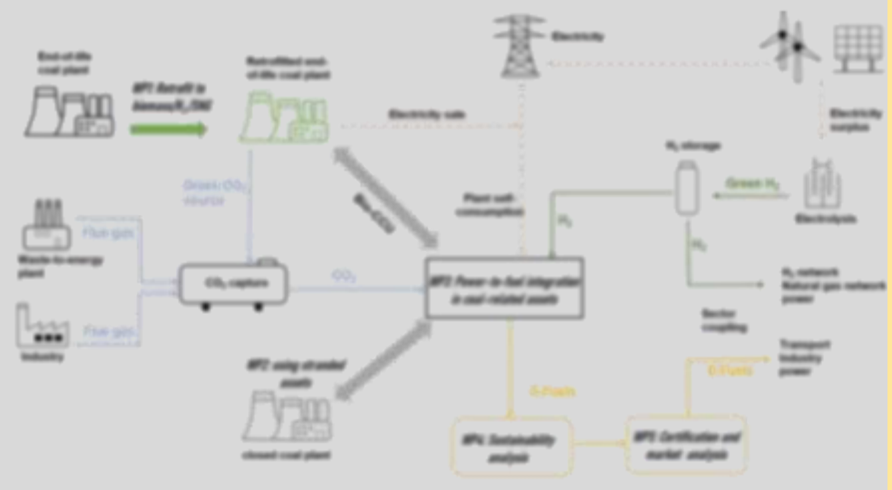
This project has received funding from the Research Fund for Coal and Steel under Grant Agreement No 101034035.

Green Deployment of E-Fuels And Liquids based on CO_2
for closed and end-of-life coal-related assets



GreenDEALCO$_2$ Project presentation

Final workshop

June 18th 2024, Essen (Germany)

Overview

- Motivation
- Using alternative energy carriers
- Case studies and technology developments
- Social & environmental analysis
- Regulatory & economic analysis
- Conclusion

Motivation

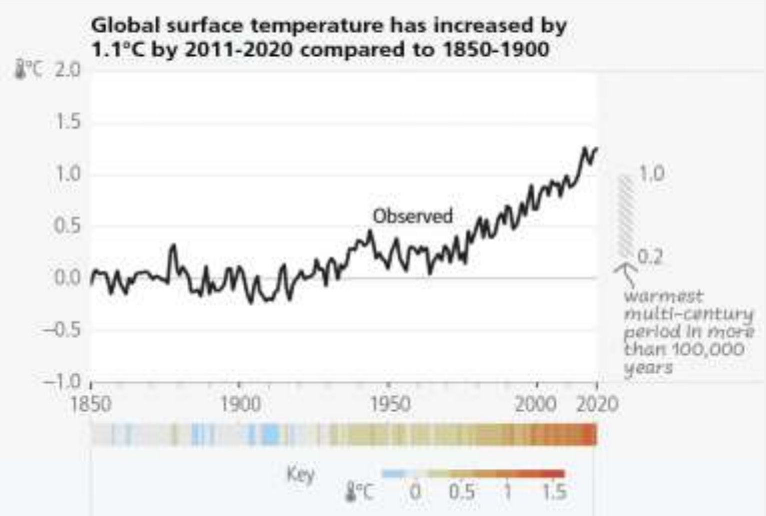
Motivation

- Measurable change in the climate:
  - Rising average temperatures
  - Rising greenhouse gas concentrations in the atmosphere
  - Dominant: CO_2 from fossil fuels and industry

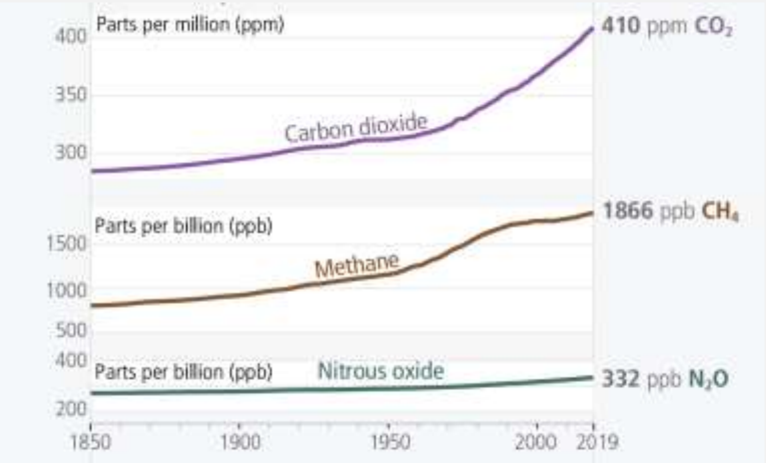
→Measures required to reduce greenhouse gas emissions

- Paris climate agreement:
  - Phasing out coal-fired power generation

Changes in global surface temperature



Concentration of the GHGs in the atmosphere



Source: IPCC (https://www.ipcc.ch/report/ar6/syr/)

Approach of GreenDEALCO_2

- The challenge:
  - Sustainable, secure and independent energy supply in Europe
  - Closed power plants and job losses

GreenDEALCO_2

Green Deployment of **E**-fuels **A**nd **L**iquids based on **CO_2** for closed and end-of-life coal-related assets

- Objective: New future perspectives for the coal industry
- Approach:
  - Retrofitting existing power plants for low-CO_2 or CO_2-free operation
  - Using shut-down power plant infrastructure for e-fuel production

General data of the project

- Funding organisation: European Commission
- Funding programme: Research Fund for Coal & Steel
- Project start: August 2021
- End of the project: July 2024
- Budget: € 2.5 million

Research Fund for Coal & Steel

Universität Stuttgart

meo CARBON SOLUTIONS

Mitsubishi Power Europe

vgbe ENERGY IS US

RWE

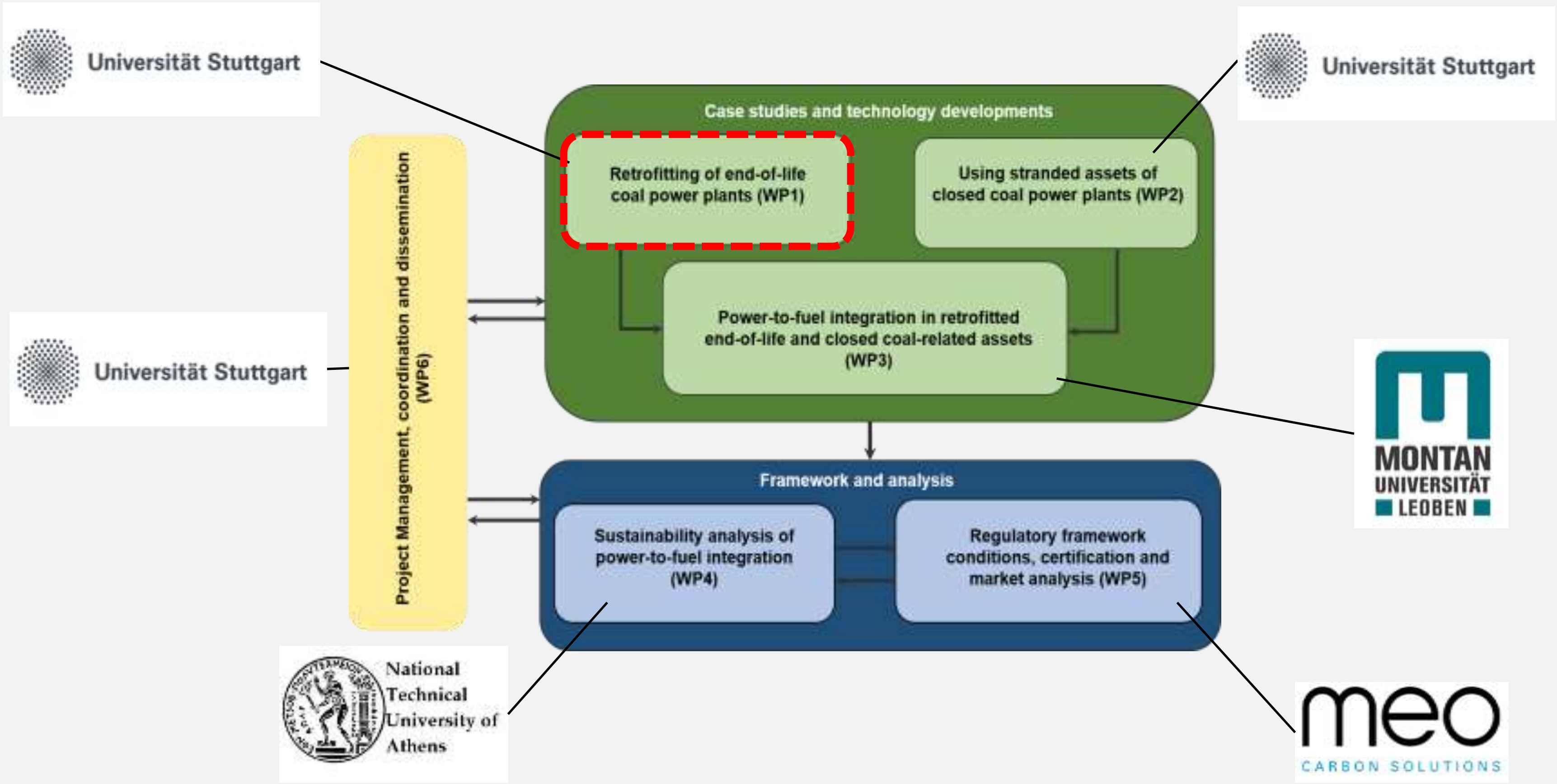
MONTAN UNIVERSITÄT LEOBEN

Verbund

National Technical University Athens

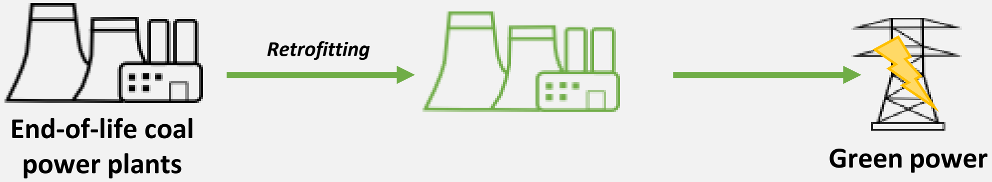
MOTOR OIL

Steps to achieve the overall goal

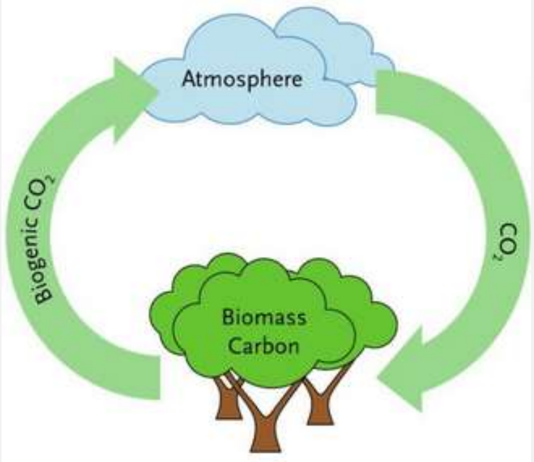
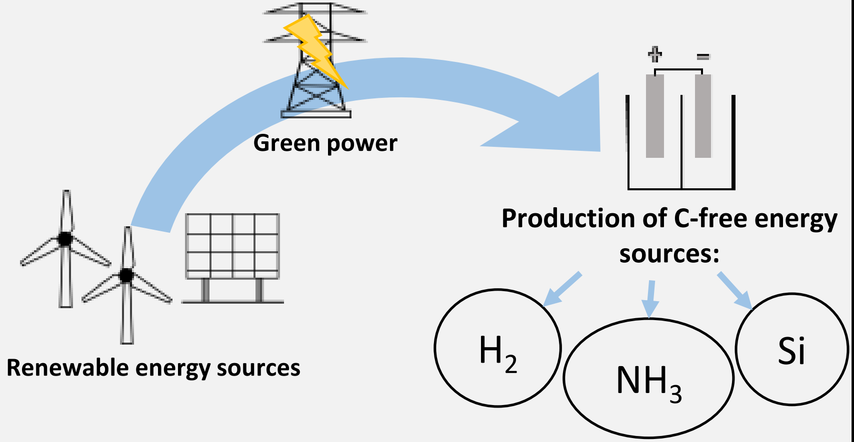


Using alternative energy carriers

Concept

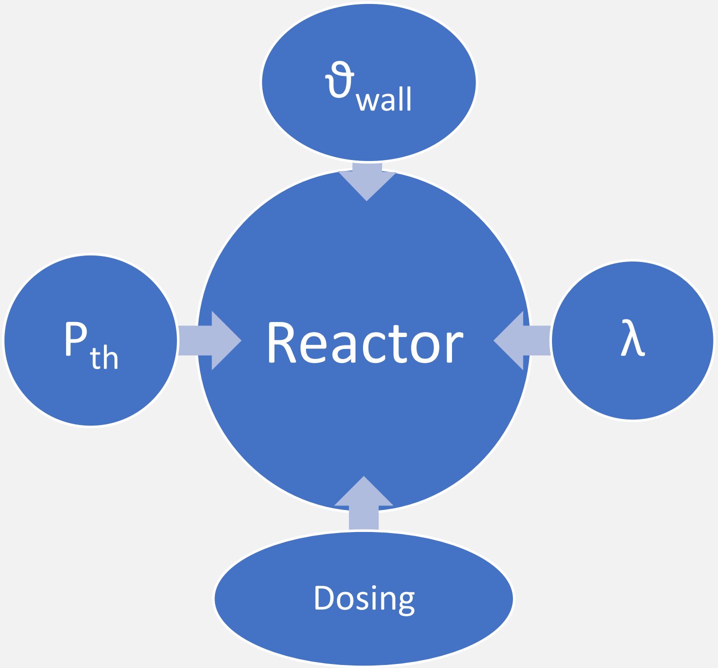


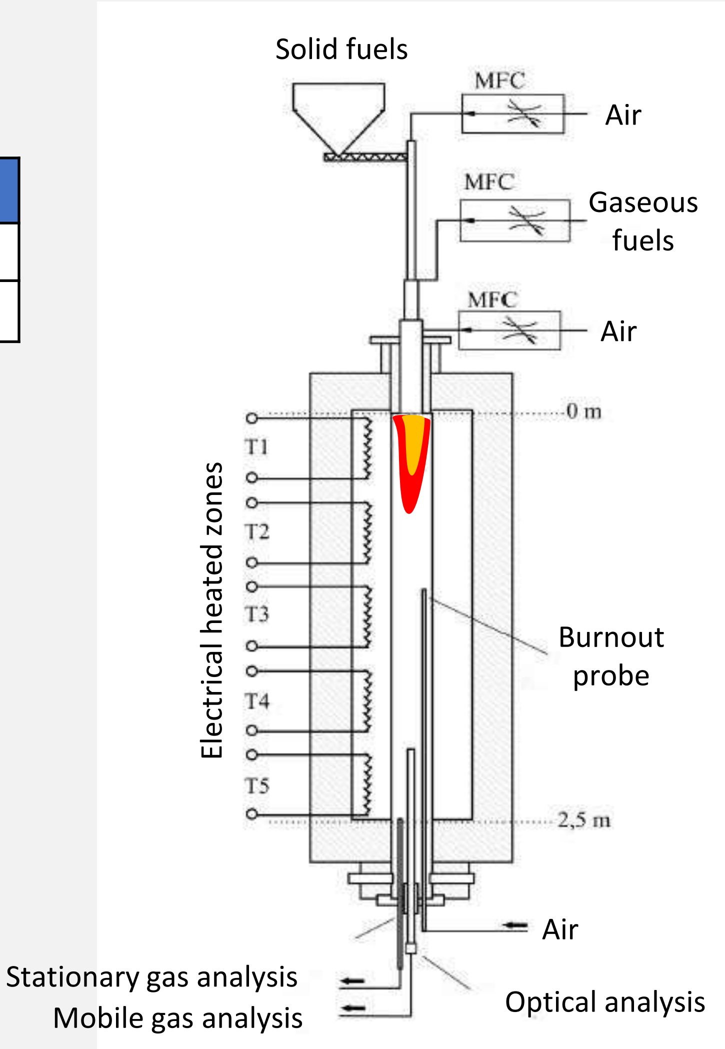
Fuels analysed

Biogenic fuels	Synthetic energy carriers
 Source: IEA Bioenergy	

Test facility

Technical Data			
Thermal power:	< 20 kW	Wall temperature:	800 – 1500 °C
Length:	2,5 m	Diameter:	200 mm



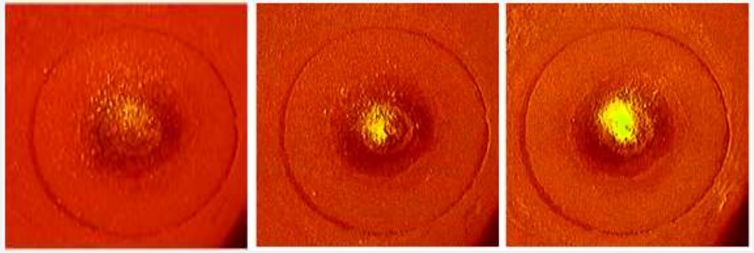


Hydrogen

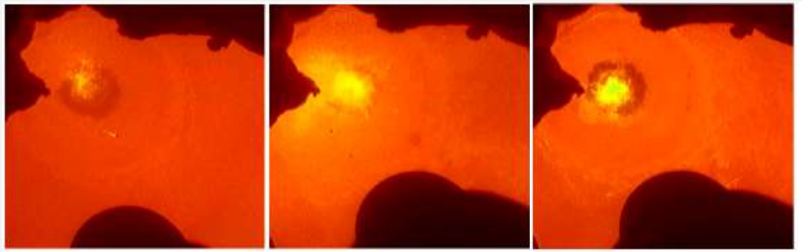
- Pure combustion:
  - Compact and more intensive reaction zone
  - Less radiation in the IR spectrum
  - Flame monitoring?

