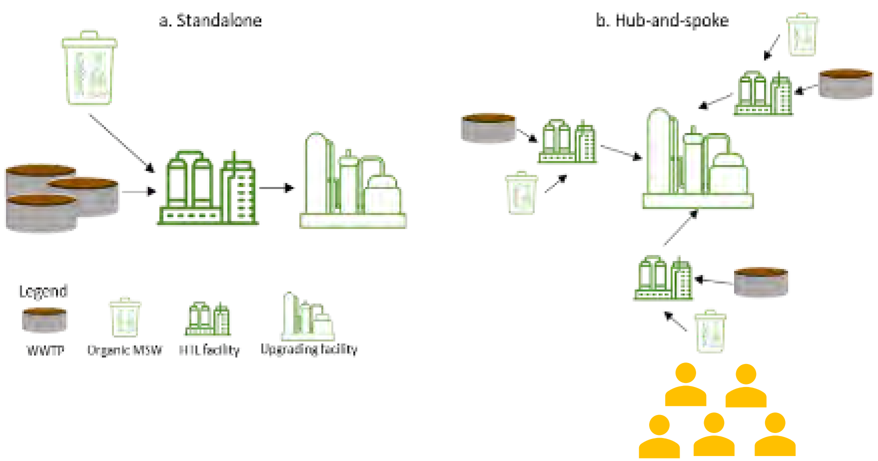
- **NL:** interested in "green projects" and low carbon fuel solutions; centralized infrastructure, Port of Rotterdam is EU's largest bunkering port
- **DE:** heavily focused on green hydrogen; oil refineries do not have green hydrogen initiatives in place are an opportunity for HTL build-out
- **SE:** open-minded to co-processing; advanced biofuels projects focused on HVO from tall oil;

Port of Rotterdam is an ideal location

SE is likely to be the first mover for co-processing HTL biocrude

Market Access HTL Biofuel

Infrastructure Potential



To the marine sector:

1. Infrastructure is key to alternative fuels implementation in the shipping industry, and may be more important than cost
2. Prefer to have biofuels supply at large bunkering ports worldwide

Market Entry Options

HTL biocrude, as-is, or partially upgraded product

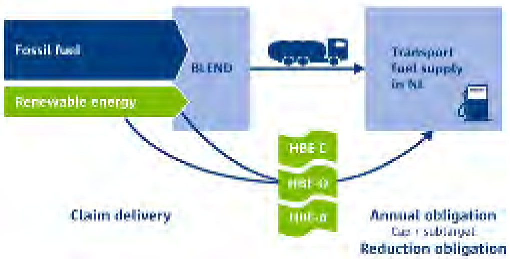
- To the marine sector, e.g. sea cargos
- To oil refineries for co-processing

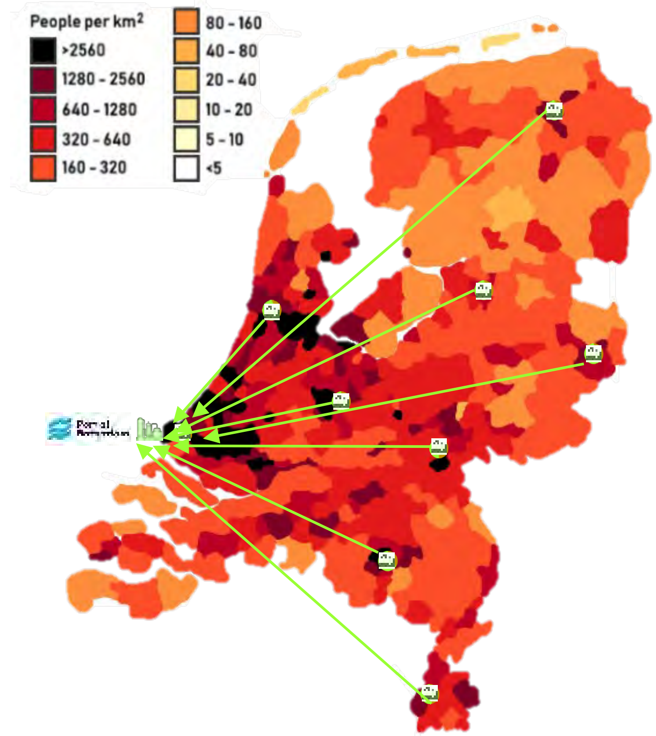
HTL finished fuels, fully upgraded product

- To fuel users, predominantly lies within the heavy-duty transport (hub-to-hub)

Implementation Scenario for The Netherlands

Supportive regulatory framework





- Europe's largest bunkering port, as well as one of the top three bunkering ports worldwide.
- Hosting 5 of 6 oil refineries in the NL
- Established market with infrastructure in place to have an HTL upgrading facility
- Rotterdam municipality and the Port of Rotterdam are aligned and support renewable fuels and biochemicals from bio-waste development

- Mono-incineration plants operating nearly 100% capacity
- Opportunities in Dutch water boards #6, #7, #8, #20
- HTL plants to process mixed feedstock (sewage sludge & biopulp)
- A demonstration project is needed to build confidence

A HTL facility mainly aggregates bio-waste

A HTL facility aggregates both bio-waste and sewage sludge from water boards 6,7,8 and 20

Partial or full upgrading facility

Market Entry Barriers

Conservative Industries

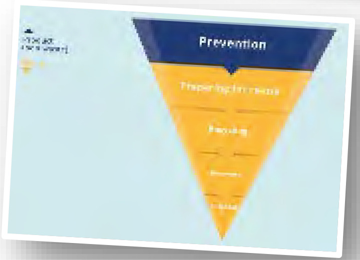
- WWTPs
- Oil refineries

The Marine Sector

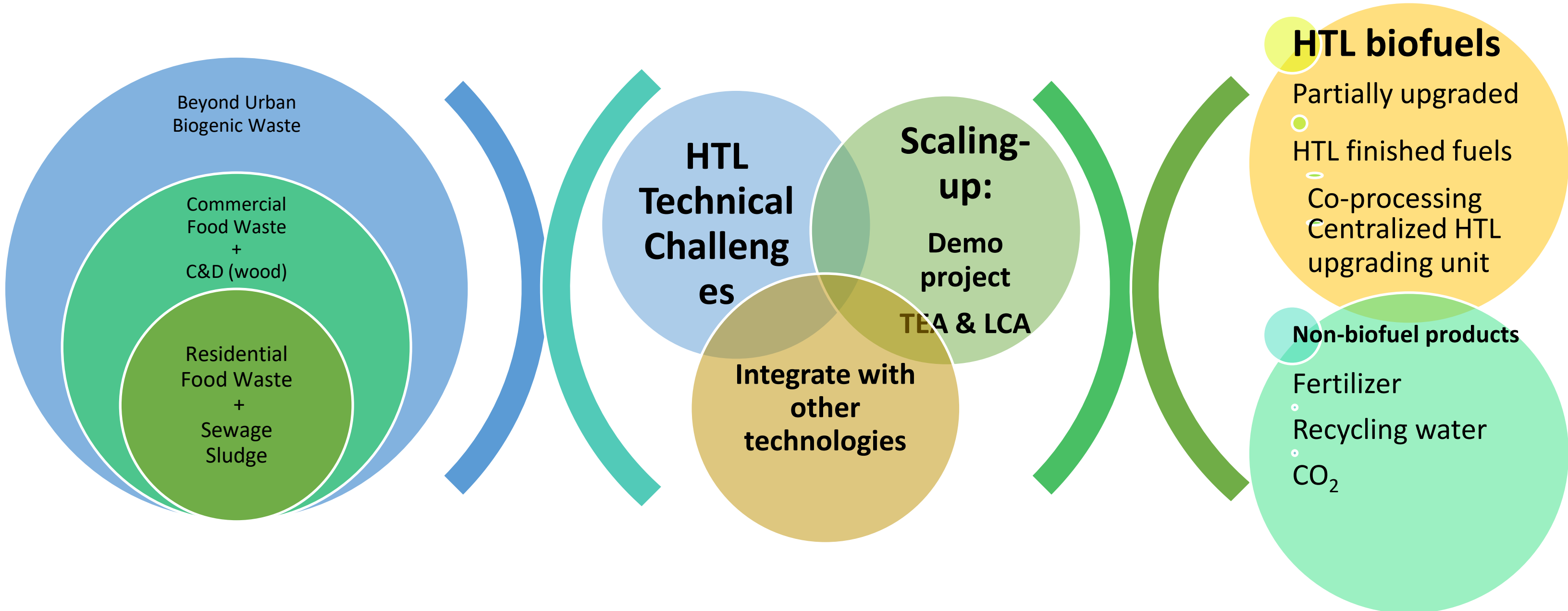
- No international marine biofuel mandates or incentives (IMO)

EU Waste Hierarchy

- HTL falls under the ‘recovery’ than ‘recycling’



NGRF Roadmap to Market



Broaden Feedstock Supply

- Mixed feedstock, and beyond urban waste
- Pre-processing center

Improve Technology & Scale Up

- Address identified technical challenges
- Improve products quality and yield
- Develop a demo with key stakeholders
- Improve TEA and LCA
- Integrate with other technologies: CCUS, PtX

Create Market Segmentation

- Short- to Mid-Term: marine & road
- Long-term: aviation
- Product vs. by-product
- Remove market entry barriers
- Geographical expansion: EU, NA, and globally

Regulatory Framework | Funding & Financing | Environmental Impact

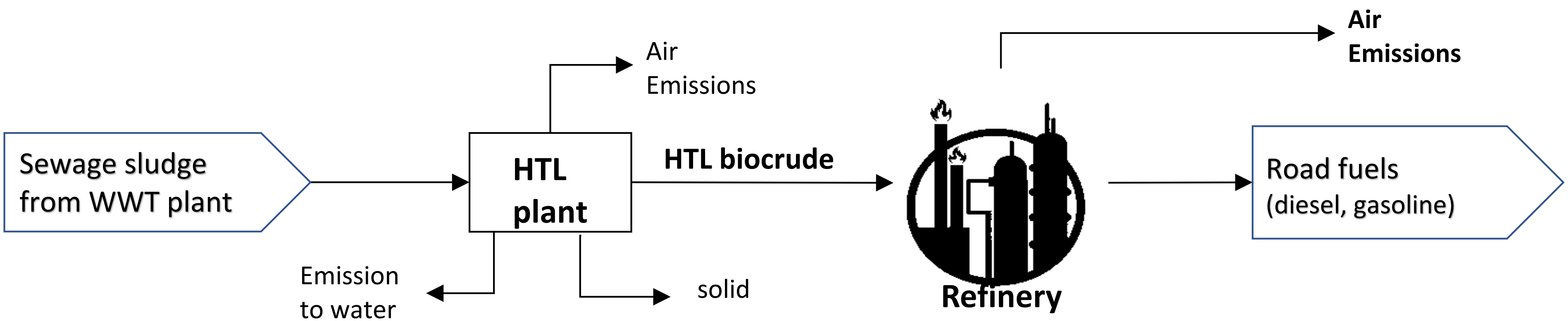
Minimum selling price

G. Alamo Serrano, SINTEF

Outline of the presentation

- ✓ Process design
  - HTL plant – biocrude production
  - Biocrude upgrading (refinery processes)
- ✓ Mass and energy balances
- ✓ Equipment and operating costs
- ✓ Biocrude production cost and minimum fuel selling price

