NATIONAL TECHNICAL UNIVERSITY OF ATHENS

SCHOOL OF MECHANICAL ENGINEERING

FIELD OF INDUSTRIAL MANAGEMENT AND OPERATIONAL RESEARCH

Τεχνολογίες Δέσμευσης και Αξιοποίησης Διοξειδίου του Άνθρακα (CO_2) – οι ευκαιρίες, οι προκλήσεις και η μελλοντική χρηματοοικονομική βιωσιμότητά τους

Technologies of Capture and Utilization of Carbon Dioxide (CO_2) – their opportunities, challenges, and their future financial viability

THESIS PRESENTATION

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Identifying the problem …

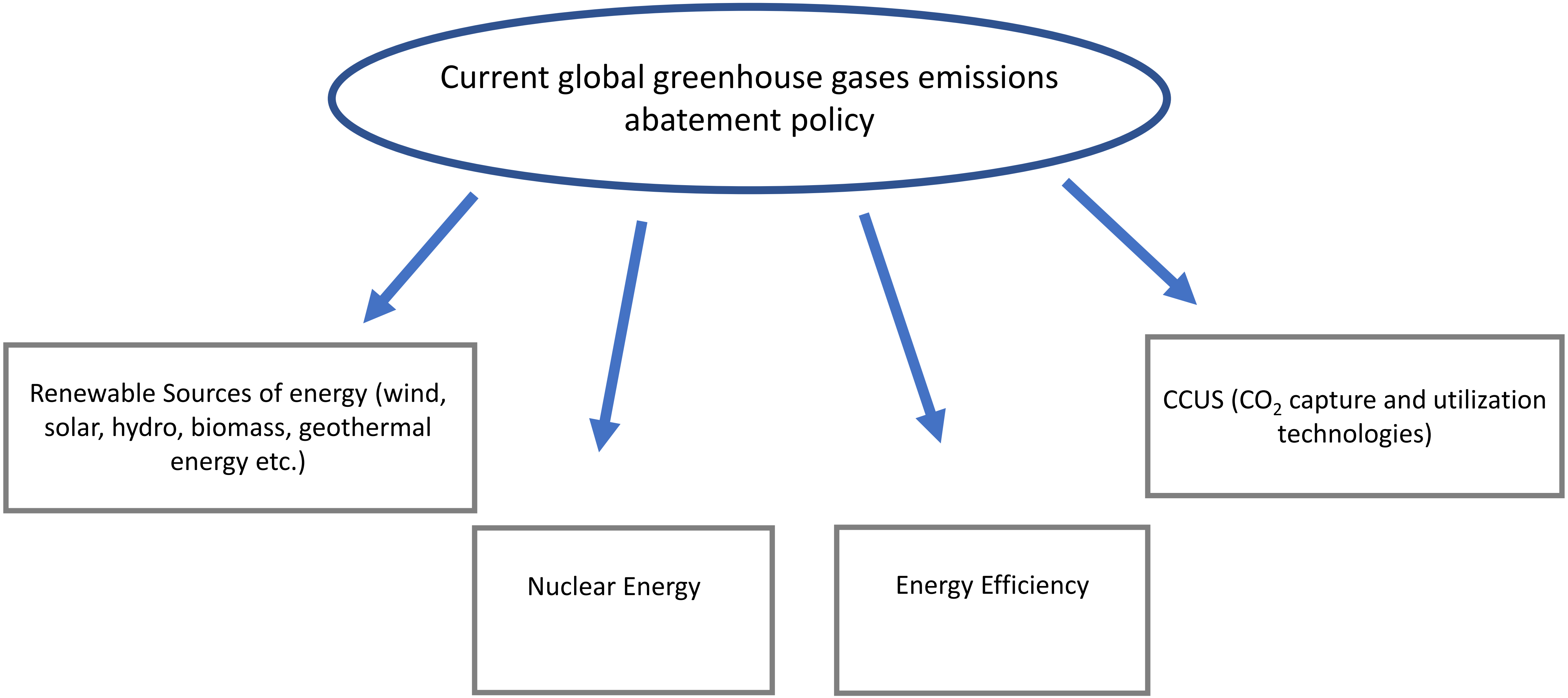
- Greenhouse gases (GHG) are the main causes for climate change, rise in mean ambient air temperature and ice melting
- Carbon dioxide (CO_2) and methane (CH_4) are the fundamental GHG
- On 11 May 2019 CO_2 concentration in the atmosphere reached 415,26 ppm for the first time in human history. Indicatively, before the industrial revolution that concentration was just 280 ppm