- As an additive to: Biomass Dried lignite

P_{th}: 100 % - 0 % 83 % - 17 % 50 % - 50 %



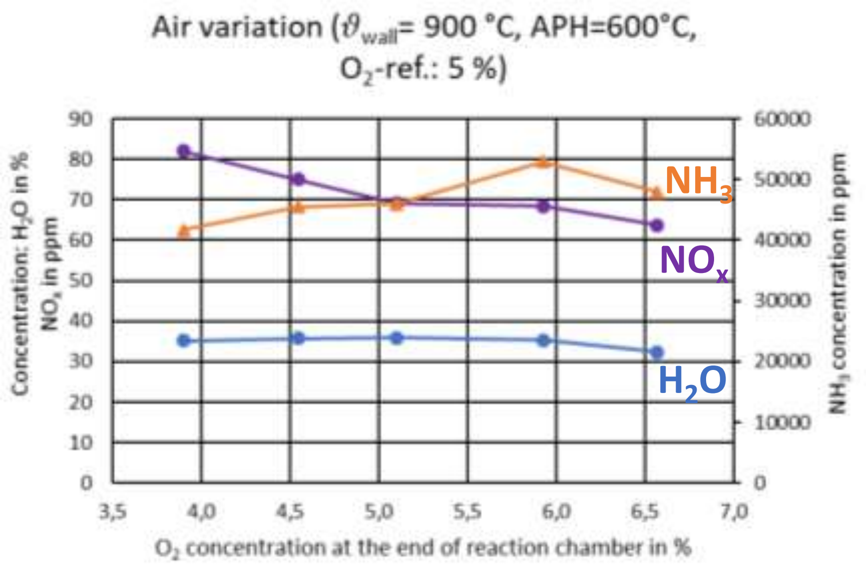
P_{th}: 100 % - 0 % 83 % - 17 % 50 % - 50 %



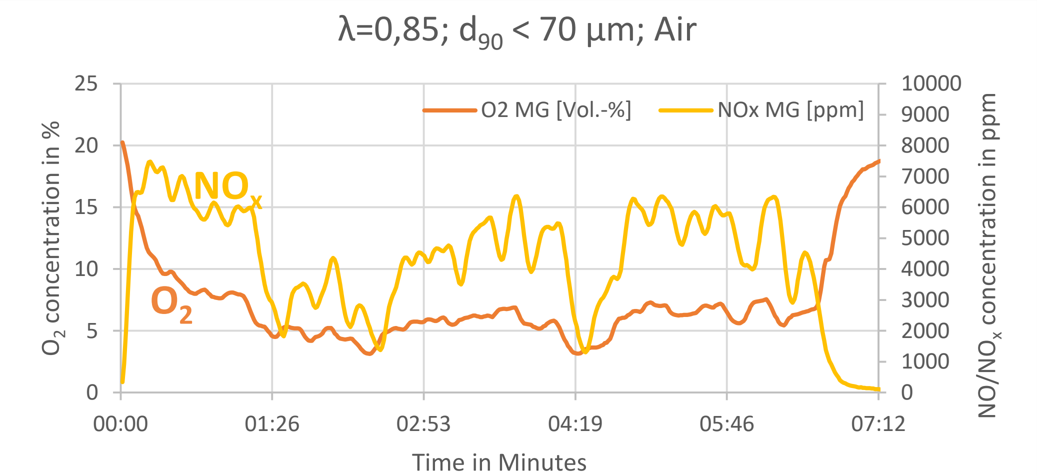
- Improved combustion: Reduction of NO_x and CO

Ammonia

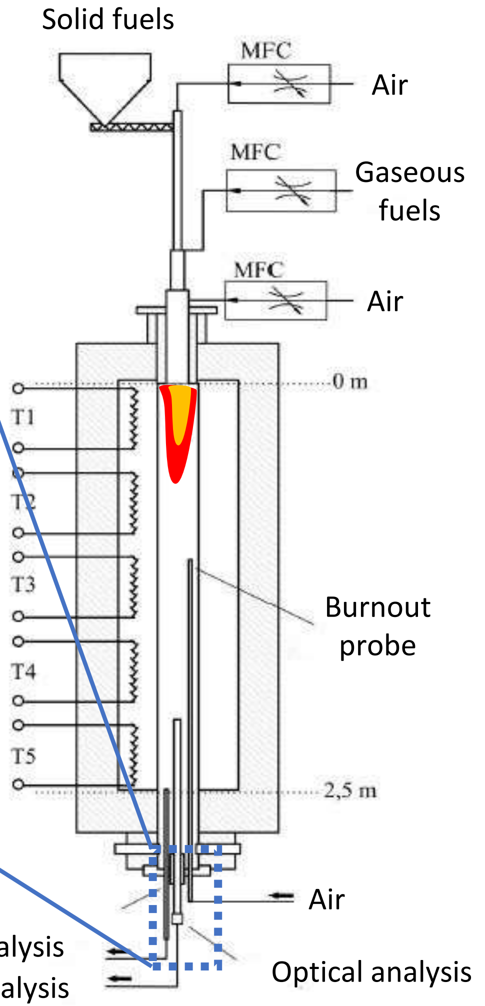
- Advantages: Higher energy density through liquid storage
  (boiling point: -33.3 °C (p_{amb}); 8.5 bar (20 °C))
- Key results:
  - Very high NH_3 slip
  - Relatively low NO_x values
  - High retention times benefit slow reaction rate
- Conclusion:
  - NH_3 combustion successful
  - Need for optimisation in the area of process control



Silicon



Optical analysis

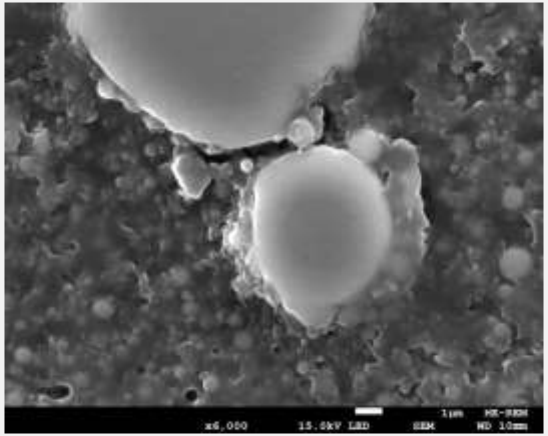


Observations:

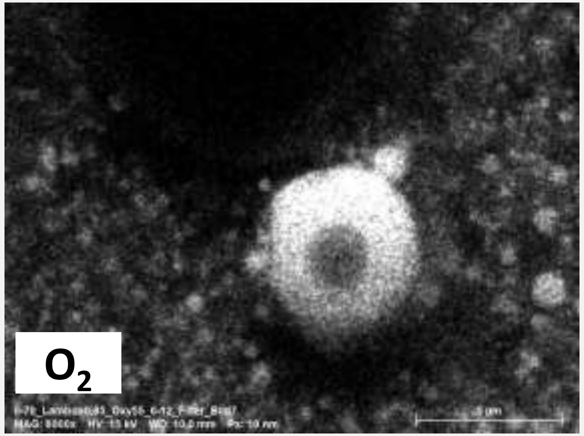
- Clear decrease in O_2 →oxidation
- High NO_x formation
- Very fine fog/particles

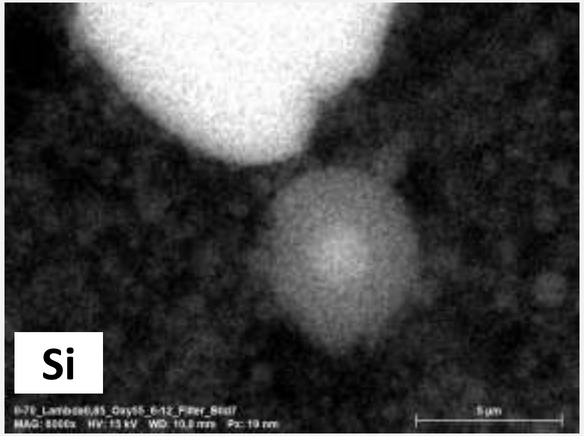
Silicon

SEM-Analysis



Chemical composition





→Very fine particle: 0.1 – 0.5 µm

Conclusion:

- Combustion possible in principle
- Particle size and dosing play a decisive role for constant operation
- Investigation of causes and measures to reduce NO_x emissions

Retrofit of lignite power plants

- Grid stabilisation through existing plants
- From a selection of various power plants, the Greek power plant Agios Dimitrios was selected
- Scenarios for operation in low-CO_2 or -free mode:

	Fuel	CO_2 emissions
Scenario 1	100 % lignite	407 t/h
Scenario 2	Lignite + wood pellets	168 t/h
Scenario 3	Wood pellets	0 t/h
Scenario 4	100 % SNG	191 t/h
Scenario 5	100 % H_2	0 t/h
Scenario 6	50 % SNG + 50 % H_2	95 t/h
Scenario 7	75 % SNG + 25 % H_2	143 t/h
Scenario 8	25 % SNG + 75 % H_2	48 t/h

Source: PPC

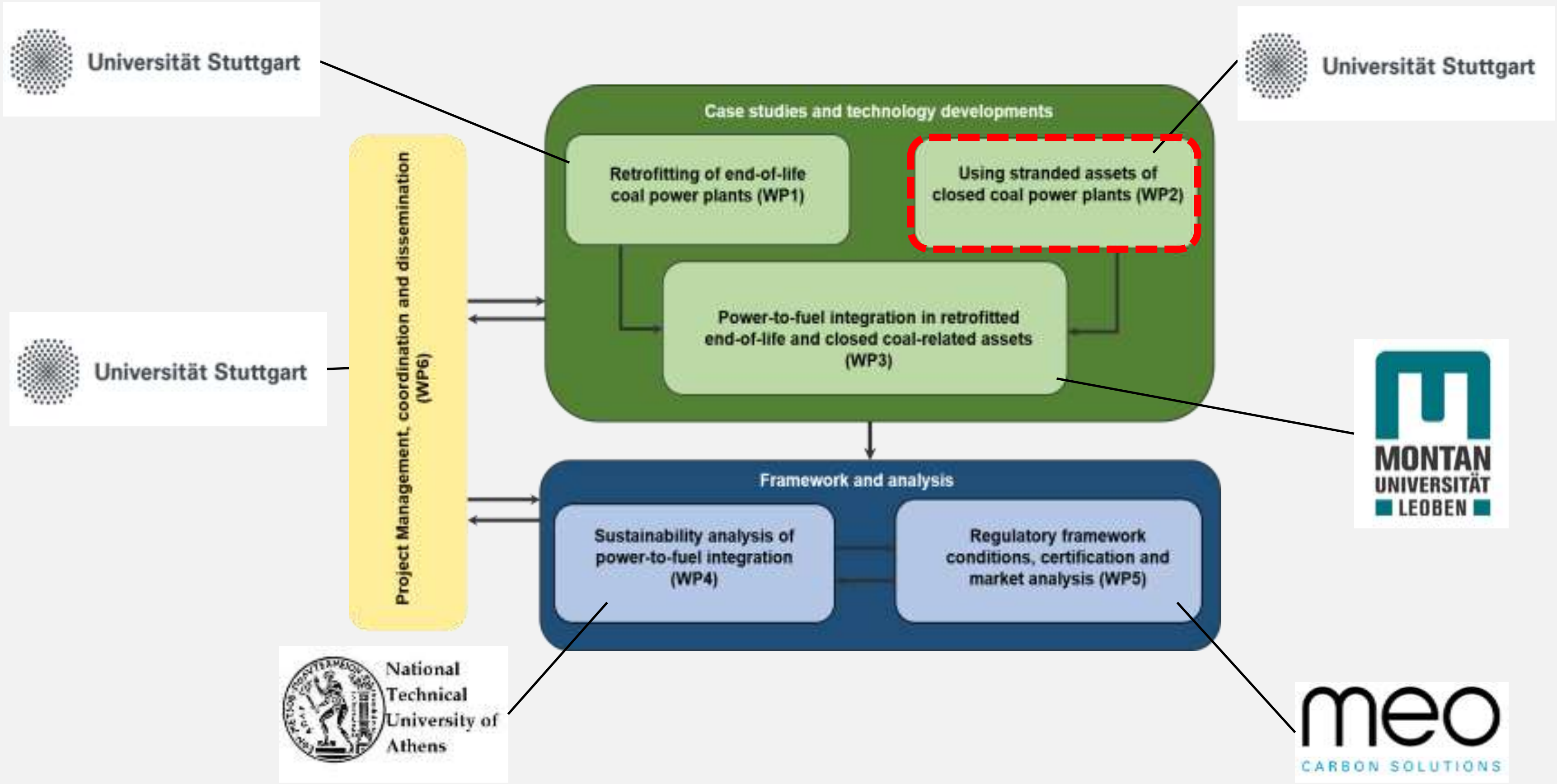
Agios Dimitrios V (Gr)