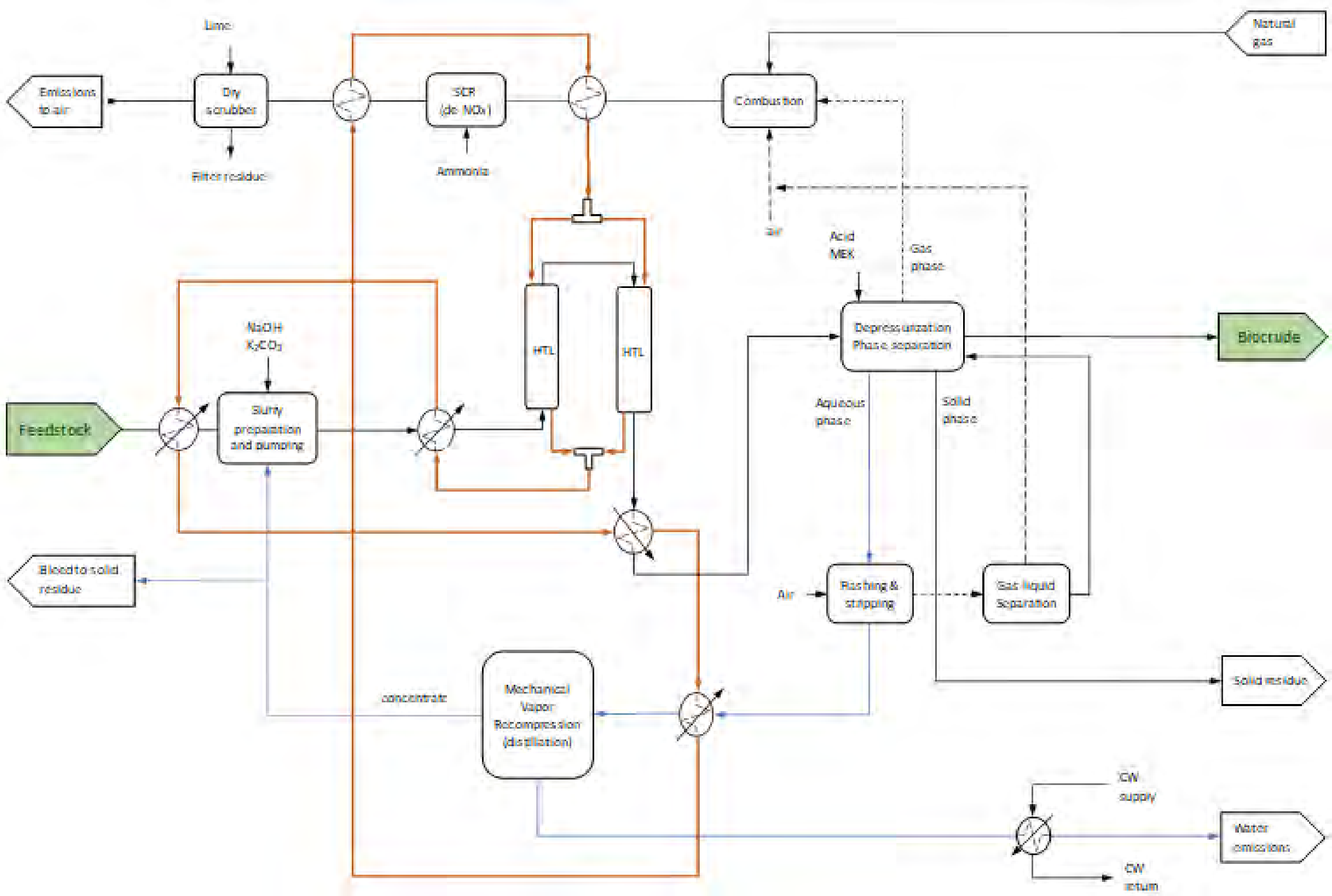
Process design



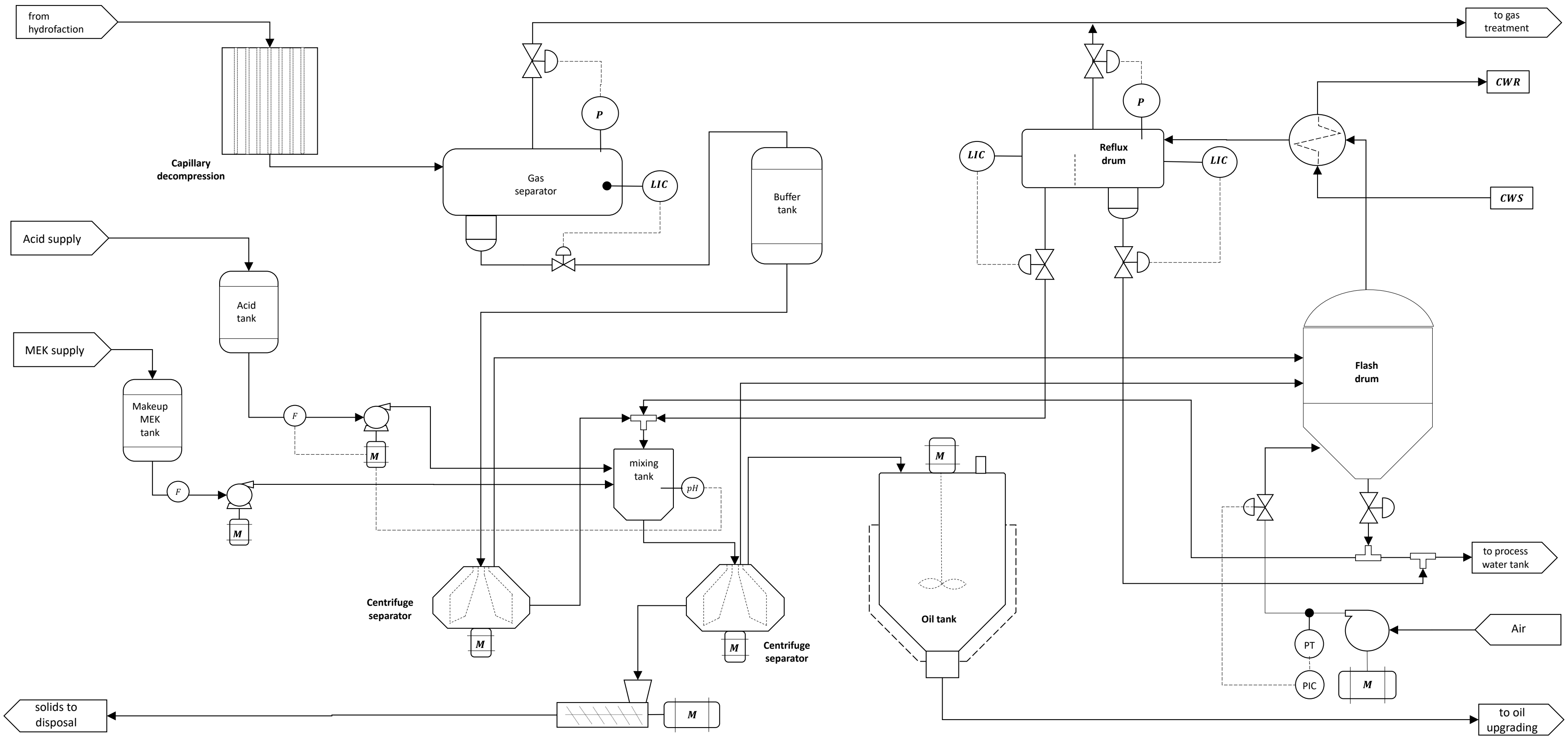
Targets:

Energy conversion: 85%
P recovery: 95%
N separation (before HTL): 70%
Scale range HTL plant: 30 – 300 dry ton/day
MFSP: < 15 €/GJ (0.6 €/liter)

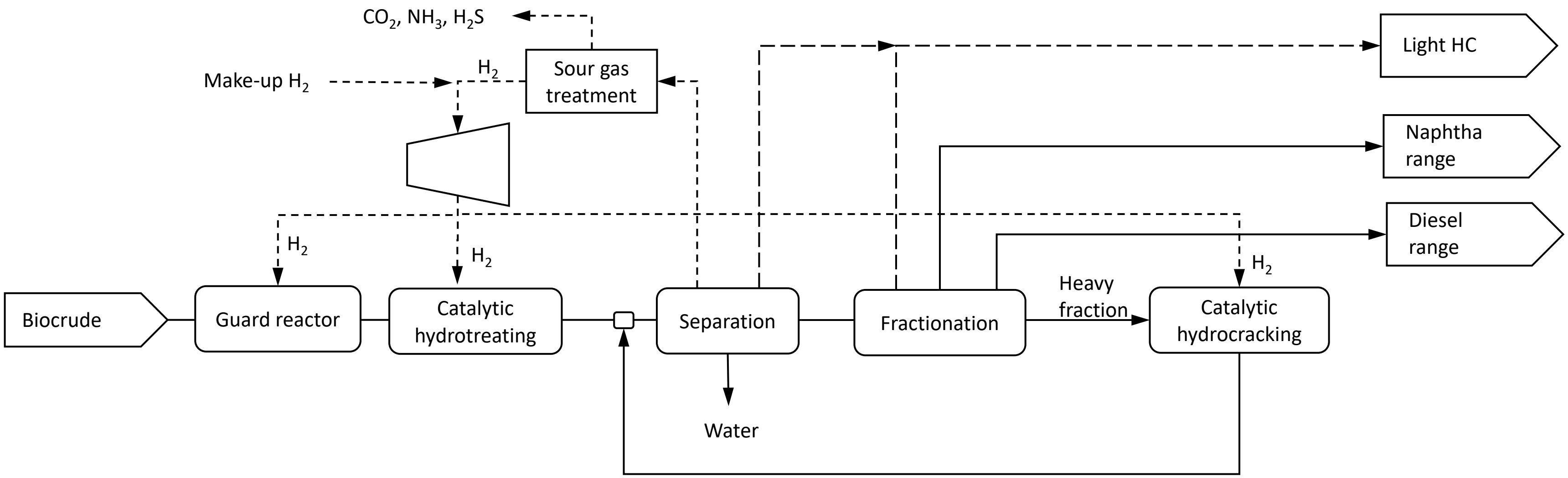
Production of HTL biocrude (baseline design)



Production of HTL biocrude (baseline phase separation)



