Professor Magnus Rønning

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Norwegian University of Science and Technology, NTNU
Trondheim Norway

Outline

- **Who we are**
  - **Group members**
- **What we do**
  - **A selection of our activities**
  - **Centre status**
- **Our lab infrastructure**
  - **Tools and techniques**
- **Internationalisation**

Who we are (1)

PhD candidates:

- Willow Dew
- Hammad Ali
- Mei Ju Goemans
- Sahra Louise Guldahl-Ibouder
- Zhihui Li
- Marcin Makosa-Szczygiel
- Alicia San Martin Rueda
- Petter Tingelstad
- Albert Miro i Rovira
- Kishore Rajendran
- Oscar Ivanez

PhD candidates:

- Moses Mawanga
- Dumitrita Spinu
- Martina Cazzolaro
- Youri van Valen
- Shirley Liland
- Jibin Antony
- Junbo Yu
- Björn Baumgarten
- Mario Casalegno
- Samuel K Regli

Postdoctoral fellows:

- Katarzyna Swirk da Costa
- Tina Bergh
- Monica Pazos Urrea

Researchers:

- Wei Zhang
- Pio Gramazio

Professors emeriti:

- Anders Holmen
- Erling Rytter

Who we are (2)

Senior engineers:

- Estelle Vanhaecke
- Samuel K. Regli

Professors:

- Edd Blekkan
- Hilde J. Venvik
- De Chen
- Magnus Rønning

Adjunct professors:

- David Waller (Yara)
- Kjell Moljord (Equinor)
- Ingeborg-Helene Svenum (SINTEF)
- Jia Yang

Senior advisor:

- Anne Hoff

Gemini (twin) centre NTNU-SINTEF

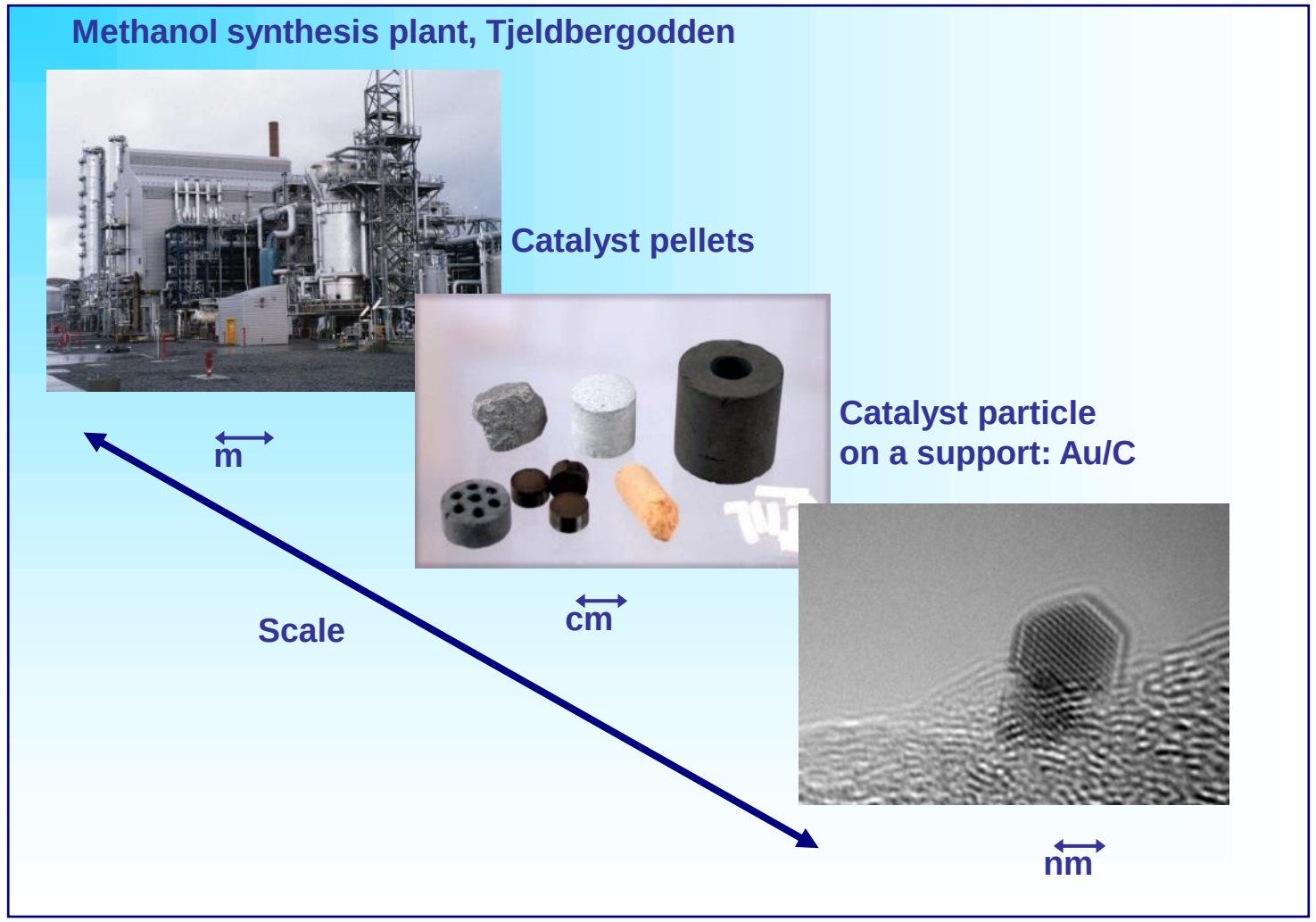
Long-term close collaboration with SINTEF

- Strong-point centre in catalysis awarded in 1998
- Gemini centre since 2007
- Sharing labs and infrastructure

Catalysis

***Catalysis research** involves phenomena ranging from full-scale industrial installations down to molecules and atoms on the surface of complex nanomaterials*

***Our teaching** is research-based, and aims to educate candidates with up-to-date and relevant knowledge and skills*



National recognition: Centre status

KinCat GEMINI CENTRE

Gemini Centre 2007 – 2027

inGAP

iCSI

sfi = Centre for Research-based Innovation

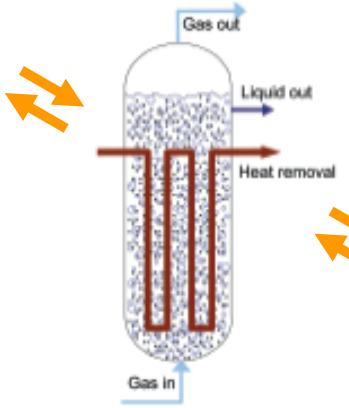
The Research Council of Norway

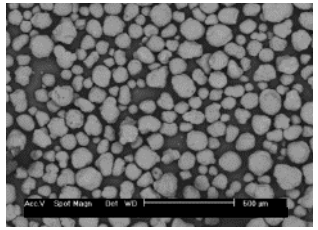
Bio4Fuels

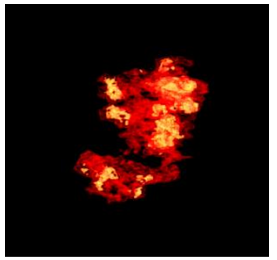
HYDROGENi

Norwegian Centre for Environment-friendly Energy Research

Innovative Natural Gas Processes and Products







Partners:

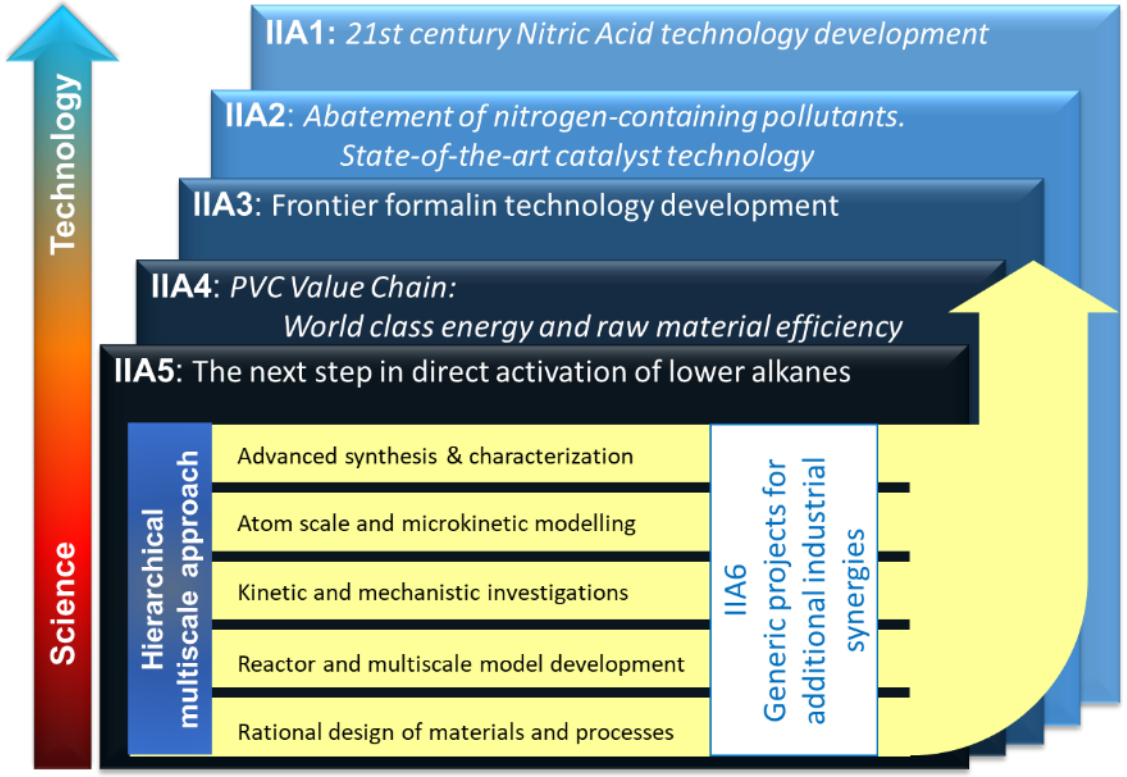
University of Oslo
NTNU
SINTEF
Borealis
INEOS
Statoil (now Equinor)
Haldor Topsøe AS (now Topsoe)
The Norwegian Research Council

- ✓Centre host: Univ of Oslo (Chem. Dept.)
- ✓Centre director: Prof. Unni Olsbye
- ✓NOK 203 millions total budget
- ✓Duration 2007-2015

https://www.mn.uio.no/kjemi/english/research/groups/ingap/

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

- ✓ A Centre for Research-based Innovation
  Centre host: NTNU (Dept. Chem. Eng.)
- ✓ Centre director: Prof. Hilde J. Venvik
- ✓ NOK 192 mill (~20 mill €) total budget
- ✓ Duration 2015-2023
- ✓ 6 Industrial Innovation Areas
- ✓ 3 research partners and 5 industrial partners
- ✓ https://www.ntnu.edu/icsi