Retrofit of lignite power plant

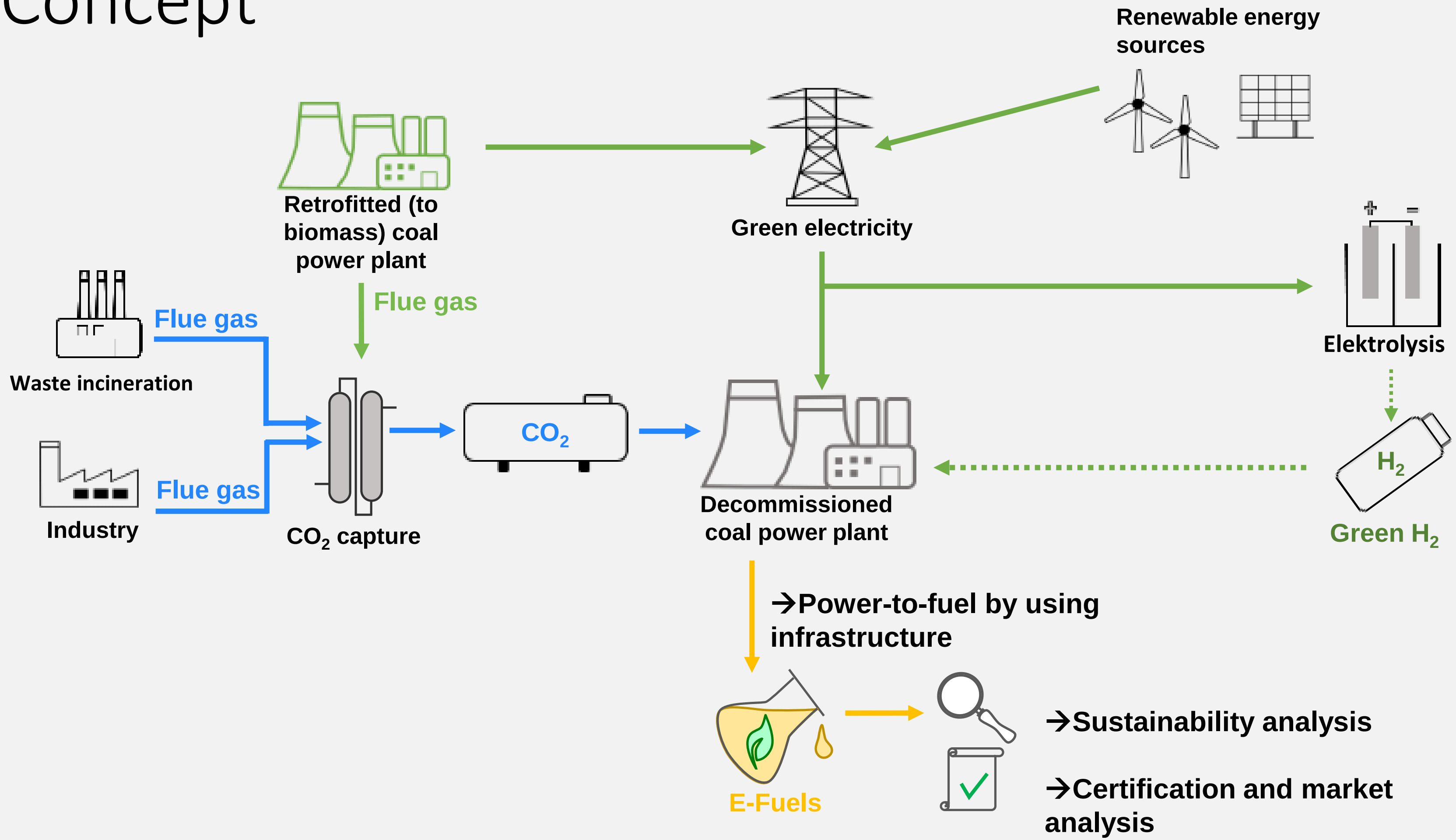
- Biomass and wood pellets (full or partial): possible
  - Adjustments to fuel dosing and logistics in particular
  - Local biomass interesting, but: gaps in supply due to natural events would jeopardise security of supply.
  - Wood pellets meet quality standards and are better suited for this purpose
- Gaseous fuels: principally possible
  - Significant advantages such as the elimination of cleaning equipment for heating surfaces and ash removal components, as well as no slagging and fouling and no erosion on the heating surfaces.
  - Significant impact on the fuel supply system and firing system such as burner design, layout, fuel supply, air supply. Process-specific measures such as gas recirculation for temperature control.
  - Significantly higher fuel flows with increasing hydrogen content →Adaption of supply

Utilisation of infrastructure from closed coal power plants for Power-to-fuel

Steps to achieve the overall goal



Concept


Renewable energy sources
Retrofitted (to biomass) coal power plant
Green electricity
Flue gas
Flue gas
Flue gas
Waste incineration
Elektrolysis
CO_2
Industry
CO_2 capture
Decommissioned coal power plant
H_2
Green H_2
→Power-to-fuel by using infrastructure
E-Fuels
→Sustainability analysis
→Certification and market analysis

Finding suitable plants

- High occurrence of suitable locations:
  - Industry: Knappsacker Hügel, Mellach,…
  - Waste incineration: Weisweiler, Herten,...
- Key sticking points: CO_2 concentration and availability
  - Industry: Fluctuating availability & low concentration (2 - 10 vol.-%)
    →Process-dependent →variation not possible
  - Waste incineration: Continuous availability & low concentration (7 - 9 vol.-%)
    →24/7 operation, BUT: oxygen enrichment possible
- Investigation of the enriched combustion concept

	Air (Standard)	‚Enriched' (real plant)	Oxyfuel (200 kW test plant)
O_2 concentration	21 Vol.-%	22 – 25 Vol.-%	100 Vol.-%
CO_2 concentration	9 – 11 Vol.-%	13 – 16 Vol.-%	> 80 Vol.-%

Evaluation of closed coal power plant sites for power-to-fuel repurposing

- Evaluation criteria for the closed coal power plant sites and the available resources
- Evaluation of nearby CO_2 source available
- Identification of suitable CO_2 capture technologies
- Identification of Use cases and Development of scenarios
- Power-to-fuel pathways

Evaluation criteria for the closed coal power plant sites and the available resources

Evaluation Criteria

- Availability of (green) CO_2 (Point Source)
- Area for new-build projects
- Grid Capacity (High- / Medium Voltage)
- Railway connection and transport infrastructure
- Heavy load road connection
- Potential for connection with an H_2 pipeline
- Water supply (cooling water, demineralised water)
- Heat supply
- Disposal of waste water
- Administration / Storage / Workshops
- Permitting procedure
- Availability of personnel

Evaluation criteria for the closed coal power plant sites and the available resources

Coal Power Plant Sites Identified:

- Power plant site in Mellach, Austria (VTP)
- Power plant site in Knapsacker Hügel (RWE)

CO_2 Sources identfied:

- Cement plant in Retznei, AT
- Sewage sludge incineration plant Knapsacker Hügel, DE

Carbon Capture Technology

- Post-combustion Carbon Capture (Amine-based CO_2 absorption process)

Power-to-fuel pathways

Identification of appropriate technologies for power-to-fuel retrofitting

Identification of E-fuel production pathways

GreenDEALCO$_2$

Power-to-fuel pathway

Identification of appropriate technologies for power-to-fuel retrofitting

- PEM electrolyzers
- Hydrogen Storage using pressurized vessels

E-fuel Pathways:

- E-Methanol
- Fischer-Tropsch
- Methanation

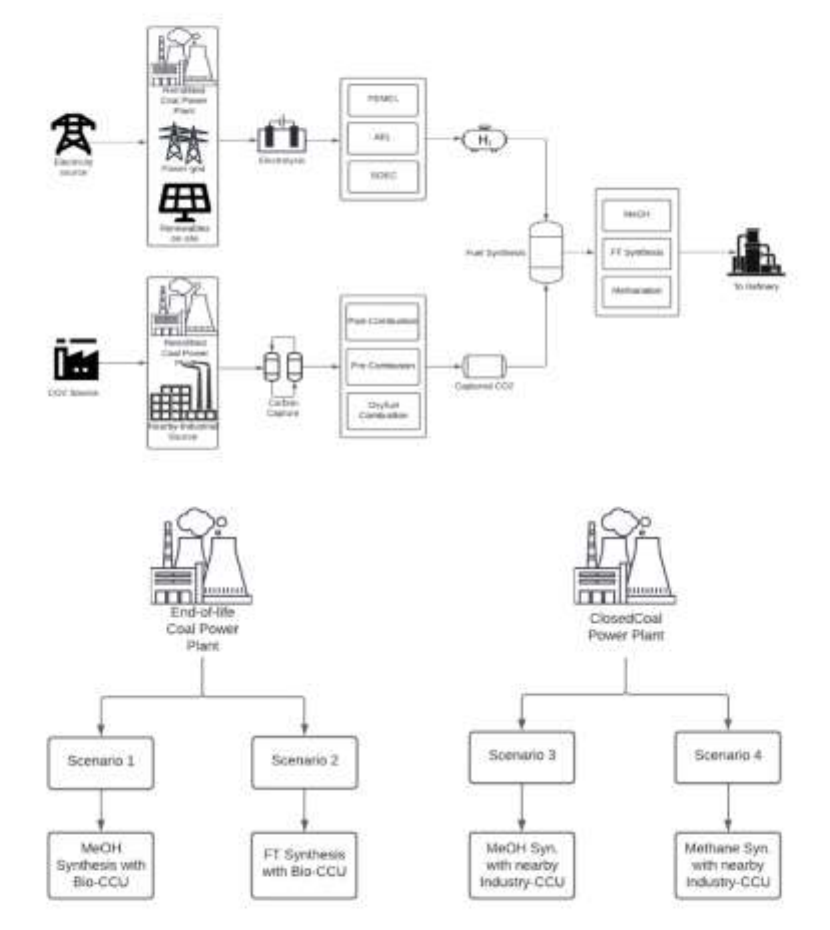
Use-cases and Scenarios

Use-case 1: End-of-life coal power plant

Agios Dimitrios V, GR

Use-case 2: Closed Coal Power

Mellach, AT



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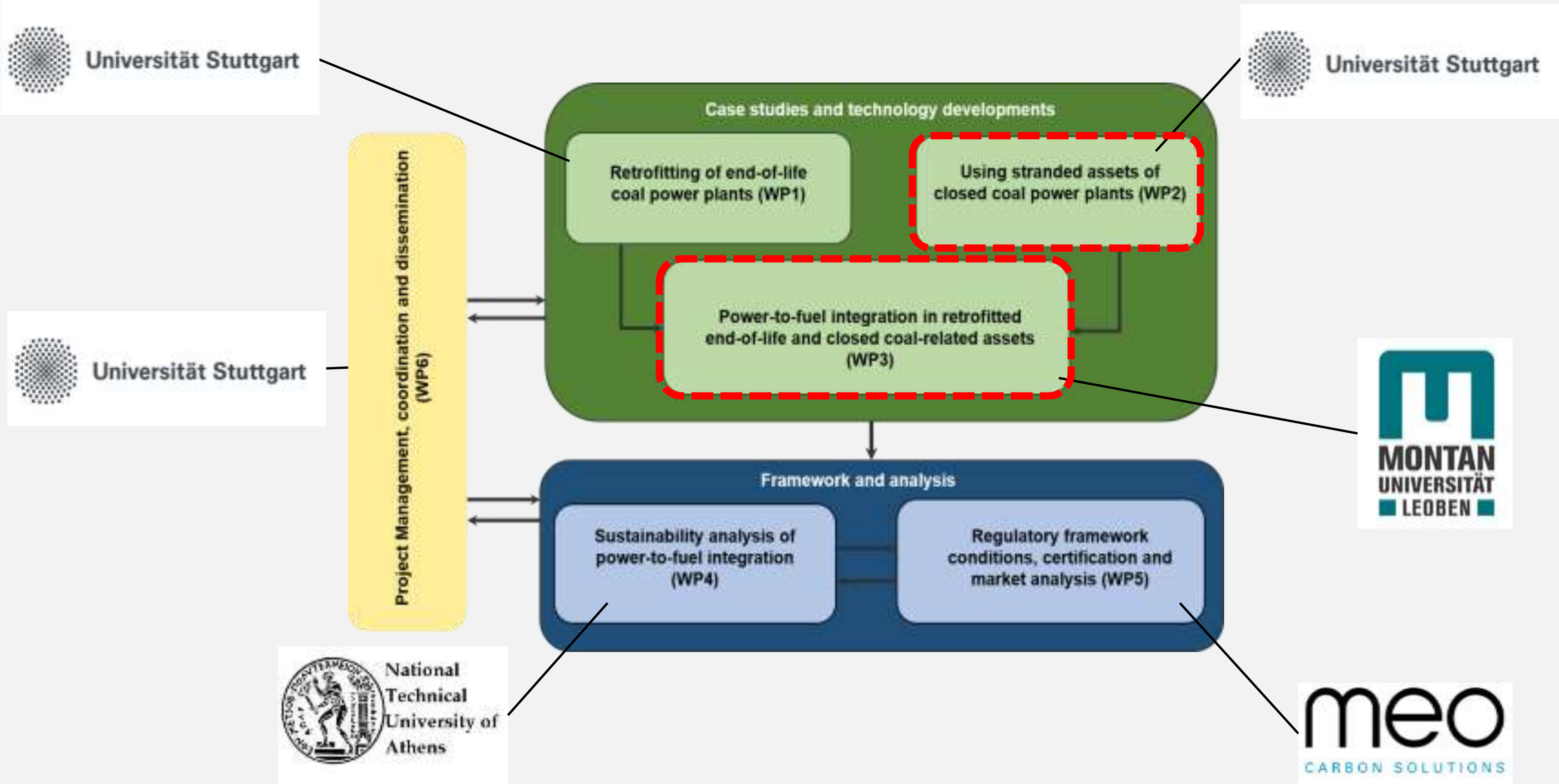
Steps to achieve the overall goal



Combined design and operational optimization of power-to-fuel plants

Goals

- Combined design and operational optimization together with time-resolved electricity market prices.
- Model based on Mixed integer linear programming
- Optimal design and operation of power-to-fuel plant

Methodology

- Setting up of the optimization model using Open Energy Modeling Framework (OEMOF)
- Development of Linear reference model and Mixed integer linear model
- Modeling of individual components and determination of input parameters, constraints, assumptions and boundary conditions
- Evaluation of use-cases defined
- Results and interpretation
- Techno-economic analysis

Combined Investment and operational optimization concept

Single-step MILP based combined approach to investment and operational optimization

Aimed at assessing new investments in green technologies at repurposed coal power plant sites

Focused on identifying the flexibility potential in power-to-fuel systems

Electrolyzer and hydrogen storage as crucial components for optimization.

The electrolyzer part-load efficiency allows for efficient load adjustment in response to fluctuating electricity prices, which in turn influences the sizing of the capital-intensive electrolyzer and hydrogen storage.

More realistic and efficient pathway for optimizing green technology investments

Modelling implementaion in oemof

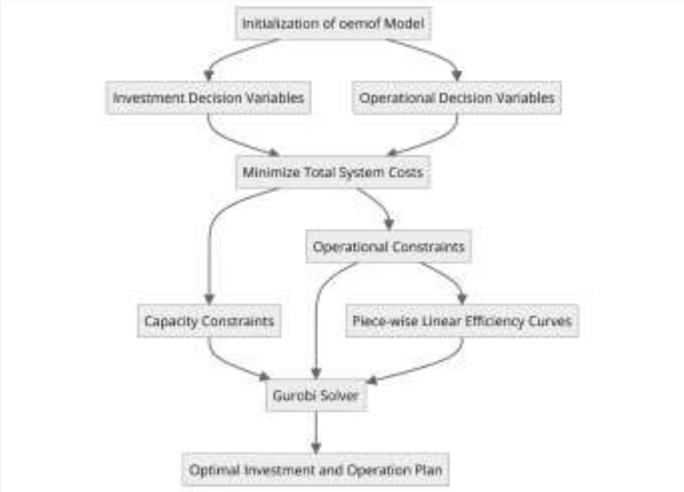
Implementation in OEMOF for combined investment and dispatch optimization

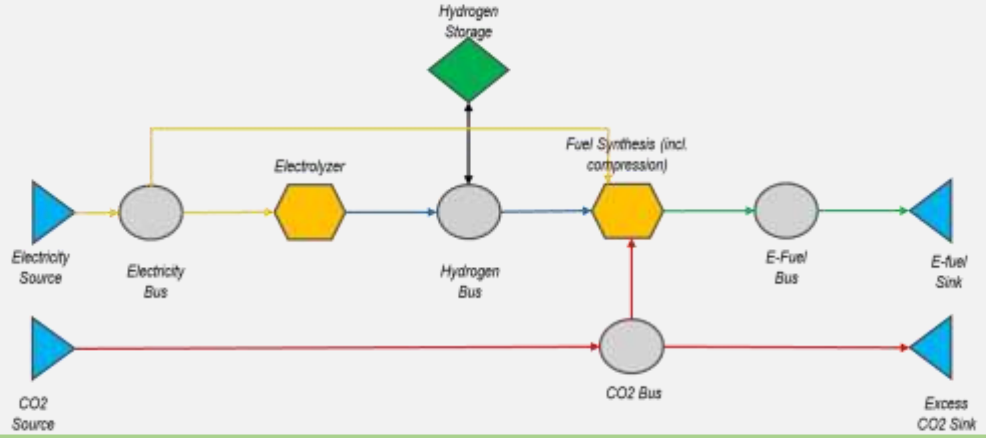
Size and operational optimization for Hydrogen storage and PEM Electrolyzer based on pwl models

Fixed CO_2 source and electricity price curve

Sizing of Fuel synthesis unit based on availability of H_2 and CO_2 and continuous operation with two times yearly scheduled maintenance.

