Biomass to Jet Fuel

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De Chen[1]

[1]Norwegian University of Science and Technology, Norway
[2]SINTEF Industry, Norway

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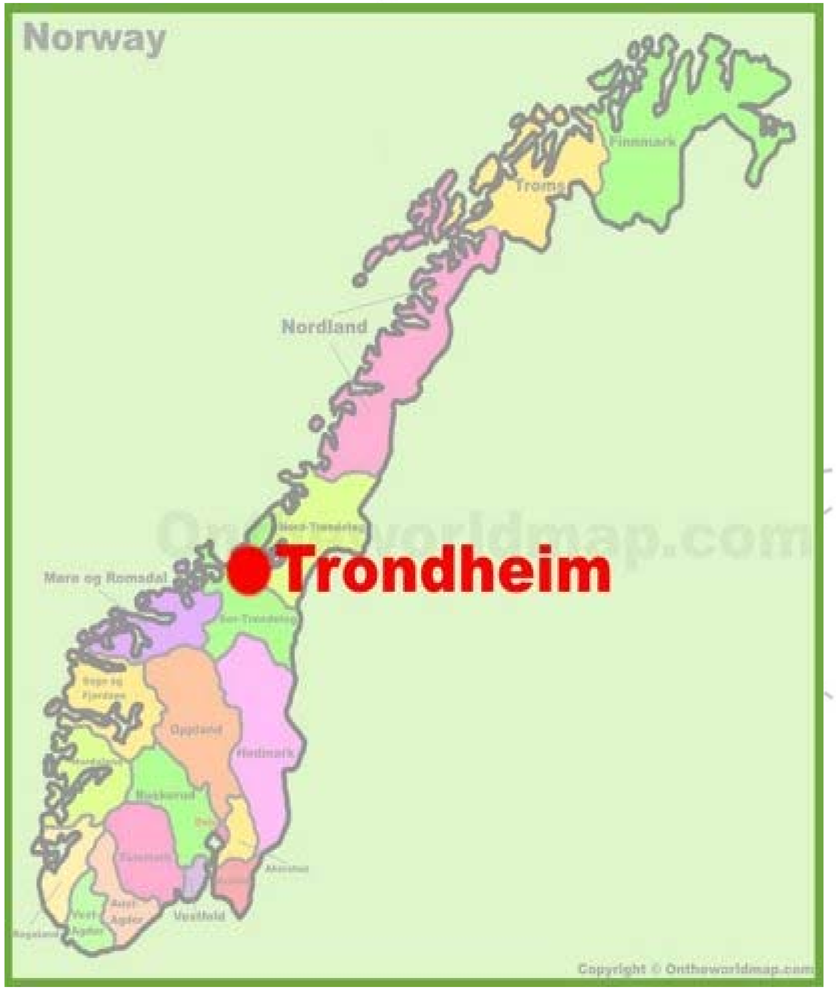

Norway, Northern Europe

Trondheim

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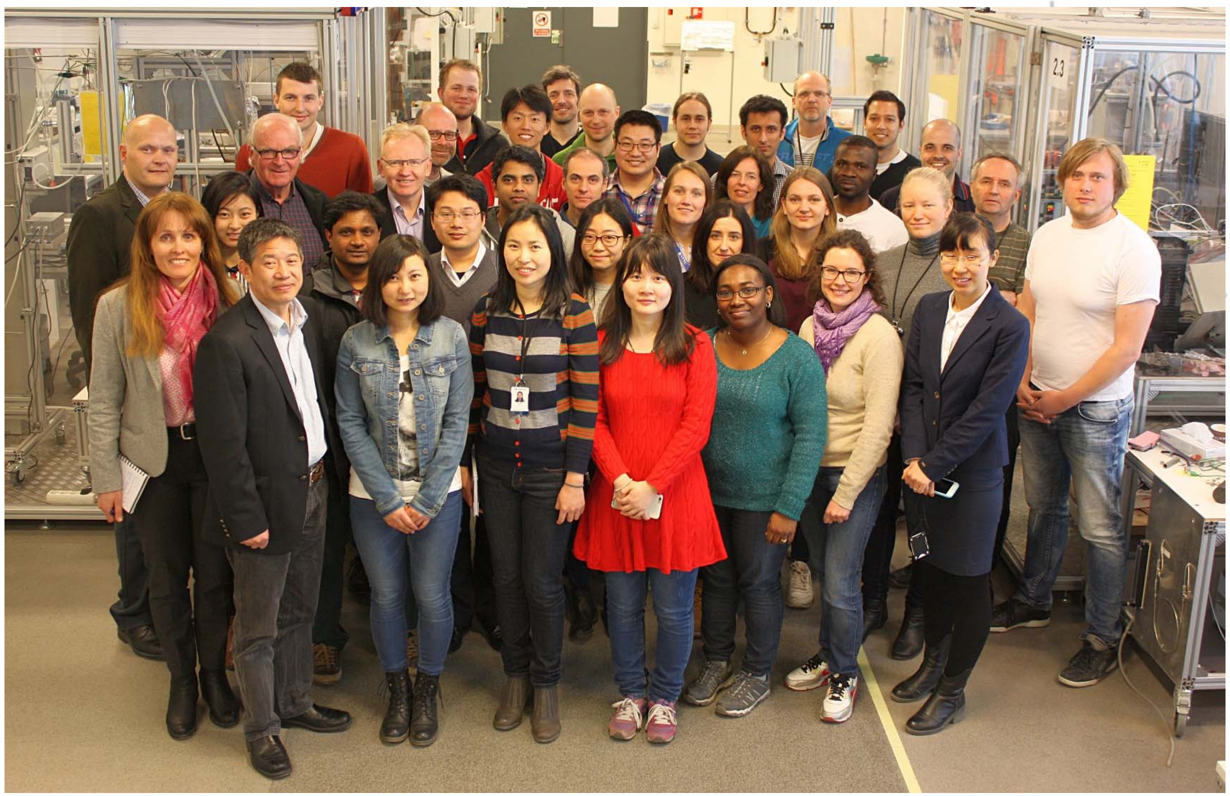
Norwegian University of
Science and Technology

- SINTEF is the largest independent research organisation in Scandinavia. We create value and innovation through knowledge generation and development of technological solutions that are brought into practical use.
- We are among the four *largest contract research institutions* in Europe.
- The **Norwegian University of Science and Technology** (**NTNU**) is a public research university in Norway. NTNU has over 8,000 employees and over 40,000 students.

Brain researchers May-Britt Moser and Edvard Moser of received **Nobel Prize** in Physiology or Medicine in 2014.

NTNU-SINTEF Kinetics & Catalysis: KinCat



KinCat is a GEMINI center appointed by NTNU-SINTEF, includes 5 professors, 3 adjunct professors, 10-12 scientists and technicians working in SINTEF, 15-25 PhD candidates and ~10 postdocs

An overview of our activity is available in our **Annual report**, link below:
https://www.ntnu.edu/documents/4760879/0/Annual+Report+2018-final-3+%28002%29.pdf/4082d497-f69d-4d0f-a0d8-d74edd96f7f7

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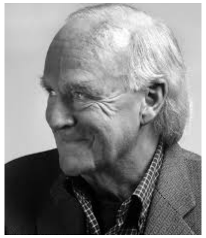
Department of Chemical Engineering

Catalysis Group

De Chen
Professor

Magnus Rønning
Professor

Edd
Blekkan
Professor



Anders Holmen
Professor
Emeritus

Hilde
Venvik
Professor

Jia Yang
Associate
Professor

Kjell
Moljord
Adjunct
Professor

Kumar R rout
Adjunct
Associate
Professor

Ingeborg
Svenum
Adjunct
Associate
Professor

- Research group consists of ca. 50 people:
  - 5 Professors, 3 Adjunct professors, about 10 fulltime research scientists holding Ph.D's, 5-10 Post.doc's and about 25 Ph.D students
- Applied Research
  - Strong links with industry
- Fundamental Research
  - Strong publication record

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KinCat

Catalysis Group – SINTEF – NTNU

Main applications

Natural gas conversion

- Upgrading of oil fractions
- Biofuels
- Environmental technology
- High temperature chemistry
- Hydrogen technology
- Photocatalysis
- Carbon nanomaterials
- Microstructured reactors

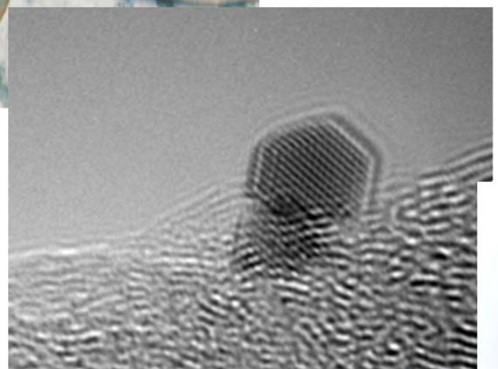
Tjeldbergodden methanol plant

~m

Catalyst pellets

Microreactor

Catalyst-particle Au/C



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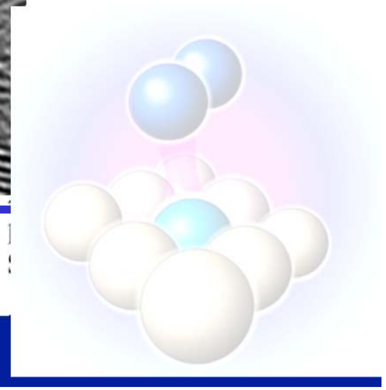


Main toolbox w/examples

Catalyst preparation

Catalyst characterisation

in situ characterization

Kinetics and reaction engineering

SSITKA, TEOM

Modelling

microkinetics, DFT

Reactor modelling

1D, 2D, CFD

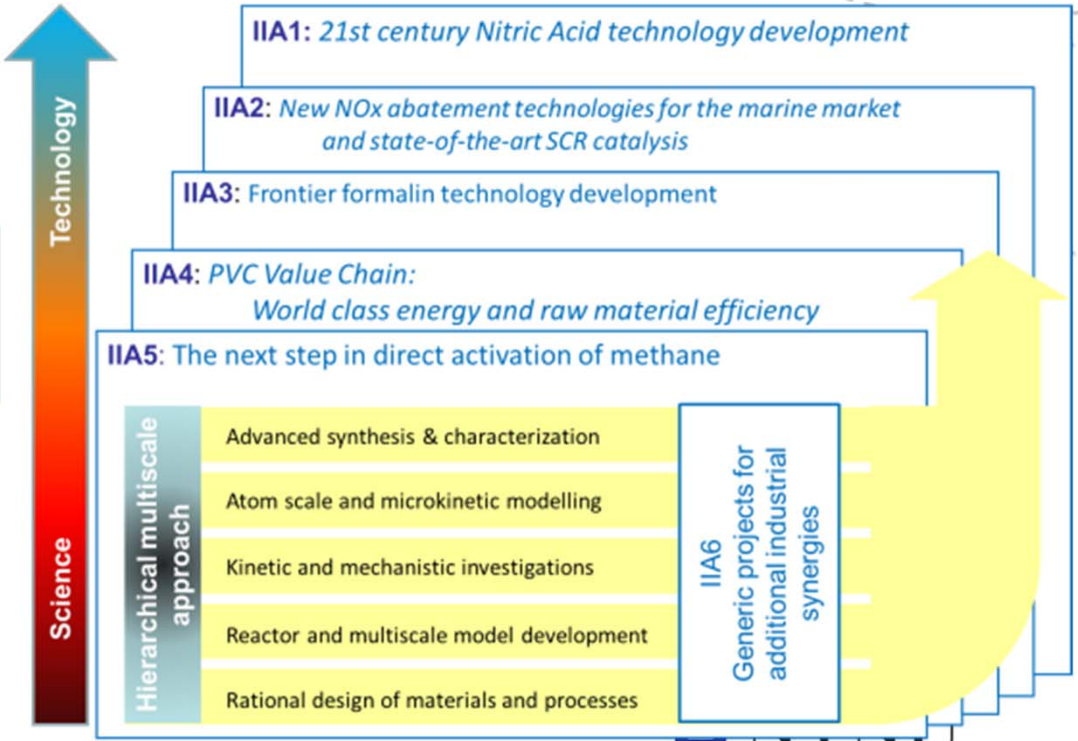
Catalysis is a broad subject, spanning from complex nanomaterials to fullscale industrial plants

iCSI – industrial Catalysis Science and Innovation for a competitive and sustainable process industry

2015-22 National Centre for Research-based Innovation (SFI)
Research Council of Norway