HTL biocrude upgrading



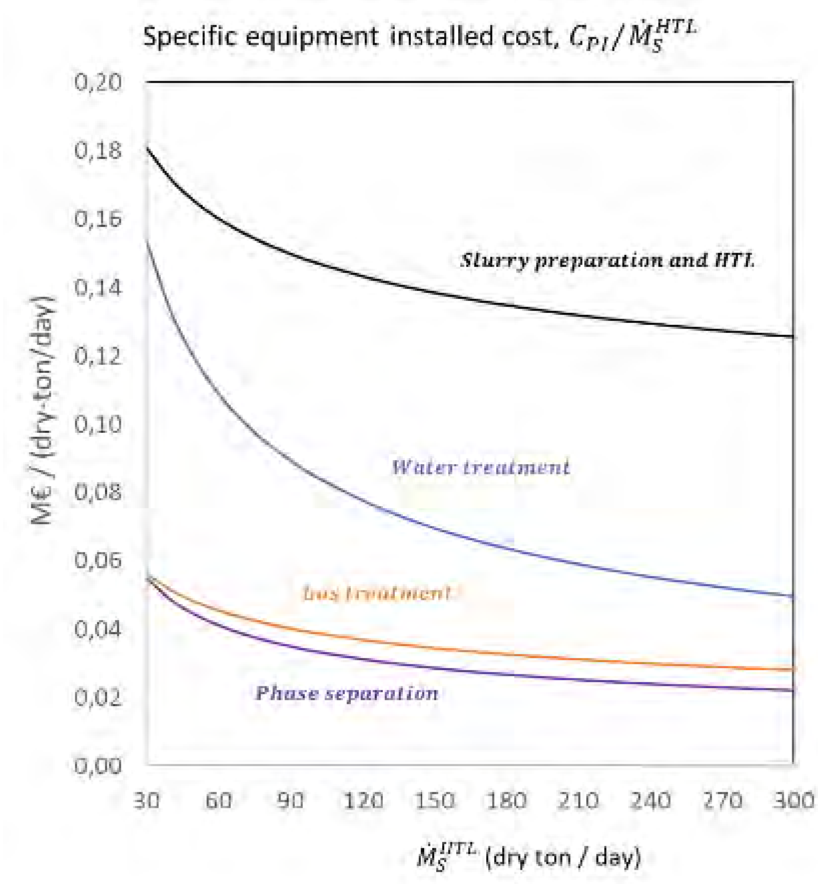
Mass and energy balances

Non-digested sewage sludge as feedstock basis in the analysis

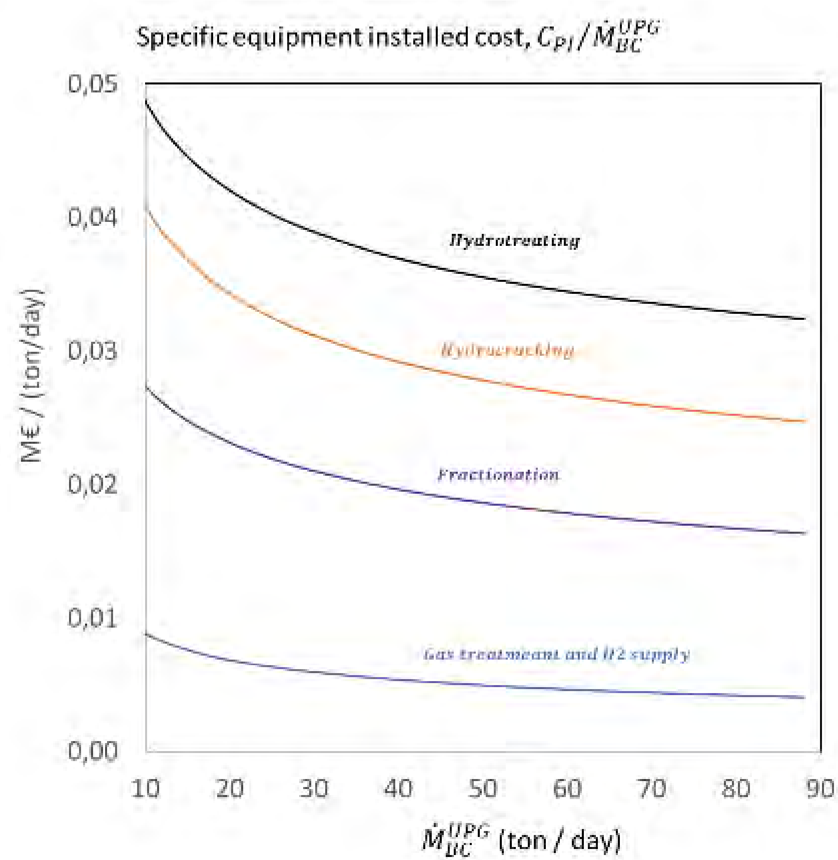
Input feed (sludge)	**1 ton (dry)**	**1 GJ**
Naphtha	0.086 ton	0.281 GJ
Middle distillate	0.100 ton	0.321 GJ
Biocrude	0.29 ton (dry)	0.73 GJ
HTL water (excl. MVR concentrate)	0.26 ton (dry)	0.17 GJ
HTL solids	0.36 ton (dry)	0.046 GJ
HTL gas	0.09 ton (dry)	0.049 GJ
Treated water	2.07 m3	0.044 GJ
Concentrate bleed	0.094 ton (dry)	0.077 GJ
NaOH + K2CO3	14 + 6 kg	-
H2 to upgrading	11.8 kg	0.027 GJ
Natural gas	35.2 kg	0.12 GJ

Installed equipment cost

Biocrude production
0.44-0.23 M€/dry-ton sludge/day

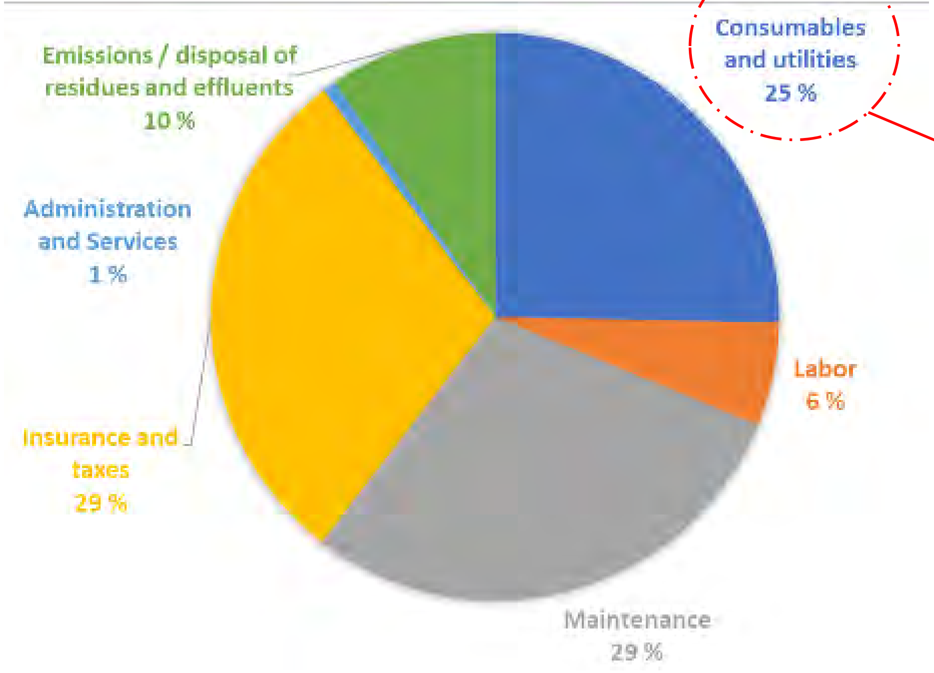


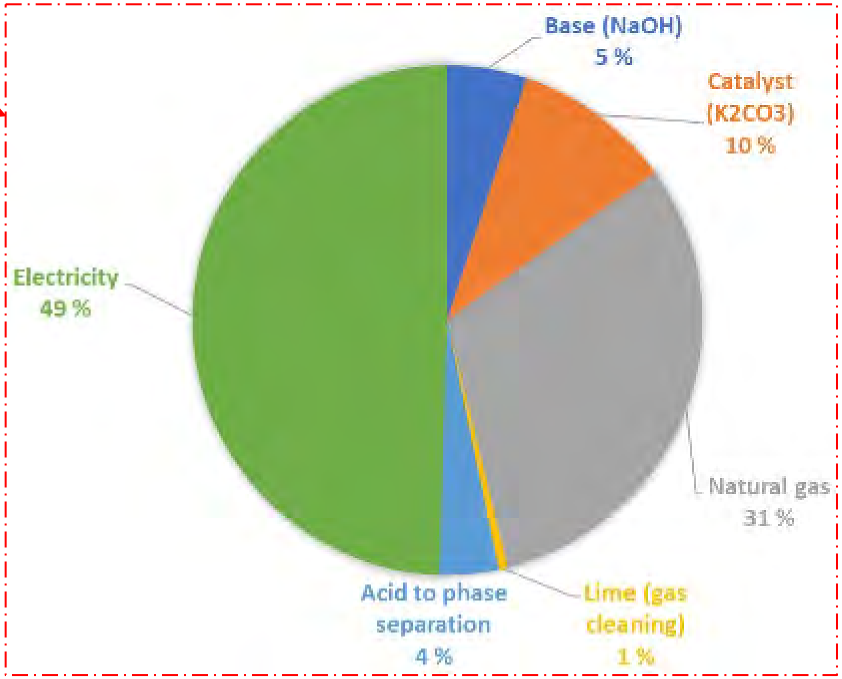
Biocrude upgrading
0.13-0.08 M€/(ton biocrude/day)



Operating and maintenance costs

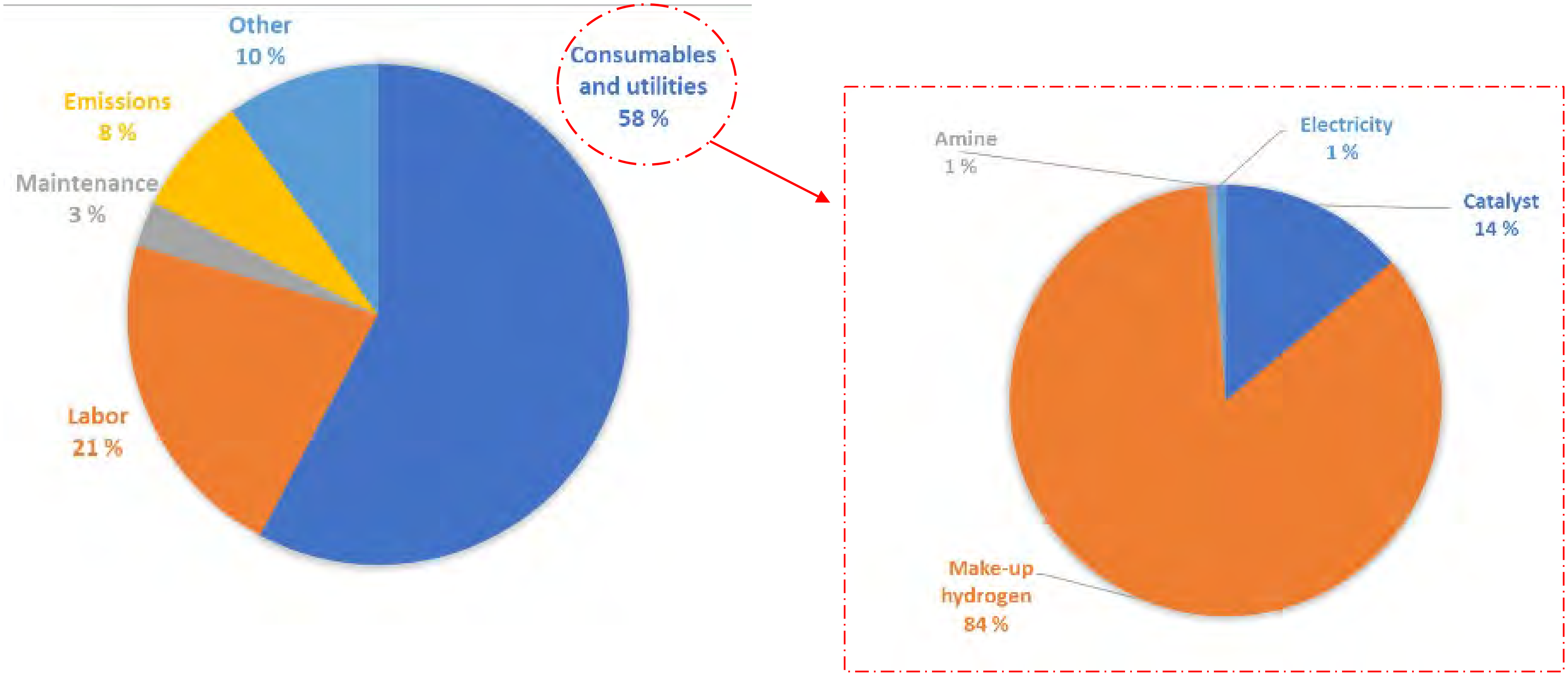
Biocrude production: **0.23 – 0.17** k€/dry-ton sludge