Solved using Gurobi Solver which uses branch-and-bound method combined with cutting planes and heuristics



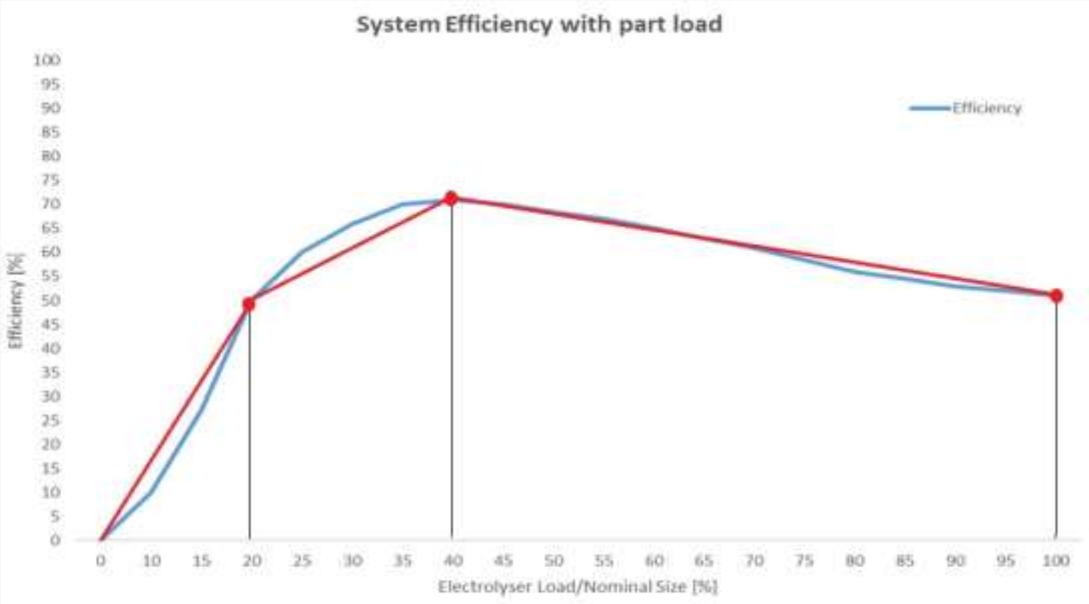


Modelling Implementaion in oemof

- PEM electrolyzer system efficiency curve for the is linearized using a piece-wise linear approach.

- The electrolyzer load is divided into three segments i.e., 0-20%, 20-40% and 40-100%

- These segments are implemented using general purpose components in oemof i.e. three OffsetConverters



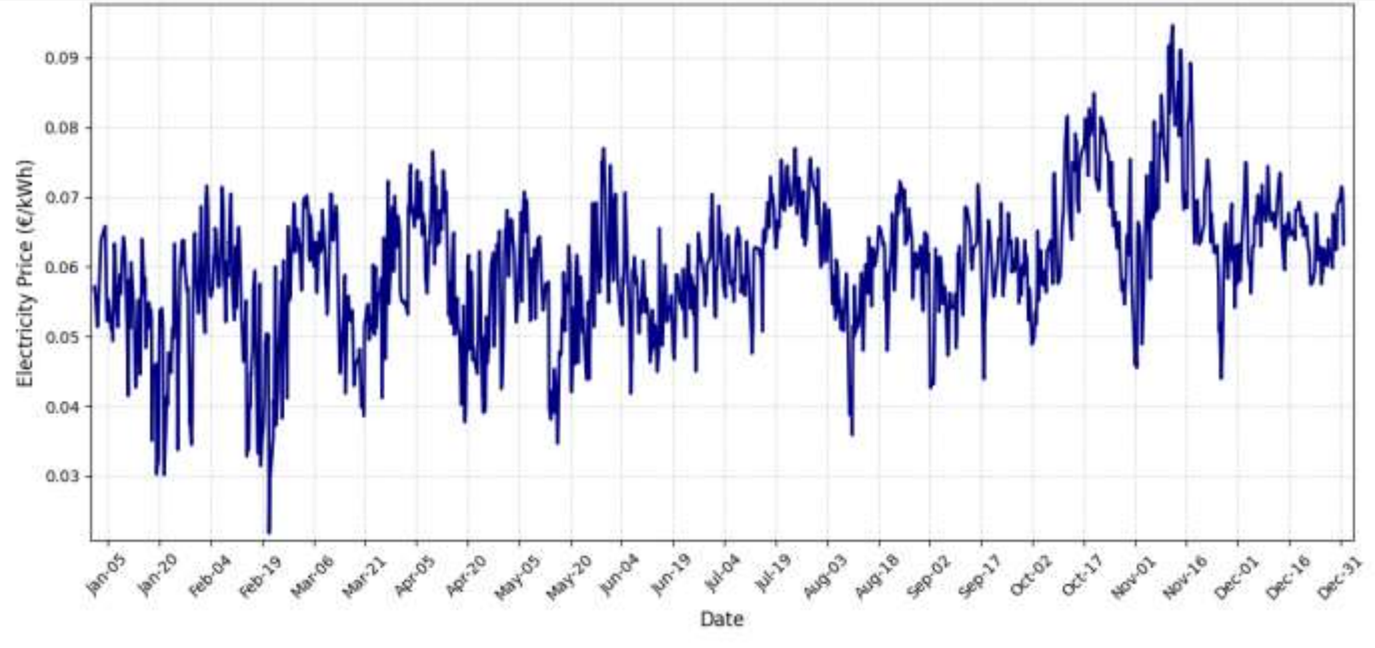
- H2 storage modelled as linear
- Fuel synthesis process also as linear

Both are non-linear processes, but piece-wise linear would have:
- *Only minor impact on overall results*
- *High impact on calculation time!*

GreenDEALCO$_2$

Modelling implementaion in oemof

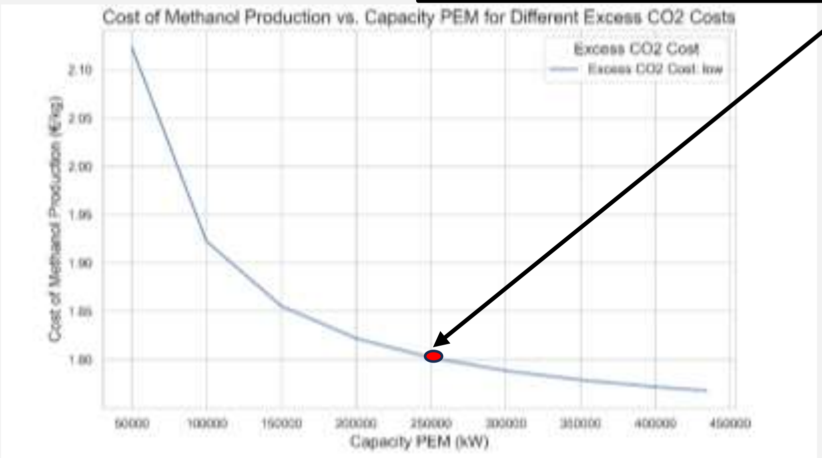
- The annual electricity price curve for 2030 is obtained from literature whose authors used curve-fitting on scaled 2020 data from the Energy Exchange Austria power exchange.
- Continuous CO_2 load profile considering two yearly scheduled maintenances for the CO2 emitting source.

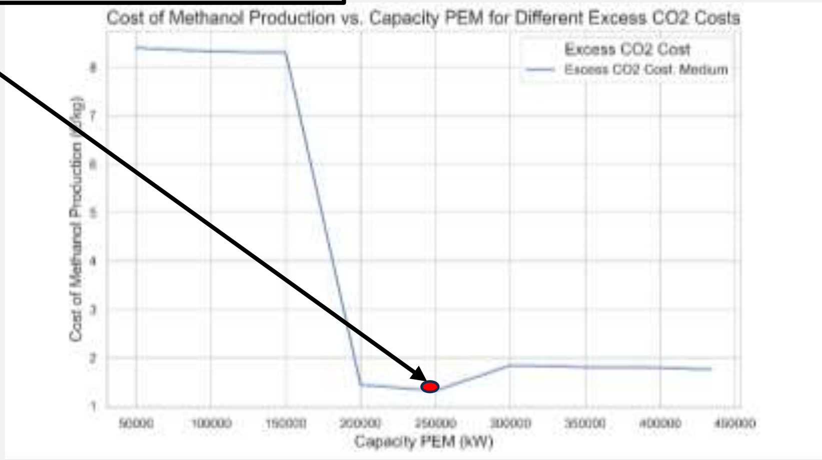


Results

- Optimization model balances higher initial costs against operational efficiency, favoring a hybrid approach of full-load and part-load operation with moderate initial investment.
- A PEM Electrolyzer of capacity 250 MW with approx. 4000 full load hours and 4000 part-load hours provides a balanced operation and relatively moderate initial investment that includes hydrogen storage.
- Optimal economic performance is achieved when the electrolyzer is able to run at 20-40% part-load, minimizing electricity use and reducing operational expenditure

Optimal size of electrolyzer with balanced full-load and part-load operational hours and storage





Discussion of results from Techno-economic analysis

- Optimized capacity (250 MW PEM electrolyzer) determined in Task 3.2
- Underlying assumptions for 2030 scenario
- The costs are within the range of the reference cost.
- The sensitivity analysis determined that small electricity price changes largely impact the levelized cost of fuel, hence these different electricity price assumptions seem to be the main factor for the large difference in LCOFs.
- The economic viability of producing e-fuels is heavily dependent on lower electricity costs.
- Strategies to reduce electricity expenses are crucial for the sustainable production of e-fuels.
- The strategic location of coal power plant sites, coupled with existing infrastructure, makes them ideal candidates for repurposing into power-to-fuel facilities. Such a transition is recommended based on our findings, as it could result in cost reductions and potentially foster new business and industrial opportunities within the region

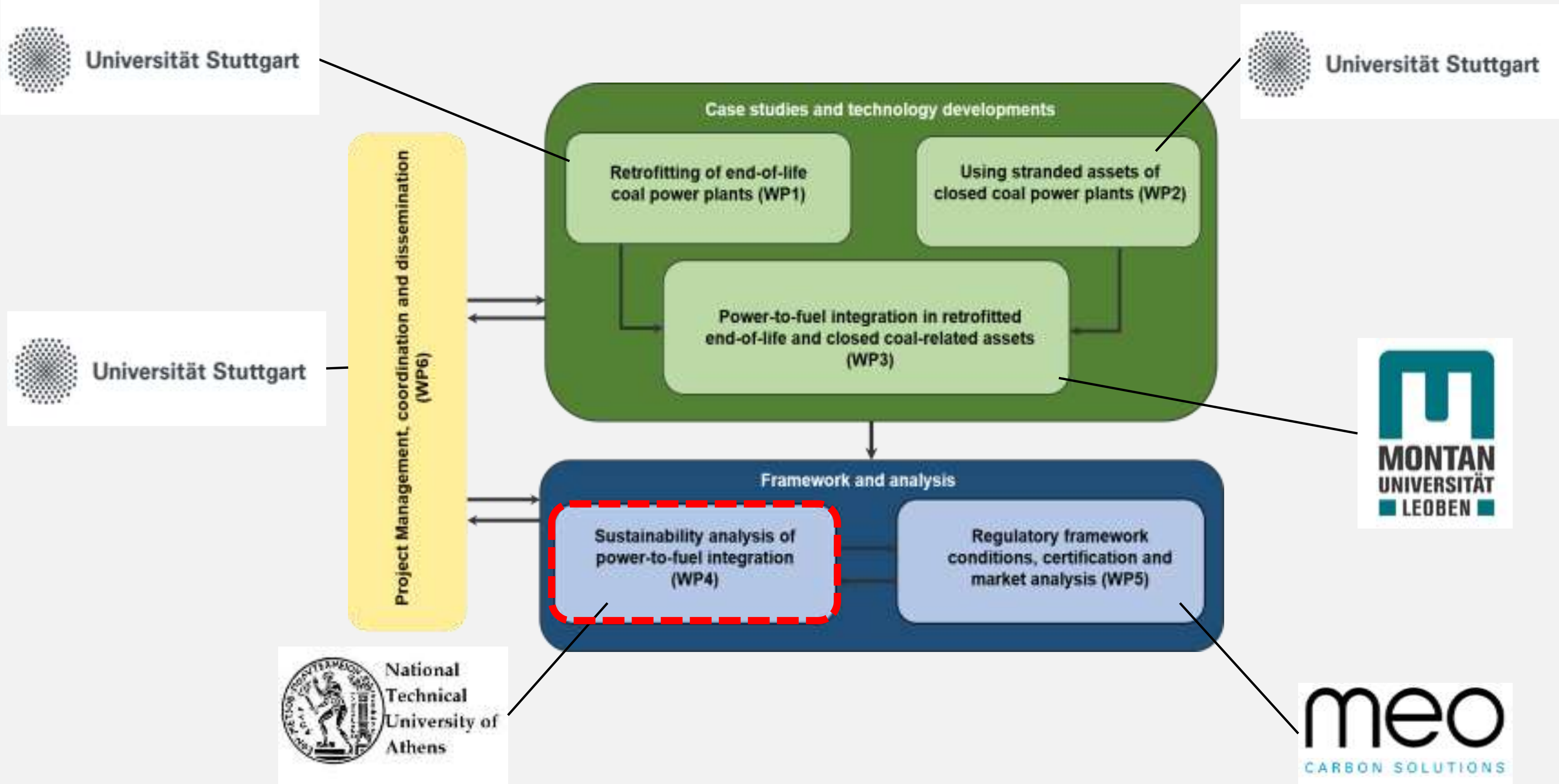
Final word

Optimization model developed in this project can determine the optimal design and operation strategy for new e-fuel production plants at repurposed coal power plant sites.

Electricity price is the single most important factor in low-cost production for e-fuel

Higher CO_2 price is recommended to make e-fuels more price competitive.

Steps to achieve the overall goal



Social and environmental analysis

June 18th 2024, Essen (Germany)

Sustainability analysis

Sustainability assessment refers to the systematic compilation and evaluation of:

- **environmental (LCA),**
- **economic (LCC), and**
- **social impacts (LCA)** related to a product or a system.

It aims at providing information of the impacts of a system or a product along their entire life cycle and supporting their improvement from a holistic perspective.

LCSA helps in clarifying the trade-offs between the three sustainability pillars, life cycle stages and impacts, products and generations by providing a more comprehensive picture of the positive and negative impacts along the product life cycle. (*Life Cycle Initiative*)

Sustainability analysis

Before conducting sustainability analysis, the products/systems that undergo investigations should be well defined. These product/systems will remain the same throughout the analysis for all three sustainability dimensions.

