P2XEnable – Remarkable CO_2 emission reductions by modular power-to-X technologies

1.3.2020 – 31.12.2023

Budget 2.1 M€ (Business Finland 1.47 M€)

Content

P2X ENABLE

Soletair Power Oy:
- Funding: BuFi & Soletair Power
- Duration: 2a
- Budget ca. 1 M€

Public project startup 03/2020, duration 2.4a

Wärtsilä Oyj:
- Funding: BuFi & Wärtsilä
- Duration: 2a
- Budget 2.5 M€

Public research project P2XENABLE:
- LUT, 1.775 M€, 2.4 a
- Aalto, 0.325 M€, 2.4 a
- Funding: BuFi 70%, LUT 20.1%, Aalto 3.7% companies 6.2%
- Research agreement between parties

Public research funding by project partners:
- Wärtsilä Oyj: 40 k€
- ABB Oy: 40 k€
- Solar Foods Oy: 20 k€
- Soletair Power Oy: 10 k€
- Elstor Oy: 10 k€
- CarbonReUse Finland Oy: 5 k€
- SMA Mineral Oy: 5 k€

WP1: PtX-technologies

How to improve energy and cost efficiency, and enable modularity with the technology research?

- Power electronics for electrolysis
- CO_2 direct air and seawater capture
- Methanol synthesis from H_2 and CO_2
- PtX and thermal energy storage

WP2: PtX in buildings

What could be the role of PtX for example in buildings? Where are the sweet spots for the business?

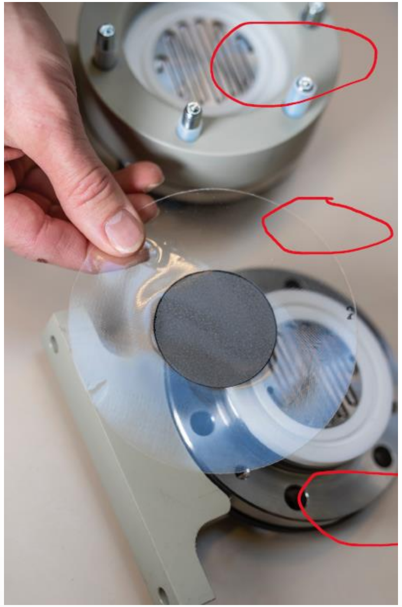
WP3: PtX techno-economics and business potential in global-local perspective

What is the techno-economics and future business potential of selected PtX applications?

WP1.1: Power electronics for electrolysis

Antti Kosonen, Jero Ahola, Vesa Ruuskanen, Georgios Sakas, Alejandro Ibáñez-Rioja, Pietari Puranen, Lauri Järvinen, Joonas Koponen

Content



PEM water electrolyzer performance

- Power quality effect
  - Energy efficiency and degradation
  - A parallel single cells PEM test bench delayed too much ⇒ Measurement carried out in FZJ

Plant level modelling

- Industrial alkaline water electrolysis
  - 3 MW plant level AWE model to analyze the operation
  - Analysis of stray currents in AWE (in collaboration with FinH2 project)
- Off-grid water electrolyzer plant dimensioning and control
  - Solar-battery-5 kW PEMWE
  - Solar-wind-battery-100 MW AWE

Standardization

- Participation to the working group "EU harmonised testing procedure: Determination of water electrolyser energy performance"

Networking

- Collaboration with FZJ, KIT (Energy Lab 2.0), DTU, EERA JP ES, and StoRIES
- 3 months research visit in autumn 2022 to FZJ

Publications (1/2)

Journal

- A. Ibáñez-Rioja, L. Järvinen, P. Puranen, A. Kosonen, V. Ruuskanen, K. Hynynen, J. Ahola, P. Kauranen, Off-grid solar PV-wind power-battery-water electrolyzer plant: Simultaneous optimization of component capacities and system control, to be published.
- G. Sakas, A. Ibáñez-Rioja, L. Järvinen, S. Pöyhönen, A. Kosonen, V. Ruuskanen, J. Ahola, Sensitivity analysis on the process conditions that affect the shunt currents and SEC in a bipolar configuration stack of an industrial scale alkaline water electrolyzer process, to be published.
- A. Ibáñez-Rioja, P. Puranen, L. Järvinen, A. Kosonen, V. Ruuskanen, J. Ahola, J. Koponen, Simulation methodology for an off-grid solar-battery-water electrolyzer plant: Simultaneous optimization of component capacities and system control, Appl. Energ. 307 (2022), https://doi.org/10.1016/j.apenergy.2021.118157.
- G. Sakas, A. Ibáñez-Rioja, V. Ruuskanen, A. Kosonen, J. Ahola, O. Bergmann, Dynamic energy and mass balance model for an industrial alkaline water electrolyzer plant process, Int. J. Hydrogen Energy 47 (7) (2022) 4328–4345, https://doi.org/10.1016/j.ijhydene.2021.11.126.
- P. Puranen, A. Kosonen, J. Ahola, Technical feasibility evaluation of a solar PV based off-grid domestic energy system with battery and hydrogen energy storage in northern climates, Solar Energy, 213 (2021) 246–259, https://doi.org/10.1016/j.solener.2020.10.089.
- J. Koponen, V. Ruuskanen, M. Hehemann, E. Rauls, A. Kosonen, J. Ahola, D. Stolten, Effect of power quality on the design of proton exchange membrane water electrolysis systems, Appl. Energ., 279 (2020), https://doi.org/10.1016/j.apenergy.2020.115791.

Publications (2/2)

Book chapter

- Chapter contribution for springer book: Smart Grids – Renewable Energy, Power Electronics, Signal Processing and Communication Systems Applications, accepted

Conferences

- A. Ibáñez-Rioja, P. Puranen, L. Järvinen, A. Kosonen, K. Hynynen, V. Ruuskanen, J. Ahola, P. Kauranen, Off-grid solar PV-wind power-battery-water electrolyser plant: Simultaneous optimization of component capacities and system control, *3rd Int. Conf. Electrolysis 2021*, Jun. 2022, Colorado, USA.
- G. Sakas, A. Ibáñez-Rioja, V. Ruuskanen, A. Kosonen, J. Ahola, O. Bergmann, Dynamic energy and mass balance model for an industrial alkaline water electrolyzer plant process, *3rd Int. Conf. Electrolysis 2021*, Jun. 2022, Colorado, USA.

M.Sc. thesis

- L. Järvinen, Design of a PEM electrolyzer test station for experimentation on power quality induced efficiency loss and cell degradation, M.Sc. Thesis, 2020, 76 p. http://urn.fi/URN:NBN:fi-fe2020120899854.

Power quality effect on PEMWE cell energy efficiency

Effect of Power Quality on the Design of PEM Water Electrolysis Systems

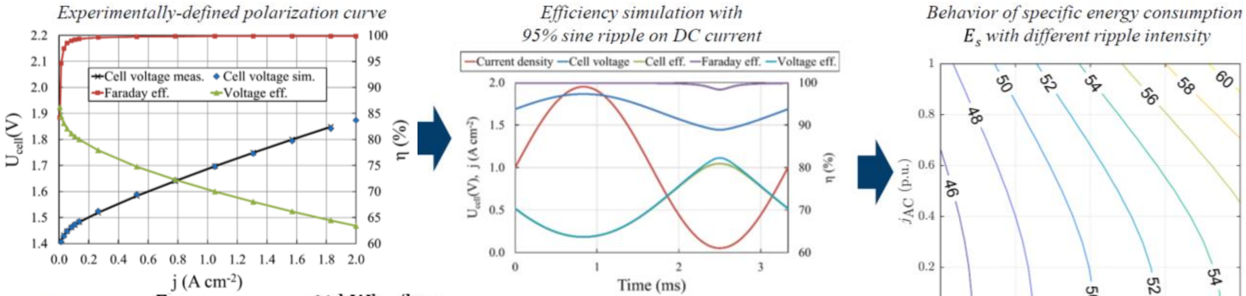
Joonas Koponen*, Vesa Ruuskanen*, Michael Hehemann (corresponding author), Edward Rauls, Antti Kosonen*, Jero Ahola* and Detlef Stolten

*= LUT University

Problem: Easy (and cheap) AC/DC converters generate DC current with significant ripples
➡ Typical for industrial 12-pulse thyristor bridge based converters

Question: *What is the effect of different current ripples on the specific energy consumption for H_2 production?*

Approach: Semi-empirical simulation model for PEM electrolysis efficiency (Nafion 117, 75°C)



Results: $\frac{E_{s\ worst\ case}}{E_{s\ ideal}} = \frac{61\ kWh_{el}/kgH_2}{55\ kWh_{el}/kgH_2} = 110\%$ (@ 3 A cm⁻², sine ripple)

same E_s ➡ $\frac{A_{cell\ worst\ case}}{A_{cell\ ideal}} = 500\%$, (saw tooth ripple = 12-pulse thyristor rectifier)

Mitglied der Helmholtz-Gemeinschaft IEK-14: Institute of Electrochemical Process Engineering

JÜLICH Forschungszentrum

- Current ripple
  - Causes additional losses ⇒ increases specific energy consumption (SEC)
  - Effect can be compensated by increasing the cell area, but it would not be feasible

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Dynamic modelling of industrial alkaline water electrolysis plant

More than 10 % of current is leakage current ⇒ It does not produce hydrogen. The problem gets worse at partial loads.

Electro chemists are working with this, mostly catalysts and membranes. Overpotentials are reduced at partial loads.

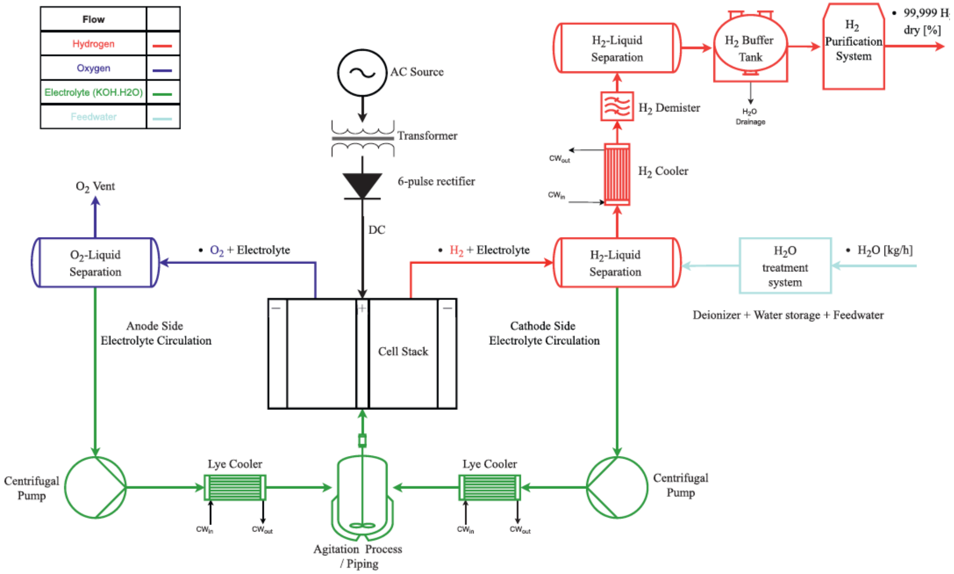


Fig. 1 — Formulated alkaline water electrolyzer plant process diagram.

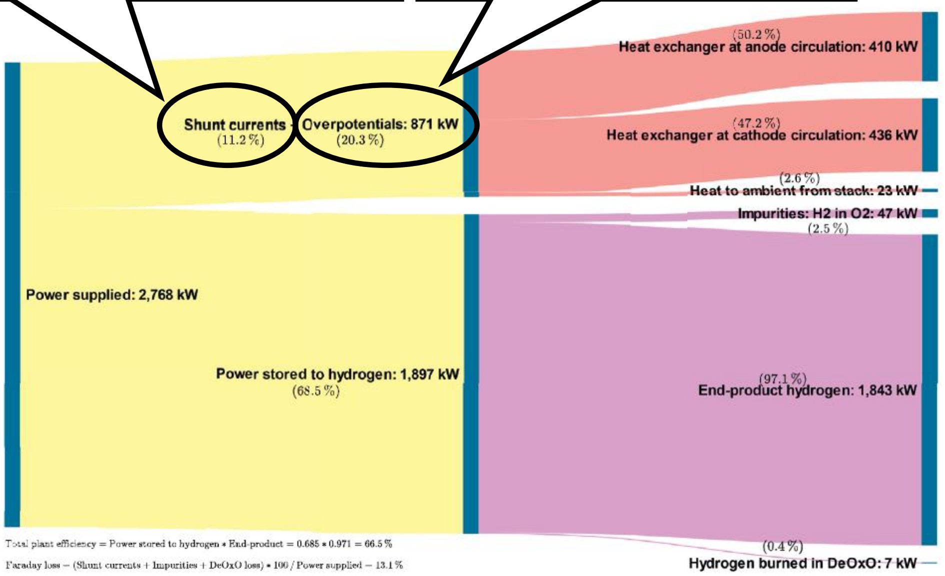
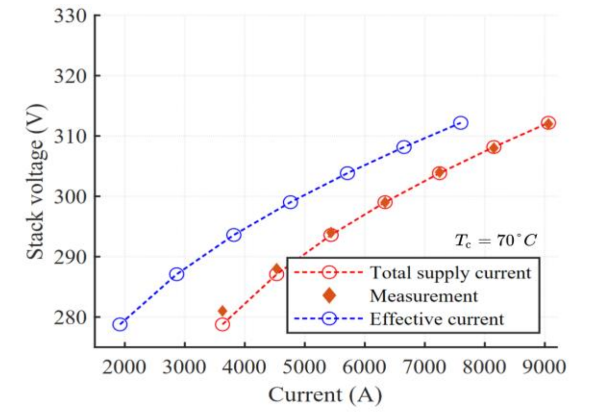
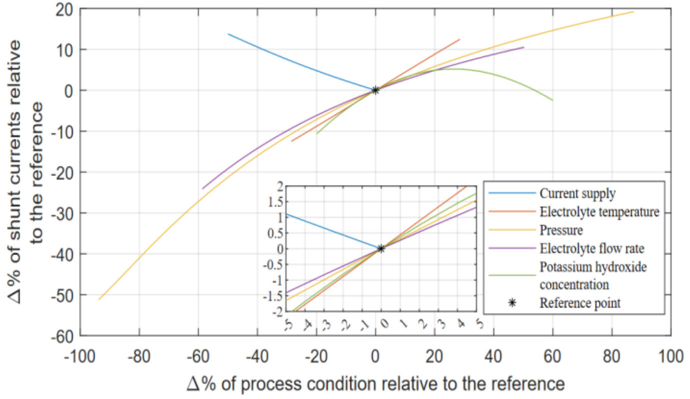
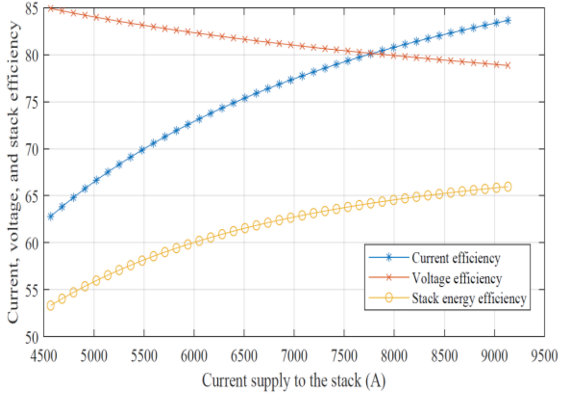


Fig. 9 — Supplied power consumption/distribution in the stack and system level.

Sensitivity analysis of the process conditions affecting the shunt currents and the SEC in an industrial-scale alkaline water electrolyzer







- Developed a shunt current model embedded in the in-house dynamic semi-empirical process model of a 3 MW and 16 bar AWE plant
- Question answered:
  - How current supply, temperature, pressure, electrolyte flow rate, and KOH concentration affect the stack's shunt currents and plant's SEC?

