# Annual Report 2022

## Norwegian Centre for Sustainable Bio-Based Fuels and Energy

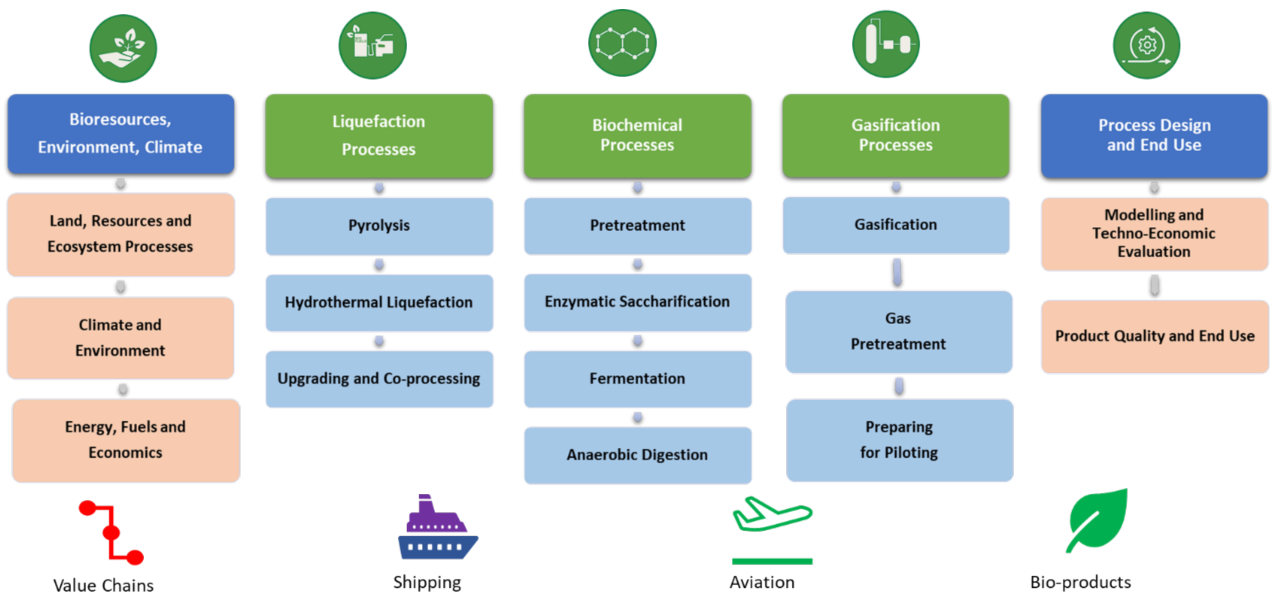
Norwegian Centre for Environmentfriendly Energy Research

BIO4FUELS

# VISION

## ENABLING SUSTAINABLE BIOFUELS PRODUCTION IN NORWAY

Bio4Fuels aims to contribute to the reduction of emissions from the Norwegian transport sector through coordinated research efforts to establish the basis for sustainable routes to advanced biofuels.




*Front picture: Silva Green Fuels' Plant at Tofte, Norway.*

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*Norwegian Centre for Environment friendly Energy Research – The Research Council of Norway*

# FROM BIO4FUELS' MANAGEMENT

In 2022, the landscape for energy security, particularly in Europe, was severely impacted in by the conflict in Europe – underlining how the current complete dependency on fossil-based energy sources is problematic. This has catalysed and driven a mobilization for energy independence – with the US and Europe establishing major investment initiatives towards the green transition.

With respect to the operations of Bio4Fuels, this has given additional opportunities for some of our key stakeholders – those focused on investing in commercial scale production in Norway. In particular, the activities and stakeholders within biogas having the opportunity of responding to the EUs Biomethane Industrial Partnership of 35 bcm annual production by 2030.

With this as a backdrop, the timing of the Bio4Fuels Days meeting, hosted by Equinor at Mongstad, gave the opportunity for an update from the main industry partners of Biozin, Silva Green Fuels and Equinor. It was also a good opportunity for developing the concept and vision for an application for a new FME from 2025 – taking on the challenge of deploying technologies for sustainable transport fuels to meet the targets of the transport sector for 2030 and 2050.

In parallel with this, there is a continued high productivity of the research partners within the research fields of the centre, with publications in high impact journals as well as continued success in getting funding through major EU-projects.

We acknowledge again the continued support of the Bio4Fuels stakeholders, both industrial and public sector, and the dedication of the research partners.

Duncan Akporiaye
Centre Leader

Svein Horn
Deputy Centre leader

# SUMMARY

The ambition of the Bio4Fuels Centre is to reduce the impact of climate gas emissions from the transport sector through sustainable and economic production of biofuels. Biomass, in particular low-grade fractions of wood from the forest and waste from agriculture, is a renewable resource that can potentially substitute the use of fossil resources in the transport sector, together with other renewable energy solutions.

There are four main routes identified for the Centre

- Breaking down the biomass to release fermentable sugars to produce bio-alcohols. This can be blended up to certain levels into existing fuels.
- Fermentation of the biomass in the absence of oxygen to produce a biogas. This biogas can be upgraded to methane, liquified or converted to hydrogen for use as fuels in transport.
- Treatment of the biomass at higher temperatures in the absence of oxygen to produce a liquid biooil, which is then upgraded to a relevant biofuel.
- Treatment of the biomass at higher temperatures to convert to a gas, followed by upgrading of the gas to a substitute biofuel.

In addition to the main routes from biomass to biofuels, it is also important to convert side streams and biproducts from the processes to products of higher value than fuels. This can be important to help the overall economics of the commercial process.

In addition to the research on the processes, Bio4Fuels has a significant activity focused on issues related to the sustainability and economics of biofuel production:

- Improving the technologies and economics of processes for converting biomass to biofuel - Investigating the sustainability and impact of large-scale use of low-grade biomass for biofuels production.
- Evaluating process concepts and testing the quality of the biofuels for existing engines.
- From the operation of the Centre so far, the following areas can be highlighted:
- A successful Kick-off meeting was arranged in February 2017, with an international guest list of industrial presenters from all over Europe and the US. This provided industrial perspective of the state of the art for technology along the whole value chain.
- The Centre has an active and highly competent board, with industry as majority representing the key stakeholders of the value chain.
- The Centre has also established an International Advisory Group with representatives from key research sectors from Finland, United Kingdom and United States.

In 2021 Bio4Fuels completed a successful mid-term evaluation which granted three more years of funding of the Centre. Evaluation panel recommendations included improvement of communication and better involvement of students and stakeholders – areas which have been implemented.

Bio4Fuels organises an annual "Bio4Fuels days" meeting:

- 2017: dedicated to the national strategy, with an excursion to visit the production of Paper (Norske Skog AS) and Biogass (Biokraft AS) at Skogn near Trondheim.
- 2018: taking on an international perspective following the release of the IPCC report, including a visit to the Oslo Biogass production site.

- 2019: Bio4Fuels took the step towards organising a regular international Bio4Fuels days by arranging a conference in Gothenburg together with the UK Supergen and the Swedish f3 centres. With over 200 participants, the conference was overbooked and provided an important platform discussing important issues within the field
- 2020: Virtual conference due to Covid-19. International view on biofuels with speakers from the EU Commission, USA, Canada, Finland and England. Virtual visit to Silva Green Fuels plant at Tofte, Hurum. Approximately 80 participants.
- 2021: Physical meeting in Drammen, including a visit to the Tofte biofuel plant. Dedicated young researcher forum on day one with focus on public acceptance of biofuels. 51 participants.
- 2022: Physical meeting at Lindås, including a visit to the Mongstad industrial site. A central topic was the new energy situation in Europe. 45 participants.

Bio4Fuels have partners that are active in representing Norway in key tasks within the International Energy Association (IEA). Specifically related to addressing important aspects related to realising climate goals dependent on research within Bioenergy. Through NTNU, Bio4Fuels research partners have been active in leading the efforts and contributing to drafting the latest IPCC report on Climate Change and Land.

Bio4Fuels, together with other FMEs, has charted the effect of Energy research in Norway within renewable energy. This was on behalf of the Norwegian research Council. The Centre is also active in contributing to the background for the debate around the role of biofuels in Norway, through organising and attending Breakfast seminar, organising webinars and responding to specific topics in the media.

Partners in the Centre are also extremely well represented in EU H2020 research program with a very significant portfolio of EU projects as well as active coordination with other research and industry partners in the EU.

Bio4Fuels has also carried out a second year "self-evaluation" on behalf of the board. This was the basis for reorganising the Centre's activities towards a stronger focus on the three most important value chains for biofuel production in Norway.

Industry partners in Bio4Fuels have established commercial production of liquified biogas for heavy duty road and ship transport and other partners plan to build commercial plants in Norway, Sweden and Finland for conversion of biomass to liquid drop in biofuels.

# Bio4Fuels Organization

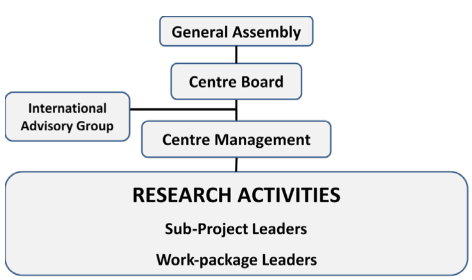
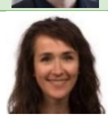



***Figure 1**: Organization of the FME Bio4Fuels Centre.*

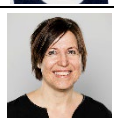
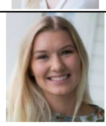
## Centre Board

Per December 2022:

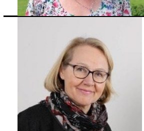
| | Name | Company/ Institution | Representing |
|---|---|---|---|
|  | Klaus Schöffel | Silva Green Fuel (Statkraft) | Technology Partners |
|  | Tyra Marie Risnes | Viken County Council | Public Partners |
|  | Per Skorge | Norges skogeierforbund | Resource Partners |
|  | Kjell Moljord | Equinor | End Users |
|  | Kine Svensson | CAMBI | Technology Partners |
|  | Petter Røkke | SINTEF Energy | Centre Leader Institute |
|  | Hans Fredrik Hoen | NMBU | Host Institute |
|  | Terese Løvås | NTNU | R&D Partner |
|  | Morten C. Melaaen | USN | R&D partner* |
|  | *Per Arne Karlsen* | *Research Council of Norway* | *Observer* |

*) Alternating every second year with RISE-Pfi, Ife and NIBIO.

## The Bio4Fuels’ Management Team

| | | | |
|---|---|---|---|
|  | Professor Duncan Akporiaye | SINTEF | Centre Leader |
|  | Professor Svein Jarle Horn | NMBU | Deputy Centre Leader |
|  | Dr. Odd Jarle Skjelhaugen | NMBU | Industrial Liaison |
|  | Dr. Janne Beate Utåker | NMBU | Administrative Manager |
|  | Ann-Solveig Hofseth | NMBU | Financial Officer |
|  | Haldis Bjerva Watson | SINTEF | Communication Officer |
|  | Camilla Fløien Angeltveit | NMBU | PhD Representative |

## The International Advisory group (IAG)

| | Advisor | Affiliation | Area of expertise |
|---|---|---|---|
|  | Prof. Patricia Thornley | Supergen Bioenergy Hub, Aston University, Birmingham (UK) | Sustainability |
|  | Dean Kristiina Kruus | Aalto University, Otaniemi, Finland (FI) | Biochemical Processes |
|  | Dr. David Dayton | Research Triangle Institute (RTI), NC (USA) | Thermochemical Process |

## Bio4Fuels Partners and Stakeholders

| Research partners in Norway | |
|---|---|
| NMBU | – The Norwegian University of Life Sciences |
| SINTEF | – Applied research, technology and innovation |
| NTNU | – The Norwegian University for Science and Technology |
| NIBIO | – The Norwegian Institute of Bioeconomy, |
| IFE | – Institute for Energy Technology |
| RISE PFI | – Research Institutes of Sweden – Paper and Fiber Institute |
| USN | – The University of South-East Norway |

| **Bioresource owners** | **Main interest** |
|---|---|
| The Norwegian Farmers Union | Biogas production from agricultural feedstocks |
| The Norwegian Forest Owners' Federation | Value from forest biomass |
| The City of Oslo, The energy recovery unit | Biogas production from food waste |
| **Tech./knowledge providers, Norwegian** | **Main interest** |
| Herøya Industry Park | Pilot plant construction |
| Cambi AS | Plants for biogas production from organic waste |
| Hyperthermics AS | High temperature biogas production from waste biomass |
| UMOE AS | Biofuel plant investments and management |
| **Tech./knowledge providers, International** | **Main interest** |
| Biomass Technology Group (NL) | Biomass to liquid (btl) pyrolysis |
| Johnson Matthey (UK) | Chemical and catalytic processing of bio-feedstocks |
| Novozymes (DK) | Enzymes for forest based biorefineries |
| Pervatech (NL) | Membrane and separation systems for organic substrates |
| Steeper ENERGY (DK) | Hydrothermal liquefaction |
| Lund Combustion Engineering as (SE) | Consultancy and software on combustion in motors |
| **Biofuel and biochemical producers** | **Main interest** |
| Silva Green Fuel AS | Biodiesel from forest biomass |
| Biozin AS | Forest based crude oil for biorefineries |
| Equinor | Feed stock supply, value chains, co-processing |
| Perstorp Bioproducts AB (SE) / Adesso Bioproducts | High quality biodiesel |
| Borregaard | Forest-based high value chemicals and bioethanol |
| Biokraft | Biogas from paper mill side-streams and fish waste |
| Ecopro AS | Biogas from organic waste |
| Norske Skog Saugbrugs | Biogas from biorefinery side-streams |
| Neste (FI) | Biorefinery |
| Alginor ASA | Seaweed products from a multifunctional biorefinery |

## Bio4Fuels' Partners and Stakeholders, continued

| Biofuel distributors and end users | Main interest |
|---|---|
| St1 Norge as | Bioethanol production and distribution in Norway |
| Avinor | BioJetFuels for Norwegian airports |
| **Government and State Partners** | **Main interest** |
| Viken Fylkeskommune | Sustainability, Resource Use, Transport policy, Techn Econ |
| Innlandet Fylkeskommune | Sustainability, Resource Use, Transport policy, Techn Econ |
| Trøndelag Fylkeskommune | Sustainability, Resource Use, Transport policy, Techn Econ |
| Follorådet | Sustainability, Resource Use, Transport policy, Techn Econ |
| Miljødirektoratet | Sustainability, Resource Use, Transport policy, Techn Econ |
| Statens Vegvesen | Sustainability, Resource Use, Transport policy, Techn Econ |
| Innovasjon Norge | Sustainability, Resource Use, Transport policy, Techn Econ |
| **Non-Governmental Organizations / Trade Organizations** | **Main Interest** |
| NOBIO | Bioenergy, Biofuels |
| Zero | Renewable Energy, Policy |

*Modified trickle bed reactors for biogas upgrading. Photo: Lu Feng, NIBIO*

## SUB-PROJECTS AND WORK-PACKAGES

The Bio4Fuels Centre is divided into 5 sub projects (SPs) and 17 work packages (WPs) as presented in figure 2 below.

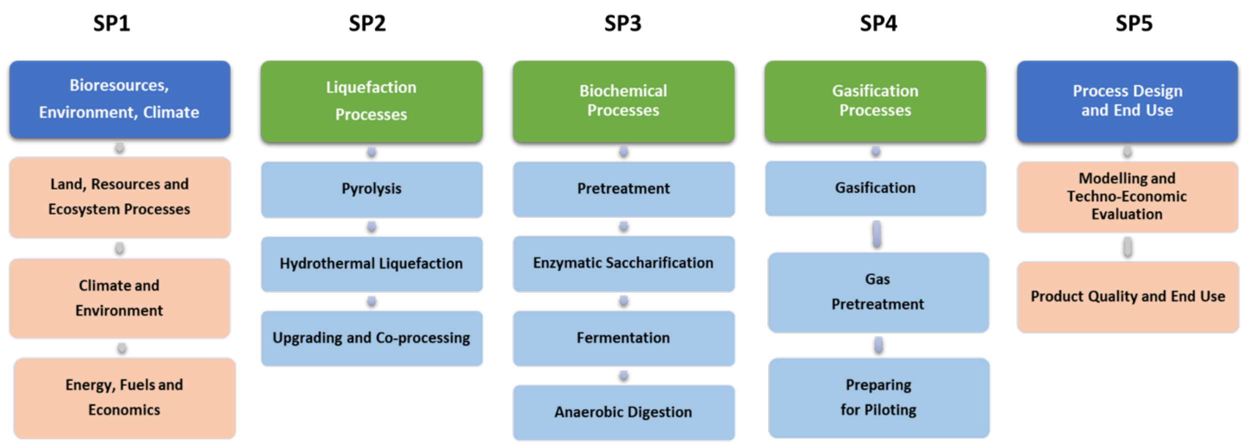
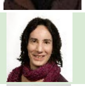
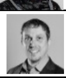



*Figure 2: The Organization of Bio4Fuels' Research*

### Sub Project Leaders

| | *Name* | *Institution* | *Main research area* |
|---|---|---|---|
|  | Francesco Cherubini (SP1) | NTNU | Bioresources, Environment and Climate |
|  | Judith Sandquist (SP2) | SINTEF | Liquefaction Processes |
|  | Aniko Varnai (SP3) | NMBU | Biochemical Processes |
|  | Morten Seljeskog (SP4) | SINTEF | Gasification Processes |
|  | Bernd Wittgens (SP5) | SINTEF | Process Design and End Use |

## Work Package Leaders

| | *Name* | *Institution* | *Main research area* |
|---|---|---|---|
|  | Rasmus Astrup (WP 1.1) | NIBIO | Land, Resources and Ecosystem Processes |
|  | Francesco Cherubini (WP 1.2) | NTNU | Bio-Resources, Environment, Climate |
|  | Per Kristian Rørstad (WP 1.3) | NMBU | Energy, Fuels and Economics |
|  | Kai Toven (WP 2.1) | RISE PFI | Pyrolysis |
|  | Judit Sandquist (WP 2.2) | SINTEF | Hydrothermal Liquefaction |
|  | Roman Tschentscher (WP 2.3) | SINTEF | Thermochemical upgrading of bio oils |
|  | Mihaela Tanase Opedal (WP 3.1) | RISE PFI | Pretreatment and Fractionation |
|  | Aniko Varnai (WP 3.2) | NMBU | Enzymatic Saccharification |
|  | Alexander Wentzel (WP 3.3) | SINTEF | Fermentation |
|  | Lu Feng (WP3.4) | NIBIO | Anaerobic Digestion and gas upgrading |
|  | Morten Seljeskog (WP 4.1) | SINTEF | Gasification |
|  | Edd Blekkan (WP 4.2) | NTNU | Gas Conditioning |
|  | Bernd Wittgens (WP 5.1) | SINTEF | Process Modelling, Technical and Economical Evaluation |
|  | Terese Løvås (WP 5.2) | NTNU | Product quality and End Use |

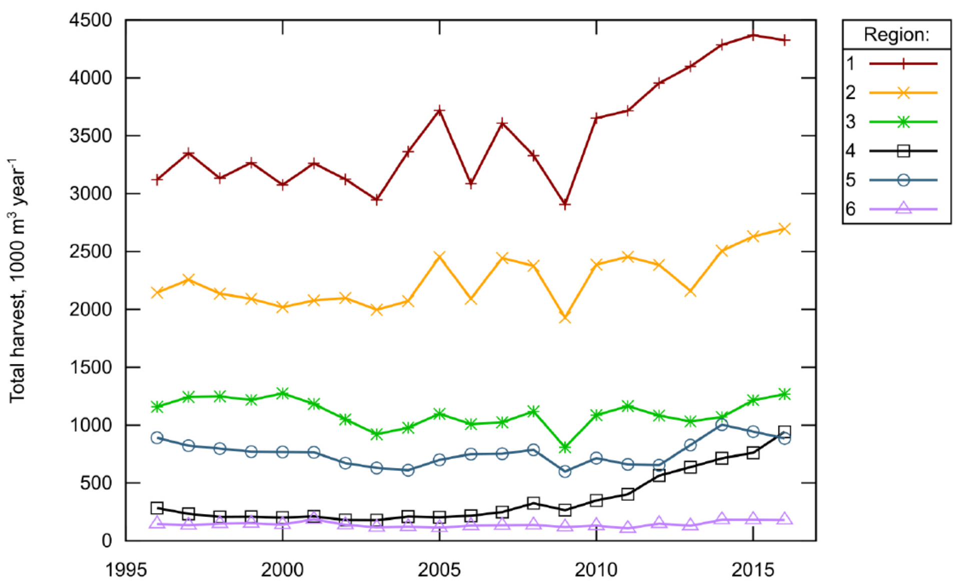
# HIGHLIGHTS FROM 2022

## Research

**SP1**

**Regional differences in timber supply**

We have good knowledge about available forest resources in Norway. It is however the more than 120000 forest owners that ultimately decide how much timber will be harvested. In this study we have invetigated the regional differences using regional data on harvests, prices, interest rates and standing stock. Region 4 – along the western coast – appears to have a different dynamic compared to the other regions. Here the harvests have been monotonically increasing despite a negative trend in real timber prices. The short-term elasticities are positive. This implies that forest owners react to short term variation in prices in the way we expect, but that there are underlying long term changes not captured by our models. We are quite certain that hurricanes and windthrow are not the reasons. For the models estimating the short-term reaction to changes in prices, a model with regional effects did not perform (statistically) better than one without. Still, if we are interested in modelling the regional timber supply – as we usually are – using regionalized models would still be preferable even though we do not gain anything at the aggregate level. This work was published in Silva Fennica:



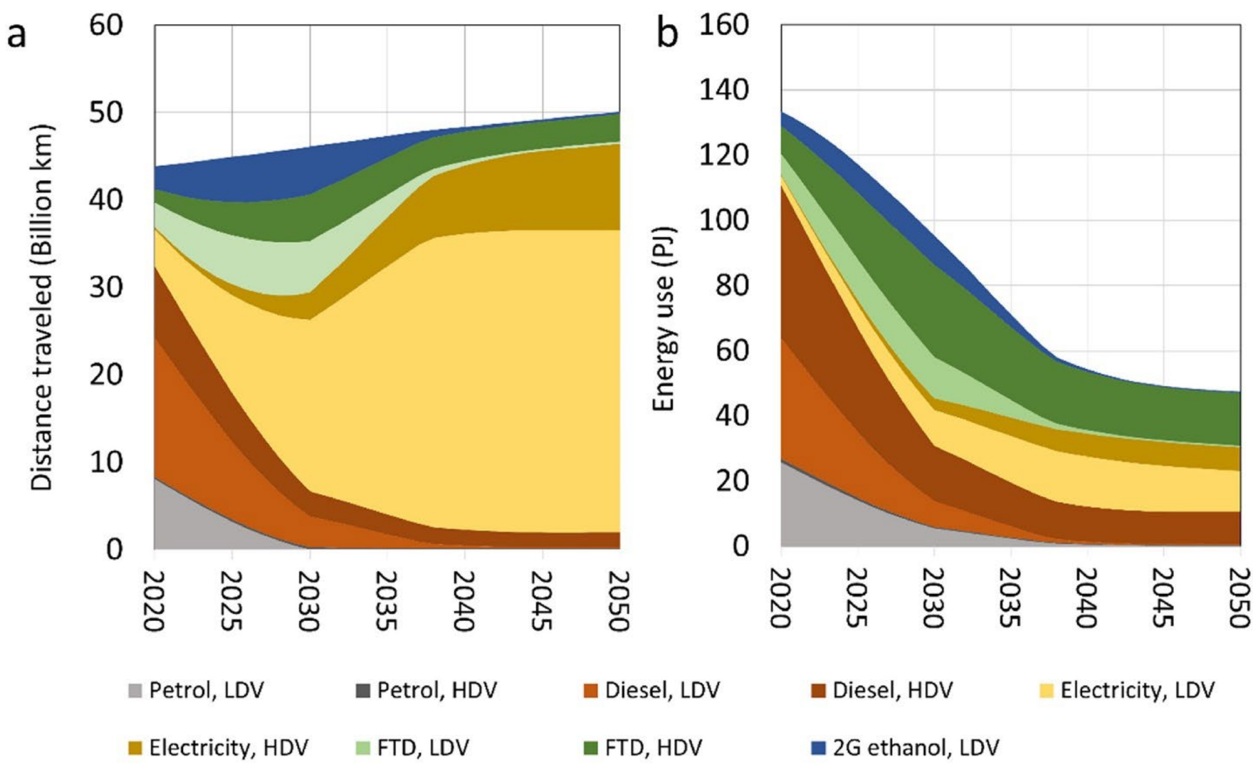

Rørstad P.K., E. Trømborg, B. Solberg (2022). **Can we detect regional differences in econometric analyses of the Norwegian timber supply?** Silva Fennica 56:1

https://doi.org/10.14214/sf.10326

**SP1**

**Unraveling the role of biofuels in road transport under rapid electrification**

Biofuels have been the predominant option for climate change mitigation in road transport for decades, but the recent expansion of electric vehicles may question this role. We model the energy use and life-cycle emissions of road transport activities until 2050 in Norway, a country with a rapid growth in vehicle electrification. Mitigation from biofuels peaks in 2030 at 3.1 ± 0.45 $MtCO_2eq$. $year^{-1}$ (30% of today's road transport emissions) and impacts on human health decrease. The largest emission savings are achieved from biofuels in trucks, buses and vans. Integrated strategies combining high electrification rates of the vehicle fleet with targeted applications of biofuels can increase the mitigation of road transport emissions. This work was published in Biofuels, Bioproducts and Biorefining (Biofpr).



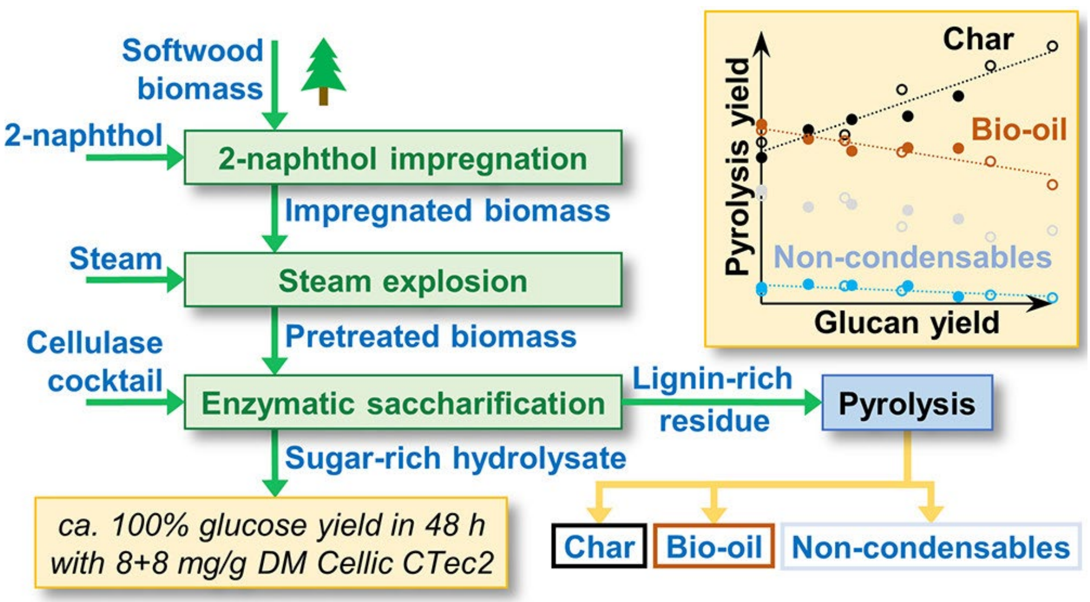

Cavalett, O., & Cherubini, F. (2022). **Unraveling the role of biofuels in road transport under rapid electrification**. Biofuels, Bioproducts and Biorefining, 16(6), 1495-1510.

https://doi.org/10.1002/bbb.2395

**SP2**

**A combined biochemical and thermochemical conversion route generating high-quality pyrolysis fractions**

In 2022, a combined biochemical and thermochemical conversion route was established, based on Biomass pretreatment (WP3.1), Enzymatic saccharification (WP3.2), and Thermochemical Upgrading (WP2.3). The process was based on a modification of steam explosion, a biomass pretreatment used by St1, with carbocation scavengers to improve lignin reactivity in the pretreated feedstock. The modified lignin promotes oxidative cellulose depolymerization by lytic polysaccharide monooxygenases (LPMOs), one of the key components in the state-of-the-art cellulase cocktails of Novozymes and enables efficient separation of the spruce feedstock into a sugar-rich hydrolysate and a highly pure lignin fraction. The process achieved close to 100% saccharification with the LPMO-containing enzyme cocktail Cellic CTec2 over 48 h incubation time, using process parameters that are close to being industrially realistic: 10% (w/v) DM feedstock loading and 8-16 mg/g DM Cellic CTec2. The generated lignin-rich saccharification residue could be upgraded into high-quality pyrolysis fractions. The study was published in ACS Sustainable Chemistry & Engineering.