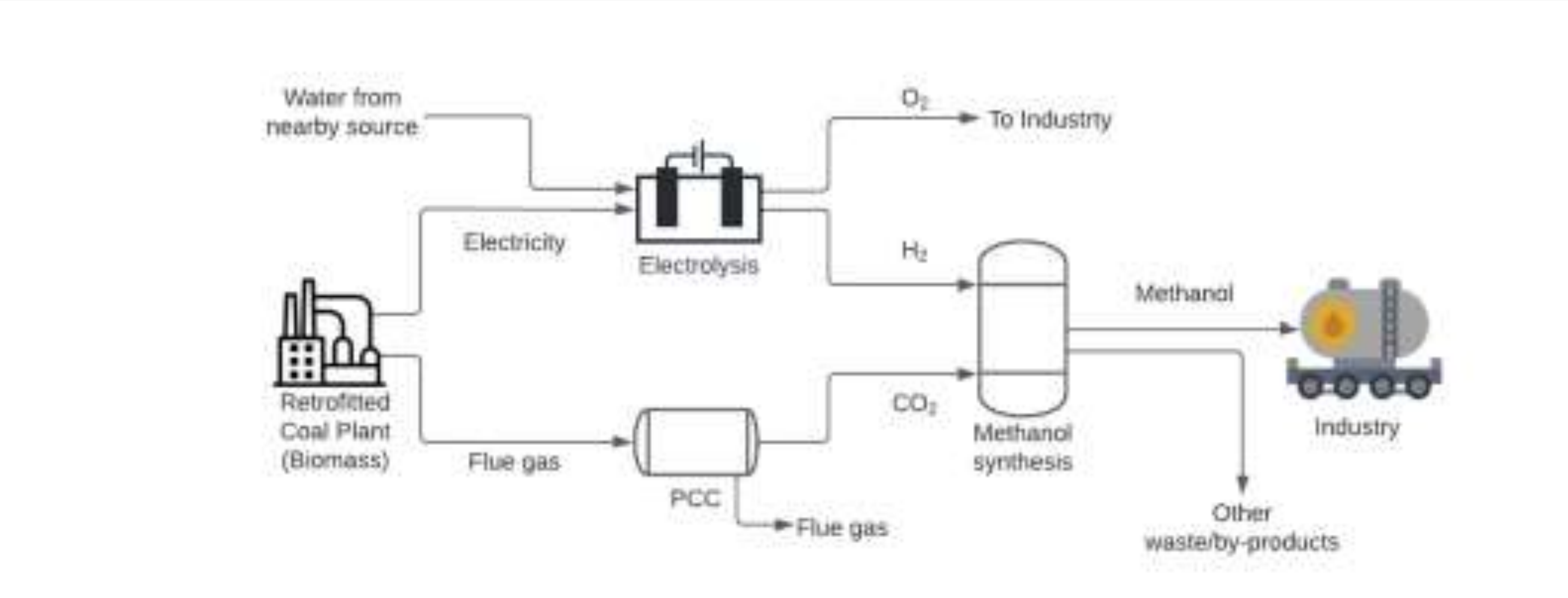
Base Case Systems

- **Power-to-Methanol** process with retrofitted coal power plant to biomass as CO_2 source
- **Power-to-SNG** process with industrial CO_2 source

Sustainability analysis

- System definition

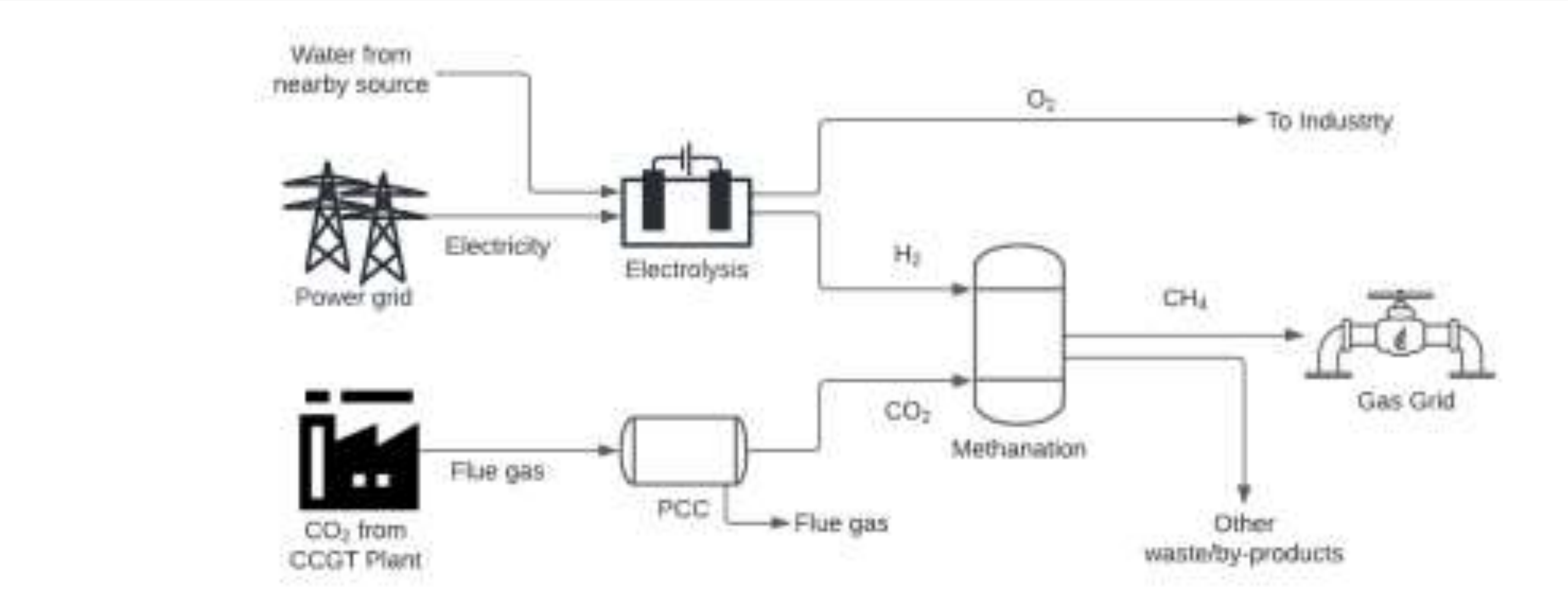
Power-to-Methanol



Sustainability analysis

- System definition

Power-to-SNG



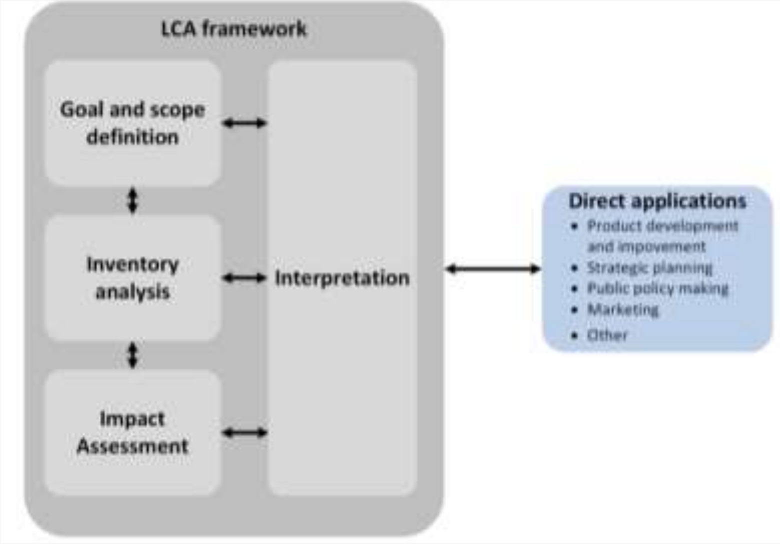
Environmental Life Cycle Analysis

Life cycle analysis of power-to-fuel integration

- Life Cycle Analysis (LCA/E-LCA)

LCA is a methodological framework used to **assess the environmental impacts** and used resources that can be attributed to a product throughout its entire life cycle, including its contribution to climate change, ozone depletion, eutrophication, acidification and other factors. Towards the standardization of LCA process, several standards have been issued by the International Organization for Standardization. According to ISO 14040/14044, a LCA consists of four main stages:

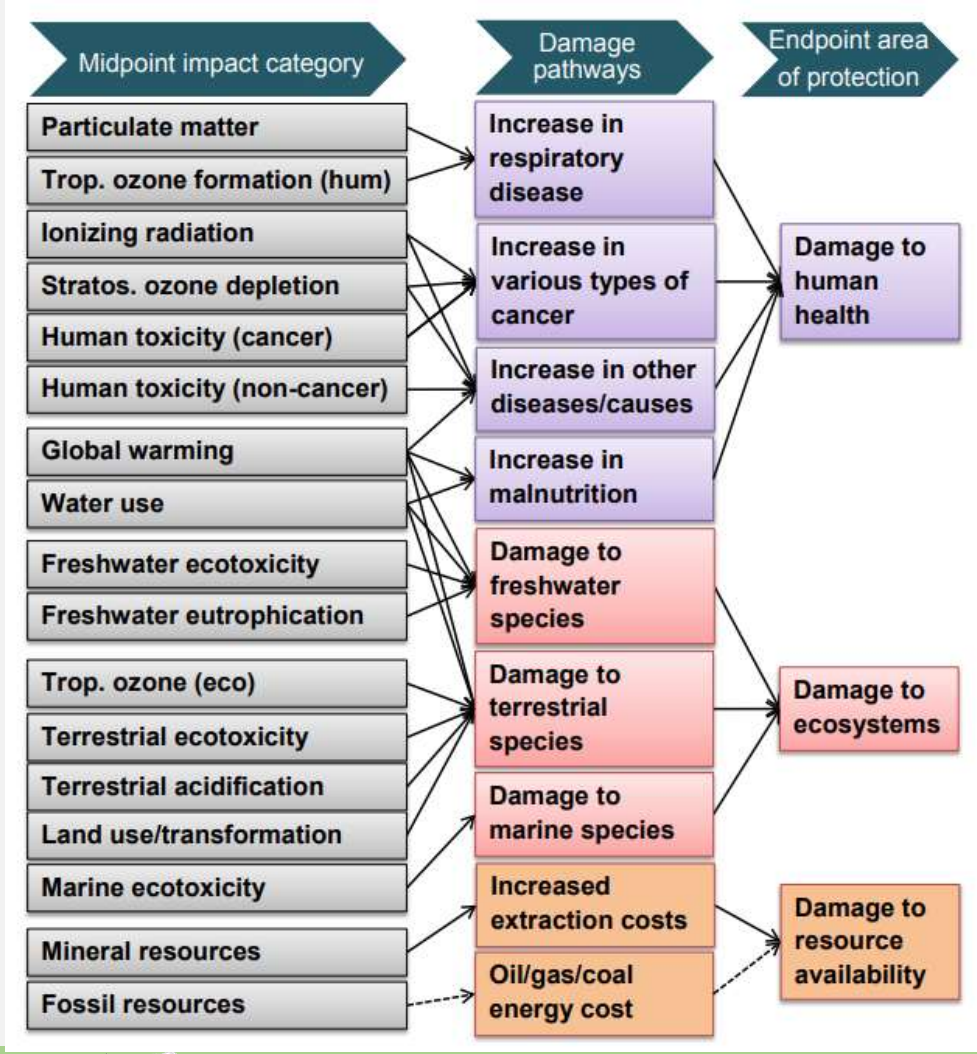
1. Goal and scope definition
2. Inventory analysis
3. Impact assessment
4. Interpretation



The figure presents the phases of LCA as defined in ISO 14040 (2006)

An impact assessment method transforms the inventory (energy and material inputs, emission) into **environmental impacts that are presented with indicators**.

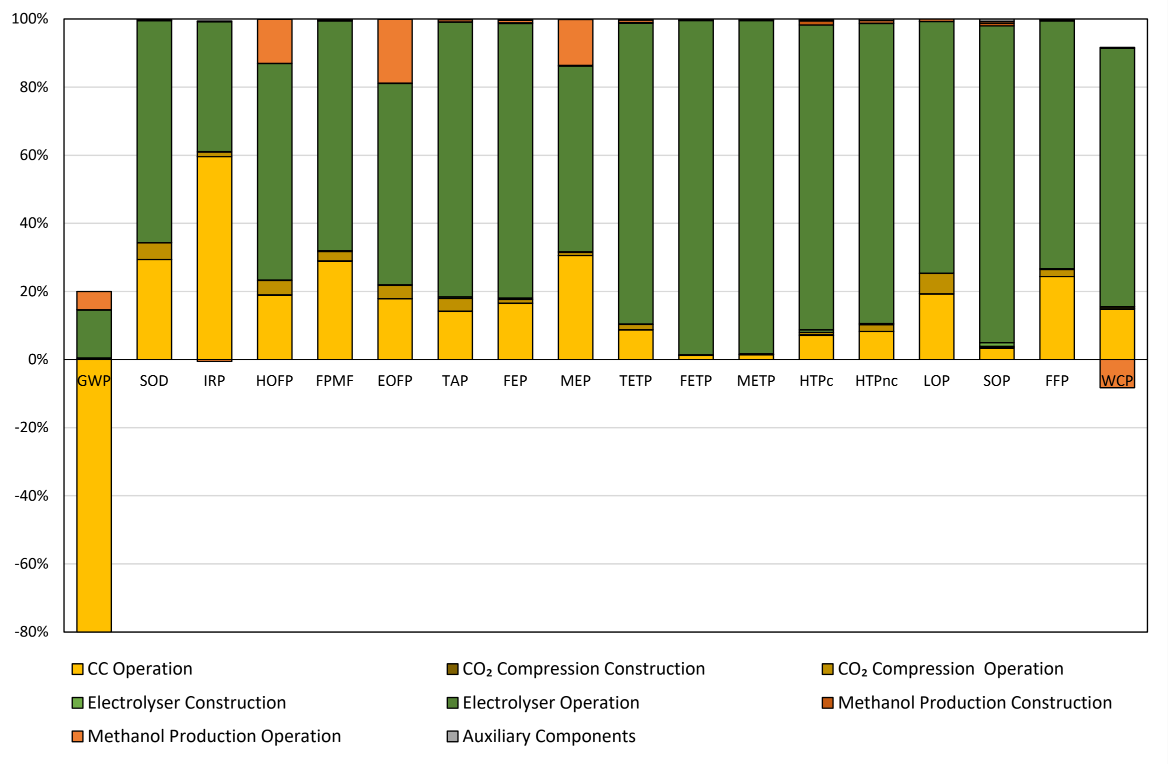
All the calculations are implemented in the LCA software SimaPro v9.3.0.3. All eighteen (18) impact categories at midpoint level and all three impact categories at endpoint level of ReCiPe are presented



Life cycle analysis of power-to-fuel integration

Power-to-Methanol

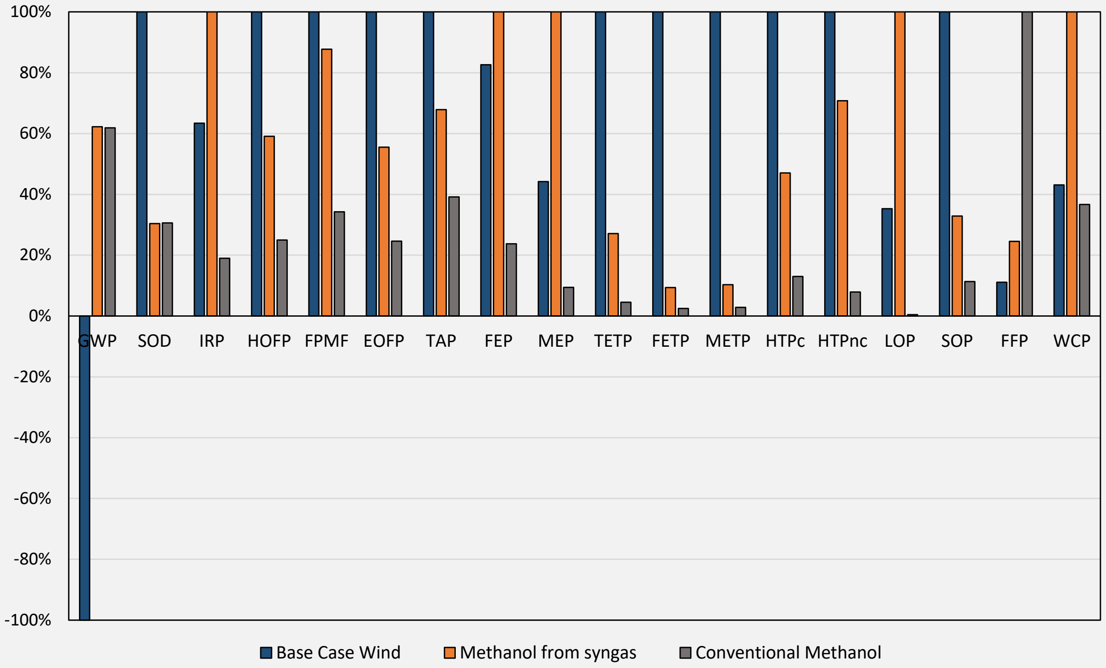
- The operational phase carries the greatest burden of the plant's environmental impact.
- The electrolyser has the greatest environmental contribution in almost all categories
- In GWP category the utilisation of CO_2 for methanol production has the greatest impact, which is also positive since CO_2 is consumed to produce methanol, while in IRP category the heat requirement of the CC unit is responsible for the large impact.