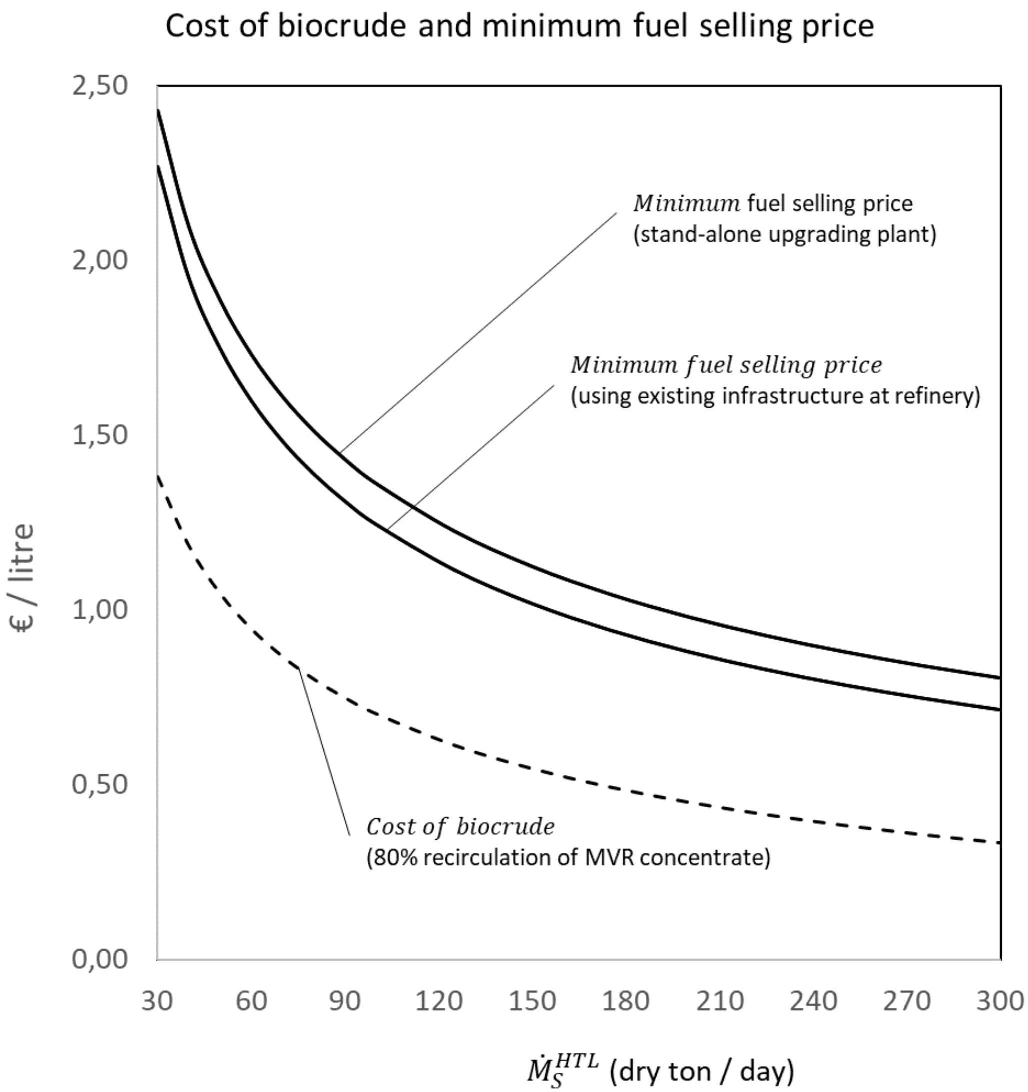


Operating and maintenance costs

Biocrude upgrading: **0.27 – 0.20** k€/ton (excluding biocrude cost)
1.65 – 0.54 k€/ton (including biocrude cost)



Minimum fuel selling price (baseline design)



Loan interest rate. %	7
Return of investment. %	10
Equity to debt ratio	30/70
Plant lifetime. years	25
Construction time. years	2
Commissioning time. years	1

Financial Model – Results & Recommendations

A. Grenon, Steeper Energy

D6.3 Financial Model

Scenarios, Assumptions, and Data Sources

- Two scenarios: 1) HTL biocrude and 2) HTL finished fuels

- Inputs that were determined to perform this analysis were:

  1. finished fuel sale price
  2. biocrude sale price
  3. the income tax rate
  4. the discount rate,
  5. the size of the plants

- Both the capital costs and operating costs for this analysis came from work package 5 (WP5), specifically, D5.3 and D5.4

- Other inputs that were used from WP5 include the time the plant is expected to be operational, the economic life of the plant, and the construction and commissioning time of the plants

- The wholesale hydrotreated vegetable oil (HVO) price was used as a reference for all finished fuels while the biocrude price was calculated based off that wholesale price with the existing average refinery's costs and profits deducted

D6.3 Financial Model-Results

The HTL biocrude scenario has the better IRR and NPV compared to the finished fuels scenario

Next Gen Road Fuel Economic Model Summary

Case: **Biocrude**

Scenario: **Case 1 (base case)**

Plant		**Units**
Nameplate Plant Capacity	75	dry tonne/day
Average Plant Capacity	68	dry tonne/day
Biocrude Produced	20	tonne/day

Capital Cost		**Millions, EUR**
Biocrude Plant	€	55.2
TOTAL Capital	**€**	**55.2**

Financial Inputs	
Assumed Utilization*	91%
Interest Rate	7.0%
Revenue and Cost Escalation	0.0%
Economic Plant Life (Years)	25
Income Tax Rate	25.0%
Discount Rate (NPV)	10.0%
Debt	70.0%
Debt Payback (Years)	25

Economic Indicators		**Millions, EUR**
Capital Cost	**€**	**55.2**
Average EBITDA	€	10.0
Unlevered, Pretax NPV	€	35.9
Unlevered, Pretax IRR		**17.3%**
Equity NPV	€	34.9
Equity IRR		**28.5%**

Revenues		**Millions, EUR**		**Per Tonne of Fuel**
Biocrude Oil Revenue	€	11.9	€	1,626
Feedstock Tipping Fees	€	4.0	€	546
Income from Gas	€	-	€	-
Total Revenues	**€**	**15.9**	**€**	**2,172**

Costs		**Millions, EUR**		**Per Tonne of Fuel**
Electricity	€	1.1	€	149
Natural Gas	€	0.7	€	92
Base (NaOH) to HTL	€	0.1	€	15
Catalyst (K2CO3) to HTL	€	0.2	€	30
Acid to phase separation	€	0.1	€	11
Lime (gas cleaning)	€	0.0	€	2
NH4OH (25% NH3) to SCR	€	0.0	€	0
Disposal of solid residue	€	0.3	€	39
Emissions to air and water	€	0.5	€	73
Labour	€	0.3	€	45
Administration and Services	€	0.6	€	75
Insurance	€	1.1	€	151
Maintenance	€	0.5	€	67
Catalyst to guard reactor	€	-	€	-
Catalyst to hydrotreating	€	-	€	-
Catalyst to hydrocracking	€	-	€	-
Amine	€	-	€	-
Fresh Water	€	-	€	-
Hydrogen	€	-	€	-
Total OPEX	€	5.5	€	747
EBITDA	**€**	**10.4**	€	1,424
Depreciation & Interest	€	5.1	€	697
Income Tax	€	1.3	€	182
Net Income	**€**	**4.0**	€	546

D6.3 Financial Model-Results

The HTL biocrude scenario has the better IRR and NPV compared to the finished fuels scenario

Next Gen Road Fuel Economic Model Summary

Case: Finished Fuels

Scenario: Case 1 (base case)

Plant		Units
Nameplate Plant Capacity	75	dry tonne/day
Average Plant Capacity	68	dry tonne/day
Biocrude Produced	20	tonne/day

Capital Cost		Millions, EUR
Biocrude Plant	€	55.2
Upgrading Capital Costs	€	5.2
TOTAL Capital	**€**	**60.4**

Financial Inputs	
Assumed Utilization*	91%
Interest Rate	7.0%
Revenue and Cost Escalation	0.0%
Economic Plant Life (Years)	25
Income Tax Rate	25.0%
Discount Rate (NPV)	10.0%
Debt	70.0%
Debt Payback (Years)	25

Economic Indicators		Millions, EUR
Capital Cost	**€**	**60.4**
Average EBITDA	€	11.4
Unlevered, Pretax NPV	€	24.3
Unlevered, Pretax IRR		**14.5%**
Equity NPV	€	22.2
Equity IRR		**20.4%**

Revenues		Millions, EUR		Per Tonne of Fuel
Finished Fuels Revenue	€	14.8	€	2,098
Feedstock Tipping Fees	€	4.0	€	566
Income from Gas	€	0.2	€	29
Total Revenues	**€**	**19.0**	**€**	**2,693**

Costs		Millions, EUR		Per Tonne of Fuel
Electricity	€	1.1	€	156
Natural Gas	€	0.7	€	95
Base (NaOH) to HTL	€	0.1	€	15
Catalyst (K2CO3) to HTL	€	0.2	€	31
Acid to phase separation	€	0.1	€	12
Lime (gas cleaning)	€	0.0	€	2
NH4OH (25% NH3) to SCR	€	0.0	€	0
Disposal of solid residue	€	0.3	€	40
Emissions to air and water	€	0.7	€	97
Labour	€	0.5	€	71
Administration and Services	€	0.6	€	85
Insurance	€	1.2	€	171
Maintenance	€	0.5	€	76
Catalyst to guard reactor	€	0.1	€	10
Catalyst to hydrotreating	€	0.1	€	8
Catalyst to hydrocracking	€	0.0	€	4
Amine	€	0.0	€	1
Fresh Water	€	0.0	€	0
Hydrogen	€	1.0	€	136
Total OPEX	€	7.1	€	1,009
EBITDA	**€**	**11.9**	€	1,683
Depreciation & Interest	€	5.6	€	788
Income Tax	€	1.6	€	224
Net Income	**€**	**4.8**	€	672