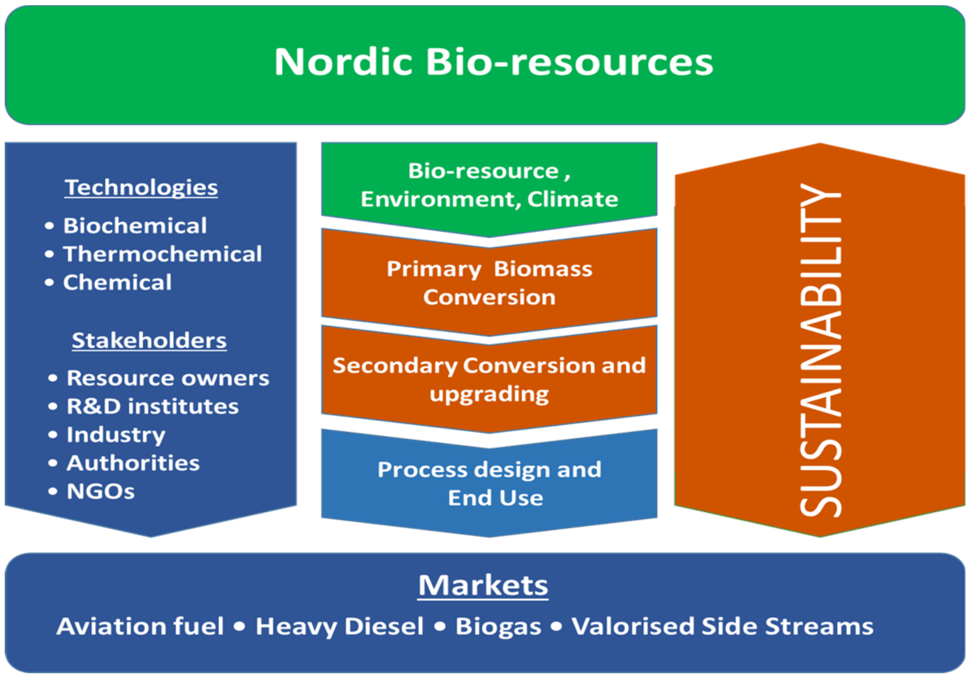
Total budget: 20 M Euro

NTNU + UiO + SINTEF



Norwegian University of Science and Technology

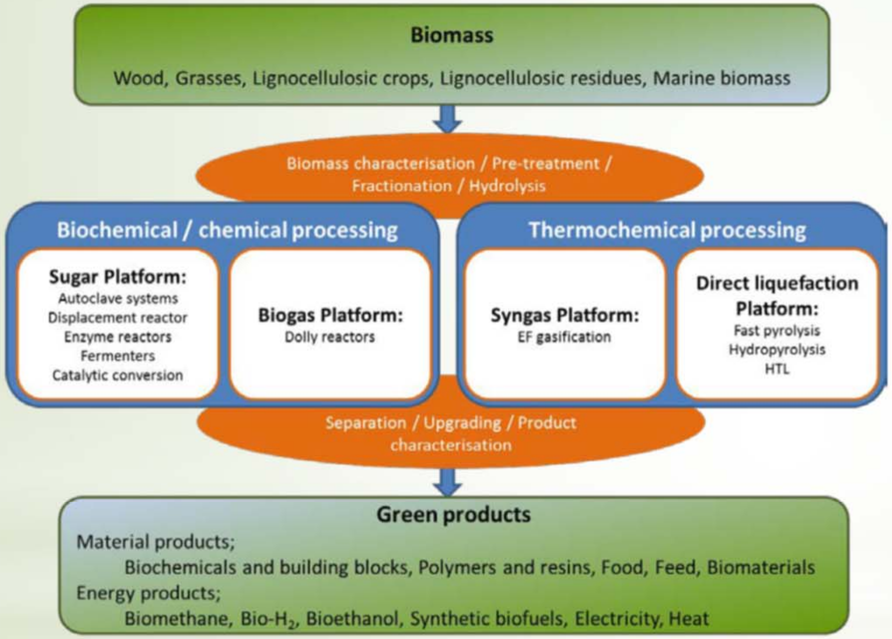
FME Bio4Fuels



- Bio4Fuels: FME (Research Center for Renewable Energy) hosted by NMBU
  - National effort, funded by the research council and partners
  - Most of the relevant research groups in Norway involved
  - 15-20 PhDs + postdocs + institutes, industry
  - Total budget: 30 M euro
- **Main focus:**
  - Transportation fuels
  - High value by-products/side-products included

NorBioLab

Central processes/infrastructures



NorBioLab adresses four central biorefinery technology platforms as defined by IEA Task 42 «*Biorefining*»:

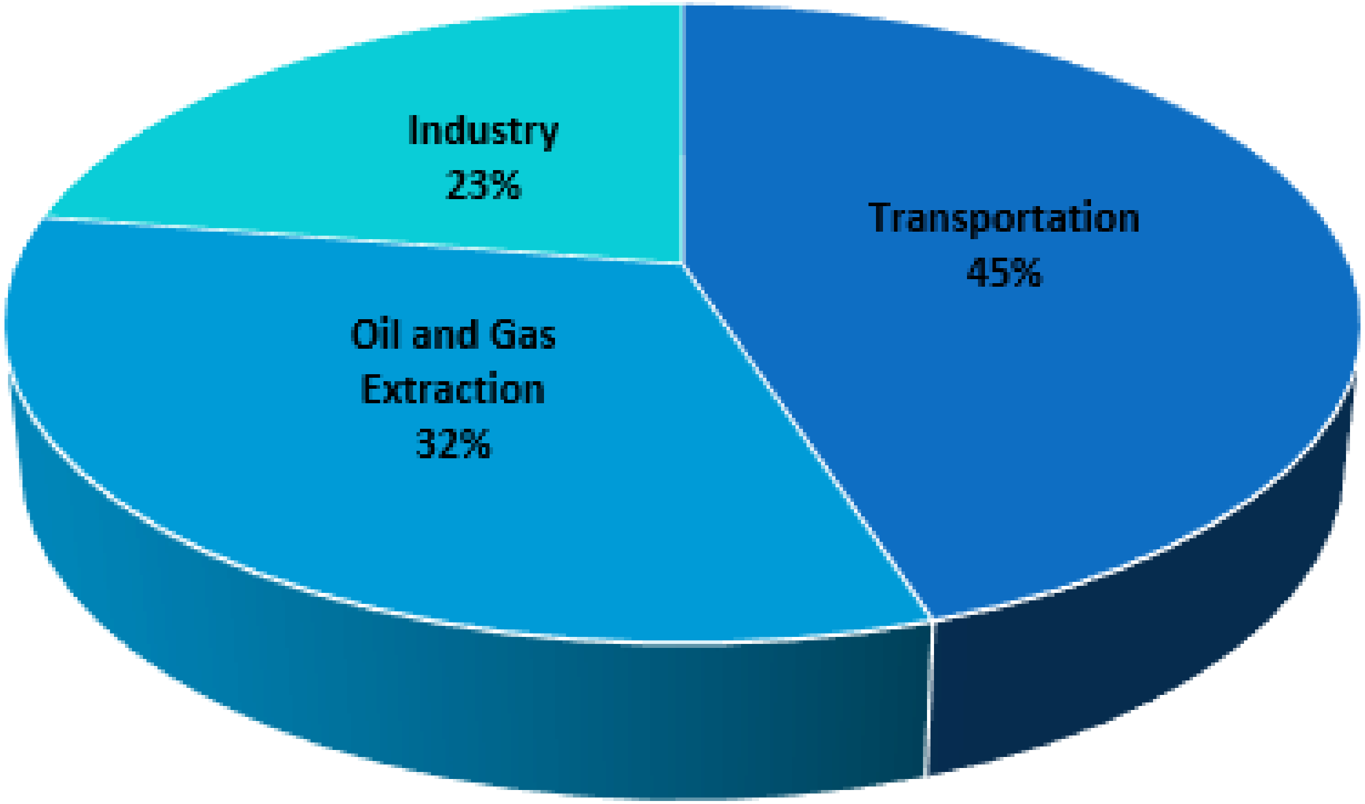
- Sugar Platform
- Biogas Platform
- Syngas Platform
- Direct Liquefaction Platform

SINTEF NMBU PFI NIBIO NORSK INSTITUTT FOR BIOØKONOMI NTNU – Trondheim Norwegian University of Science and Technology

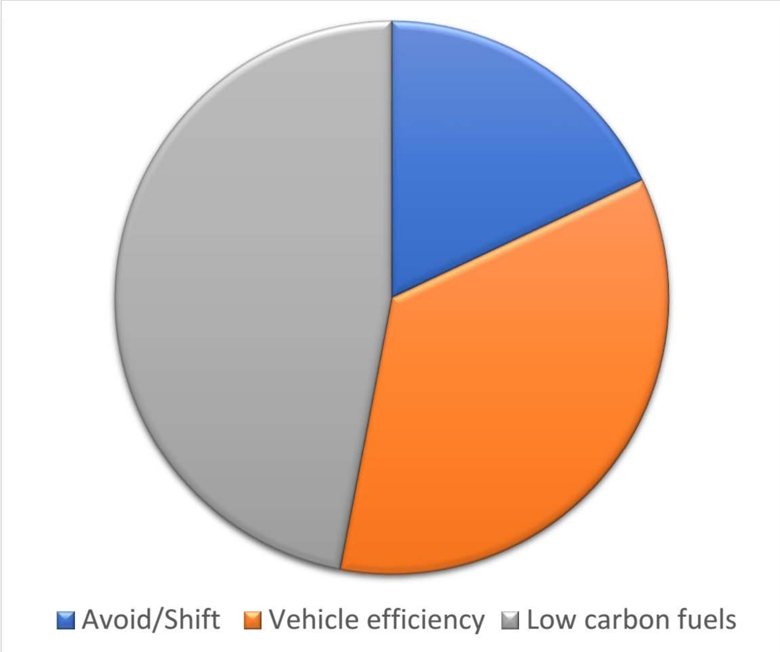
Norwegian University of Science and Technology