Life cycle analysis of power-to-fuel integration

Power-to-Methanol – Comparison to reference

- PtMeOH reduces GWP compared to the conventional scenarios.
- However, PtMeOH has a larger contribution to several impact categories. For eutrophication and ecotoxicity categories, use of wind electricity is the main factor for such results.
- Overall, the PtMeOH system results in -1065 kg CO_2 eq/tMeOH

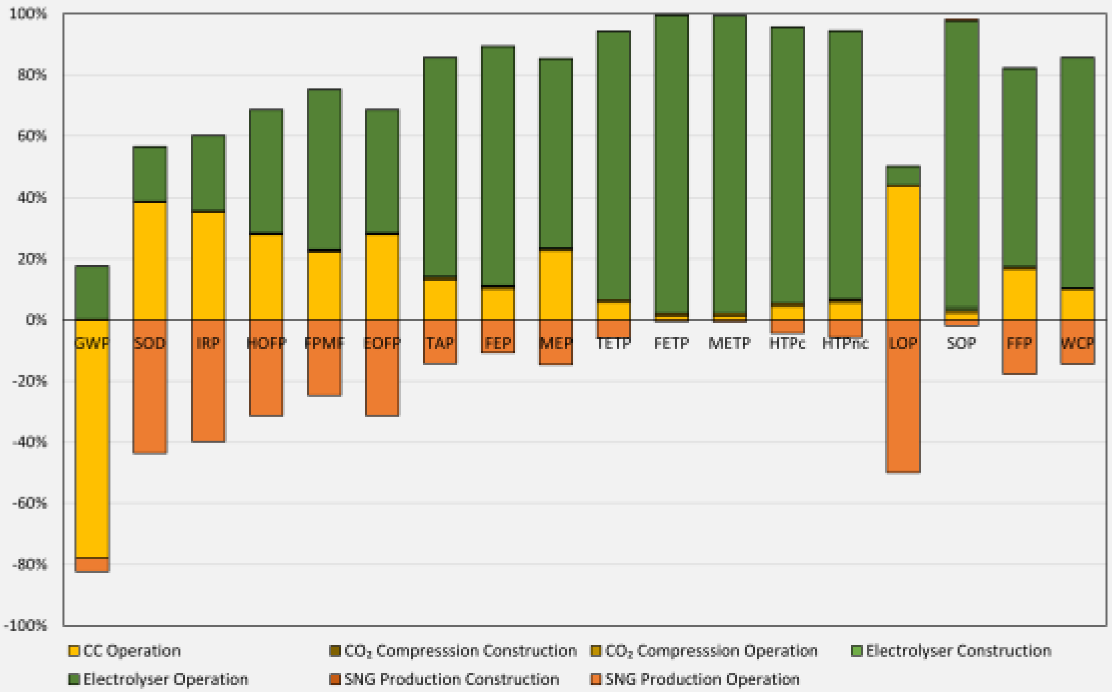


The impacts of the two reference scenarios derive from ecoinvent v3.8 database.

Life cycle analysis of power-to-fuel integration

Power-to-SNG

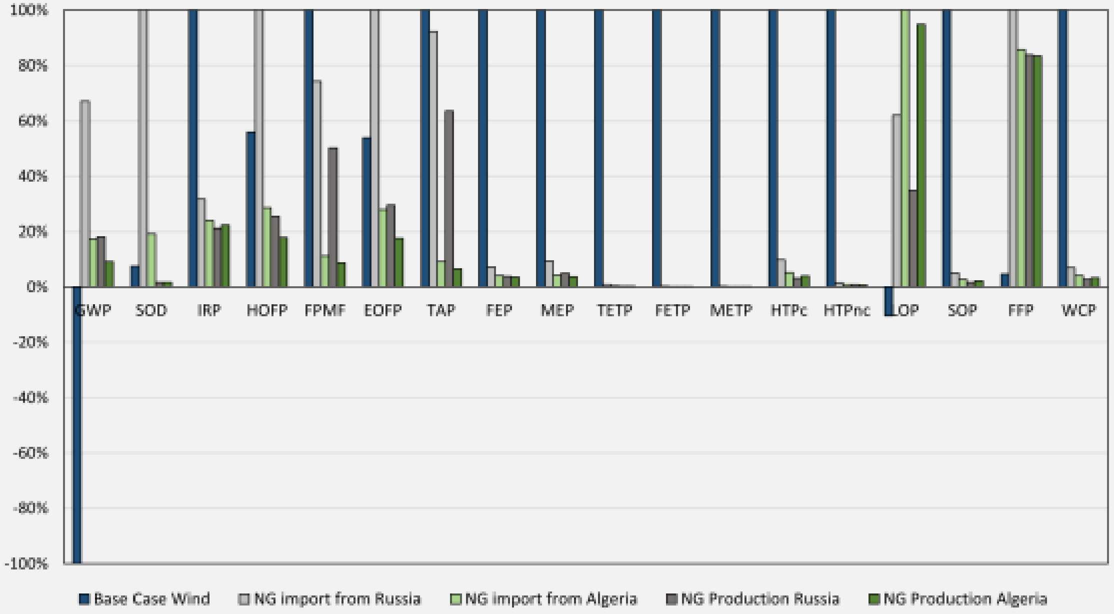
- The operational phase carries the greatest burden of the plant's environmental impact.
- The electrolyser has the greatest environmental contribution in most categories.
- In GWP category the utilisation of CO_2 for SNG production has big positive impact since CO_2 is consumed to produce SNG.
- Steam production during SNG production process results in positive environmental impact on all categories since it is considered that it replaces the conventional steam production for industrial steam on the market.



Life cycle analysis of power-to-fuel integration

Power-to-SNG – Comparison to reference

- PtSNG reduces GWP compared to the conventional scenarios.
- However, PtSNG has a larger contribution to several impact categories. For eutrophication and ecotoxicity categories, use of wind electricity is the main factor for such results.
- Overall, the PtSNG system results in -1887 kg CO_2 eq/tSNG



The impacts of the reference scenarios derive from ecoinvent v3.8 database.

Life cycle analysis of power-to-fuel integration

Conclusions

- CO_2 utilisation leads the GWP resulting in an overall positive impact.
- The electrolyser is responsible for the greatest environmental contribution in all categories except Global Warming Potential (GWP) and Ionizing Radiation (IRP).
- The operational phase carries the greatest burden of each plant's environmental impact.
- Energy consumption dominates most of the analysed impact factors.
- Environmental impacts of the process are highly dependent upon the electricity used.
- The base case scenarios significantly reduce carbon dioxide emissions compared to the conventional scenarios; however, they have a larger contribution to several impact categories such as IRP, FPMF, all ecotoxicity categories, SOP and finally WCP.
- The consideration of O_2 as an avoided product, replacing the cryogenic distillation process on the market for liquefied O_2, provides a significant positive impact on the environmental performance of the overall PtMeOH process.

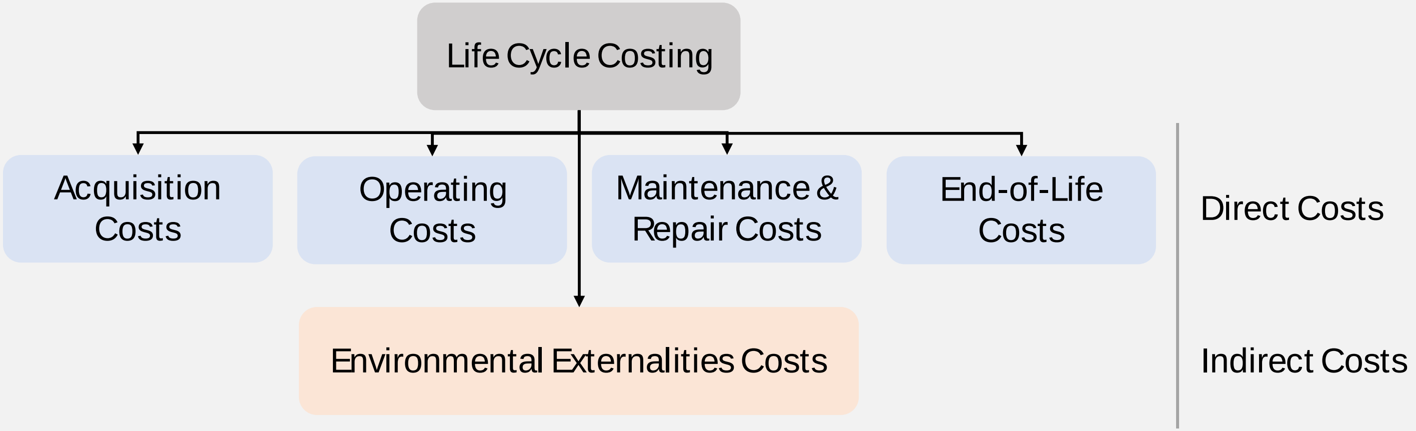
Economic Life Cycle Analysis

Life cycle costing of power-to-fuel integration

- Life Cycle Costing (LCC)

Life Cycle Costing (LCC) is a valuable technique that is used for predicting and assessing the cost performance of constructed assets.

Life Cycle Cost Assessment (LCC) has the aim to assess the costs of a product over its entire life cycle, including the acquisition, operating, maintenance, and disposal costs. In this task, the LCC is carried out in a similar procedure as the LCA, including the four main stages of LCA.



Life cycle costing of power-to-fuel integration

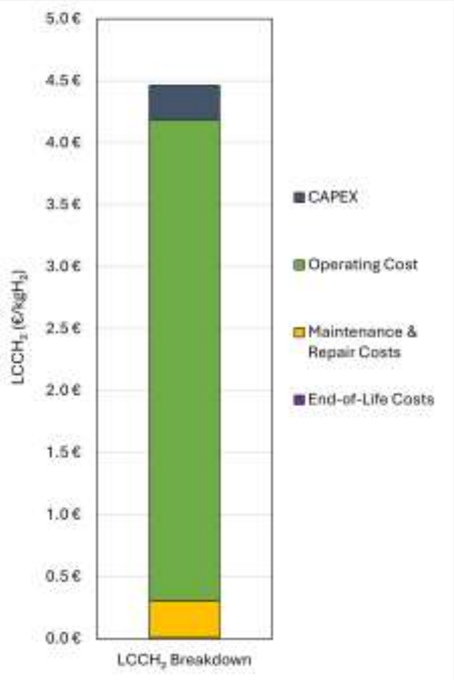
Due to the large scale of the plants the only realistic scenarios that it would be possible to be in operation by 2030 for PtSNG and 2050 for PtMeOH. The following Tables include operational and cost data regarding (i) acquisition costs; (ii) operating costs; (iii) maintenance and repair costs; (iv) end-of-life costs; and (v) costs for environmental externalities for all separate systems of the power-to-fuel integration plants.

Economic assumptions used in LCC analyses

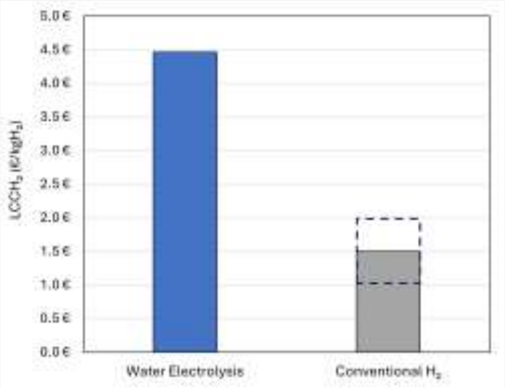
Parameter	Value
Exchange Rate	0.94 €/US$
Interest Rate (i)	8 %
Plant Lifetime	20 years
Year Basis	2023
Plant Location	Greece
Capacity Factor	90 % (328 days/year)
Tax Rate	22 %
Labor Costs	29.792,00 € per operator per year

Life cycle costing of power-to-fuel integration

Breakdown of Life Cycle Costs



Green H_2 production



Breakdown of LCC for green hydrogen production with PEM electrolyser (€/tH_2) and comparison with grey H_2 selling price

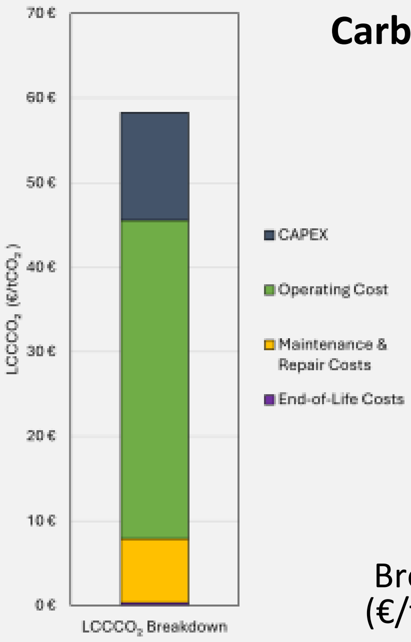
- For methanol production the total electolyser capacity reaches 1850 MW (2050 scenario)
- PEM efficiency was considered equal to 77.5 %
- Electricity costs were considered equal to 90 €/MWh

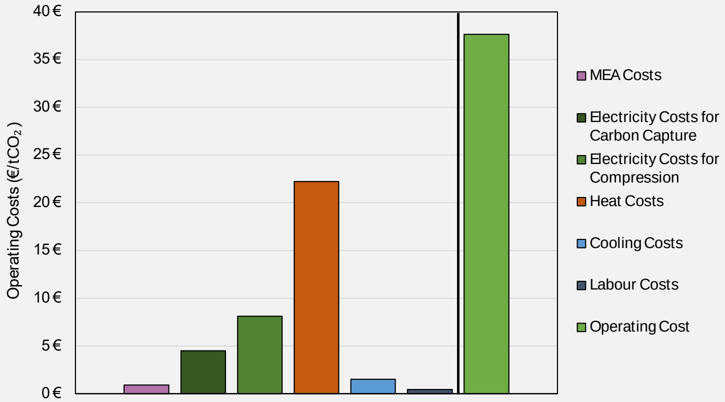
- Operating costs emerge as the primary driver in the overall Life Cycle Costs of hydrogen production
- The cost of green hydrogen is typically higher due to the large amount of electricity required for water electrolysis in combination with high electricity costs.

Life cycle costing of power-to-fuel integration

Breakdown of Life Cycle Costs

Carbon Capture



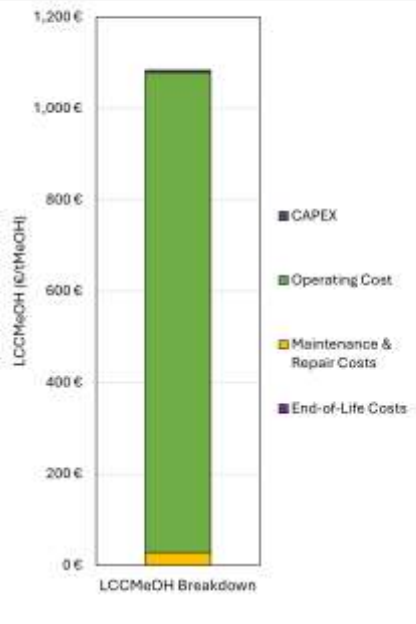


Breakdown of LCC for Carbon Capture (€/tCO_2) and overview of the operating costs

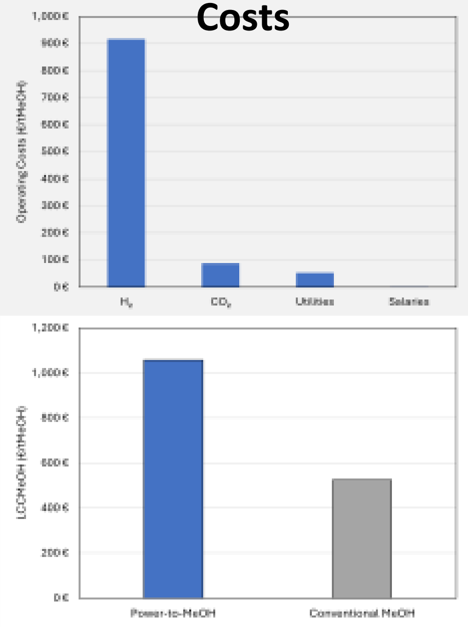
- For the Power-to-MeOH system, 313 tCO_2/h are captured from the total of 348 tCO_2/h of the flue gas of the biomass power plant.
- The cost of carbon capture arises at 58.25 €/tCO_2.
- The operating cost stand out as the major contributor to the overall LCC of CO_2 capture,
- The major contributor to the high operating costs is the heat costs mainly due to the heat required to operate the reboiler of the carbon capture unit, followed by the electricity costs incurred in both the carbon capture unit and the CO_2 compression system.