Major legislative efforts towards mitigating climate change

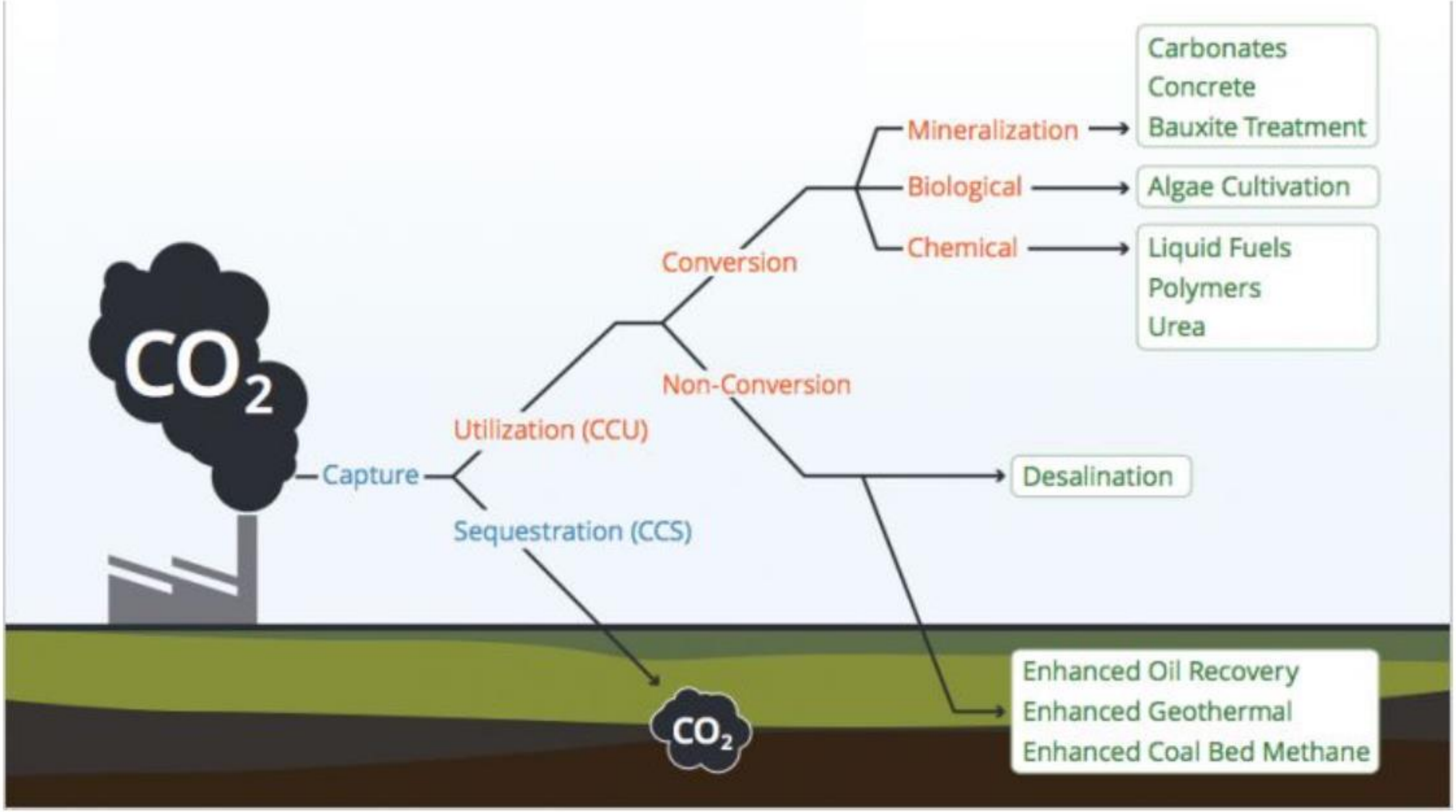
- Kyoto protocol (1997)
- 21^{o} United Nations Conference (COP 21 - UN Paris Agreement 2015)

Major supporting tools of the above legislative efforts

- Sustainable Development Goals –SDG's (UN General Assembly agenda for 2030) (2016)
- COP 26 (Glasgow 2021)


Current global greenhouse gases emissions abatement policy
Renewable Sources of energy (wind, solar, hydro, biomass, geothermal energy etc.)
Nuclear Energy
Energy Efficiency
CCUS (CO_2 capture and utilization technologies)

Pathway of all possible options available of CCUS



Necessity and major benefits from the expansion of CCS

- Offer the possibility to continue using fossil fuels, while at the same time emissions fall → Offer the possibility to close carbon cycle
- No need for CO_2 transport while at the same time they can be used for offsetting CO_2 emissions of the transport sector
- Offer the possibility of an insurance policy against any possible greenhouse gases leakage