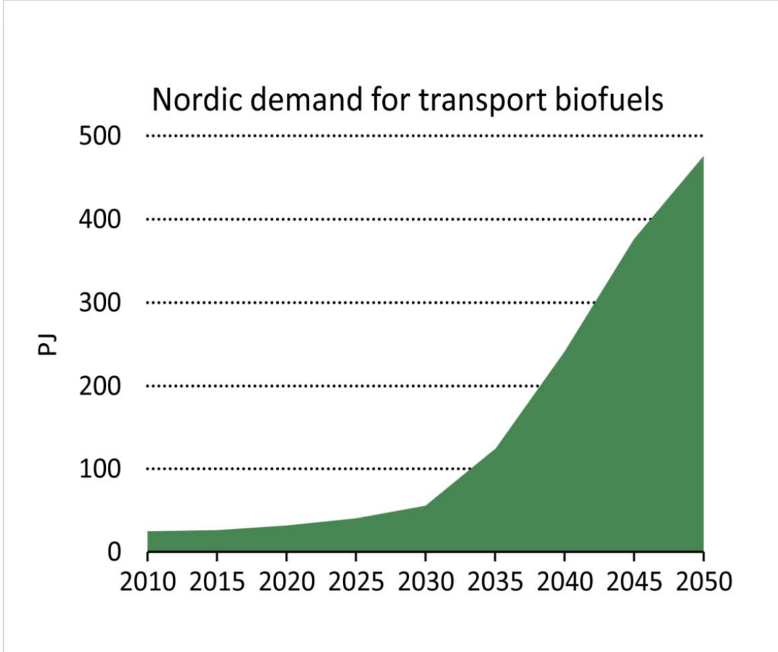
Total budget: 10 M Euro

Sources of CO_2 emissions in Norway

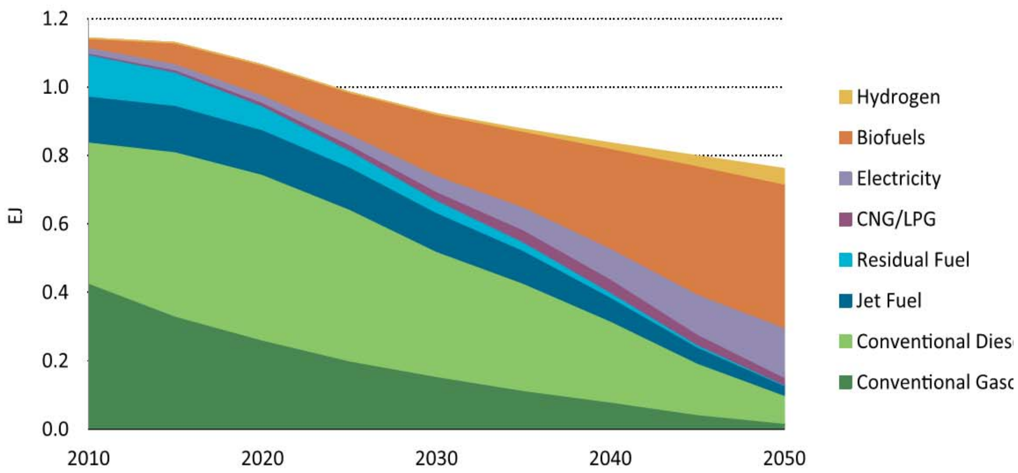


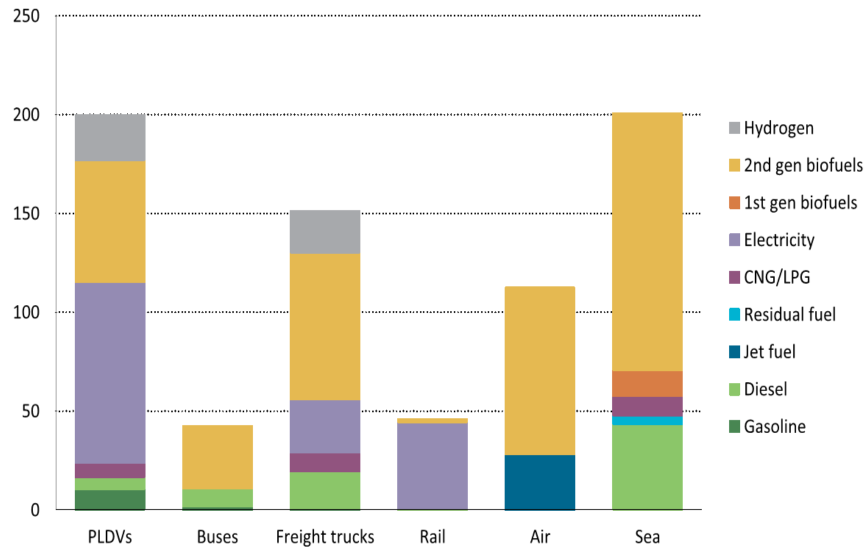
Emission Reductions in transport sector





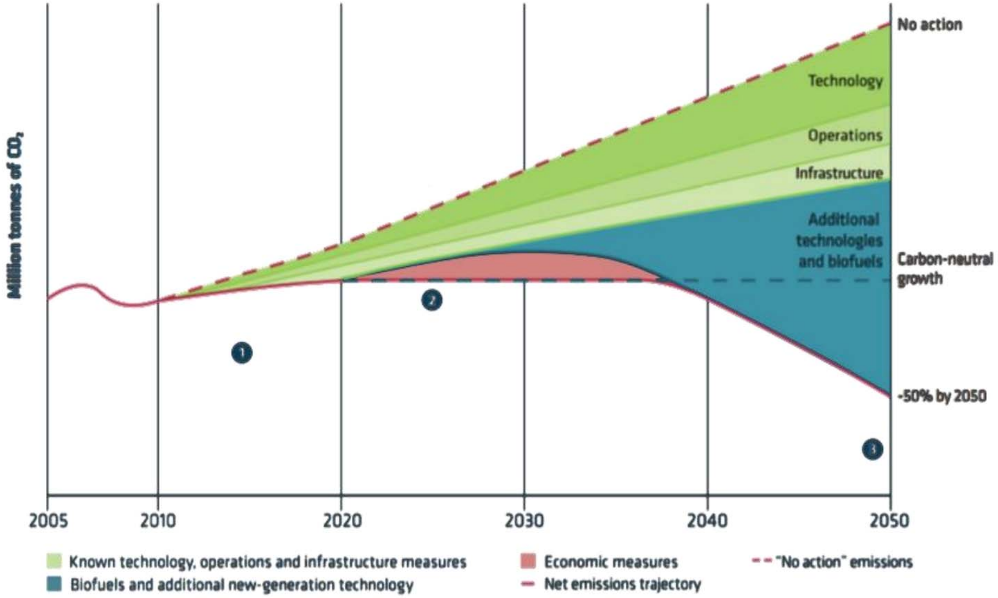
a. Top panel: by fuel source, 2010-2050



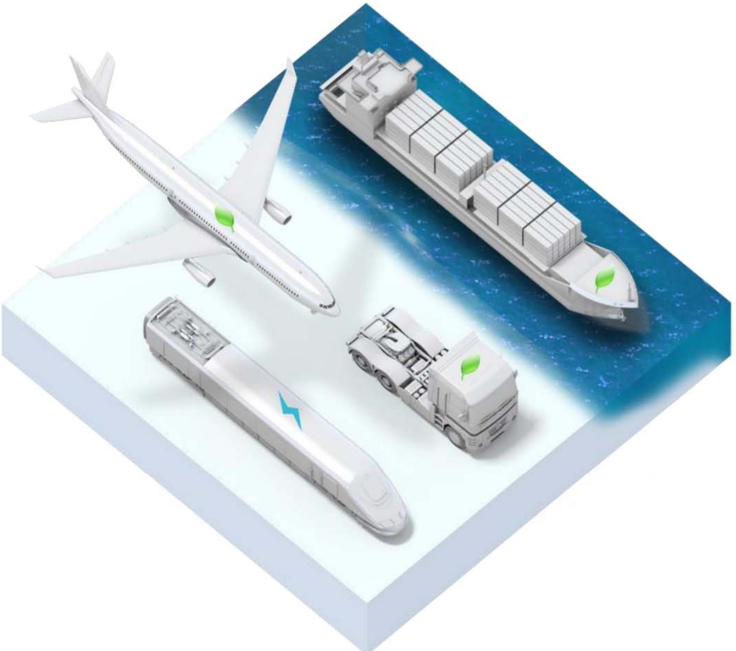


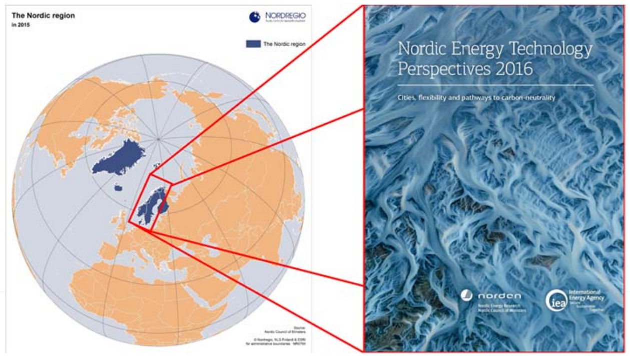
Long-distance transport

Figure 1. **Mapping out the industry commitments**



Source: ATAG, 2013





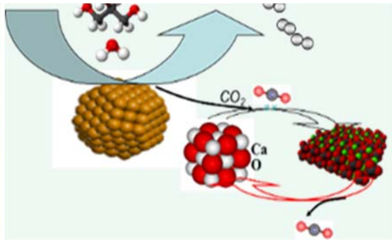
Target in Norway,

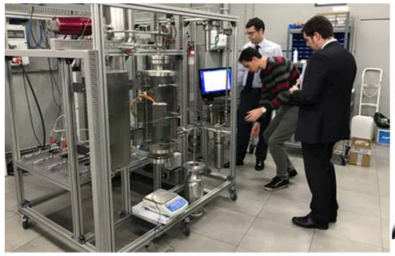
- 30% biofuels share of transportation fuels in 2030

Potential of biomass for biofuels in Norway

- The estimated range of biomass potential in Norway is about 104-167 PJ
- The energy consumed in Transportation in Norway is about 58 TWh, equivalent to 208 PJ

Renewable and Sustainable Energy Reviews 15 (2011) 3388– 3398





Catalytic conversion of Lignocellulosic Biomass at IKP, NTNU

De Chen/Kumar R Rout
Department of Chemical Engineering
Norwegian University of Science and Technology

NTNU
Norwegian University of Science and Technology

Projects ongoing for biomass conversion

- Hydrogenloylisis of cellulose and biomass to C_2-C_6 diols**.**

- Upgrading of bio-oils to chemicals and fuels

- fast hydropyrolysis, hydrodeoxygenation (HDO), hydrogen production.

- Catalytic pyrolysis of biomass to aromatics and olefins for biopolymes

- One-pot conversion of biomass (derived compounds) to hydrogen

- Hydrogenation and oxidation of oxygenates

- **Biomass to Aviation fuel (B2A)**

Catalyst design, Synthesis and Characterization
Carbon supported Catalysts

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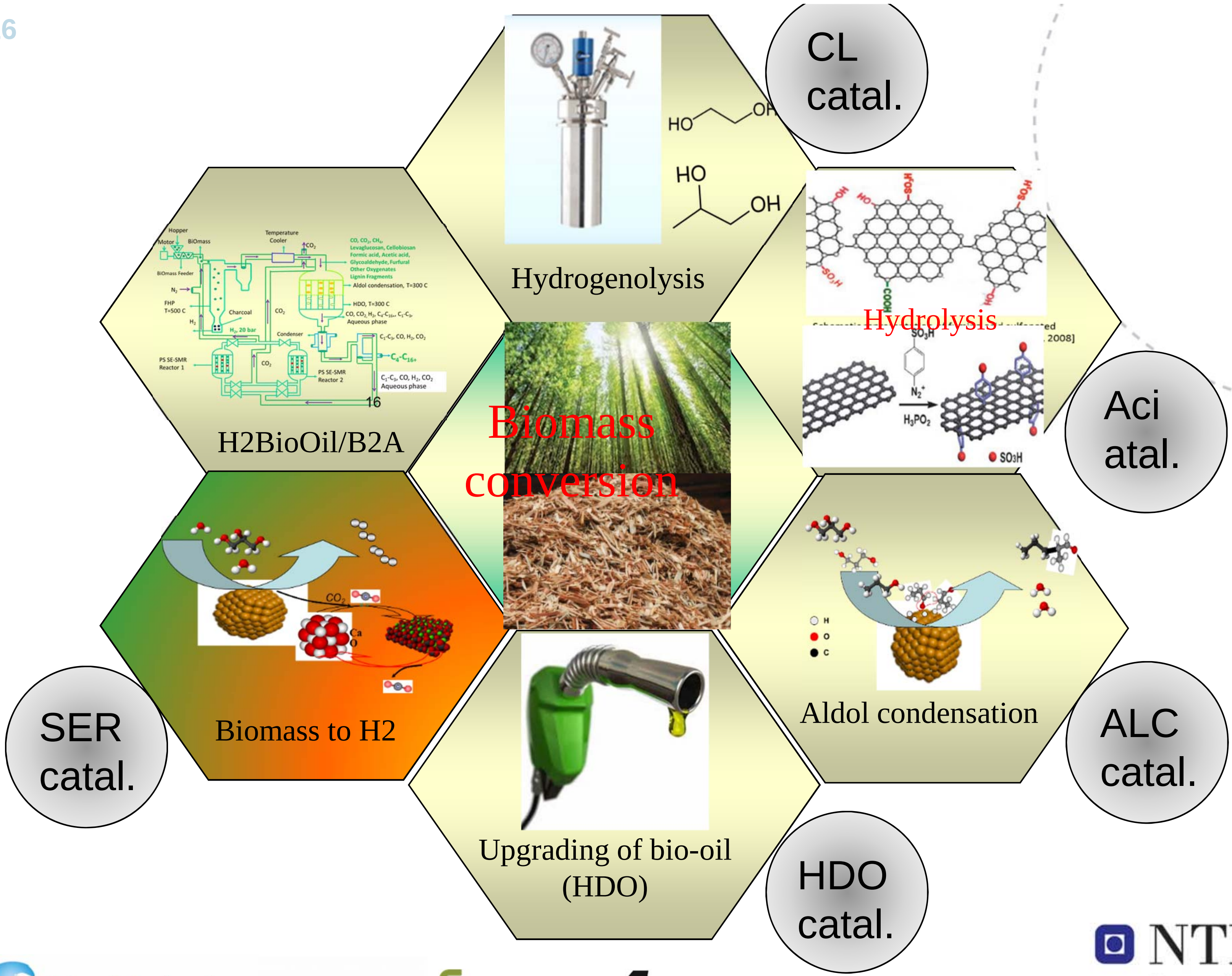
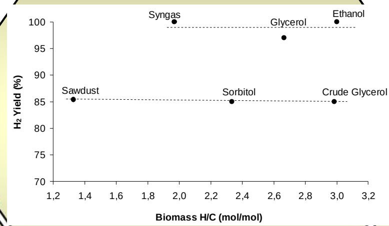
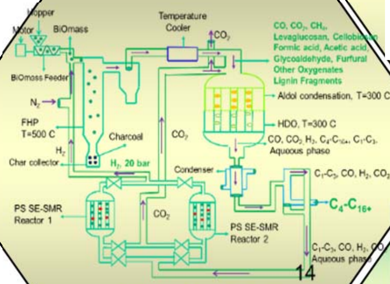
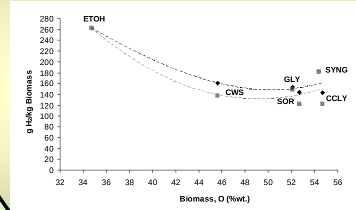


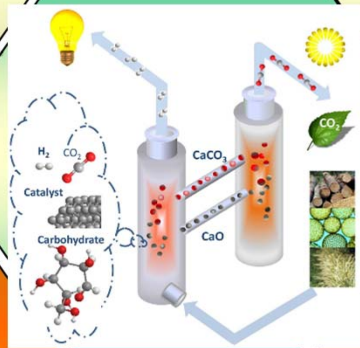
Hydrogenolysis
CL catal.
Hydrolysis
Aci atal.
H2BioOil/B2A
Biomass conversion
Aldol condensation
ALC catal.
Biomass to H2
SER catal.
Upgrading of bio-oil (HDO)
HDO catal.

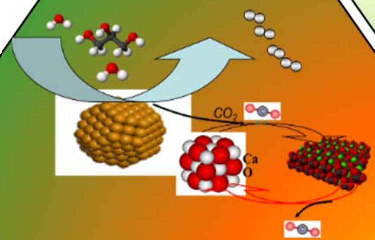




H2BioOil







Biomass to H2

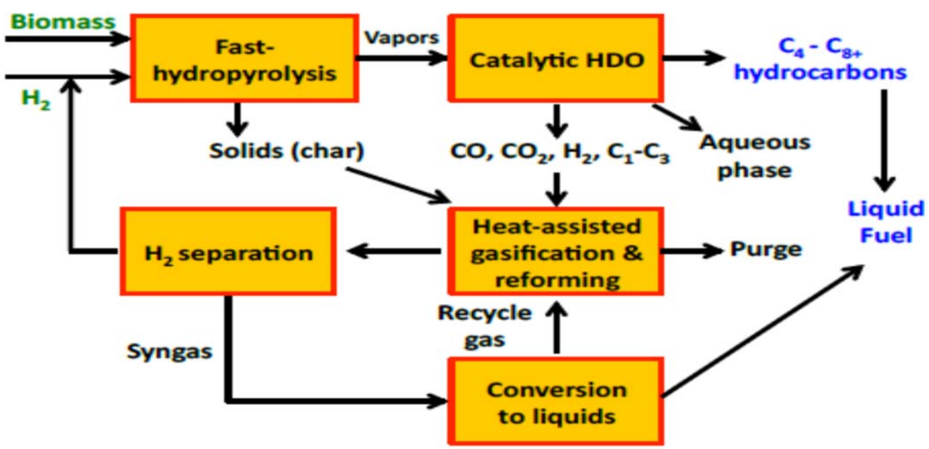
Flexible feedstocks; gas, liquids and solids

Process development

- Reactor
- Process
- Scaling up

H2BioOil

- Efficiency is the key problem in utilization of renewable energy, and the efficiency in biomass utilization is low [1].
- Hydrodeoxygenation (HDO) process has been extensively studied to upgrade bio-oils. But, upgrading bio-oils to fuels and chemicals remains formidable challenges, partially due to the complexity in composition with more than 300 compounds.
- Therefore, as a step towards alternative process to produce hydrocarbon fuel, Venkatakrishnan et al. [2] have proposed the *H_2BioOil* process based on biomass fast-hydropyrolysis (FHP) combined with vapor-phase catalytic HDO, where the cooling down-heating up processes and coke formation of unsaturated bio-oils could be avoided. Thus it can achieve high fuel yield and high energy efficiency.