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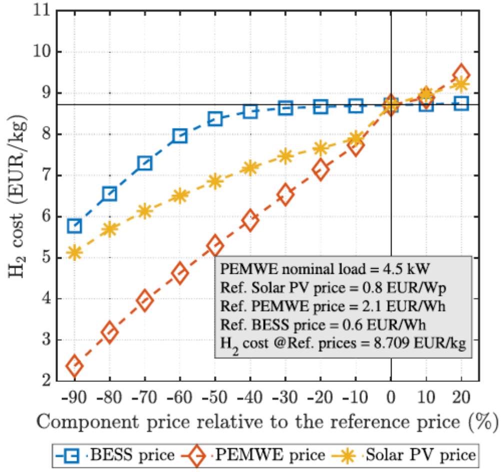
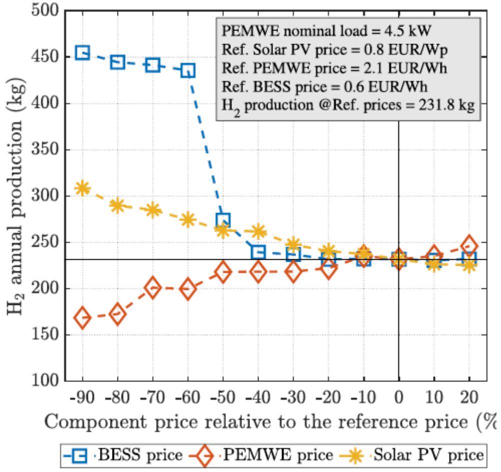
Simulation methodology for optimization of component capacities and system control in off-grid WE plants

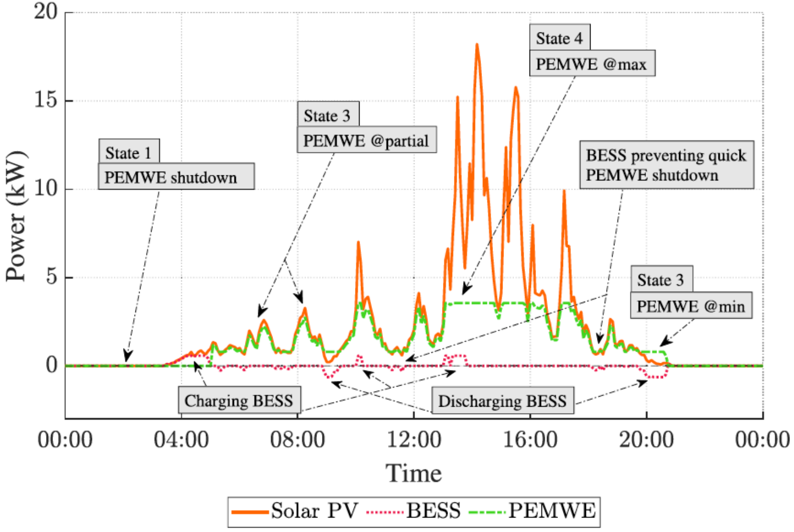
- Developed a methodology to optimize simultaneously component capacities and system control
- Main results for system: 4.5 kW PEMWE + Solar PV + BESS
  - Cost of WE has a critical role to reduce the cost of green hydrogen
  - Battery is just used to provide steadier power and to avoid rapid electrolyzer shutdowns



(a) Cost of the hydrogen produced.

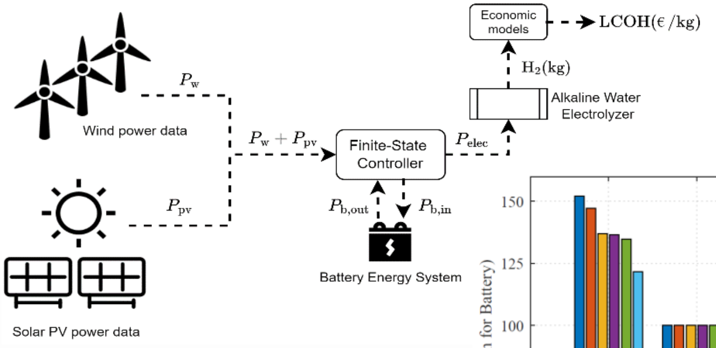


(b) Total production of hydrogen

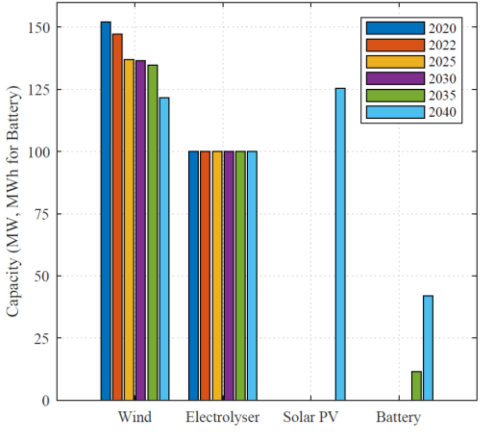


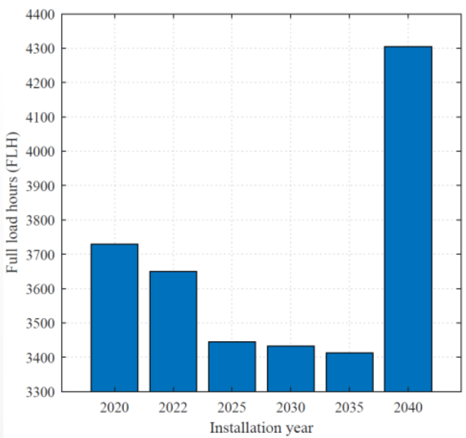
Off-grid solar-wind-battery-water electrolyzer plant

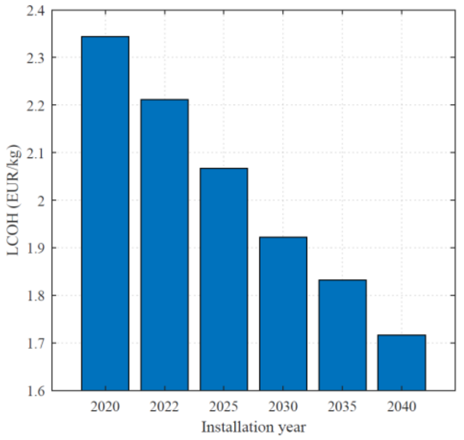
- Second study: 100 MW AWE + Solar PV + Wind power + BESS
- Updated economic and technical models: *LCOH calculation, 30 years plant simulation, component's degradation and replacements, CAPEX and OPEX of different installation years based on components learning curves*



- Main results:
  - Only wind power with no solar PV for the current price scenario (3% discount rate)
  - LCOH below 2 €/kg before 2030 (3% discount rate)
  - Battery is not economically beneficial until year 2035–2040 (3% discount rate)
  - Solar PV and battery beneficial before 2035 with higher discount rates (5% and 7%)





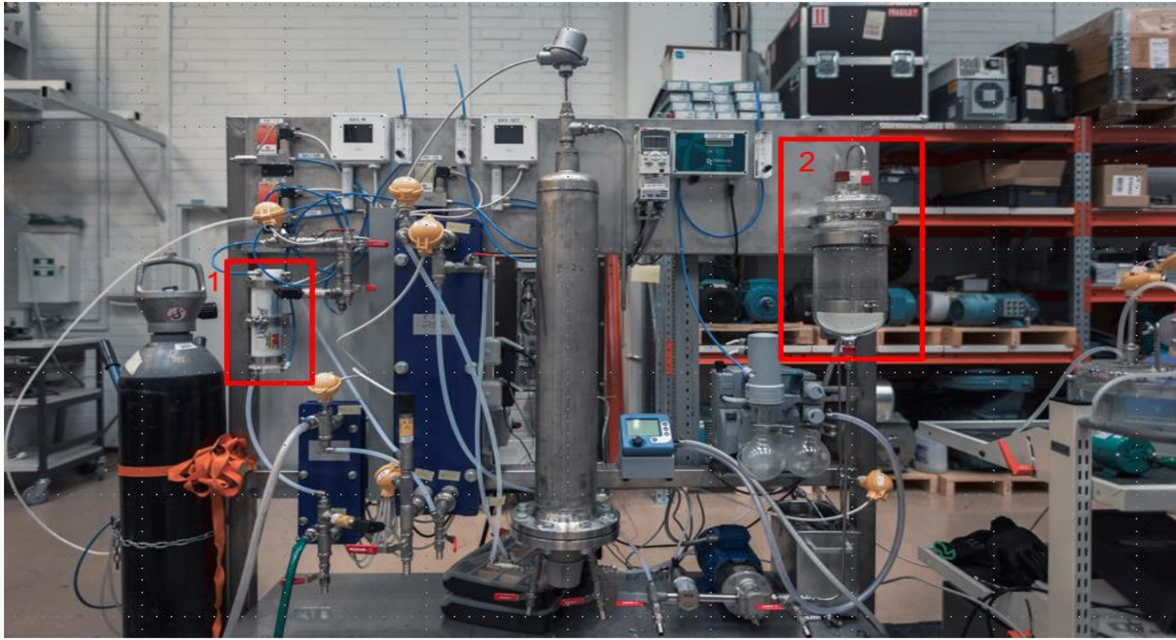


WP1.2: CO_2 direct air and seawater capture

Tuomas Koiranen, Harri Nieminen, Arto Pihlajamäki, Sepideh Mohammadisepasi, Soheil Aghajanian

CO_2 capture in membrane contactor

- Experimental work involved absorption of CO_2 into amino acid salt (potassium glycinate) solution, in a polypropylene hollow-fiber membrane contactor
- Experimental unit included the whole cycle including CO_2 absorption and solvent regeneration. Heat exchangers and other main auxiliary equipment included



Experimental CO_2 capture unit (original design)
1: membrane contactor 2: solvent regeneration

CO_2 capture in membrane contactor

- **The absorption performance of the membrane-solvent system was found good**
  - Effective CO_2 capture was observed
  - Mass transfer process could be described by established theory
  - Estimated values of mass transfer coefficients were comparable to literature references
  - Limited long-term testing showed no degradation in membrane performance (but without impurities)

CO_2 capture in membrane contactor

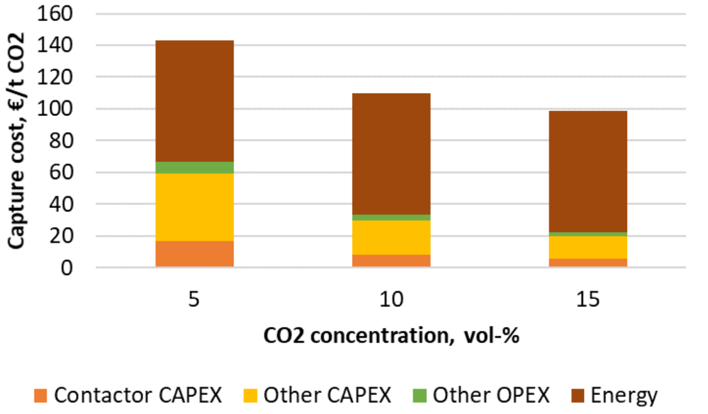
- **Solvent regeneration problems**
  - Insufficient solvent regeneration because of high CO_2 content in solution entering the contactor)
  - A simplistic configuration for the regeneration step was not found effective
  - The aim was to operate at vacuum and low temperature in order to use low-cost heat
  - Under mild conditions, equilibrium could not be reached in the designed regeneration unit

Attempts to improve solvent regeneration (CO_2 liberation)

  - Use of the PTFE contactor for solvent regeneration (CO_2 stripping) would have been interesting but could not be done due to contactor failure
  - An ultrasonic probe was acquired and tested but no improvement in performance was found

CO_2 capture in membrane contactor

- Rough cost estimates were prepared for cases at 5–15% CO_2 in inlet gas
  - Total capture cost varied from 143 €/t CO_2 (5%) to 99 €/t (15%)
  - **Energy for solvent regeneration** (and not contactor CAPEX) is the main contribution in total cost. Alternative solvents may have significant effects to decreased costs
  - **Significant reduction in equipment volume** is found compared to conventional equipment (columns) in scale-up.



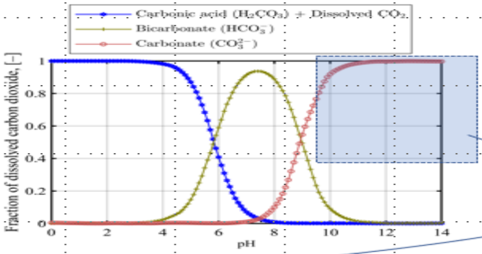
Alternative Process study: Integration of a calcium carbonate

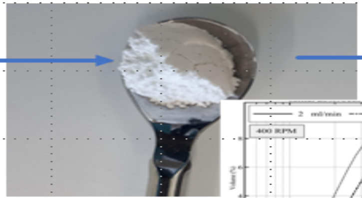
$$CO_{2(g)} \rightarrow CO_{2(aq)}$$

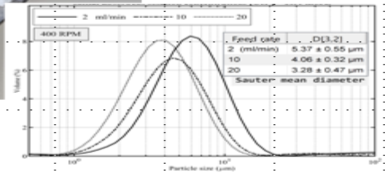
$$CO_{2(aq)} + OH^{-}_{(aq)} \Leftrightarrow HCO^{-}_{3(aq)}$$

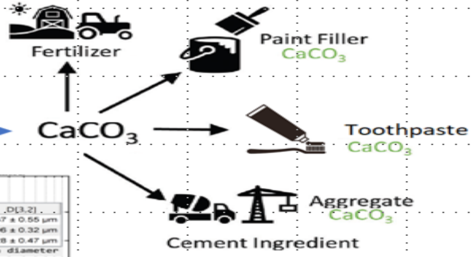
$$HCO^{-}_{3(aq)} + OH^{-}_{(aq)} \Leftrightarrow H_2O_{(l)} + CO^{2-}_{3(aq)}$$

$$CO^{2-}_{3(aq)} + 2\,Na^{+}_{(aq)} + CaCl_{2(aq)} \rightarrow CaCO_{3(s)} \downarrow + 2\,NaCl_{(aq)}$$









Total negative CO_2 emissions 6-8 t/a for 50 kg/d CO_2 capture (10 vol-%), 39 t $CaCO_3$/a

Average $CaCO_3$ price roughly: 700-800 EUR/t Market 450-9000 EUR/t (low/high quality)

Scalable process with NaOH solvent, small energy costs due to avoiding regeneration stage.

Process development reported, Doctoral thesis: Soheil Aghajanian, Reactive crystallisation studies of caco3 processing via a co2 capture process…, 2022

I. **Aghajanian**, S., and Koiranen, T. (**2020**). Dynamic modelling and semibatch reactive crystallization of calcium carbonate through CO2 capture in highlyalkaline water. *Journal of CO2 Utilization*, 38, pp. 366-374.

II. **Aghajanian**, S., Nieminen, H., Laari, A., Koiranen, T. (**2021**). Integration of a calcium carbonate crystallization process and membrane contactor–based CO2 capture. *Separation and Purification Technology*, 274, pp. 119043.

III. **Aghajanian**, et al. (**2021**). Real-time fault detection and diagnosis of CaCO3 reactive crystallization process by electrical resistance tomography measurements. *Sensors*, 21(21), 6958.

IV. Koulountzios, P., **Aghajanian**, S., Rymarczyk, T., Koiranen, T. and Soleimani, M. (**2021**). An ultrasound tomography method for monitoring CO2 capture process involving stirring and CaCO3 precipitation. *Sensors*, 21(21), 6995.

V. **Aghajanian**, S., et al.., (**2022**). Real-time monitoring and insights into process control of micron-sized calcium carbonate crystallization by an in-line digital microscope camera. *Chemical Engineering Research and Design*, 177, pp. 778-788.