YARA · K.A.Rasmussen NORWAY · dynea · inovyn · TOPSOE · SINTEF · UiO

NTNU

RESULTS

iCSI KEY FIGURES 2015-2024

100 scientific publications (peer reviewed)

>200 presentations at seminars and conferences

11 popular disseminations

4 patent applications

16 PhD

iCSI funded candidates, graduated or in progress

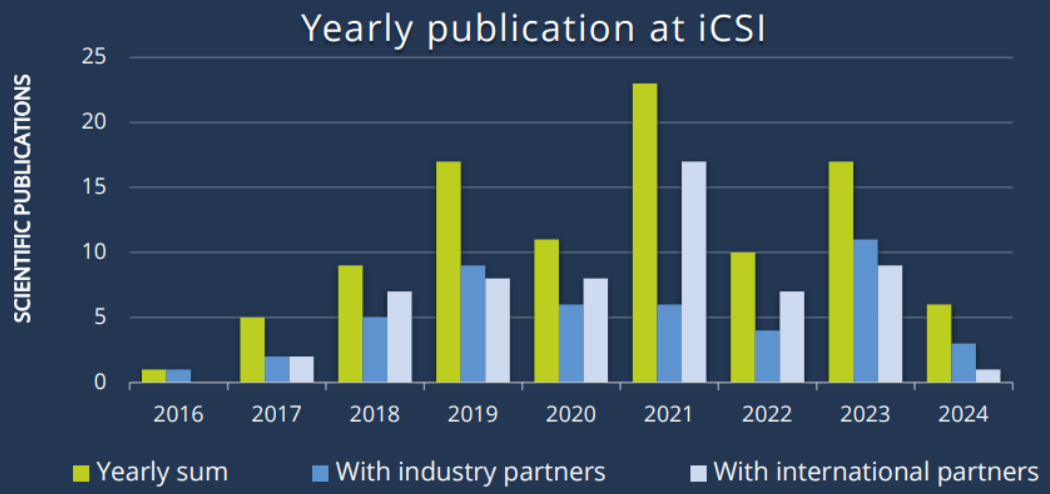
6 iCSI postdoctoral fellows

42 MSc

Theses on iCSI topics

21 PhD

iCSI associated with other funding, graduated



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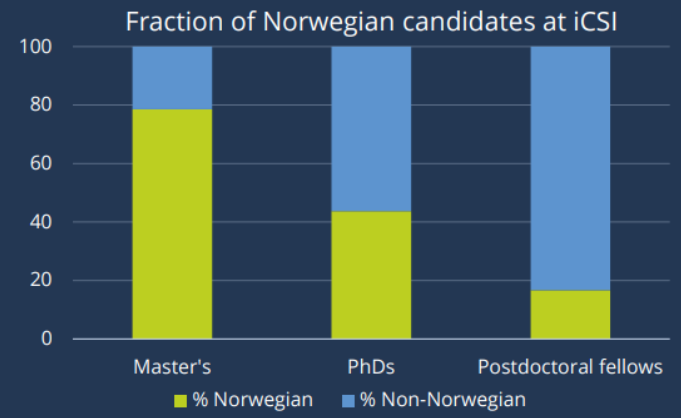
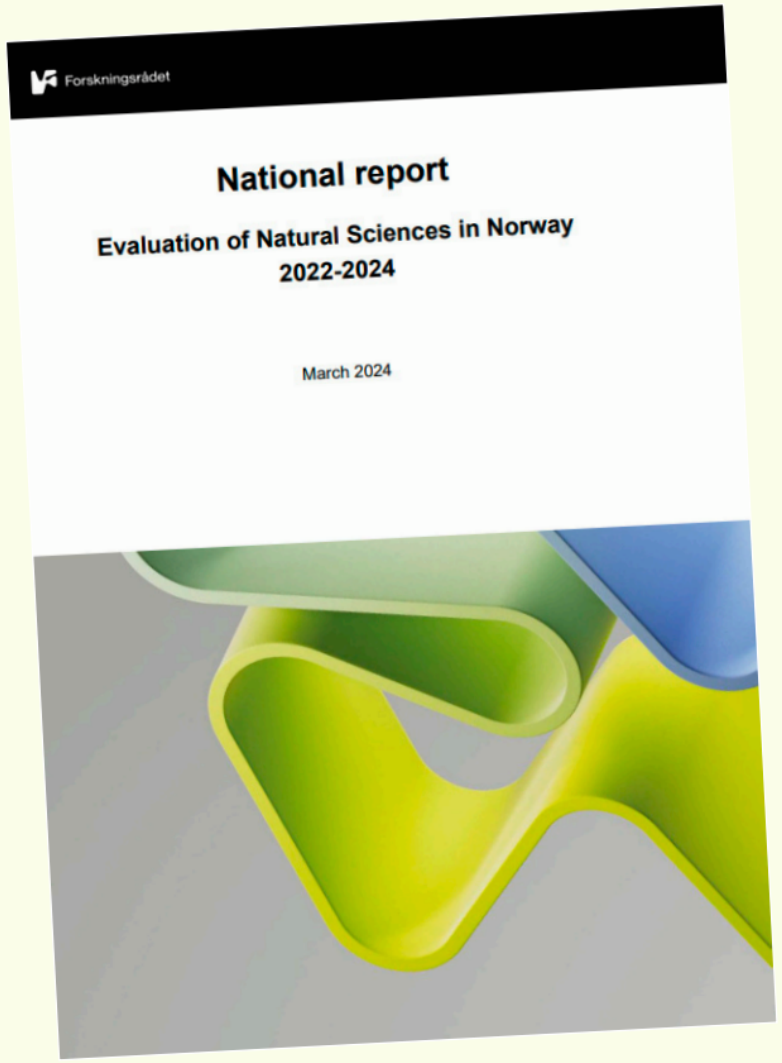




"A small selection of the impact cases submitted to the evaluation is provided here and illustrates the breadth of the research as well as its often significant impact. The cases include development and transfer of more sustainable technologies to industry, rapid uptake of results from fundamental research (.....), and helping tackle decarbonisation of the energy system."

"Case: SFI iCSI: During 2015-16, the centre started research to deepen understanding of catalysis in the production of PVC, nitric acid and formaldehyde – bulk chemicals for which there are large markets and many industrial uses, and of which members of the industrial consortium are major producers. iCSI developed new methods and protocols which were used by the industrial partners to increase yields, reduce energy consumption, develop new process technologies and reduce the risk of environmental pollution. The 4 PhD and 18 master's graduates associated with the projects up to 2023 now work in the chemicals industry or universities, and are using their education to significantly reduce the climatic and environmental impacts of chemical processes, and form part of a much bigger cohort of graduates and postgraduates from the centre taking similar skills with them to industry."

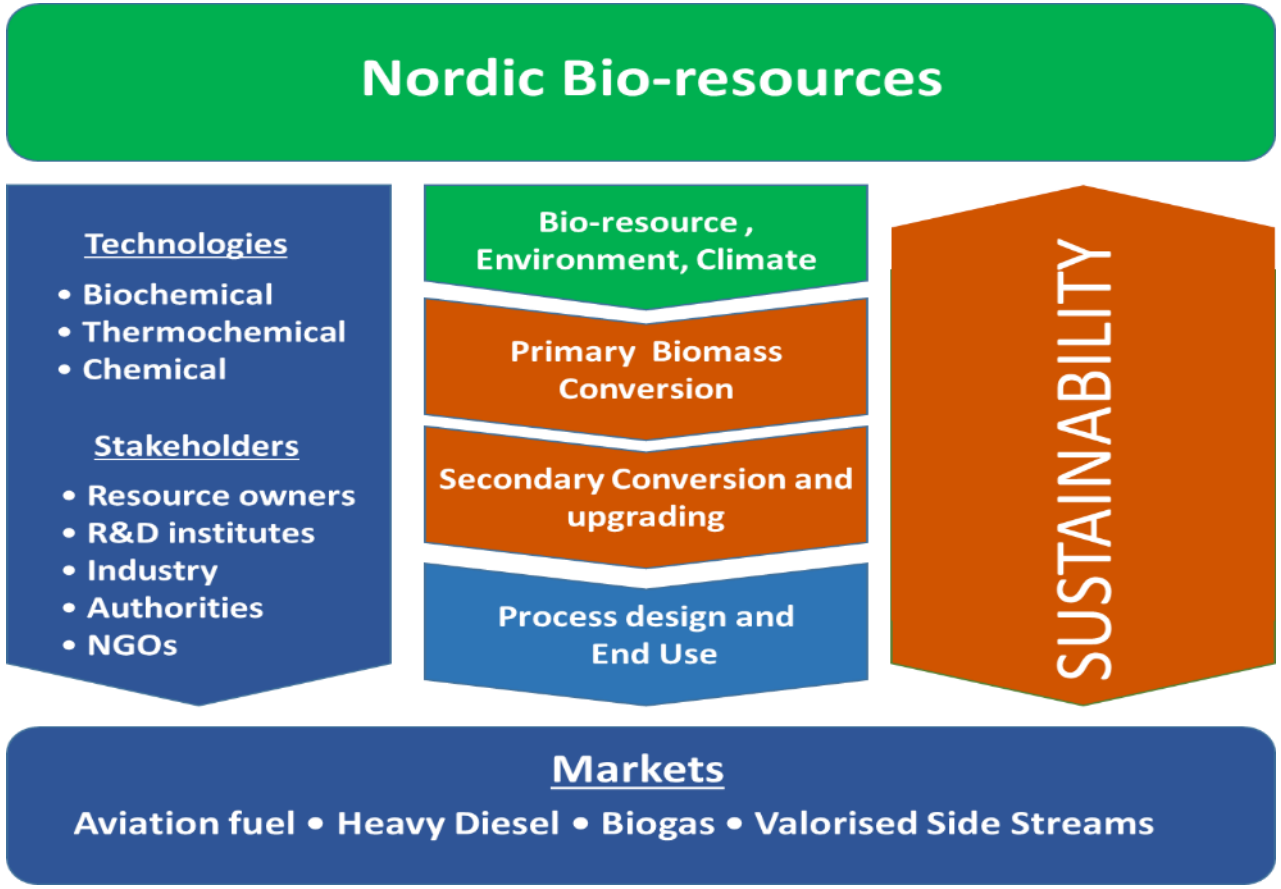
EvalNat report 2024

iCSI highlighted as one of 3 national impact cases in chemistry

- **Bio4Fuels**: FME (Research Centre for Renewable Energy) hosted by NMBU (2017-2025)
  - Most of the relevant research groups in Norway involved