D6.3 Financial Model-Results

The economics are only better with scale (8x plant capacity)

Next Gen Road Fuel Economic Model Summary

Case: Biocrude

Scenario: Case 1 (base case)

Plant		**Units**
Nameplate Plant Capacity	600	dry tonne/day
Average Plant Capacity	548	dry tonne/day
Biocrude Produced	161	tonne/day

Capital Cost		**Millions, EUR**
Biocrude Plant	€	247.6
TOTAL Capital	**€**	**247.6**

Financial Inputs	
Assumed Utilization*	91%
Interest Rate	7.0%
Revenue and Cost Escalation	0.0%
Economic Plant Life (Years)	25
Income Tax Rate	25.0%
Discount Rate (NPV)	10.0%
Debt	70.0%
Debt Payback (Years)	25

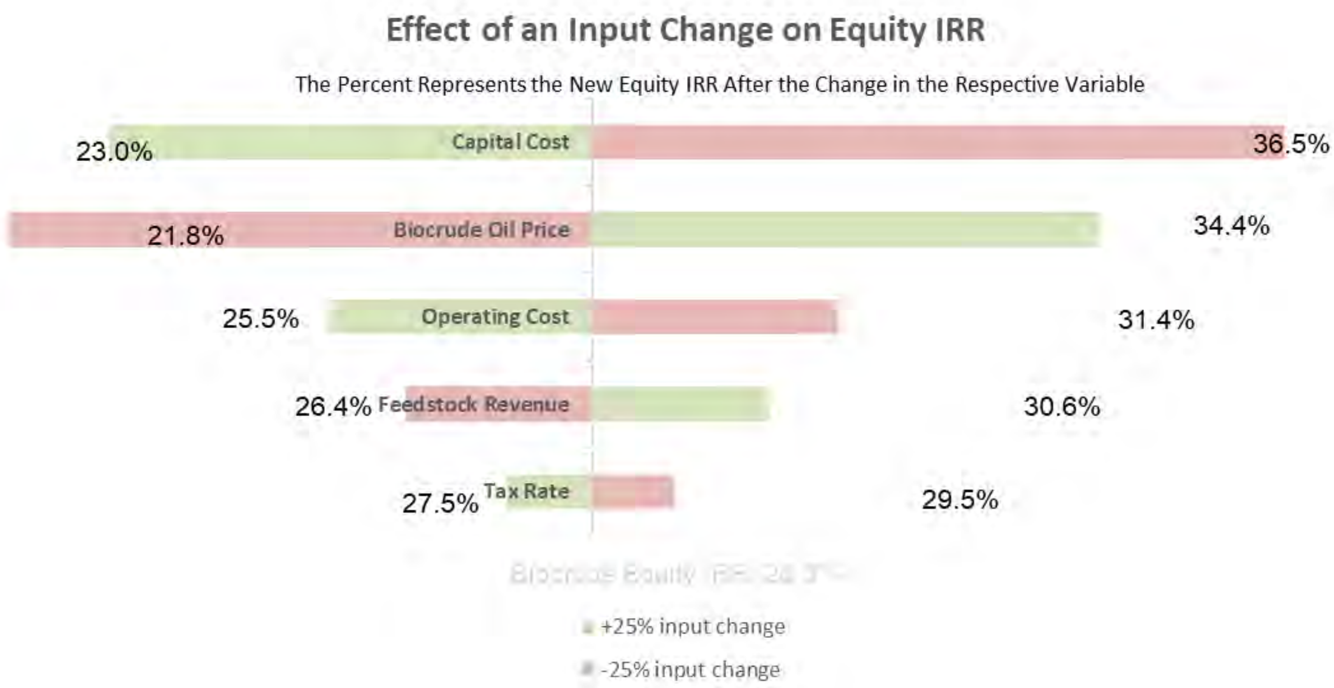
Economic Indicators		**Millions, EUR**
Capital Cost	**€**	**247.6**
Average EBITDA	€	89.6
Unlevered, Pretax NPV	€	476.2
Unlevered, Pretax IRR		**28.2%**
Equity NPV	€	392.8
Equity IRR		**47.0%**

Revenues		**Millions, EUR**		**Per Tonne of Fuel**
Biocrude Oil Revenue	€	95.3	€	1,626
Feedstock Tipping Fees	€	32.0	€	546
Income from Gas	€	-	€	-
Total Revenues	**€**	**127.3**	**€**	**2,172**

Costs		**Millions, EUR**		**Per Tonne of Fuel**
Electricity	€	8.7	€	149
Natural Gas	€	5.4	€	92
Base (NaOH) to HTL	€	0.9	€	15
Catalyst (K2CO3) to HTL	€	1.7	€	30
Acid to phase separation	€	0.6	€	11
Lime (gas cleaning)	€	0.1	€	2
NH4OH (25% NH3) to SCR	€	0.0	€	0
Disposal of solid residue	€	2.3	€	39
Emissions to air and water	€	4.3	€	73
Labour	€	0.3	€	6
Administration and Services	€	2.5	€	42
Insurance	€	5.0	€	85
Maintenance	€	2.2	€	37
Catalyst to guard reactor	€	-	€	-
Catalyst to hydrotreating	€	-	€	-
Catalyst to hydrocracking	€	-	€	-
Amine	€	-	€	-
Fresh Water	€	-	€	-
Hydrogen	€	-	€	-
Total OPEX	€	33.9	€	579
EBITDA	**€**	**93.3**	€	1,592
Depreciation & Interest	€	22.9	€	390
Income Tax	€	17.6	€	301
Net Income	**€**	**52.8**	€	902

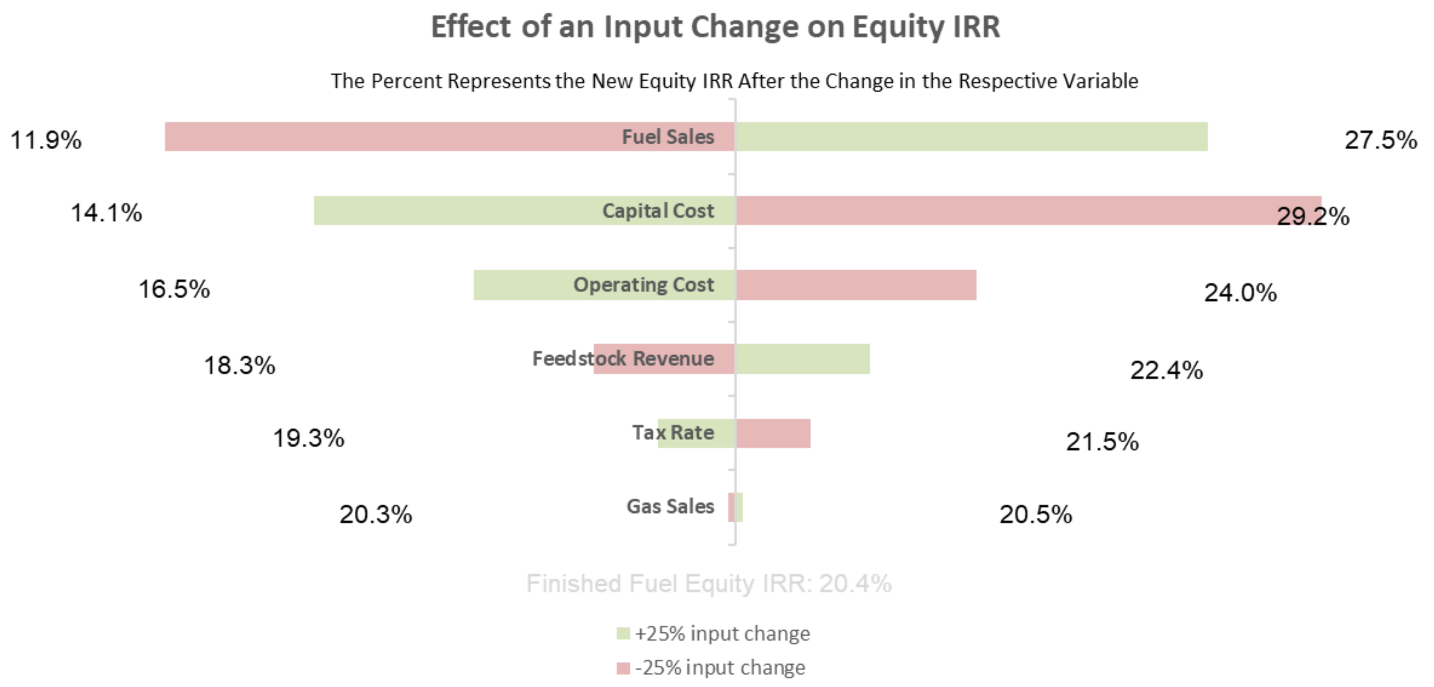
D6.3 Financial Model-Sensitivity Analysis

Sensitivity Analysis: In the HTL biocrude scenario a percent change in **capital costs** would yield the biggest change to equity IRR. Followed by **product sales** as the second most sensitive item, **operating costs** third, **feedstock tipping fees** from sewage sludge fourth, and **tax rate fifth.**



D6.3 Financial Model-Sensitivity Analysis

Sensitivity Analysis: In the finished fuels scenario, a percent change in **product sales** would yield the biggest change to equity IRR. Followed by **capital costs** as the second most sensitive item, **operating costs** third, **feedstock tipping fees** from sewage sludge fourth, **tax rate** fifth, and **gas sales was the least** sensitive.



D6.3 Financial Model-Plant Rollout

Multiple Plant Rollout

1. A total of 134 plants over approximately 27 years were constructed resulting in an NPV of over €1.2 billion
2. This rollout was only done on HTL biocrude facilities and used the unlevered, pre-tax NPV value to show the total value on the table
3. Plant NPVs are discounted at 10% and it's assumed 6 plants per year will be built from 2033 to 2050
4. All other assumptions in the individual plant model are used here

Biocrude Plant Buildout and Resulting NPV (Millions, EUR)

Year	2023	2024	2025	2026	2027	2028	2029	2030	2031	2032	2033	2050
New HTL Plants			0	1	1	3	4	5	6	6	6	6
Total Plants Announced		0	0	1	2	5	9	14	20	26	32	134
Total Plants Completed					0	0	1	2	5	9	14	116
New Plant NPV		0	0	36	36	108	144	180	215	215	215	215
Cumulative Investment			0	0	28	83	193	386	635	938	1,270	7,397
Aggregate NPV	1,233											

D6.3 Financial Model-Recommendations

Insights and Recommendations

1. Promising economics for sewage sludge based HTL plants and HTL + upgrading units when incentives are present should encourage investment

2. Biofuel incentives are crucial. The stronger they are the better the returns for an HTL plant

3. To aid in plant rollout risk mitigation strategies should be pursued according to the sensitivity analysis:

    - Long term fuel offtake and price agreements could be reached to reduce the risk associated with market price volatility

    - Significant operating costs could also be hedged

Environmental Impact

E. Medina Martos, CENER

Overview of T5.4

Purpose: To Evaluate the environmental performance of the complete value chain proposed in NGRF.