Life cycle costing of power-to-fuel integration

Methanol



Breakdown of Life Cycle Costs



Breakdown of LCC for MeOH production (€/tMeOH), overview of the operating costs and comparison with conventional methanol selling price

- The overall LCCMeOH results in 1091 €/tMeOH.
- The operating costs stand out as the major contributor, accounting for 1059 €/tMeOH.
- H_2 emerges as the most significant contributor, accounting for more than 85 % of the overall operating costs.
- Substantial cost difference between the two methods for producing methanol. Power-to-MeOH: 1091 €/tMeOH, while conventional methanol: 525 €/tMeOH, based on market data.
- The comparison indicates the need of incentives for investments in Power-to-Fuel processes

Cost Parameters for MeOH production		
H_2 Cost	4.46	€/kgH_2
CO_2 Cost	58.25	€/tCO_2

Life cycle costing of power-to-fuel integration

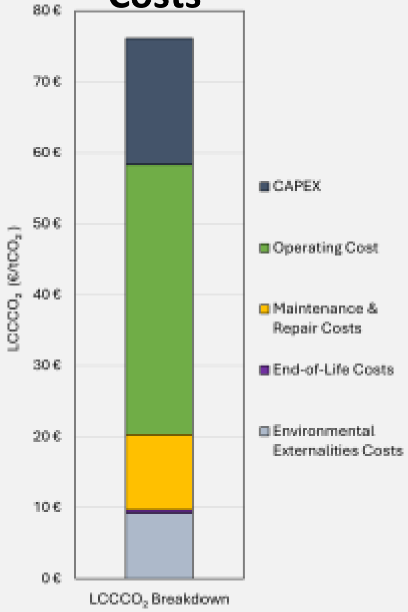
SNG

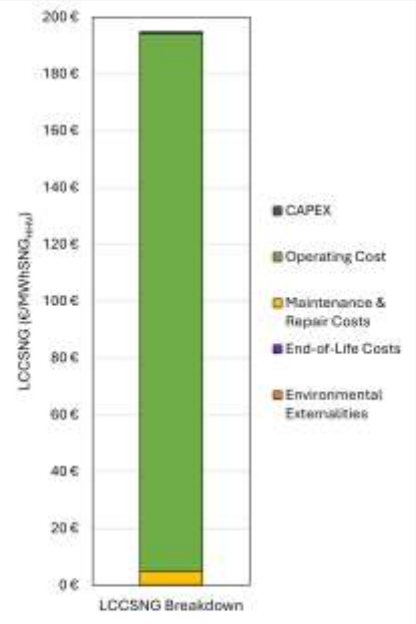
- For SNG production the total electolyser capacity reaches 500 MW (2030 scenario)
- PEM efficiency was considered equal to 67 %
- Electricity costs were considered equal to 90 €/MWh

- For the Power-to-SNG system, 54.45 tCO_2/h are captured from the total of 61.5 tCO_2/h of the flue gas of an industrial emitter, while 6.05 tCO_2/h are emitted.

H_2 Cost	5.17	€/kgH_2
CO_2 Cost	76.09	€/tCO_2

Breakdown of Life Cycle Costs





- The levelized LCC for the power-to-SNG rise to 2960 €/tSNG or 195 €/MWhSNG$_{HHV}$.
- H_2 and CO_2 costs are higher compared to the costs for Meoh production due to the smaller scale of the systems.

- The operating costs dominate the LCCSNG production, accounting for more than 95 % of the total LCCSNG

Life cycle analysis of power-to-fuel integration

Conclusions

- The operating costs which include mainly the costs of electricity, heat, and cooling, and the costs of raw materials dominate the LCC of all systems due to either the vast amounts of electricity and heat required for the processes in combination with high energy costs, or due to the high procurement cost of the raw materials.
- The expenses associated with both carbon capture and hydrogen production play a crucial role in determining the overall LCCMeOH and LCCSNG.
- Hydrogen produced by water electrolysis is considerably more expensive (4.46 €/kgH2) than the conventionally produced H2 (which varies between 1-2 €/kgH2).
- The carbon capture system requires a substantial upfront investment, which is only reasonable if it operates for a long period of time.
- Without further use of CO2 either in terms of carbon capture and storage (CCS) or in terms of carbon capture and utilisation (CCU) (i.e. for the production of chemicals and fuels), the CO2 would be emitted into the atmosphere and emission allowances will need to be paid for. This will result in an economic burden that is greater than the initial CO2 emission.

Social Life Cycle Analysis

Social Life Cycle Analysis

- Social Life Cycle Analysis (SLCA)

Social Life Cycle Assessment (S-LCA) is a methodology utilized for evaluating the societal impacts of products and services across their entire life cycle, from raw material extraction to disposal.

The SLCA framework adopts a stakeholder-centric approach, focusing on the examination of potential impacts across various stakeholder groups. This approach aligns with the core principle of social sustainability, emphasizing the identification and management of both positive and negative effects on individuals or groups of people (stakeholders). Social impacts are categorized based on the five main stakeholder groups: (i) worker, (ii) consumer, (iii) local community, (iv) society and (v) value chain actors, to facilitate practical implementation and ensure the comprehensive coverage of the framework.

The investigation of the social acceptance is an important part of SLCA.

WP4 – Task 4.4 Socio-political investigation

- Socio-political investigation of the acceptance of power-to-fuel technologies

The aim of this task is to perform an **investigation of public acceptance of E-fuels** and the processes for their production. Experts from a wide range of backgrounds (policymaking, decision making, technical, market and academic) will be contacted through the consortium and interviewed using questionnaires in a Delphi-type study comprising of at least two stages, to evaluate the performance of the developed scenarios for accelerating E-fuel market penetration. The influence of environmental and economic performance on public acceptance, as well as the maximization of benefits for EU communities through job creation, reduction of fuel imports and increased energy security, will be the main points of interest.

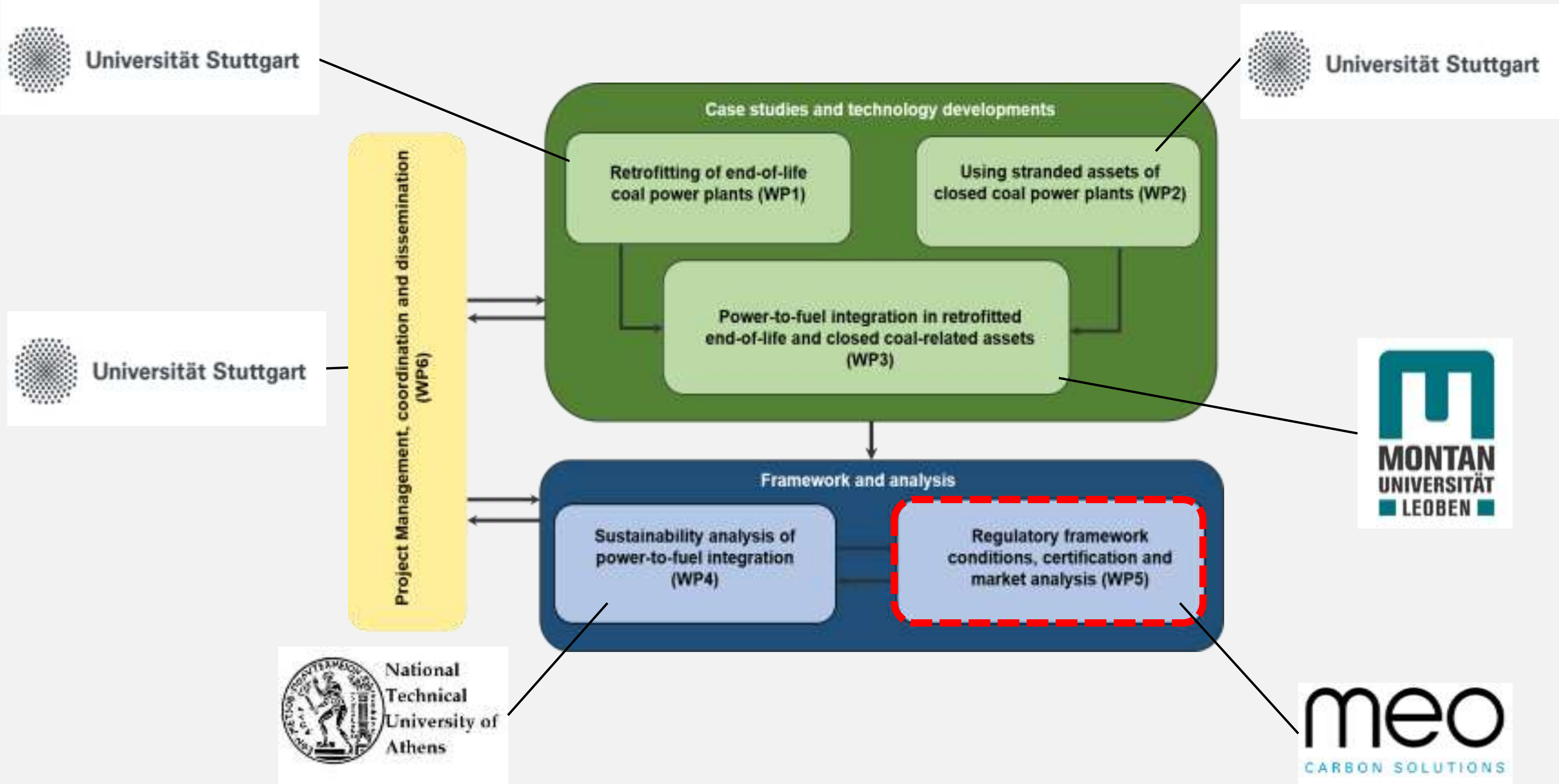
Links to survey

General Public: https://forms.gle/8MRNXFoNHrEpMXqv6

Links to survey

Stakeholders: https://forms.gle/7tafEZ9QMZ39KWS99

Steps to achieve the overall goal



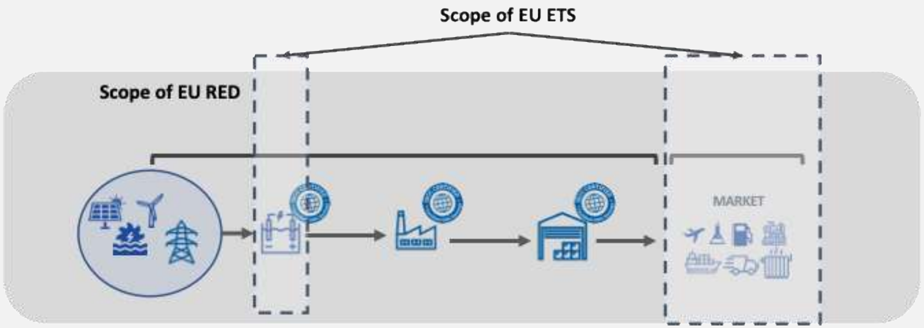
Regulatory framework conditions, certification and market analysis

EU provides comprehensive framework

- There is already an **extensive regulatory framework at EU level**. The **Renewable Energy Directive (RED)** and associated delegated acts are highly relevant.
- There are also **other EU frameworks for the aviation** (ReFuel Aviation) **and shipping** (FuelEU Maritime) sectors that will be relevant in the future.
- Regulations include, for example, sustainability requirements for electricity, greenhouse gas emission thresholds in production and energy and/or greenhouse gas quotas in the sectors.
- **E-Fuels** are defined as **“renewable fuels of non-biological origin” (RFNBO)** which means liquid and gaseous fuels which energy content is derived from renewable sources other than biomass.
- The **member states are obliged to implement** the EU requirements. In some areas they have a certain amount of flexibility, so that based on the target markets, member state specific details should be taken into account.

Analysis of EU ETS for RFNBOs'

- For RFNBOs', the **EU ETS scheme applies to hydrogen production, aviation and maritime transport**
- The EU ETS carbon budget and the RFNBO threshold for greenhouse gas emissions are two different instruments to reduce carbon emissions along the supply chain, which are not contradictory but complementary
- **CO2 from the EU ETS is eligible for the production of e-fuels**, but double counting of EU ETS credits and RFNBO CO_2 credits must be avoided



Comparative analysis of relevant legal frameworks

Criteria		RED II without DAs	RED II with DAs	ReFuel Aviation	CORSIA	FuelEU Maritime	MARPOL	UK	Germany	Austria	Greece	Denmark
General	Relevant documents	DIRECTIVE (EU) 2018/2001; DIRECTIVE (EU) 2009/30/EC	Delegated Regulation (to be adopted)	ReFuelEU Aviation proposal (draft)	ICAO Documents	FuelEU Maritime proposal (draft)	MARPOL agreement Annex VI Energy Efficiency Design Index (EEDI)	Renewable Transport Fuel Obligation (RTFO)	BImSchG; 38.BImSchV; Biokraft-NachV; Power-to-Liquid Strategy	Kraftstoff-verordnung BGBl. II Nr. 398/2012	National Energy and Climate Plan; National Strategy for Hydrogen (draft)	National Energy and Climate Plan; Power-to-X Strategy
	Sector scope	Energy sector, Road Transport, Aviation, Maritime	Energy sector, Road Transport, Aviation, Maritime	Aviation	Aviation	Maritime	Maritime	Road Transport	Road Transport, Aviation	Road Transport	Energy, Road Transport, Aviation	Industry, Energy, Heavy Transport, Shipping, Aviation
	Country scope	European Union	European Union	European Union	International	European Union	International	United Kingdom	Germany	Austria	Greece	Denmark
	Year of introduction	2018	June 2023	Planned 2023	2020	Planned 2025	2011	2022	2021	2012	2021	2021
Quota type	Energy/Volume quota	✓	✓	✓	NA	NA	NA	✓	✓	✓	NA	NA
	Energy/Volume Sub-quota for E-fuels	NA	NA	✓	NA	NA	NA	✓	✓	✓	NA	NA
	GHG quota/intensity	✓	NA	NA	NA	✓	✓	NA	✓	✓	NA	NA
Criteria for renewable electricity	Additionality	✓	✓	✓	NA	✓	NA	✓	NA	NA	NA	NA
	Eligible source	✓	✓	✓	NA	✓	NA	✓	NA	NA	NA	NA
	Temporal correlation	✓	✓	✓	NA	✓	NA	✓	NA	NA	NA	NA
	Geographical correlation	✓	✓	✓	NA	✓	NA	✓	NA	NA	NA	NA
Proof of renewable electricity	GoO	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
	PPA	NA	✓	✓	NA	✓	NA	✓	NA	NA	NA	NA
	Direct connection	✓	✓	✓	NA	✓	NA	✓	NA	NA	NA	NA
Eligible CO2 sources	Biogenic	NA	✓	✓	NA	✓	NA	✓	NA	NA	NA	NA
	Fossil	NA	✓	✓	NA	✓	NA	✓	NA	NA	NA	NA
	Direct air capture	NA	✓	✓	NA	✓	NA	✓	NA	NA	NA	NA
GHG calculation methodology	Method	✓	✓	✓	✓	✓	NA	✓	✓	✓	NA	NA
	Minimum savings	✓	✓	✓	✓	✓	NA	✓	✓	✓	NA	NA
	Fossil comparator value	✓	✓	✓	✓	✓	NA	✓	✓	✓	NA	NA

✓ = Specification for the criteria is available in the legal framework

NA = Specification for the criteria is not available in the legal framework

Electricity sourcing requirements to count the sourced electricity as fully renewable

	Direct connection	Grid connection			
		>90% RES	<18 gCO_2eq/MJ	Imbalance settlement period	Electricity from the grid with further requirements
Additionality	✓*	✗	✗	✗	✓**
Temporal correlation	✗	✗	✓	✗	(✓)
Geographical correlation	✗	✗	✓	✗	✓
Renewable PPA	✗	✗	✓	✗	✓

* 36 months; ** 36 months (transition period criteria applicable to plant installated by 01 January 2028), no operating or investment aid

Eligible CO_2 sources for emission credit

Allowed sources

- Activities listed under Annex I of Directive 2003/87/EC (limited to max. 2041)
- CO_2 captured from the air
- Production or combustion of biofuels, bioliquids and biomass fuels
- Combustion of RFNBOs and RCFs
- Naturally released CO_2 from a geological source