CO_2 seawater capture

- **Aim and objectives**
  - Development of intensified modular membrane technology for CO_2 capture from seawater using electrodialysis. Feasibility, efficiency and durability of membranes (commercial and modified) will be studied.
- **Actions**
  - Construction of BiPolar Membrane ElectroDialysis (BPED) set-up in lab-scale.
  - Testing the set-up with commercial membranes and modified (polyelectrolyte multilayer) ones
  - Feasibility study, process modelling and conceptual planning of CO_2 seawater capture proof-of-concept
- **Outcomes**
  - Seawater capture proof-of-concept

Background

- Electrodialysis in $CaCO_3$ precipitation from brine by shifting pH from about 8 (natural seawater/brine) to 9 - 9.2

$$HCO_3^- + 2Na^+ + OH^- + Ca^{2+} + 2Cl^- \leftrightarrows CO_3^{2-} + H_2O + Ca^{2+} + 2Na^+ + 2Cl^- \leftrightarrows H_2O + 2Na^+ + 2Cl^- + \mathbf{CaCO_3(s)}$$

Blue = in sea water/brine
Red = added base

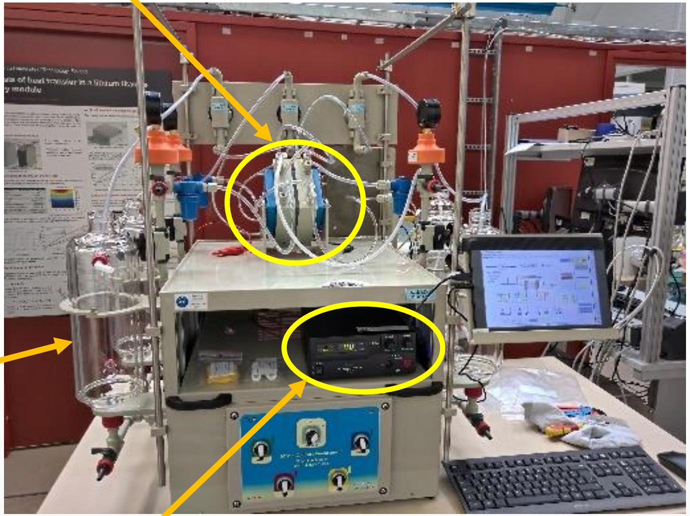
- Brine:

Reagent	g/L
Na_2SO_4	8.380219
$NaHCO_3$	0.13
NaCl	48.15131
KCl	1.528205
$MgCl_2$	10.98107
$CaCl_2$	2.382338
Na_2CO_3	0.0424

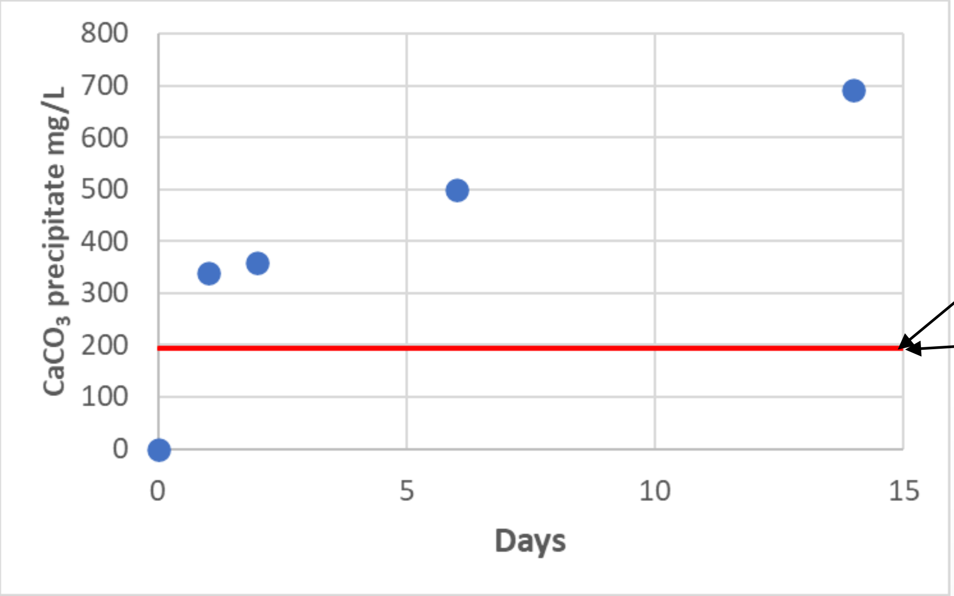
- At about pH = 9, precipitate can be observed

Results (1/3)

- Lab-scale set-up (PCCell GmbH) assembled



Results (2/3)



Precipitated amount of $CaCO_3$ from synthetic brine at 30°C using the base solution from the BPED system. Red line stand for theoretical max when CO_3^{2-} is limiting.

Reagent	g/L
Na_2SO_4	8.380219
$NaHCO_3$	0.13
NaCl	48.15131
KCl	1.528205
$MgCl_2$	10.98107
$CaCl_2$	2.382338
Na_2CO_3	0.0424

Precipitate over theoretical max of brine from dissolving CO_2 from air.

Results (3/3)

- CO_2 seawater capture was simulated for mid-sized desalination plant:

  (Valtteri Veijalainen, Feasibility study for CO_2 capture from seawater using an electrodialysis process, MSc Thesis, LUT University, 2021)
- Plant produce 36.5 Mt brine/year ⇨ 13 400 t $CaCO_3$ by using BPED
- CAPEX 96.8 M€
- OPEX 52.6 M€
- BPED easy to scale-up ⇨ large amount of CO_2 could be removed

Conclusions (1/2)

- BPED works well for acid/base production (high water splitting efficiency)
- BPED process works in precipitating $CaCO_3$ from desalination brine but:
  - $CaCO_3$ crystallisation kinetics slow due to dilute brine solution,
  - Crystals do not settle well (must be separated by filtering or centrifuge)
  - Crystals weak and break easily

Conclusions (2/2)

- Large scale process simulations show economically unfeasible process
  - Price for $CaCO_3$ about 4000–5000 €/t
  - Justification for usage of this process: e.g. reduction of atmospheric CO_2, Reduction ocean acidification

- Process has great potential to reduce CO_2 from atmosphere since BPED easy to scale-up and there are around 20 000 desalination plants globally

WP1.3.1: Methanol synthesis from CO_2 and H_2

Tuomas Koiranen, Arto Laari, Pavel Maksimov

Intensification methods for methanol synthesis

- ✓ Removal of thermodynamic limitations in methanol synthesis by a sorption-enhanced process Doctoral thesis: Pavel Maksimov, Methanol synthesis via CO_2 hydrogenation ia a periodically operated multifunctional reactor, 2022
  - The topic was studied:
  - experimentally with sorption-enhanced methanol synthesis
  - by dynamic modelling of methanol process

$$CO + 2H_2 \rightleftharpoons CH_3OH$$

$$CO_2 + H_2 \rightleftharpoons CO + H_2O$$

$$CO_2 + 3H_2 \rightleftharpoons CH_3OH + H_2O$$

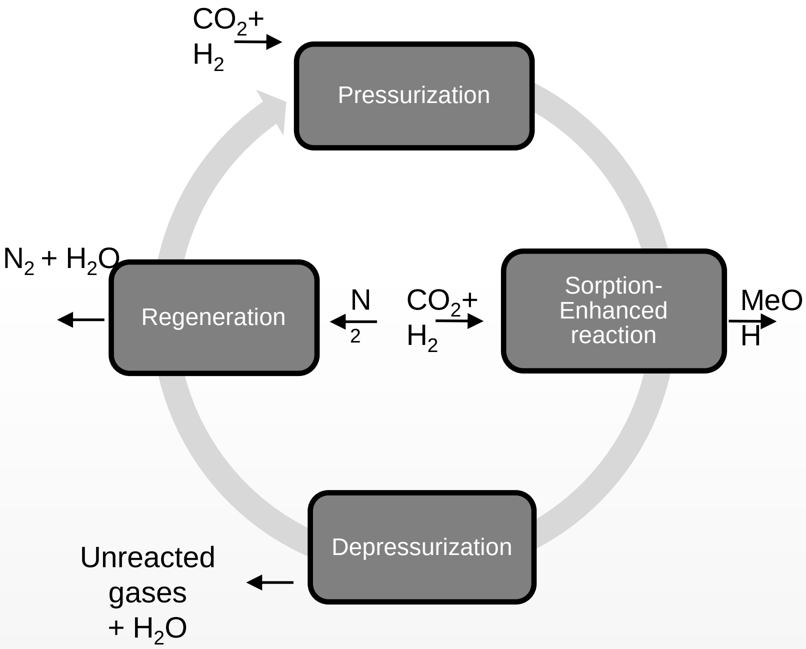
- ✓ Development of millichannel reactor
  - by CFD simulations (Aalto)
  - by heat transfer mock-up experiments, design calculations, and CFD simulations

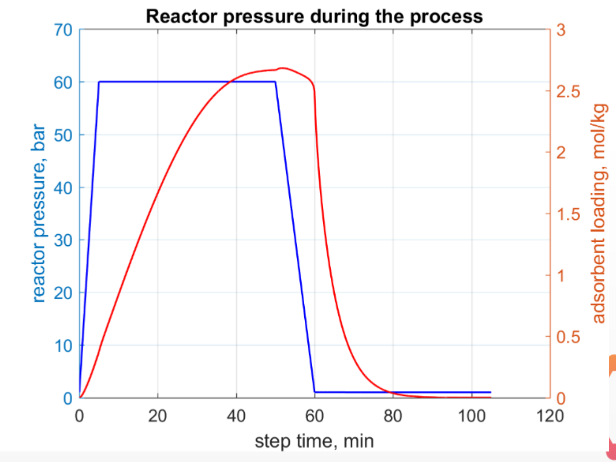
M.Sc. Thesis, Mohamed Nuzair Ahamed, Evaluation of plate & shell type heat exchanger as millichannel reactor in methanol synthesis, LUT University, 2022

Sorption enhanced MeOH synthesis process

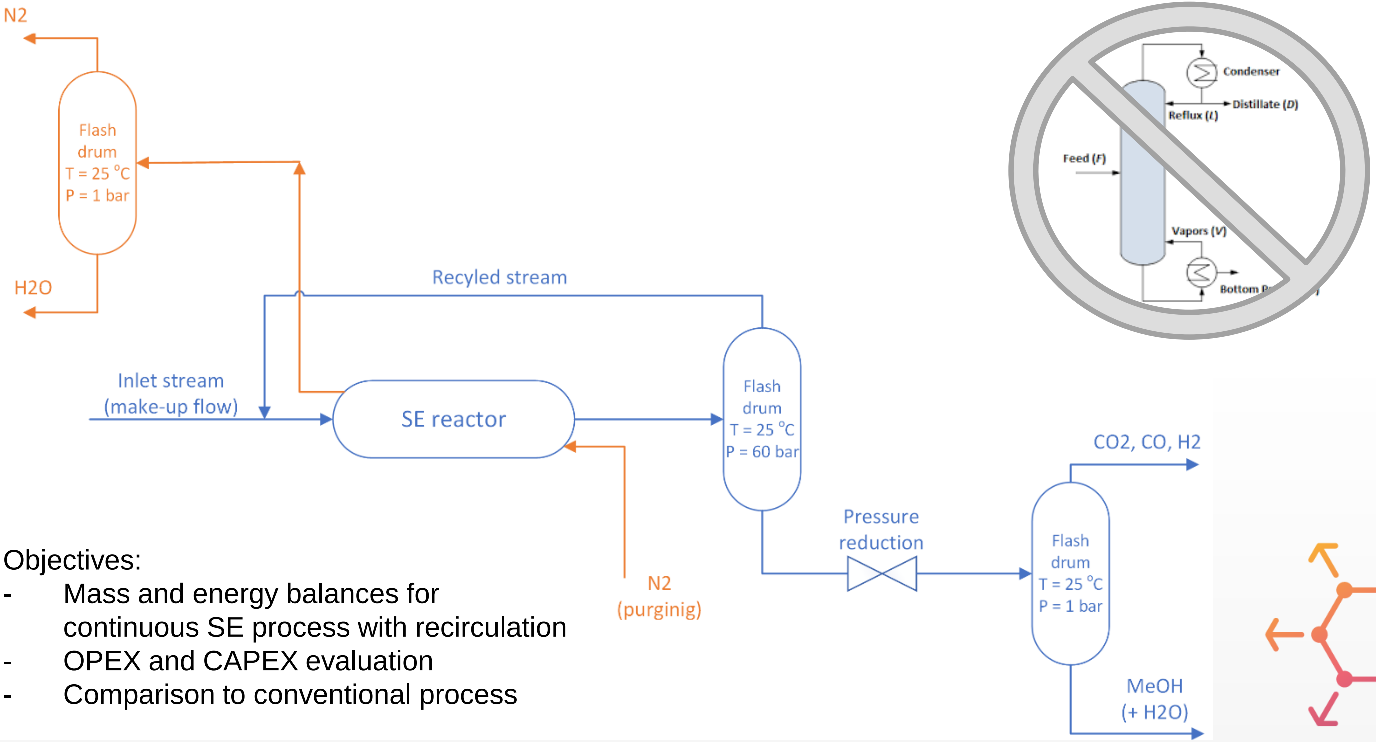
Cyclic operation of fixed bed reactor:
- Reaction phase with adsorption
- Regeneration of the catalyst-adsorbent bed

At least two parallel fixed bed reactors are required





Process design

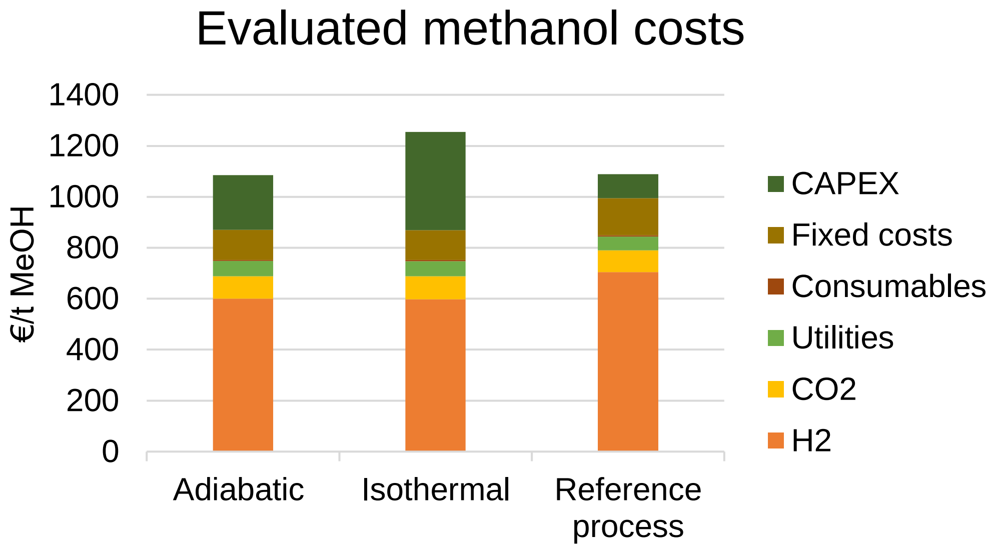


Objectives:
- Mass and energy balances for continuous SE process with recirculation
- OPEX and CAPEX evaluation
- Comparison to conventional process

Techno-economic analysis

Basis of the cost analysis

- Methanol capacity 11 kt/a (for adiabatic) and 16 kt/a (for isothermal)
- Plant lifetime 20 years
- Interest rate 8 %
- Cost for CO_2 50 €/t
- Cost for H_2 3000 €/t



Development of a millichannel HEX reactor

- Plate & shell type heat exchanger as millichannel reactor

M.Sc. Thesis, Mohamed Nuzair Ahamed, Evaluation of plate & shell type heat exchanger as millichannel reactor in methanol synthesis, LUT University, 2022

- ✓ The reactor can tolerate high temperatures (up to 600 °C) and pressures (100 bar)
- ✓ Modular structure, easy scale-up, low costs
- ✓ Removes efficiently reaction heat
- ✓ Catalyst can be inserted to the channels as catalytic foam

Conclusions

- Dynamic fixed-bed reaction-adsorption and stripping reactor model developed
- In-house MATLAB codes available adaptaptable to different SE reactions
- Optimization of reaction conditions (temperature, catalyst/adsorbent ratio) in time-dependent mode.
- Process simulation for equipment sizing and cost estimation by integrating in-house model to ASPEN –steady state simulations.