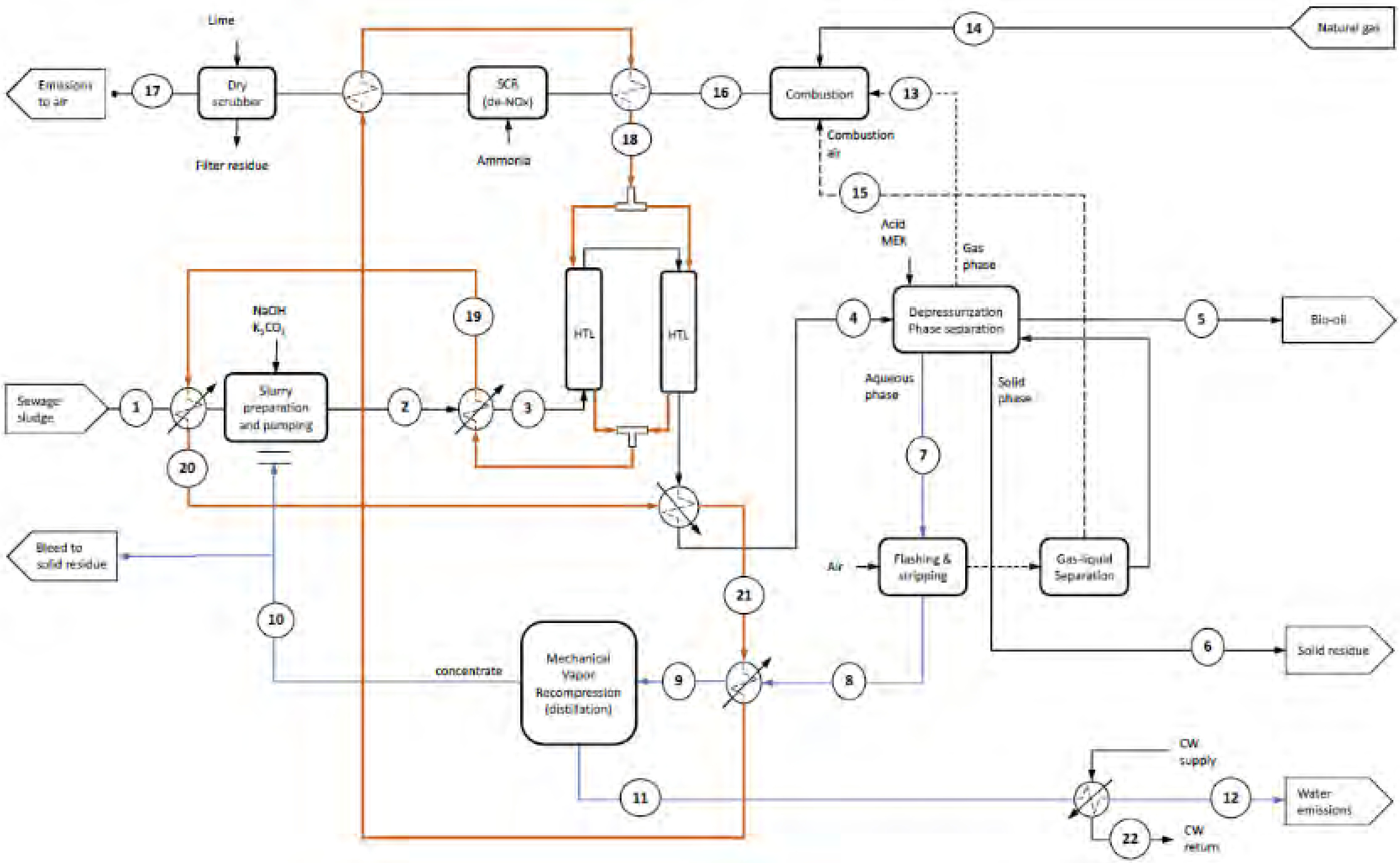
Comprised stages:

- Decentralized production of biocrude via HTL of sewage sludge.
- Centralized upgrading of biocrude into drop-in fuels.
- Land application of HTL solid.

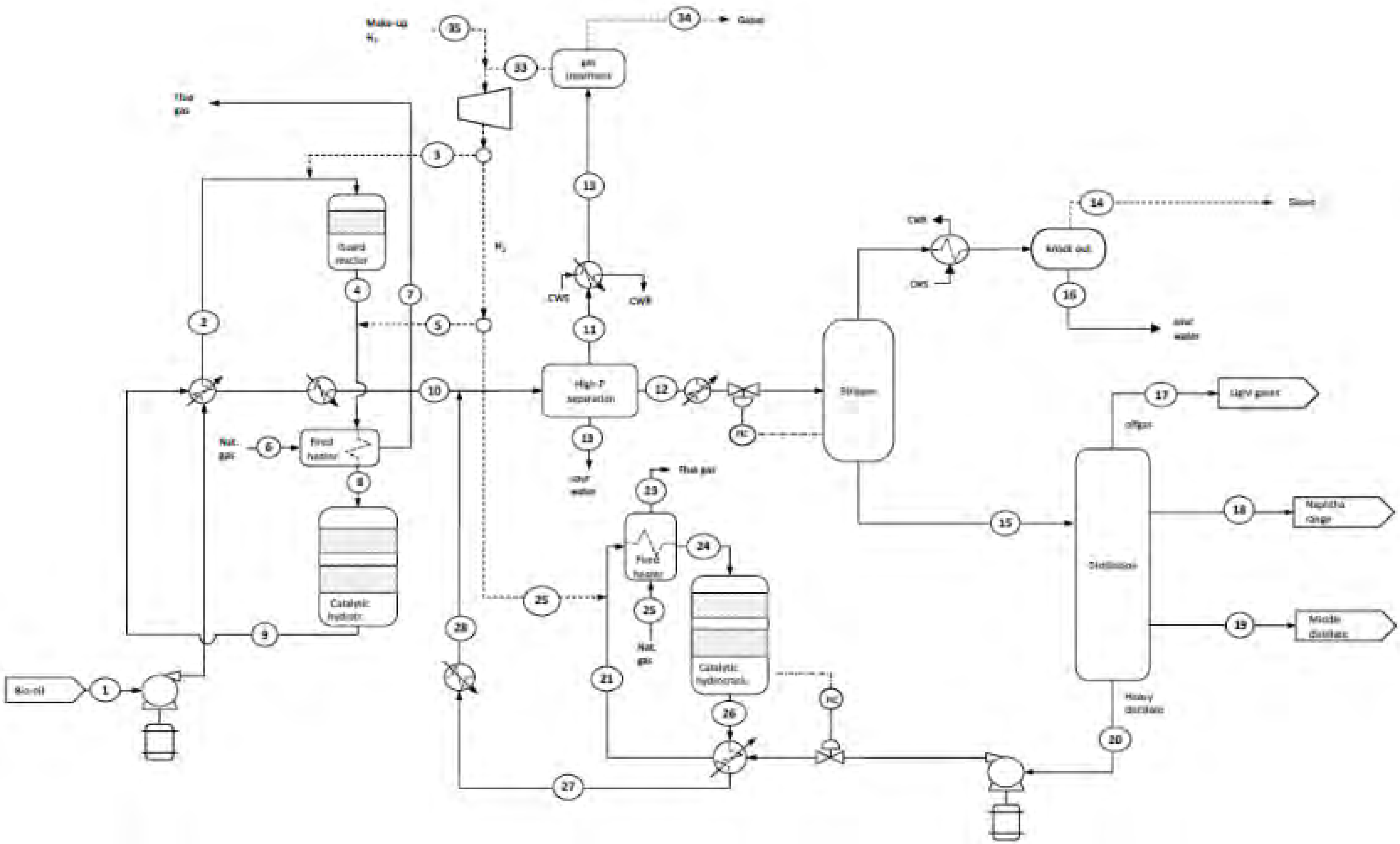
Specific objectives:

- Selection of case study (in consonance with D5.3 & D5.4).
- Compiling a comprehensive Life Cycle Inventory (LCI) from D5.3 & D5.4.
- Identifying lacking technical data to be completed from literature sources.
- Life Cycle modelling of value chain stages not included within the technical scope of NGRF (i.e. co-products and wastes management).
- Life Cycle Impact Assessment of selected case. Identification of hotspots and possible improvements.

Decentralized production of biocrude



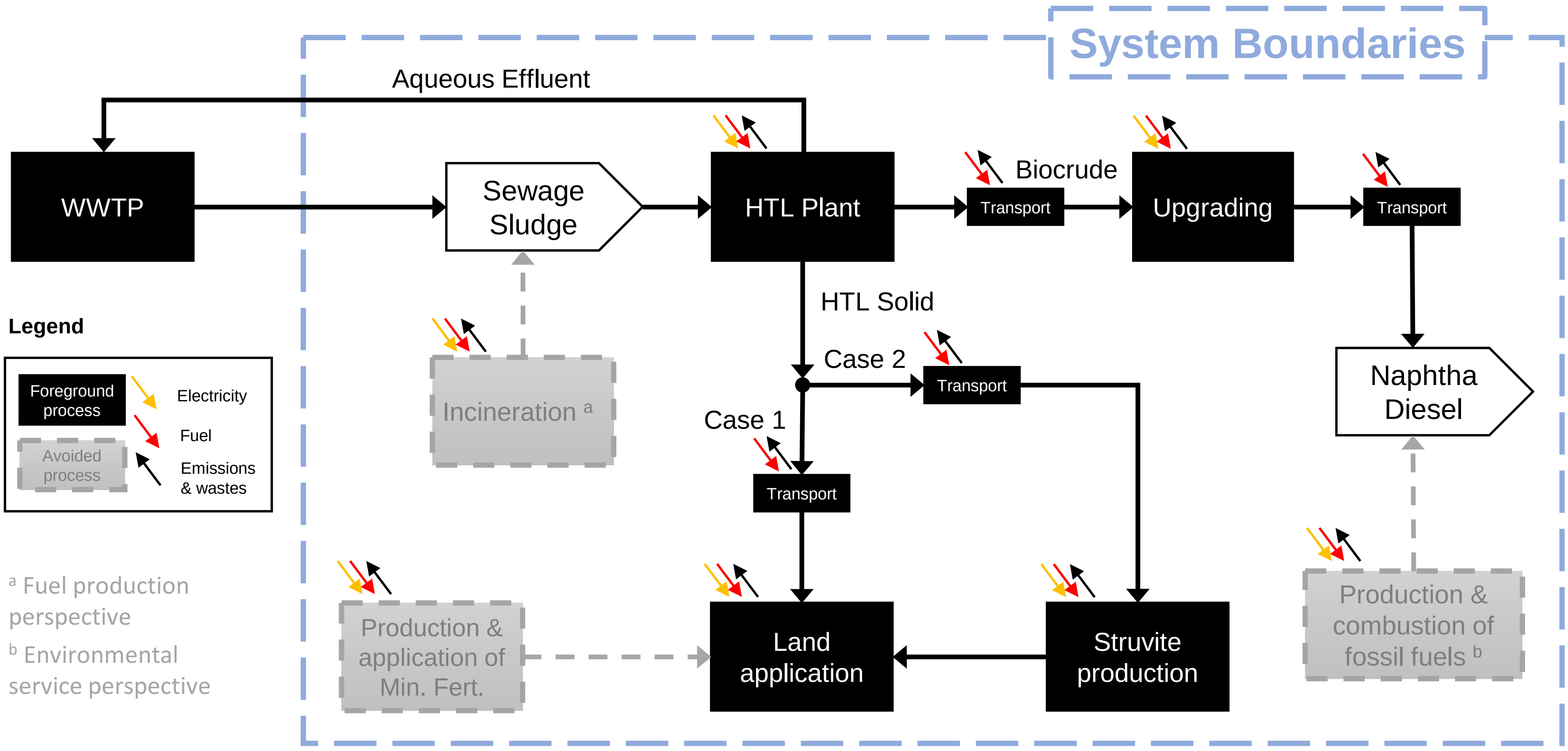
Centralized upgrading of biocrude into drop-in fuels



Goal and scope definition

Studied Cases:

- **Case 1**: HTL solid directly applied on land.
- **Case 2**: HTL solid used to produce struvite, which is later applied on land.