Pathway of Capture Options CCS

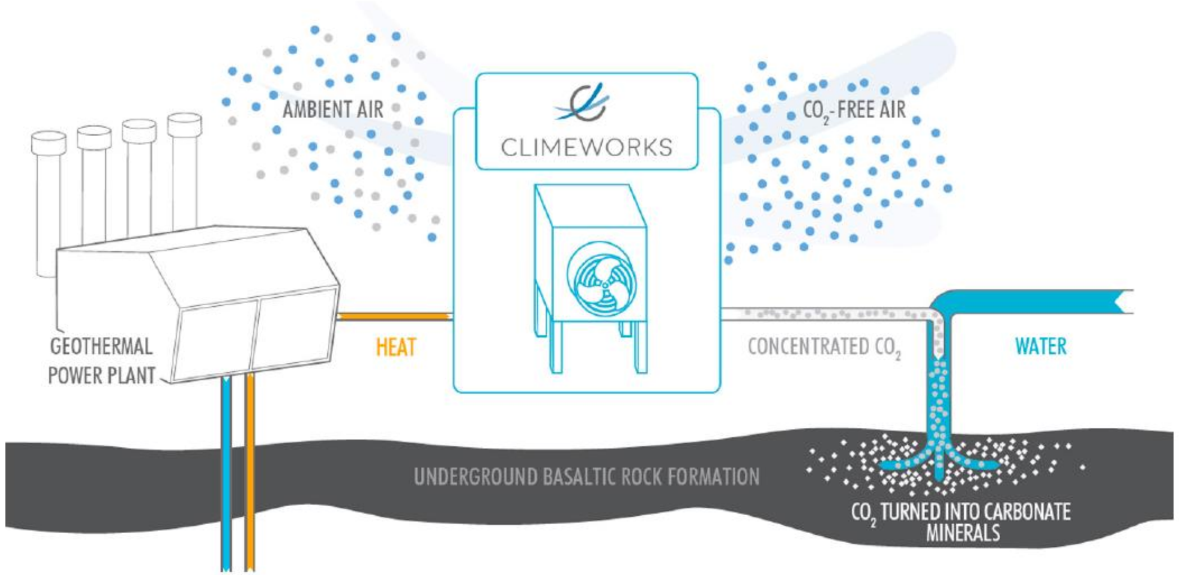
CCS

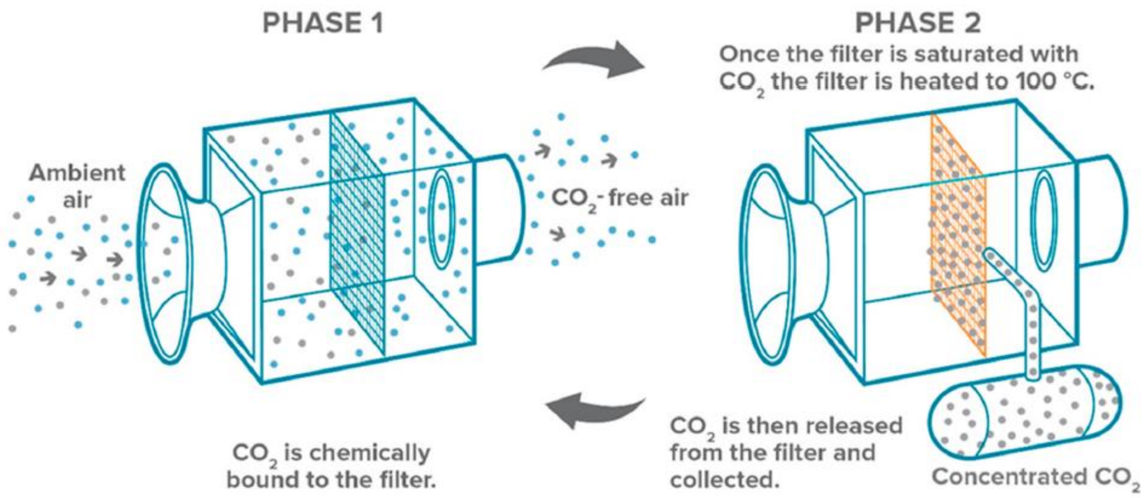
- Capture of CO_2 from the flue gases (point sources)
- Capture of CO_2 from ambient air (DA(C)C) - Direct Air Carbon Capture

climeworks

General Information

- Pioneer company in DACC at industry level
- Swiss company with its operation to be located in Iceland (Orca plant)
- Takes advantage of the abundant geothermal energy of Iceland
- Co-operation with Carbfix intended for injection of CO_2 into basalts and its permanent sequestration through mineralization in the subsoil (Injectable solution of CO_2 coupled with water)