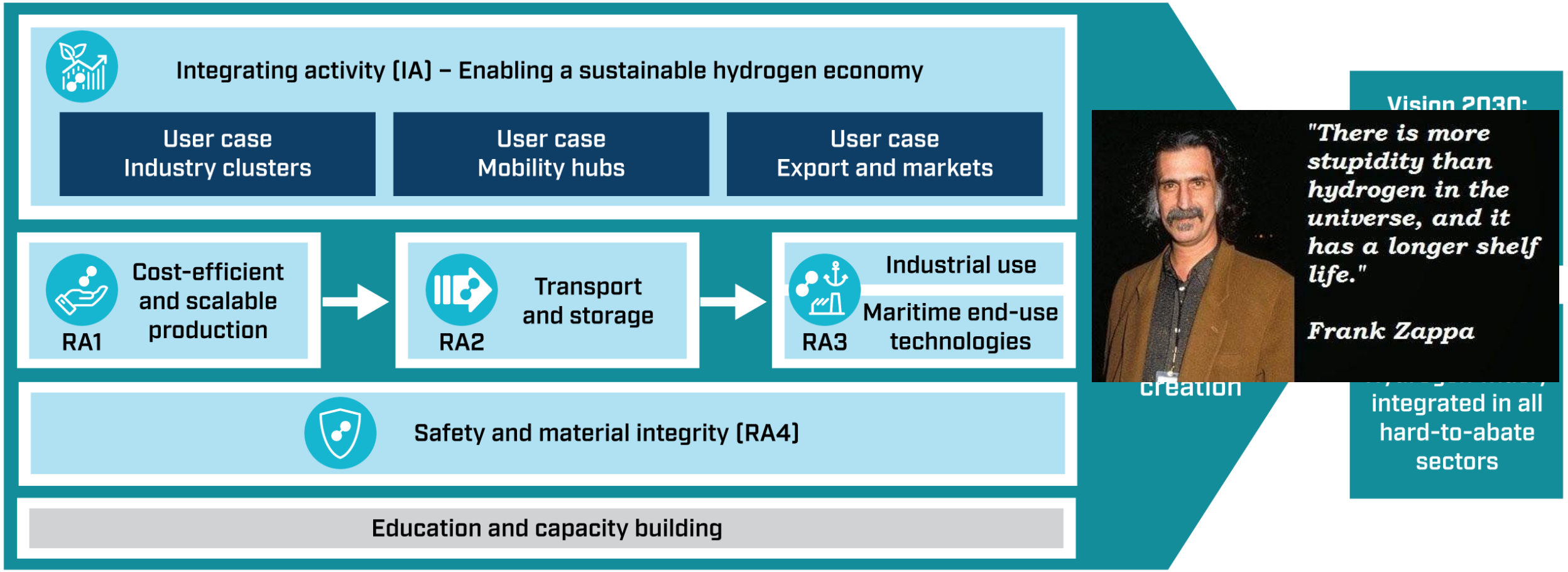
- **Main focus:**

  Transportation fuels
  - High-value by-products/side-products included



https://www.nmbu.no/en/research/projects/bio4fuels

FME HYDROGENi – Hydrogen for net zero by 2050



FME (Research Center for Renewable Energy) hosted by SINTEF (2022-2030)
https://hydrogeni.no/

HYDROGENi partners

R&D partners:

- SINTEF
- IFE Institute for Energy Technology
- NTNU Kunnskap for en bedre verden
- Universitetet i Oslo
- UiT Norges arktiske universitet
- USN Universitetet i Sørøst-Norge

Energy companies:

- equinor
- GASSCO
- wintershall dea
- vår energi

Power companies:

- Statkraft
- ANEO
- NORDKRAFT
- Troms Kraft

Process industries:

- HAVRAND Hydro
- INEOS Tyssedal
- YARA
- Ferrolegeringsindustriens Forskningsforening
- Air Liquide
- CASALE

Maritime operators:

- KONGSBERG
- Bergen Tankers as
- HAVhydrogen
- ABB
- TECO 2030
- HYON
- Corvus Energy
- Wilhelmsen
- SAMSUNG
- SAMSUNG HEAVY INDUSTRIES

Safety specialists:

- DNV
- Havtil
- KYSTVERKET
- SAFETEC
- HYEX SAFETY

Clusters/ Interest groups :

- HERØYA INDUSTRIPARK
- Fornybar Norge
- RENERGY Renewable Energy Cluster
- maritime cleantech
- ENERGI I NORD
- Mo Industripark as

Vendors:

- slb
- AkerSolutions
- GASNOR
- PERMASCAND
- Norwegian Hydrogen
- SICK Sensor Intelligence.
- TechnipFMC
- HYDROGEN MEM-TECH
- AKER HORIZONS
- CoorsTek
- BERGEN ENGINES ON LAND. AT SEA.
- vallourec
- nel
- REINERTSEN NEW ENERGY
- altera
- JOTUN
- hystar
- Z·E·G
- Panametrics a Baker Hughes business

Other

- The Research Council of Norway
- Norwegian Centre for Environmentfriendly Energy Research

Cost-efficient and scalable production – RA1

Research Area 1 aims to develop the necessary technologies for enabling cost-effective and large-scale H_2 and NH_3 production technologies

Green H_2 production

Blue H_2 production

NH_3 production and cracking

KinCat activities:

- **Low-temperature NH_3 cracking**
- **NH_3/H_2 membrane separation**

HYDROGENi

New SFI centre proposal (2024)

Industrial Catalysis 4.0
ICAT 4.0 will enable **industrial development** of the next generation **sustainable low-emission** and **smart chemical processes**

Catalytic processes in the green transition  Application of Artificial Intelligence in Catalysis Research

5 nationally important value chains

- Ammonia
- Methanol
- Low-carbon fuels / SAF
- CO_2
- Critical raw materials

Industry partners:

- Yara
- Dynea
- Equinor
- K.A. Rasmussen
- ++?

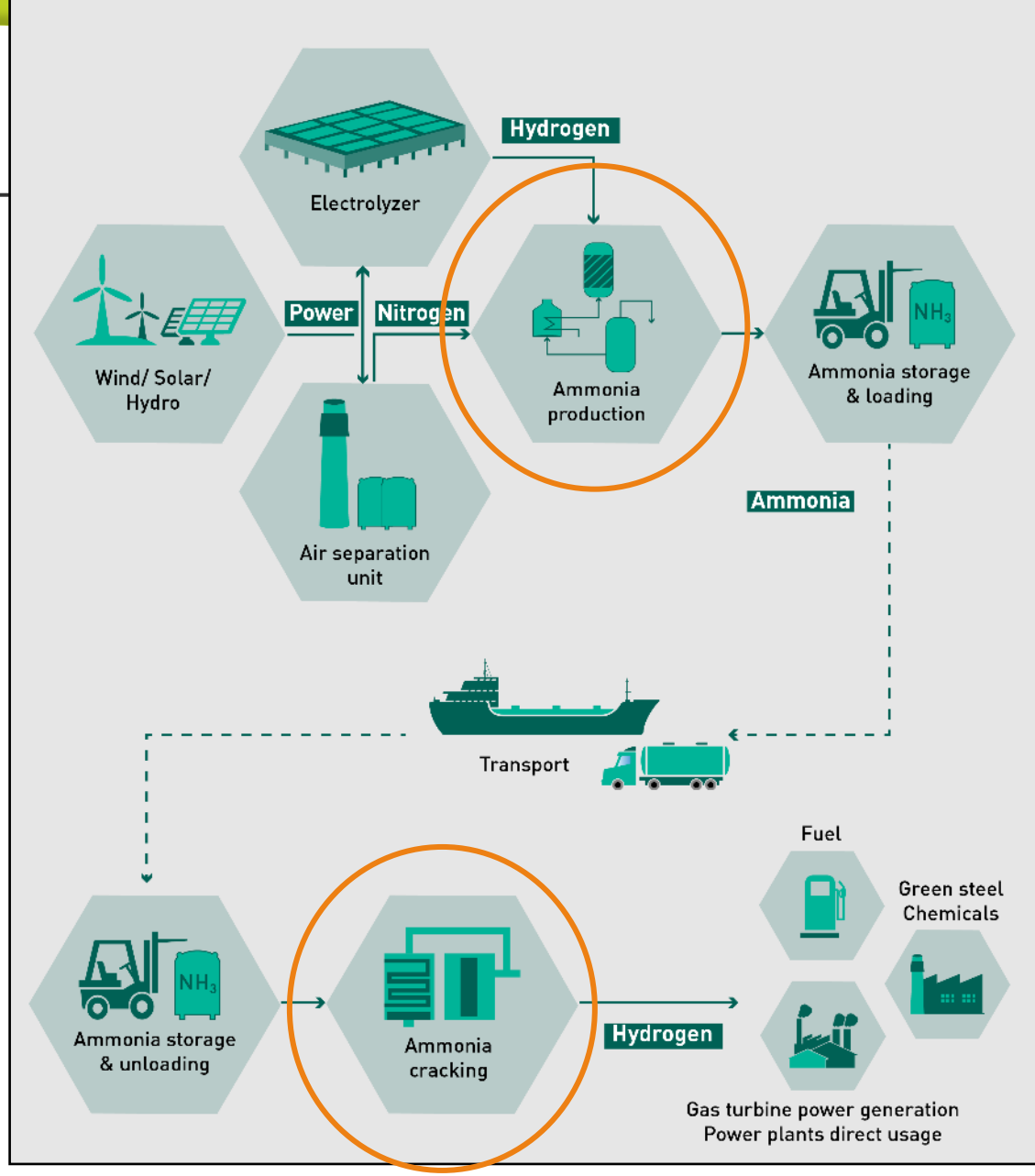
Ammonia as energy carrier

Global commodity, mainly used to produce nitrogen-based fertilizers

Approximately 175 million tonnes are produced annually

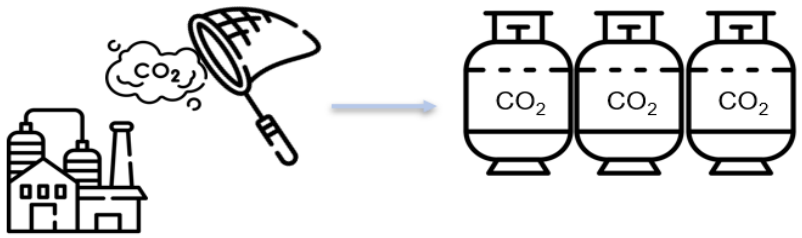
~50% of all nitrogen atoms in your body have passed over a Fe ammonia synthesis catalyst

NH_3 production causes ~1% of total greenhouse gas emissions



Ammonia as Hydrogen carrier | FLEXIM. https://www.flexim.com/us/hydrogen-flowmeters-assisting-energy-transition/ammonia-hydrogen-carrier

Can CO_2 be a feedstock?