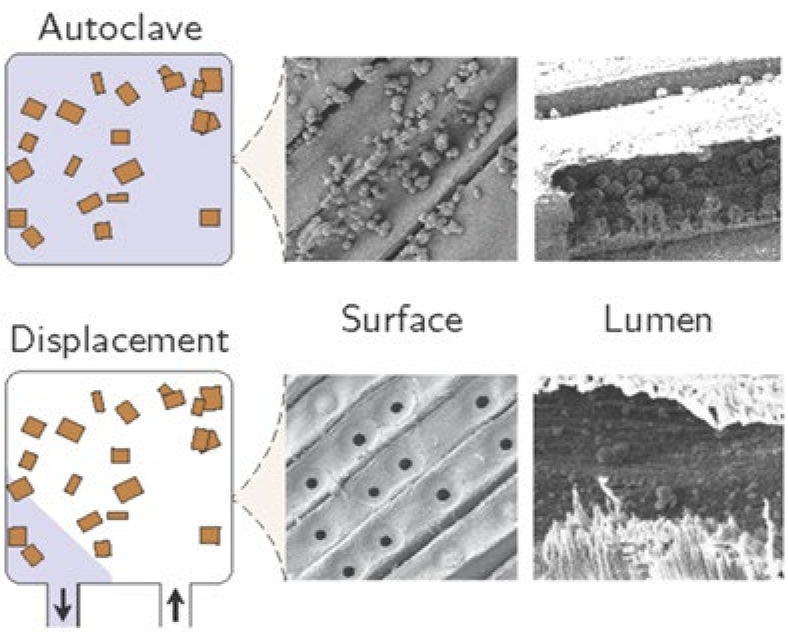



Hansen, L. D., Østensen, M., Arstad, B., Tschentscher, R., Eijsink, V. G., Horn, S. J., & Várnai, A. (2022). **2-Naphthol Impregnation Prior to Steam Explosion Promotes LPMO-Assisted Enzymatic Saccharification of Spruce and Yields High-Purity Lignin**. ACS Sustainable Chemistry & Engineering. 10 (16) 5233–5242. https://doi.org/10.1021/acssuschemeng.2c00286

**SP3**

**Morphology of lignin structures on fiber surfaces after organosolv pretreatment**

The redeposition of lignin to the fiber surface after organosolv pretreatment was studied using two different reactor types. Results from the conventional autoclave reactor suggest that redeposition occurs during the cooling down stage. Redeposited particles appeared to be spherical in shape. The size and population density of the particles depends on the concentration of organosolv lignin in the cooking liquor, which is consistent with the hypothesis that reprecipitation of lignin occurs when the system is cooled down. The use of a displacement reactor showed that displacing the spent cooking liquor with fresh cooking liquor helps in reducing the redeposition and the inclusion of a washing stage with fresh cooking liquor reduced the reprecipitation of lignin, particularly on the outer fiber surfaces. Redeposition of lignin was still observed on regions that were less accessible to washing liquid, such as fiber lumens, suggesting that complete prevention of redeposition was not achieved. The study was published in Biopolymers.



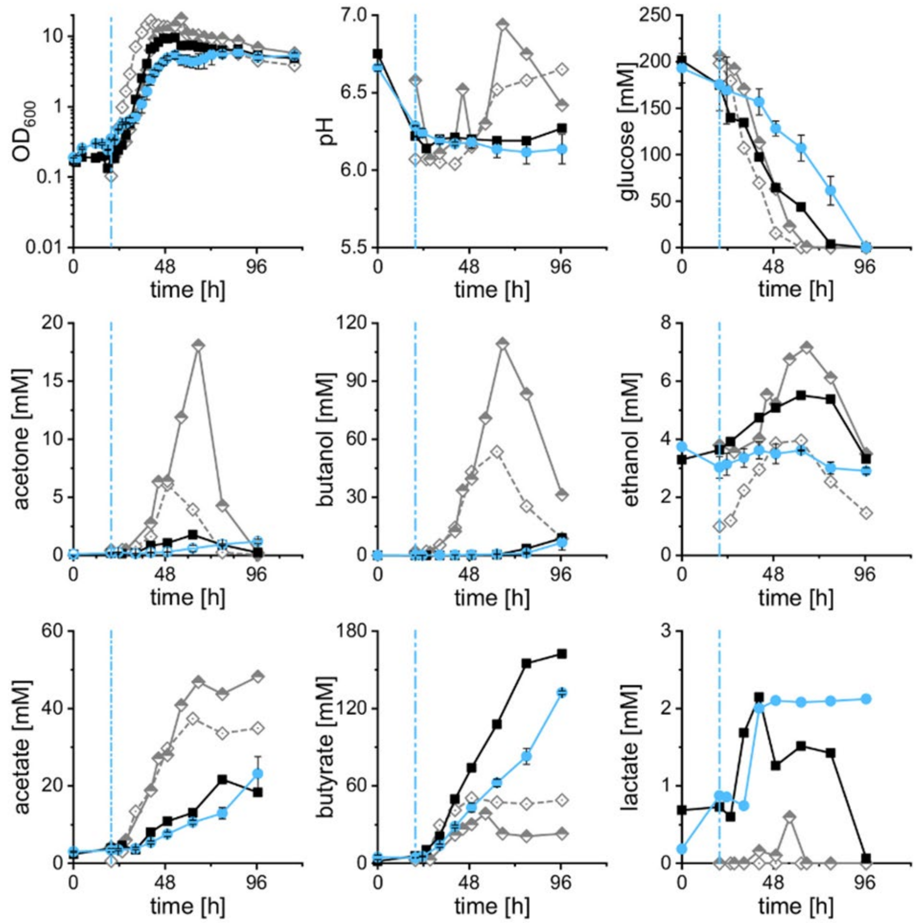

Joseph, P., Ottesen, V., Opedal, M. T., & Moe, S. T. (2022). **Morphology of lignin structures on fiber surfaces after organosolv pretreatment**. Biopolymers, 113(9), e23520.

https://doi.org/10.1002/bip.23520

**SP3**

**Increased Butyrate Production in Clostridium saccharoperbutylacetonicum from Lignocellulose-Derived Sugars**

Platform chemicals such as butyrate are usually produced chemically from crude oil, resulting in the carry-over of harmful compounds. The selective production of butyrate using sustainable resources or waste without harmful by-products can be achieved by bacteria such as clostridia. The hyper-butanol producer Clostridium saccharoperbutylacetonicum N1-4(HMT) was converted into a hyper-butyrate producer. Butyrate production with very small amounts of by-products was established with glucose and the sustainable lignocellulosic sugar substrate Excello extracted from spruce biomass by the Bio4Fuels' partner Borregaard. The study was published in Applied and Environmental Microbiology.



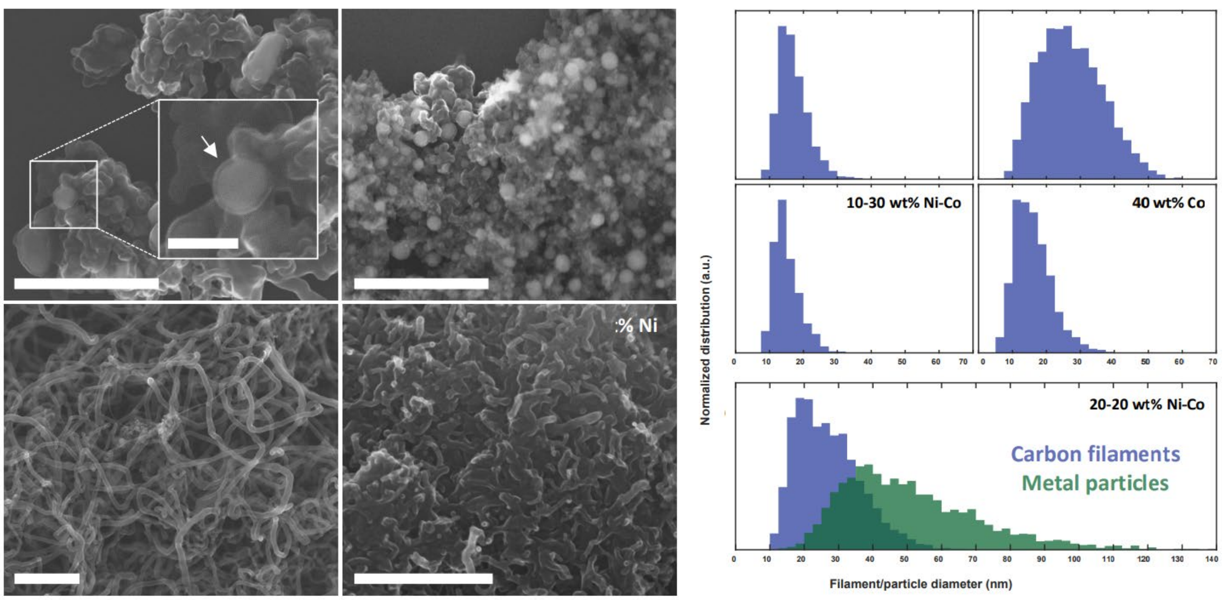

Baur, S. T., Markussen, S., Di Bartolomeo, F., Poehlein, A., Baker, A., Jenkinson, E. R., Daniel, R. & Dürre, P. (2022). Increased butyrate production in Clostridium saccharoperbutylacetonicum from lignocellulose-derived sugars. Applied and Environmental Microbiology, 88(7), e02419-21.

https://doi.org/10.1128/aem.02419-21

**SP4**

**Steam Reforming of Biomass Gasification Tar**

Experimental model studies on catalytic steam reforming of biomass gasification tar have been carried out. Effects of key operating conditions and Ni-Co/Mg(Al)O catalyst synthesis parameters were investigated. Tar compounds are completely converted, but methane is more difficult to convert. Preliminary results suggest optimum steam/temperature window minimizing deactivation by coke formation and sintering. Efficient H2/CO ratio adjustment by simultaneous WGS equilibration was demonstrated in model environment. The results contribute to the understanding of the highly attractive resistance towards deactivation by coke formation of Ni-Co catalyst systems. The work was published in Chemical Engineering Transactions.




Lysne, A., Madsen, K. O., Antony, J., Rout, K. R., & Blekkan, E. A. (2022). **Effects of Ni-Co Ratio on Deactivation and Coke Formation in Steam Reforming of Hydrocarbon Impurities from Biomass Gasification with Ni-Co/Mg (Al)O Catalysts**. Chemical Engineering Transactions, 92, 37-42.

https://doi.org/10.3303/CET2292007

## Doctoral Defenses

### Line Degn Hansen (NMBU, WP3.2)

Photo: Håkon Sparre, NMBU

On 14 June 2022 Line Degn Hansen defended her thesis “Leveraging $H_2O_2$-fuelled activity of lytic polysaccharide monooxygenases in cellulase cocktails for improved bioprocessing of lignocellulosic biomass”.
The work was performed at the Faculty of Chemistry, Biotechnology and Food Sciences, NMBU, supervisors: Aniko Varnai and Svein Jarle Horn.

*Evaluation Committee:*
*First Opponent: Jane Wittrup Agger, Technical University of Denmark (DK)*
*Second opponent: Maurizio Bettiga, Italbiotech Srl, (IT)*
*Coordinator: Åsmund Røhr Kjendseth, NMBU*

### Prajin Joseph (NTNU, WP3.4)

*Photo: Kristin Syverud, RISE-Pfi*

On 16 December 2022 Prajin Joseph defended his thesis “Organosolv pretreatment of Norway Spruce: Ethanol pretreatment for Biorefinery applications”.

The work was performed at

- The Institute for chemical process technology (NTNU), supervisor: Størker Moe
- RISE Pfi, supervisor: Mihaela Tanase-Opedal

*Evaluation Committee:*
*First Opponent: Martin Lawoko, KTH (SE)*
*Second opponent: Päivi Rousu, VP, R&D, IPR fra Chempolis Oy (FI)*
*Coordinator: Edd Blekkan, NTNU*

## SP Leader Meetings 2022

The Centre’s sub-project leaders have the responsibility to follow up the WP leaders in their SP with regards to research progress, reporting and workplans. Management has met with the SP leaders six times during 2022 (virtual due to geography and Covid-19). This has considerably improved the information flow in the Centre, as well as the management of it.

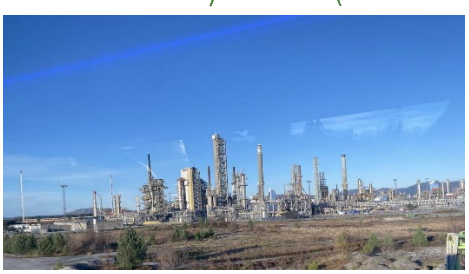
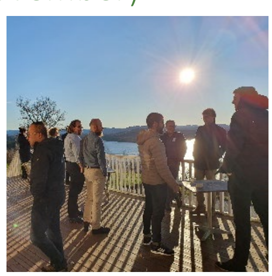
## Open webinars in 2022

| Date | Title |
|---|---|
| 27 Januar | **Public Acceptance of Biofuels**<br>- *Public acceptance issues related to biofuels and other issues of proper engagement, social consequences of premises of certain approaches,* Søren Løkke, University of Aalborg<br>- *Wider issues of social acceptance in the energy transition including other aspects (ethical, etc) with learnings from cases,* Tanja Winther, FME INCLUDE / University of Oslo<br>- *Quantitative modelling and representation of social acceptance - Approaches, challenges and future outlooks,* Oskar Vågerö, University of Oslo / FME INCLUDE<br>- *Acceptance for biofuels as a climate solution,* Anne Marit Post-Melbye, Zero<br>- *Biofuels – views from Adesso BioProducts AB/AS, the largest producer in Norway,* Lars Lind, Adesso Bioproducts<br>- *How can we better engage and communicate with the context of bioenergy?,* Zoe Harris, University of Surrey |
| 7 April | **Biofuels for Marine Shipping**<br>- *IEA Bioenergy Report "Progress Towards Biofuels for Marine Shipping",* Sune Tjalfe Thomsen, University of Copenhagen<br>- *Alternative Marine fuels at Equinor* – Kjell Moljord, Equinor<br>- *Bio-e-methanol; marine flexible fuel where efficiency and safety are maintained all the way to the propeller* – Dag Nikolai Ryste, GlocalGreen<br>- *FME MoZEES R&D on Battery and Hydrogen Technology for Maritime Applications* – Øystein Ulleberg, Institute for Energy Technology, IFE<br>- *Marine fuels from pyrolysis of bio-waste and esterified with higher alcohols – the PyroMarProject* – Dr. Fanny Langschwager, University of Rostock |
| 9 June | **IPCC Sixth Assessment Report – the role of biofuels**<br>- *Biofuels and climate change mitigation in the IPCC Sixth Assessment Report*, Otávio Cavalett, NTNU<br>- *The role of biofuels in a Paris compliant transition,* Anne Marit Post-Melbye, ZERO<br>- *IPCC Sixth Assessment report –Bioenergy in a Norwegian context*, Asbjørn Torvanger, CICERO |
| 9 November | **Standardization of Biofuel**<br>- *Sustainability Criteria for Biofuels*, Mats Nordum, Norwegian Environment Agency<br>- *Qualification of Alternative Aviation Fuels*, Bastian Rauch, DLR<br>- *Biodiesel under the RED-directive, experiences from certification and standardization*, Lars Lind, Adesso Bioproducts<br>- *Standardisation of Biofuel*, Knut Aune, Standards Norway |

## Centre Status Meetings 2022

| Date | Program |
|---|---|
| 16 March | - What is innovation? Sigrid Gåseidnes, Dean KBM, NMBU<br>  o Discussion<br>- Potential Innovation in Bio4Fuels – 5 minutes' presentations from the Bio4Fuels' Work Packages<br>  o SP1<br>  o SP2<br>  o SP3<br>  o SP4<br>  o SP5<br>- A Bio4Fuels' Research Fund |
| 15 June | - Status for the Bio4Fuels Centre – by Duncan Akporiaye, Sintef Industry<br>- Status from WP5.1: *From Laboratory Data to Full-scale Process Modell*, Filippo Bisotti, SINTEF Industry<br>- Status from WP4.1 and 4.2: *Gasification of a biorefinery lignin by-product: an experimental and simulated study of bubling fluidized bed and entrained flow reactor performances*, Marianne Eikeland, USN and Morten Seljeskog, SINTEF Energy<br>- Status from SP3: Public Defence: Line Degn Hansen, NMBU<br>- Status from WP2.2: *Pyrolysis for biofuels – Activity status update*, Kai Toven, RISE-Pfi<br>- Status from WP1.3: *The biomass harvesting potential to meet increasing bio-economy demands for biofuel,* Per Kristian Rørstad, NMBU |
| 6 - 7 Sep | **Two days' meeting at Ersgard, Stjørdal, Norway**<br>6 September: Status and Plans for all SPs<br>- Major achievements so far<br>- Status Activities for 2022<br>- Proposed Plans for 2023 – 2024<br>7 September: Bio4Fuels after 2024 – Input to a Vision for a New FME<br>- Group Work |
| 16-17 Nov | Bio4Fuels Days 2022 (see next section) |

## Bio4Fuels Days 2022 (16 -17 November)


*Photos: Duncan Akporiaye, SINTEF and Janne Beate Utåker, NMBU*

*16 November Open, International Meeting (Westland Hotel, Mongstad, Norway)*

Welcome, Duncan Akporiaye, Centre Leader

**The New Energy Situation in Europe**

- *The Role of Bioenergy in the Net Zero Roadmap to 2050, and the Importance of Bioenergy in the EU Energy Mix*, Luc Pelkmans, IEA Bioenergy (Teams)

- *The role of biomethane in the future renewable energy mix in Europe*, Harmen Dekker, CEO European Biogas Association (Teams)
- *Sustainable fuels and chemicals at Johnson Matthey*, Gareth Williams, Johnson Matthey
- *Biozin – Clean Energy from Norwegian Forests*, Åse-Lill Fossan Østli, CTO Biozin (Teams)
- *Silva Green Fuel - Demonstrating groundbreaking Biofuel Technology*, Per Arne Hellebust, CEO, Silva Green Fuel

**Site Visit at Equinor's Refinery at Mongstad**
Due to security restrictions, we were unfortunately not allowed to visit the refinery. Visit by bus to the Mongstad Industry Park, Benedikte Fanebust Søreidet, Equinor

**Equinor's Acitities at Mongstad**

- *About "Industriutvikling Vest"*, Einar Vaage, Equinor
- *Equinor's Refinery - Biofuels*, Anne-Berit Hjorth Viken, Equinor
- *Comments and Questions*, Anne-Berit Hjorth Viken and Kjell Moljord, Equinor

**Poster Session with Refreshments**
The PhD students and post docs in Bio4Fuels presented their ongoing work in a poster session. Professor Patricia Hornley (Aston University, part of Bio4Fuels' International Advisory Group) and professor Svein Horn (NMBU) evaluated the posters and the -presentation. The winner of Bio4Fuels Days 2022 Poster Prize: Cristian Bolaño Losada (WP3.4, NMBU).

*Photos: Janne Beate Utåker, NMBU*

### *Thursday 18 November Bio4Fuels Partners' Meeting (Physical)*

**Introduction** by Svein Horn, Deputy Centre leader

SP1: *Green shift in the EU maritime sector: country-based climate benefits and potentials of drop-in and hydrogen-based biofuels up to 2050*, Marcos Djun Barbosa Watanabe, NTNU

SP2: *Co-pyrolysis of biomass and plastic wastes to high-quality liquids*, Zhihui Li, PhD Student, NTNU

SP3: *Enzymatic Saccharification*, Svein Horn, NMBU

SP4: *Deactivation and Coke Formation in Steam Reforming of Hydrocarbon Impurities from Biomass Gasification with Ni-Co/Mg(Al)O Catalysts*, Ask Lysne, NTNU

SP5 *Numerical and experimental investigations of liquid biofuels under CI conditions*, Michal Lewandowski, NTNU

**Young Researchers' Session and Group Work**
The PhD students and postdocs had a separate meeting with Professor Patricia Hornley (Aston University, part of Bio4Fuels' International Advisory Group) and Kjell Moljord (Equinor):

- Research Training in Academia and Industry
  - How does Equinor Recruit researchers?
    - Financing
    - The Industrial PhD Scheme at the Research Council
  - Research training in the UK
    - Industry Involvement
    - Educational Pathway in the UK
- Biofuels policy and future biofuel deployment
- How is the Industry Involvement among PhD Students and post docs in Bio4Fuels?

How to Secure Good Involvement between PhD Students, post docs and Industry in a new FME Centre

The other meeting delegates performed group work:

- Introduction to Group work by Duncan Akporiaye
- Key achievements so far
- Work Plans 2023-2025 – how to achieve greatest impact/relevance for today's situation
- Input to new concept for new FME centre
- Presentations from the Group Work

**Final Session**
Reflections and Summary, Bio4Fuels' International Advisory Group: Patricia Thornley and Kjell Moljord.

## Bio4Fuels Newsletters

To improve the communication of the Centre's activities, newsletters have been sent out to the Bio4Fuels partners in the spring, summer, autumn and December of 2022. Management's communication officer Haldis Bjerva Watson is dedicated to this work, contacting the research partners in person and collecting the latest within technology, publications, innovation, recruitment etc.


Link to 2022 Newletters:
https://www.nmbu.no/en/services/centers/bio4fuels/news/newsletters/node/44948

# BIO4FUELS INDUSTRIAL STAKEHOLDERS' INSIGHTS

## AVINOR

Aviation is a typical hard-to-decarbonize sector with high abatement cost and few alternatives to fossil fuels compared to other sectors. Electrified aircraft can potentially play an important role, and a lot of resources is being invested in developing hydrogen-fueled aircrafts.

*Photo: AirBP*

But sustainable aviation fuel (SAF) will play a key role in the green transition. It can be used in existing aircraft and infrastructure with no need for modifications, and it is the only technology that we know will work for long distances.

Norway was the first country worldwide to introduce an effective biofuel blend-in mandate for biofuel (2020). In 2021 the EU Commission proposed a European blend-in mandate starting at 2 % in 2025, and increasing every 5 years, to 63 % in 2050.

Norway is well positioned for large scale production of sustainable aviation fuel from forestry residues. The volume can make more than 30 % of the national jet fuel consumed.

A high renewable share and infrastructure for CCUS and bio-$CO_2$ are important assets for jet fuel. But large-scale investment decisions remain to be seen. Research and development to increase the maturity of feedstocks and production processes are of high importance.

## BIOZIN

The Biozin project is a consortium between Biozin Holding AS, Bergene Holm AS and Shell with a vision to establish Norway's first full-scale production facility for advanced biofuels based on forest residues, low quality logs and sawmill by-products utilizing Shell's groundbreaking IH2® technology.

The production facility will be located in Åmli, Norway, on a 160,000 m$^2$ industrial plot that has been allocated and zoned for the plant.  Initially, the annual production is estimated to be 110,000 m$^3$ of advanced biofuel per year.


*Preliminary 3D-model of the planned Biozin Åmli plant. Photo: Biozin.*

There have been multiple positive developments since the Biozin project passed "Decision Gate 2" in June 2022:

- The EU innovation Fund has awarded Biozin a grant of € 75 million. The allocation will be distributed during the construction period, and the first 10 years of operation. Twenty-three large-scale projects have received funding since 2021. Biozin is the only Norwegian project on this list.
- In November 2022, Biozin received NOK 507 million in support from Enova. The support from Enova will further contribute to the realization of the Biozin project's new and innovative technology on a full scale.
- Testing of the IH2® technology has made good progress at the demo plant at the Shell Technology Center in Bangalore, India. The efforts to further de-risk the technology will continue through 2023.

*Ongoing site preparation at Åmli, Noway. Photo: Biozin.*

- The lease agreement with Jordøya Tomteutvikling AS (JTU), was signed in October 2022. Åmli Municipality is the largest shareholder of JTU. Consequently, the development of the site in Åmli has commenced. The preparation of the site, such as removal of trees, rock blasting, levelling etc. is expected to be completed at the end of 2023.
- To accommodate the project's positive progress, Biozin Holding AS has doubled its workforce since October 2022.
  Shell and Biozin are progressing the Biozin Project as a fully integrated project. Concept Select is planned for mid-year 2023, while the Final Investment Decision will hopefully take place during 2H 2024.

## ST1

St1 in an energy company that researches and develops economically viable, environmentally sustainable energy solutions to become the leading producer and seller of CO2-aware energy. Work in Bio4Fuels is towards the same goal to explore renewable solutions to replace fossil energy. The R&D laboratory forms a world-class
entity with a Cellunolix® demonstration biorefinery in Kajaani.

St1 has a strong focus on lignocellulosic feedstock. The St1 research team is further developing the Cellunolix concept, producing advanced ethanol from sawdust, a processing residue from the sawmill industry, and the enzymes at enhanced capacity in the biorefining process. The research results and development work can immediately be taken seamlessly to production for testing on a demonstration scale, and the results can be returned to the development work. 100% of the feedstock of our advanced ethanol production is waste based. Renewable energy is used in production and energy efficiency has been one of our top priorities.

Advanced ethanol biorefineries produce other bioproducts in addition to ethanol. St1 is involved in several lignin application developments together with universities and private partners. Some of the promising applications are, for example, bitumen replacement in asphalt production, the replacement of fossil components in resins production, and biochar production for the steel industry. Through our R&D activities, as well as by participating in partnership-funded R&D projects, we continuously look for new potential sustainable feedstocks for producing advanced fuels. For example, recycled wood, bark, and waste streams from the chemical forest industry have proven to be great local feedstocks.

*St1 Cellunolix® demonstration biorefinery in Kajaani, Finland. Photo: St1*

## INNLANDET FYLKESKOMMUNE

The Inland County – Adventurous Opportunities
Innlandet county has long traditions as forest county no. 1 in Norway. Approximately 40 % of all forest harvested in Norway is taken out in Inland Norway, and this amounts to between 4.2 and 4.6 million m3 of forest annually. Annually, about 1.2 million m3 of pulpwood is exported to Sweden. In addition, there is branches and tops that remains in the forest after logging. This provides great opportunities for new industry based on the raw material from the forest.

Through the “Innlandsporteføljen” (Inland Portfolio), which will be ready in May, the county municipality, together with the County Governor and Innovation Norway carry out a survey of Inland Norway's most important green innovation projects. The inland portfolio will identify and highlight innovation projects from the county's business sector, as well as uncover inland opportunities and barriers to green development. The result of this work will be a portfolio that shows the most value-creating, innovative and circular innovation projects in Inland Norway, and what it takes to realize them.

Companies like Glocal Green are one such example of a company with great potential for circular use of input factors, while at the same time the raw materials for the factory will be able to facilitate circular use. The concept allows for the establishment of economically sustainable commodity flows for biological waste and residual raw materials – from forests, agriculture, aquaculture and other biological waste management to produce biomethanol. This biomethanol can be used as a fuel for internal combustion engines, as a hydrogen carrier for fuel cells and as an ingredient for the chemical industry.

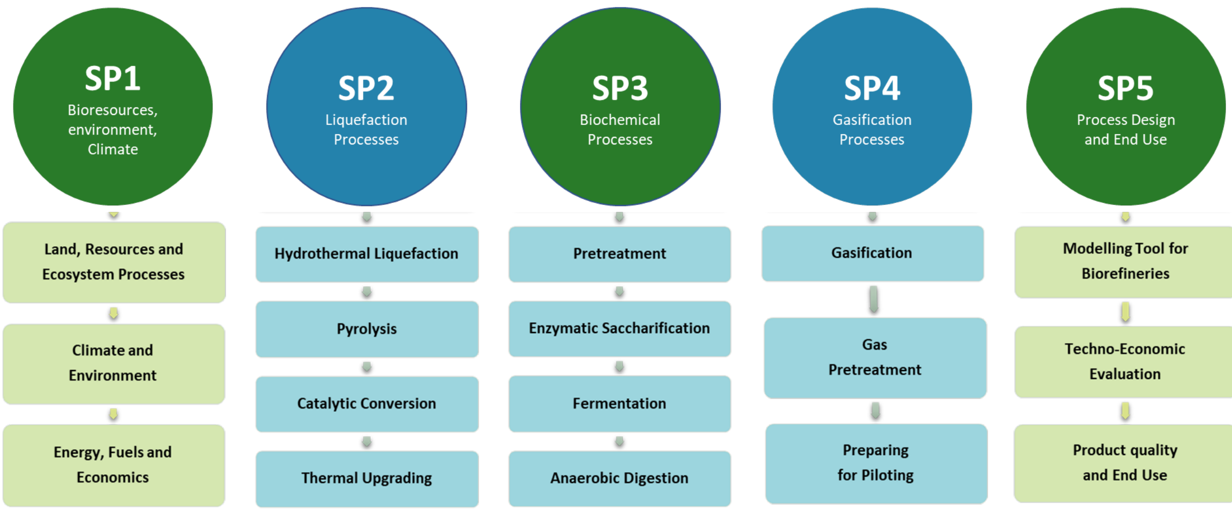
Similar projects that take care of side streams and contribute to solving climate challenges are what we are looking for in Inland Norway.

*Mjøsa, Innlandet County, Norway. By Øyvind Holmstad. CC BY SA 2.0*

# HIGHLIGHTS FROM BIO4FUELS' WORK PACKAGES

As shown below, the high-level value chain (SP (sub project)) establishes interaction across focussed research activities (work packages (WP)), addressing the five challenges of bioresources (SP1), Liquefaction Processes (SP2), Biochemical Conversion (SP3), Gasification Processes (SP4) and End use (SP5).

Within this organisational structure, Bio4Fuels has focus on and coordinates the activities along the value chains, addressing specific challenges and bottlenecks needed to go from resources to products using the most relevant technological approaches for biofuels production.



| ***SP1: Bio-resource, Environment and Climate*** |
|---|
| - Resource use and availability in Norway.<br>- Climate change impacts and mitigation<br>- Economic policies for sustainable biofuel economy |
| SP Leader: Francesco Cherubini |

| | |
|---|---|
| WP1.1 | Land, Resources and Ecosystem Processes (Rasmus Astrup, NIBIO) |
| WP1.2 | Climate and Environment (Francesco Cherubini, NTNU) |
| WP1.3 | Energy, Fuels and Economics (Per Kristian Rørstad, NMBU) |

## *Background and approaches*

This subproject addresses sustainability aspects related to bio-resources with a particular focus to the Norwegian context. Research activities in this domain include the availability and options for procurement of bio-based resources under different management strategies, modeling biomass-to-biofuels value chains and their climate change mitigation potential, environmental impacts, and socio-economic implications.

State-of-the-art modelling tools are applied to simulate forest state and structure and cost-supply curves of wood resources. Value chains of biofuel options are compiled and assessed under a life-cycle perspective, and climate change mitigation potentials of their large-scale deployment explored. Their contributions to multiple sustainability indicators are quantified, as well as market dynamics and impacts on welfare. The analysis includes current and near-term economic measures and policies governing the many aspects of Scandinavian biofuel economy with the view to outlining potential sound economic policies to enable a sustainable biofuel economy in Norway and Scandinavia.