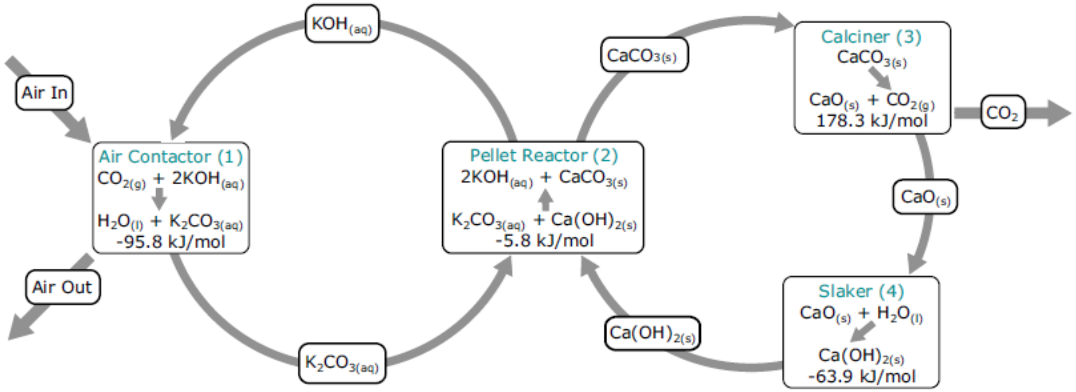
Technical Information

- One of its CO_2 Collectors = 2000 trees in terms of absorption capacity of CO_2
- Gained the impressions and thus has been selected as part of Microsoft's carbon removal portfolio to help reach negative emissions by 2030
- Capture Potential= 4000 t CO_2 / year for the whole Orca plant