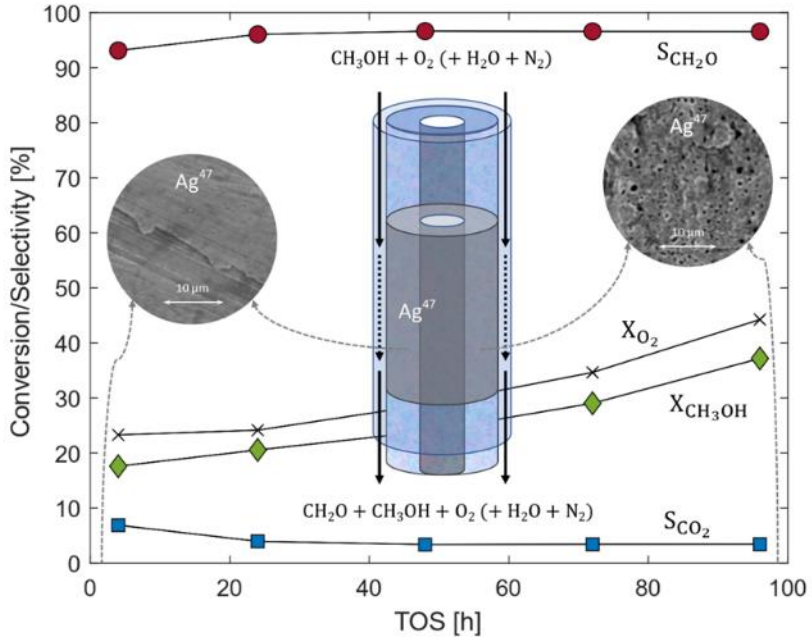
CCSU

- Added-value carbon containing products
- Liquid fuels

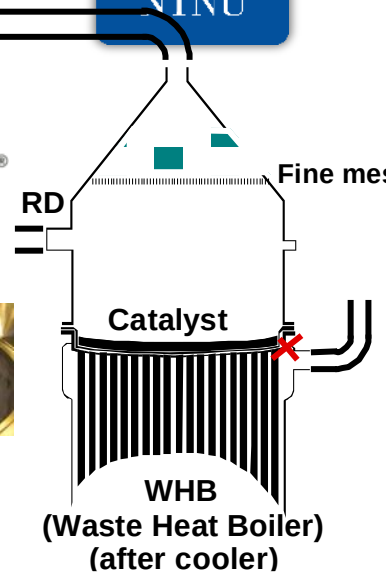
- Decrease in emissions
- Limit to Fossil Fuels consumption

- Severe energy penalties for CO_2 conversion
- But: Chemicals and liquid fuels are needed
- Can we use CO_2 as a carbon source and develop a true circular system?

Frontier formalin technology development



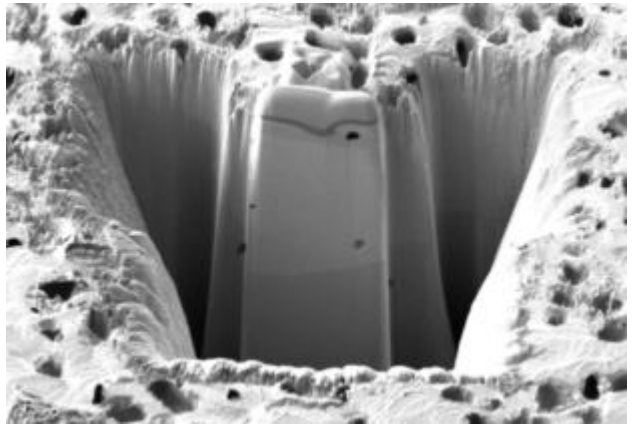
Lervold, S. et al. Chemical Engineering Journal 2021, 423, 130141.



$$CH_3OH_{(g)} \xrightarrow{O_{(a)}} CH_2O_{(g)} + H_{2(g)} \qquad \Delta H = +84\ \frac{kJ}{mol}$$

$$CH_3OH_{(g)} + \frac{1}{2}O_2 \rightarrow CH_2O_{(g)} + H_2O_{(g)} \qquad \Delta H = -159\ \frac{kJ}{mol}$$

FIB-SEM tomography



- ✓ New kinetic and mechanistic insights through annular reactor concept
- ✓ New knowledge on (O, H) dissolution, induced restructuring dynamics and mechanistic impact
- ✓ Refined industrial test protocols and global kinetic model (SINTEF Industry)

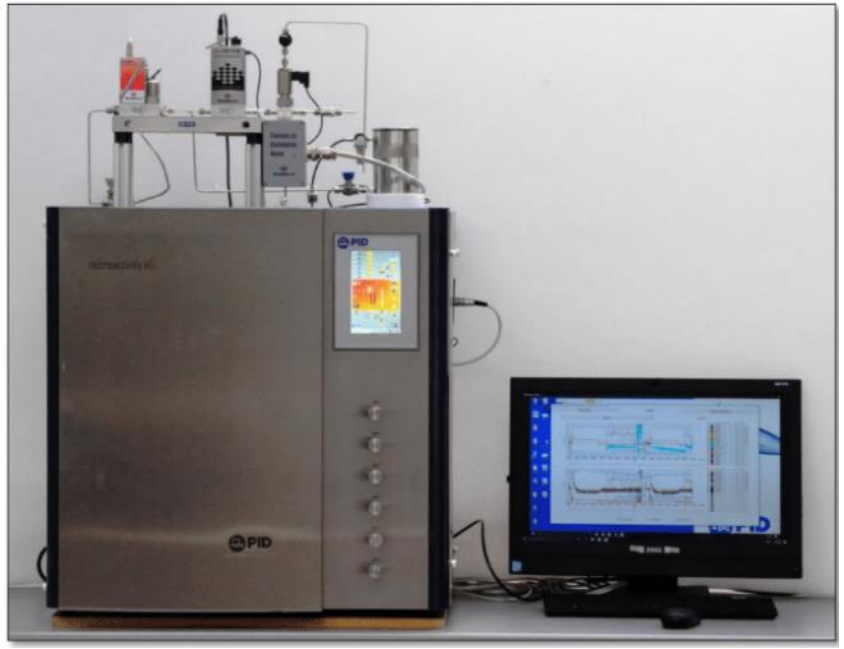
Infrastructure and tools

- **International facilities**
  - ESRF, Max-Lab, etc
- **National infrastructure**
  - NTNU NanoLab
  - RECX
  - NorTEM
- **Computational tools**
  - Sigma2 supercomputer
  - IDUN cluster at NTNU
- **Our own labs**
  - Catalyst synthesis, characterisation and testing facilities
  - Lab tour later today!

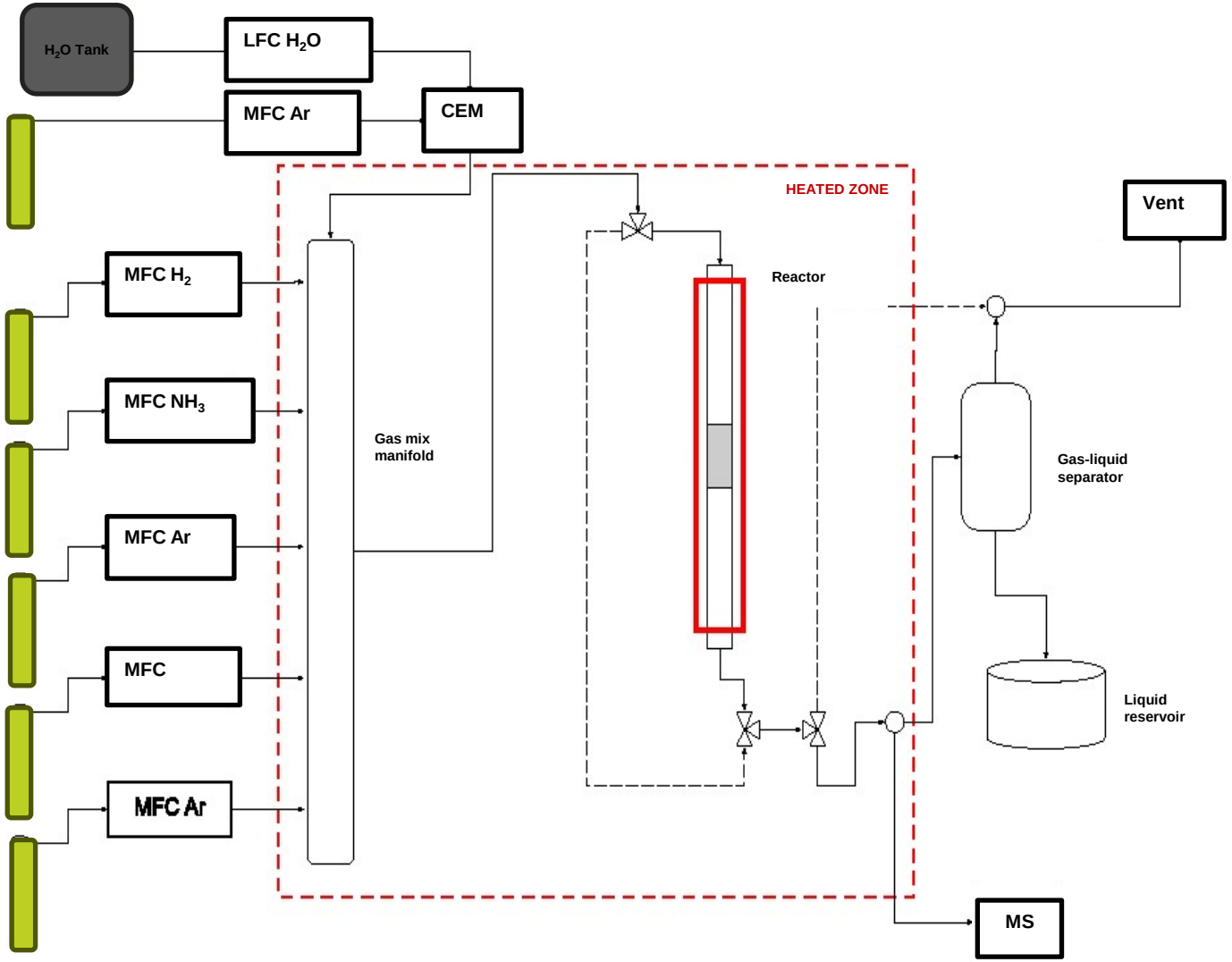
The European Synchrotron Radiation Facility (ESRF)