Exclusions

- CO_2 from deliberately combusted fuels
- CO_2 where capturing benefit was already considered in other provisions of the law

Certification requirements are derived from legal framework

European Union

Renewable Energy Directive (RED):

Three pillars:

- Sourcing of renewable electricity for RFNBOs
- GHG savings
- Traceability and mass balance

Transposition

Member States

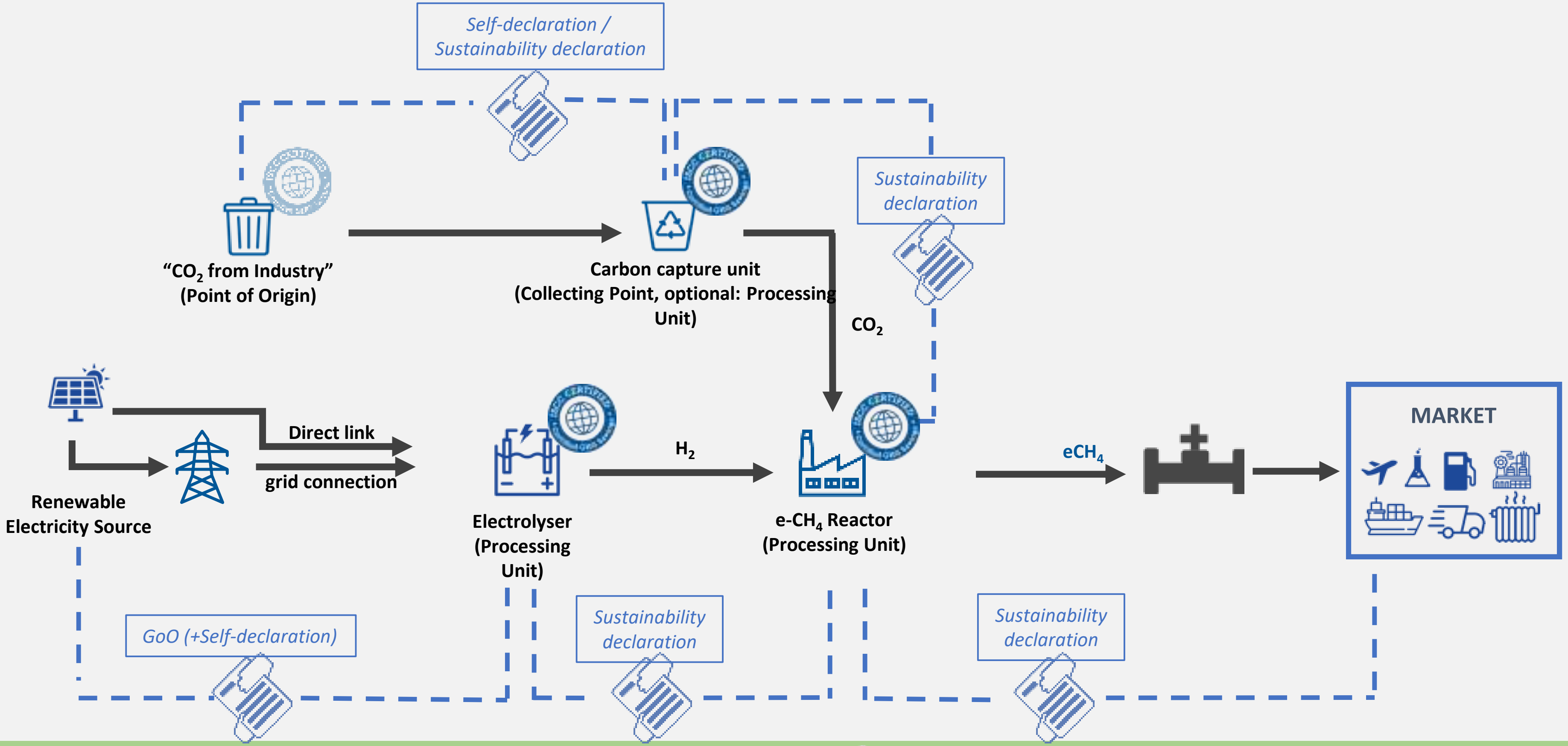
Flexibility for transposition into national law e.g.:

- Recognition and monitoring of certification bodies (e.g. Germany)
- ….

Recognized voluntary certification schemes

Certification Requirements | Guidance for System Users, Auditors | Ensuring Integrity

Exemplary certification concept for e-Methane



Results of RFNBO pilots meta study

1. Some requirements are not in place as they are not defined in the current project phase, e.g. because:
   - Decision have not been made when it comes e.g. to different supply chain options
   - Contracts haven‘t been set up
   - Systems haven‘t been implemented

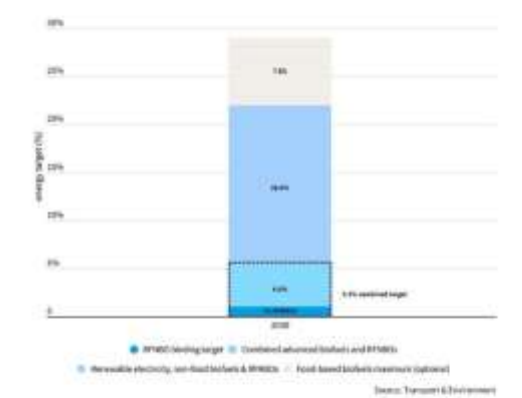
2. Lack of clarity in some definitions/ requirements
   - Individual, e.g. Required information included PPAs
   - Conceptual, e.g. Proof of geographical zones concept outside EU similar to bidding zones in EU

Current e-fuels market and outlook

Climate Targets

European Green Deal

- ✓ Europe has set ambitious climate goals, achievable through drastic GHG-emissions across all energy-intensive industries, including power generation, transport, industry and buildings.



Synthetic fuels

- ✓ Mandates for synthetic low-carbon fuels have been established by the EU (REDIII, ReFuelEU, FuelEU).
- ✓ Produced from [biogenic] carbon and [green] hydrogen through processes like methanation, methanol synthesis and Fischer-Tropsch.
- ✓ Potential to be low-carbon or carbon-neutral with carbon capture technologies.

Utilization of closed coal power plants

Reliability and Security

- ✓ By transitioning away from traditional coal-based energy production, which can be subject to supply chain vulnerabilities and environmental concerns, PtX technologies offer a resilient and sustainable energy solution.

Energy mix diversification

- ✓ The utilization of closed coal-related assets for PtX technologies facilitates the diversification of the energy mix and promotes the penetration of renewable energy sources (RES). By combining PtX technologies with RES, effective integration between the two technologies can potentially reduce reliance on fossil fuels, mitigate greenhouse gas emissions and avoid impactful curtailments. In addition, the existing sizeable plot plan allows the “in-house” development of sizeable RES supported by the already existing grid-connection infrastructure.

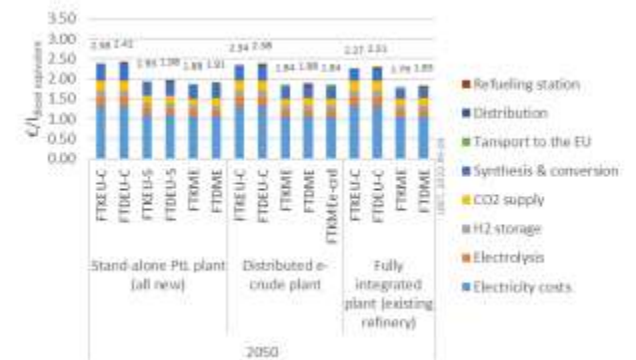
Potential to address social challenges

- ✓ By repurposing closed coal assets for PtF technologies, new economic opportunities are created, fostering job creation and economic revitalization in regions historically reliant on coal mining or power generation.

Current e-fuels market and outlook

Production costs

- ✓ Initial costs were up to 7 euros/liter in 2015.
- ✓ Projected to decrease to 1-3 euros/liter by 2050 due to increased production, efficiency, and lower renewable electricity prices.



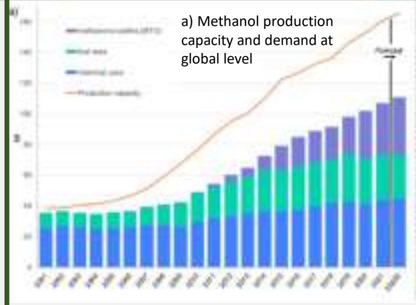
Source: Concawe

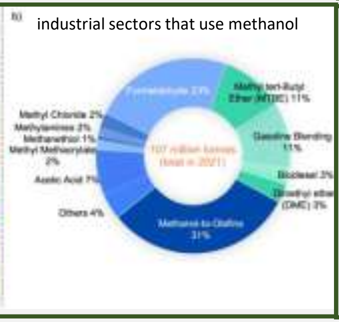
- ✓ Viability of Power-to-X (PtX) technologies depends on low electricity prices as well as CO2 and hydrogen transportation, distribution and storage infrastructure.
- ✓ Water availability and affordability is an important factor as regions with water scarcity may rely on seawater desalination which increases costs.

Market segmentation by synthesis route

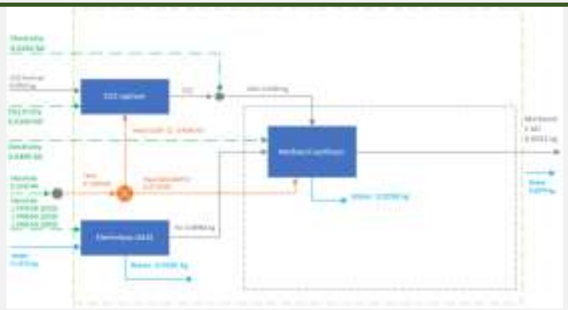
Methanol Route

- Methanol demand expected to reach over 120 Mt by 2025 and 500 Mt by 2050.
- E-methanol production currently costly but expected to become competitive with fossil fuels by 2035.
- Various global projects planned to produce e-methanol, leveraging renewable energy and CO2 capture. e-MEOH capacities 13.9 million tons by 2029.
- Currently, 800-1600 USD/t, future: 250-630/t (w/t CO2 credits).



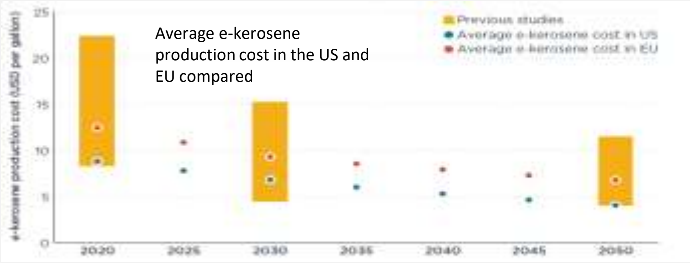


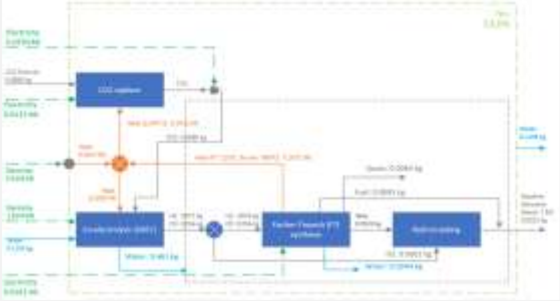
Production Routes



Fischer-Tropsch-Route for e-Kerosene

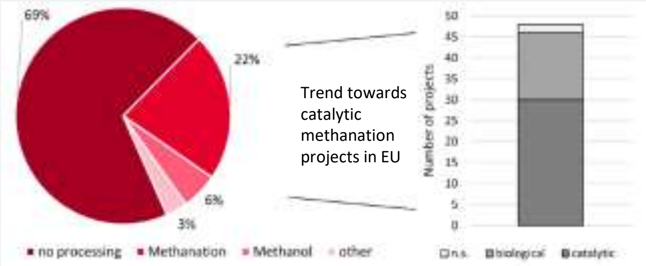
- E-kerosene considered promising for aviation sector decarbonization.
- Production costs expected to decrease over time.
- Numerous e-kerosene projects (25 commercial industrial scale and 20 demos) in the EU, with significant production capacities planned by 2030.
- Production cost: US $4 per gallon (€0.9 per liter) by 2050, EU $6.70 per gallon (€1.5 per liter) by 2050.

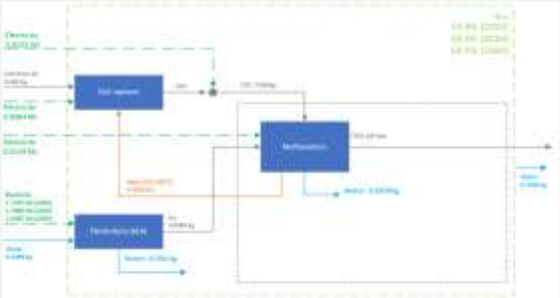




Methanation Route

- [Biogenic] Carbon Dioxide primarily converted into methane for injection in natural gas grid
- Catalytic methanation more prevalent in larger projects.
- Several, mainly pilots, e-methane projects operational or under construction in Europe.
- Estimated cost price of e-methane vary significantly: for 2030 around 23-110 USD/MMBtu and for 2050 around 15-60 USD/MMBtu.





Market enablers and barriers

Enablers

Legislation and Policy Mechanisms

- ✓ EU policies drive demand for e-fuels.
  - ✓ European Green Deal
    - ✓ RED III – RefuelEU – FuelEU
    - ✓ Hydrogen and Decarbonized Gas Market Package
    - ✓ EU Taxonomy Regulation (2020/852/EU)
  - ✓ Hydrogen Accelerator

- ✓ National regulations and incentives promoting the adoption of e-fuels.
  - ✓ CfDs (under development)
  - ✓ Public subsidies (direct funding or tax exemptions)
  - ✓ National Energy and Climate Plans (NECPs)
  - ✓ Demand side incentives Carbon pricing mechanisms like the EU Emissions Trading System (ETS).

Potential Funding Sources

- ✓ Public funding from EU programs, national governments, and regional initiatives support e-fuel projects.
- ✓ Private investments from companies and financial institutions are crucial for large-scale deployment.
- ✓ Partnerships between public and private sectors can enhance funding opportunities and project viability.

Barriers

Technological Barriers

- ➢ High production costs for e-fuels compared to fossil fuels.
- ➢ Low energy efficiency vs fossil equivalents
- ➢ Need for technological advancements and scaling up of production capacities.
- ➢ Economic feasibility dependent on reducing costs of renewable electricity, electrolysis, and CO2 capture which is dependent of available technology maturity.

Infrastructure and Supply Chain Barriers

- ➢ Limited infrastructure for production, distribution, and storage of e-fuels.
- ➢ Need for development and adaptation of existing fuel supply chains.
- ➢ Transportation and logistical challenges for distributing e-fuels.

Regulatory and Policy Barriers:

- ➢ Regulatory uncertainties and lack of harmonized standards across regions.
- ➢ Need for clear and supportive policy frameworks to encourage investment.
- ➢ Challenges in meeting stringent certification and sustainability criteria for e-fuels.

Barriers

Market Acceptance and Demand Barriers

- ➢ Excessive acquisition costs (CAPEX/ OPEX)
- ➢ Established fossil fuel markets (existing infrastructure and networks)
- ➢ Consumer and industry acceptance of e-fuels as viable alternatives.
- ➢ Lack of awareness and education on the benefits of e-fuels.

Environmental and Social Barriers

- ➢ Lack of Environmental impact assessments to address social acceptance issues.
- ➢ Competition for resources (e.g., water, land) with other renewable energy projects.
- ➢ Need for wider dissemination and community involvement in project planning and implementation to address public concerns.

Conclusions of WP5 for GreenDealCO2

- EU provides comprehensive framework with sustainability requirements for electricity, CO2 sourcing and GHG calculation

- Certification is based on these requirements. Pilots show that certification is ready to be applied with some remaining conceptual unclarities imposed by regulation

- Market analysis shows that eFuels have big economic potential….. (MOH?)

Conclusion

Conclusion

- Successful progress of the project → Duration until the end of July
- Studies show high potential:
  - High occurrence of attractive locations
  - Decarbonisation opportunity for industries
- High market potential for e-fuels
- Reaching the next level:

Completed		In progress		Next level
RECPP RE-PURPOSING COAL POWER PLANTS	→	GreenDEALCO2	→	Demonstration project

Thank you!

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