Fast-hydropyrolysis:
rapid heating of biomass in an H_2 environment to temperatures of about 500 ^{0}C, to produce vapors and biochar.

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[1] MacKay, D.J.C., *Sustainable Energy – without the hot air*. 2008: UIT Cambridge.
[2] V. K. Venkatakrishnan, et al, *Green Chem* **2015**, *17*, 178-183.

Price of Biofuel: Four sensitive parameters

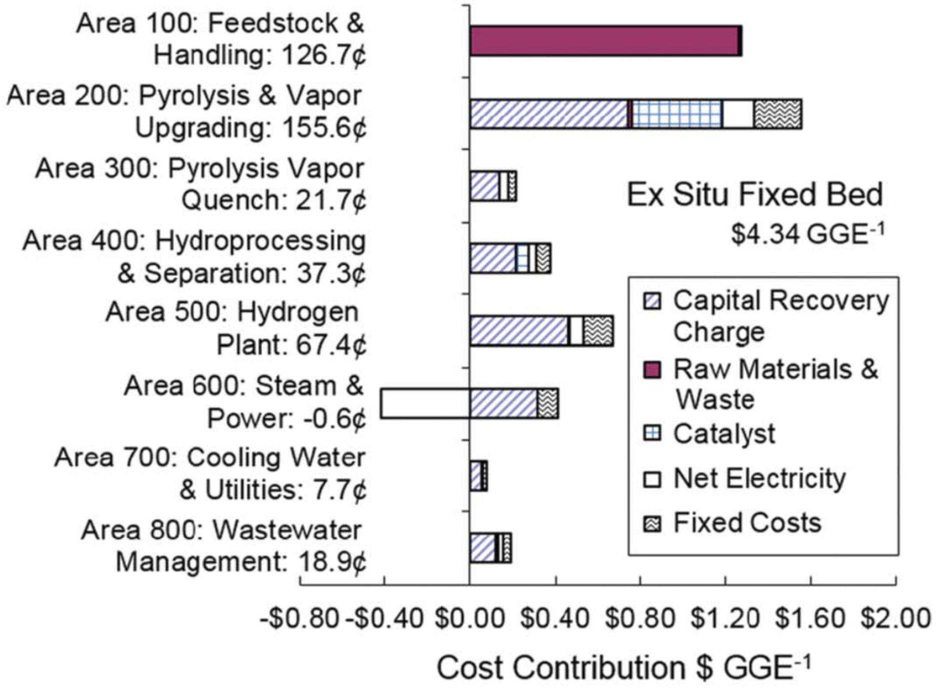
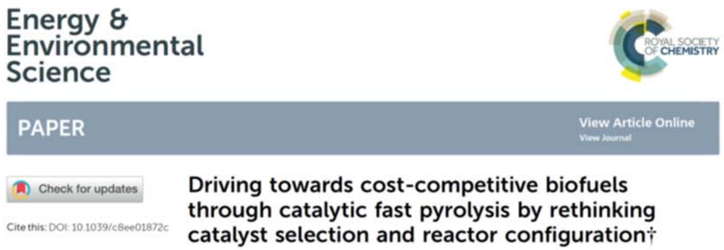


Fig. 6 Modelled cost breakdown (in 2014$) for the production of hydrocarbon fuels *via* fixed-bed CFP with Pt/TiO_2.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Cite this: DOI: 10.1039/c8ee01872c

Driving towards cost-competitive biofuels through catalytic fast pyrolysis by rethinking catalyst selection and reactor configuration†

Carbon yield is the key for commercial viability

10% relative improvement of carbon yield reduce about 0.08-0.1 €/kg

- Biomass price
- Carbon yield
- Catalyst price and stability
- Hydrogen price (supply)

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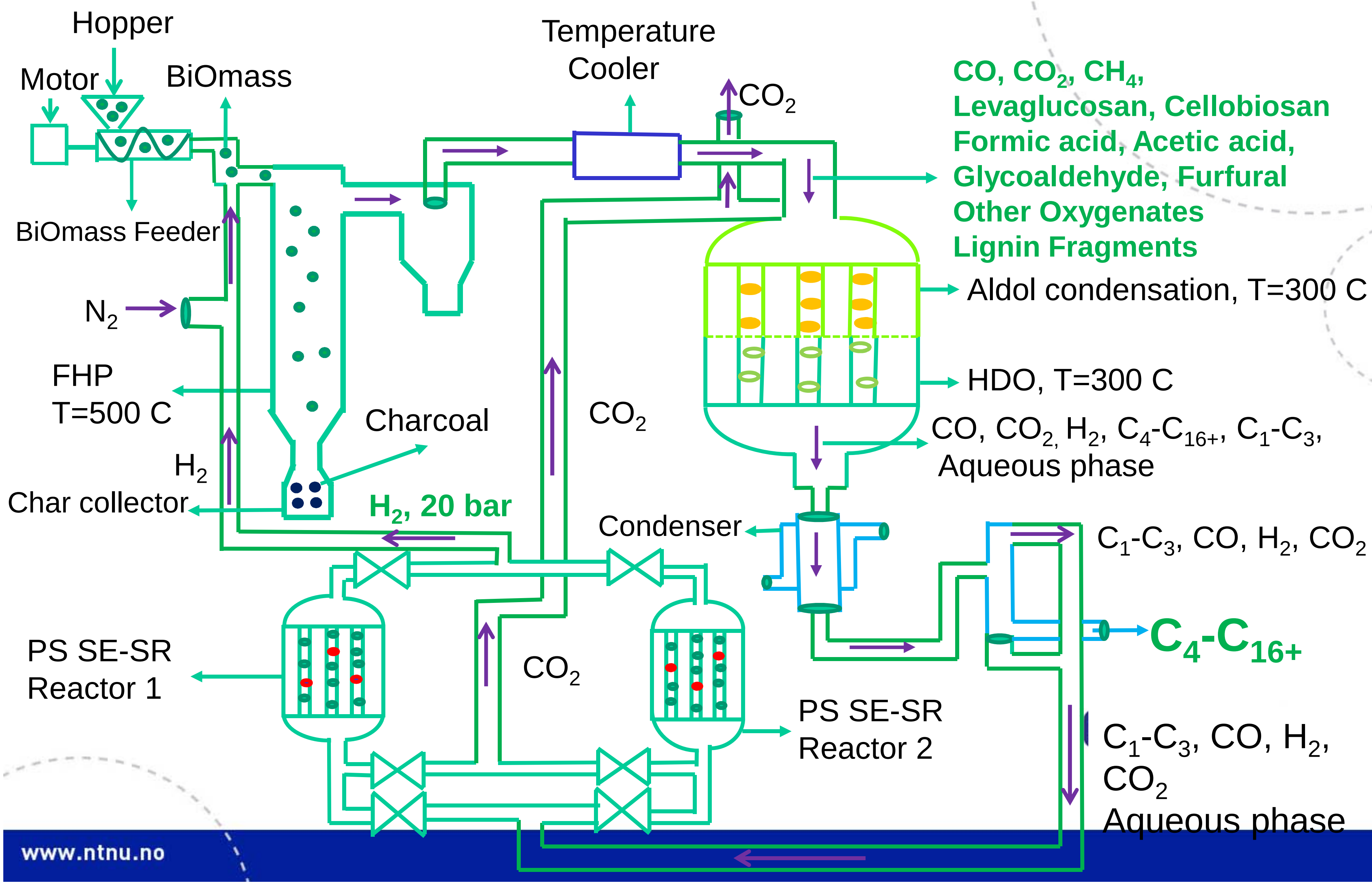
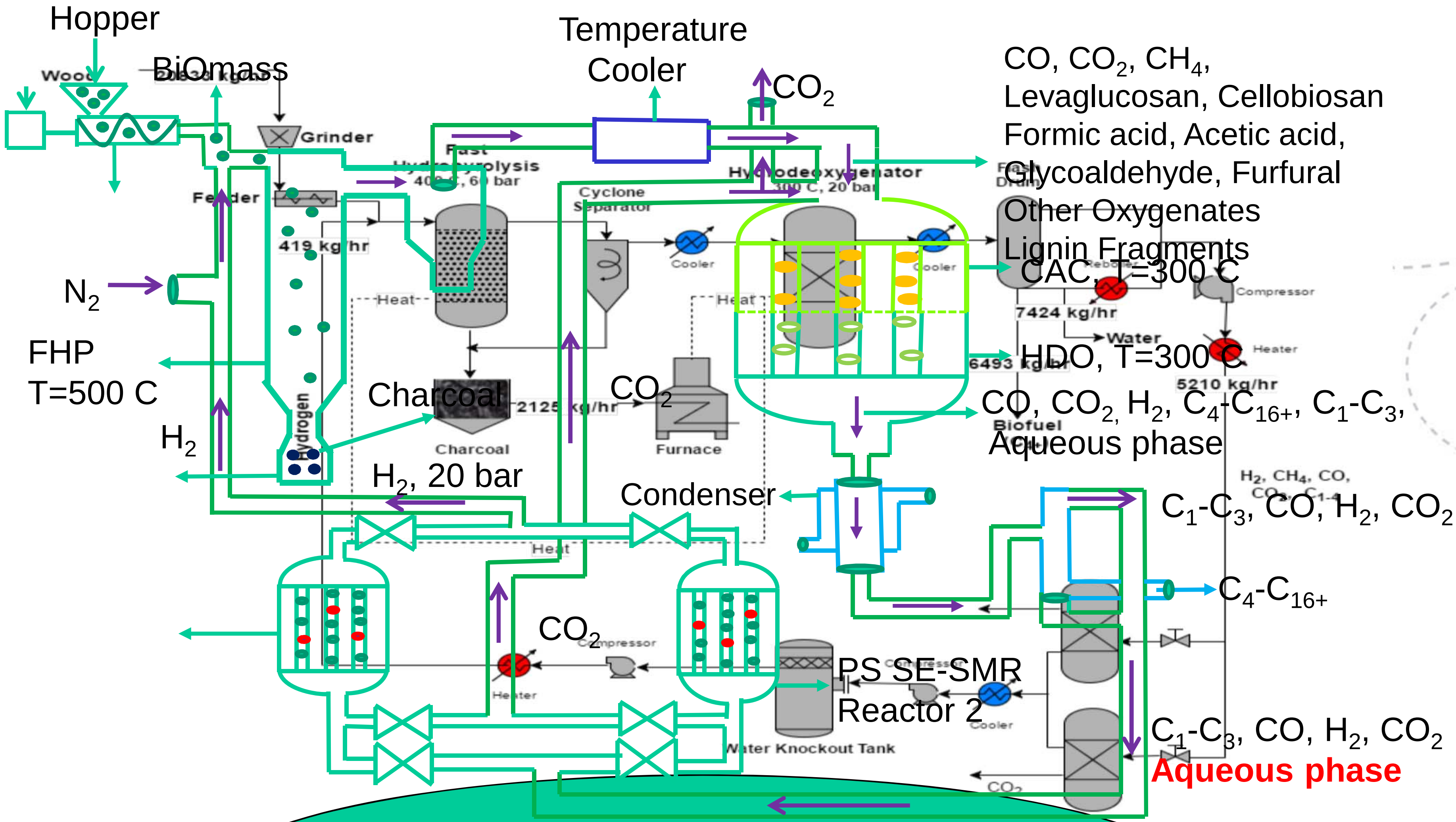
Patented modified *H_2BioOil* by *NTNU/SINTEF*

PCT/EP2020/050929, GB1900553.7



Process Evalutation of H2BioOil



In-situ hydrogen production from C1-C...

Sufficient enough for H2BioOil??