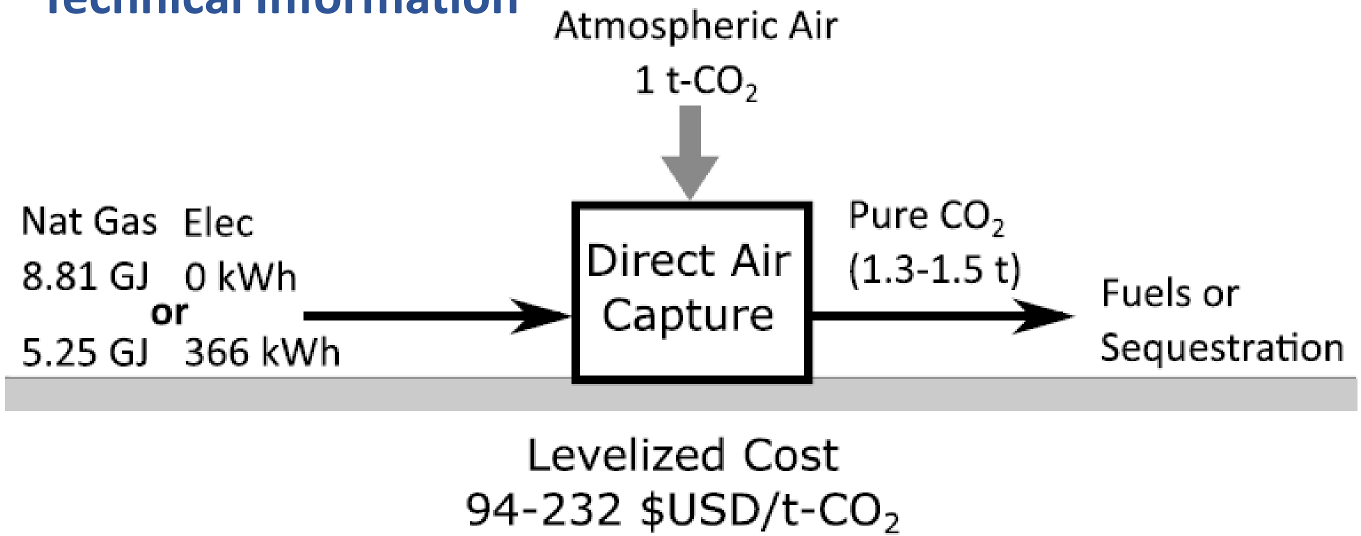
Carbon Engineering

General Information

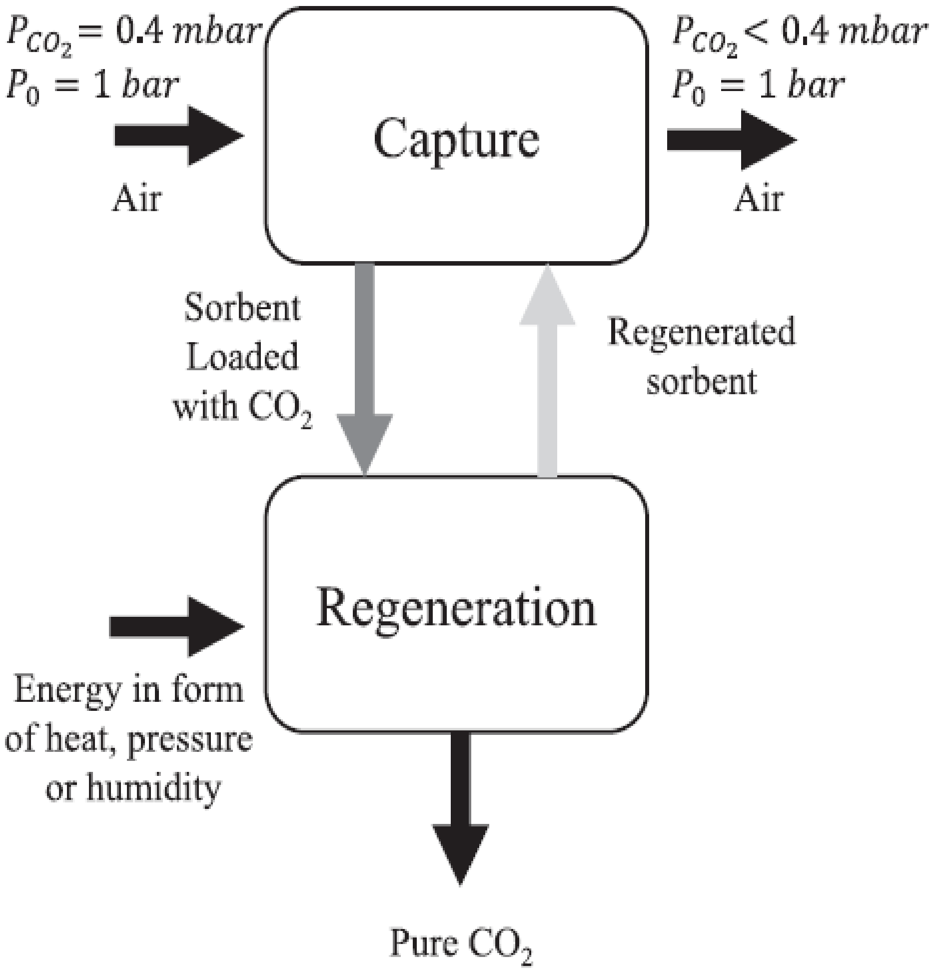
- Canadian company that also operates in DACC
- Uses aqueous sorbents, and CO_2 is captured through two chemical loops/processes
- Additional capture is being accomplished with goal of further exploiting CO_2 (acts also as a CCU)



Technical Information



Sorbent choice and its regeneration process



Why DACC (Direct Air Carbon Capture) or just DAC (Direct Air Capture) prevailed as major CCS ;

- Absence of CO_2 transportation costs for sequestration
- CO_2 concentration in ambient air is 2500:1 (moles air/moles CO_2) SO it isn't sustainable any possible technology that prepares or gives energy in the adducted air before the regeneration process and thus canceling out any other possible capture technology from ambient air

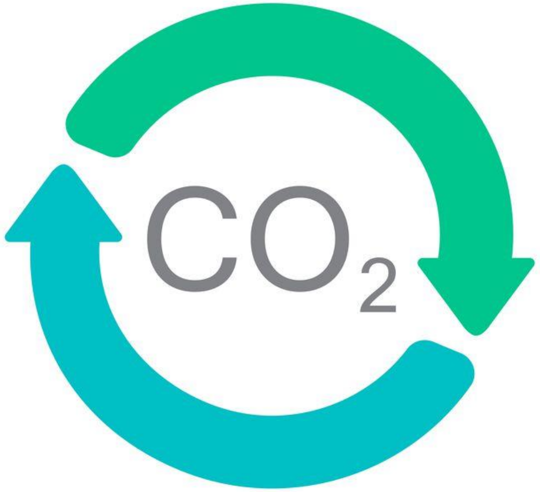
Technoeconomic of DACC

- Innovative idea that it can only be improved
- According to APS (American Physical Society) if the sequestration cost is above 570 €/t CO_2 the technology in the long run isn't financially viable
- Target of financial viability of all DACC in (€/ t CO_2): Levelized cost of capture < EU ETS carbon allowances (in European Level)
- Cash flows that due to the need for external funding so far are calculated through the following formula: $CF = P = Revenue - OPEX$

Comparison between Climeworks and Carbon Engineering

Table	Climeworks	Carbon Engineering
CO_2 capture potential (thousands t CO_2/year)	4	980
CO_2 re-emission percentage (%)	10	40
Investment cost of the plant (M €)	9.5	1.07
Levelized cost of capture (€ / t CO_2)	1140	200
Plant full capacity completion (year)	End 2021	End 2023

CO_2 Capture and Utilization Technologies (CCU)