The research results are expected to provide useful information to industries and public authorities about the best ways to manage biomass feedstocks, biofuel production technologies, and biofuel applications under the dual goal of renewable energy supply and climate change mitigation. In the remaining lifetime of the center, we will develop a sustainability assessment framework and apply it to the novel technologies emerged in Bio4Fuels. The analysis will show the main opportunities and barriers, dependency on national and imported biomass feedstocks, and potential co-benefits and trade-offs with other SDGs (integration of environmental, social, and economic indicators).

## WP1.1 Land, Resources and Ecosystem Processes - Rasmus Astrup

The activities in WP1.1 will in the future be linked with the activities of SmartForest with the aim of developing the digitally enabled sustainable feedstock supply chains based on Norwegian forests.

In 2022, WP1.1 focused on analysing energy wood rawmaterial scenarios - or feedstock baskets - from a practical viewpoint. The main aim of the research was to evaluate the economic effect of transferring part of current, lower quality stem wood from pulp to energy wood assortment by modifying the tree-bucking instructions used in modern cut-to-length harvesters.


*Photo: Heikki Korpunen, NIBIO*

The analysis was carried out by utilising tree-bucking simulations and following logistic cost-benefit calculations. The study was carried out in collaboration with Biozin and their wood supply collaborators in Åmli area.

Firstly, real-life harvesting stem data was collected from freshly harvested spruce dominated clear-cut sites. Secondly, different tree-bucking instructions were created for test simulations. The tree-bucking instructions were created in such ways that the minimum small-end diameters of pulp logs were modified to increase from six to twelve centimeters in one-centimeter classes. That enabled more treetop stem volume to be utilized for energy wood. The sawlog dimensions were considered to remain the same in all cases, and eventually the total sawlog volumes remained the same in each simulation. Thirdly, cost levels of pulp and energy wood fragment logistics were collected from forestry professionals and statistics for economic evaluations.

According to our findings, increment of 2 cm in the small end diameter of energy wood assortment increased the energy wood volume for only 1% of the total roundwood volume, and obviously at the same time decreased similar amount of pulp wood. If increment of 5% would be desired to the energy wood assortment volume, it would require minimum of 12 cm top end diameter to the energy wood logs.

The cost evaluations revealed that, after the wood and procurement costs being approximately 40%, the long-distance transportation was the most important logistic cost factor by 23 - 30% share of total costs. Additionally, according to a comparison of pulpwood and energy wood from roundwood logistic costs, in the distances under 170 kilometers from stand to mill, the energy wood logistic chain can be competitive in comparison to pulp wood logistic chain. Train transportation was a competitive option on longer distances.

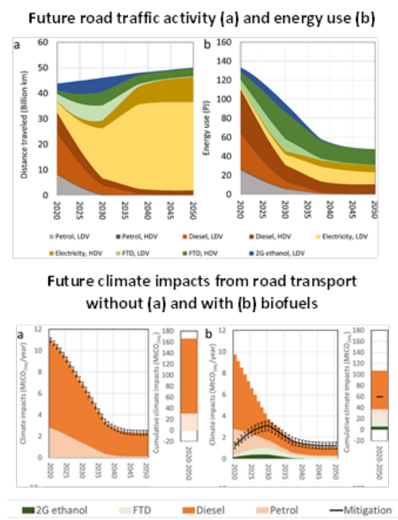
In order to fulfill the increasing forest biomass demand in the future, it can be worthwhile for the bioenergy industry to reach for other, currently underutilized rawmaterial fragments such as rotten logs. Furthermore, during the year 2022 EU suggested limitations to roundwood uses that would significantly limit the utilization of stem wood for energy purposes.

## WP1.2 Bio-Resources, Environment, Climate - Francesco Cherubini

Our research activities in 2022 have explored the climate change mitigation potential of large-scale biofuel production and use in the Norwegian transport sector. The work primarily focused on advancing our understanding of the key factors shaping the climate change mitigation benefits of biofuels, the sustainable resource potential availability, and applications to case studies for the road and shipping sectors.

The main findings are connected to corresponding scientific articles in international peer-reviewed journals. A couple of highlights:

- *Unraveling the role of biofuels in road transport under rapid electrification*



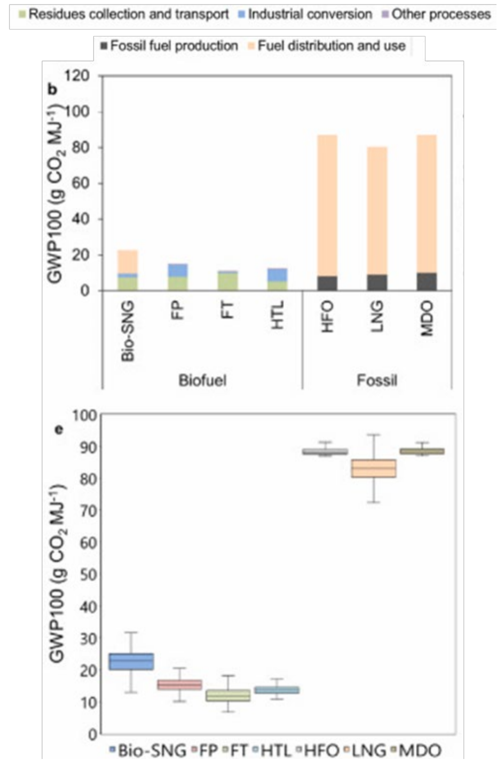

Biofuels have been the predominant option for climate change mitigation in road transport for decades, but the recent expansion of electric vehicles may question this role. We model the energy use and life-cycle emissions of road transport activities until 2050 in Norway, a country with a rapid growth in vehicle electrification. Mitigation from biofuels peaks in 2030 at 3.1 ± 0.45 $MtCO_2eq.\ year^{-1}$ (30 % of today's road transport emissions), and impacts on human health decrease. The largest emission savings are achieved from biofuels in trucks, buses and vans. Integrated strategies combining high electrification rates of the vehicle fleet with targeted applications of biofuels can increase the mitigation of road transport emissions.

Cavalett, Otávio; Cherubini, Francesco. (2022) Unraveling the role of biofuels in road transport under rapid electrification. *Biofuels, Bioproducts and Biorefining*. Full paper available at: https://onlinelibrary.wiley.com/doi/10.1002/bbb.2395

- *Climate change mitigation of drop-in biofuels for deep-sea shipping in Norway*

Unlike short-sea shipping that can rely on electrification of coastal vessels, drop-in biofuels are among the most promising options for deep-sea shipping decarbonization. In our study, we assess the climate change mitigation potential of various marine biofuels produced from forest residues in Norway sing a prospective life-cycle assessment (LCA) where the projected trends in the energy and transport sectors are integrated with improvements in the biofuel value chain for the next decades (2030–2050). Relative to fossil-based alternatives, climate mitigation potentials of biofuels range from 65 % to 87 %. The explicit modeling of technology and socio-economic changes under future policy scenarios indicates a reduction in the climate impacts of biofuels by up to 54% in 2050 when compared to the impacts from the current situation. The residues potentially available in Norway today are sufficient to meet the demand for liquid fuels in deep-sea shipping, providing an annual climate change mitigation of 0.9–1.1 million tons of CO2-eq (equal to 6–7 % of today's climate impacts from the entire transport sector in Norway).

**Climate change impacts of marine biofuels and fossil fuels**




Barbosa Watanabe, Marcos Djun; Cherubini, Francesco; Cavalett, Otávio. (2022) Climate change mitigation of drop-in biofuels for deep-sea shipping under a prospective life-cycle assessment. *Journal of Cleaner Production*. Full paper available at: https://doi.org/10.1016/j.jclepro.2022.132662

Other scientific papers in 2022 connected to Bio4Fuels:

Barbosa Watanabe, Marcos Djun; Cherubini, Francesco; Tisserant, Alexandre Fabien Regis; Cavalett, Otávio. (2022) Drop-in and hydrogen-based biofuels for maritime transport: Country-based assessment of climate change impacts in Europe up to 2050. *Energy Conversion and Management*. https://doi.org/10.1016/j.enconman.2022.116403

Iordan, Cristina Maria; Giroux, Baptiste Abel Rene; Næss, Jan Sandstad; Hu, Xiangping; Cavalett, Otávio; Cherubini, Francesco. (2022) Energy potentials, negative emissions, and spatially explicit environmental impacts of perennial grasses on abandoned cropland in Europe. *Environmental impact assessment review*. https://doi.org/10.1016/j.eiar.2022.106942

Løvenskiold, Anne Cecilie; Hu, Xiangping; Zhao, Wenwu; Cherubini, Francesco. (2022) Comparing the climate change mitigation potentials of alternative land uses: Crops for biofuels or biochar vs. natural regrowth. *Geography and Sustainability*. https://doi.org/10.1016/j.geosus.2022.11.004

Næss, Jan Sandstad; Hu, Xiangping; Gvein, Maren Haug; Iordan, Cristina Maria; Cavalett, Otávio; Dorber, Martin; Giroux, Baptiste Abel Rene; Cherubini, Francesco. (2022) Climate change mitigation potentials of biofuels produced from perennial crops and natural regrowth on abandoned and degraded cropland in Nordic countries. *Journal of Environmental Management*. https://doi.org/10.1016/j.jenvman.2022.116474

Næss, Jan Sandstad; Iordan, Cristina Maria; Muri, Helene; Cherubini, Francesco. (2022) Energy potentials and water requirements from perennial grasses on abandoned land in the former Soviet Union. Environmental Research Letters. https://iopscience.iop.org/article/10.1088/1748-9326/ac5e67

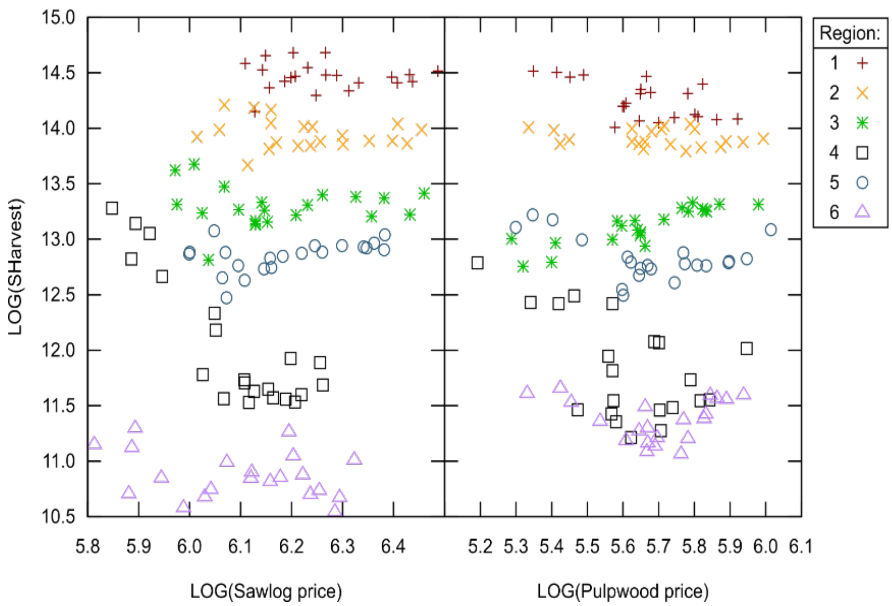
Vera, Ivan; Wicke, Birka; Lamers, Patrick; Cowie, Annette; Repo, Anna; Heukels, Bas; Zumpf, Colleen; Styles, David; Parish, Esther; Cherubini, Francesco; Berndes, Göran; Jager, Henriette; Schiesari, Luis; Junginger, Martin; Brandão, Miguel; Bentsen, Niclas Scott; Daioglou, Vassilis; Harris, Zoe; van der Hilst, Floor. (2022) Land use for bioenergy: Synergies and trade-offs between sustainable development goals. Renewable and Sustainable Energy Reviews. https://doi.org/10.1016/j.rser.2022.112409

## WP1.3 Energy, Fuels and Economics – Torjus Bolkesjø/Per Kristian Rørstad

We have good knowledge about the available forest resources in Norway. It is however the more than 120000 forest owners that ultimately decide how much timber will be harvested. In a recent study we have studied the regional differences using regional data on harvests, prices, interest rates and standing stock.

Region 4 – along the western coast – appears to have a different dynamic compared to the other regions. Here the harvest has been monotonically increasing despite a negative trend in real timber prices. The short-term elasticities are positive. This implies that forest owners react to short term variation in prices in the way we expect, but that there are underlying long term changes not captured by our models. We are quite certain that hurricanes and windthrow are not the reasons.

For the models estimating the short-term reaction to changes in prices, a model with regional effects did not perform (statistically) better than one without. Still, if we are interested in modelling the regional timber supply – as we usually are – using regionalized models would still be preferable even though we do not gain anything at the aggregate level.




*Relationship between timber harvest and timber price*

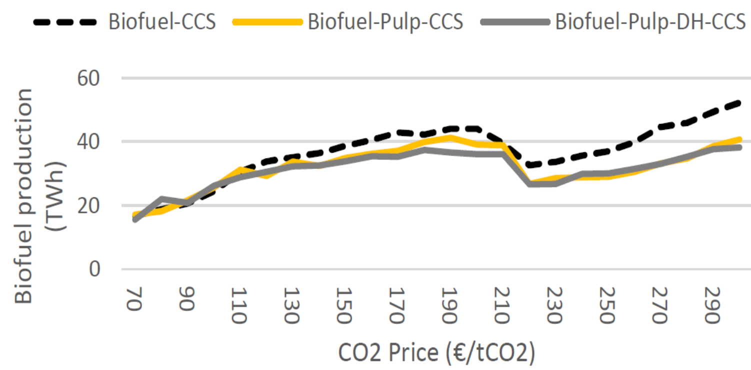
The results show that the econometric specification influences the parameter values, and it is thus complicated to directly compare results in different timber supply studies.

The study is published as: Rørstad P.K., E. Trømborg, B. Solberg (2022). Can we detect regional differences in econometric analyses of the Norwegian timber supply? *Silva Fennica* **56:**1 https://doi.org/10.14214/sf.10326

In another study we have demonstrated the effect on biomass supply and biofuel production in the Nordics of large-scale Bio-CCS deployment in biofuel plants (Biofuel-CCS), kraft pulp mills (Biofuel-Pulp-CCS) and biomass boilers in district heating (Biofuel-Pulp-DH-CCS). We have assumed that the negative emissions from this is included in EU ETS, i.e., that the plant owner will receive a payment for the $CO_2$ capture and storing equal to the quota price. The Nordic Forest Sector Model (NFSM) is used for the simulations.

As expected, the biofuel production scale is effectively stimulated by trading negative emission. For all three scenarios, there is an increasing trend in biofuel production. At a $CO_2$ price of about 200 €/ton there is a shift in biofuel production technology leading to a decrease in the biofuel production and increase in the $CO_2$ production.

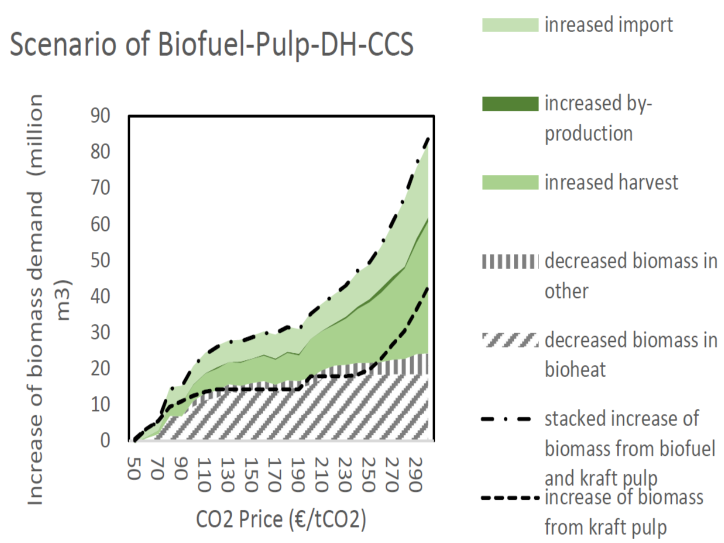
When the quota price becomes high enough, CCS will be more valuable than producing biofuels.




*The amount of biofuel production as a function of the $CO_2$ price.*

The production of biofuel will decrease significantly when large scale Bio-CCS also become deployed in kraft pulp. The additional effect from adding CCS also in district heating is low. This indicates that biofuel production and pulp production compete over the feedstock, while district heating uses other type of biomass.

The demand for pulpwood will increase sharply for the large-scale deployment of Bio-CCS in kraft pulp mills and biofuel plants while in district heating it will not. Both harvest and import of wood start to increase nearly when the pulpwood currently used in district heating instead is used in biofuel and kraft pulp production. Increased consumption of forest residues and bark is necessary in district heating to compensate for the reduced use of pulpwood.




*The effect on biomass demand as a function of the $CO_2$ price.*

| ***SP2: Liquefaction Processes*** |
|---|
| - Develop novel technologies for direct conversion of lignocellulosic feedstocks to transport biofuels – through pyrolysis and hydrothermal liquefaction<br>- Increase the robustness of the liquefaction and catalytic processes throughout the whole value chain.<br>- Increase the energy efficiency through the whole value chain |
| SP Leader: Judit Sandquist |

| | |
|---|---|
| WP2.1 | Pyrolysis (Kai Toven, RISE PFI) |
| WP2.2 | Hydrothermal Liquefaction (Judit Sandquist, SINTEF ER) |
| WP2.3 | Thermochemical Upgrading (Roman Tschentscher, SINTEF Industry) |

*Background and approaches*

The liquefaction value chain focusses on one of the major routes for the conversion of solid biomass to biofuels and related products. The conversion processes involve high temperature treatments that aim to achieve the desired composition of the biofuel. The major challenge is to achieve this in as few processing steps as possible, minimising the overall costs.

This subproject includes two technologies, pyrolysis and hydrothermal liquefaction for biomass conversion to intermediates and two catalytic technologies, one to upgrade the bio-oils to transportation-quality biofuels and a chemo-catalytic conversion to valuable chemical- Ethylene glycol and Propylene glycol production. The sub-project uses mainly experimental approaches.

With regards to pyrolysis, biomass conversion by pyrolysis combined by anaerobic digestion to increase the overall energy efficiency of the process is investigated. In addition, a two-step pyrolysis process, pyrolysis with direct vapour upgrading to produce a higher quality suitable as drop-in fuel for marine or aviation fuel blends is being developed. The HTL work package focuses on the development of a more robust and feedstock flexible technology by understanding and controlling the inorganics during the process through experiments and modelling. In addition, operational challenges such as feeding depressurization and the influence of the feedstock properties are investigated in a continuous mini pilot.

The catalytic processes are focusing on increased simplicity and stability of the catalysts. For upgrading, development of a simple and robust catalytic bio-oil/biocrude upgrading process as well as fractionation and detailed analysis of the different streams are carried out. The main focus of the chemo-catalytic conversion is enhancing the catalyst stability of the copper catalyst. In addition, electrochemical conversion is studied.

The TRL range of the SP is 3-5.

## WP2.1 Pyrolysis - Kai Toven

a) 

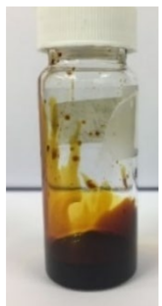
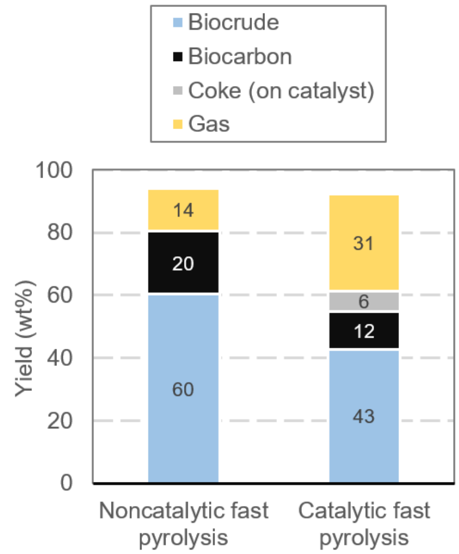
c) 
b) 
d) 


***Photo:*** *The Bio4Fuel research team at RISE PFI are exploring catalytic pyrolysis of waste wood for producing a biocrude quality suitable for upgrading in to a marine or aviation drop in fuel.*
*a) Waste wood feedstock. b) Applied zeolite catalyst pellets with coke formation. c) Low-viscous organic biocrude sample produced two-step catalytic fast pyrolysis of waste wood d) Product yields obtained in noncatalytic and two-step catalytic fast pyrolysis conversion of waste wood.*

Pyrolysis processes are of particular interest for direct conversion of biomass and residue feedstocks into liquid biofuels, biochemicals and biocarbon materials. In Bio4Fuels, the research team at RISE PFI are addressing with two novel conversion routes for cost efficient production of biobased transportation fuel based on pyrolysis technology. First, coproduction of biogas transportation fuel, biocrude and biocarbon is addressed by combining intermediate pyrolysis technology and anaerobic digestion. Second, a novel two-step catalytic fast pyrolysis process is addressed as a route for direct conversion of biomass and organic waste feedstocks into a low molecular biocrude suitable for further upgrading to a marine or aviation "drop in fuel". As compared to previous work on catalytic fast pyrolysis technology, the main strategy here is to develop a two-step catalytic process that allows using contaminated organic waste like waste wood and non-recyclable plastic waste as feedstocks. Today these feedstocks cannot be material recycled and goes to direct combustion. Key innovations here are that catalyst deactivation due to deposit of inorganic contaminants from the feedstock on the catalyst can be avoided in two-step pyrolysis process and that the use of organic waste material as feedstocks will reduce carbon footprint and improved profitability of the process.

In 2022, a study to explore biocrude production by catalytic fast pyrolysis of waste wood was initiated. In this study a noncatalytic and a two-step catalytic fast pyrolysis conversion process were compared as routes for producing liquid biofuels from waste wood. Typical product yields obtained for the two processes are shown in Figure 1. Noncatalytic conversion gave about 60 wt% biocrude liquid yield whereas somewhat lower liquid product yield was obtained for the catalytic conversion process. In catalytic conversion, lower liquid product yield was expected as catalytic decarboxylation reactions which takes place in catalytic conversion gives increased gas formation and lower liquid product yield. The liquid biocrude obtained in noncatalytic conversion was free of inorganic contaminant but high contents of water, oxygen and acids gives too extensive upgrading demand for converting the biocrude into a liquid fuel suitable as transportation fuel. The catalytic conversion process gave a phase separated condensate product composed of an aqueous and an organic biocrude. Here, the organic biocrude product is a possible precursor for producing biobased aviation drop in biofuel as the organic biocrude is rich in aromatics and contain low amounts of oxygen, water and contaminants. However, the product yield of the organic biocrude product is low, so alternative applications are needed for the byproducts to avoid too high carbon loss from the process.

## WP2.2 Hydrothermal Liquefaction - Judit Sandquist

Hydrothermal Liquefaction (HTL) is a thermochemical process that uses high pressures and temperatures near the critical point of water to convert biogenic materials into liquid fuel intermediates. HTL is particularly relevant for high-moisture feedstocks such as organic residues and sludges, as it takes advantage of the water present in these materials and avoids an energetically costly drying step.

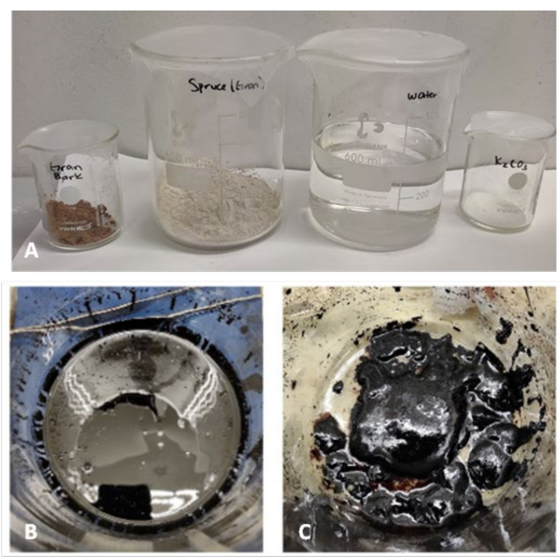



**Figure 1.** A) Hydrothermal liquefaction reactants, showing ground spruce bark, ground spruce wood, water, and catalyst. B) Bio-oil from continuous HTL under supercritical conditions (400C, 300 bar). C) Bio-oil from continuous HTL under sub-critical conditions (350C, 300 bar).

At conditions near the critical point (at either a sub- or supercritical temperature) water is a compressible liquid, and the heat of evaporation is avoided. Under these hydrothermal conditions, the water has physical and chemical properties which result in chemical reactions that break bonds in the organic structure of biogenic materials and convert them to fuel intermediates.

In 2022, investigation of continuous lab-scale HTL on Norwegian woody biomass with varying percentages of bark were ongoing. The reactor was originally funded by the Norwegian national infrastructure project, NorBioLab2, and has been operated since 2020 within various projects. In 2021, the focus was on developing procedures for continuous reactions, while in 2022, the aim was to put these procedures into action. However, while some reactions were successful, a gap was identified in the preparation of the bio-feedstock which required investigation (Figure 2).

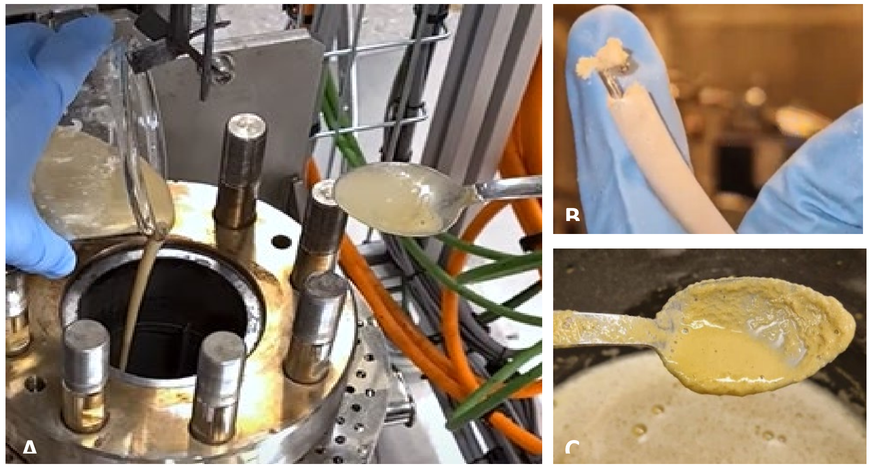



Figure 1. Differences noticed in the slurry consistency. (A) Slurry consistency from experiments in 2021. (B) and (C) are slurries with powder from new milling equipment where (B) depicts a clog in plastic tubing combing from the slurry tank.

Previous successful experiments had used bio-feedstock prepared by NTNU laboratories, but these labs were no longer able to provide this service. In 2022, SINTEF Energy Research invested in milling equipment to prepare the material in a size and shape that is suitable for quick processing of high volumes of biomass. However, initial experimental attempts by the summer researcher showed that this transition to in-house biomass preparation would need to be optimized before experiments could continue (Figure 3). The optimization studies will be completed in 2023.

Meanwhile, previous work from 2021 was presented at IConBM2022 by Judit Sandquist and was later published in the Chemical Engineering Transactions Journal in July 2022. This work investigated the differences between sub- and supercritical HTL reactions using the reactor in batch mode, with varying percentages of bark present. The products of the batch experiments were analyzed by TGA, FTIR, and TOC analysis. The results indicated temperature as the primary variable affecting yields and product characteristics. Here, the most exciting conclusion was that bark did not appear to affect biocrude quality, indicating its addition in HTL could increase production while using a material that is otherwise considered waste.

After the optimization studies for in-house bio-feedstock preparation are completed in 2023, the goal is not only to further investigate continuous HTL of woody biomass with varying percentages of bark, but also begin an experimental campaign investigating residence time, stirring speeds, and mixed tree species feedstocks. Our research aim is to continue to contribute to the development of a more efficient way of producing renewable fuels from waste and residue materials.

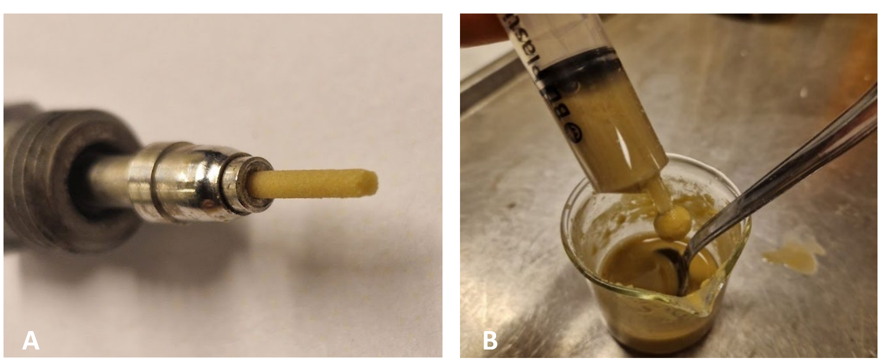
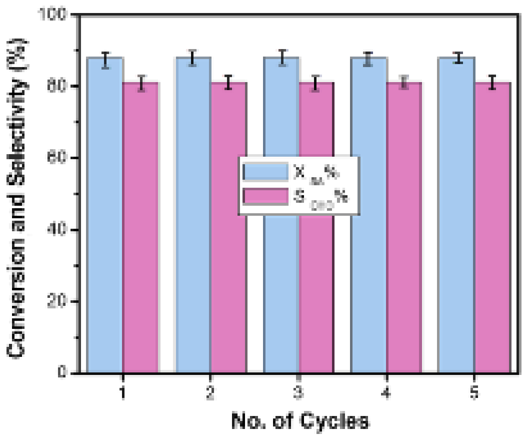



**Figure 2.** Clog in tubing (A) and dewatering observed by the initial syringe tests performed during the first stages of slurry optimization (B).