Catalyst testing – kinetics

-Our bread and butter

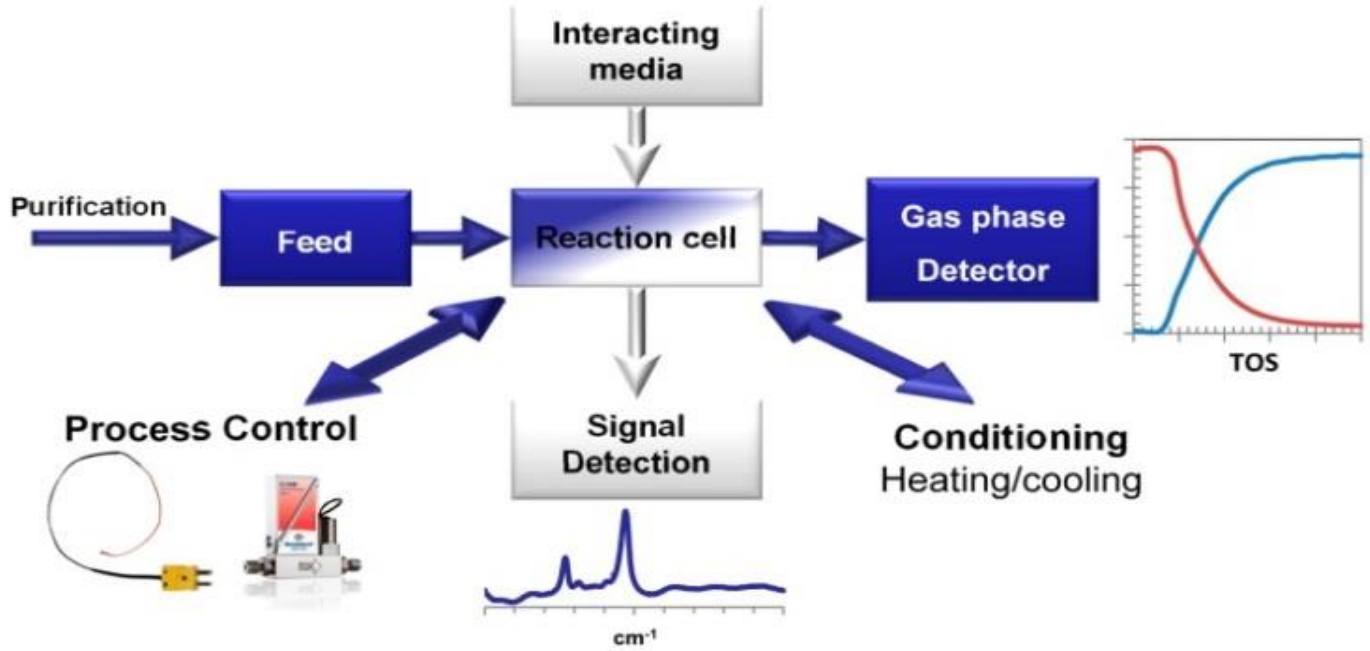


PID/ Micromeritics
Microactivity-EFFI unit



Operando characterisation in catalysis

-Adapting the properties of an industrial reactor along two axes



N.E. Tsakoumis, A.P.E. York, D. Chen, M. Rønning, *Catal. Sci. Technol. 5 (2015) 4859-4883*

Swiss-Norwegian Beamlines (SNBL) at ESRF

-BM31

- X-ray absorption spectroscopy
- Powder X-ray diffraction
- Pair distribution function (pdf)
- UV-Vis-NIR spectroscopy
- Time-resolved measurements
- Controlled reaction conditions
- Mass spectrometry analysis
- 30 years of development

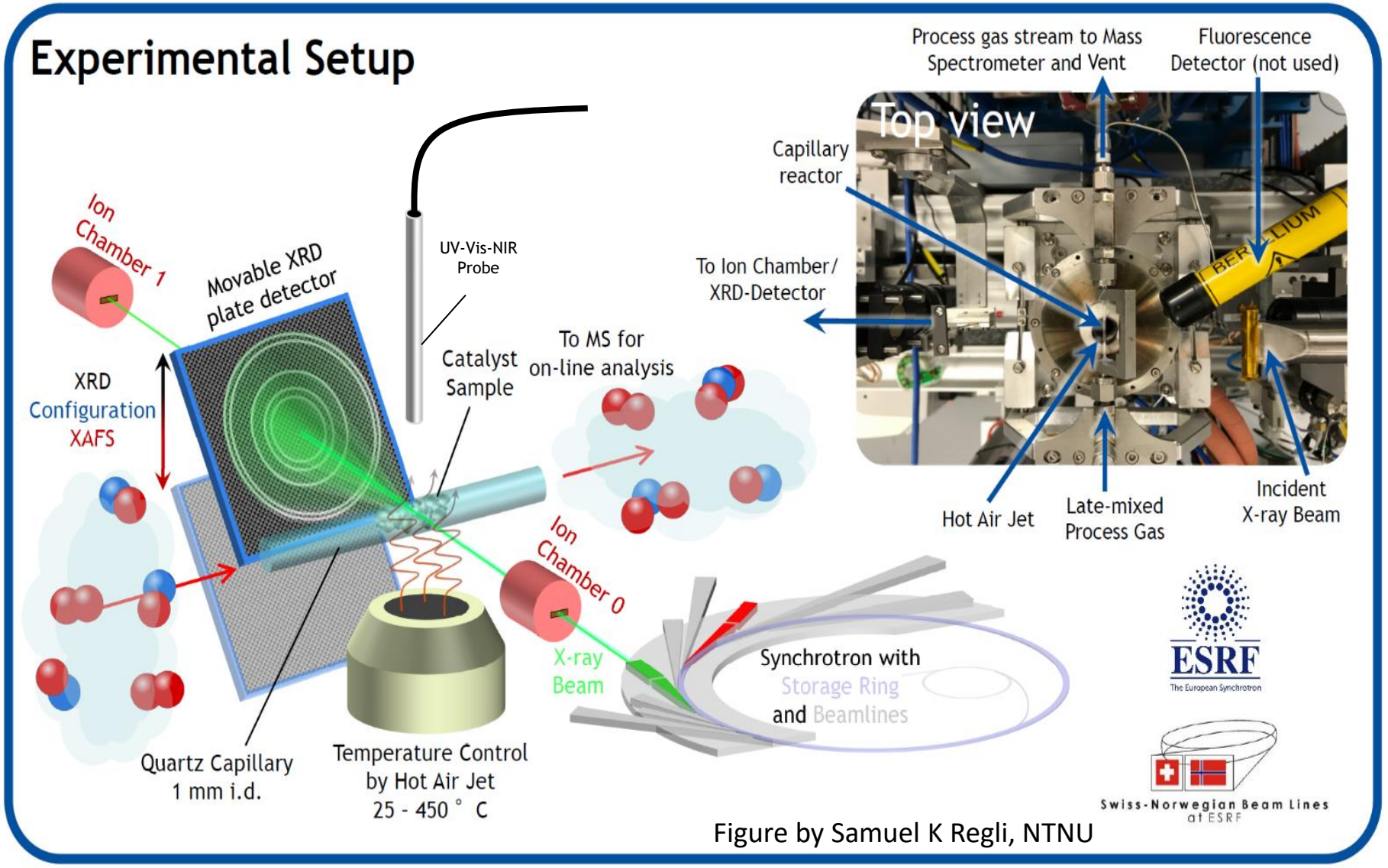


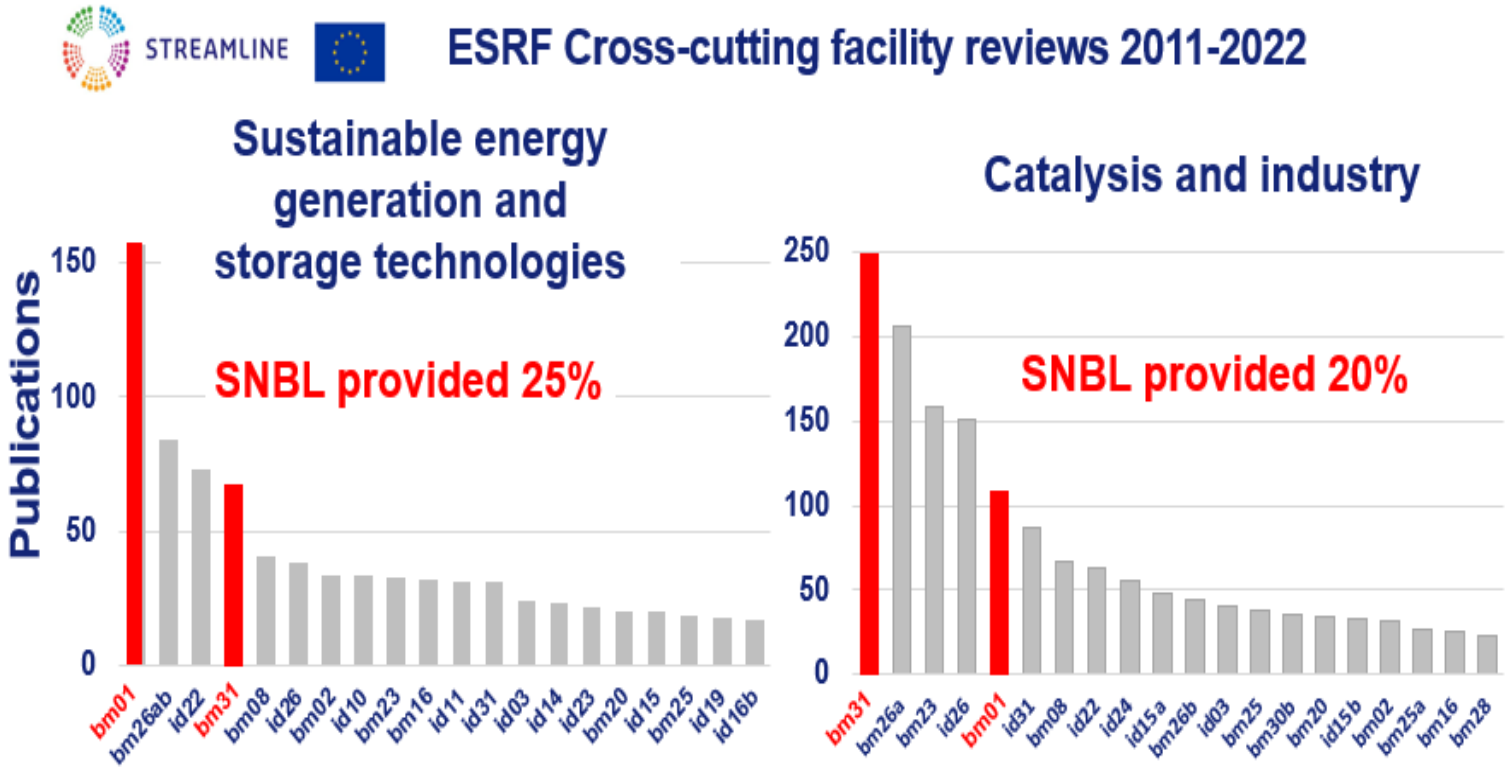
Figure by Samuel K Regli, NTNU

The Swiss-Norwegian Beamlines (SNBL)

From about 30 beamlines in total at ESRF:

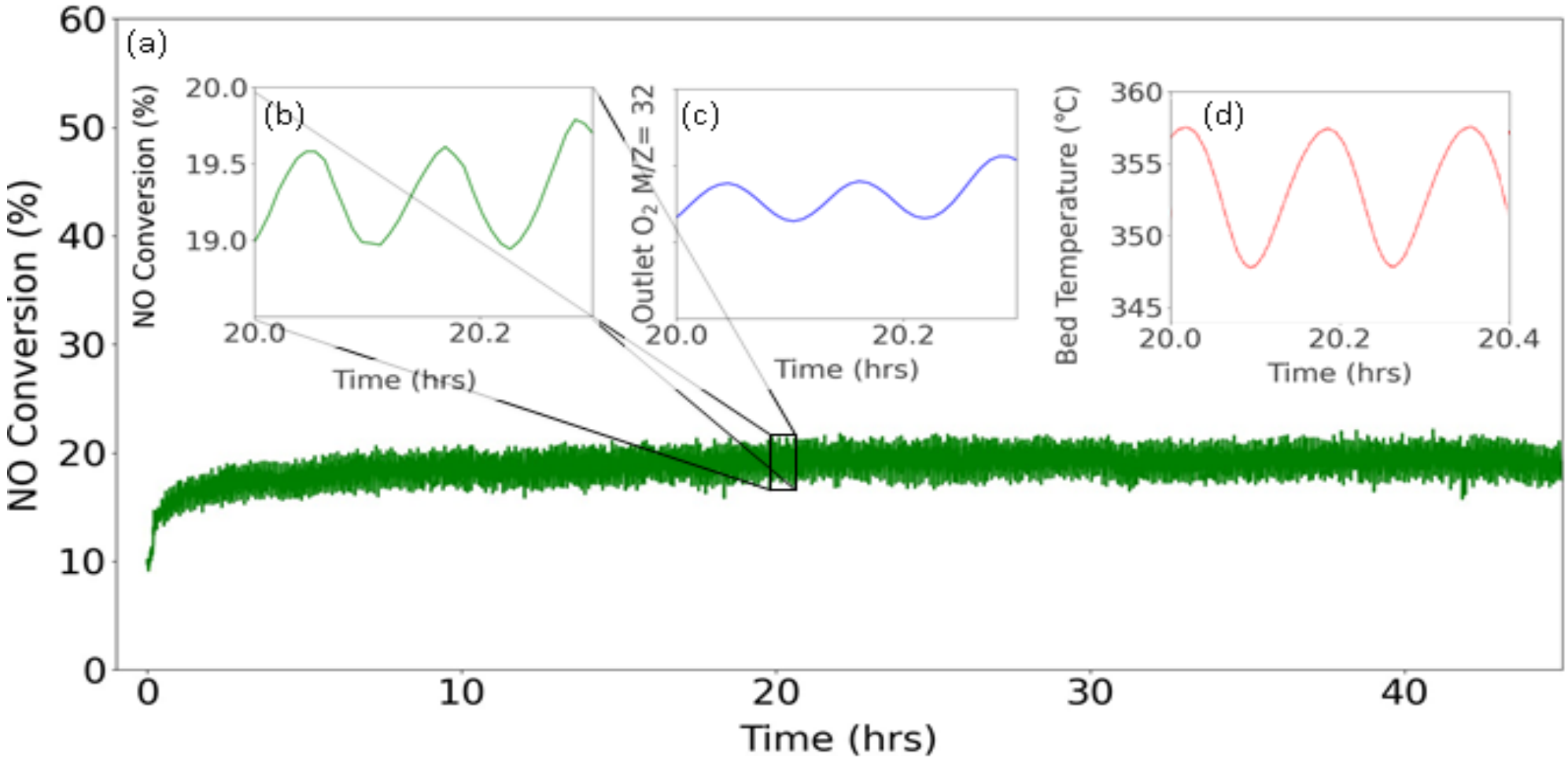
The output from the 2 SNBL beam-lines stands out

Only 7% of the available beamtime at ESRF, but 20-25% of the output publications



Swiss-Norwegian Beam Lines at ESRF

Operando XAS of NO oxidation to NO_2 for nitric acid production over Ru/γ-Al_2O_3

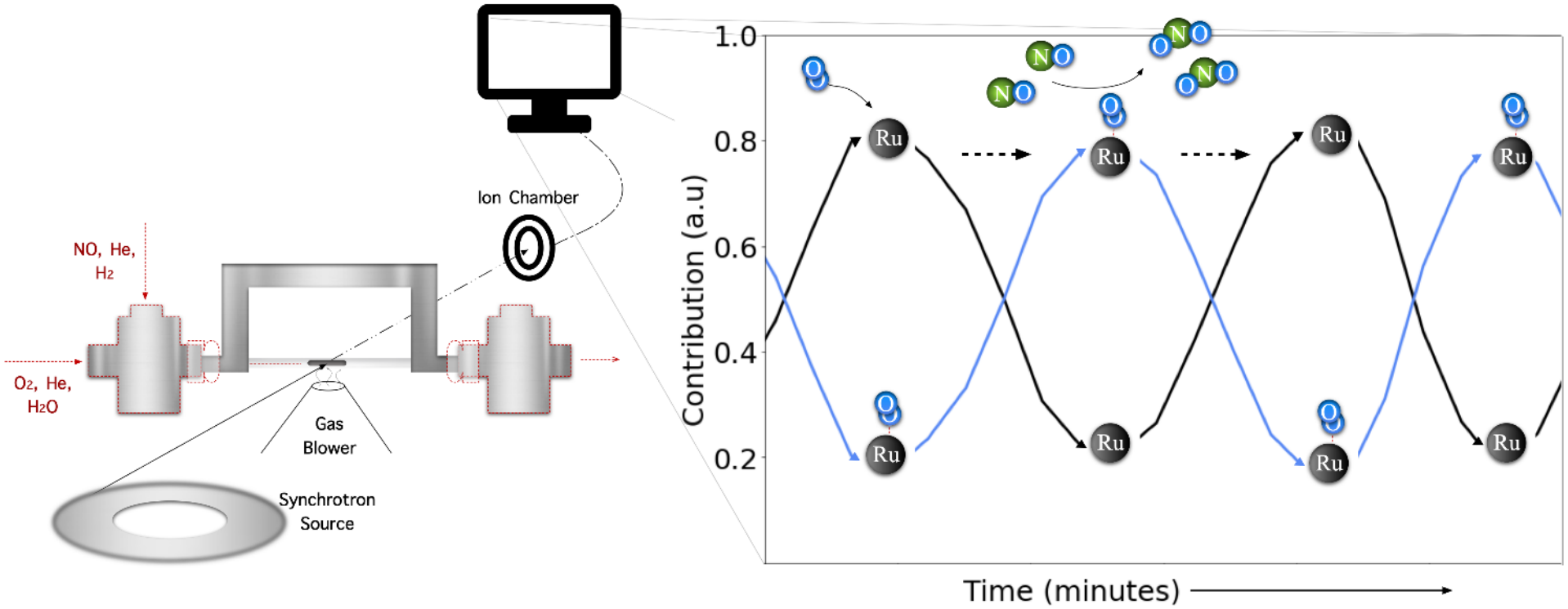


J. Gopakumar, P.M. Benum, I.-H. Svenum, B.C. Enger, D. Waller, M. Rønning, Chem. Eng. J., 475 (2023) 146406

Operando XAS of NO oxidation to NO_2 for nitric acid production over Ru/γ-Al_2O_3

Sample	Ru^0	Ru^{+4}	Reduced χ^2 (10^{-4})
$Component_A$	99.6%	0.4%	2.6
$Component_B$	71.6%	28.4%	1.1

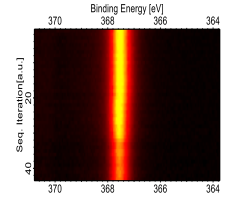
Bulk Ru
Surface Ru

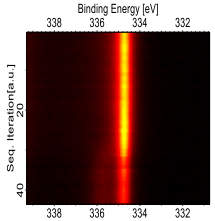


J. Gopakumar, P.M. Benum, I.-H. Svenum, B.C. Enger, D. Waller, M. Rønning, Chem. Eng. J., 475 (2023) 146406

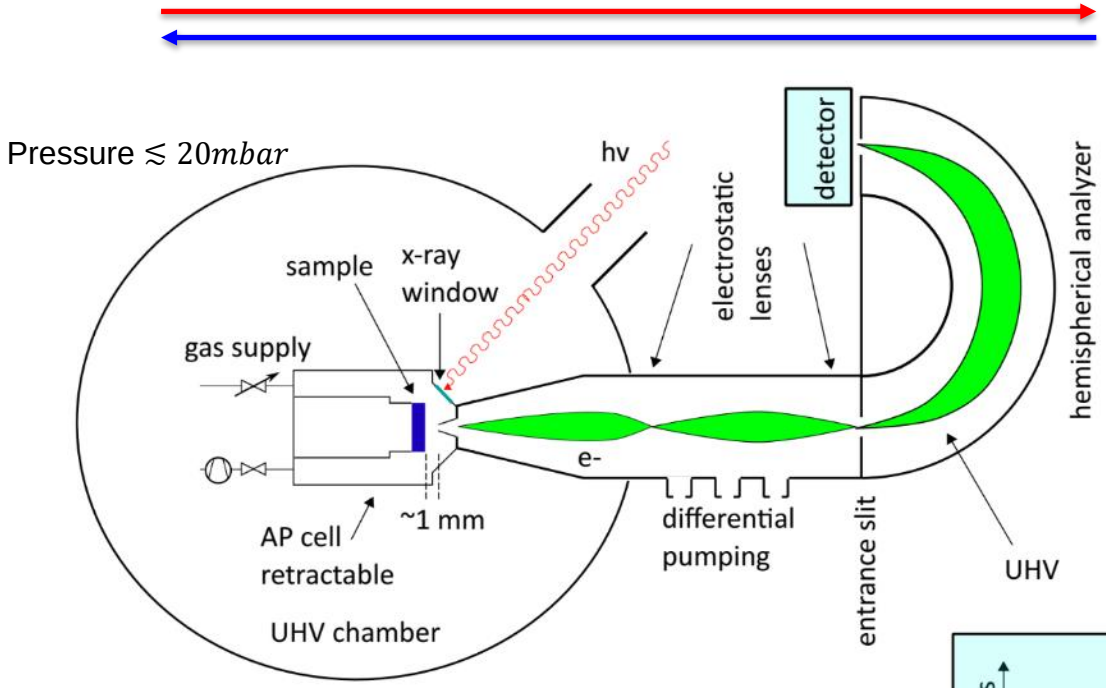
Near ambient pressure XPS

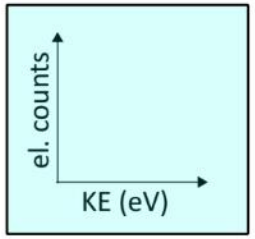
XPS core level dynamics





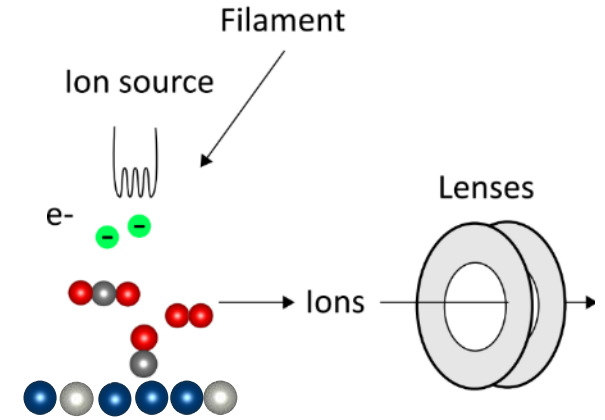
Temperature cycling (example)