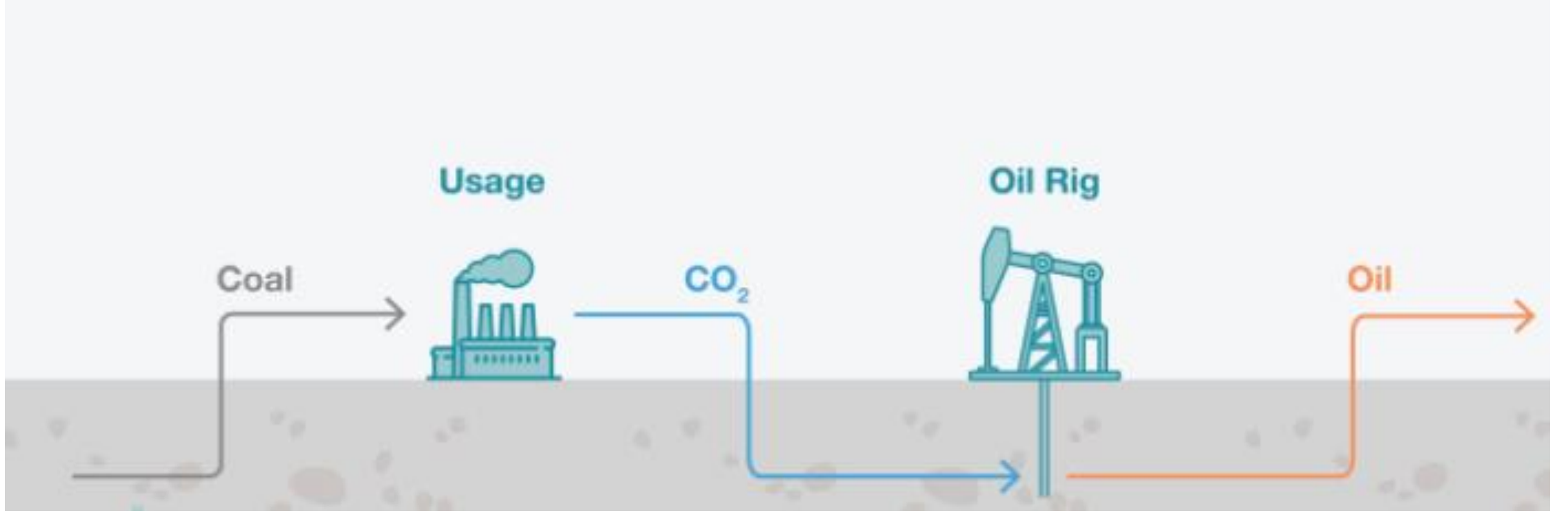
Major advantages of CCU:

- Promotion of circular economy
- Value creation from waste

Major disadvantages of CCU:

- High energy conversion needs
- CO_2 transportation costs

Enhanced Oil Recovery (EOR)



General Information

- Method used for oil recovery from almost depleted reservoirs
- Most advanced CCU technology at the moment – major application in UAE
- CO_2 injection helps to decrease the viscosity of the remaining oil and thus oil is more easily recovered improving productivity
- Permanent sequestration of CO_2 in the subsoil through this process

Major external parameters that influence further expansion of EOR technology

- World crude oil demand
- Percentage of almost depleted reservoirs in the production line
- Supply and technical characteristics of the supplied CO_2

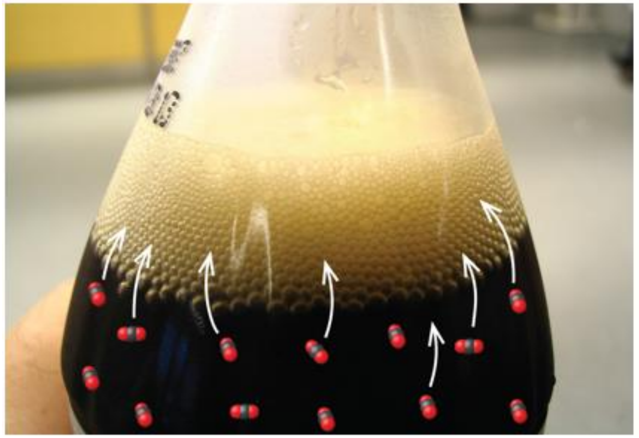
Direct Uses of CO_2

1. In greenhouses -> Increased fertility by 50%
2. As a refrigerant (R744)
3. In soft drinks
4. In fire extinguishers
5. In pharmaceutical industry as a stimulant of the respiratory

Absence of conversion costs

BUT

Zero technical and environmental benefits from any possible production of post-processed goods