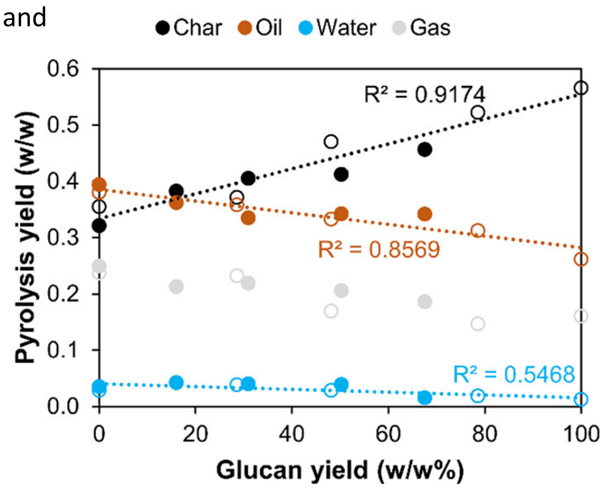
## WP2.3 Thermochemical Upgrading – Roman Tschentscher

During the year 2022 within Bio4Fuels and associated national and European projects the research activities continued to focus on catalyst materials development and testing as well as conversion process parameter studies for scale up and feasibility studies in future.

The RCN IndNor project NanoCat4Fuels has ended in autumn 2022. The project focus was to develop and evaluate hydrotreatment catalysts based on active metal nanoparticles deposited on commercial supports. The developed catalyst systems show a high selectivity combined with stable conversion activity for up to five runs. Both bioliquids produced by hydrothermal liquefaction (HTL) and pyrolysis liquids have been tested. With the initially lower oxygen contents the HTL liquids produce higher amounts of hydrocarbons. During this cooperation with Anna University in Chennai/India three journal publications have been published in 2022, while another two are still in preparation. The work has been presented at various international conferences and will be continued on a bilateral basis with respect to student exchange, research stays and collaborative publications. Further development towards continuous operation and scale up of the materials has been proposed in a Horizon-Europe project proposal, which has been submitted in March 2023.




The cooperation with NMBU within the RCN-funded research project Enzymes4Fuels has resulted in another publication investigating the combined hydrolysis and pyrolysis process specifically investigating the effect of prior impregnation on the carbohydrate yield and pyrolysis liquid. The obtained correlations between pre-processing, hydrolysis enzyme activity and yields of pyrolysis product fractions provided the basis for a process design study including process economics, which has already been submitted as journal publication. Most importantly, the pyrolysis of partly hydrolysed residues can be performed without typical issues such as clogging, charring, gum formation as in the case of pure lignin pyrolysis. Further optimising the pyrolysis conditions towards lower residence times at the high temperature step is expected to increase the amounts of pyrolysis liquids as compared to char.




In the field of electrochemical upgrading of bioliquids the selection of electrode materials has been completed. Currently kinetic studies and effects of process parameters are studied with the aim to minimise condensation and repolymerisation of lignin monomers. A litre-scale continuous electrochemical cell has been designed and is currently being decommissioned enabling the production of several hundreds of millilitres of upgraded liquids.

The results of the individual projects mentioned above will be presented at various relevant bioeconomy and catalysis conferences including during 2023, including RRB, EUBCE, Europacat and ESEE.

| *SP3: Biochemical Processes* |
|---|
| |
| SP Leader: Anikó Várnai |

| | | |
|---|---|---|
| WP3.1 | Pretreatment and Fractionation (Mihaela Tanase-Opedal, RISE PFI) | TRL: 3-5 |
| WP3.2 | Enzymatic Saccharification (Anikó Várnai, NMBU) | TRL: 1-6 |
| WP3.3 | Fermentation (Alexander Wentzel, SINTEF Industry) | TRL: 2-5 |
| WP3.4 | Anaerobic digestion and gas upgrading (Lu Feng, NIBIO) | TRL: 1-5 |

## *Background and approaches*

This value chain focuses on applying biotechnology-based approaches to convert relevant biomass to biofuels and value-added chemicals. Softwood, such as Norway spruce, which constitutes Norway's largest proportion of land-based plant biomass, is known for its resilient structure and complexity and, therefore, has seldom been considered as feedstock for the biochemical production of biofuels. Biochemical conversion of biomass for 2$^{nd}$ generation bioethanol production is currently available commercially for perennial agro-based biomass. Based on these processes, the primary target of this subproject is to establish economically viable conversion of Norway spruce to a variety of biofuels (including ethanol, long-chain alcohols, microbial oil and methane) and biomaterials (lignin- and cellulose-based materials but also various fermentation products), employing important recent technological improvements in the field. Depending on the maturity of the technology, the WPs operate at varying technology readiness levels (TRLs), from formulation and verification of novel concepts to R&D and demonstration of technologies at pilot and demonstration scale, as indicated in the header above.

In the first step of the process, i.e. pretreatment, we focus on processing technologies that enable selective separation of lignin, hemicellulose and cellulose, and thereby facilitate efficient downstream use of all main constituents of lignocellulose feedstocks. In the following saccharification step, our target is to improve the currently suboptimal conversion yield and efficiency by identification of enzyme activities that are critical for softwood conversion and of process design that enables efficient use of novel oxidative enzymes. Next, we assess a large collection of fermenting bacteria and oleaginous fungi for their potential to convert the solubilized sugars to short-chain alcohols, including ethanol, and microbial oil, respectively, in an industrially feasible way. Complementarily to this process, softwood with or without pretreatment is subjected to anaerobic digestion to produce biogas. Here we focus on enhancing biological methanation of biogas by optimizing process conditions and consider sorption-enhanced reforming of biogas for the industrially competitive production of hydrogen. In connection with SP5, we work on assessing the choice of fermentation technology, including the end product, and whether keeping the saccharification and fermentation steps separate or combining them is more feasible for softwood conversion with the selected technologies. Moreover, we aim to further enhance process efficiency by utilizing residual side streams from the saccharification and fermentation steps for methane production by anaerobic digestion.

## *Highlights*

Within *Pretreatment* (WP3.1), we have further optimized a pilot-scale reactor at RISE-PFI to carry out organosolv pretreatment with lignin displacement for lignin removal and co-operated with downstream activities in technology development and techno-economical assessment of selected conversion routes. Within *Enzymatic Saccharification* (WP3.2), we have established a combined biochemical and thermochemical conversion route (with WP2.3 *Thermochemical Upgrading*) that is based on the modification of biomass pretreatment to improve lignin reactivity in the pretreated feedstock. The modified lignin promotes oxidative cellulose depolymerization and enables efficient separation of the sugar fraction from a quasi-pure lignin-rich saccharification residue, which can be then upgraded into high quality pyrolysis oil. With respect to *Fermentation* (WP3.3), we are working with St1 to improve their process efficiency using simultaneous saccharification and fermentation, while we have selected the best oil-producing fungi and optimized growth conditions for biooil production. Activities in *Anaerobic Digestion* (WP3.4), have successfully increased methane productivity during biogas production by supplying hydrogen to biogas reactor.

In 2022, we continued our focus on combining the better connecting our activities in WP3.2 with the activities of other WPs in the Centre (both within SP3 but also with other SPs) and of Bio4Fuels-associated projects. On the one hand, we established a combined biochemical and thermochemical conversion route, involving *Biomass pretreatment* (WP3.1), *Enzymatic saccharification* (WP3.2), and *Thermochemical Upgrading* (WP2.3). Techno-economic models (WP5.2) for the upstream (pretreatment and saccharification) and downstream (pyrolysis of the lignin-rich residue) processes have been developed in a major cross-SP collaborative effort. On the other hand, we carried out and completed a collaborative work within SP3 embracing all four WPs, with the aim to improve resource utilization and bioenergy production in a biochemical lignocellulose biorefinery. Norway spruce-derived residues generated along the biochemical value chain (SP3) were collected and evaluated for biogas production in WP3.4.

We have also published several publications within prestigious journals, including scientific papers and conference presentations together with industrial partners and across SPs.

In 2021, a new *Centre for Research-Based Innovation* (SFI) project on Industrial Biotechnology (SFI-IB) was awarded by The Research Council of Norway for the period 2020-2028. Industrial biotechnology entails the industrial application of modern biotechnological methods, enzymes, and microorganisms for production of a very wide range of commodities, including chemicals, pharmaceuticals, food and feed ingredients, detergents, textiles, energy, materials and polymers. The complementary nature of the two Centres Bio4Fuels and SFI-IB provides an excellent platform for the diversification of product portfolio that may be created from Norwegian biomass, via the mutually beneficial interactions between the two Centres. In 2022, we started working in collaboration with the SFI-IB Centre, which is exemplified by a joint review paper on "*Engineering cellulases for conversion of lignocellulosic biomass*" in *Protein Engineering, Design and Selection* (doi: 10.1093/protein/gzad002).

## WP3.1 Pretreatment and Fractionation - Mihaela Tanase-Opedal

In 2022, we have been working with developing a novel organosolv pretreatment process for selective fractionation of Norway spruce. In recent years, environmental demands and a shift towards a sustainable and economically feasible biorefinery have promoted better utilization of forest resources. Valorization of the entire biomass, both pulp-products and value-added by-products, is a prerequisite for reducing the environmental footprint of the process. The concept of using fiber materials and polymers derived from the biomass to thermoformed fiber products is appealing since such a product would be completely based on renewable resources.

Therefore, we have been working on developing a process for the production of fiber–lignin biocomposites. In particular, we tested in-house produced organosolv lignin as a sizing additive to prepare thermoformed pulp products (Figure 3.1.1). The addition of organosolv lignin decreased the wettability and swelling of the thermoformed product. These effects are due to the organosolv lignin being distributed on the fiber surface and filling in the pores and cavities of the fibers, thereby providing a tighter fit within the thermoformed materials. In conclusion, our results encourage the use of organosolv lignin as sizing additive to thermoformed products, which can improve water resistance, a feature useful in sustainable packaging applications.

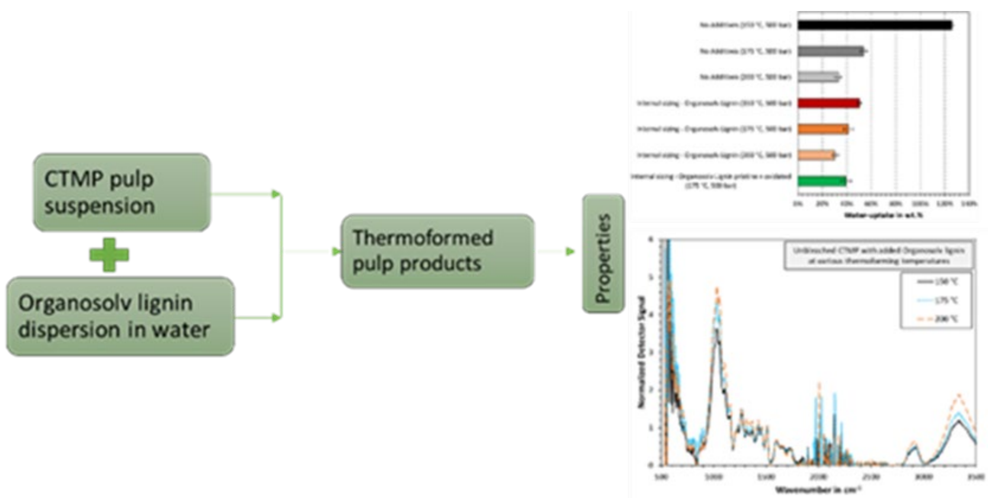



***Figure 3.1.1***: *Process scheme for the use of organosolv lignin as sizing additive to prepare thermoformed pulp products.*

This work resulted in a scientific article entitled "*Organosolv lignin as a green sizing agent for thermoformed pulp products*" and authored by Mihaela Tanase-Opedal and Jost Ruwoldt and was published in *ACS Omega* (https://doi.org/10.1021/acsomega.2c05416).

### PhD thesis on organosolv lignin defended

Bio4Fuels PhD student Prajin Joseph successfully defended his PhD thesis entitled "*Organosolv pretreatment of Norway spruce: Ethanol pretreatment for biorefinery applications*" on December 16, at RISE PFI (Figure 3.1.2). The PhD work was carried out both at the Department of Chemical Engineering at NTNU with supervision of Størker Moe and at RISE PFI with co-supervision of Mihaela Tanase-Opedal. The first opponent was Professor Martin Lawoko from KTH, Sweden, the second opponent Päivi Rousu, VP, R&D, IPR from Chempolis Oy, Finland, and the third opponent and administrator was Prof. Edd Blekkan from NTNU.

***Figure 3.1.2**: Bio4Fuels PhD student Prajin Joseph with his PhD committee after he successfully defended his thesis on Dec. 16, 2022 at RISE-PFI.*

## Talk at the Nordic Wood Biorefinery Conference 2022

In October 2022, Mihaela Tanase-Opedal participated in the Nordic Wood Biorefinery Conference held on 25-27 October 2022 in Helsinki, Finland, where she promoted the work on «Sustainable organosolv lignin polymer in thermoformed fiber products» as a part of Bio4Fuels in an oral presentation.


***Figure 3.1.3**: Mihaela Tanase-Opedal, the leader of WP3.1 'Pretreatment and fractionation' of Bio4Fuels presents RISE-PFI's results at the Nordic Wood Biorefinery Conference in Helsinki, Finland in October 2022.*

## WP3.2 Enzymatic Saccharification - Anikó Várnai

Within WP3.2, we work in close collaboration with Bio4Fuels partners Novozymes, Borregaard and St1 towards improving the efficiency of today's state-of-the-art enzyme blends in depolymerizing softwood-type feedstocks, which are in abundance in Norway. One of our innovations relates to the development of industrial setups to improve the efficiency of commercial cellulase blends by harnessing the action of the oxidative enzymes called LPMOs (lytic polysaccharide monooxygenases), a key component in today's enzyme blends, in a more efficient way than it is done in current industrial processes.

In 2022, we put more focus on **better connecting our activities in WP3.2 with the activities of other WPs in the Centre** (both within SP3 but also with other SPs) and of Bio4Fuels-associated projects. In early 2022, NMBU published a major cross-SP collaborative effort in *ACS Sustainable Chemistry & Engineering* (DOI: 10.1021/acssuschemeng.2c00286). In this work, we have established a combined biochemical and thermochemical conversion route, based on *Biomass pretreatment* (WP3.1), *Enzymatic saccharification* (WP3.2), and *Thermochemical Upgrading* (WP2.3), as shown in Figure 3.2.1. The process is based on the modification of steam explosion, a biomass pretreatment used by St1, with carbocation scavengers to improve lignin reactivity in the pretreated feedstock. The modified lignin promotes oxidative cellulose depolymerization by LPMOs, one of the key components in the state-of-the-art cellulase cocktails of Novozymes, and enables efficient separation of the spruce feedstock into a sugar-rich hydrolysate (for fermentation) and a highly pure lignin fraction (for pyrolysis).

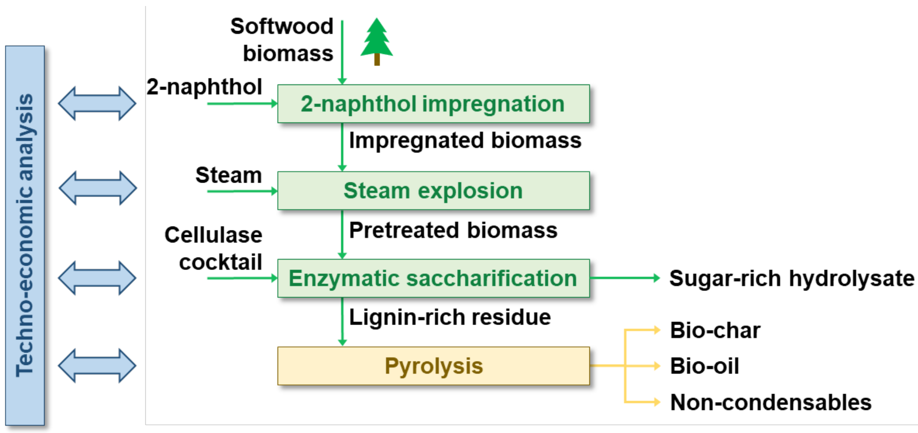



***Figure 3.2.1****: The process scheme of the combined biochemical and thermochemical conversion route. Softwood impregnation with the carbocation scavenger 2-naphthol prior to steam explosion enabled complete saccharification of the pretreated feedstock, partly due to improved LPMO activity, and yielded high-quality saccharification rests for valorization by pyrolysis.*

During the course of the year, we have built on this process and assisted WP5.2 *Techno-Economic Evaluation and Scale of Economy* in developing a model for the upstream (pretreatment and enzymatic saccharification) and downstream (pyrolysis of the lignin-rich residue) processes that enable upscaling. The results have been accepted for publication in two conference proceedings to the 33rd European Symposium on Computer Aided Process Engineering (ESCAPE33), which will be held in June 2023. While revealing the importance of pretreatment type due to the large impact of the redox state of the lignin on the saccharification efficiency with modern LPMO-containing cellulase cocktails, our findings bring closer the prospect of an economically viable spruce-based biorefinery by combining biochemical and thermochemical conversion routes.

Moreover, **we built on our previous innovation** relating to better harnessing the action of LPMOs in biomass saccharification by supplying external $H_2O_2$. In a **proof-of-concept study**, we were able **to sustain oxidative cellulose depolymerization by LPMOs during a simultaneous saccharification and fermentation (SSF) process anaerobically** with externally added $H_2O_2$ (Figure 3.2.2). Importantly, continuous supplementation of $H_2O_2$ in an SSF setup enabled us to maintain micromolar levels of $H_2O_2$, which were sufficient to drive the LPMO reaction while not harming microbial fermentation of the sugars to lactic acid. Our findings were published in the journal *Biotechnology and Bioengineering* (doi: 10.1002/bit.28298). While further process optimization is needed, the present results show that modern LPMO-containing cellulase cocktails such as Novozymes' Cellic CTec2 can be used in SSF setups, without sacrificing the LPMO activity in these cocktails.

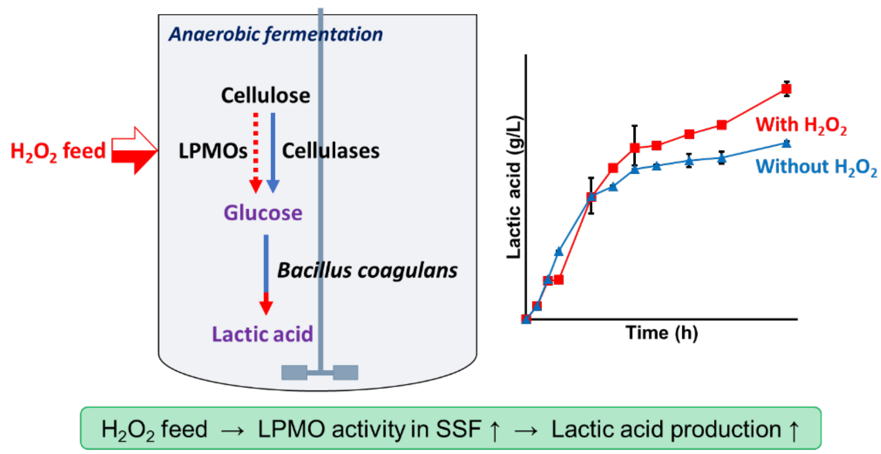



***Figure 3.2.2****: The process scheme of one-pot conversion of cellulose to lactic acid in an anaerobic simultaneous saccharification and fermentation (SSF) setup with $H_2O_2$ feeding that enables harnessing LPMO activity.*

Moreover, we put **more focus on engaging the Bio4Fuels stakeholders to a higher extent**. NMBU hosted St1 researcher Siiri de Ruijter in February 2022 (Figure 3.2.3) where she visited NMBU's research facilities and discussed a closer cooperation between Bio4Fuels and St1. In a follow-up, NMBU performed experiments at 1L bioreactor scale to suggest conditions that may be implemented in the 600m$^3$ reactors located at St1's demonstration plant in Kajaani, Finland.

***Figure 3.2.3****: PhD students Line Hansen and Camilla Angeltveit, st1 researcher Siiri de Ruijter and SP leader Anikó Várnai. Biorefining laboratory at NMBU. Photo: Svein Horn.*

Last but not least, **PhD student Line Degn Hansen defended her thesis** entitled "*Leveraging $H_2O_2$-fuelled activity of lytic polysaccharide monooxygenases in cellulase cocktails for improved bioprocessing of lignocellulosic biomass*" on June 14, 2022. Later in the autumn 2022**, PhD student Camilla Angeltveit visited Prof. Tina Jeoh's laboratory at the University of California, Davis, Colorado**. The focus of her visit aimed to better understand how cellulose oxidation by LPMOs impacts cellulose depolymerization by cellobiohydrolases. Working in Prof. Jeoh's laboratory was a great experience for Camilla where she gained a better understanding of her research topic, made new professional contacts and new friends, and got the possibility to explore the great diversity of what California has to offer.

## WP3.3 Fermentation - Alexander Wentzel

### a) Mixotrophic Gas Fermentation

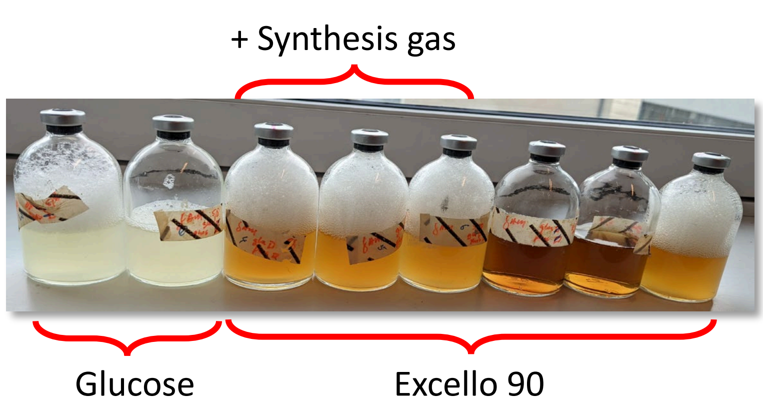
Continued work on studying bacterial mixotrophy using *Clostridium scatologenes*

Specific gas-fermenting bacteria (acetogens) are capable of utilising sugar-based substrates and single carbon rich gases (synthesis gas, $CO_2$) simultaneously for growth and product formation. Combining sugar-based substrates with such gases could be a pivotal game-changer with regards to consolidating and valorising a range of carbon-rich waste feedstocks.

During 2022, work in Bio4Fuels' WP3.3 continued on establishing and studying co-utilisation of sugar/glycerol-based feedstocks with synthesis gas waste streams. Based on previous results, the work focused on the strictly anaerobic, gas-fermenting bacterium *Clostridium scatologenes* that can produce several important C4 and C6 fermentative products. In mixotrophic experiments performed by SINTEF it was found that *C. scatologenes* thrives well upon addition of C1 gas feedstock under mixotrophic conditions, boosting carbon utilisation and product output.

As a proof of concept, we applied Excello 90, a sugar by-product from Borregaard's BALI process, in a cultivation experiment with the addition of synthesis gas ($CO_2$+$H_2$). In the presence of the gas, the bacteria grew more reliably and to higher cell densities than in its absence. Subsequently, we employed a screening approach to assess mixotrophic growth and product formation on different single sugars and Excello 90. Most sugars, including the Excello 90 mixed substrate were readily utilised for growth, while detailed analysis of product formation is currently ongoing.

The results obtained confirm that *C. scatologenes* is an ideal, robust candidate for mixotrophy for further work in Bio4Fuels. Nevertheless, in the next period, we will also test other thermophilic and mesophilic strains, including strains selected in previous WP3.3 activities for expanding the spectrum of products and waste feedstocks addressable by the mixotrophy concept.



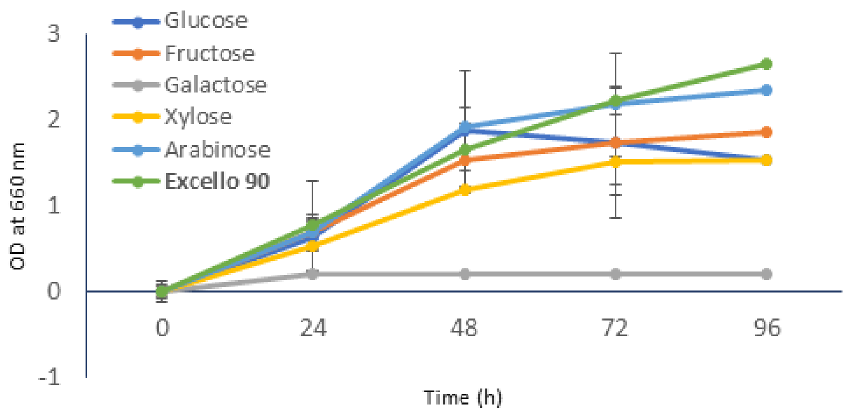



Figure. (top left) Setup for anaerobically filling serum flasks with pressurised gas. (top right) Results from cultivating *C. scatologenes* on Excello 90 and synthesis gas (80:20 $H_2$:$CO_2$, 2 bar); growth on glucose as a control. (bottom) Growth profiles of *C. scatologenes* cultivated on different sugars and synthesis gas (80:20 $H_2$:$CO_2$, 2 bar).

## b) Consolidated bioprocessing of lignocellulose for microbial lipids

**Simultaneous saccharification and fermentation of lignocellulose by thermotolerant oleaginous *Mucoromycota* and co-culture of them with the cellulolytic fungi for producing microbial lipids**

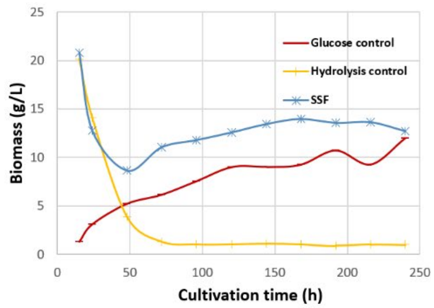
A set of promising oleaginous *Mucoromycota* strains selected based on the previous studies were used for developing simultaneous saccharification and fermentation (SSF) of lignocellulose materials for microbial lipid production. The selected strains were *Mucor circinelloides*, *Cunninghamella blakesleana, Absidia glauca, Absida corymbifera, Rhizopus stolonifera, Mortierella hyaline, Mortierella alpina and Umbelopsis vinacea.* All strains are able to accumulate lipids in amount of 30 – 60% of the total biomass.

As a first step of SSF development, we performed a thermotolerance experiment for identifying the highest temperature these fungi can tolerate. This will allow us to increase SSF temperature to approach the optimal for enzyme activity and subsequently reduce dosage of the commercial enzyme. Thermotolerance screening showed that *Absidia corymbifera* strain is thermotolerant and able to grow well even at 45°C, with its optimal at 40°C. Flask scale experiments were conducted to study lipid accumulation, dose of enzyme and temperature influence. Then, an upscale experiment in 2L bioreactors was performed in 2022 at SINTEF in close collaboration with NMBU, involving several visits of NMBU staff at SINTEF's laboratories in Trondheim. The pellet growth and the thermotolerance range of the strain made the experiment successful. In addition, a pre-test was performed in 1L bioreactors at KBM (NMBU) to evaluate the performance of the SSF system feeding with $H_2O_2$ to improve the hydrolysis boosting the LPMO activity.

Further, we are working to develop a consolidated bioprocess that does not rely on commercial enzymes. The process consists of co-cultivate our oleaginous fungi strains in combination with other fungi strains that produce the required hydrolytic enzymes. Compatible combinations were selected to develop this process. Currently, we are working on this topic in collaboration with the Utrecht University developing genetic methods to monitor the evolution of the process and understand which synergies or drawbacks take place using omic technologies.

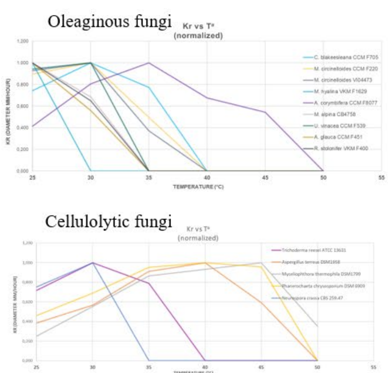
**Bioreactor scale-up of SSF using *A. corymbifera* at 40°C**

**Biomass evolution of bioreactor scale-up experiment**

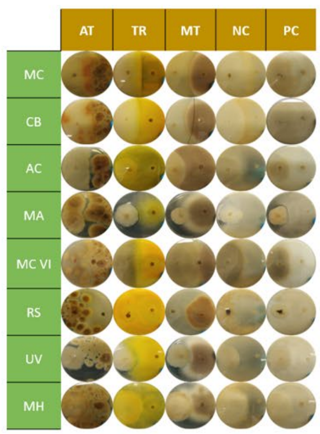



**Flask scale experiments of co-culture of cellulolytic strains with oleaginous strains**

**Screening of thermotolerance for oleaginous and cellulolytic fungi**



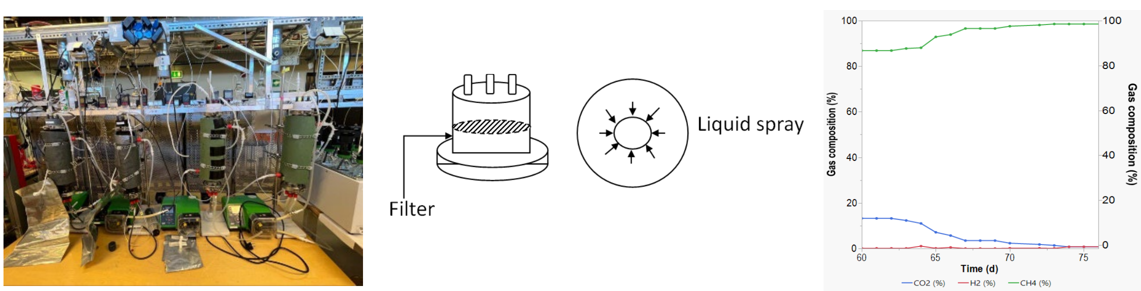

**Compatibility screening for coculture**




**SSF experiment in shake flasks**

## WP3.4 ANAEROBIC DIGESTION AND BIOGAS UPGRADING - LU FENG

In 2022, within WP3.4 we focused on modifying and expanding our lab-scale anaerobic trickle bed reactors (1 liter) for biogas upgrading of $CO_2/H_2$ to methane as well as on optimizing the process. We now have the capacity to operate four reactors (Figure 3.4.1a) and can compare the conversion of either $CO_2/H_2$ mixtures or biogas with $H_2$ addition to methane (see Figure 3.4.1c). Furthermore, we replaced the reactor head with a 3D-printed version containing a filter (see Figure 3.4.1b) to prevent the inoculum's particles from interfering with biofilm formation. On the process side, we also optimized the supplement of micro and macro-nutrients. Furthermore, we successfully enriched a typical hydrogenotrophic methanogen, *Methanobacterium*, from mixed culture, by periodically adding an isolated *Methanobacterium* sp. to the trickle bed reactor under both mesophilic and thermophilic conditions in a bioaugmentation approach (Figure 3.4.2) and thereby enhanced the reactor's performance. Based on the inoculum composition, we are currently mapping the conversion pathway. Our reactors now achieve a 99% gas conversion rate when $H_2$ and $CO_2$ are used as input gas, and the produced $CH_4$ has a purity over 98.5%. Our work, entitled '*Bioaugmentation of enriched hydrogenotrophic methanogens into trickle bed reactors for $H_2/CO_2$ conversion*' has been accepted for oral presentation at the 31st European Biomass Conference and Exhibition (EUBCE) held in Bologna, Italy, in June 2023, and a manuscript is currently under preparation.