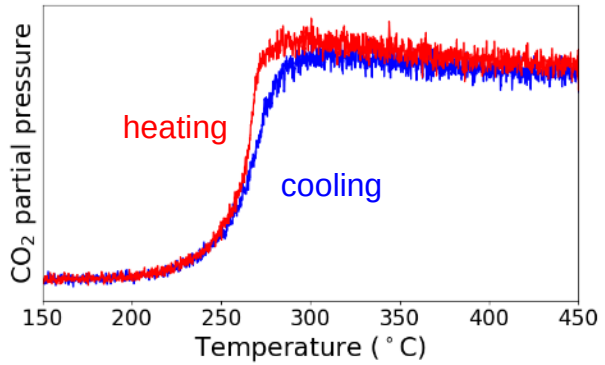


MAX IV Laboratory
HIPPIE beamline

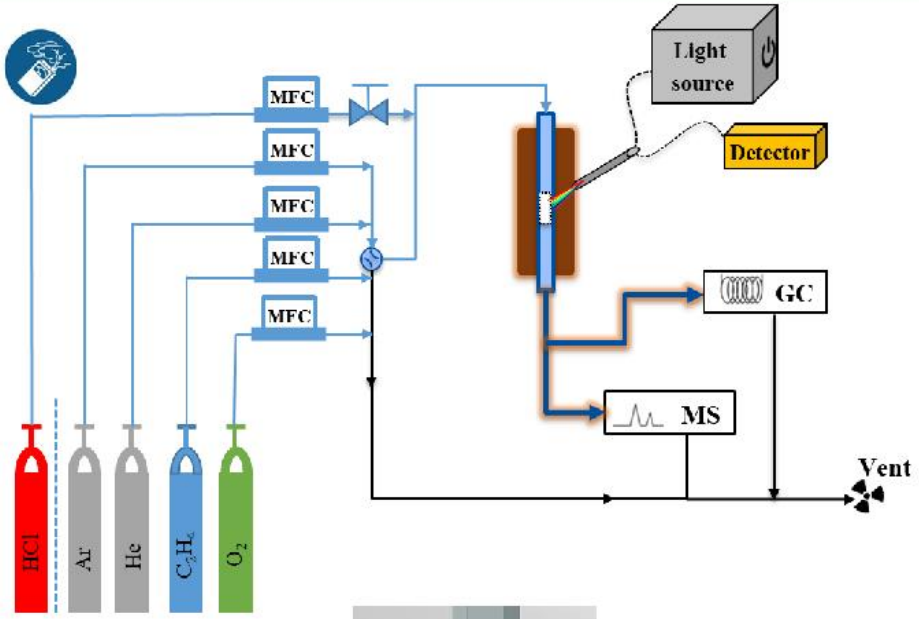
Reactants/products (QMS)

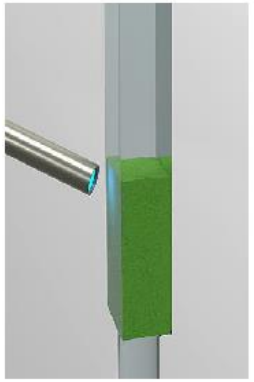


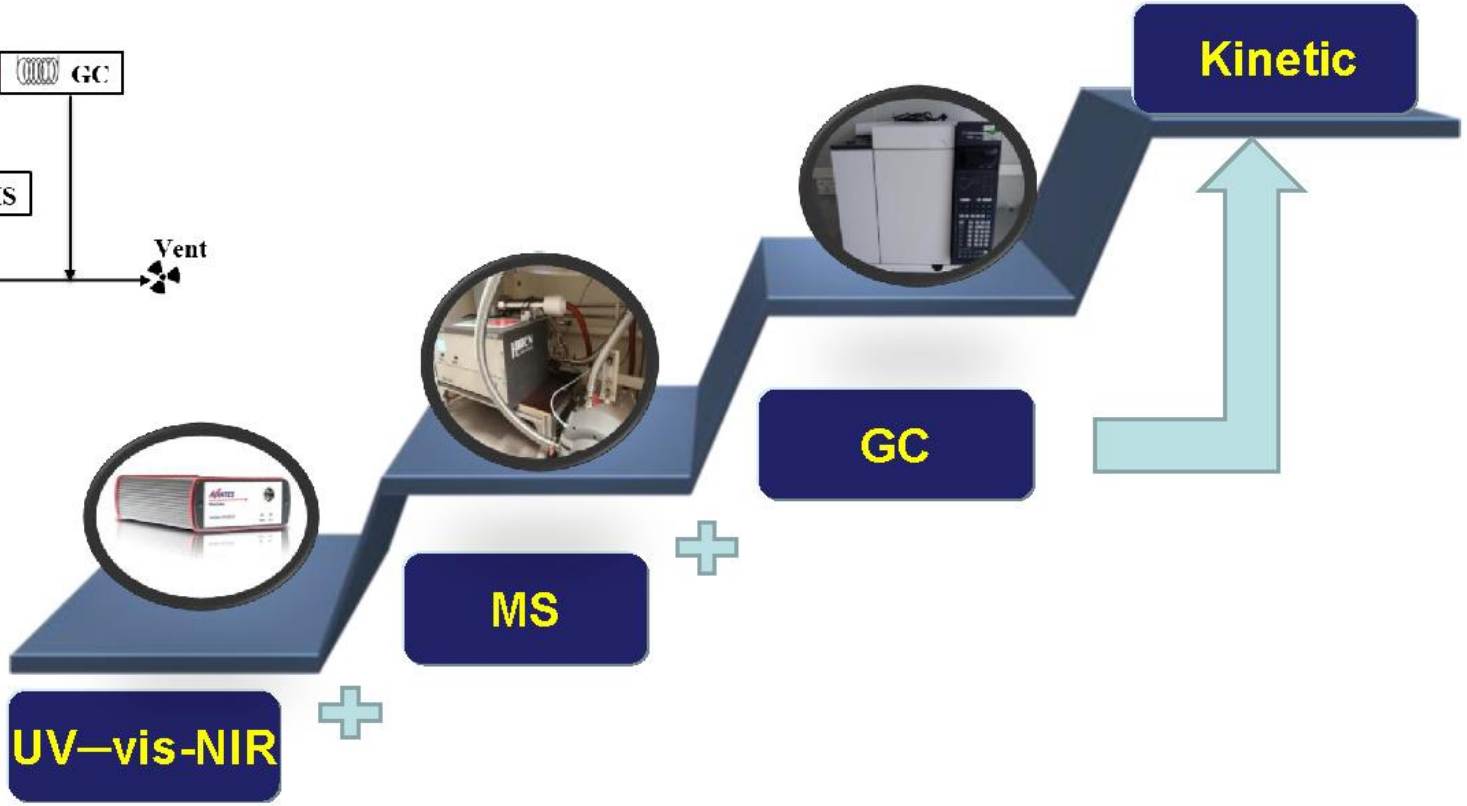
Sample surface,
(for example PdAg)



Operando setup schematic: kinetic study of time and spatial evolution of metal oxidation state



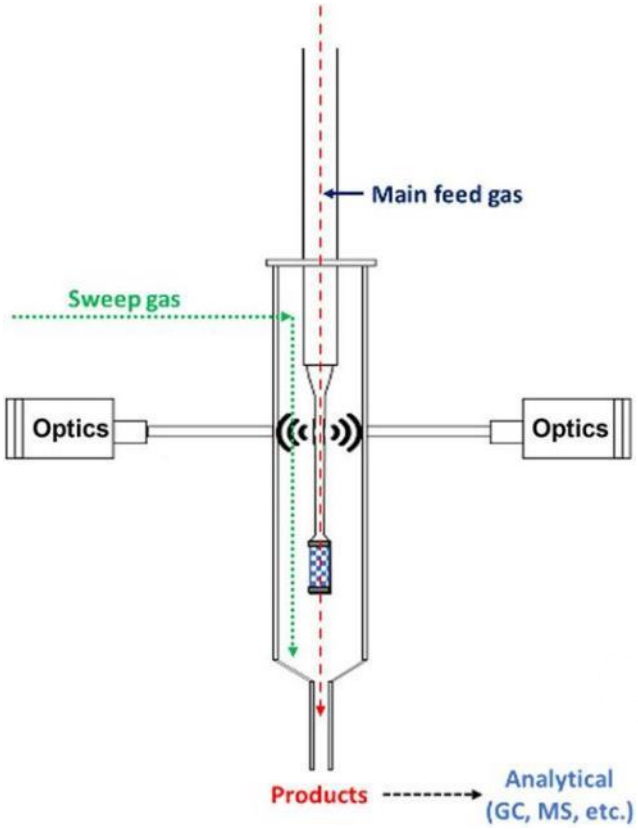




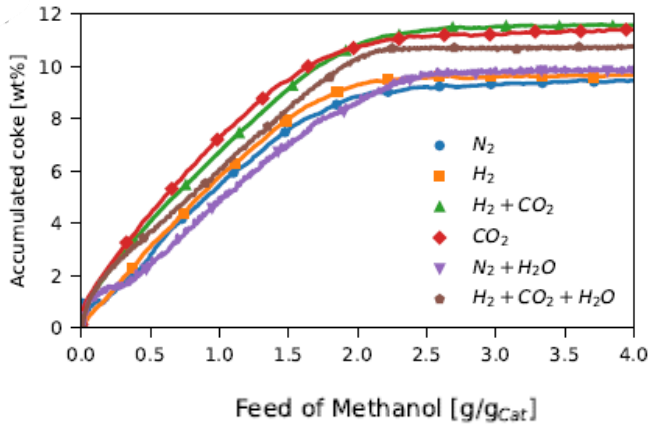
ACS Catalysis, 6(10), 2016, 7030 , J. Catal. 352 (2017) 218

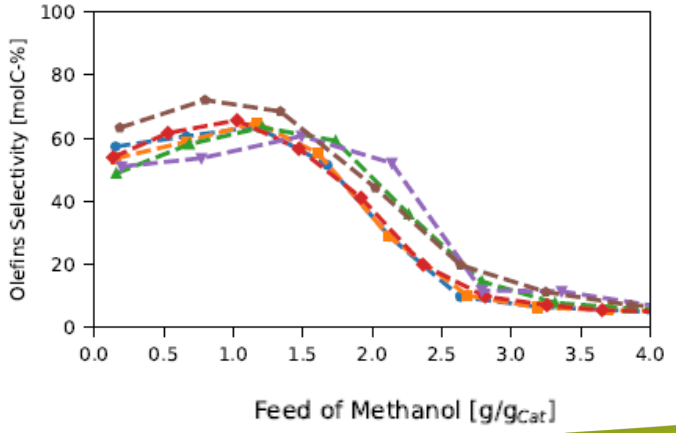
NTNU

ISMA - In Situ Mass Analyzer



- Oscillating microbalance reactor
  - Continuous flow catalytic reactor with plug flow characteristics
  - Mass measurement detects mass changes during reaction
    - $\Delta m = k_o (1/f_1^2 - 1/f_o^2)$
- Operando characterization of all processes leading to mass change of a catalyst
  - Coking
  - Oxidation
  - Reduction
  - Vaporization
  - …….
- Example: Preliminary experiments looking at MTO over SAPO-34 Coking (left) and olefins selectivity (right):