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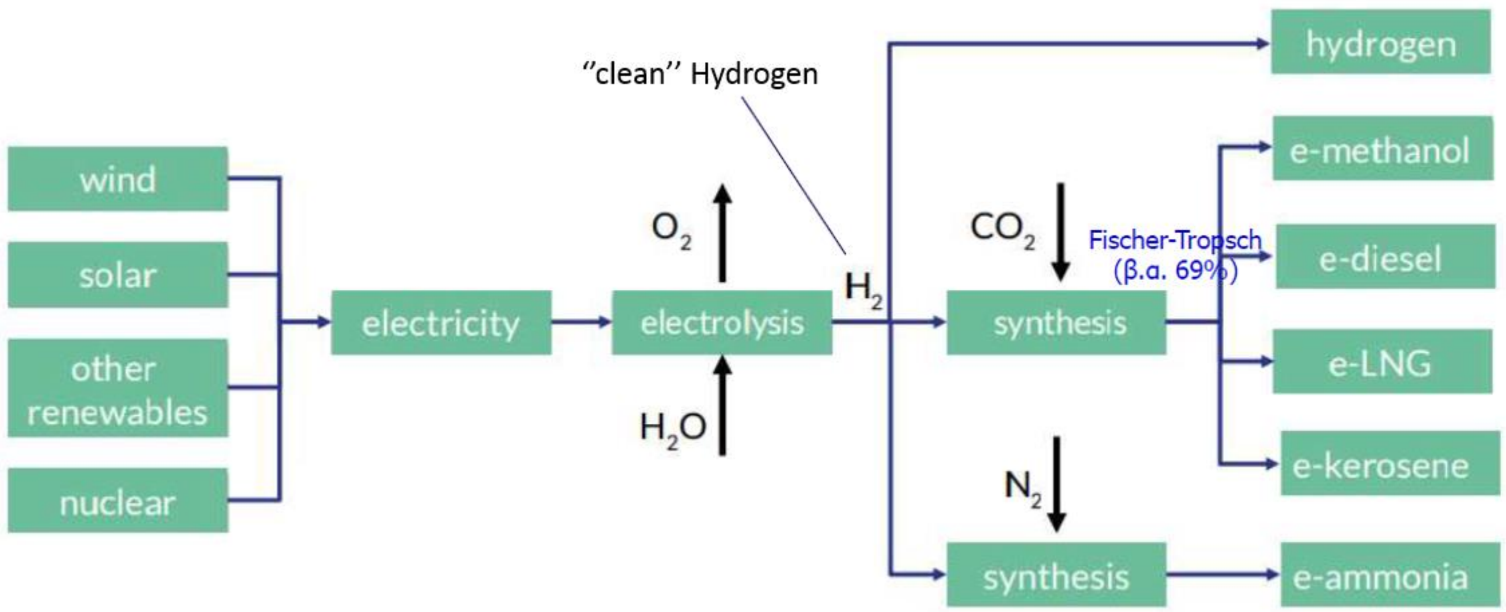
E-Fuels



General Information

- Chemical type -> $C_xH_yO_z$
- Feedstock for their making: CO_2 and H_2
- Conversion through chemical process Fischer-Tropsch

Opportunities for their expansion

- Liquid fuels advantages (high energy density)
- Alternative in the decarbonization of the transport sector

Necessary Requirements for their expansion

- Green hydrogen as feedstock otherwise it cancels out the CO_2 capture potential (high re-emission percentage from LCA)
- No need for new infrastructures ("drop-in" replacements)
- Compliance with typical RON, MON, CN numbers

Major barriers

- CO_2 molecule stability-> energy intensive break-down process, creation of undesirable by-products from the above catalytic chemical reactions
- Costs of supply and compression of H_2

Polymers - Biofuels – Chemicals

LanzaTech
capturing carbon. fueling growth.