(a) (b) (c)

***Figure 3.4.1**: Modified trickle bed reactors for biogas upgrading. (a) The experimental setup; (b) the 3D-printed reactor head with a filter incorporated; (c) example output of the online gas composition measurement.*

*Mesophilic fermentation:*

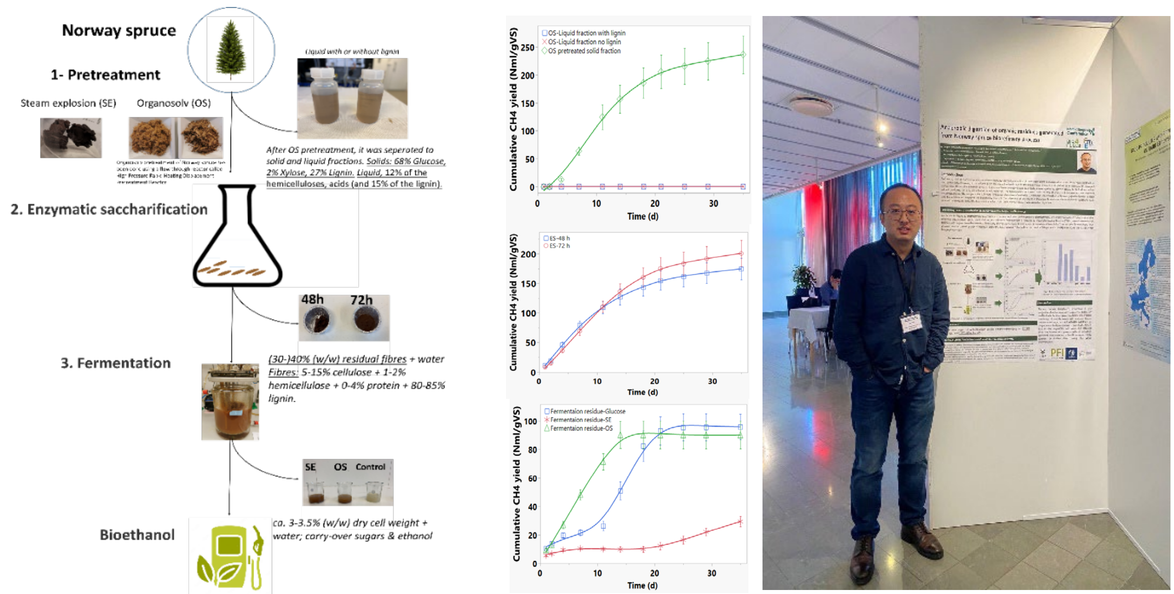
| | No enrichment | 1-month enrichment | 3-month enrichment |
|---|---|---|---|
| Methanosarcina | 7.1 | 7.7 | 6.8 |
| Ca_Caldatribacterium | 4.1 | 7.3 | 7.7 |
| Methanobacterium | 2.8 | 3.2 | 6.3 |

*Thermophilic fermentation:*

| | No enrichment | 1-month enrichment | 3-month enrichment |
|---|---|---|---|
| Methanobacterium | 3 | 9.6 | 9.2 |
| f__midas_f_2701_OTU_10 | 5.1 | 6.2 | 9.1 |
| midas_g_112 | 6.7 | 6.3 | 5.8 |

***Figure 3.4.2**: Relative abundance of selected microbes after anaerobic digestion without or with gas enrichment with $H_2$ and bioaugmentation with isolated Methanobacterium sp. Methanobacterium spp., a typical hydrogenotrophic methanogen, were enriched over time from mixture culture as a result of $H_2$ addition.*

On the other hand, we have carried out and completed a collaborative work within SP3, aiming to improve resource utilization and bioenergy production in a biochemical lignocellulose biorefinery. Norway spruce-derived residues generated along the biochemical value chain in SP3 were collected and evaluated for biogas production (Figure 3.4.3a). These fractions mainly consist of unconsumed sugars/polysaccharides, lignin and/or waste cell biomass. Despite their high lignin content, we were able to obtain almost 50% of the theoretical biogas/$CH_4$ yield without any observed inhibition during the anaerobic digestion process (Figure 3.4.3b). The results were presented at the Nordic Biogas Conference in Linköping, Sweden, in October 2022 under the title '*Anaerobic digestion of organic residues generated from Norway spruce biorefinery process*' (Figure 3.4.3c).




(a) (b) (c)

***Figure 3.4.3***: *Cross-SP work aiming to increase bioenergy production from Norway spruce in a biochemical lignocellulose biorefinery. (a) The experimental setup showing the Norway spruce-derived fractions that were evaluated for biogas production; (b) The biogas yields from the selected fractions; (c) presentation of the work at the Nordic Biogas Conference in October 2022.*

| ***SP4: Process design and End Use*** |
| --- |
| |
| SP Leader: Morten Seljeskog |

| | |
| --- | --- |
| WP4.1 | Gasification (Morten Seljeskog, SINTEF Energy) |
| WP4.2 | Gas Conditioning (Edd Blekkan, NTNU) |
| WP4.3 | Preparing for Piloting and Up-scaling (Klaus Jens, USN) |

Background and approaches

Gasification is a thermochemical process where carbonaceous fuels are converted into combustible gases often referred to as syngas. There are different types of gasification technologies such as fixed-bed, fluidized-bed, and entrained flow. Depending on gasification temperature the ash inside the reactor is either molten or in a dry solid state.

The laboratory-scale reactor available for experimental activities in SP4 WP4.1, can be configured with simple geometric arrangements to operate both in entrained flow and in fixed/fluidized slagging bed mode, and is as such, a highly flexible instrument to study so-called new “fuels of opportunity”, typically waste streams with high ash content and low market end-value.

Biomass gasification and subsequent fuel and chemicals synthesis allows for a seamless transition from fossil raw materials to a renewable economy with a limited need to replace existing infrastructure, since the resulting fuels can be designed to fulfil all technical requirements of conventional engines.

A main difficulty in the development of this route is the thermal efficiency of the overall process, where gas cleaning and conditioning is an important factor. There are two relevant gasification routes for fuel synthesis: entrained flow and fluidized bed gasification. Syngas from such processes must be converted to syngas with a high efficiency in order to maximize the thermal efficiency of the process. Hot gas cleaning would be the most economical and efficient route. However, the technology is immature and therefore the available technologies rely on liquid absorption, thus requiring gas cooling and subsequent reheating before further conversion. WP4.2 addresses the gas cleaning challenges in SP4.

Based on existing data from experimental work and simulations, reliable process models will be developed within SP4, for a complete gasification and gas cleaning system, eventually as a refinery integrated system. These models will be used to perform parameter variations to optimize process design. Flow behaviour will be simulated, while process concepts will be analysed using flow sheeting software. Finally, optimized process combinations will be established, based on both simulations and experimental results from all WP’s and a theoretically optimal solution chosen for pilot plant design.

Biofuels derived from biological materials can replace petrol, diesel and other fossil-based fuels. Resent figures from Statistic Norway indicate that about 3.7 million solid $m^3$ of primary forest residues are left in the forests each year after harvest, without including natural felling + 800,000 tons of waste wood from households and industrial activities.

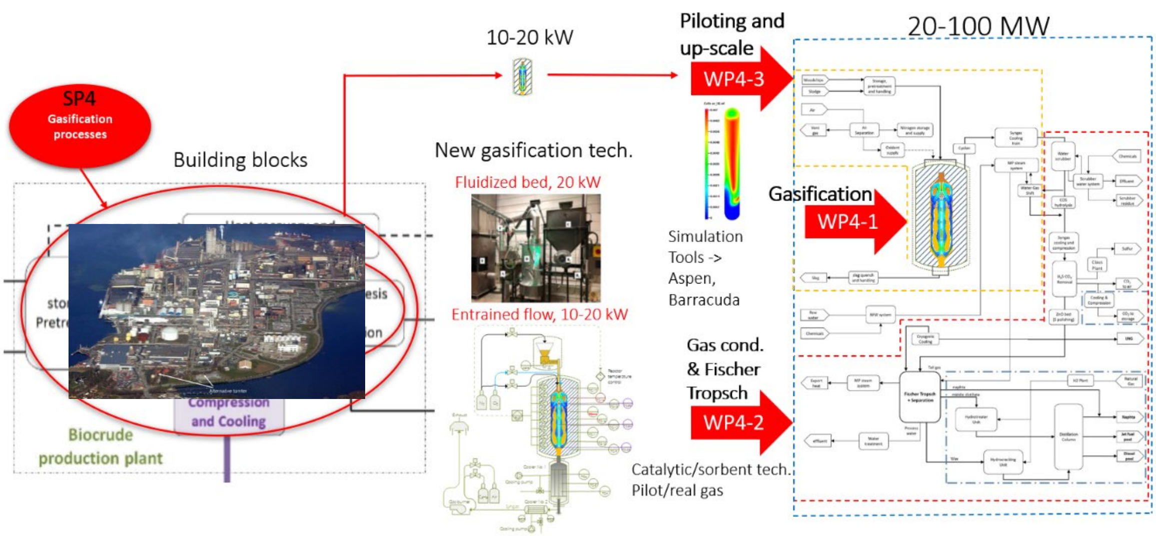



*Figure: The main outcome of the work in SP4 is the specification of a full-scale industry cluster, integrated process solution, based on thermochemical conversion of selected carbonaceous feedstocks (by gasification, producing high-value clean syngas to supplement existing sidestreams…or converted to a liquid fuel through Fischer Tropsch).*

**2021 SP4 Gasification Processes:** Several pilot-scale campaigns have been successfully performed on *Gasification* (WP4.1) in SINTEFs Entrained Flow Reactor (EFR) and in USNs bubbling bed reactor. USN is also building competence on CFD and system simulations related to the scale-up and integration of the final full-scale biofuel plant (WP4.3).

NTNU is progressing in their work on the development of catalytic technologies for Gas Conditioning (WP4.2) and have performed a number of related experimental campaigns. They are also developing numerical models for the same purpose.

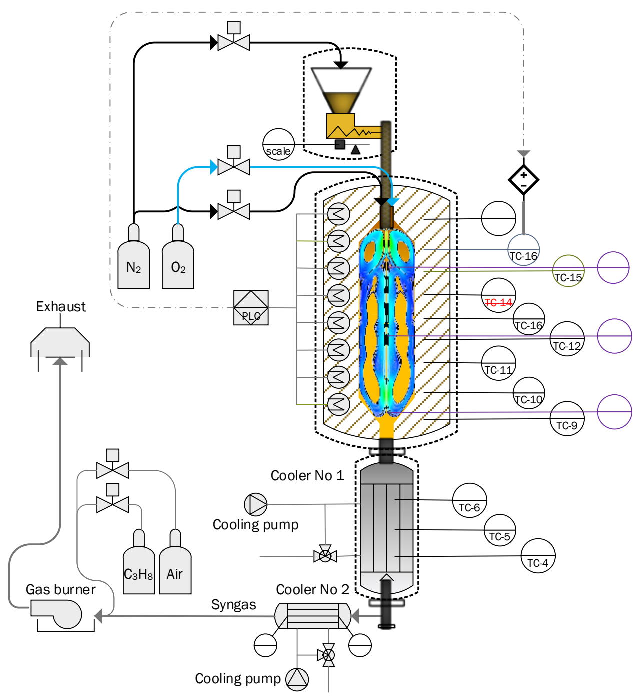
Achievements

- The results from the EFR show that the combination of increased reactor pressure (-> increased residence time and gas reactant concentrations) and using pure oxygen (-> increased residence time and oxygen concentration) instead of air as oxidizer allows us to achieve the same syngas properties as in a 10-fold larger atmospheric EFR with similar and higher % cold gas efficiency (CGE) Power, CGE fuel and carbon conversion CC for around the same λ and reactor temperature.
- Successful campaigns showing the capability of the EFR to handle milled lignin residues from ST1s production facilities in Finland resulting in a satisfactory syngas composition. Adding steam into the gasification process will allow us to tune the H2:CO ratio towards FT requirements.
- Fundamental research to build numeric models for the prediction of ash behavior using specialized software tools.
- A computational model based on Multi-Phase Particle-In-Cell (MP-PIC) approach was developed for both the bubbling bed and the entrained flow gasification reactor.
- A kinetics-based simulation model has been developed in the Barracuda® software and is currently being validated against the experimental results from USN and SINTEF on lignin gasification.
- A new model and method have been stablished to determine the critical amount of ash in fluidized bed systems, and thus provide the necessary tools to accomplish a more efficient and economical utilization of biomass in the future.

– Two peer reviewed publications.
– Two new gasification related projects; Biosyngas, NCS C+.
– Established a new catalyst system for tar and hydrocarbon reforming has been tested and optimized for this purpose
– Quantafuel, new industry partner via WP4.2 Edd Blekkan.

## WP4.1 Gasification - Morten Seljeskog

In 2022, pelletized hydrolysed lignin was successfully gasified in the entrained flow reactor rig, at SINTEF Energy AS. A schematic illustration of the EFR along with all its sub-systems, as well as the physical layout and sizing of the reactor and hopper, is shown in Figure 2. The inner diameter of the reactor volume is 200 mm, and has a height of 800 mm. A gas chromatograph of type Varian CP-4900 was used for measuring the syngas composition, from a sample stream extracted between cooler No1 and No2.



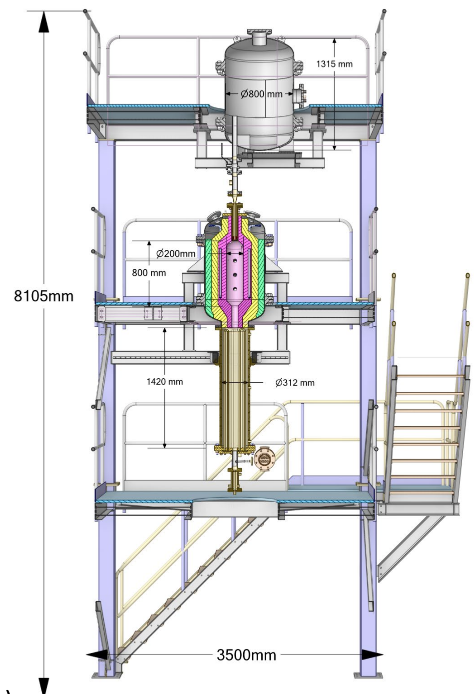




**Figure 2**: a) The ER reactor an it's subsystems b) The EFR is built into a frame for easy access to the hopper and for reactor for cleaning and maintenance.

The slag/ash/unconverted materials are collected in a container at the bottom outlet after the main cooler. All thermocouples are situated inside the refractory and do not penetrate the inner core wall. TC16 regulates the reactor core temperature according to a predefined setpoint by adjusting the electrical power, provided by a 40 kW transformer, to the heating elements. TC14 is used for overheating monitoring and TC33-35 can be installed to verify the reactor core temperature. Six electrically heated elements, type Kanthal Super 1700 918, Lu '440', are circumferentially distributed inside the refractory lining to preheat and control the reactor core gas volume to the reactor setpoint temperature before the start of an experiment and maintain this during gasification. The reactor was pre-heated at 100 °C/h overnight to the reactor setpoint temperature. The oxidant, here industry quality O2, was supplied from gas cylinders.

During the lignin gasification experiments, several input variables were kept constant, i.e., feedstock rate/power (2 kg/h or 11.5 kW), reactor pressure (8.2 bar(a)) and temperature (1150 °C), as well as the N2 stream for feedstock transport (60.2 Nl/min), with corresponding variances of, s2 = 0.52/0.01, 0.07, 120.1 and 1.72. Then a variation in the experimental series was run, where the O2 stream to the burner was varied (6.1-26.2 Nl/min) in stair steps to obtain a variation in the air-to-fuel ratio between 0.18-0.82. In Exp #6-11, extra N2 was added to the burner (3-21.4 Nl/min) either to increase or keep the burner head velocity constant, while reducing the O2 stream. Exp #12-15 were run with an increasing steam-to-biomass ratio (0.5-1.5), while reducing the O2 stream to the burner. The steam was injected through a transversal tube as shown in Figure 3a, with7x2 Ø1 mm injection ports, angled 20 ° upwards.

The burner head is shown in Figure 3b, with a central feedstock injection and its circumferential oxidant injection ports. The so-called burner ring is also indicated, which can easily be exchanged to optimize injection angle and velocity, vis-à-vis the present reactor pressure. The current burner head configuration and reactor pressure resulted in velocities between 10.7-52.5 m/s.

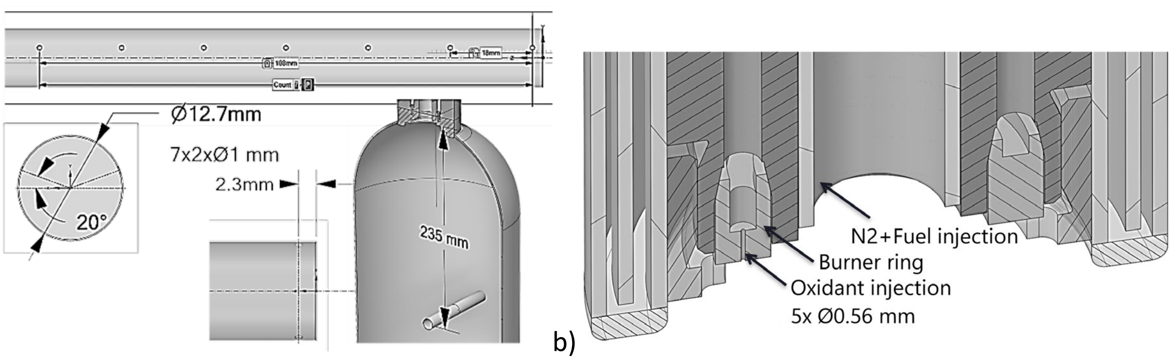
a) 


**Figure 3**: a) the water-cooled burner head with an exchangeable burner ring. b) Steam injection tube situated in the reactor core center, 7x2x Ø1mm injection holes, angled 20° upwards.

The results from the gasification of lignin are given in Table 2, by syngas composition (vol%) and production (Nl/min), with varying amounts of oxidant and steam. Corresponding values for Cold Gas Efficiency, CGE (%) and Carbon Conversion Efficiency, CCE (%) are also given.

**Table 2**: The results from the gasification of lignin, given by syngas composition and production with varying amounts of oxidant and steam, with calculated Cold Gas Efficiency, CGE (%) and Carbon Conversion Efficiency, CCE (%).

| Exp. | air-fuel ratio, λ | Residence time (s) | Steam-to-fuel ratio | CH4 (%) | CO2 (%) | H2 (%) | CO (%) | H2/CO | Syngas (Nl/min) | CGE (%) | CCE (%) |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Exp. 1 | 0.7 | 24.0 | - | 1.4 | 47.3 | 16.7 | 34.6 | 0.5 | 91 | 32% | 89% |
| Exp. 2 | 0.8 | 24.1 | - | 0.8 | 57.7 | 12.6 | 28.9 | 0.4 | 92 | 25% | 93% |
| Exp. 3 | 0.6 | 23.5 | - | 2.3 | 39.0 | 18.9 | 39.6 | 0.5 | 93 | 41% | 92% |
| Exp. 4 | 0.7 | 21.7 | - | 1.4 | 39.0 | 19.4 | 40.2 | 0.5 | 102 | 40% | 94% |
| Exp. 5 | 0.5 | 21.4 | - | 2.4 | 32.4 | 21.8 | 43.3 | 0.5 | 103 | 46% | 93% |
| Exp. 6 | 0.4 | 24.4 | - | 4.8 | 28.3 | 25.4 | 41.1 | 0.6 | 94 | 38% | 62% |
| Exp. 7 | 0.4 | 22.6 | - | 4.7 | 28.7 | 25.2 | 41.0 | 0.6 | 109 | 39% | 66% |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Exp. 8 | 0.4 | 24.1 | - | 4.5 | 26.3 | 25.9 | 43.0 | 0.6 | 95 | 40% | 66% |
| Exp. 9 | 0.2 | 22.9 | - | 8.0 | 18.2 | 29.6 | 43.7 | 0.7 | 100 | 47% | 60% |
| Exp. 10 | 0.2 | 20.9 | - | 2.9 | 9.0 | 40.7 | 47.3 | 0.9 | 109 | 60% | 68% |
| Exp. 11 | 0.3 | 24.3 | - | 2.5 | 22.2 | 30.8 | 44.5 | 0.7 | 90 | 44% | 68% |
| Exp. 12 | 0.4 | 21.2 | 0.5 | 3.9 | 26.3 | 35.0 | 34.6 | 1.0 | 104 | 64% | 93% |
| Exp. 13 | 0.4 | 19.3 | 1.0 | 2.6 | 26.3 | 41.5 | 29.5 | 1.4 | 114 | 74% | 99% |
| Exp. 14 | 0.4 | 18.5 | 1.5 | 2.7 | 28.2 | 43.9 | 25.2 | 1.7 | 118 | 79% | 101% |
| Exp. 15 | 0.2 | 18.2 | 1.5 | 3.7 | 22.5 | 48.7 | 25.0 | 1.9 | 121 | 91% | 99% |

These results have also successfully been simulated by PhD. candidate Nastaran Samani at USN. She has built a multiscale Eulerian-Lagrangian CPFD model to simulate the entrained flow reactor for lignin as biomass. The model accounts for various factors, including heat and mass transfer, pyrolysis, reactions, radiation, and interactions between the gas phase and particles. The CPFD model has been validated by the above experimental data and will be used to examine the impact of various operating parameters.

## WP4.2 Gas Conditioning - Edd Anders Blekkan (WP leader)

The equipment needed for upgrading of the syngas from the gasifier represents a major part of the investment in a BTL plant. The activities include gas conditioning (involving gas cleaning, conversion of tar and hydrocarbons and adjustment of the composition) as well as catalytic conversion of the clean syngas to desired products. The figure below shows an example of the work performed studying the conversion step: Cobalt is the chosen catalyst system for hydrocarbon production (the Fischer-Tropsch synthesis, or FTS). Biomass as the feedstock to the gasifier introduces many inorganic elements that potentially can deactivate the syngas conversion catalyst if the gas cleaning is poorly designed or malfunctions.

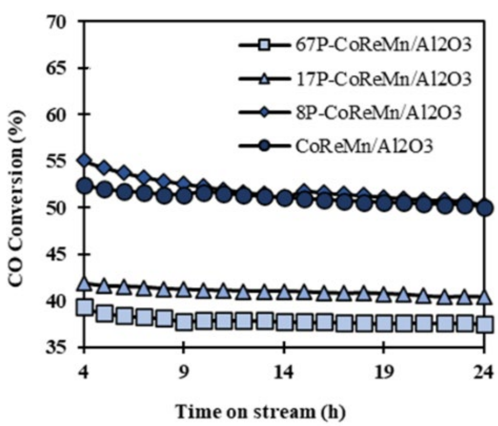



*Figure: CO conversion in the FTS over a CoMn/alumina catalyst with different loadings of phosphorus.*

The figure shows a typical experiment, where a Co-based FTS catalyst is poisoned by increasing levels of phosphorus (P) ; no P , or poisoned by 800 ppm (8P), 1700 ppm (17P) or 6700 ppm (67P) phosphorus. The results show that this catalyst tolerates small amounts of P well; 800 ppm has no influence on the activity, here shown as CO conversion at fixed space velocity. But even the lowest loading (8P) has an impact on the selectivity in an undesired manner. This is reflected as more light products and less of the desirable hydrocarbon liquids, and this effect increases with increasing P content on the catalyst.

**Publications in 2022:**

Lysne A., Madsen K.O., Antony J., Rout K.R., Blekkan E.A., 2022, Effects of Ni-Co Ratio on Deactivation and Coke Formation in Steam Reforming of Hydrocarbon Impurities from Biomass Gasification with Ni-Co/Mg(Al)O Catalysts, Chemical Engineering Transactions, 92, 37-42. DOI:10.3303/CET2292007

Ivanez, O., Groven, A.S., Rout, K.R., Blekkan, E.A., 2022. Phosphorus deactivation on Co-based catalysts for Fischer-Tropsch, submitted, Topics in Catalysis.

## WP4.3 Preparing for piloting and up-scale – Marianne Eikeland/ Klaus Jens

Ramesh Timsina defended his Ph.D. the 24.02.22. The title was Modeling and simulations of bubbling fluidized bed and entrained flow biomass gasification reactors. The objectives of Timsina's thesis was experimental and computational study of the biomass gasification processes, with focus on wood chips, wood pellets, and grass pellets at different biomass feed rates and airflow rates. The CPFD models were validated against the experimental results. The CPFD models have been widely used for optimization and parametric studies for the different types of reactors. The results from the developed CFD models are of practical importance for the commercialization of bubbling fluidized and entrained flow biomass gasification reactors. from laboratory/pilot- to full-scale. The thesis can be found at https://openarchive.usn.no/usn-xmlui/handle/11250/2976140.

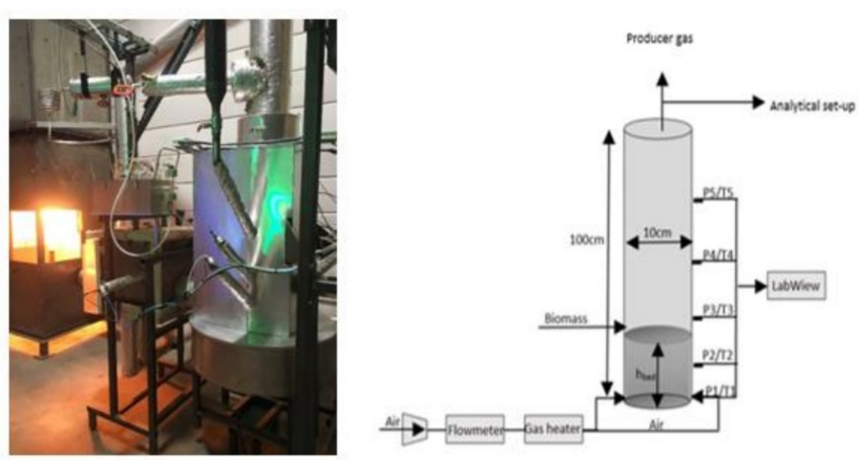



*Figure: 20 kW bubbling fluidized bed gasification (BFBG)*

The project FLASH (predicting the Flow behavior of ASH mixtures for production of transport biofuels in the circular economy) has been a successful project in cooperation between USN, SINTEF Energy, BOKU Austria and the University of Aalto, Finland. The project was financed with 10 MNOK from NFR- Energi X with the duration: 2018-2021. Nora C Furuvik has been a Ph.D. student within this project. She defended her Ph.D. Thises the 04.03.22. The title was Modelling of ash melts in gasification of biomass. The aim of this work was to assess the ash related challenges leading to bed agglomeration and de-fluidization during gasification of biomass in fluidized beds. Experimental modeling were combined in order to gain a fundamental understanding and a deeper insight into the physical and chemical mechanisms involved in the bed agglomeration processes. The agglomeration tendencies for different biomasses were studied, where the main focus was on the ash melting behaviour and the major ash forming elements Si, K and Ca. Grass, wood, straw and bark were selected to represent general biomass samples with large compositional variations, which cover a wide range of the biomass available for liquid biofuel production in Norway. The thesis can be found at https://openarchive.usn.no/usn-xmlui/handle/11250/2980114.

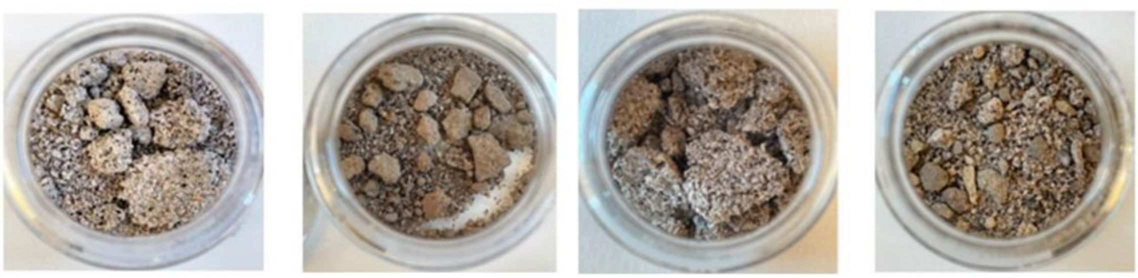


Figure: Agglomerates formed during the fluidization experiments with (a) grass, (b) wood (c) straw and (d) bark.

Ph.D. student Nastaran A. Samani (USN) is developing Computational Particle Fluid Dynamics (CPFD) models in Barracuda. Her simulations are validated based on experiments in the two gasification reactors at SINTEF and USN. Experimental optimization of the Entrained Flow- (EF) gasifiers is difficult and challenging therefore, simulation tools are becoming imperative and valuable tools for process optimization towards the desired downstream applications. One of the challenging factors to make a good CPFD model of the EF gasifier is making a model of the geometry of the feed system, which in addition to feed of biomass, includes several injection points for the O2 as illustrated in the figure. The temperature at the top of the rector becomes high (around 1400°C) because of the combustion zone and convert the biomass to volatiles and char. The char is converted to product gas at lower temperatures down in the reactor in the gasification zone. It is essential to make a good model of the inlet boundaries to obtain good and reliable results from the simulation out through the hole gasification system.