- No breakthrough was achieved in sorption-enhanced process development
- More research is needed to develop novel catalytic and sorption materials for methanol synthesis

- Plate & shell HEX reactor needs further testing in pilot scale

Publications

Maksimov, P. et al. (2020). “Gas phase methanol synthesis with Raman spectroscopy for gas composition monitoring”. *RSC Advances*, vol. 10, pp. 23690–23701.
Maksimov, P. et al. (2021). “Methanol synthesis through sorption enhanced carbon dioxide hydrogenation”. *Chemical Engineering Journal*, vol. 418, 129290.
Maksimov, P. et al. (2022). “Sorption enhanced carbon dioxide hydrogenation to methanol: process design and optimization”. *Chemical Engineering Science*, vol. 252C, 117498.
Nieminen, H., Maksimov, P., Laari, A., Väisänen, V., Vuokila, A., Huuhtanen, M., Koiranen, T., Process modelling and feasibility study of sorption-enhanced methanol synthesis, Chemical Engineering and Processing - Process Intensification.

Izbassarov, D., Nyári, J., Laitinen, A., Laari, A., Santasalo-Aarnio, A., Vuorinen, V., A three-dimensional conjugate heat transfer model for methanol synthesis in a modular millireactor, Chemical Engineering Science, 258 (2022), 117765

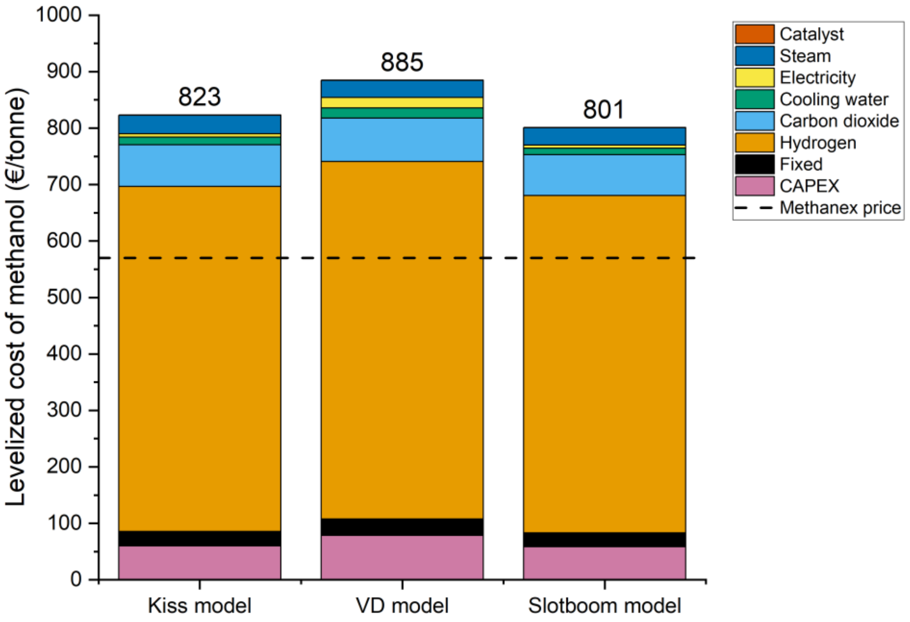
M.Sc. Thesis, Mohamed Nuzair Ahamed, Evaluation of plate & shell type heat exchanger as millichannel reactor in methanol synthesis, LUT University, 2022

WP1.3.2: Methanol synthesis from H_2 and CO_2

WP/task leader: Annukka Santasalo-Aarnio
Main researchers during the period: Ville Vuorinen, Marko Korhonen, Markus Laitinen, Judit Nyári, Daulet Izbassarov

Levelized cost of methanol – TEA evaluation
Kinetic model evaluation

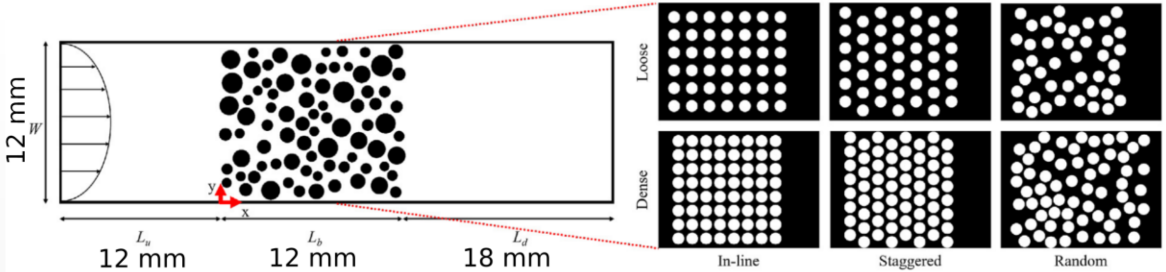
- 10% difference in the levelized cost
- Cost 40–55% above fossil methanol
- Newest kinetic model shows the best KPIs
- Hydrogen cost most significant cost element



J. Nyári, D. Izbassarov, Á.I. Toldy, V. Vuorinen, A. Santasalo-Aarnio, Choice of the kinetic model significantly affects the outcome of techno-economic assessments of CO_2-based methanol synthesis, Energy Convers. Manag. 271 (2022), https://doi.org/10.1016/J.ENCONMAN.2022.116200.

Fixed-bed reactor study

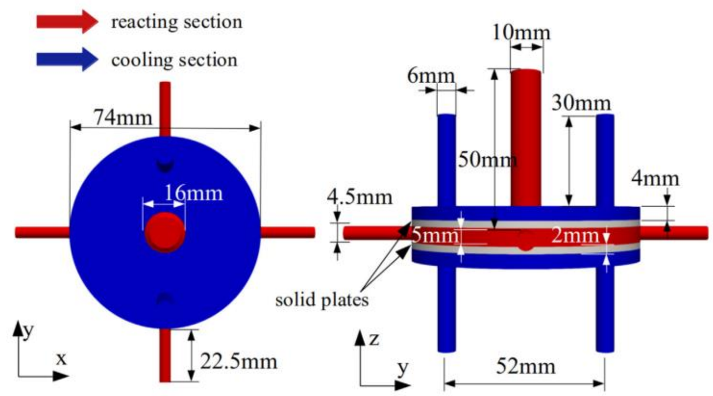
- For the fixed-bed reactor considered here, the isothermal setup outperformed the adiabatic one
- Methanol single-pass yield varied between 7–25% within the studied parameters
- A min. catalyst volume fraction of 50% required to approach methanol yields predicted by ideal mixing assumptions



D. Izbassarov, J. Nyári, B. Tekgül, E. Laurila, T. Kallio, A. Santasalo-Aarnio, O. Kaario, V. Vuorinen, A numerical performance study of a fixed-bed reactor for methanol synthesis by CO_2 hydrogenation, Int. J. Hydrogen Energy 46 (29) (2021) 15635–15648, https://doi.org/10.1016/j.ijhydene.2021.02.031.

A prototype reactor study with computational tools

- “A three-dimensional conjugate heat transfer model for methanol synthesis in a modular millireactor”
- High D_t / d_{cat} ratio → continuum porous media
- The effects of inlet temperature and pressure considered



D. Izbassarov, J. Nyári, A. Laitinen, A. Laari, A. Santasalo-Aarnio, V. Vuorinen, A three-dimensional conjugate heat transfer model for methanol synthesis in a modular millireactor, Chem. Eng. Sci. 258 (2022), https://doi.org/10.1016/j.ces.2022.117765.

Conclusions from the work

- The suggested reactor design exhibited excellent thermal characteristics in typical operating conditions
- Methanol single-pass yield varied between 9–23% within the studied parameter range according to the CFD model
- Impact of kinetic models for the TEA analysis

- 4 journal papers from Aalto research group – Techno-economic model development for large scale methanol production from synthetic methanol:

J. Nyári, M. Magdeldin, M. Larmi, M. Järvinen, A. Santasalo-Aarnio, Techno-economic barriers of an industrial-scale methanol CCU-plant., J. CO2 Util. 39 (2020), https://doi.org/10.1016/j.jcou.2020.101166.

WP1.4: PtX and thermal energy storage

Tero Tynjälä, Markku Nikku, Eero Inkeri, Konstantin Zaynetdinov, Ilia Barbanov,

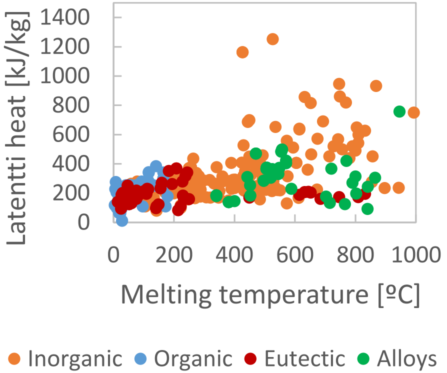
Actions

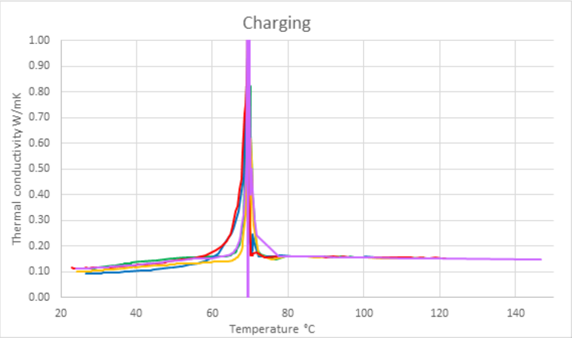
- Survey of optimal materials for storing thermal energy in different temperature levels as sensible heat, latent heat or reaction heat.
- Experimental and numerical study of material properties, phase change behavior and chemical reactions in different conditions.
- Effect of geometry, materials and storage operation on energy storage performance in charging and discharging.
- Integration of thermal energy storages to PtX processes (Electrolysis, DAC, hydrocarbon synthesis)

Properties of latent heat and thermo-chemical energy storage materials

- Survey for PCM and TCM heat storage materials
  - Bulk and tailored materials available
  - Water as low-temperature reference (210 kJ/kg with Δ*T* of 50ºC)
  - Thermal conductivity measurements conducted for stearic acid and erythritol
- Benefits
  - Higher energy density
  - Higher temperature levels possible
  - Stable heat flux during phase change
- Barriers for utilization
  - High cost of tailored materials
  - Low thermal conductivity
  - Material compatibility issues, corrosion, subcooling, material degradation

Phase change materials (PCM)





Thermochemical materials (TCM)

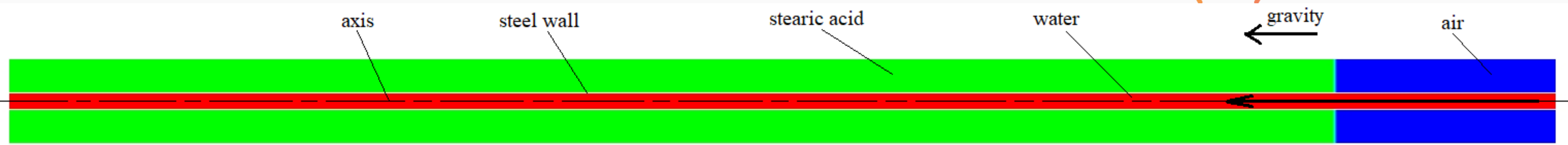
Material	Reaction temperature [˚C]	Energy density [kJ/kg]
Calcium carbonate	973-1273	761
Strontium carbonate	900-1200	742
Calcium hydroxide	400-600	845
Cobalt oxide	900	3029
Manganese oxide	1000	300-1000
Ammonia	400-700	2000
Magnesium hydride	300-480	844
Titanium hydride	650-750	204
Calcium hydride	1100-1400	3924

Thermal energy storage test device and CFD modelling (1/2)

- A laboratory scale latent heat storage is constructed
- The device can be used for characterizing different phase change materials and to provide data for model validation
- Stearic acid (melting temperature is about 70 °C) is used as a phase change material (l_s = 201.6 kJ/kg)
- Water is used as a heat transfer fluid
- Several tests are performed with different direction of the water flow (from top and bottom)
- The experimental data is used in developing and validation of the CFD and process models

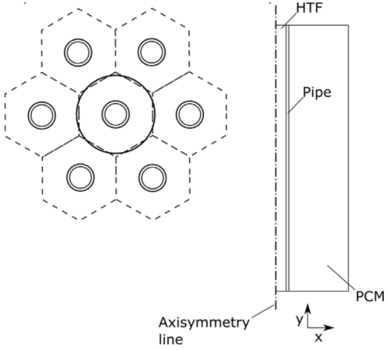
Thermal energy storage test device and CFD modelling (2/2)

- CFD model of the latent heat storage is developed
- Both solidification and melting of PCM can be simulated
- Main conclusions
  - Including natural convection into the model significantly reduces the computational speed, however, it is essential for modelling of latent heat storages
  - PCM phase change properties differ depending on initial state (hysteresis effect); accurate properties must be obtained separately for solidification and melting
  - CFD results can be used for improving the dynamic process model, which is more suitable for case studies and system integration modelling due to much higher computational speed

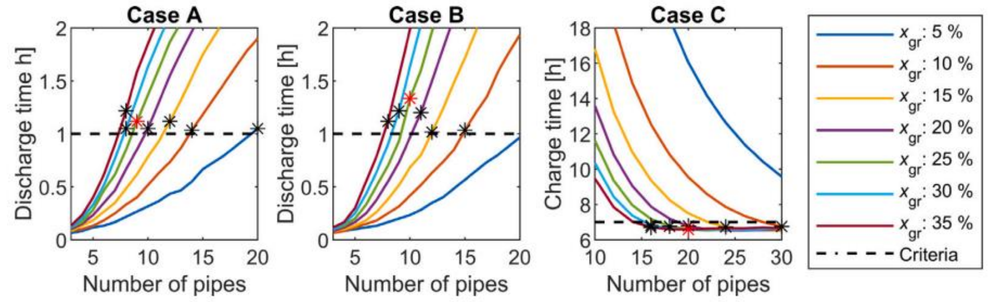


Process model – geometry optimization

- Represent shell-and-tube heat exchanger for PCM TES with axisymmetric 2D domain
- Possibility to optimize geometry, such as
  - Number of pipes
  - Pipe length
  - Distance between pipes
  - Number of fins or amount of additive for enhancement of thermal conductivity
  - Mass of PCM
- Method allows technical and economic optimization



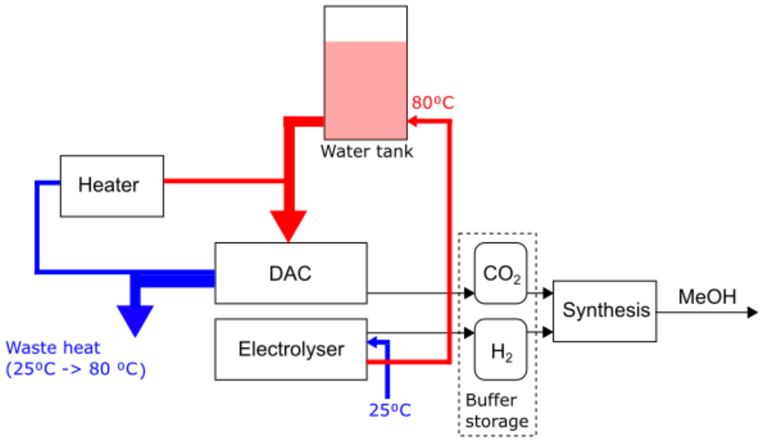
Model one pipe-PCM section of a bundle

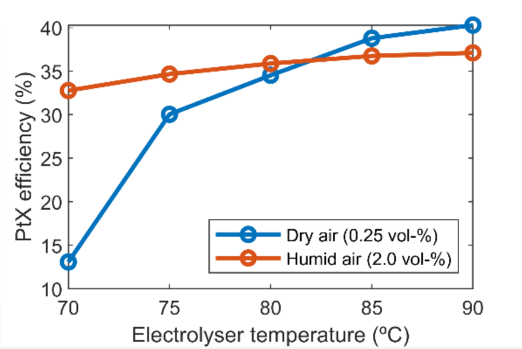


Detailed results published in:
E. Inkeri, T. Tynjälä, M. Nikku, Numerical modeling of latent heat thermal energy storage integrated with heat pump for domestic hot water production, Appl. Therm. Eng. 214 (2022), Article 11881, https://doi.org/10.1016/j.applthermaleng.2022.118819.