Goal and scope definition

Adopted approaches:

Case	Approach	Functional Unit	Env. Benefits from substituted processes
1	Fuel Production	1 MJ produced fuel	• Sludge Incineration • Mineral fertiliser production and application
1	Sludge Management	1 tonne treated sludge	• Fossil fuels • Mineral fertiliser production and application
2	Fuel Production	1 MJ produced fuel	• Sludge Incineration • Mineral fertiliser production and application
2	Sludge Management	1 tonne treated sludge	• Fossil fuels • Mineral fertiliser production and application

Other considerations:

- Allocation: Naphtha 47.9%; Diesel: 52.1%
- Geographical scope: Denmark
- Sewage Sludge enters the system with zero environmental burdens.
- No environmental burdens assumed for infrastructures.
- Cut-off criteria (reported impacts): 5%

Life Cycle Inventory (LCI)

Modelling features:

- Data from D5.3 and D5.4 (Techno-economic Analysis).
- Background processes from Ecoinvent database.
- Emissions from land application of HTL solid and Struvite, and avoidance of mineral fertilisers based on data from Tonini et al. (2019)[1].
- 1% annual thermal fluid leakage considered.
- The specified consumption of catalysts was averaged over a plant lifetime of 25 years and 8,000 working hours per year.
- NG combustion was modelled as ideal only generating (CO_2 and H_2O).
- No emissions were assigned to the combustion of the produced fuels, as these were assumed to be of biogenic origin.
- Biocrude was assumed to be transported 100 km from the HTL plant to the upgrading plant.
- Land application of HTL solid and struvite was assumed to require 50 km transportation to the application site.
- The emissions from the combustion of the produced liquid fuels and HTL gas were assumed as biogenic.

[1] Tonini, D., Saveyn, H.G.M., Huygens, D., 2019. Environmental and health co-benefits for advanced phosphorus recovery. Nat Sustain 2, 1051–1061. https://doi.org/10.1038/s41893-019-0416-x

Life Cycle Impact Assessment (LCIA)

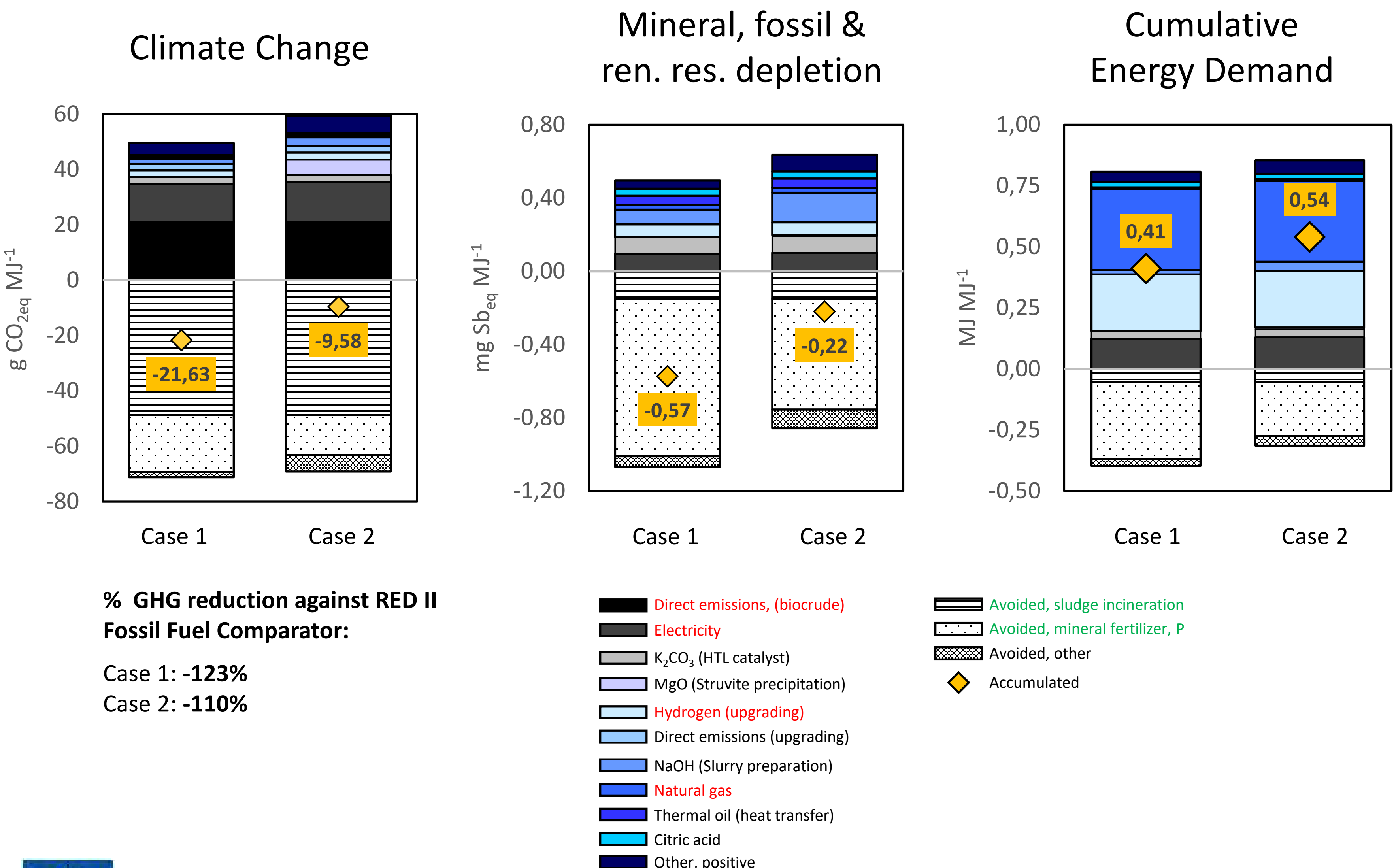
Calculation features:

- LCIA method: ILCD 2011 Midpoint.
- Considered impact categories: Climate Change (CG); Mineral, fossil and renewable resources depletion (MFRRD); and (Fossil) Cumulative Energy Demand (CED).
- Calculation tool: Simapro 9.3

Sensitivity analysis:

- **Process inputs**
  - NG demand
  - Electricity demand
  - Hydrogen demand
- **Alternative Electricity mix**
  - Netherlands (more fossil-based mix)
  - Renewable energy (wind turbine)
- **Alternative substituted sludge treatment**
  - Anaerobic digestion
  - Composting
  - Landfilling
- ***Combined effects***

Life Cycle Impact Assessment (LCIA) – Fuel producing approach



% GHG reduction against RED II Fossil Fuel Comparator:

Case 1: **-123%**
Case 2: **-110%**

Life Cycle Impact Assessment (LCIA) – Fuel producing approach

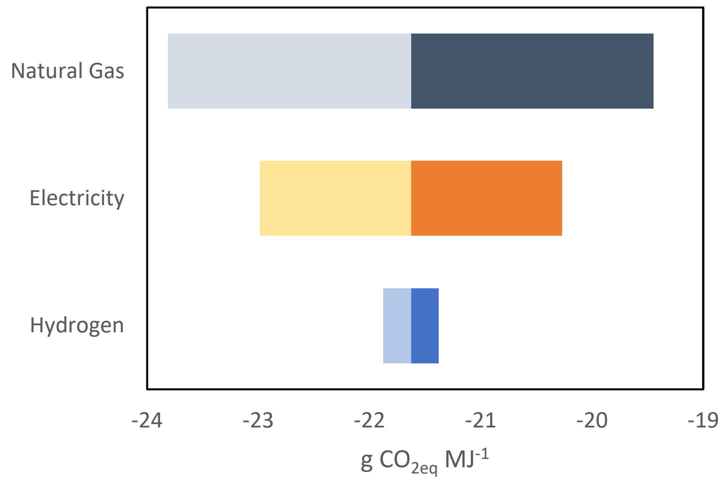
On P recovery:

	Case 1, HTL solid	Case 2, Struvite
% P plant uptake	76.5 %	90 %
Avoided P_2O_5, kg kg^{-1}	0.05	0.38
Produced, kg kg^{-1} BC	3.52	0.30
Avoided P_2O_5, kg kg^{-1} BC	**0.17**	**0.12**

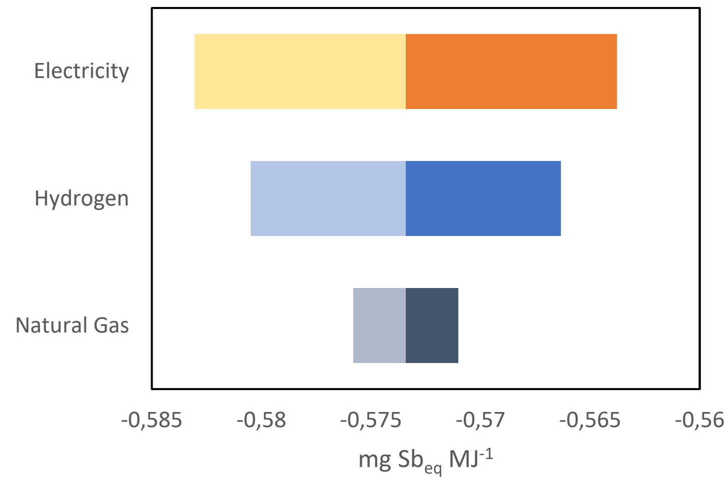
Despite struvite can replace more P_2O_5 than the raw HTL solid, the yield of struvite per kg produced biocrude is much less than that of the HTL solid. This results in Case 1 avoiding 0.17 kg mineral fertiliser per kg produced biocrude, as compared to Case 2 avoiding 0.12 kg.