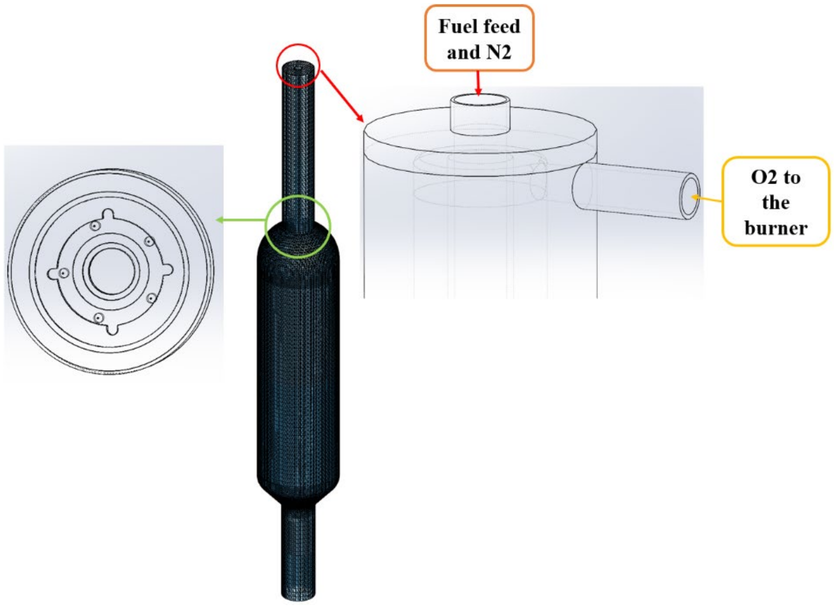



*Figure: Boundaries for the inlet of the EF reactor designed in a CPFD model*

Samani has participated at two conferences in simulation and modelling. The topic of the conference papers where simulations of the bubbling fluidised bed gasification reactor at USN.

At the 10th Vienna International Conference on Mathematical Modelling MATHMOD 2022,Vienna Austria, 27–29 July 2022 she presented the paper Evaluating the impacts of temperature on a bubbling fluidized bed biomass gasification using CPFD simulation model

At the 63rd International Conference of Scandinavian Simulation Society, SIMS 2022, Trondheim 20-21 September 2022, she presented the paper Eulerian-Lagrangian simulation of air-steam biomass gasification in a bubbling fluidized bed gasifier

The 19.12.22 Nastaran passed the Ph.D. midterm evaluation.

| ***SP5: Process design and End Use*** |
|---|
| - Identify most promising process configurations<br>- Efficient and clean end use |
| SP Leader: Bernd Wittgens |

| | |
|---|---|
| WP5.1 | Modelling Tools (Heinz Preisig, NTNU)<br>Techno-Economic Eval. / Scale of Economy (Bernd Wittgens, SINTEF Industry) |
| WP5.2 | Product quality and End Use (Terese Løvås, NTNU) |

## *Background and approaches*

Sub-project 5 is divided into two activities, namely the need for a better model-based description of processes combined with an evaluation of their economical viability. The second major part considers the testing of biobased and zero-emissions fuels for primarily internal combustion engines.

The viability of processes products will be addressed using high level modelling tools for Biorefineries with an approach that requires an integration of knowledge from various fields such as biotechnology, process technology, control and material properties to generate the predictive capabilities of the process models required for design and operations (first-generation process flowsheets used as basis for conceptual design of process instrumentation and control philosophy).
These models are than utilized to perform a techno-Economic Evaluation will be applied to the initial crude process design giving an early phase cost estimation followed by in-depth analyses of the best candidate processes. A framework for process design analysis and optimization (Task 5.1.1.) will be developed and jointly utilized for design and development of business cases for industrial implementation and thus generate insight into the framework needed for a successful commercialization of the most promising technologies.

Finally, the activities related to product Quality and End Use will aim to use state-of-the-art simulation and diagnostic tools to develop a framework for optimizing operational cost, energy efficiency and minimizing emissions from biofuel combustion. Focus will include regulated emissions such as NOx, CO, UHC and particulate emissions (soot). Fundamental combustion studies will be performed to map the overall performance of these fuels and ensure safe, clean and durable utilization of biofuels, including studies of new biofuels as well as an effects of blending into conventional fuels. Approaches will look to coupling state-of-the-art two-phase flow modelling and combustion chemistry with advanced engine and turbine measurements and optical diagnostics tools.

## WP5.1.1 Modelling Tool for Biorefineries

Heinz Preisig, Robert Pujan, Vinay Gautam, Alberto Rodriguez Fernandez

Modelling chemical and biological processes is intrinsically a multi-scale and multi-disciplinary problem that requires expert knowledge from different scientific domains. Furthermore, modelling and controlling biorefinery processes is particularly difficult due to their complexity and non-linearity, the heterogeneous and seasonally fluctuant feedstocks, and the high uncertainty in bioprocess kinetics. All of this causes uncertainties in the assessment and operation that slow down the identification of the optimum process designs for industrial realisations of most biorefineries concepts, thus leading to a slow implementation of biorefineries. Correspondingly, the absence of robust, holistic, and predictive models directly transmits into a knowledge gap in design, assessment, and implementation.

Fortunately, the rapid technological evolution over recent decades initiated a radical change in problem-solving capacities and prospects, shifting more and more towards computer-aided model design and simulation. However, the increasing interest and expectations in model implementation place high demands on the modeller, prompting a growing need for more effective and accessible model-generation tools. The concepts of topology and ontology are particularly convenient for addressing this: The concept of mapping process structures into a graphical representation of a directed graph, showing the topology of the model, has been standardised as part of NTNU's involvement in EC projects all of which are related to the digitisation of data and modelling software (CEN-CWA-17960: ModGra-a Graphical representation of physical process models https://www.cencenelec.eu/media/CEN-CENELEC/CWAs/RI/cwa17960_2022.pdf ). Moreover, NTNU's **ProMo** (Process Modeller) software suite builds on ontologies and implements topology technology. **ProMo** is highly structured, forcing the mathematical structure to be built systematically from a minimal basic variable set, the configuration sets for thermodynamics and mechanics being the main ones. Building on ontologies makes it possible to highly automate the generation of code and model-application ontologies and generate communication data pipelines. The resulting process models are intelligible by humans and machines and introduce easy-to-capture systematics and holistic views on the interiors of process systems. The model development is highly-automated, providing an easy-to-access, understandable, transparent, and rapid generation of models.

Accordingly, **NTNU's** Process Systems Engineering group works on the ontology-based, topology-utilising model design environment **ProMo**, schematically depicted in Figure 1. **ProMo** utilises the facilities of the **Horizon2020** project **MarketPlace** (info: https://www.the-marketplace-project.eu/, platform: https://staging.materials-marketplace.eu/ ) and **VIPCOAT** (info: https://ms.hereon.de/vipcoat/ , platform: https://vipcoat-oip.com/ ). Based on the user-specified process structure in topologies, the **ProMo** suite assembles the mathematical model using ontologies. It makes them available as an extension to the European Materials Modelling Council's **EMMO**, that is, the European Material Modelling Ontology (EMMC: https://emmc.info/, and https://emmc.eu/). Furthermore, **ProMo** enables the construction of process models using a graphical tool and generates simulation code. All these facilities are used to model biorefinery-relevant processes, which are assembled in a compound model library that can be utilised in the graphical editor to generate bio-process models. So far, the library covers steady-state and dynamic models for processes like a reactive flash tank, distillation, membrane filtration, adsorption, fermentation, pipes and valves, extraction, and fermentation.

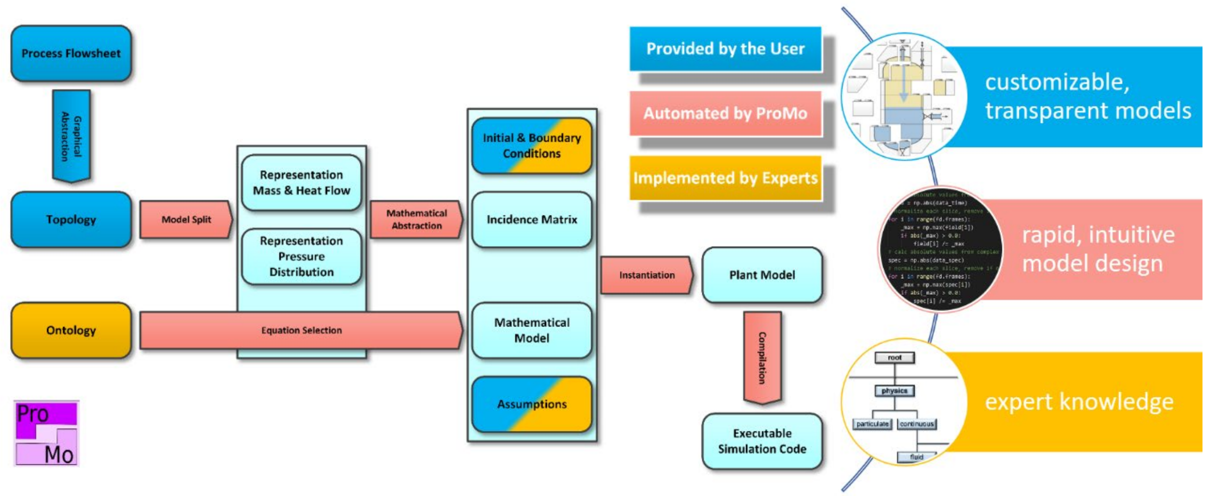



*Figure 3: The composition of the modelling suite* **ProMo**

The endeavour made much progress in the last two years, working on **ProMo's** code splicing, model initialisation, and open-source distribution via web access interfaces and the registration of **ProMo** at the two platforms **MarketPlace** and VIPCOAT using a new technology that enables the remote use of the software. In addition, NTNU is soon publishing its comprehensive library of equations in the form of a knowledge graph, making it available across the network and the knowledge-analytical tools developed in the AI community. Furthermore, NTNU promoted **Bio4Fuel** dissemination with journal papers like ***Ontology-Based Process Modelling - with Examples of Physical Topologies*** (Preisig, 2021) and ***Systematic modelling of flow and pressure distribution in a complex tank*** (Pujan & Preisig, 2022). The group also participated in conferences like **ESCAPE** and **WCCM** with papers, posters and talks like ***Ontologies in computational engineering*** (Preisig et al., 2021) and ***Systematic Modelling of Transport Processes across Interfaces*** (Pujan & Preisig, 2021), and *Systematic Modelling of Distillation Columns based on Topologies and Ontologies* (Pujan, Sengupta and Preisig). Additional to scientific publications, the **NTNU TekNat** blog post ***Power to the Modeller*** (Pujan & Preisig, 2021) (available at: [www.ntnu.no/blogger/teknat/en/2021/04/13/](www.ntnu.no/blogger/teknat/en/2021/04/13/)) proved to be a valuable approach for the public. With our paper submission ***Systematic Biorefinery Modelling with ProMo*** (Pujan & Preisig, 2022) to the World Sustainable Energy Days 2022 (**WSED**) invited for publication and oral presentation at **WSED's** Young Energy Researchers Conference in April 2022, the next year continues where 2021 left off. An update on the developments will be published in 2023 at the ESCAPE conference (submitted as Pujan. R., Into the Valley of Death; accepted for publication in 33rd European Symposium on Computer Aided Process Engineering (ESCAPE33), June 18-21, 2023, Athens, Greece.

## WP5.1.2 Techno-Economic Evaluation and Scale of Economy - Bernd Wittgens

*(other authors: Aniko Varnai (NMBU), Roman Tschentscher, Bernd Wittgens, Filippo Bi, Matteo Gilardi (SINTEF Industry) )*

Biofuel production has been researched extensively, though generally either biochemical conversion or thermochemical conversion processes are utilized. Integration of both is scarcely applied. Within Bio4Fuels an attempt was made to develop a process which maximize the conversion of lignocellulosic biomass, a biorefinery converts biomass into energy (biofuels, bio-oils) and high-value bioproducts. The combined power and fuel generation is particularly attractive for energy transition and reduction of non-biogenic $CO_2$ emissions. Biomass conversion requires a series of complex treatments. The development of reliable models is essential for scaling up and designing.

Soft-modelling approach provides a simplified description of the system without losing accuracy. During 2022 we performed modelling of a joint activity performed in WP2 and WP3, an enzymatic saccharification process (See Figure 1) and the subsequent pyrolysis of the solid residues. The narrative for the integration was the potential utilization of the sugar fractions towards high value chemicals through fermentation and the production of as well pyrolysis oils and biochar form the solid residues.

A soft model for steam explosion (after impregnation with carbocation scavengers) and enzymatic saccharification (boosted with $H_2O_2$-driven oxidative depolymerization by LPMO enzymes) has been evaluated. These are two key pre-treatments for the extraction of carbohydrate fraction prior to pyrolysis of lignin-rich solids to produce the bio-oil. The proposed saccharification model (Gilardi, 2023)[1]accurately predicts experimental data in the range of interest for steam explosion temperature and enzyme concentrations investigated.

For the saccharification a direct scale-up and the process configuration of the upstream processes in a biorefinery described by (Hansen et al. 2022)[2], via direct translation of the reported laboratory-scale biomass treatments was performed. The selected process layout (Figure 1) is based on the experimental setup by Hansen et al. with the following modifications: (1) after the steam explosion, the pH of the biomass slurry was set to 5.0 (pH optimum of the cellulases in the subsequent saccharification step) in a single step using NaOH, instead of using an acetic acid/acetate buffer solution and then a caustic solution, for scalability. (2) A filtration stage was added after the saccharification step to separate the lignin-rich saccharification residue (solids) from the sugar solution (liquid/aqueous phase). This step is expected to reduce the residual moisture content of the lignin-rich residue and thus, lead to energy savings in the drying step before the pyrolysis unit.

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[1] M. Gilardi, F. Bisotti, O. T. Berglihn, R. Tschentscher, V. G.H. Eijsink, A. Várnai, B. Wittgens; Soft modelling of spruce conversion into bio-oil through pyrolysis – Note I: steam explosion and LPMO-activated enzymatic saccharification; PROCEEDINGS OF THE 33rd European Symposium on Computer Aided Process Engineering (ESCAPE33), June 18-21, 2023, Athens, Greece

[2] L.D. Hansen et al., 2022, 2-Naphthol impregnation prior to steam explosion promotes LPMO-assisted enzymatic saccharification of spruce and yields high-purity lignin. ACS Sustainable Chemistry & Engineering; 10(16), 5233-5242

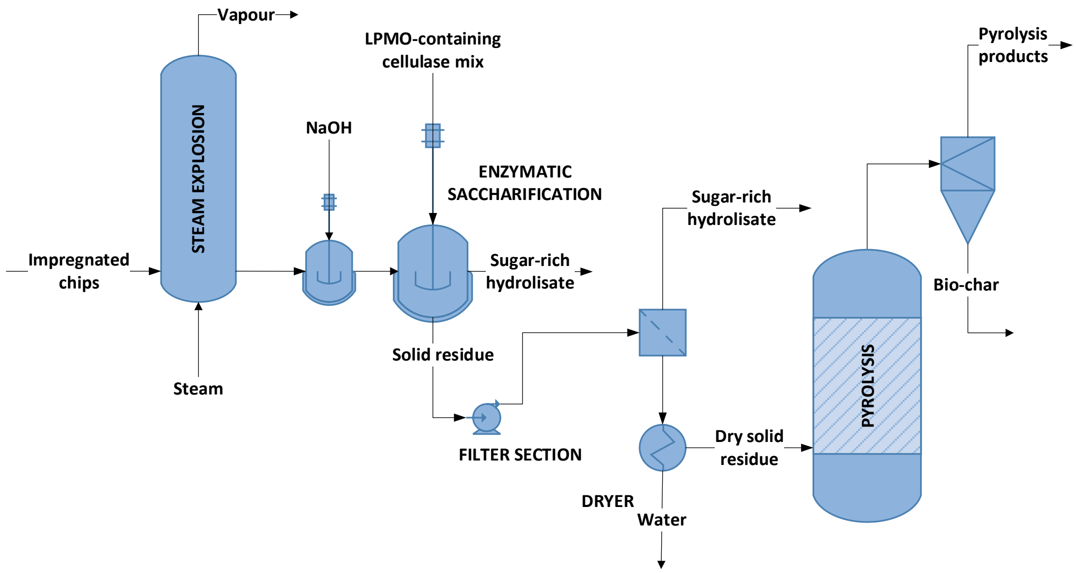



**Figure 4 - Simplified layout of the investigated upstream processes of a softwood-based biorefinery. The picture does not include the impregnation step prior to the steam explosion.**

The experimental results for the biomass pre-treatment model enable the scale-up of the impregnation–steam explosion–enzymatic saccharification process from laboratory to pilot scale while leading to the identification of the main parameters determining the selective and nearly complete removal of the polysaccharide fraction. At the projected scale, the steam explosion was the most determining step of the studied process setup since it had a direct influence on the subsequent enzymatic saccharification step. Correct tuning of the steam explosion operating conditions led to an optimal process yield. The hemicellulose and cellulose fractions were almost depleted after steam explosion and enzymatic saccharification. The lignin fraction did not seem to undergo major chemical/physical transformation due to the impregnation pre-treatment. This emerges both from the experimental data and the model. Lignin remains in the insoluble fraction in the investigated process since its extraction and valorization require stronger operative conditions as in pyrolysis.

Lignin and residual cellulose can be subjected to pyrolysis, a key biorefinery step for improved valorization of biomass. During biomass pyrolysis thousands of compounds are formed, thus, a simplified approach must be adopted for the sake of modelling. Lumped kinetic models address a simplified description of the system by catching relevant features of the product mixture. The model provides a quantitative characterization of the main product classes (aldehydes, carboxylic acids, phenols, furans, etc.) and can be used as a numerical tool for roughly scaling up pyrolysis reactors in a softwood-based biorefinery.

A pyrolysis model where two previously validated kinetics describing pyrolysis of lignocellulosic biomass published by Ranzi[3] for the cellulose and hemicellulose part, and Dussan[4] for the lignin fraction to characterize the thermal conversion of lignin-rich biomass to biofuels are merged to get a more effective description of the product distribution. The latter, the lignin-specific part of the model, is composed of

[3] E. Ranzi et al., 2014, Kinetic modeling of the thermal degradation and combustion of biomass, Chemical Engineering Science, 110, 2-12

[4] K. Dussan et al., 2019, A model of the chemical decomposition and pyrolysis kinetics of lignin, Proceedings of the Combustion Institute, 37, 2697-2704

four pseudo-lignin building blocks (LIG-1 to LIG-4) as in the model by Dussan (Dussan et al. 2008) while the stoichiometry of lignin pyrolysis reactions was modified. Overall, our lumped kinetics model contained 16 reactions and 49 species describing lignin pyrolysis. The kinetics model has been implemented in MATLAB 2022a code. The pyrolysis reactions occur in a fluidized bed reactor, where solid particles are circulated by the generated gas, and the gas itself guarantees continuous mixing inside the reactor. Thus, we modelled the fluidized bed as an isothermal plug flow reactor (PFR), with the following assumptions to simplify the calculations: the generated gas drags and entrains the small solid particles in a plug flow, while the gas and solid phases are vigorously mixed in the system, and this leads to almost isothermal conditions in the reactor volume. These simplifications provided us with a general simplified model that could be incorporated into a COCO simulation flowsheet, instead of using a descriptive and compute-intensive computational fluid dynamics (CFD) model. Furthermore, this work aims at the preliminary validation of the lumped kinetic model using experimental data from (Hansen et al. 2022).

The lumped model shows a qualitatively good agreement over a limited number of experimental data applied to scale up a spruce-based biorefinery combining biochemical and thermochemical conversion routes as in Hansen (Hansen et al., 2022). Although lumped kinetics itself, which simplifies the thermo- and bio-chemical processes into a comprehensive model, presents some limitations to the accuracy of the model, it allows flowsheet implementation and thereby easier and more efficient workflow during scale-up. Sensitivity analysis of the pyrolysis process allowed us to identify the optimal temperature window for operating a large-scale pyrolysis reactor, and, remarkably, it provided a rough estimate of the residual solid (biochar), bio-oil, and light gas fractions, as well as of the product distribution in the bio-oil.

The models generated are data-driven, which means their kinetics and yields are specific for the given case, though based on the developed methodology it is possible to extend the models provided new data are made available. The developed model for the entire process will be utilized to perform a scale-up of the process and a technical economic evaluation. The evaluation will identify the economic bottlenecks and might give rise to a redesign of the process.

## WP5.3 Product quality and End Use - Terese Løvås

The **ComKin group at NTNU** investigates liquid biofuels using experimental and numerical techniques. The activities in 2022 were focused on the valorization of low-quality biomass, such as the organic fraction of municipal solid waste and sewage sludge, through **hydrothermal liquefaction** (HTL) and gasification.

In collaboration with Aalborg University, Denmark, the emission formation of HTL fuel and reference Diesel blends were investigated experimentally. This analysis used two different HTL fuel qualities: directly distilled after hydrothermal liquefaction, here called bio-crude (BC) and distilled after additional hydrotreating, here called HT. Both distillation result in 10 different fractions ranging from gasoline-, over aviation- and diesel-type fuel qualities. Different distillation fractions and reference Diesel are blended and optimized to fulfill the EU norm EN590 for automotive Diesel fuels concerning, among others, water and sulfur content. Three blends are selected for further analysis:  5% (HTDM-5) and 10% (HTDM-10) of upgraded HT fuel and 10% (BCDM-10) of the bio-crude distillation (BC). ComKin's optical accessible compression-ignited chamber (OACIC) was employed to compare the **emission formation** of the blends **experimentally** to pure reference Diesel (RD). Figure 3 shows the results for carbon mono - and dioxide (CO, CO2) and nitrogen oxides, here NO + NO2. The HTL fuel blends show no significant change in CO and

CO2, indicating that the fuel's burnout and fuel efficiency levels can be maintained by replacing some parts of the fossil RD with bio-originated components. Both the bio-crude and hydrothermally treated distillates contain fuel-bonded nitrogen; hence, their presence in a fuel blend poses the potential to increase NOx emission via the fuel-NOx route. The results show, however, that these small amounts of 5 – 10 % in the fuel blend do not increase NOx emissions notably.

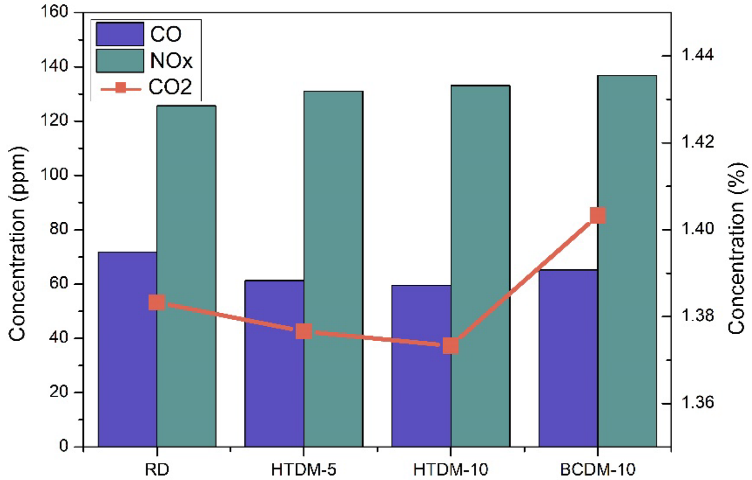



**Figure 5: Emission measurements of reference Diesel (RD) and the HTL/RD fuel blends.**

For further analysis of these results and HTL fuels in numerical models, **surrogate formulations** for the different HT distillates have been developed. Surrogate formulations allow the representation of key characteristics of fuel samples by a fixed set of chemical components. These can be either used for experiments or to mimic the fuel sample in simulations. The developed method combines typical surrogate species for gasoline, aviation, and diesel applications and alcohols, ethers, and nitrogen-containing species to mimic the impact of bio-derived components. For the selection of surrogate species, the group contribution method is employed. Following this principle, each surrogate species represents a functional group, e.g., ethanol includes the alcohol group -OH, Dimethyl ether (DME) the ether group C-O-C, n-decane an alkane group with ten carbon atoms, and toluene and naphthalene aromatic groups. As a result, various chemical species can be represented by a much smaller set of surrogate species. All selected species are listed in Table 1.

**Table 1: Selected surrogate species and their typical application.**

| | | Typical application | | | |
|---|---|---|---|---|---|
| **Functional group** | **Surrogate species** | Gasoline fuel | Aviation fuel | Diesel fuel | Bio-component |
| Alkane | n-decane | | X | X | |
| | n-heptane | X | X | X | |
| | iso-octane | X | X | | |
| Aromatics | toluene | X | X | X | |
| | alpha-methyl-naphthalene | | | X | |

| | | | | | |
|---|---|---|---|---|---|
| Cyclo-alkanes | cyclo-hexane | | X | | |
| Ether | Ethyl tertiary-butyl ether (ETBE) | | | | X |
| | Dimethyl ether (DME) | | | | X |
| Alcohol | Ethanol | X | | | X |
| Nitrogen components | Pyridine | | | | X |

Surrogates for all the distillation fractions of the upgraded/hydrotreated (HT) HTL fuel used in the engine test have been compiled using a linear least-square fit optimization. Targets for the optimization are the ultimate component analysis of the distillates (C:H:O:N-ratio), the amount of aromatic, alcohol, and cyclic components, and the liquid density. Concerning engine simulations, this allows representing global combustion parameters and fuel properties (**lower heating value**) and combined with a detailed chemistry model **emission prediction** of CO2, CO, unburned hydrocarbons, sooting tendency (aromatic content), and thermal and prompt NOx, as well as fuel-NO (nitrogen components). Figure 4 shows surrogate composition exemplary for gasoline fuel (distillate fraction 2, light fraction), aviation fuel (distillate fraction 3, medium fraction), and Diesel fuel (distillate fraction 7, heavy fraction) and Figure 5 the comparison of alcohol and fuel-nitrogen content of the surrogate formulation and the fuel samples.

Together with LOGE AB, a reaction mechanism including all surrogate species above has been compiled. Based on this reaction mechanism, the **emission potential of HTL fuels** (derived from MSW, sewage sludge, and others) and different applications (automotive, aviation, light- and heavy-duty) will be estimated compared to fossil fuels.

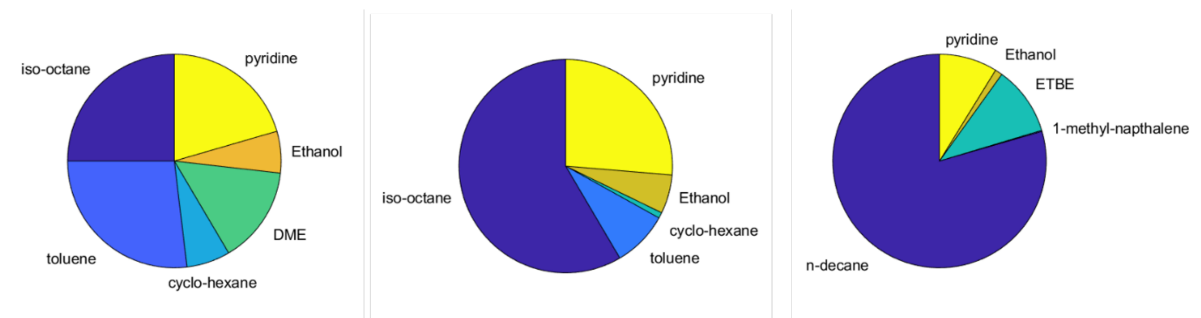



**Figure 6: Exemplary surrogate composition from left to right: gasoline, aviation fuel, diesel fuel.**

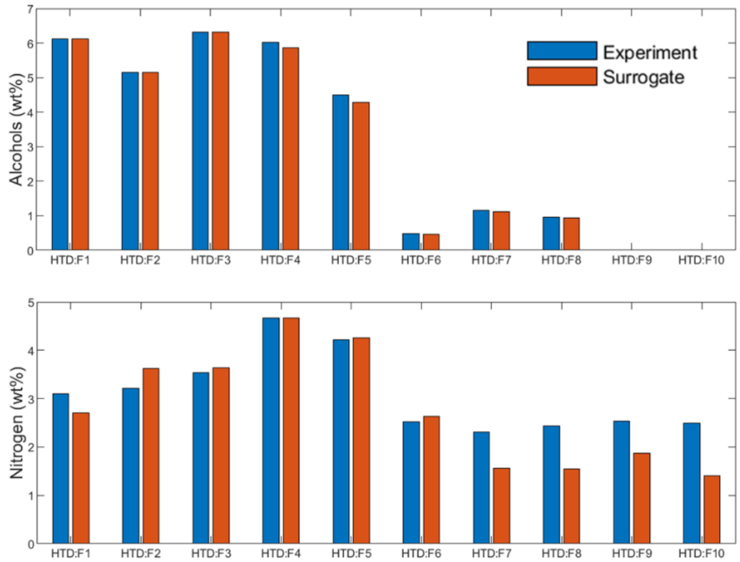
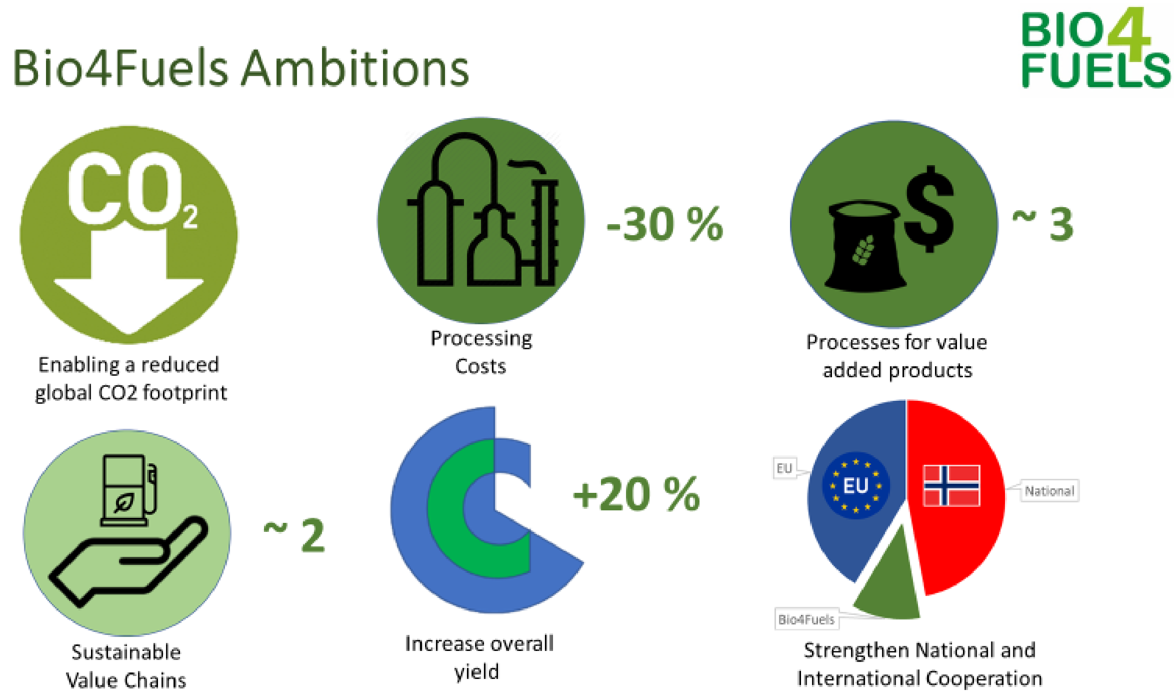



**Figure 7: Comparison of the surrogate formulation and the fuel sample (experiment). Top: alcohol content, bottom: nitrogen content.**

## Bio4Fuels' Key Performance Indicators




## International Cooperation

Bio4Fuels has from the very start of the operation of the Centre had a significant level of international cooperation at all levels. This presentation presents and overview of the wide range of International engagement though out the Centres.