Thermal integration

- Case study for thermal integration of DAC, electrolyser and MeOH synthesis using TES
- Increasing of electrolyser temperature increases PtX performance
  - Increases waste heat utilization rate
  - Decreases cost of produced methanol
  - Increases PtX efficiency
  - Air humidity has positive effect on DAC performance and PtX efficiency





P2X ENABLE

Publications

1. E. Inkeri, T. Tynjälä, M. Nikku, Numerical modeling of latent heat thermal energy storage integrated with heat pump for domestic hot water production, Appl. Therm. Eng. 214 (2022), Article 11881, https://doi.org/10.1016/j.applthermaleng.2022.118819.
2. H. Karjunen, E. Inkeri, T. Tynjälä, Mapping bio-CO_2 and wind resources for decarbonized steel, e-methanol and district heat production in the Bothnian Bay, Energies 14 (24) (2021), https://doi.org/10.3390/en14248518.
3. E. Inkeri, 2021. Modelling of component dynamics and system integration in power-to-gas process. D.Sc. Thesis, available at: https://urn.fi/URN:ISBN:978-952-335-760-0.
4. Yadav, Devanand. M.Sc. Thesis. Application of CFD for the analysis of medium-scale LHTS for district heating, published 2/2021. http://urn.fi/URN:NBN:fi-fe202102094244.
5. Zaynetdinov, Nikku, Tynjälä. CFD modelling of solidification and melting in the experimental shell-and-tube latent heat storage. Abstract accepted to the 17th International Heat Transfer Conference, full paper submittion 31.12.2022
6. I. Barbanov. Thermochemical energy storage development for humid air heat recovery, M.Sc. Thesis, to be published in early 2023.

WP2 – P2X in buildings

Risto Soukka, Mariia Zhaurova, Mika Luoranen, Kaisa Grönman, Kanitta Ruaysap

P2X in buildings (1/2)

The main aim is to determine the technical feasibility of PtX applications for buildings. **The main focus will be on the applications of CO_2 capture from supply/exhaust air** integrated with heat storages. One objective is to create feasible business models for utilizing PtX applications (CO_2 capture from supply/exhaust air stream) in buildings, including: Life Cycle Cost perspectives, Revenue logic for different players (building owner/user, service and technology providers), Carbon Footprint considerations for different CO_2 utilization paths.

Actions

1. Construction of Simulink based energy system model for buildings, including CO_2 capture from supply/exhaust air integrated with novel energy storage solutions.
2. Development of business models by applying life cycle costing from different actor's perspective: building owners, service providers, technology providers.
3. Calculation of carbon footprint for alternative PtX applications.

Outcomes

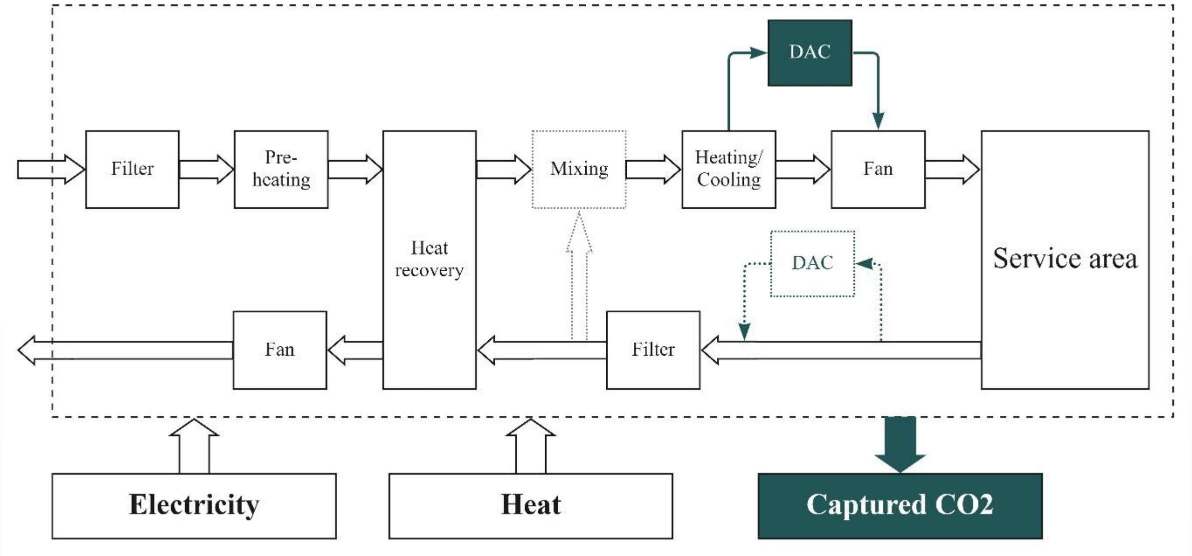
- **Energy model for buildings** with integrated PtX systems including CO_2 capture, synthesis and energy storages.
- Benefits of CO_2 utilization potential as part of a building energy system.
- **Potential PtX applications** for building concepts.
- Business models for PtX applications for buildings.

P2X in buildings (2/2)

Trade offs between energy savings in buildings and good indoor air quality

- Increasing evidence that indoor environmental quality influence human health and productivity

A Simulink based energy system model for buildings, including CO_2 capture



Air supply and heating:

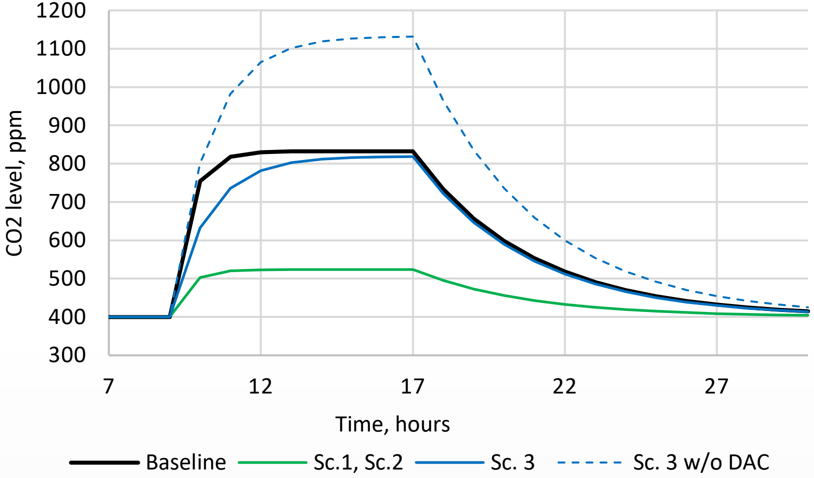
- Energy demand
- Energy related GHG emissions
- Air flow and indoor air parameters:
  - CO_2 concentration, relative humidity, temperature, pressure

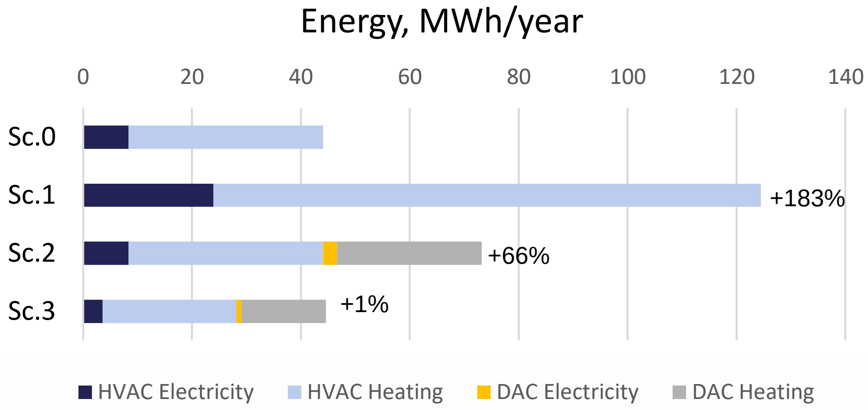
DAC:

- Energy demand
- Energy related GHG emissions
- Amount of captured CO_2

Energy demand and indoor CO_2 level

A hypothetical office building in Finland, ~1900 m2, designed airflow 1.5 dm3/s*m^2



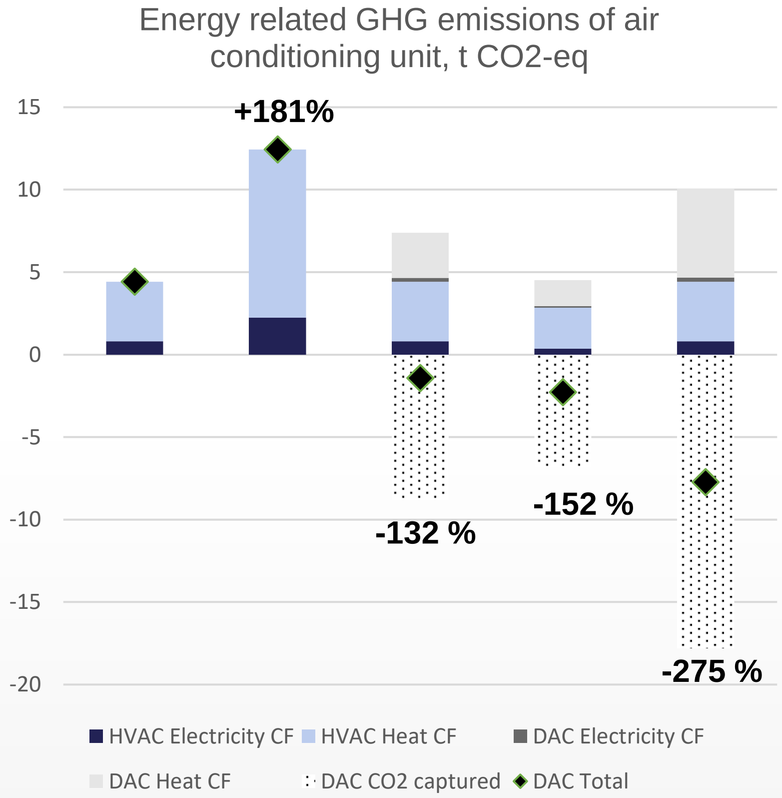


Sc.2 and Sc.3 – captured CO_2 is a benefit

	Airflow, dm^3/s*m2	**CO_2 level, ppm**
Sc. 0. Baseline	1.5	820
Sc. 1. Increased airflow*	5.2	520
Sc. 2. Baseline + DAC	1.5	520
Sc. 3. Decreased airflow + DAC	0.9	820

*might not be supported by building's HVAC unit

Indoor CO_2 level and GHG emissions



A hypothetical office building in Finland, ~1900 m2, designed airflow 1.5 $dm^3/s*m^2$

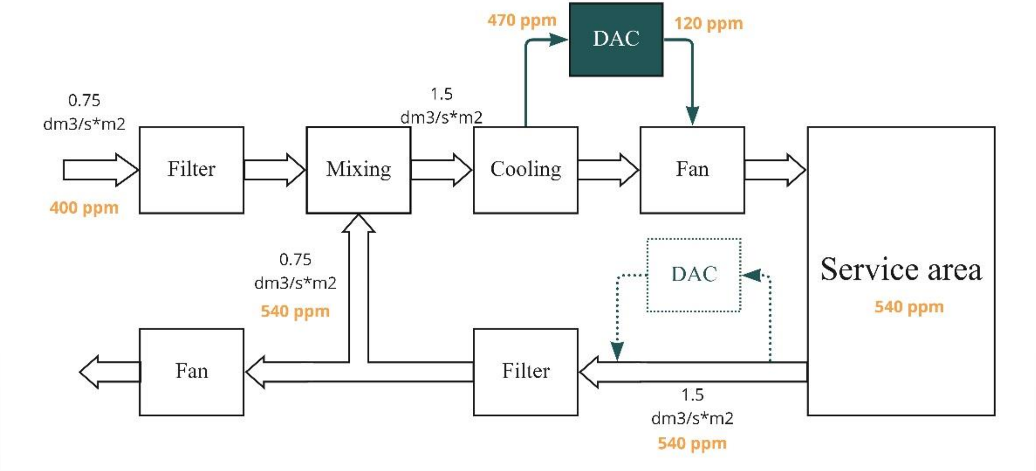
	Airflow, m3/s	Indoor CO_2 level, ppm	CO_2 captured, t/y
Sc. 0. Baseline	2.8	820	-
Sc. 1. Increased airflow	9.8	520	-
Sc. 2. DAC	2.8	520	8.8
Sc. 3. Decreased airflow + DAC	1.66	820	6.8
SC.4 DAC from extract air	2.8	820	17.8

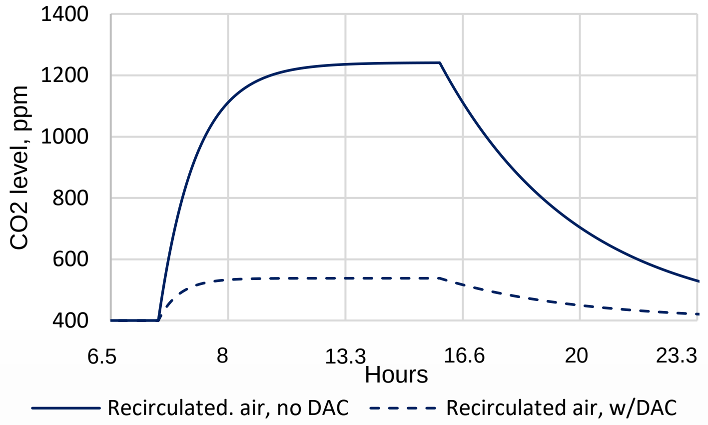
CO2 capture potential of an office building

Airflow dm3/s,m2	1	1.5	2	
CO2 captured, t/y	5.9	8.8	11.7	8-hours, working days
CO2 captured, t/y	7.4	11.0	14.7	10-hours, working days

Recirculated air and CO_2 levels

A hypothetical office building in Hong Kong, ~1900 m^2 with recirculated air, designed airflow 0.75 $dm^3/s*m^2$





Amount of CO_2 can be potentially captured from a 1900 m^2 office building

		Hong Kong	Finland
Supply air	W/o recirculation	4	8.8
	W/ recirculation	10	
Extract air	W/o recirculation	12	17.8
	W/ recirculation	24	

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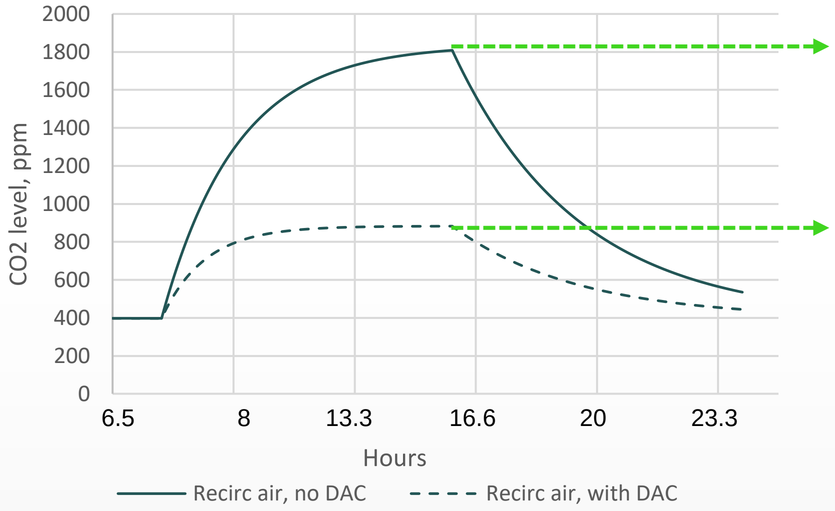
CO_2 levels and human health



CO_2 levels in buildings:

High increase (1400–1800 ppm):

- significantly reduced the accuracy in all performance tasks, attention and memory task.
- 10–20% relative increased in student absence (aggregate data on demographic and socioeconomic variables).