Sketch: A. Karlsson et al.,
Rev. Sci. Instrum. 94, 065108 (2023)

Methods: Scanning precession electron diffraction (SPED)

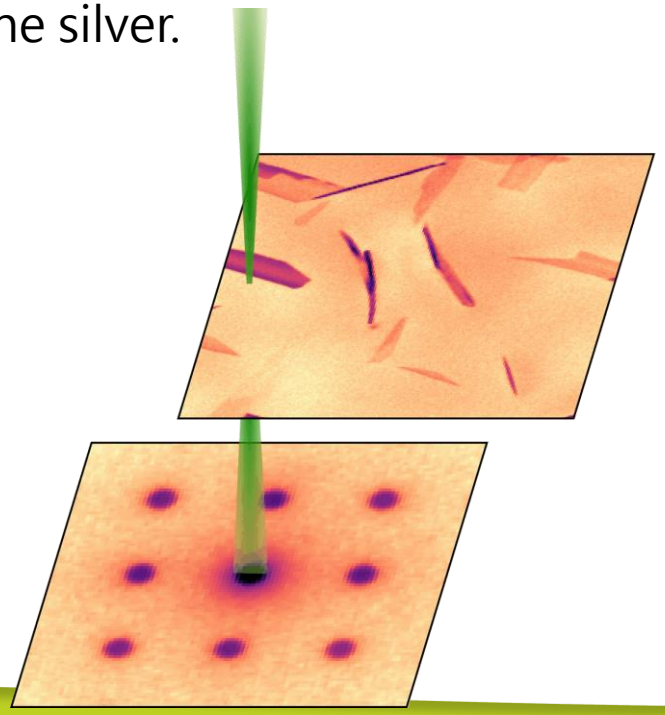
4D-STEM

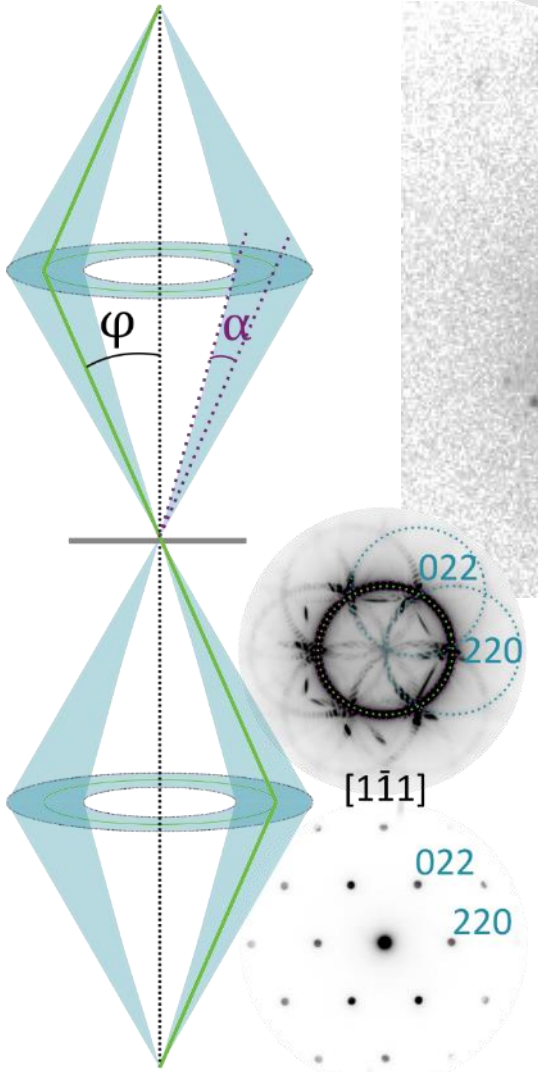
What SPED is a 4D-STEM method. The beam (∽1 nm) is precessed and scanned while a 2D diffraction pattern is collected at each probe position.

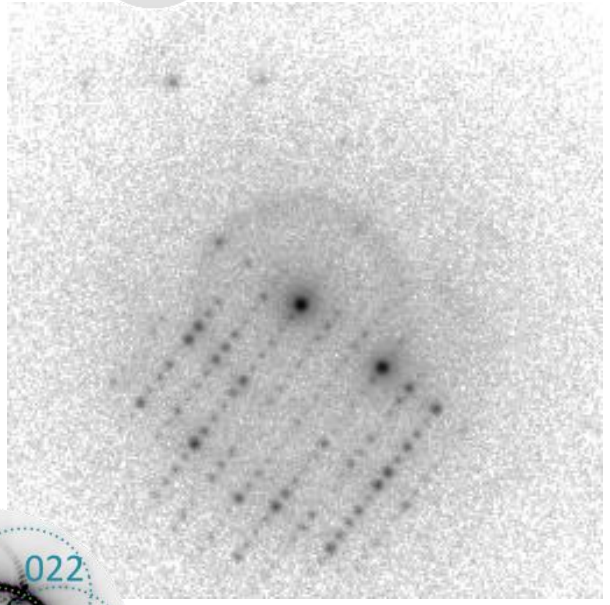
How 4D datasets are collected from FIB-made cross-sectional lamellae, analysed by template matching using *pyxem*, and visualised using *MTEX*.

Why The local crystal orientation is obtained in the in the (sub-)surface of the silver.

Indirectly see the crystal with **lower dose** and **better statistics** than atomic resolution imaging







30

Materials modelling of catalytic systems

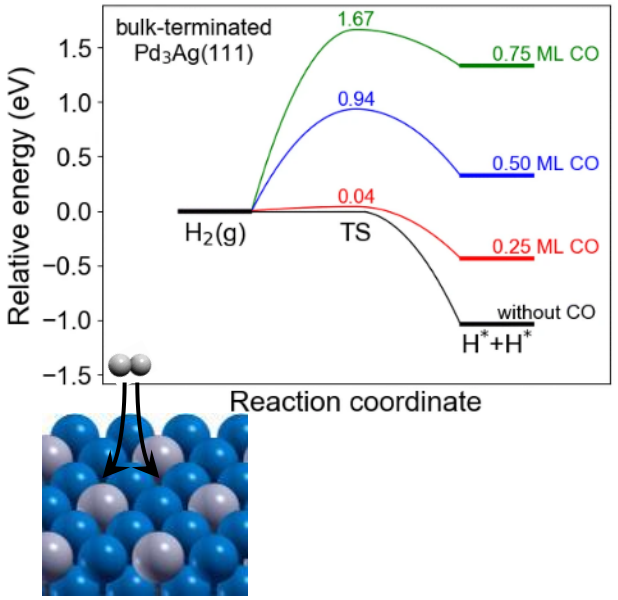
We use density functional theory (DFT) to gain information about

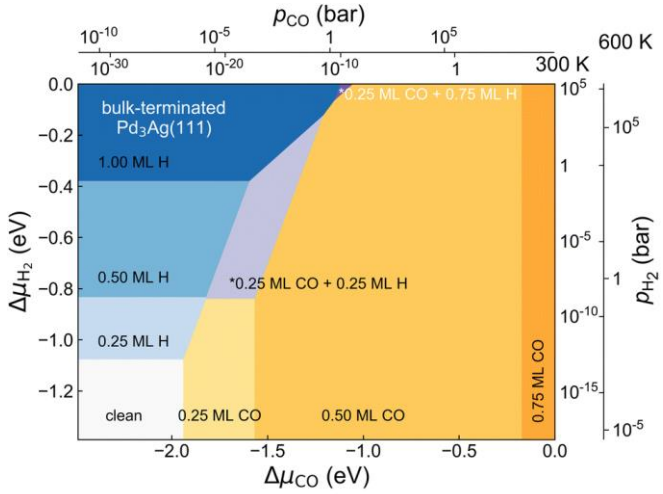
- Structures and energetics
- Thermodynamics
- Reaction kinetics

→ mechanistic insight

↔ Interplay with experiments

PdAg systems and CO inhibition (H2MemX project)





Svenum et al. Top. Catal. (2021)

Supercomputing facilities provided by Sigma2

https://www.sigma2.no/hpc-and-storage-systems

Internationalisation

European Commission

Marie Skłodowska-Curie Actions

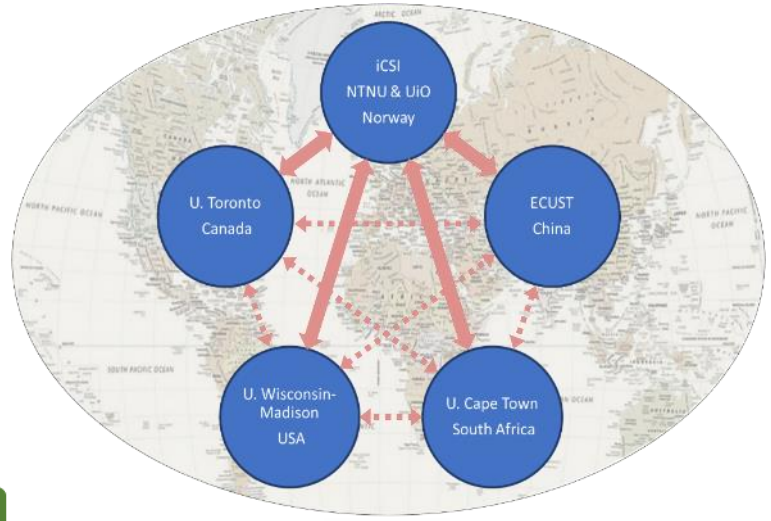
The Research Council of Norway

INTPART - CATHEX

FAST CARD

MesoSi - CO_2

Design of low-cost and carbon-resistant Ni-based mesoporous silica for chemical CO_2 utilization through tri-reforming of methane



MONACAT

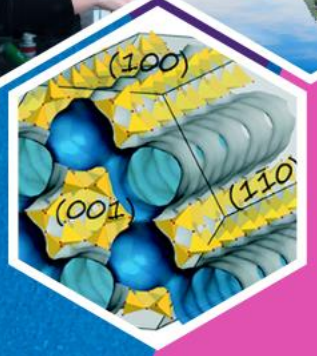
FREECATS
Doped Carbon Nanostructures as Metal-Free Catalysts

BIKE

TEMPORARY LOGO
C-NET

EFCATS
European Federation of Catalysis Societies

Mastering the Force of Catalysis



EUROPACAT

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August 31th - September 5th, 2025

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