### International Agencies and Policy Forums

| Internationale Arena | Activities | |
|---|---|---|
| IPCC - Intergovernmental Panel on Climate Change. | Active in contributing to the the IPCC (NTNU) | |
| IEA Bioenergy | Representation in a number of Tasks 32, 34, 39 and 45. | |

| | | |
|---|---|---|
| ETIP Bioenergy – European Technology and Innovation Platform | Reprsenting Norway and coordinating input from industry and research partners in Norway | |
| European Bioenergy cluster | Take part in the dialogue with the EU commission and organise dedicated workships. | |
| Circular Bio-based Europe partnership program | Participation as industry and research member, contributing to the strategic research agenda | |

## INTERNATIONAL STAKEHOLDERS

With respect to the consortium of partners, the Centre has the strong involvement of a range of leading Nordic and European technology providers, given in Table below. This Nordic/European network is expanded through the involvement of associated partners, from the USA. These partners are active in the research activities and had a significant role in the Bio4fuels kick-off, providing an international perspective with respect to the state of the art. These partners will in the future operation of the Centre, will also be active as hosts for short mobility tours of students and researchers from the centre to obtain experience in specific areas in an industry context.

| International Stakeholders | Country | Main interest |
|---|---|---|
| Biomass Technology Group | NL | Biomass to liquid (btl) pyrolysis |
| Johnson Matthey | UK | Chemical and catalytic processing of bio-feedstocks |
| Novozymes | DK | Enzymes for forest based biorefineries |
| Pervatech | NL | Membrane and separation systems for organic substrates |
| Steeper ENERGY | DK | Hydrothermal liquefaction |
| Lund Combustion Engineering ab | SE | Consultancy and software on combustion in motors |
| Preem | SE | Biofuels production and distribution in Sweden/Norway |
| Neste | FI | Upgrading of Biooil |

*Bio4Fuels' International Stakeholders*

## International Advisory Group

As an important part of the governance of the Bio4Fuels Centre, an International Advisory group has been established with the role of providing an international perspective and evaluation of the scientific activities of the Centre. As outlined under the structure and organisation of the Centre, the members of the Advisory Group have been selected to represent perspectives from Nordic, European and USA, in addition to having deep scientific insight to some of the main pillars of the Centre.

## Networks

Combined in the Centre, most of the research partners have an extensive network of international contacts and collaboration. These include coordinating input to Mission Innovation, representation in EERA, involvement in mobilising input to the revision of the important SET plan for which the Bio4Fuels centre has been proposed as one of the Flagship projects in SET-Plan Action 8 (Renewable fuels and bioenergy) and participating and coordinating national input to the European Technology and Innovation Platform within Bioenergy (ETIP).

For Bio4Fuels, specific links are established with research groups and activities, as listed in the table below. at PNNL, Sandia and RTI in the USA. All partners were involved in the official kick-off of the Bio4Fuels centre and opportunities for collaboration within various international programs are being considered. Within the research topic of final end use of biofuels, Bio4Fuels partners are invited to receive information on the DOE funded project "Co-optima", through participation in the stakeholder Webinars.

## EU Research Projects

Many of the research partners involved in the Centre have established a significant portfolio of European projects, both from FP7, H2020 and now within the new Horizon Europe. As of 2022, Bio4Fuels research partners were involved in at least 21 active EU projects, one of which is the Green Deal project PyroCO2. The projects cover different stages of the Bio4Fuels value chain in addition to different ranges of TRL scale, with several projects focussing on pilot scale demonstration of key technologies. The engagement of the Bio4Fuels research partners in so many EU projects is an indication of the level of scientific expertise of the work being carried out in the Centre.

**Selected examples of current running associated EU projects within Horizon 2020 and Horizon Europe**

# Recruitments and Education

**PhD student Eirik Ogner Jåstad (WP1.3), NMBU**

This PhD project was a part of the work package Energy, Fuels and Economics, WP1.3. The aim of my PhD-project is to use economic models to find implication of forest biofuel production in the Nordic countries. In 2018, had I focus on two studies, one that focusing on implications in the traditional forest sector if large amount of biofuel is produced within the Nordic countries. The second study investigates which level of subsidy needed for making biofuel production competitive with the fossil fuel.

The results show that the fossil fuel price must increase with 2-3x from today's level or the producers have to get an equivalent level of subsidy for making biofuel production competitive at today's raw material costs. Large investments of biofuel will give some structural changes in the traditional forest sector, the main findings are that harvest and utilizing of harvest residues will increase, similar will the net import to the Nordic countries increase simultaneously as the pulp and paper industry will reduce their production.

**Supervisors:** Per Kristian Rørstad and Torjus Folsland Bolkesjø, NMBU.

Eirik Ogner Jåstad defended his PhD degree on 1 December 2020.

**PhD student Junhui Hu (WP1.3), NMBU**

This PhD project investigates the availability of forest-based biomass for biofuel production in both short term and long-term perspectives. The geographical border is expected to start with Norway and expand to Nordic countries and even Northern Europe.

The current annual harvest of forest is much less than the annual growth in Norway, and the government has set the target for total advanced biofuels used in road to 4% from 1st Jan 2020. This implies the huge potential and necessity for exploring the forest resources for producing the advanced biofuels from forest-based biomass, and this will play a vital role in phasing fossil fuel out in transportation sector and create a low carbon environment. However, the production of forest-based biofuel is far than mature due to various reason like technology immaturity, lacking policy support and raw materials competition.

The raw materials for forest-based biofuels are the biomass from harvest residues and by-products from sawmill, like chips, bark, sawdust, and shavings (as shown in the figure below). However, these materials will not only be used for biofuels, they are also in demand for other industries, like panels, pulp, and paper, as well as electricity and heat. Therefore, the availability and cost of forest-based biomass for biofuels becomes an important topic for discussing the cost and potential of biofuel production in the future.

**Supervisor**: Per Kristian Rørstad, NMBU

Junhui Hu (June) started as a PhD student in Bio4Fuels in October 2020.

**PhD student Martina Cazzolaro (WP2.4), NTNU**

This project is a part of the work package Catalysis for biomass conversion to chemicals, WP2.4 and aims to develop a stable copper-based catalyst for selective hydrogenation of hydroxyacetone to 1,2-propanediol, a major commodity chemical. Hydroxyacetone is a by-product of various biomass-based processes: biomass pyrolysis, sugar hydrogenolysis, glycerol dehydration. The main challenge of the project is the catalyst stability towards deactivation. In order to achieve this goal, carbon supports are tested. Platelet carbon nanofibers (PCNF) were prepared via carbon vapor deposition of CO and $H_2$ at 600°C over iron powdered nanoparticles. Various catalysts were prepared using PCNF and varying Cu precursors (nitrate, acetate, and basic carbonate) and impregnation solvents (water, ethanol, isopropanol). Characterization of the catalysts and catalyst activity tests will follow.

Moreover, surface treatment of PCNF will be explored, as surface oxidation, foreign-ion doping or confinement effect can be used to tune the surface properties of the carbon nanofibers. She also spent 3 weeks in Haldor Topsoe in June 2018 to learn their experiences and I enjoyed a lot the stay there.
**Supervisors**: Jia Yang and De Chen, NTNU.
Martina Cazzolaro will defend her PhD in 2023.

**PhD Student Line Degn Hansen (WP3.2), NMBU**

This PhD project is a part of the work package *Enzymatic saccharification* (WP3.2) and will focus on enzymatic saccharification of Norway spruce, with special attention on process optimization and integration. Biochemical biomass-to-liquid processes and the currently available commercial enzyme cocktails have been developed for grasses and hardwood materials and are not optimized for Norwegian biomass. In this project, we are going to identify enzyme components, such as redox and hemicellulolytic accessory enzymes, that are critical for efficient saccharification of softwood. Moreover, the recent discovery of the novel catalytic mechanism of lytic polysaccharide monooxygenases (LPMOs) creates an opportunity to considerably improve saccharification yields by optimizing process parameters including different feed strategies of $H_2O_2$, the enzyme's co-substrate. The obtained knowledge will be applied to allow better integration of the saccharification and fermentation steps. In addition, the effect of pretreatment type on saccharification and fermentation, regarding the composition of enzyme cocktail and process conditions, will also be assessed to achieve higher overall yields while minimizing process costs.
**Supervisor**: Aniko Varnai, NMBU
Line Degn Hansen defended her PhD in June 2022.

**PhD student Camilla Fløien Angeltveit (WP3.2), NMBU**

This PhD project is a part of the work package Enzymatic saccharification (WP3.2) and will focus on lytic polysaccharide monooxygenases (LPMOs) role during enzymatic saccharification processes. The use of LPMOs together with the classical hydrolytic enzymes has been shown to greatly increase the depolymerization of lignocellulosic biomass. The ratio between hydrolases and accessory enzymes like LPMOs needs to be tailored for the specific substrates. Most commercial enzyme cocktails are tailored for agricultural waste biomass. In my PhD I will be focusing on creating better and more cost-efficient enzyme cocktails for depolymerization of softwood materials like Norway spruce.

Hydrogen peroxide appears to be the key to the successful depolymerization of polysaccharides by LPMOs. At the same time, the addition or production of hydrogen peroxide must be strictly controlled to hinder inactivation of the LPMOs. I will also investigate the role of LPMOs in simultaneous saccharification and fermentation processes (SSF) and determine the effect of hydrogen peroxide feed compared to in situ generated to improve the overall saccharification efficiency and yield.

**Supervisor**: Svein Jarle Horn, NMBU.

Camilla Fløien Angeltveit started as a PhD student in Bio4Fuels in August 2020.

**PhD student Simona Dzurendova (WP3.3), NMBU**

The PhD project is part of the work package WP3.3, Fermentation, where one of the objectives is to develop utilization of lignocellulose hydrolysates as a source of carbon for production of microbial lipids by oleaginous fungi fermentation. Oleaginous fungi are able to produce lipids with fatty acids profile similar to vegetable or fish oils. Oleaginous fungi are able to perform concomitant production of lipids and other valuable components as for example chitin/chitosan and polyphosphate. Lignocellulose hydrolysates are liquid materials rich in saccharides, but as shown by our studies, it also contains possible inhibitors of fungal growth. Therefore, there is a need to perform high-throughput screening of different fungal strains and growth conditions in order to find the most suitable fungal producer and optimise composition of lignocellulose-based media for the scale up of the process. Currently we are using synthetic growth media for the bioprocess development that allows us to have full control over the effect of certain micro- and macronutrients on the production of lipids and other valuable co-products, such as chitin/chitosan and polyphosphates. For the process development, we are using a micro-cultivation system combined with vibrational spectroscopy.

**Supervisor**: Volha Shapaval, NMBU.

Simona Dzurendova defended her PhD on 23 April 2021.

**PhD student Cristian Bolaño Losada (WP3.3), NMBU**
**Developing consolidated bioprocessing of lignocellulose materials**

IEA-roadmap reports that 20-30% of global energy demand could be supplied from the conversion of biomass. Lignocellulose biomass, due to its high abundancy and relatively low cost, has been positioned as one of the most important type of biomass for biofuels and biorefineries. Despite of almost a decade of research on the production of biofuels from lignocellulose biomass this process still suffers from the lower economical sustainability in comparison to the fossil-based processes.
In recent years it has been shown that lignocellulose materials can potentially be used to produce single cell oils (SCOs) by microbial fermentation and attention has been taken in microbial consortia or co-cultures with the aim to convert lignocellulose material to sugars directly in one step.
The main aim of the thesis is to develop a consolidated bioprocessing of lignocellulose material by utilizing microbial co-culturing and/or simultaneous saccharification and fermentation.
*The main sub-tasks:*

- Develop submerged fermentation of hydrolysed lignocellulose materials by oleaginous. filamentous Mucoromycota fungi as a reference bioprocessing of lignocellulose to SCOs.
- Investigate a possibility to co-culture cellulolytic fungi and oleaginous Mucoromycota fungi for SCOs production.
- Investigate to what extend simultaneous saccharification and fermentation process can be performed with a reduced amount of enzymes.
- To investigate a possibility to co-culture oleaginous fungi and algae by using hydrolysed lignocellulose materials.
- To utilize and develop application of vibrational spectroscopy for monitoring of CBP.

**Supervisor**: Volha Shapaval, NMBU.
Cristian Losada started as a PhD student in Bio4Fuels in August 2020.

**PhD student Oscar Luis Ivanez Encinas (WP4.2), NTNU**
**Conversion of synthesis gas from fish waste gasification over cobalt catalysts**

The increasing development of the global industry demands further energy production. The main source of energy are the fossil fuels and their use has been increasing every year. In 2016, more than 80 % of primary energy in the world was provided by fossil fuels. The new policies and future scenarios, where the increased prices of the fossil fuels and the demand of cleaner fuels, make necessary alternatives of fuel production.
Within these alternatives, the interest in the Fischer Tropsch Synthesis (FTS) increased in recent years. The FTS converts synthesis gas to hydrocarbons. The selectivity of the FTS can be optimized in order to obtain different products. Among these products, light olefins represent added value compared to fuels, which always will be the main product.
The syngas can be produced from different sources such as natural gas, coal or biomass. One interesting feedstock for the syngas is the biomass. This renewable energy source is abundant and opens the possibility to improve the total yield of different industries by using waste as a feedstock for the FTS. The total aquaculture production in Norway in 2018 was 1.354.941 tons, with 68% of the amount being editable. This represents an opportunity to valorize the fish waste in order to reduce the economic loses and improve the efficiency of the industries.

In this context, cobalt-based catalysts are going to be studied in the FTS with emphasis on olefin selectivity from biomass, BTL. The catalysts are going to be prepared by different synthesis methods, characterized by several standard and advance techniques, and tested in the FTS. The reaction condition choose for the project will favor the light olefin production. Due to the selection of fish waste as feedstock for the syngas, the project will be focused on the effect of several components present on this syngas source, which could affect the performance of the catalytic activity and selectivity. In addition, in order to improve the catalytic activity and selectivity, different metal oxides and noble metals will be studied as catalysts promoters.
**Supervisor**: Edd Blekkan, NTNU.
Oscar Encinas started as a PhD student in Bio4Fuels in August 2020.

**PhD Student Ramesh Timsina (WP4.3), USN**

This PhD project is a part of the work package Preparing for Piloting and Up-scaling, WP4.3. The main objective is to establish computational fluid dynamics and process simulation models as basis for the preparation of the pilot plant for biofuel production. The models will include pre-treatment of feedstock, thermal treatment, as well as separation and extraction steps. The thermal conversion technologies gasification, pyrolysis and hydrothermal liquefaction will be studied and evaluated. Experiences from studies in the other work packages will be used to make the framework for the simulation models, and a process flow sheet will be generated.

An important part of the project is to find overall process with minimal waste and high-energy yield for such process plants. Based on existing data from experimental work and simulations, reliable process models will be developed. These models will be used to analyse the results of parameter variations to optimize the process design. The process flowsheets will then be the basis for conceptual design operations. A theoretically optimal solution will be chosen for a pilot plant design.
**Supervisor**: Klaus Jens, USN.
Ramesh Timsina defended his PhD in February 2022.

**PhD student Ask Lysne (WP4.2), NTNU**
**Catalytic Steam Reforming of Hydrocarbons from Biomass Gasification**

The increasing awareness of the effects of greenhouse gas emissions on the global environment has made the supply of renewable energy sources evident as a major challenge for future sustainable development. The International Energy Agency (IEA) has estimated a 42-50 % increase in the global energy demand by 2035 compared to the 2009 consumption. The transportation sector accounts for around 25 % of the global CO2 emission, where 90 % utilizes petroleum-based fuels. The substitution of currently applied fossil fuels by liquid fuels produced from renewable resources can hereby provide an efficient reduction of the global net CO2 emission. The annual growth of terrestrial plants stores more than 3 times the global energy demand, and biomass is in practice the only viable feedstock regarding production of renewable carbon-based liquid fuels. The successful integration of biomass gasification and Fischer-Tropsch synthesis in biomass-to-liquid fuel (BTL) technology is however limited by the intermediate gas conditioning of the synthesis gas (syngas) requiring the removal of inorganic, organic and particulate contaminants and adjustment of the

composition in order to adapt to the subsequent catalytic fuel synthesis process step. The elimination of tars is one of the most cumbersome challenges to the commercialization of such processes. The PhD project is addressing catalytic steam reforming, converting tars and lighter hydrocarbons to syngas as well as H2/CO/CO2 ratio adjustment by the water-gas shift reaction as part of this key gas conditioning step. The performance of a series of mixed oxide Ni-Co/Mg(Al)O catalysts prepared from hydrotalcite precursors are currently being investigated.
**Supervisor**: Edd A. Blekkan, NTNU. Co-supervisor: Kumar R. Rout.
Ask Lysne started as a PhD student in Bio4Fuels in August 2019.

**PhD student Zhongye Xue (WP5.3), NTNU**

Project title: *Experimental and Numerical Study of Low-Carbon Biofuels in Internal Combustion Engines*.
This project is focuses on a detailed experimental and numerical investigation of 2nd generation type biofuels in compression ignition engines. Various combustion parameters will be investigated with a focus on emissions of $NO_x$ and soot. Fundamental experimental research on combustion of the biofuels will be carried out in collaboration with the current research team, employing a well-equipped engine laboratory and specially designed combustion rig with optical access for optical measurements. This enables detailed studies of the ignition and flame structure in the combustion chamber as well as particle formation. Matching the experimental data with results from detailed kinetic simulations using a stochastic reactor model will be an important part of the PhD project.
**Supervisor**: Terese Løvås, NTNU.
Zhongye Xue PhD started as a PhD student in Bio4Fuels in September 2020.

**PhD student Nastaran Ahmadpour Samani (WP4.3), USN**

Project title: *Computational particle fluid dynamics (CPFD) and process simulations modeling of biomass gasification reactors*.

The primary goal of this project is to establish computational particle fluid dynamics and process simulation models to generate insight into the framework needed for process design and pilot plant planning. The models will be used as a basis for the successful piloting of gasification technology to produce biofuels or valuable chemicals from biomass.

The gasification reactor systems bubbling fluidized bed reactor and entrained flow reactor will be investigated. Different gasification reactor technologies and designs require different necessities. The PhD work will establish the differences for optimal plant operating parameters. CPFD models will be developed both for the bubbling fluidized bed gasifier at USN and the entrained gasifier at SINTEF Energy. The models will be validated by experimental results. The models will be used to analyze the results of parameter variations to optimize the process design.

**Supervisor**: Marianne Sørflaten, USN
Nastaran Ahmadpour Samani started as a PhD student in Bio4Fuels in May 2021.

**PhD student Zhihui Li (WP2.2), NTNU**

Project title: *Co-pyrolysis of biomass and plastic to produce high quality liquid.*

Bio-oil is considered as a potential alternative to traditional energy petroleum, however, bio-oil directly converted from biomass has drawbacks of low heating value, corrosion problems during storage and transfer and instability, because of the high oxygen content (20-60 wt%) in the biomass. Hydrodeoxygenation (HDO) process is one of the most widely used, while upgrading bio-oil by HDO method has a high requirement of plant, and the catalysts for HDO are easily to be deactivated due to the coke formation. In this work, plastic can be considered as a hydrogen donor to achieve in-situ HDO process, by mixing plastic and biomass as the feedstock. At the same time, clay, a very cheap material was applied as an in-situ catalyst during pyrolysis. Modifications were carried out on bentonite and aluminum pillared bentonite clay showing the potential of an alternative to commercial fluid catalytic cracking (FCC) catalyst. Clay catalyzed bio-oil showed low oxygen content (< 10wt%) and high liquid yield (> 60wt%).
**Supervisor**: De Chen, NTNU
Zhihui Li started as a PhD student in Bio4Fuels in December 2021.

**PhD student Prajin Joseph (WP3.1), NTNU/RISE-Pfi**

Project title: *Organosolv pretreatment of Norway Spruce: Ethanol pretreatment for Biorefinery applications*.

The main objective of the PhD work was to develop and demonstrate in lab-scale an efficient organosolv based fractionation process of Norway spruce to increase the accessibility of cellulose to enzymes and produce high value biopolymers. High purity and low molecular mass organosolv lignin are desirable properties for high value chemicals and products based on organosolv lignin. The results were included in four journal publications and 2 posters presented at international conferences.

Supervisors: Mihaela Tanase Opedal, RISE-Pfi and Størker Moe, NTNU
Prajin Joseph started as a PhD student in 2018 and defended his thesis on 16 December 2022.

## COURSES GIVEN BY BIO4FUELS RESEARCHERS

The researchers connected to the Bio4Fuels Centre are involved in various courses at NTNU, NMBU and USN. In this way, our research themes and results are present and made relevant for new students in Norway.

### Courses at NTNU

Energy and Process Engineering, Specialization Project, 15 credits (ECTS)
Engineering Thermodynamics 1 7,5 credits (ECTS)
Industrial Ecology, Project, 15 credits (ECTS)
Climate Change Mitigation, 7,5 credits (ECTS)
Nanotechnology, Specialization Project, 15 credits (ECTS)
Catalysis, Specialization Course, 7,5 credits (ECTS)
Chemical Engineering, Specialization Project, 7,5 credits (ECTS)
Chemical Engineering, Specialization Project, 15 credits (ECTS)
Industrial Chemistry and Refining, 7,5 credits (ECTS)
Reaction Kinetics and Catalysis, 7,5 credits (ECTS)
Experts in Teamwork - Biofuels - a Solution or a Problem? 7,5 credits (ECTS)
Biofuels and Biorefineries, 7,5 credits (ECTS)
Life Cycle Assessment and Environmental Systems Analysis, 7,5 credits (ECTS)
Climate Change Mitigation, 7,5 credits (ECTS)

### Courses at NMBU

Biogas Technology, 5 credits (ECTS)
Bioenergy, 10 credits (ECTS)
Applied Biocatalysis and Biorefining, 5 credits (ECTS)
Energy and Process Technology Main Topic, 15 credits (ECTS)
Energy Policy and Regulation, 10 credits (ECTS)

### Courses at USN

Bachelor:

Bærekraftig ressursutnyttelse (Sustainable Resource Management), 10 credits (ECTS)
Organisk kjemi med biopolymere (Organic Chemistry with Biopolymers), 10 credits (ECTS)
Separasjonsteknikk (Separation Technology),10 credits (ECTS)
Energieffektivisering (Energy Efficiency) , 10 credits (ECTS)
Fornybare energisystemer (Renewable Energy Systems), 10 credits (ECTS)
Klima, miljø og LCA (Climate, Environment and LCA), 5 credits (ECTS)

Master:

Gas Purification and Energy Optimization,10 credits (ECTS)
Water Treatment and Environmental Biotechnology, 10 credits (ECTS)
Combustion and Process Safety, 10 credits (ECTS)
Hydrogen and Energy Technology, 10 credits (ECTS)
Process Technology and Equipment, 10 credits (ECTS)

# Personnel and Recruitment

## Personnel

| Name leader | Institution | Main research area |
|---|---|---|
| Rasmus Astrup (WP 1.1) | **NIBIO** | Land, Resources and Ecosystem processes |
| Francesco Cherubini (WP 1.2) | **NTNU** | Bio-Resources, Environment, Climate |
| Per Kristian Rørstad (WP 1.3) | **NMBU** | Energy, Fuels and Economics |
| Kai Toven (WP 2.1) | **RISE PFI** | Pyrolysis |
| Judit Sandquist (WP 2.2) | **NTNU** | Hydrothermal Liquefaction |
| Roman Tschentscher (WP 2.3) | **SINTEF** | Thermochemical upgrading of bio-oils |
| Mihaela Opedal (WP 3.1) | **RISE PFI** | Pretreatment and Fractionation |
| Aniko Varnai (WP 3.2) | **NMBU** | Enzymatic Saccharification |
| Alexander Wentzel (WP 3.3) | **SINTEF** | Fermentation |
| Lu Feng (WP 3.4) | **NIBIO** | Anaerobic digestion and gas upgrading |
| Morten Seljeskog (WP 4.1) | **SINTEF** | Gasification |
| Edd Blekkan (WP 4.2) | **NTNU** | Gas Conditioning |
| Klaus Jens (WP 4.3) | **USN** | Preparing for piloting and up-scale |
| Bernd Wittgens (WP 5.1) | **SINTEF** | Process Modelling, Technical and Economical Evaluation |
| Terese Løvås (WP 5.2) | **NTNU** | Product quality and End Use |
| | | |
| Francesco Cherubini (SP1) | **NTNU** | Bio-resource, Environment and Climate |
| Judit Sandquist (SP2) | **SINTEF** | Liquefaction Processes |
| Aniko Varnai (SP3) | **NMBU** | Biochemical Conversion |
| Morten Seljeskog (SP4) | **SINTEF** | Gasification Processes |
| Bernd Wittgens (SP5) | **SINTEF** | Process design and End Use |
| | | |
| Duncan Akporiaye | **SINTEF** | Centre Leader |
| Svein Jarle Horn | **NMBU** | Vice Centre Leader |
| Odd Jarle Skjelhaugen | **NMBU** | Project Leader |
| Janne Beate Utåker | **NMBU** | Administrator |
| Ann-Solveig Hofseth | **NMBU** | Financial Officer |
| Haldis Bjerva Watson | **SINTEF** | Communication Officer |
| Camilla Fløien Angeltveit | **NMBU** | PhD Contact / Communication Officer |

## RECRUITMENT

### PhD Students with finance from the Bio4Fuels budget:

| Name | Nationality | Duration | Gender | Topic |
|---|---|---|---|---|
| Angeltveit, Camilla F. | Norwegian | 17.08.2020 – 16.08.2023 | F | The role of LPMOs during enzymatic saccharification processes |
| Cazzolaro, Martina | Italian | 01.08.2017 – 30.04.2022 | F | Catalytic biomass conversion |
| Dzurendova, Simona | Slovakia | 14.09.2017 – 23.04.2021 | F | Bioconversion of lignocellulose materials into lipid rich fungal biomass. |
| Encinas, Oscar L. I. | Spanish | 24.08.2020 – 24.10.2023 | M | Conversion of synthesis gas from fish waste gasification over cobalt catalysts |
| Hansen, Line Degn | Danish | 01.06.2017 – 15.06.2022 | F | Optimization of enzymatic conversion of biomass to platform chemicals |
| Hu, Junhui | Chinese | 05.10.2020 – 04.10.2023 | F | Analyzing the role of biomass and biofuel in the Nordic energy, forest and transportation sectors towards 2050 |
| Jåstad, Eirik Ogner | Norwegian | 01.02.2017 – 31.12.2020 | M | Models for Economic Assessments of Second-Generation Biofuel Production |
| Losada, Cristian B. | Spanish | 10.04.2020 – 10.04.2023 | M | Fermentation on developing multi-organism system for lipid production |
| Lysne, Ask | Norwegian | 12.08.2019 – 11.08.2022 | M | Catalytic Steam Reforming of Hydrocarbon Impurities from Biomass Gasification |
| Timsina, Ramesh | Nepal | 24.09.2018 – 24.02.2022 | M | Preparing for Piloting and Up-Scale |
| Xue, Zhongye | Chinese | 16.09.2020 – 15.09.2023 | M | Experimental and Numerical Study of Low-Carbon Biofuels in Internal Combustion Engines |
| Samani, Nastaran | Iran | 01.05.2021 – 30.04.2024 | F | Computational particle fluid dynamics (CPFD) and process simulations modelling of biomass gasification |
| Zhihui Li | Chinese | 01.12.2021 – 30.11.2024 | F | Co-pyrolysis of biomass and plastic to produce high quality liquid |

### Postdoctoral Researchers with financial support from Bio4Fuels budget

| Name | Nationality | Duration | Gender | Topic |
|---|---|---|---|---|
| Lewandowski, Michal | Poland | 04.04.2019 – 03.04.2022 | M | Product quality and End Use |
| Morales, Marjorie | Chile | 01.09.2019 – 31.08.2023 | F | Bio-resource, Environment and Climate |
| Wahid, Radziah | Malaysia | 01.03.2017 – 05.09.2019 | M | Biogas |