Moderate increase (945 ppm):

- decrease in scores in activity levels, information usage and strategy
- sick building syndrome's symptoms, especially in eye irritation and upper respiratory symptoms

Savings from improved productivity and health can be higher than costs of energy needed for adequate ventilation

CO_2 capture potential in buildings

In Finland, there are 20 043 480 m^2 of office buildings (4% of all buildings)

- Airflow: 2 $dm^3/s*m^2$
- Capture efficiency: 56%, 10-hours, working days

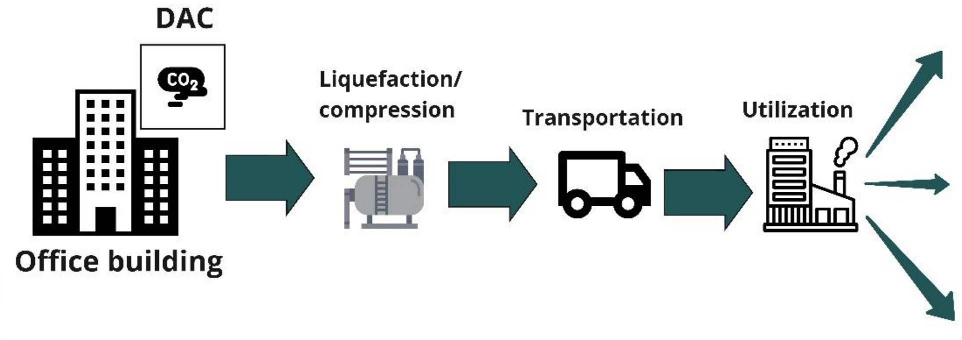
From all office buildings in Finland 155 kt CO_2 can be captured per year

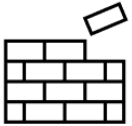
0.3% of total CO_2 emissions in Finland

From extract air 188 kt CO_2 can be captured per year

In Hong Kong: 12 539 800 m^2 of office buildings.
Depending on the HVAC and DAC configurations, 29 – 159 kt CO_2 can be captured

CCU from building (1/2)



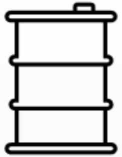


Construction block from steel slag

- Long-term CO_2 storage
- Possible negative carbon footprint
- Utilization of waste materials ↔ limited availability of material

Concrete curing

- A process of keeping fresh concrete in a moist and warm condition enough so that the hydration of cement can continue
- Emissions reduction can be achieved by substitution of steam curing with CO_2 curing

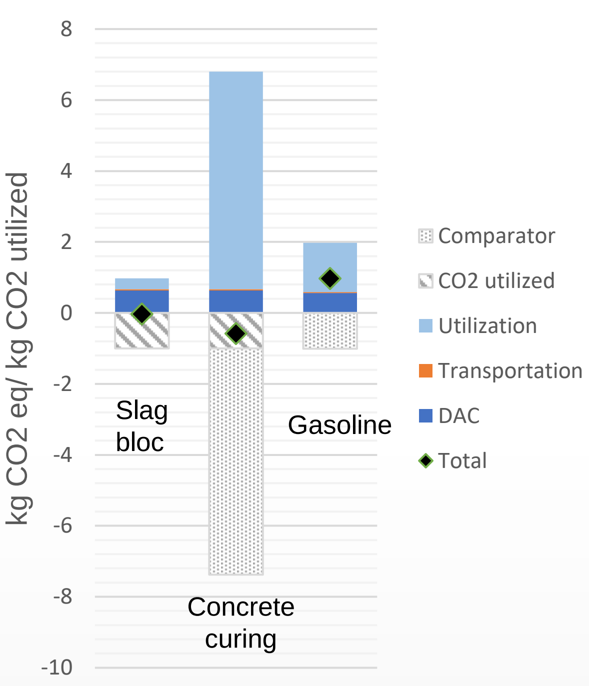


Gasoline

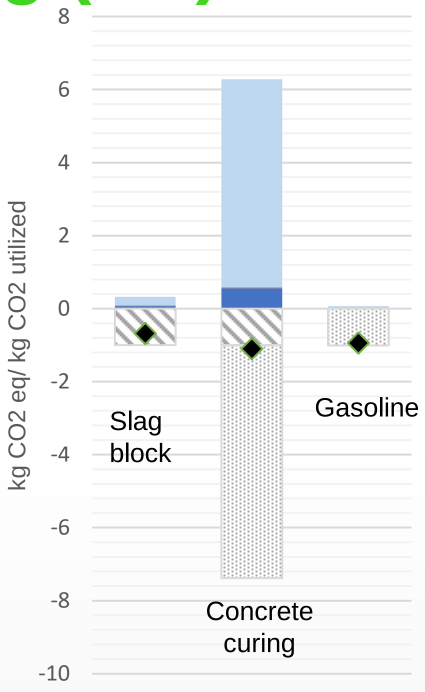
- Short-term CO_2 storage

P2X ENABLE

CCU from building (2/2)



Baseline:
electricity grid, NGas, district heating



Improved:
renewable electricity and heat from biomass

- Mineral carbonation can lead to the emissions reduction even with already available energy sources
- Concrete curing provides a higher reduction of the emissions, but the emissions from the concrete production should be considered
- Construction blocks from waste materials have a lower carbon footprint
- Feedstock other than steel slag can be used, but the assessment of the emissions is needed in each case
- Feedstock availability and the production costs might be an issue
- The impact from energy sources is highest for the gasoline production

Conclusions

- Based on the literature the technology (DAC in buildings) can be applied to improve people performance in buildings
- Conducting CO_2 capture from recycling air or exhaust air increases the potential from the climate point of view
- Buildings are not a promising CO_2 source due to a low density of buildings in Finland, but better possibilities exist in other markets from that perspective
- Technology offers potential also for energy savings

WP3: PtX techno-economics and business potential in global-local perspective

Overview on Outcomes

Christian Breyer, Tansu Galimova, Mahdi Fasihi, Dmitrii Bogdanov, Siavash Khalili, Upeksha Caldera, Gabriel Lopez

Content

Activities

- Benefits of global e-fuel/e-chemical trading
- Electrolyser capacity demand in global-local resolution
- Power-to-Food and agriculture sector for energy

Networking

- Dena (German Energy Agency): three common activities, one on CO_2 as raw material, one on e-fuels/chemicals trading, one on DAC-kerosene for aviation (this in cooperation with Ludwig-Bölkow-Systemtechnik and ClimateWorks Foundation)
- Shell International: e-fuels/chemicals global trading
- TransnetBW: e-fuels imports to Europe using shipping and pipelines also including e-hydrogen
- ETIP-PV and Fortum: analysis on solar hydrogen in comparison to blue hydrogen
- OTH Regensburg: electricity-based CO_2 removal options (carbon fibres, silicon carbide)
- CO2 Value Europe: collaboration on the value of e-fuels from CCU perspective

Publications (1/3)

Journal (3x jufo 3, 4x jufo 2, 2x jufo 1)

- Fasihi M., Weiss R., Savolainen J., Breyer C., 2021. Global potential of green ammonia based on hybrid PV-wind power plants, Applied Energy, 294, 116170; DOI: https://doi.org/10.1016/j.apenergy.2020.116170
- Galimova T., Ram M., Bogdanov D., Fasihi M., Khalili S., Gulagi A., Karjunen H., Mensah T.N.O., Breyer C., 2022. Global demand analysis for carbon dioxide as raw material from key industrial sources and direct air capture to produce renewable electricity-based fuels and chemicals, Journal of Cleaner Production, 373, 133920; DOI: https://doi.org/10.1016/j.jclepro.2022.133920
- Vartiainen E., Breyer C., Moser D., Medina E.R., Busto C., Masson G., Bosch E., Jäger-Waldau A., 2022. True Cost of Solar Hydrogen, Solar RRL, 6, 2100487; DOI: https://doi.org/10.1002/solr.202100487
- Bogdanov D., Gulagi A., Fasihi M., Breyer C., 2021. Full energy sector transition towards 100% renewable energy supply: integrating power, heat, transport and industry sectors including desalination, Applied Energy, 283, 116273; DOI: https://doi.org/10.1016/j.apenergy.2020.116273
- Lopez G., Farfan J., Breyer C., 2022. Trends in the global steel industry: Evolutionary projections and defossilisation pathways through Power-to-Steel, Journal of Cleaner Production, 375, 134182; DOI: https://doi.org/10.1016/j.jclepro.2022.134182
- Breyer C., Khalili S., Bogdanov D., Ram M., Oyewo A.S., Aghahosseini A., Gulagi A., Solomon A.A., Keiner D., Lopez G., Østergaard P.A., Lund H., Mathiesen B.V., Jacobson M.Z., Victoria M., Teske S., Pregger T., Fthenakis V., Raugei M., Holttinen H., Bardi U., Hoekstra A., Sovacool B.K., 2022. On the history and future of 100% renewable energy systems research, IEEE Access, 10, 78176-78218; DOI: https://doi.org/10.1109/ACCESS.2022.3193402
- Khalili S., Breyer C., 2022. Review on 100% Renewable Energy System Analyses – A Bibliometric Perspective, IEEE Access, accepted, October 30; DOI: https://doi.org/10.1109/ACCESS.2022.3221155
- Galimova T., Ram M., Breyer C., 2022. Mitigation of air pollution and corresponding impacts during a global energy transition towards 100% renewable energy system by 2050, Energy Reports, 8, 14124-14143; DOI: https://doi.org/10.1016/j.egyr.2022.10.343
- Caldera U, Breyer C., 2022. Climate change mitigation through afforestation on arid land with renewable electricity based desalination, Nature Sustainability, DOI: http://doi.org/10.1038/s41893-022-01056-7

Publications (2/3)

con’t Journal

- Mertens J., Breyer C., Arning K., Bardow A., Belmans R., Dibenedetto A., Erkman S., Gripekoven J., Leonard G., Nizou S., Pant D., Reis-Machado A.S. Styring P., Vente J., Webber M., Sapart C.J., 2022. Carbon capture and utilization: More than hiding CO_2 for some time. Joule, accepted, January 6; DOI: https://doi.org/10.1016/j.joule.2023.01.005
- under review (6: e-steel in Europe, e-hydrogen in Europe, e-fuels trading, e-CDR Egypt, e-CF, e-SiC),
- to be submitted (7: e-protein, e-methanol, e-FTL, e-methane, trading enhanded method, Greenland, DAC-kerosene for aviation)

Conference

- Lopez G., Galimova T., Fasihi M., Bogdanov D., Breyer C., 2022. Towards Defossilised Steel: Supply Chain Options for a Green European Steel Industry, 17th SDEWES Conference, Paphos, Cyprus, November 9
- Galimova T., Fasihi M., Bogdanov D., Breyer C., 2022. Impact of international transportation options on cost of green e-hydrogen supply: Global cost of hydrogen and consequences for Germany and Finland, presented at 8th International Conference on Smart Energy Systems, Aalborg, Denmark, September 13-14
- Keiner D., Mühlbauer A., Lopez G., Breyer C., 2022. Techno-economic assessment of atmospheric CO2-based carbon fibre production enabling negative emissions, 2nd International Conference on Negative Emissions, June 17-22, 2022, Gothenburg, Sweden
- Mühlbauer A., Keiner D., Galimova T., Breyer C., 2022. Analysis of production routes for silicon carbide using air as carbon source empowering negative emissions, 2nd International Conference on Negative Emissions, June 17-22, 2022, Gothenburg, Sweden
- Caldera U., ElSayed M., Aghahosseini A., Breyer C., 2022. Costs and Benefits of Afforestation with Renewable Electricity Based Desalination: Case Study for Egypt, 2nd International Conference on Negative Emissions, June 17-22, 2022, Gothenburg, Sweden

Publications (3/3)

Chapter

- Breyer C., Bogdanov D., Khalili S., Keiner D., 2021. Solar photovoltaics in 100% renewable energy systems. Chapter 14 in Photovoltaics Volume In: Meyers R.A., Encyclopedia of Sustainability Science and Technology, Springer, New York; https://doi.org/10.1007/978-1-4939-2493-6_1071-1

Report

- Ram M., Galimova T., Bogdanov D., Fasihi M., Gulagi A., Breyer C., Micheli M., Crone K., 2020. Powerfuels in a Renewable Energy World - Global volumes, costs, and trading 2030 to 2050, LUT University and Deutsche Energie-Agentur GmbH (dena), Lappeenranta and Berlin, ISBN 978-952-335-551-4
- Breyer C., Fasihi M., Micheli M., Oyewo A.S., Schmidt P., Weindorf W., 2022. E-Kerosene for Commercial Aviation, From Green Hydrogen and CO2 from Direct Air Capture – Volumes, Cost, Area Demand and Renewable Energy Competition in the United States and Europe from 2030 to 2050, Deutsche Energie-Agentur, Ludwig-Bölkow-Systemtechnik, LUT University, Berlin, Ottobrunn, Lappeenranta

Most important insights during the project

Trading of e-fuels

- e-ammonia is the first e-fuel which is more competitive than fossil fuel based ammonia
- e-methanol and e-liquids (kerosene jet fuel, etc.) become competitive around 2030 or earlier
- DAC evolves to a major source for CO_2 as raw material for e-hydrocarbons, more important than point sources
- global trading of e-fuels comprises about 30% of global demand and can reduce the cost by up to 30%
- e-hydrogen is not suited for global trading due to prohibitive transport cost, except pipeline transport in limited range
- importing countries can reduce their risk profile with a portfolio strategy of various exports around the world

Electrolyser demand

- estimate on electrolyser demand leads to about 17 TW by 2050: 10.8 TW (energy), 5.1 TW (chemicals), 1.2 TW (steel)
- this corresponds to about 63,500 TWh_{H2} by 2050: 40100 TWh_{H2} (energy), 19,000 TWh_{H2} (chemicals), 4400 TWh_{H2} (steel)
- Power-to-X Economy is the right term for the arising energy-industry system, including power-to-H_2-to-X

Power-to-Food

- huge market arising for e-protein, based on low-cost electricity, e-CO_2 and e-ammonia
- arable land shrinks, soil degradation continues while higher living standards and more people induce more demand
- e-protein is a huge opportunity to reduce the most fundamental threat of lacking food

Researcher seminar (1/2)

Seminar 1

- Galimova: Supply of CO_2 as raw material: sustainable and unavoidable point sources vs direct air capture
- Galimova: Investigation for first insights on Agriculture form an energy system perspective

Seminar 2

- Galimova: The role of electric fuels and electric chemicals in a future 100% renewable energy systems and their global trading patterns
- Galimova: How electric fuels can help to reduce the global air pollution issue

Seminar 4

- Fasihi: Global potential of green ammonia based on hybrid PV-wind power plants

Seminar 5

- Fasihi: Power-to-X: Global potential of synthetic liquid hydrocarbons based on hybrid PV-wind power plants and Fischer-Tropsch technology

Researcher seminar (2/2)

Seminar 6

- Fasihi: Power-to-X: Global potential of e-methanol based on hybrid PV-wind power plants
- Bogdanov: Perspectives of the global e-fuels and e-chemicals trading
- Galimova: Impact of international transportation options on cost of green e-hydrogen supply: Global cost of hydrogen and consequences for Germany and Finland
- Lopez: Securing a Green Power-to-Steel Supply for Europe