Process Evalutation of H2BioOil

Charcoal Yield (%)	Carbon (C_{4+}) Recovery (%)	Energy Efficiency (%)	Fuel Energy Content (ege/ton biomass)
5	57	72.5	172.6
10	54	74.9	163.4
15	51	77	154.1
20	48	81.1	144.8

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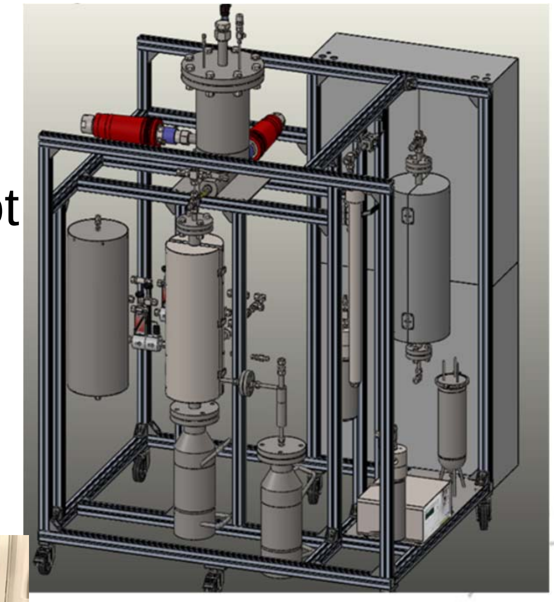
Venkatakrishnan et al, Green Chemistry, 2015, 178

Catalysts and process development at different scales

Mini-pilot



40-1000 gm/hr
Up to 20 bar
Up to 200 g catal.
catalyst pellet

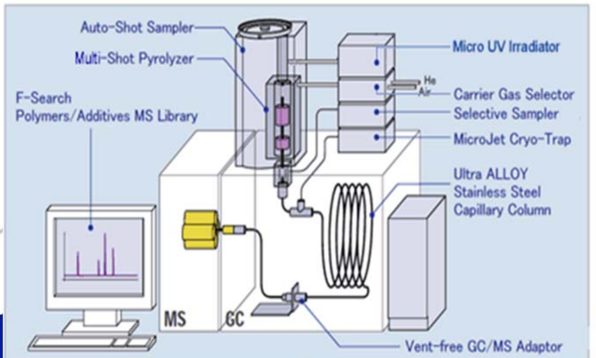
Fluidized bed reactor

10-400g/hr

Entrained flow reactor

1-10 gm/hr

Micro, pyr-GC-MS



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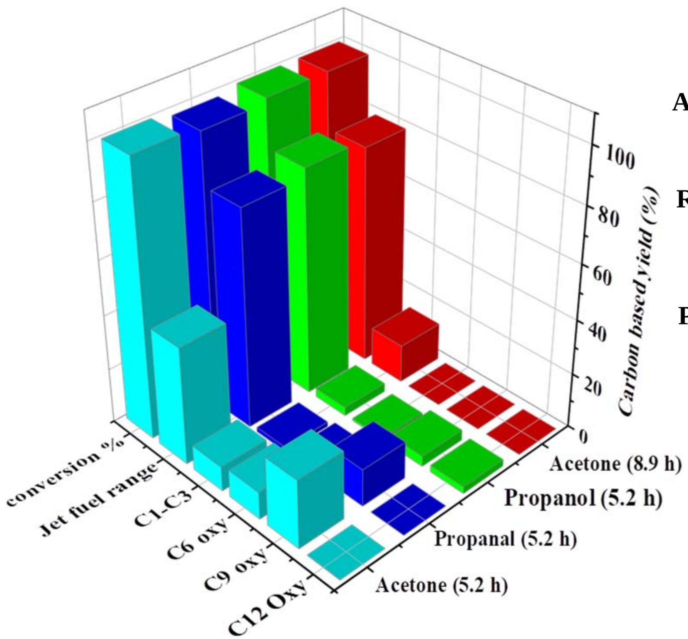
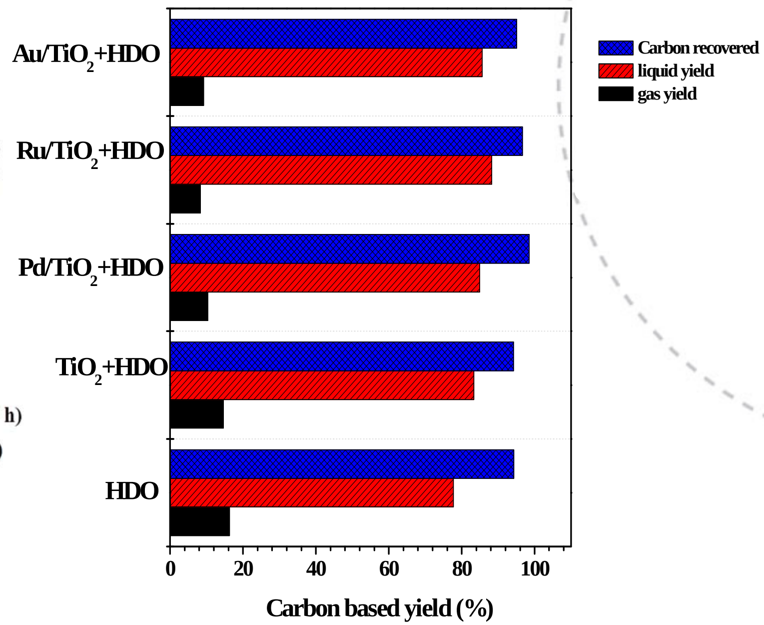
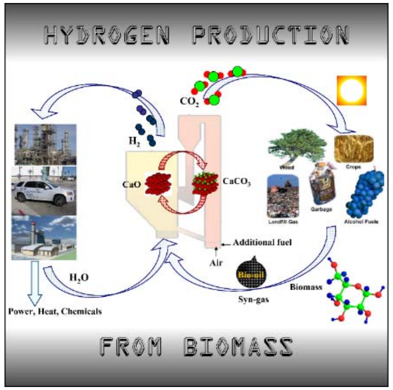




Tested in mini pilot plant (catalyst pellets)

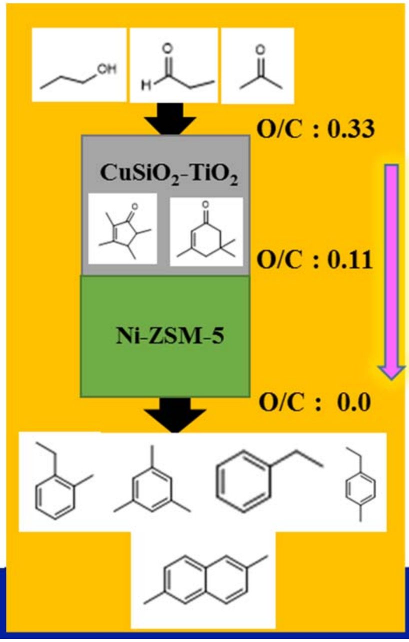
-2014

2019



99.9 % purity
80% energy efficiency
Flexible feed

2016



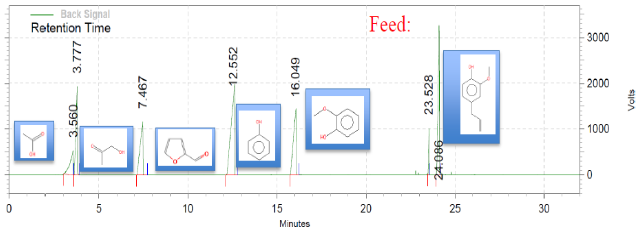
2018

O <1 wt%

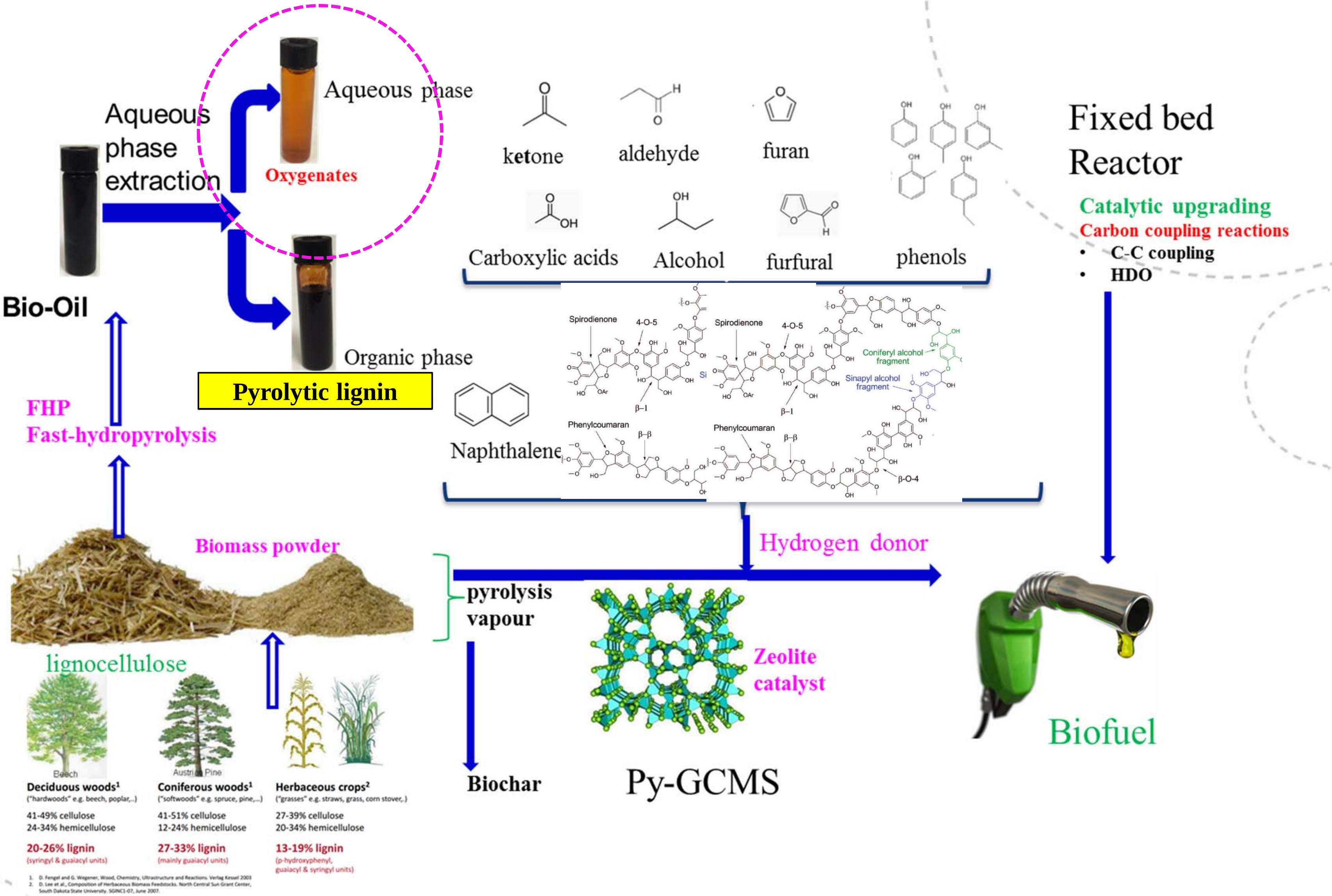
HDO: Simulated bio-oil,
6 compounds
Lab fixed bed reactor

Multicomponent feed:

Feed 10-08-2017	wt %
water	28,7
Acetic acid	12,3
Acetol	13,8
Furfural	10,6
Phenol	15,7
Guaiacol	9,07
Eugenol	10,4

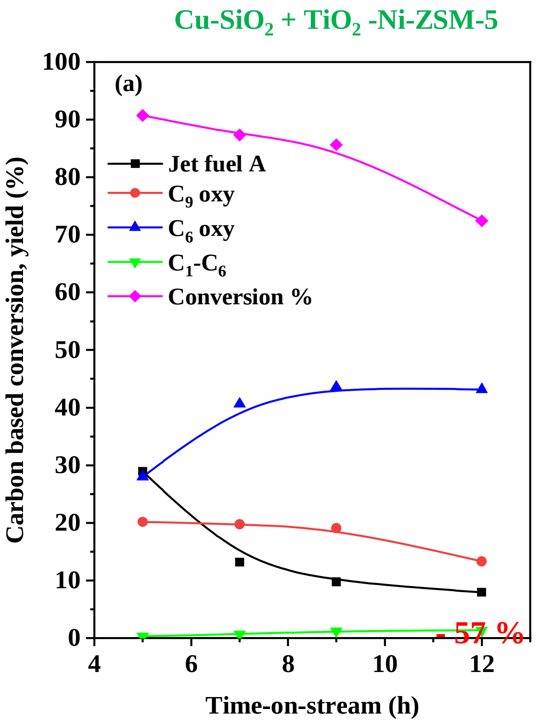


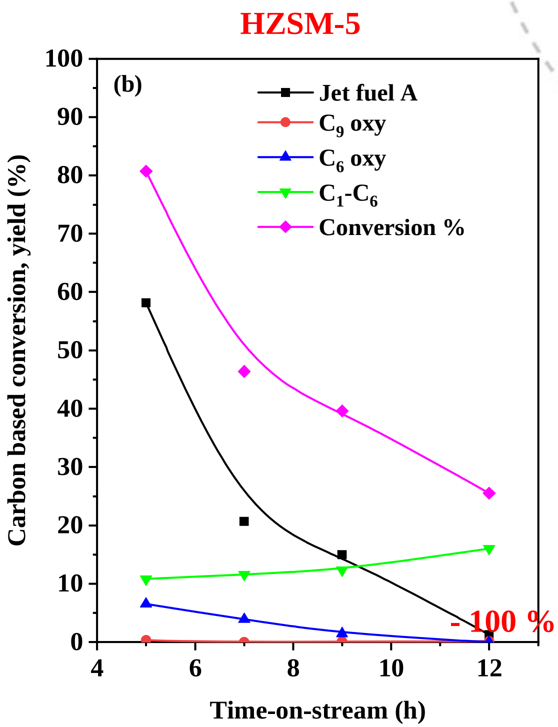
Tandon Reaction: Aldol condensation followed by HDO



Stability and product spectrum analysis:

Tandem reaction vs State-of-the art catalyst





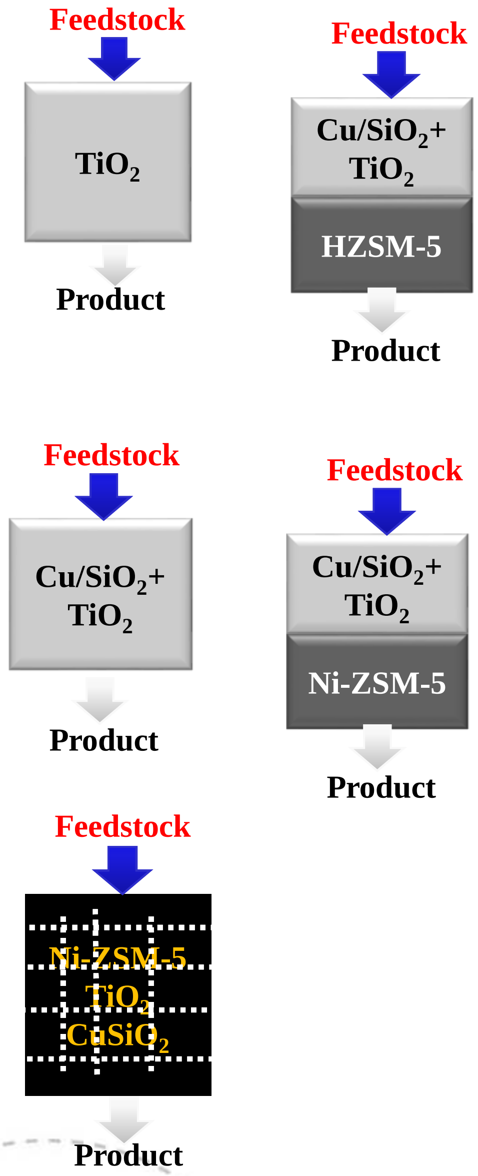
➢ **Reaction conditions :**

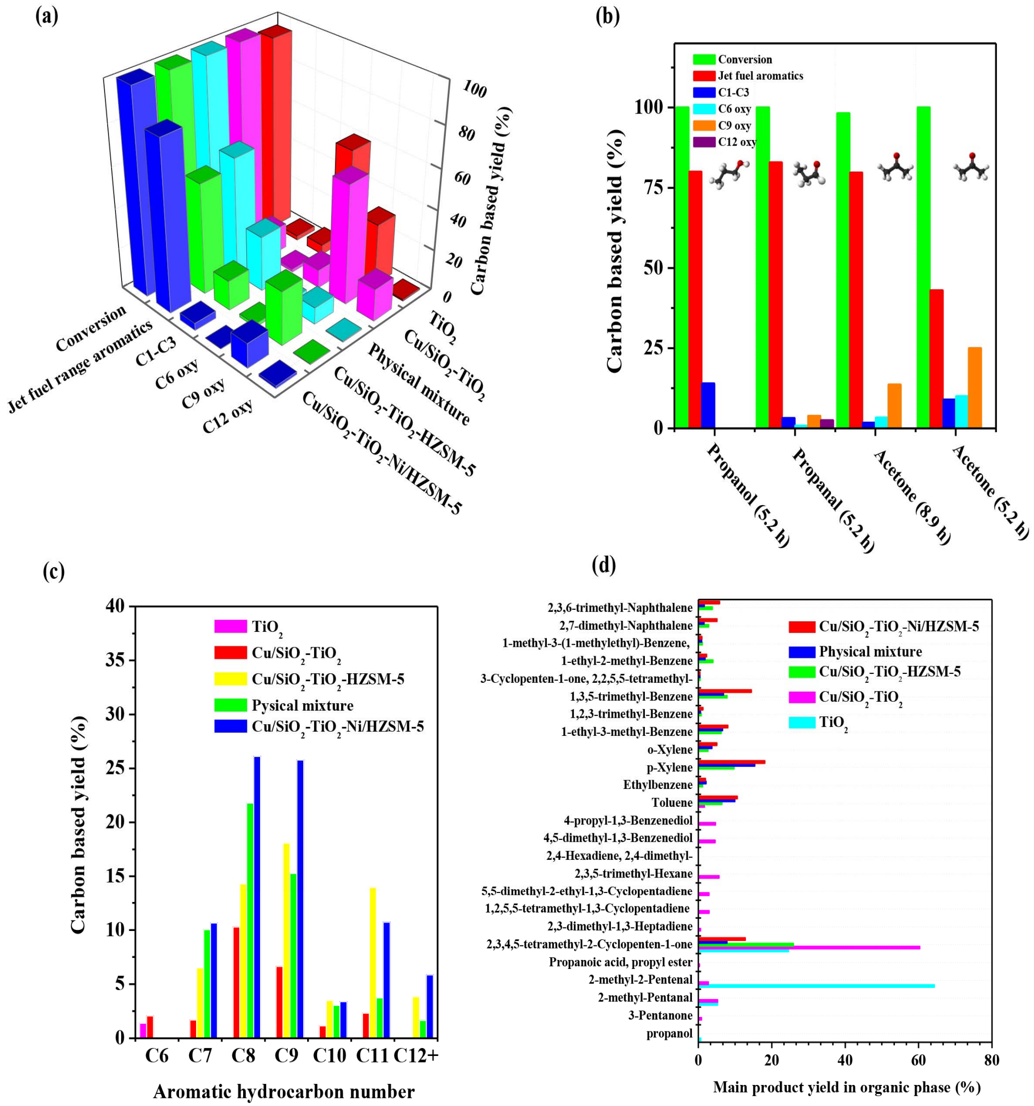
- Temperature: 300 °C
- Total reactor pressure: 1 bar (H_2: 0.2 bar)
- 1/WHSV: 0.26 h

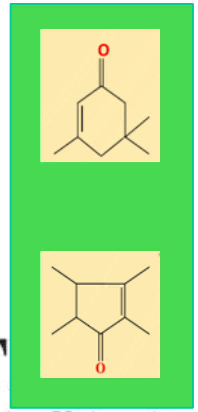
Dual bed catalyst: relatively stable hydrocarbon pool after 7 hours

Conventional HZSM-5 has fast deactivation rate

Catalyst dependent oxygenates conversion to high yield aromatics

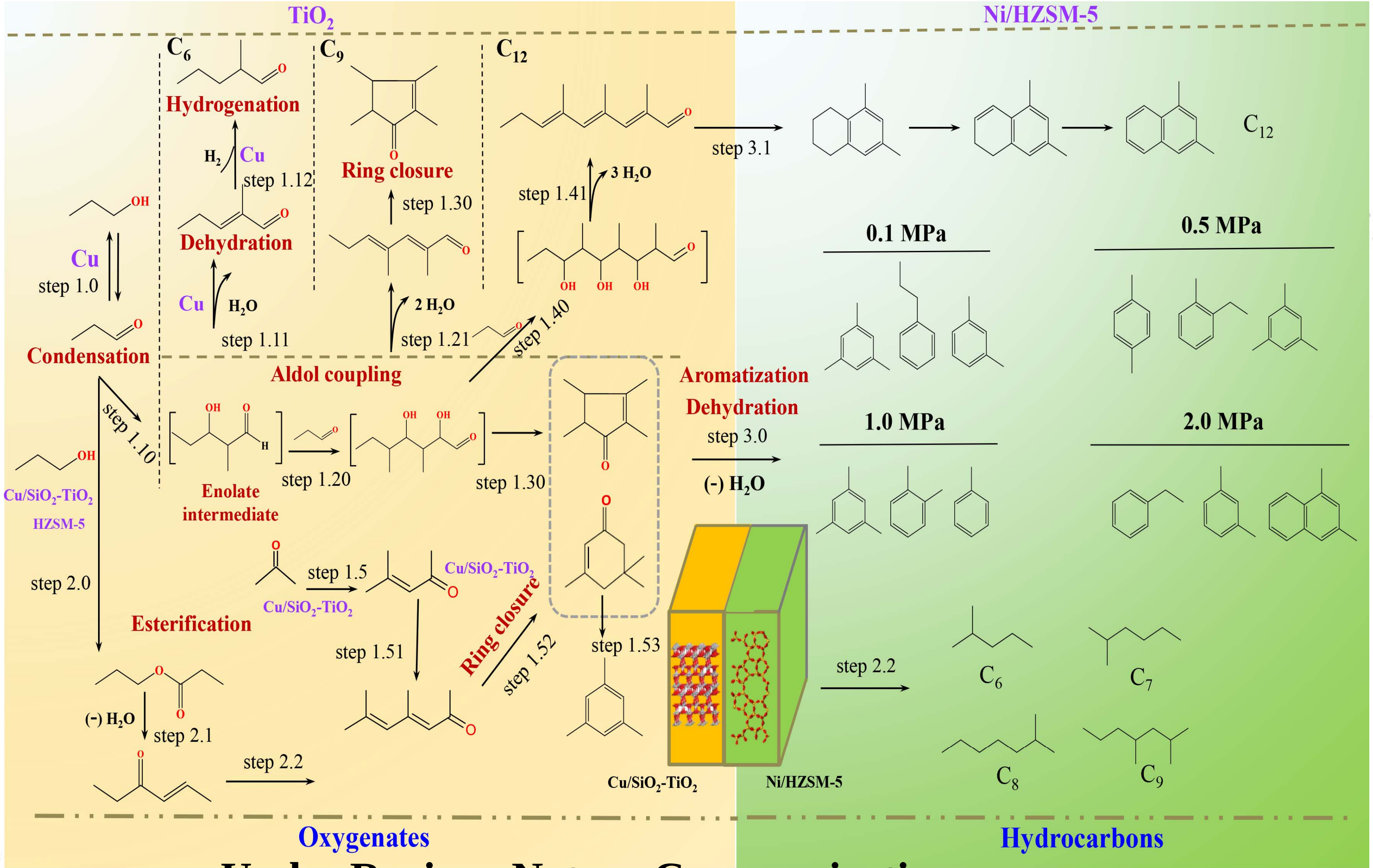






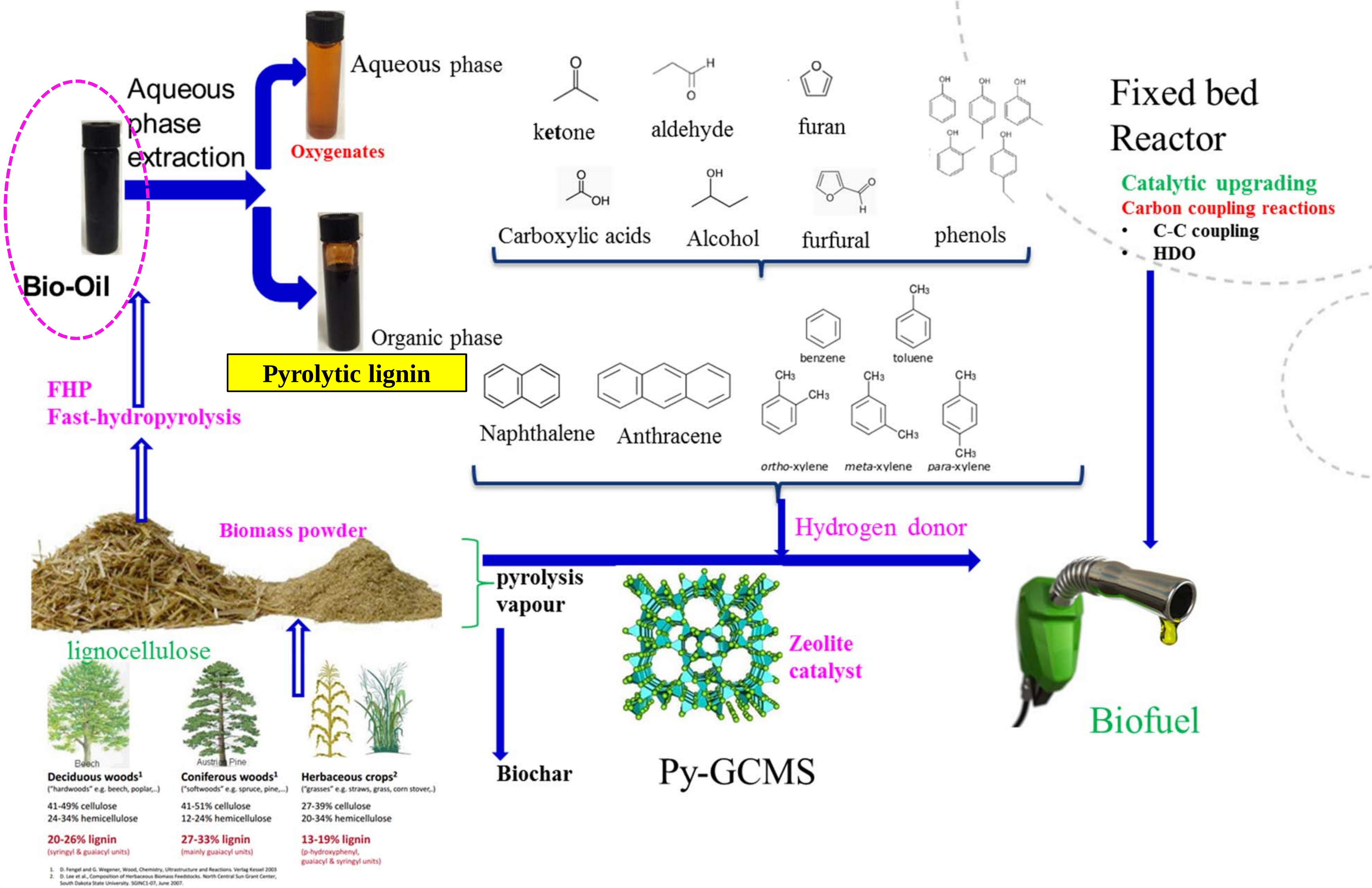
New reaction route:

- **Tandem C-C coupling and hydrodeoxygenation reactions**



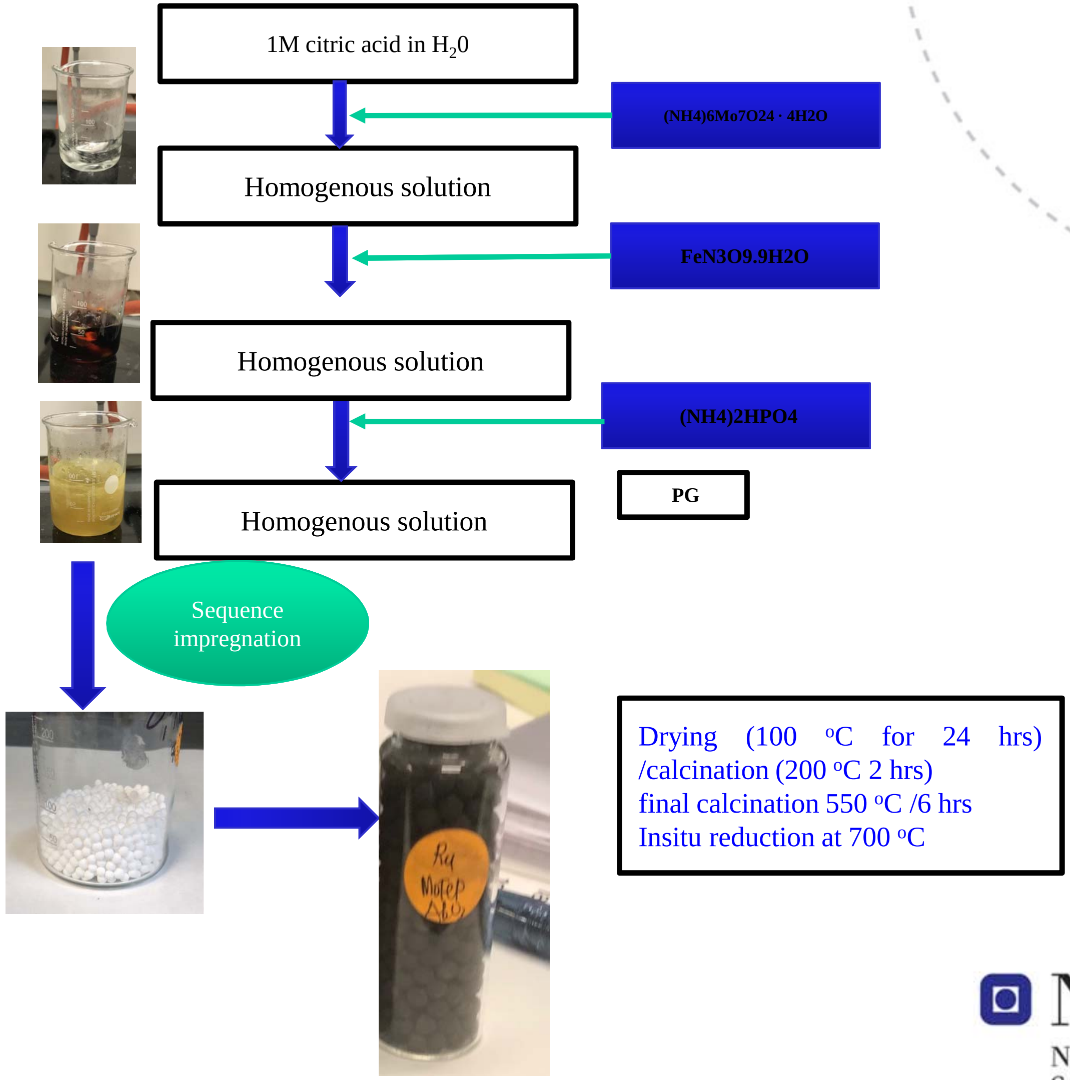
Under Review: Nature Communications

Tandon Reaction in the Pilot plant



Modified Pichini Synthesis method:

- Paper 5: Ru-MoFeP-Al_2O_3 synthesis for HDO Reaction

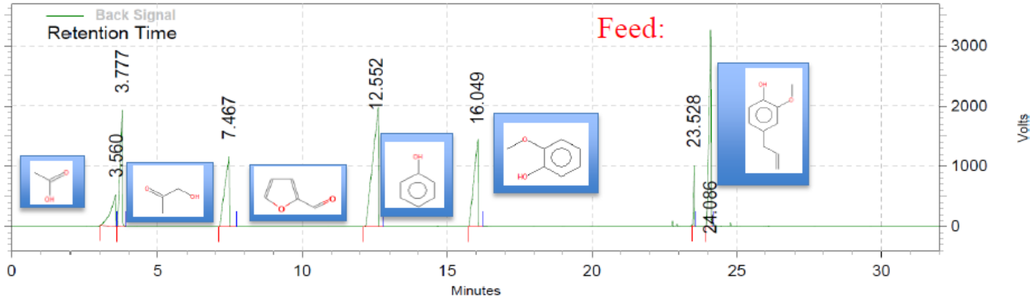


0.1 wt% Ru

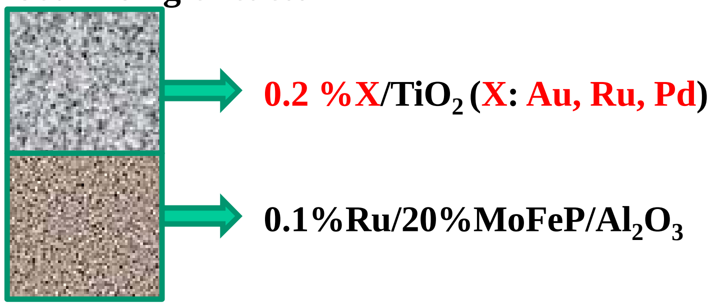
Feedstock and Experiment condition

Multicomponent feed:

Feed 10-08-2017	wt %
water	28,7
Acetic acid	12,3
Acetol	13,8
Furfural	10,6
Phenol	15,7
Guaiacol	9,07
Eugenol	10,4



Dual bed in single reactor



Reaction Conditions

Temperature : 400 °C

Pressure : 20 bar, 13 bar H_2

WHSV : 0.5/h

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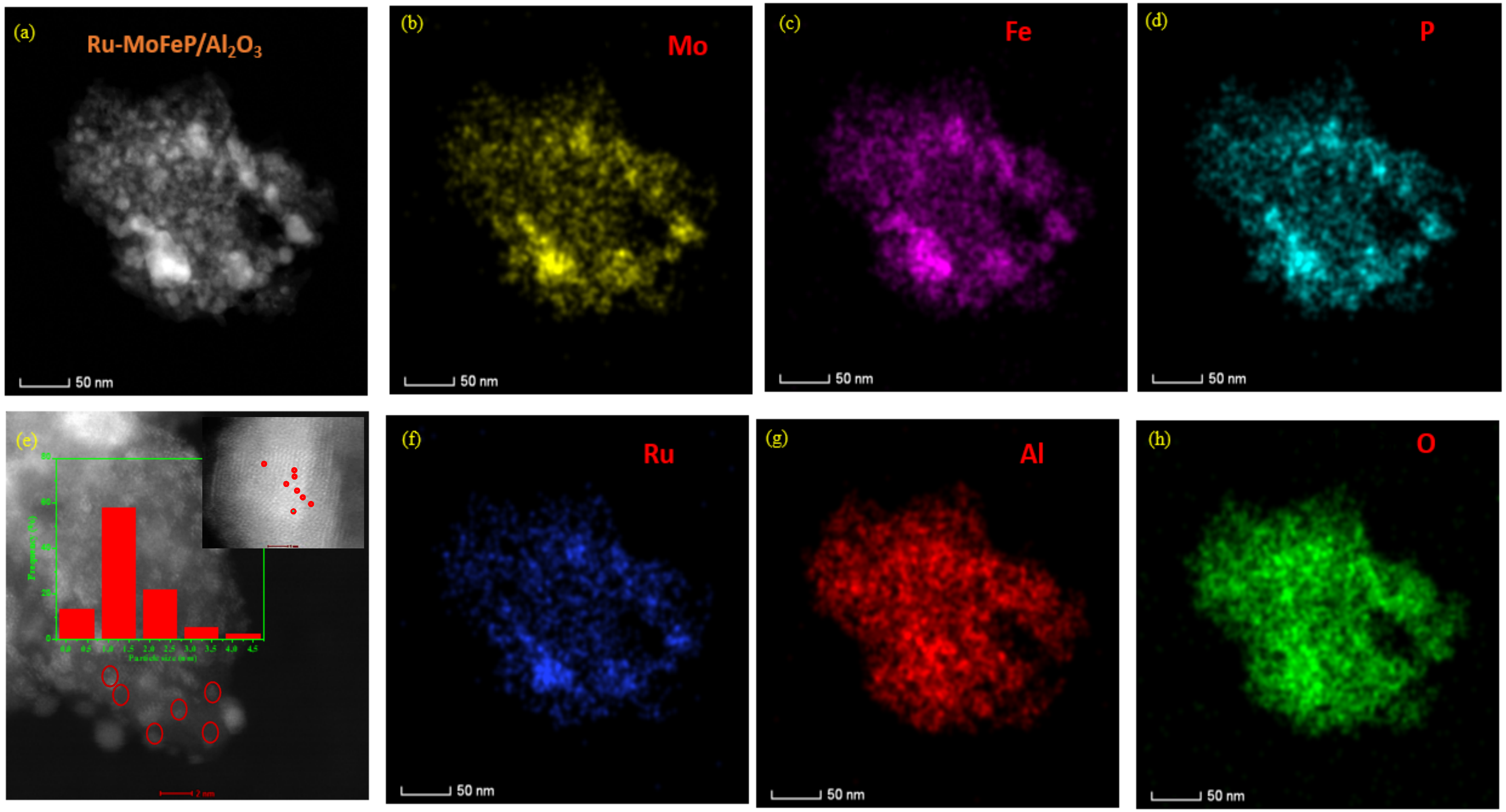
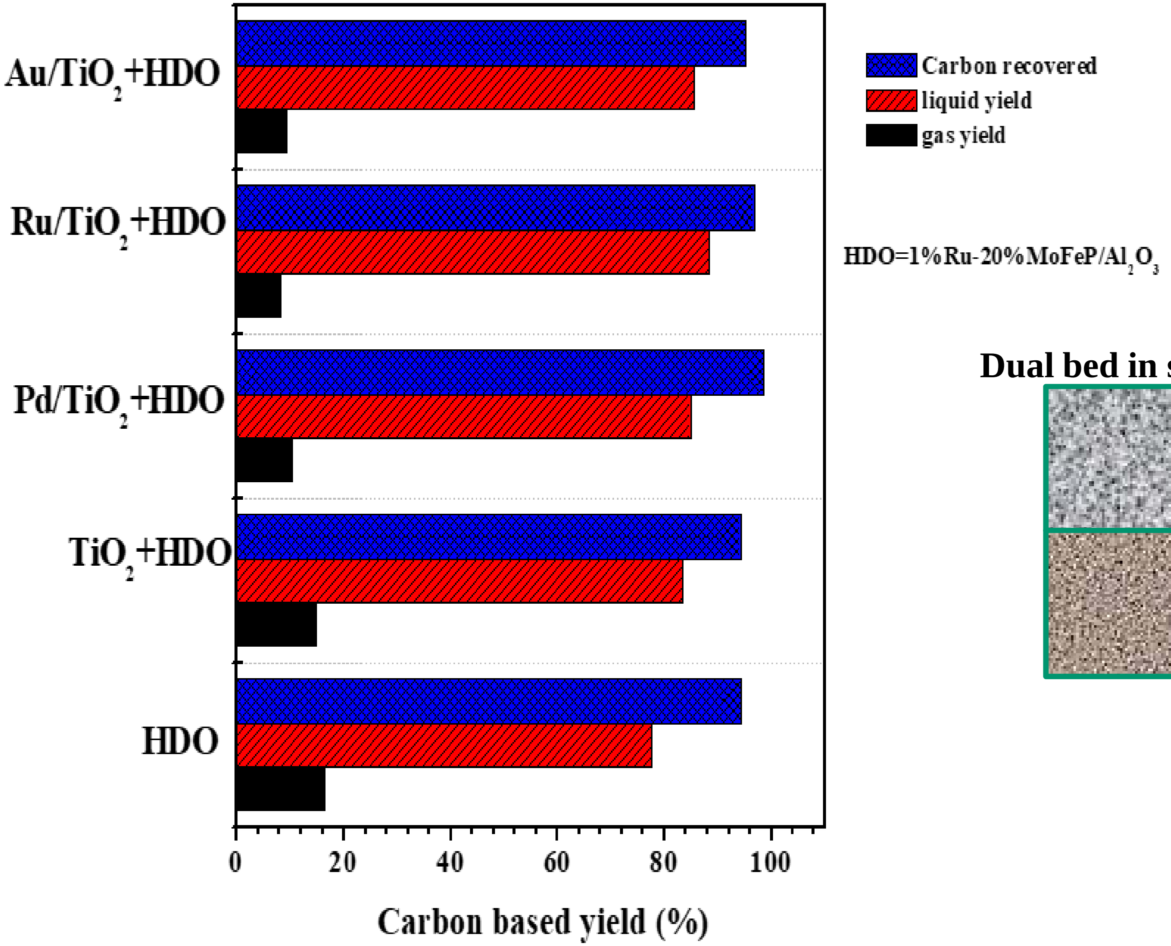
HAADF-STEM/EDS image 0.1 wt% Ru-20 wt% MoFeP/Al_2O_3