LCIA – Sensitivity Analysis – Process inputs

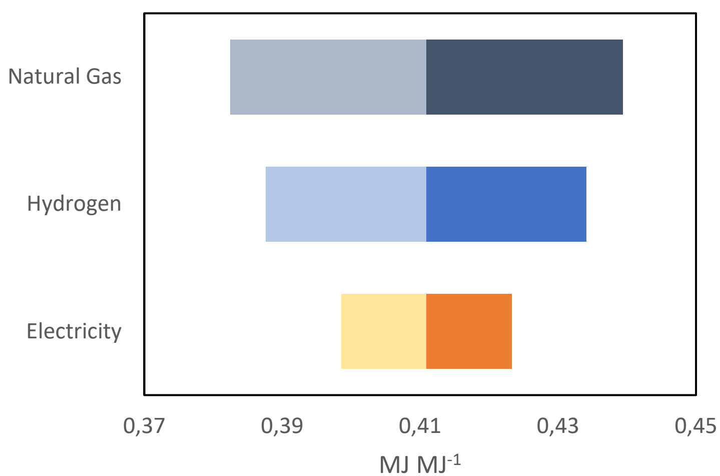
Climate Change

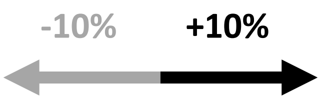


Mineral, fossil & ren. res. depletion



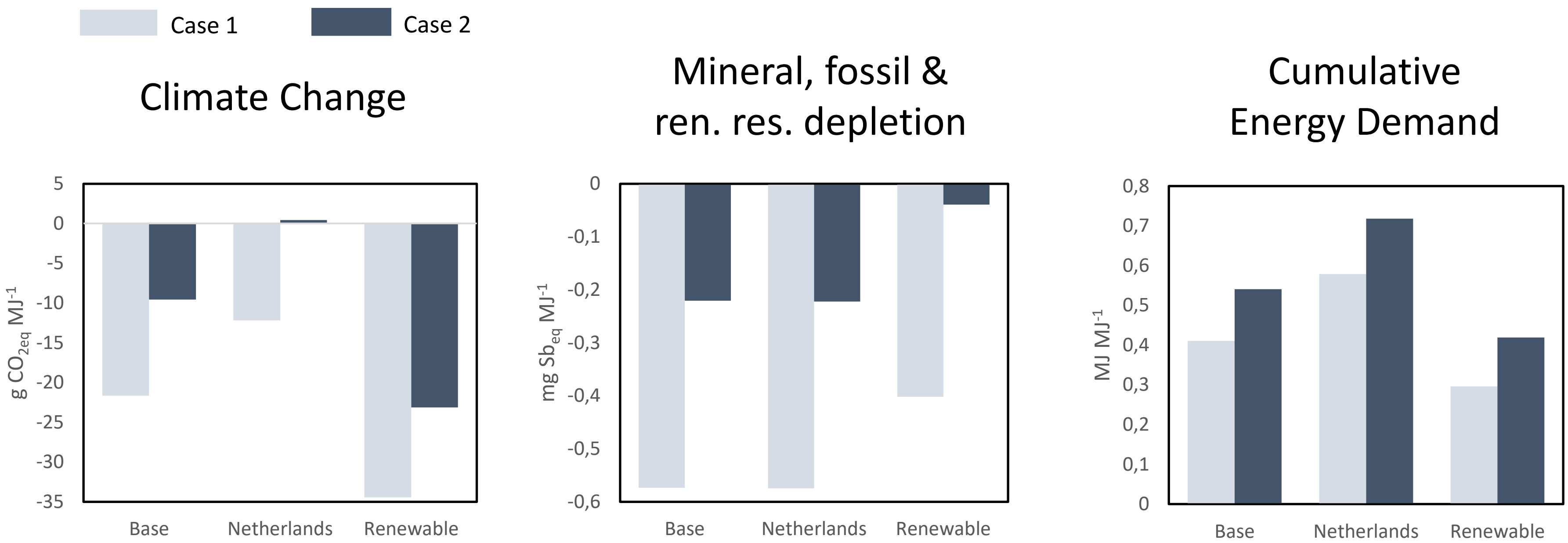
Cumulative Energy Demand





- All selected parameters show symmetric responses.
- The CG category is the highest sensitive one.
- MFRRD category shows little variability.

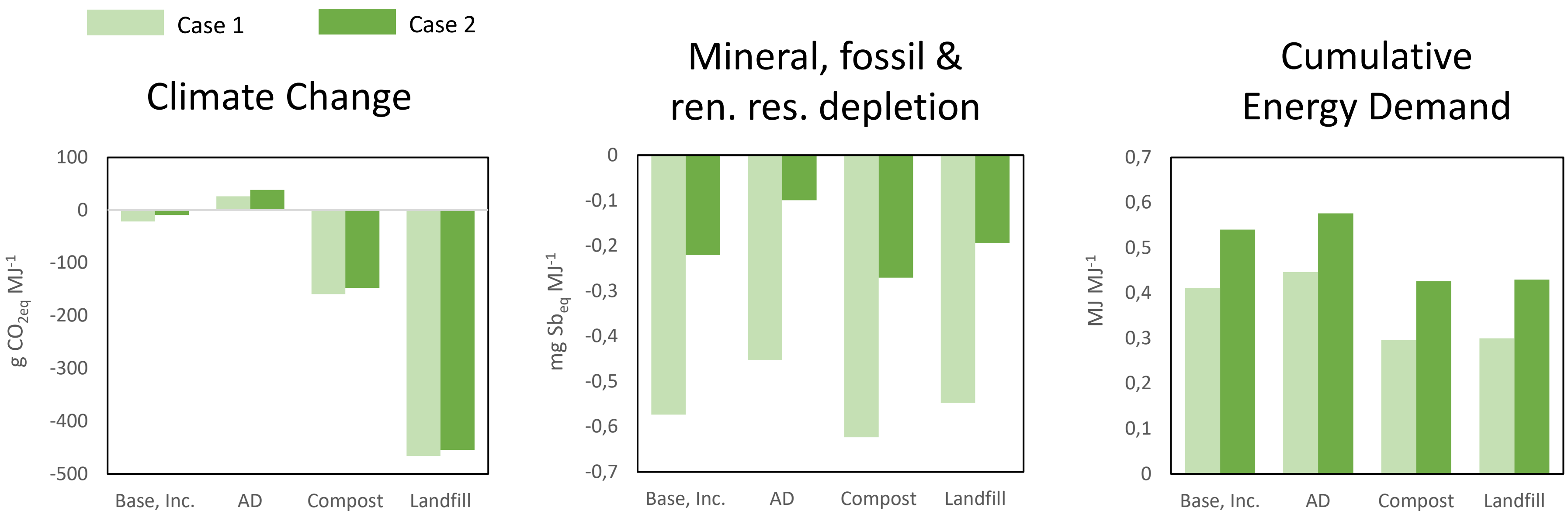
LCIA – Sensitivity Analysis – Electricity Mix*



- The assumed Electricity Mix strongly impacts the CG and CED categories.
- Assuming NL mix implies ca. +10 g CO_2 eq MJ^{-1} and ca. -17 MJ MJ^{-1}.
- Assuming 100% Renewable electricity implies ca. -13 g CO_2 eq MJ^{-1}.
- Even when assuming NL mix, Case 1 attains 113% reduction against RED II comparator.

* Only applied to foreground system.

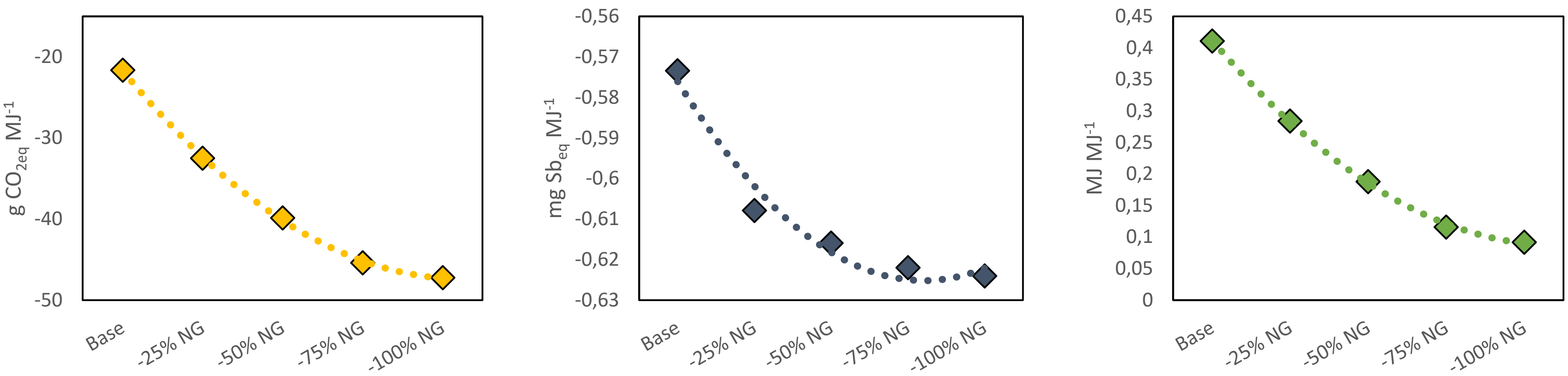
LCIA – Sensitivity Analysis – Avoided Sludge Treatment



- Composting and landfilling scenarios should only be taken as illustrative, but this figures help us understand the relevance of the displaced sludge treatment being assumed.
- AD is a robust management option. Less environmental credits in the CG category are obtained as compared to incineration.

LCIA – Sensitivity Analysis – Combined effects

- MVR electric load reduced by 50%.
- Reduced NG demand in biocrude production.



- Attaining (-40) – (-50) g CO_{2eq} MJ^{-1} and 0.1 – 0.2 MJ MJ^{-1} seems reasonable.

Concluding remarks

- The consumption of electricity, hydrogen and natural were identified as the most relevant inputs affecting the environmental performance.
- Direct application of the HTL solid can avoid more mineral fertiliser than the application of struvite.
- The considered sewage sludge management option being shifted could be a potential driver for plant location.
- GHG avoidance of >100% can be achieved even when assuming an electricity mix with a considerable fossil-based contribution.
- Reducing NG consumption could drive to figures of (-40) – (-50) g CO_{2eq} MJ^{-1} and 0.1 – 0.2 MJ MJ^{-1}.
- The production of drop-in fuels via the NGRF pathway has been proven as an environmentally sound option aiming at GHG avoidance and sewage sludge management.

Panel discussion:
The future of HTL produced biofuels

Chair: Thomas Helmer, Aalborg University

Panel: Lasse Rosendahl, Aalborg University

Steen Iversen, Steeper

Jostein Gabrielsen, TOPSOE

Daniele Bianchi, ENI

Johannes Schürmann, GoodFuels

Joey van Elswijk, Port of Amsterdam

NEXTGEN roadfuels

This project has received funding from the European Union's Horizon 2020 Research and Innovation Programme under Grant Agreement No 818413

Thank you!

Project Partners

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