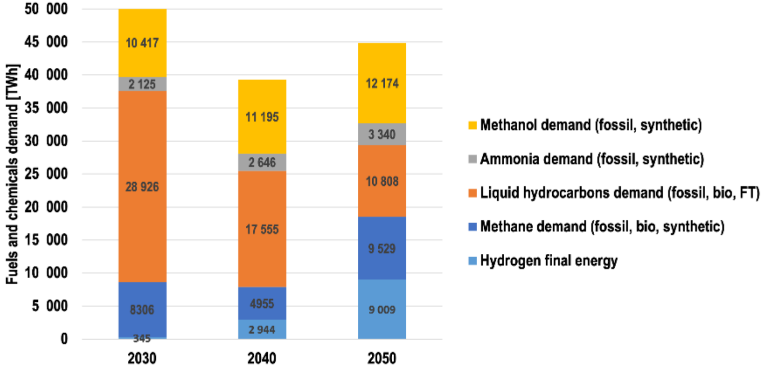
Seminar 7

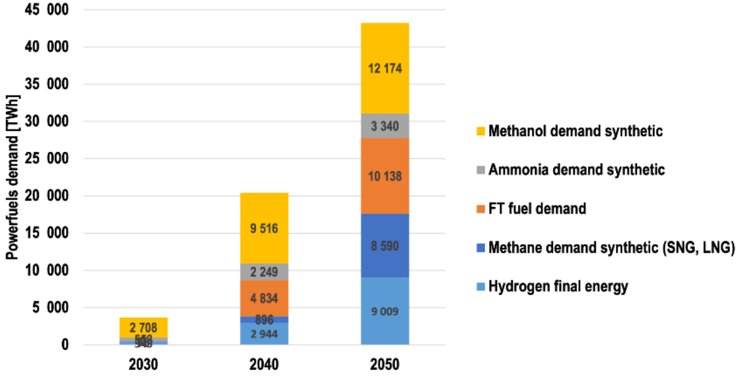
- Fasihi: Global potential of e-methane based on hybrid PV-wind power plants
- Khalili: 100% renewable energy systems research: Review on the field with bibliometrics including e-fuels and the Power-to-X economy
- Caldera: Afforestation with renewable electricity based desalination as a climate change mitigation technology

In total

- 14 presentations during the project
- 7 different researchers contributed to the research of this WP

Global demand for e-fuels





Fuels and Chemicals in general:

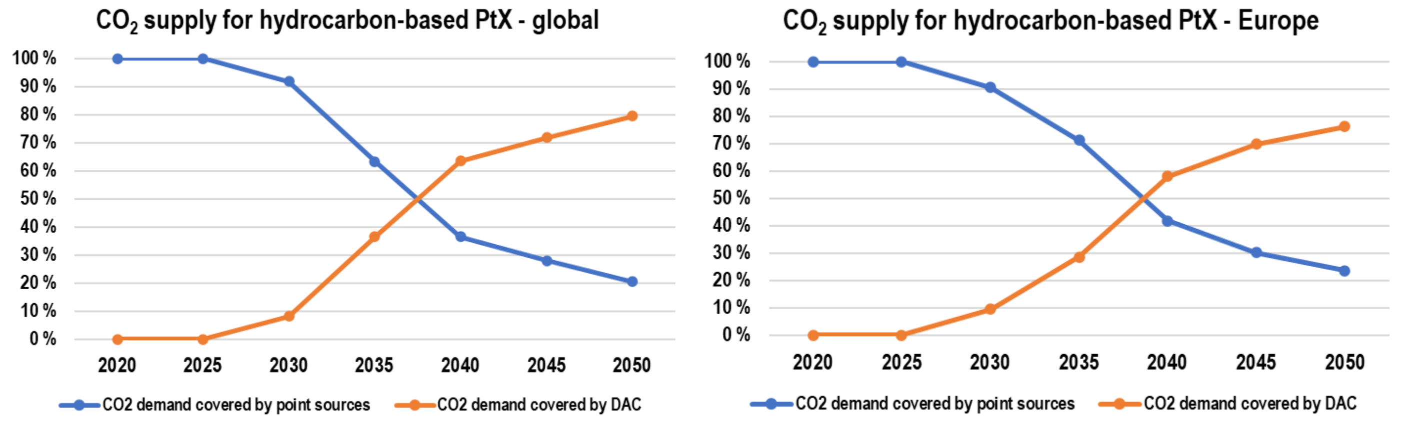
- steady growth of chemicals
- Methanol represents non-Ammonia chemicals
- liquid hydrocarbons are in steady decline, mainly due to electrification of road transportation
- Methane demand in decline until 2040 with increase towards 2050, with some uncertainty for substitution of Methane by Hydrogen

e-fuels and e-chemicals:

- first markets in 2030
- strong growth over the decades
- less uncertainty for synthetic chemicals
- highest uncertainty for Methane demand due to substitution by Hydrogen (heat) and Ammonia/Methanol (marine)

Development of DAC demand: e-CO_2

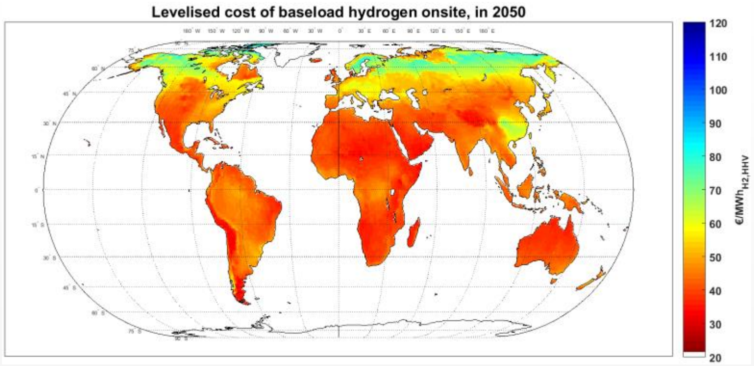
- Finally, 80% of global CO_2 raw material demand needs to be covered by DAC, while the DAC demand in Europe is slightly lower at 76%
- Industrial phase-in of DAC is critical in 2020s, as point sources are available, while DAC requires a first market ramp-up for massive scaling in 2030s and 2040s
- DAC and carbon utilisation (DACCU) is the first huge phase in DAC deployment
- DAC of carbon and storage (DACCS) is expected to be the second huge phase for DAC demand starting in 2040s (not included in diagrams below)

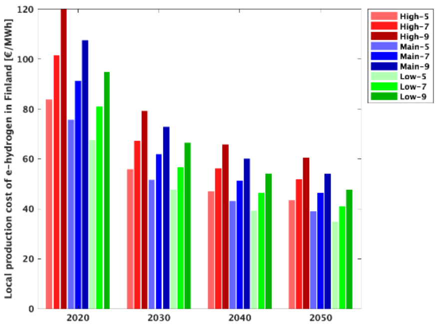


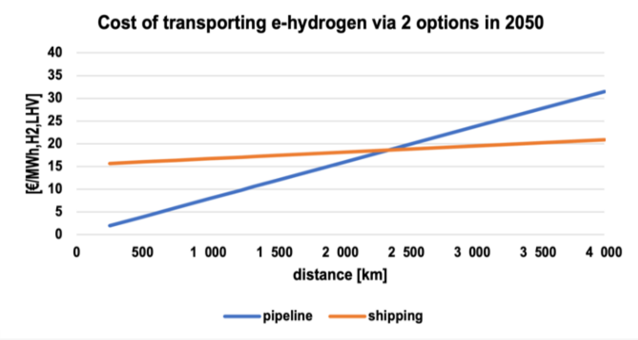
e-fuels trading: e-hydrogen

Detailed results for e-hydrogen trade investigated (international collaboration with TransnetBW)

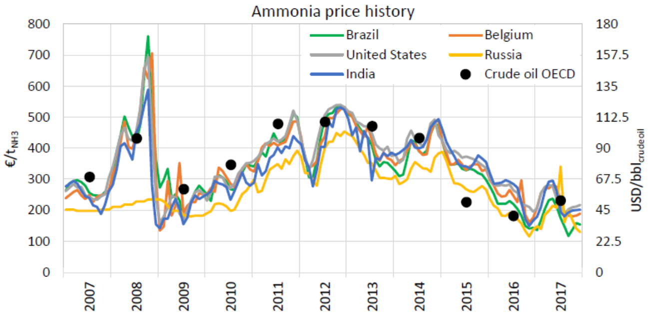
- **Renewable-electricity based hydrogen can be produced at acceptable cost anywhere in the world**
- **To better assess attractiveness of imports transportation infrastructure needs to be considered**
- **Imported hydrogen costs were found to be significantly higher than H_2 produced domestically (case FI, DE)**
- **Local supply of H_2 is more economical across both cases and all years, since transportation costs are high**
- **Pipeline transport is lower in cost for short distances, whereas shipping is more economical for distances over 1500 km**







e-fuels trading: e-ammonia (1/2)



Green e-ammonia the most likely first mainstream e-fuel/e-chemical

- Green e-ammonia can be produced from 370-450 €/t by 2030
- Production costs at best sites could decline to 285-350 €/t by 2050
- Fossil ammonia cost 150-500 €/t in 2010s, strongly dependent on oil price
- Solar PV is a dominating source of energy supply for ammonia production
- Right now green e-ammonia is THE LEAST COST option; fossil methane prices (80 €/MWh_{NG}) and steam coal prices (>200 US$/$t_{coal}$) lead to higher cost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Global potential of green ammonia based on hybrid PV-wind power plants

Mahdi Fasihi[a,*], Robert Weiss[b], Jouni Savolainen[c], Christian Breyer[a]

HIGHLIGHTS

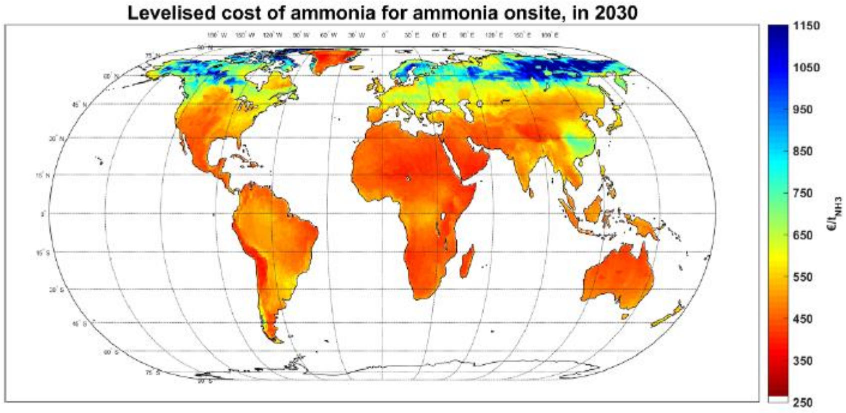
- Green ammonia can be produced for 370–450 €/tonne in all continents by 2030.
- The production costs at the best sites could decline to 285–350 €/t_{NH3} by 2050.
- Coal-based ammonia in China is the first to be substituted by green ammonia.
- Flexible synthesis units have a major role in low-cost green ammonia production.
- PV is a dominating source of power supply to islanded plants in most of the world.

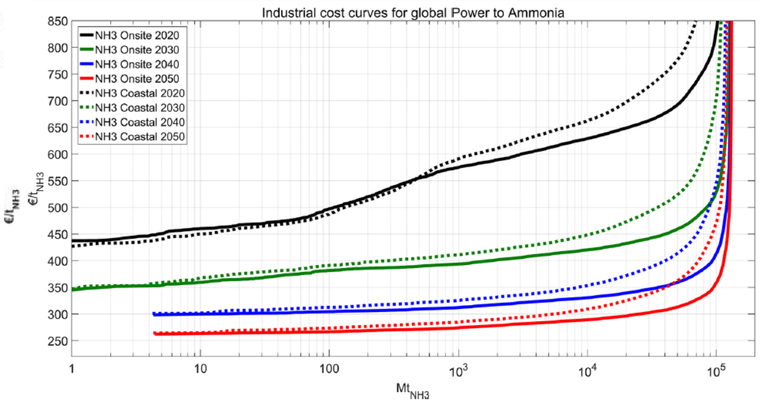
ARTICLE INFO

Keywords:
Hybrid PV-wind
Battery
Power-to-Ammonia (PtA)
Power-based chemicals
Power-to-X

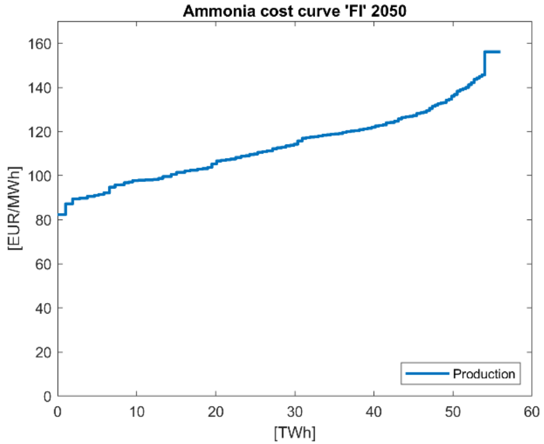
ABSTRACT

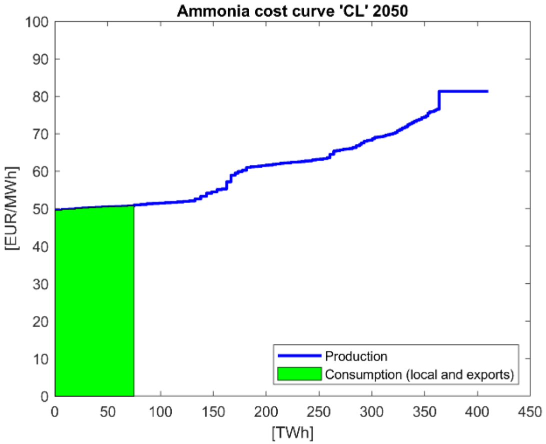
Ammonia is one of the most commonly used feedstock chemicals globally. Therefore, decarbonisation of ammonia production is of high relevance towards achieving a carbon neutral energy system. This study investigates the global potential of green ammonia production from semi-flexible ammonia plants utilising a cost-optimised configuration of hybrid PV-wind power plants, as well as conversion and balancing technologies. The global weather data used is on an hourly time scale and 0.45° × 0.45° spatial resolution. The results show that, …

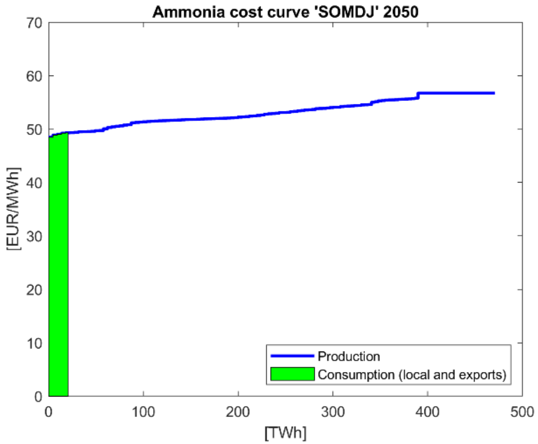


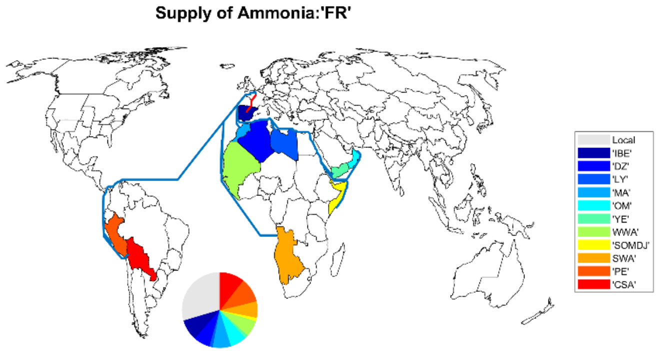


e-fuels trading: e-ammonia (2/2)









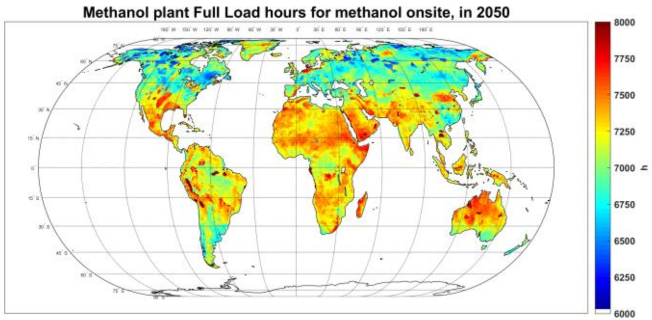
Total local consumption of Ammonia : 47.3 TWh
Total consumption from local production: 14.0 TWh
Total consumption from imports: 33.3 TWh