- **HAADF-STEM-EDS image : Highly dispersed metal clusters**

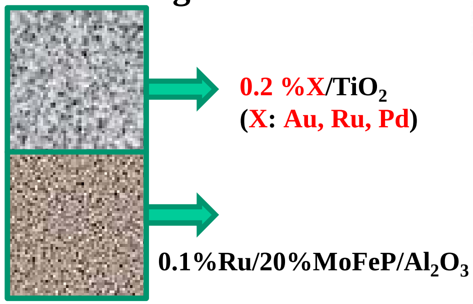


< 0.1-1 nm, possibly some single atoms or subnanoclusters

Effects of upstream bed on phenol conversion and O/C ratio



Dual bed in single reactor



ACS Catalysis: accepted

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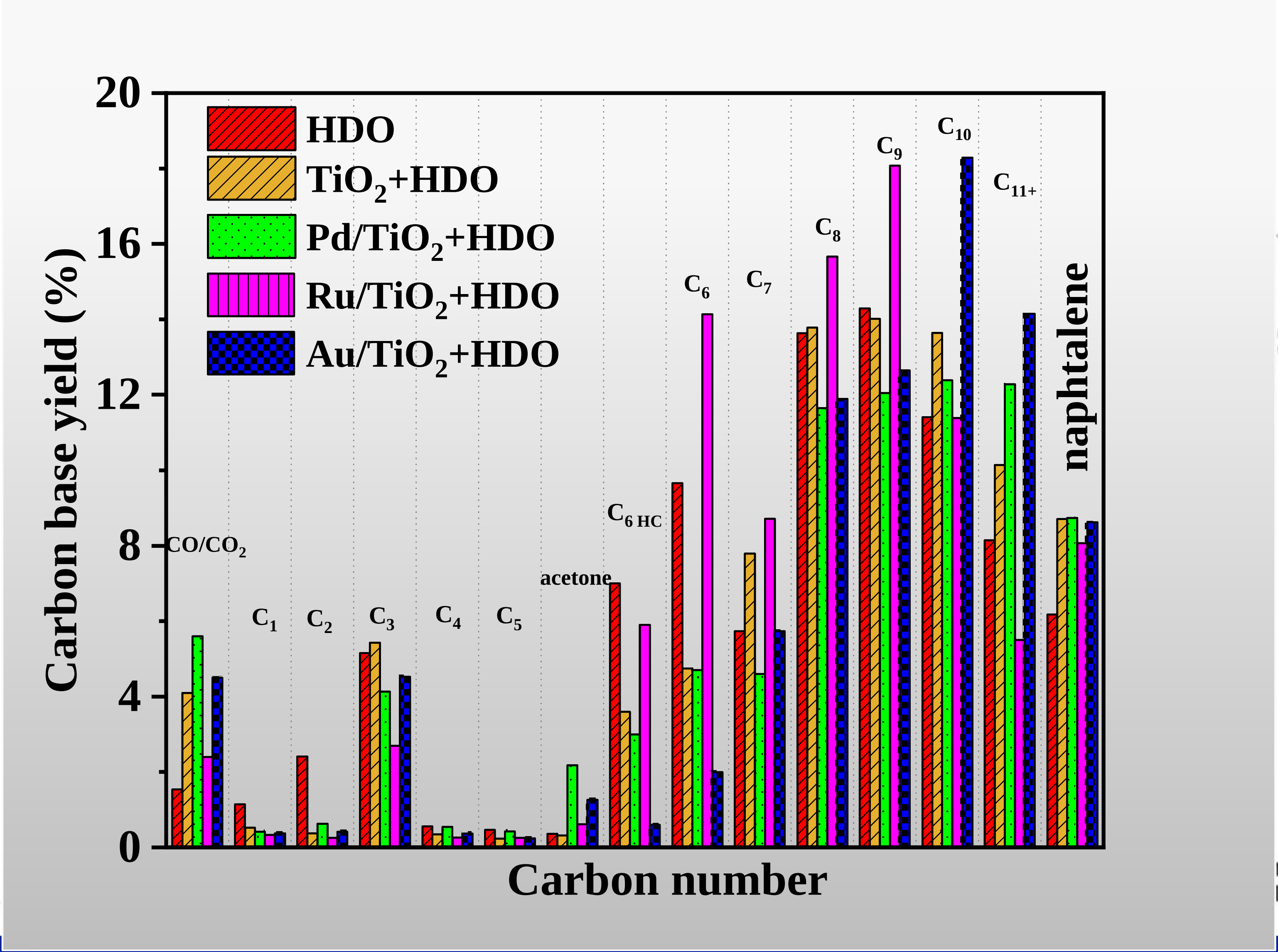
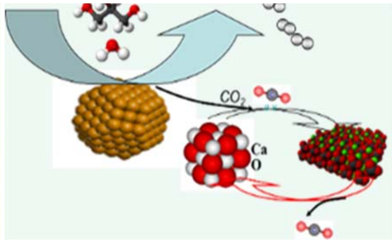
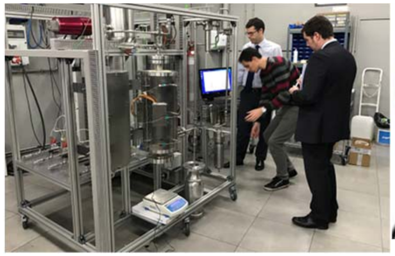
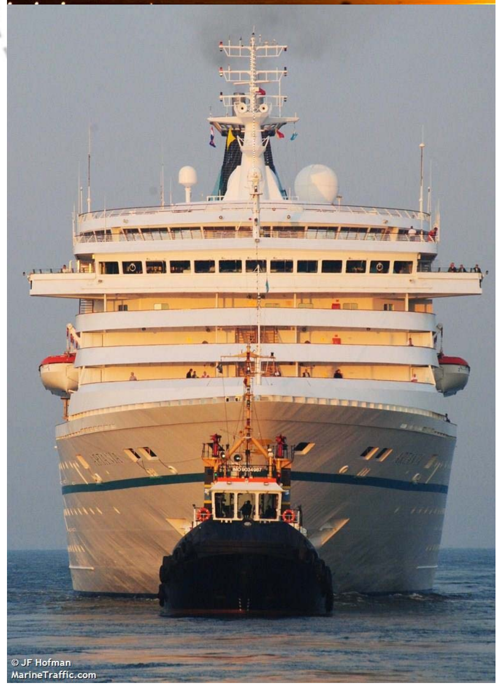
Detailed analysis of the recovered Carbon in liquid and gas phase





Biomass to Avaiation Fuel (B2A)

De Chen/Kumar R Rout
Department of Chemical Engineering
Norwegian University of Science and Technology

NTNU
Norwegian University of Science and Technology

Goal statement

- **Goal**: is to develop a catalytic fast hydropyrolysis (CFHP) technology platform for an integrated two stage catalytic upgrading, which is capable of producing cost competitive biofuels at greater can be market responsive by controlling the product distribution to meet market demand of jet fuel and diesel.
- **Outcome**: Advance the state of technology by demonstrating the production of fuel blendstocks (<1wt% O) from optimized processes for ex-situ CHFP coupled with hydroprocessing that achieve a minimum fuel selling price of less than 900 €/t with greater than 85% of the fuel in the Jet fuel and diesel range
- **It will be achieved** by developing low cost, highly active and stable catalysts to obtain high carbon yield of targeted fuels, as well as on-site hydrogen supply.

Proposed project overview

- **KPN project**, 4 years

  1st year: catalyst development,

  2nd year: ex-situ CFHP,

  3rd year mini pilot plant,

  4th year design and proposal of large pilot plant

- **Budget:** 50 MNOK
- **Partners**: NTNU, SINTEF, QuantaFuel AS. St1, Avinor, Equinor

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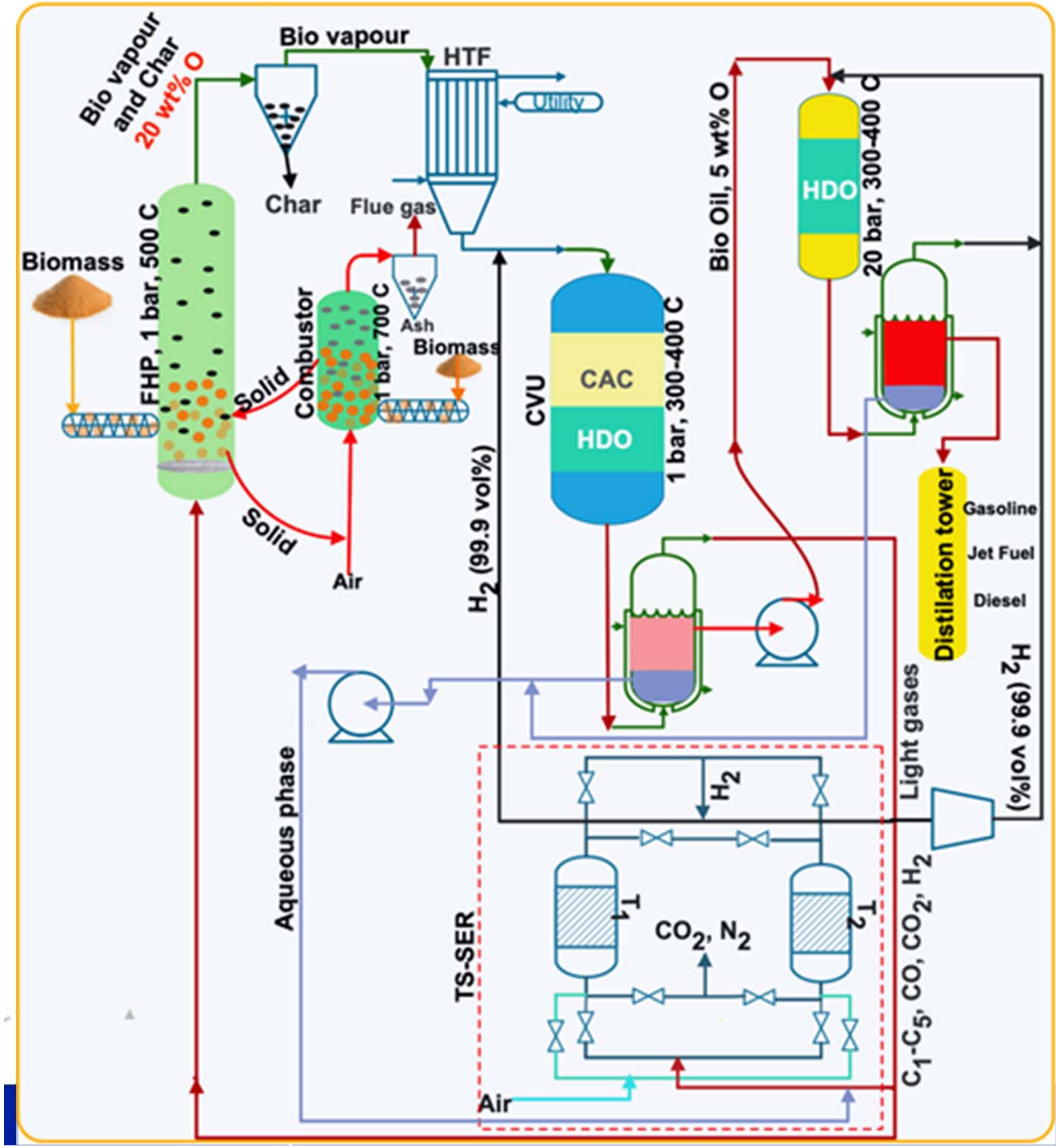
Project overview: B2A



- 230-250 kg biofuels/t dry biomass
- <900 €/t biofuels
- 85% in liquids Jet fuels and diesel

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Price of Biofuel: Four sensitive parameters

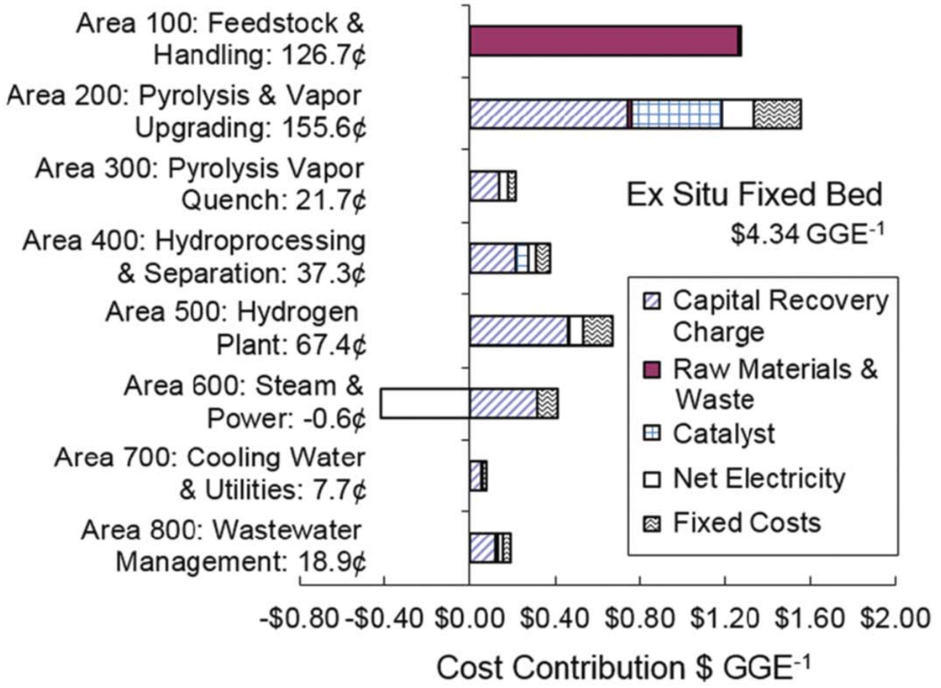

Fig. 6 Modelled cost breakdown (in 2014$) for the production of hydrocarbon fuels *via* fixed-bed CFP with Pt/TiO_2.


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Driving towards cost-competitive biofuels through catalytic fast pyrolysis by rethinking catalyst selection and reactor configuration†

Carbon yield is the key for commercial viability

10% relative improvement of carbon yield reduce about 0.08-0.1 €/kg

- Biomass price
- Carbon yield
- Catalyst price and stability
- Hydrogen price (supply)

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Project overview: Barriers to be addressed and actions (cont.)

- Low-cost stable catalysts for:
  - in-situ CFHP catalyst (Red mud+Dolomite)
  - C-C coupling catalysts (Cu/SiO2 + TiO2/Al2O3 or C)
  - Hydrogen generation catalysts (Ru/Ni-Co /MgAl2O4)
  - HDO catalysts (Ru/MoFeP/Al2O3)
  - Hypothesis driven catalyst design
  - On-site hydrogen supply and waste stream management
    - Hydrogen generation by sorption enhanced reforming of the light gas (mostly the CO) and aqueous phase residues with high yield of hydrogen and low cost

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Thank you!
Trondheim