## Other researchers 2021

| Name | Institution | Name | Institution |
|---|---|---|---|
| Ljubisa Graviolic | IFE | Alex Nelson | IFE |
| Antonio Oliviera | IFE | Saimi Sultana Kasi | IFE |
| | | | |
| Roar Linjordet | NIBIO | Nicolas Cattaneo | NIBIO |
| Hege Bergheim | NIBIO | Carolin Fischer | NIBIO |
| Heikki Korpuen | NIBIO | Nils Egil Søde | NIBIO |
| | | | |
| Boris Zimmermann | NMBU | Achim Kohler | NMBU |
| Per Kristian Rørstad | NMBU | Aniko Varnai | NMBU |
| Erik Trømborg | NMBU | Volha Shapaval | NMBU |
| Yi-Kuang Chen | NMBU | Vincent Eijsink | NMBU |
| Hafeez Rehman | NMBU | Thales Costa | NMBU |
| Jon Gustav Kirkerud | NMBU | | |
| | | | |
| Khare Shivang | NTNU | Otavio Cavalett | NTNU |
| Maren Haug | NTNU | Vinay Kumar | NTNU |
| | | | |
| Kenneth Aasarød | RISE Pfi | Jost Ruwoldt | RISE Pfi |
| Arild Blakstad | RISE Pfi | Cornelis van der Wijst | RISE Pfi |
| Ingebjørg Leirset | RISE Pfi | Marita Dørdal Helgheim | RISE Pfi |
| Johnny Melbø | RISE Pfi | Kristin Stensønes | RISE Pfi |
| Anne Marie Reitan | RISE Pfi | Javier C Romeo | RISE Pfi |
| | | | |
| Liang Wang | SINTEF Energy | Jørn Bakken | SINTEF Energy |
| Michaël Becidan | SINTEF Energy | Annar Bremnes | SINTEF Energy |
| Øyvind Skreiberg | SINTEF Energy | Mette Bugge | SINTEF Energy |
| Per Carlsson | SINTEF Energy | Helen Langeng | SINTEF Energy |
| Roger Khalil | SINTEF Energy | Gonzalo Del Alamo | SINTEF Energy |
| Inge Sannum | SINTEF Energy | Maria N P Olsen | SINTEF Energy |
| Jorunn Hølto | SINTEF Energy | Jacob Stang | SINTEF Energy |
| Petter Røkke | SINTEF Energy | Birger Rønning | SINTEF Energy |
| Jørund Aakervik | SINTEF Energy | | SINTEF Energy |
| | | | |
| Inga Marie Aasen | SINTEF Technology | Olaf Trygve Berglihn | SINTEF Technology |
| Sidsel Markussen | SINTEF Technology | Sylvia Weging | SINTEF Technology |
| Ruth Elisabeth Stensrud | SINTEF Technology | Oxana Eide | SINTEF Technology |
| Merete Wiig | SINTEF Technology | Anders Brunsvik | SINTEF Technology |
| Torbjørn Pettersen | SINTEF Technology | Frank Ormøy | SINTEF Technology |
| Theresa Rücker | SINTEF Technology | Arne Erik Rekkebo | SINTEF Technology |
| Tor Erling Unander | SINTEF Technology | Morten Frøseth | SINTEF Technology |
| Terje Øyangen | SINTEF Technology | Pawel Piatek | SINTEF Technology |
| Francesca Di Bartolameo | SINTEF Technology | Morten Frøseth | SINTEF Technology |

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|---|---|---|---|
| Tone Haugen | SINTEF Technology | Susan Maleki | SINTEF Technology |
| Ingvild Aune | SINTEF Technology | Malene Jønsson | SINTEF Technology |
| Anna Sofie Lewin | SINTEF Technology | Giang-Son Nguyen | SINTEF Technology |
| Lars Vik | SINTEF Technology | Kenneth Schneider | SINTEF Technology |
| Kari Hjelen | SINTEF Technology | Ina Beate Jenssen | SINTEF Technology |
| Kjell Domaas Josefsen | SINTEF Technology | Sidsel markussen | SINTEF Technology |
| Bendik Sægrov-Sorte | SINTEF Technology | Stig Rune Ulla | SINTEF Technology |
| Jody Veendaal | SINTEF Technology | Heiko Gaerter | SINTEF Technology |
| | | | |
| Marianne Eikeland | USN | Britt Moldestad | USN |
| | | | |

# MEDIA, PUBLICATIONS, SCIENTIFIC TALKS AND DISSEMINATION

Data from Cristin https://app.cristin.no/

## COMMUNICATION AND OUTREACH 2022

**Ahmadpour Samani, Nastaran; Eikeland, Marianne Sørflaten.**
Eulerian-Lagrangian simulation of air-steam biomass gasification in a bubbling fluidized bed gasifier. *Linköping Electronic Conference Proceedings* 2022 (192) s.386-392, USN

**Barbosa Watanabe, Marcos Djun; Cherubini, Francesco; Cavalett, Otávio.**
Green shift in the EU maritime sector: country-based climate benefits and potentials of drop-in and hydrogen-based biofuels up to 2050. Bio4Fuels Days 2022; 2022-11-16 - 2022-11-17, NTNU

**Baur, Saskia Tabea; Markussen, Sidsel; di Bartolomeo, Francesca; Poehlein, Anja; Baker, Anna; Bengelsdorf, Frank R.; Jenkinson, Liz; Daniel, Rolf; Dürre, Peter.**
Conversion of the solvent producer Clostridium saccharoperbutylacetonicum into a butyrate producer. Annual Conference of the Association for General and Applied Microbiology (VAAM); 2022-02-21 - 2022-02-23, SINTEF

**Dupuy--Galet, Benjamin Xavier; Kohler, Achim; Shapaval, Volha.**
Duetz-MTPS combined with HTS-FTIR spectroscopy biochemical profiling for high-throughput screenings of oleaginous microalgae. International Conference on Renewable Resources & Biorefineries; 2022-06-01 - 2022-06-03, NMBU

**Dupuy--Galet, Benjamin Xavier; Zimmermann, Boris; Kohler, Achim; Shapaval, Volha.**
Vibrational spectroscopy monitoring of microalgae-fungi co-cultures as a strategy to microalgae-based lipid production. Elevating Nordic algal biotechnology conference; 2022-06-08 - 2022-06-10, NMBU

**Dzurendová, Simona; Zimmermann, Boris; Byrtusova, Dana; Slany, Ondrej; Kohler, Achim; J. Urs, Mounashree; Cord-Landwehr, Stefan; Moerschbacher, Bruno; Certik, Milan; Shapaval, Volha.**
Novel fungal source of aminopolysaccharides and aminopolysaccharide-glucans complexes. European summit of industrial biotechnology; 2022-11-14 - 2022-11-17, NMBU

**Feng, Lu; Opedal, Mihaela Tanase; Bartolomeo, Francesca Di; Markussen, Sidsel; Varnai, Aniko; Jarle Horn, Svein.**
Anaerobic digestion of organic residues generated from Norway spruce biorefinery process. Nordic Biogas Conference; 2022-10-04 - 2022-10-06, NIBIO SINTEF NMBU

**Guo, Ning; Ren, Zhengru; Lewandowski, Michal; Netzer, Corinna.**
Predictions of emission and flammability limit of MILD combustion of ammonia and syngas. The 39th International Symposium on Combustion; 2022-07-24 - 2022-07-29, NTNU

**Hansen, Line Degn; Varnai, Aniko; Eijsink, Vincent; Horn, Svein Jarle.**
Hydrogen peroxide feeding for LPMO-assisted cellulose saccharification using cellulase cocktails. 3rd LPMO Symposium; 2022-11-09 - 2022-11-11, NMBU

**Hansen, Line Degn; Østensen, Martin; Arstad, Bjørnar; Tschentscher, Roman; Eijsink, Vincent; Horn, Svein Jarle; Varnai, Aniko.**
2-Naphthol impregnation prior to steam explosion promotes LPMO-assisted enzymatic saccharification of spruce and yields high-purity lignin. 3rd LPMO Symposium; 2022-11-09 - 2022-11-11, SINTEF NMBU

**Jåstad, Eirik Ogner.**
Nordic Clean Energy Scenarios. Bioenergiapäivä (Bioenergy day); 2022-10-24 - 2022-10-24, NMBU

**Lewandowski, Michal; Pasternak, Michal; Løvås, Terese.**
Simulations of ammonia spray evaporation, cooling and mixture formation in a direct injection compression ignition engine. 7th International Conference on Contemporary Problems of Thermal Engineering CPOTE 2022; 2022-09-20 - 2022-09-23, NTNU

**Lewandowski, Michal; Xue, Zhongye; Netzer, Corinna; Emberson, David; Løvås, Terese.**
Relation between MILD combustion and LTC strategies in diluted compression ignition conditions. 39th International Symposium on Combustion; 2022-07-24 - 2022-07-29, NTNU

**Mahmoodinia, Mehdi; Ma, Jianyu; Rout, Kumar Ranjan; Blekkan, Edd Anders.**
Evaluation of Manganese-based Solid Sorbents for High Temperature Desulphurization of Biomass-Derived Syngas. 19th Nordic Symposium on Catalysis; 2022-06-06 - 2022-06-08, NTNU

**Rørstad, Per Kr..**
Bærekraftig høsting av biomasse fra skogen. Bioenergidagene 2022; 2022-11-22, NMBU

**Rørstad, Per Kr..**
Fornybar energi og bærekraft i matproduksjonen. Hvordan produsere nok, sunn og trygg mat i samsvar med FNs bærekraftsmål?; 2022-10-12, NMBU

**Rørstad, Per Kr..**
How much extra biomass can we actually harvest from our forest to meet increasing bio-economy demands for biofuel, and how and where should or could this harvest be taking place? BIOWATER final summer camp; 2022-06-08, NMBU

**Rørstad, Per Kr..**
Integrering av samfunnsvitenskap i FME Bio4Fuels. FME-kontaktmøte høsten 2022; 2022-10-27, NMBU

**Sandquist, Judit.**
Hva er biodrivstoff?. SINTEF 2022, ENERGISINT

**Sandquist, Judit.**
Hvordan produseres biodrivstoff og hva forskes på? Høydepunkter fra FME Bio4Fuels. Bioenergidagene; 2022-11-21 - 2022-11-22 ENERGISINT

**Sandquist, Judit.**
Introduction to biofuels. Workshop: the role of biofuels in decarbonizing the Norwegian transport system (UC3b); 2022-05-05 - 2022-05-05, ENERGISINT

**Sandquist, Judit.**
Status biodrivstoff 2022 (i Norge og verden).
ENERGISINT

**Sandquist, Judit; Everson, Nikalet; Delic, Asmira; Olsen, Maria Nicte Polanco.**
Hydrothermal Liquefaction of Bark-containing Nordic Biomass. ICONBM 2022; 2022-06-05 - 2022-06-08, ENERGISINT

**Tõlgo, Monika; Hegnar, Olav Aaseth; Østby, Heidi; Varnai, Aniko; Vilaplana, Francisco; Eijsink, Vincent; Olsson, Lisbeth.**
Comparison of Six Lytic Polysaccharide Monooxygenases from Thermothielavioides terrestris Shows That Functional Variation Underlies the Multiplicity of LPMO Genes in Filamentous Fungi. *Applied and Environmental Microbiology* 2022 ;Volum 88.(6), NMBU

**Wentzel, Alexander.**
Biotechnological process for sustainable value creation from industrial CO2. GENESIS project's open day workshop; 2022-04-05 - 2022-04-05, SINTEF

**Wentzel, Alexander.**
Biotechnological process for sustainable value creation from industrial CO2. AXELERA CCU event; 2022-09-08 - 2022-09-08, SINTEF

**Wentzel, Alexander.**
Bioteknologisk prosess til bærekraftig verdiskaping fra industriell CO2. Teknas CO2-konferanse 2022; 2022-01-19 - 2022-01-20 SINTEF

**Wentzel, Alexander.**

Demonstrating sustainable value creation from industrial CO2 by its thermophilic microbial conversion into acetone. NorCore Green Deal event; 2022-02-17 - 2022-02-17, SINTEF

**Wentzel, Alexander; di Bartolomeo, Francesca; Watson, Haldis Bjerva.**
Sustainable value creation from industrial CO2 - Technological, industrial, and societal perspectives on the Green Deal implementation; 2022-09-21 - 2022-09-21, SINTEF

**Zimmermann, Boris; Shapaval, Volha; Kohler, Achim; Tafintseva, Valeria; Dzurendova, Simona.**
Primjena vibracijske spektroskopije u mikrobnoj biotehnologiji. Joint seminar of the Division of Organic Chemistry and Biochemistry of the Ruer Boškovi Institute and the Section for Organic Chemistry of the Croatian Chemical Society; 2022-02-22, NMBU

**Zimmermann, Boris; Shapaval, Volha; Kohler, Achim; Tafintseva, Valeria; Dzurendova, Simona; Byrtusova, Dana; Blomqvist, Johanna; Karin Hillevi; Langseter, Anne Marie; Kòsa, Gergely; Forfang, Kristin.**
Applications of vibrational spectroscopy in microbial biotechnology. XIV Meeting of Young Chemical Engineers; 2022-02-24 - 2022-02-25, NMBU

## PhD Theses

**Joseph, Prajin.**
Organosolv pretreatment of Norway spruce: Ethanol pretreatment for Biorefinery applications. Trondheim: NTNU 2022 (ISBN 978-82-326-6088-9) 91 s. Doctoral theses at NTNU(385)
NTNU

**Hansen, Line Degn.**
Leveraging H2O2-fuelled activity of lytic polysaccharide monooxygenases in cellulase cocktails for improved bioprocessing of lignocellulosic
biomass. ÅS: NMBU/KBM 2022 (ISBN 978-82-575-1902-5) 178 s. Philosophiae Doctor (PhD) Thesis
NMBU

## Scientific Publications 2022

Data from Cristin https://app.cristin.no/

| Publication | CiteScore 2022 |
|---|---|
| **Joseph, Prajin; Ottesen, Vegar; Tanase-Opedal, Mihaela; Moe, Størker T..** Morphology of lignin structures on fiber surfaces after organosolv pretreatment. *Biopolymers* 2022 ;Volum 113.(9), RISE-PFI NTNU | 4.3 |
| **Barbosa Watanabe, Marcos Djun; Cherubini, Francesco; Cavalett, Otávio.** Climate change mitigation of drop-in biofuels for deep-sea shipping under a prospective life-cycle assessment. *Journal of Cleaner Production* 2022 ;Volum 364. s.1-11, NTNU | 15.8 |
| **Barbosa Watanabe, Marcos Djun; Cherubini, Francesco; Tisserant, Alexandre Fabien Regis; Cavalett, Otávio.** Drop-in and hydrogen-based biofuels for maritime transport: Country-based assessment of climate change impacts in Europe up to 2050. *Energy Conversion and Management* 2022 ;Volum 273., NTNU | 18.0 |
| **Baur, Saskia Tabea; Markussen, Sidsel; di Bartolomeo, Francesca; Poehlein, Anja; Baker, Anna; Jenkinson, Elizabeth R.; Daniel, Rolf; Wentzel, Alexander; Dürre, Peter.** Increased Butyrate Production in Clostridium saccharoperbutylacetonicum from Lignocellulose-Derived Sugars. *Applied and Environmental Microbiology* 2022 ;Volum 88.(7) s.1-21, SINTEF | 7.8 |
| **Baur, Tina; Wentzel, Alexander; Dürre, Peter.** Production of propionate using metabolically engineered strains of Clostridium saccharoperbutyl-acetonicum. *Applied Microbiology and Biotechnology* 2022 ;Volum 106.(22) s.7547-7562, SINTEF | 8.8 |
| **Cavalett, Otávio; Cherubini, Francesco.** Unraveling the role of biofuels in road transport under rapid electrification. *Biofuels, Bioproducts and Biorefining* 2022 ;Volum 16.(6) s.1495-1510, NTNU | 7.3 |
| **Chytil, Svatopluk; Li, Chao'en; Lee, Woo Jin; Lødeng, Rune; Holmen, Anders; Blekkan, Edd Anders; Burke, Nick; Patel, Jim.** Experimental and Theoretical Studies on Water-Added Thermal Processing of Model Biosyngas for Improving Hydrogen Production and Restraining Soot Formation. *Industrial & Engineering Chemistry Research* 2022 ;Volum 61.(26) s.9262-9273, NTNU SINTEF | 6.6 |
| **Furuvik, Nora Cecilie Ivarsdatter; Wang, Liang; Jaiswal, Rajan; Thapa, Rajan Kumar; Eikeland, Marianne Sørflaten; Moldestad, Britt Margrethe Emilie.** Experimental study and SEM-EDS analysis of agglomerates from gasification of biomass in fluidized beds. *Energy* 2022 ;Volum 252., ENERGISINT USN | 2.9 |
| **Hansen, Line Degn; Eijsink, Vincent; Horn, Svein Jarle; Varnai, Aniko.** $H_2O_2$ feeding enables LPMO-assisted cellulose saccharification during simultaneous fermentative production of lactic acid. *Biotechnology and Bioengineering* 2022, NMBU | 7.2 |

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|---|---|
| **Hansen, Line Degn; Østensen, Martin; Arstad, Bjørnar; Tschentscher, Roman; Eijsink, Vincent; Horn, Svein Jarle; Varnai, Aniko.** 2-Naphthol Impregnation Prior to Steam Explosion Promotes LPMO-Assisted Enzymatic Saccharification of Spruce and Yields High-Purity Lignin. *ACS Sustainable Chemistry and Engineering* 2022 ;Volum 10.(16) s.5233-5242, NMBU SINTEF | 14.5 |
| **Hashemi, Seyedbehnam; Solli, Linn; Aasen, Roald; Lamb, Jacob Joseph; Horn, Svein Jarle; Lien, Kristian Myklebust.** Stimulating biogas production from steam-exploded birch wood using Fenton reaction and fungal pretreatment. *Bioresource Technology* 2022; Volum 366. NTNU NMBU NIBIO | 17.4 |
| **Iordan, Cristina Maria; Giroux, Baptiste Abel Rene; Næss, Jan Sandstad; Hu, Xiangping; Cavalett, Otávio; Cherubini, Francesco.** Energy potentials, negative emissions, and spatially explicit environmental impacts of perennial grasses on abandoned cropland in Europe. *Environmental impact assessment review* 2022 ;Volum 98. NTNU | 7.6 |
| **Lysne, Ask; Madsen, Kristin Øxnevad; Antony, Jibin; Rout, Kumar Ranjan; Blekkan, Edd Anders.** Effects of Ni-Co Ratio on Deactivation and Coke Formation in Steam Reforming of Hydrocarbon Impurities from Biomass Gasification with Ni-Co/Mg(Al)O Catalysts. *Chemical Engineering Transactions* 2022 ;Volum 92. s.37-42. NTNU | 1.6 |
| **Magnussen, Eirik Almklov; Zimmermann, Boris; Blazhko, Uladzislau; Dzurendová, Simona; Dupuy--Galet, Benjamin Xavier; Byrtusova, Dana; Muthreich, Florian; Tafintseva, Valeria; Liland, Kristian Hovde; Tøndel, Kristin; Shapaval, Volha; Kohler, Achim.** Deep learning-enabled Inference of 3D molecular absorption distribution of biological cells from IR spectra. *Communications chemistry* 2022; Volum 5.(1). NMBU UiB | 8.0 |
| **Næss, Jan Sandstad; Hu, Xiangping; Gvein, Maren Haug; Iordan, Cristina Maria; Cavalett, Otávio; Dorber, Martin; Giroux, Baptiste Abel Rene; Cherubini, Francesco.** Climate change mitigation potentials of biofuels produced from perennial crops and natural regrowth on abandoned and degraded cropland in Nordic countries. *Journal of Environmental Management* 2022 ;Volum 325.(A). NTNU | 11.4 |
| **Rørstad, Per Kr..** Payment for CO2 sequestration affects the Faustmann rotation period in Norway more than albedo payment does. *Ecological Economics* 2022; Volum 199. NMBU | 10.9 |
| **Rørstad, Per Kr.; Solberg, Birger; Trømborg, Erik.** Can we detect regional differences in econometric analyses of the Norwegian timber supply?. *Silva Fennica* 2022 ;Volum 56.(1). NMBU | 2.8 |
| **Samani, Nastaran Ahmadpour; Thapa, Rajan Kumar; Moldestad, Britt Margrethe Emilie; Eikeland, Marianne Sørflaten.** Evaluating the impacts of temperature on a bubbling fluidized bed biomass gasification using CPFD simulation model. *IFAC-PapersOnLine* 2022; Volum 55.(20) s.618-623. USN | 1.5 |
| **Sandquist, Judit; Everson, Nikalet; Delic, Asmira; Olsen, Maria Nicte Polanco.** Hydrothermal Liquefaction of Bark-containing Nordic Biomass. *Chemical Engineering Transactions* 2022 ;Volum 92. s.97-102. ENERGISINT | 1.6 |
| **Vera, Ivan; Wicke, Birka; Lamers, Patrick; Cowie, Annette; Repo, Anna; Heukels, Bas; Zumpf, Colleen; Styles, David; Parish, Esther; Cherubini, Francesco; Berndes, Göran; Jager, Henriette; Schiesari, Luis; Junginger, Martin; Brandão, Miguel; Bentsen, Niclas Scott; Daioglou, Vassilis; Harris, Zoe; van der Hilst, Floor.** Land use for bioenergy: Synergies and trade-offs between sustainable development goals. *Renewable & Sustainable Energy Reviews* 2022; Volum 161. NTNU | 28.5 |
| **Wang, Liang; Becidan, Michael; Lindberg, Daniel; Furuvik, Nora Cecilie Ivarsdatter; Moldestad, Britt Margrethe Emilie; Eikeland, Marianne Sørflaten.** Sintering Behaviors of Synthetic Biomass Ash. *Chemical Engineering Transactions* 2022 ;Volum 96. s.271-276. ENERGISINT USN | 1.6 |
| **Østby, Heidi; Varnai, Aniko; Gabriel, Raphael; Chylenski, Piotr; Horn, Svein Jarle; Singer, Steven W; Eijsink, Vincent.** Substrate-Dependent Cellulose Saccharification Efficiency and LPMO Activity of Cellic CTec2 and a Cellulolytic Secretome from Thermoascus aurantiacus and the Impact of $H_2O_2$-Producing Glucose Oxidase. *ACS Sustainable Chemistry and Engineering* 2022. NMBU | 14.5 |
| **CiteScore 2022 Average** | 9.11 |

# ASSOCIATED PROJECTS

In addition to the research activities financed directly within Bio4Fuels, the partners and stakeholders in the centre aim to stimulate and coordinate additional research and demo activities. These associated projects are focussed towards EU funding as part of the internationalisation strategy, as well as nationally based funding in order to provide a larger platform for addressing the overall challenges within the field. The range of associated EU and Nationally funded projects are listed below.

## EU FINANCED PROJECTS

| Project | Total budget [mNOK] | Short Description of Project | Bio4Fuels Stakeholders involved |
|---|---|---|---|
| PERFECOAT | 50 | New bio-based rindustrial coating ingredients | SINTEF Industry, Borregaard |
| EnXylaScope | 60 | New enzyme systems for xylan conversion into consumer products | SINTEF Industry |
| PyroCO2 | 440 | Demonstration of scalability of chemicals and materials production from CO2 using biotech-based CCU route | SINTEF Industry |
| AC2OCEM | 43 | Accelerating Carbon Capture using Oxyfuel Technology in Cement Production - Biomass used instead of coal in the kiln) | NTNU (Indecol), Sintef Energy |
| EHLCATHOL | 40 | Chemical Transformation of Enzymatic Hydrolysis Ligning (EHL) with Catalytic Solvolysis to Fuel Commodities under mild Conditions | |
| BL2F | 50 | Biofuels from black liquor via HTL | SINTEF Energi, SINTEF AS, Neste |
| NextGenRoadFuels | 46 | Biofuels from sludge and organic waste via HTL | SINTEF Energi, Steeper |
| SET4Bio | | Supporting the implementation of the SET Plan Action 8 | SINTEF Energi |
| TULIPS | 325 | DemonsTrating lower pollUting soLutions for sustaInable airPorts acrosS Europe // multiple technologies; for Bio4Fuels, SAF is relevant | SINTEF Energi, Avinor |
| EEA-Baltic | 8 | Novel high-performance polymers from lignocellulosic feedstock | NTNU (Indecol). |
| EBIO | 42 | Electrochemical upgrading o crude bio liquids | SINTEF Industry, BTG |

| | | | |
|---|---|---|---|
| BRISK2 | 60 | Transnational access of research infrastructure as well as research on monitoring, process design and costing | SINTEF Industry |
| LIBERATE | 60 | Conversion of Lignin to value added chemicals | SINTEF Industry |
| Pulp&Fuels | 49 | The Pulp & Fuel project, funded by the EU under Horizon 2020, studies how renewable fuel production can be integrated with pulp production to achieve positive synergies for the production of 2nd generation biofuels at a competitive price. | SINTEF, RISE |
| SelectiveLi | 5 | Conversion of Lignin to value added chemicals | SINTEF Industry |
| Waste2Road | 60 | Conversion of Biogenic Waste via HTL and Pyrolysis to Advance Biofuels | SINTEF Industry, EGE |
| CONVERGE | 49,9 | Production of biomethanol through gasification-sorption enhanced reforming-membrane enhanced methanol synthesis | IFE |
| MEMBER | 77,2 | Production of hydrogen from biogas through membrane-assisted sorption-enhanced reforming | IFE, ZEG Power |
| FunEnzFibres | NMBU: 8,5 | Enzymatic upgrading of cellulosic fibres with LPMOs (redox enzymes) for the production of textiles and nanocellulose | Borregaard, Novozymes |
| MarketPlace | 8 | MarketPlace is aiming at an integrated computing hub for simulatoins | |
| CUBE (ERC Synergy grant) to V.G.H. Eijsink | 100 | Unravelling the secrets of synthetic and biological Cu-based catalysts for C-H activation | |

## NATIONALLY FUNDED PROJECTS

| Project | Total budget [mNOK] | Short Description of Project | Bio4Fuels Stakeholders involved |
|---|---|---|---|
| SLUDGEFFECT | 10,5 | Life cycle effects from removing hazardous substances in sludge and plastic through thermal treatment | NTNU (Indecol). N.B.: Bio4Fuels explicitly provided a letter of support |
| FORBIOCHAR | 8 | Evaluating producing biochar from forest biomass. | skogeierforbunnet |
| BYPROVALUE | 10 | Production of lipids, chitin/chitosan, glucans and polyphosphate | Borregaard |
| LIGNOLIPP | 12 | Production of high-value lipids and chitin/chitosan | Borregaard |
| OIL4FEED | 12 | Production of high-value lipids | Borregaard |
| SAFE | 10 | Developing a novel multicomponent microbial biomass as a salmon feed from Nordic woody feedstock | Borregaard |
| Enable | 25 | Enable addresses how new, technologies within the energy and transport sector can contribute to a climate friendly transition in Norway | |
| NorENS | 11 | NorENS analyse how technologies and policies in the European energy transition is likely to affect the Norwegian energy system and the economics of energy production in Norway | |
| Climate Smart Forestry Norway (CSFN) | 25 | To improve the scientific foundation for CSF by developing a framework for holistic assessments of forest management that simultaneosly consider carbon, other biophysical forcings, substitution, and risk of natural distrubance. | |
| Bio4Fuels | 236,6 | | |
| B2A | 20 | Conversion fo biomass to aviation fuels | NTNU, SINTEF, St1 |

| | | | |
|---|---|---|---|
| BioFT | 12,8 | Optimization of the process for production of fuels via Fischer-Tropsch synthesis | SINTEF Industry |
| Bio4-7Seas | 10,5 | Biofuels for climate change mitigation in of deep-sea shipping | NTNU (Indecol). |
| BioPath | 10 | Advancing the understanding of regional climate implications of bioenergy systems | NTNU (Indecol) |
| The Norwegian Seaweed Biorefinery Platform (SBP-N) | NMBU: 4.5 | Platform for development of economically and environmentally sustainable biorefinery processes from seaweeds (macroalgae) | SINTEF, NTNU, NMBU |
| GasPro | 333 | Increase the energy efficiency of the entrained flow biomass gasification technology for bio-fuel production | NTNU, Dr Tian Li, Prof.Terese Løvås, SINTEF Energy |
| Low Emission Center | 333 | Use of ammonia and hydrogen blenads as carbon free fuels in off shore applications. | |
| Modulært energigjenvinningsanlegg for avfall | 11,7 | Build and demonstrate modular waste-to-energy small-scale plant in Norway | TeamTec? |
| BioSynGas | 25 | Next generation Biogas production through the Synergetic Integration of Gasification | NTNU |
| GasPro | 16,7 | Increase the energy efficiency of the entrained flow biomass gasification technology for bio-fuel production | NTNU, Dr Tian Li, Prof.Terese Løvås, SINTEF Energy |
| FunAccess (NNF Emerging Investigator grant) to A. Varnai | 13,9 | Leveraging the mechanisms how fungi increase plant cell wall Accessibility for improving accessibility of cellulosic fibres for complete saccharification and fibre upgrading | |
| CAHEMA | 10 | Use of ammonia and hydrogen blenads as carbon free fuels in ICE for marine transport. | |
| CircWood | 37.5 | Reuse and recycling of wood, resource availability and environmental impacts. | |

# ACCOUNTS 2022

Overview of the accounts for 2022, reported to the Research Council of Norway on 20 January 2023, approved in February 2023.

| **Project costs** | **Actual** | **Budget** | **Finance Specification** | **Actual** | **Budget** |
|---|---|---|---|---|---|
| Payroll and indirect expenses | 31 179 | 41 069 | In-Kind NMBU | 4 153 | 4 538 |
| Procurement of R&D services | 0 | 0 | Public funding | 8 130 | 14 578 |
| Equipment | 1 343 | 1 863 | Private funding | 5 933 | 5 384 |
| Other operating expenses | 5 392 | 1 828 | International funding | 2 317 | 1 625 |
| | | | The Research Council | 17 380 | 17 053 |
| | | | | | |
| **Total** | **37 914** | **44 760** | | **37 914** | **43 178** |

# ACKNOWLEDGEMENTS

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## AUTHORS

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## Bio4Fuels Stakeholders

alginor
AVINOR
BIOKRAFT
ZERO
CAMBI - recycling energy
Oslo
HERØYA INDUSTRIPARK
ecopro
BIOZIN
nobio Norsk Bioenergiforening
Norske Skog
Statkraft
Statens vegvesen
Hyperthermics THE GREEN SHIFT REVOLUTION
Norges Skogeierforbund
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