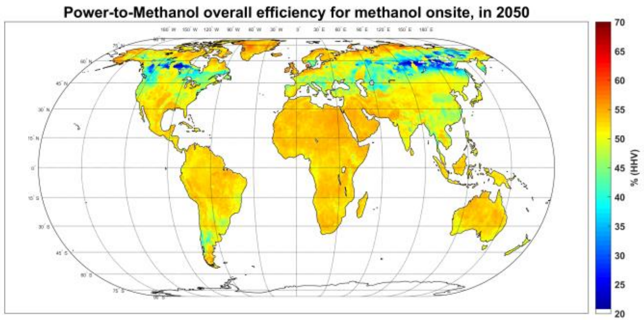
- Ammonia as a first case: see cost in Finland vs Chile vs Somalia
- Country classes introduced
- Based on: Doing business index (World Bank), Corruption perception index (Transparency International), Rule of Law index
- Classes impact: class 1 (15% max import), 2 (10%), 3 (7%), 4 (4%), 5 (2%)
- Next steps: refinements, expansion to methanol, FT, SNG/LNG

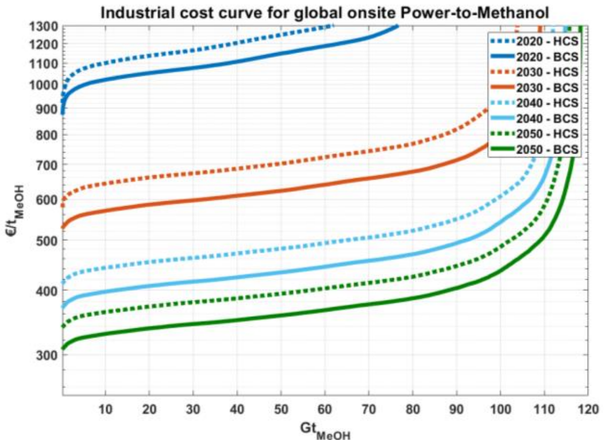
e-fuels trading: e-methanol

Detailed results for all major e-fuels/chemicals investigated

- All major e-fuels/chemicals investigated: e-ammonia, e-methanol, Fischer-Tropsch fuels, e-methane/LNG
- e-methanol is projected to be cost competitive towards 2030
- e-ammonia is the least cost way of ammonia production as of now with the very high fossil fuel prices
- Fischer-Tropsch fuels are projected to be cost competitive from 2030 onwards in best sites in the world
- e-methane/LNG may be much less relevant due to high probability of methane substitution by other options



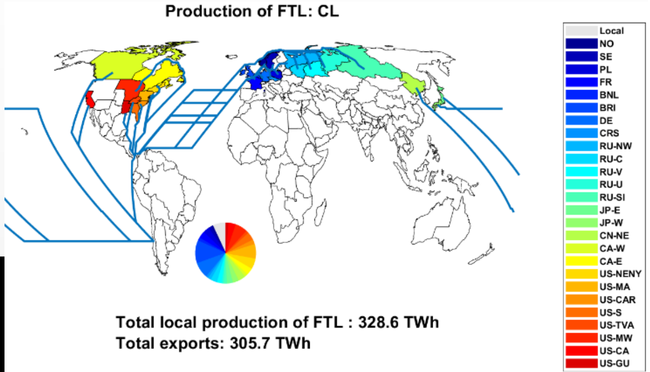


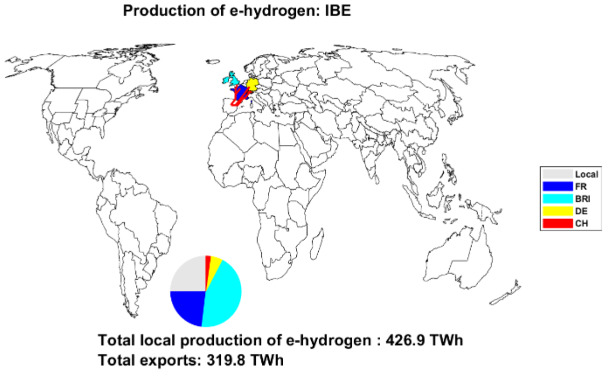


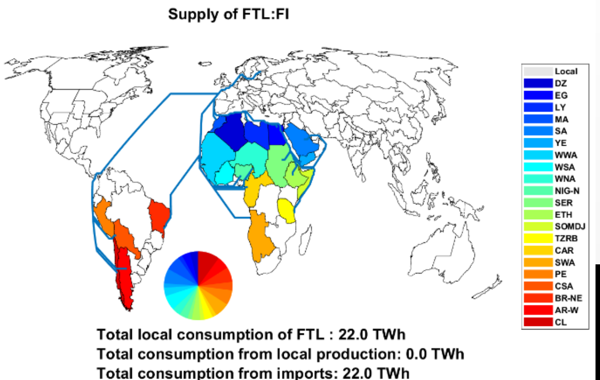
e-fuels trading: e-FTL

Detailed e-fuels trading methodology developed and applied for all major e-fuels/chemicals

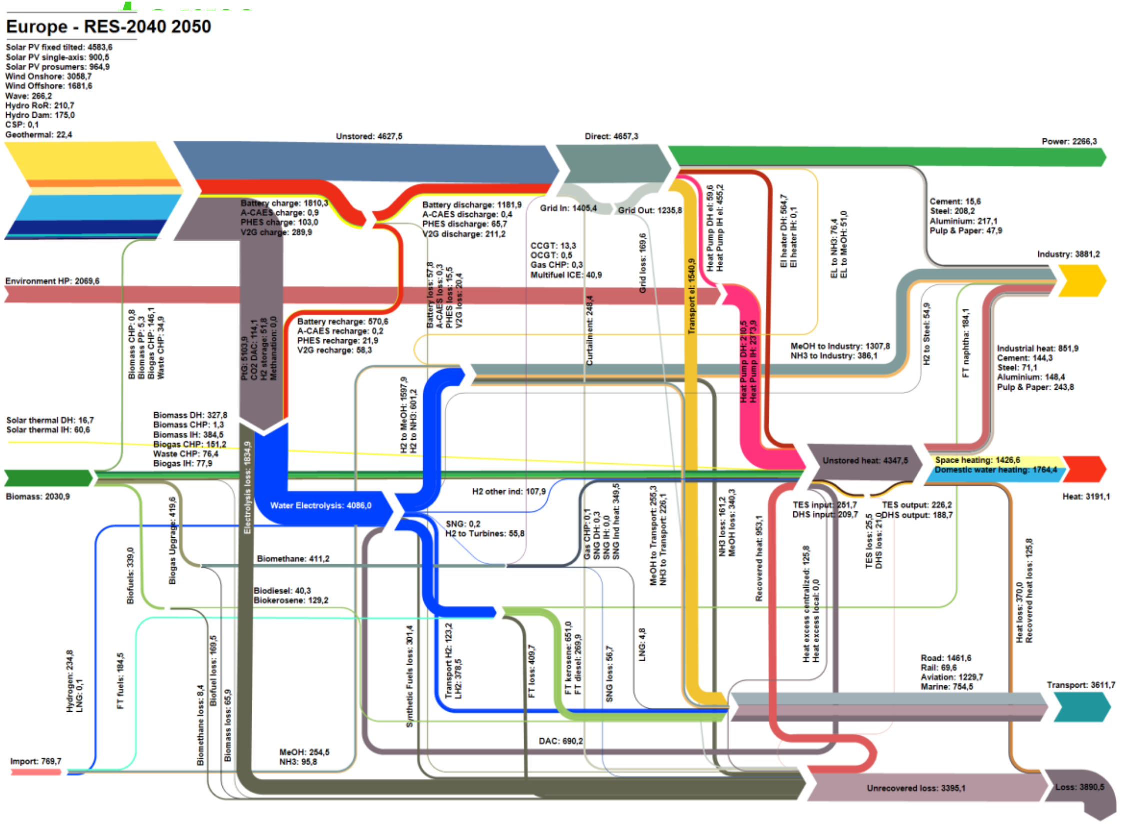
- Trading of methanol and FTL is more beneficial due to lower shipping costs and higher share of electricity in final cost, while ammonia can be mostly produced locally
- Chile, Peru, Oman, West Australia are the main exporters in all cases, though the results are significantly influenced by export class limitations limiting exports from some other countries with low-cost e-fuels production
- Hydrogen is mostly locally produced and if imported, imported via pipelines from neighbouring regions
- In 2050 local production of e-fuels and e-chemicals in Finland may be not cost feasible, except hydrogen which is produced locally due to high hydrogen transportation cost
- Lower WACC and lower RE capex lead to higher competitiveness of local production of e-fuels and e-chemicals
- Results for e-fuels trading presented in yesterday’s Researchers Seminar







Power-to-X Economy as new characteristic



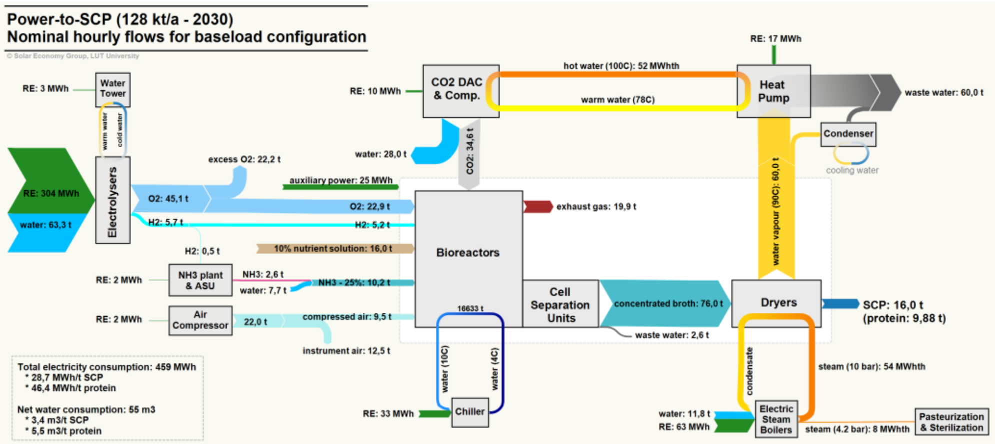
- Zero CO_2 emission low-cost energy system is based on electricity
- Core characteristic of energy in future: Power-to-X Economy
    - Primary energy supply from renewable electricity: mainly solar PV and wind power
    - Direct electrification wherever possible: electric vehicles, heat pumps, desalination, etc.
    - Indirect electrification for e-fuels (marine, aviation), e-chemicals, e-steel;
    - power-to-hydrogen-to-X as important element, but not characteristic

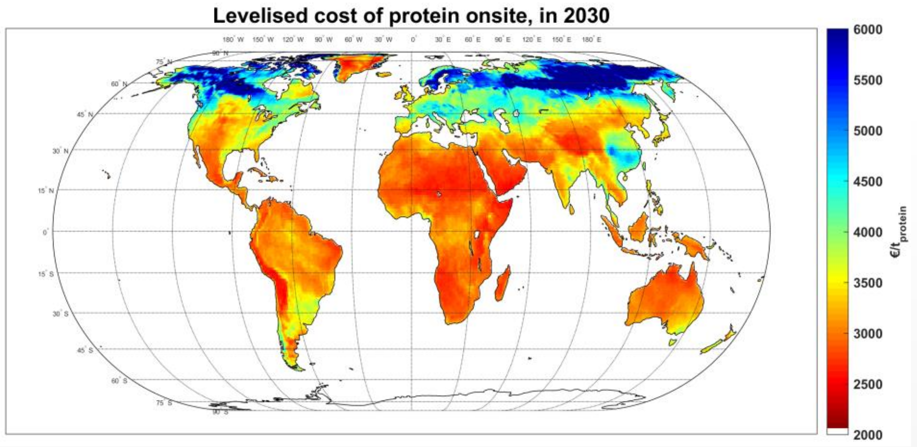
Source: Power-to-X economy: Breyer, Bogdanov, Ram, Khalili, Lopez, et al., Progress in Photovoltaics, under review
Diagram: Greens/EFA, 2022

Power-to-Food: e-protein

Power-to-Food

- detailed model has been prepared for e-protein production of electricity, water and air to food
- excellent solar and wind resources lead to low e-protein costs
- pressure on food supply and ecosystems can be massively reduced with e-protein





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Thank you for your attention …
… and to the team!

all publications at: www.scopus.com/authid/detail.uri?authorId=39761029000
new publications also announced via Twitter: @ChristianOnRE

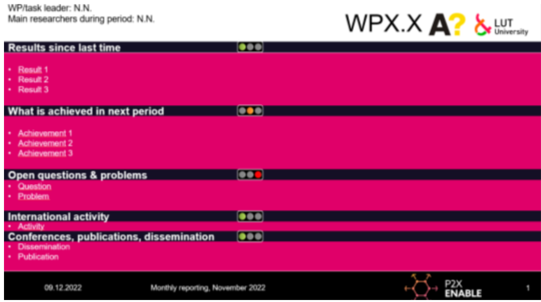
WP4: Management and dissemination

Antti Kosonen

Results (1/2)

Management

- Internal monthly meetings arranged to discuss about the latest results
  - One slide from each WP/task with the traffic lights
  - Totally 23 meetings arranged
- Interim reports delivered to BuFi
  - Totally 7 interim reports + final report
- Seven research seminars arranged
  - Totally 9+9+7+5+2+9+9 = **50 presentations**
  - Presentation material shared (slides and recordings) in Teams and webpage
- Seven steering group meetings + kickoff meeting
  - Presentations + meeting notes



Results (2/2)

PUBLICATIONS

Journal Articles

Modelling the effect of CO2 loading of aqueous potassium glycinate on CO2 absorption in a membrane contactor
H. Nieminen, P. Maksimov, A. Laari, T. Koiranen, Front. Chem. Sci. Eng. 31 (2022), Article 982891.
Process modelling and feasibility study of sorption-enhanced methanol synthesis
H. Nieminen, P. Maksimov, A. Laari, V. Väisänen, A. Vuokila, M. Huuhtanen, T. Koiranen, Chem. Eng. Process. 179 (2022), Article 109052.
Sorption enhanced carbon dioxide hydrogenation to methanol: Process design and optimization
P. Maksimov, H. Nieminen, A. Laari, T. Koiranen, Chem. Eng. Sci. 252 (2022), Article 117498.
Trends in the global steel industry: Evolutionary projections and defossilisation pathways through power-to-steel
G. Lopez, J. Farfan, C. Breyer, J. Clean. Prod. 375 (2022), Article 134182.
Mitigation of air pollution and corresponding impacts during a global energy transition towards 100% renewable energy system by 2050
T. Galimova, M. Ram, C. Breyer, Energy Reports 8 (2022) 14124–14143.
On the history and future of 100% renewable energy systems research
C. Breyer, S. Khalili, D. Bogdanov, M. Ram, A.S. Oyewo, A. Aghahosseini, A. Gulagi, A.A. Solomon, D. Keiner, G. Lopez, P.A. Østergaard, H. Lund, B.V. Mathiesen, M.Z. Jacobson, M. Victoria, S. Teske, T. Pregger, V. Fthenakis, M. Raugei, H.

Dissemination

- Webpages (https://p2xenable.fi) have been available
  - Seminar material
  - Publications (27 journal + 4 conf. articles)
- Conferences arranged together with City of Lappeenranta
  - Conference on Green Electrification 13–15 Sep. 2021 in Lappeenranta
  - Conference on Future Energy Solutions 8–9 Nov. 2022 in Lappeenranta

Project overview

- Funding reserved to the research visits were mainly moved to the salaries
- Project ending postponed to the end of this year