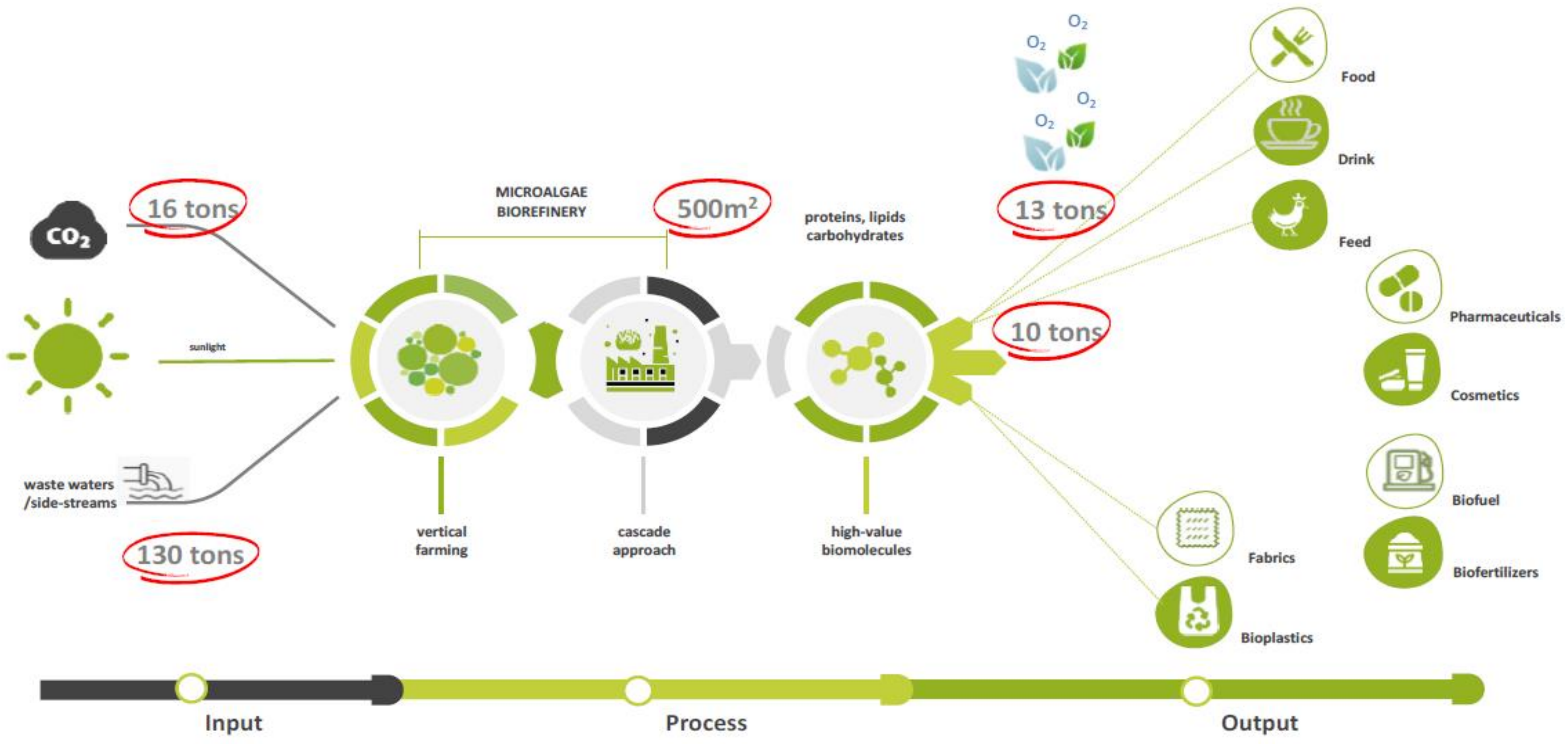
Off-gas fermentation from CO_2 to biofuels mainly for the production of ethanol from sources of carbon waste

twelve

Conversion of CO_2 to chemicals, construction products that usually are produced from fossil fuels

- Partnership with purpose of converting CO_2 to polypropylene
- 1,87 M € external funding with purpose of formalization of this partnership (2019)

Biotechnology company - Solmeyea



General Information

- Off gas fermentation and gasification system coupled with a vertical cultivation system of microalgae that converts CO_2 into exploitable high protein value biomass
- Final products that serve 9 of 17 SDG's
- Yet in pilot operation at "Demokritos – Greece's National Science & Research Center" with goal of a forthcoming industrial scalability
- Uses autotrophic, mixotrophic and heterotrophic cultivation of microalgae

CCU Technologies Comparison

Comparison Criteria

1) Technology Readiness – Scalability
2) GHG emissions from the capture and conversion process of CO_2
3) SDG's goals achievement
4) Geographical and geological limitations
5) Investment and Operational costs

Table	Levelized Cost (€ / t CO_2)	Investment Cost (M €)
EOR	40 + 30	40, if we don't assume an existing oil reservoir
Direct Uses of CO_2	30	We assume existing infrastructure
E-fuels	278 + 30	0.95
LanzaTech - Twelve	80 + 30	300
Solmeyea	18000 up to 250 + 30 (Depends on the scalability)	2.2

EU ETS

General Information:

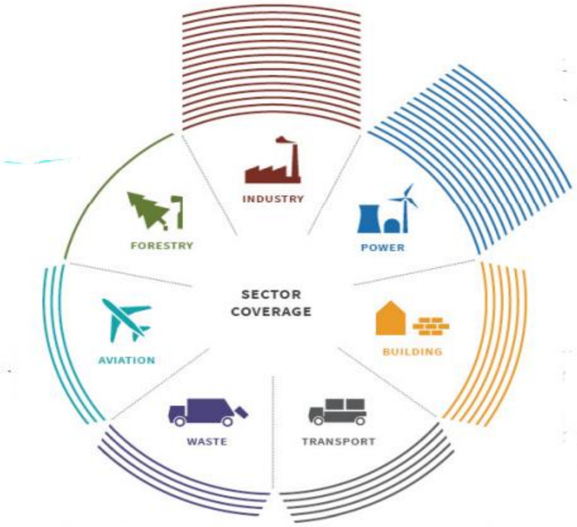
- 4 phases of operations (started in 2005), now in phase 4 (2021-2030)
- Issuance of key legislation directives concerning pollutants, CO_2 and certifications and control of carbon capture technologies (CCS)

Cover up sectors:

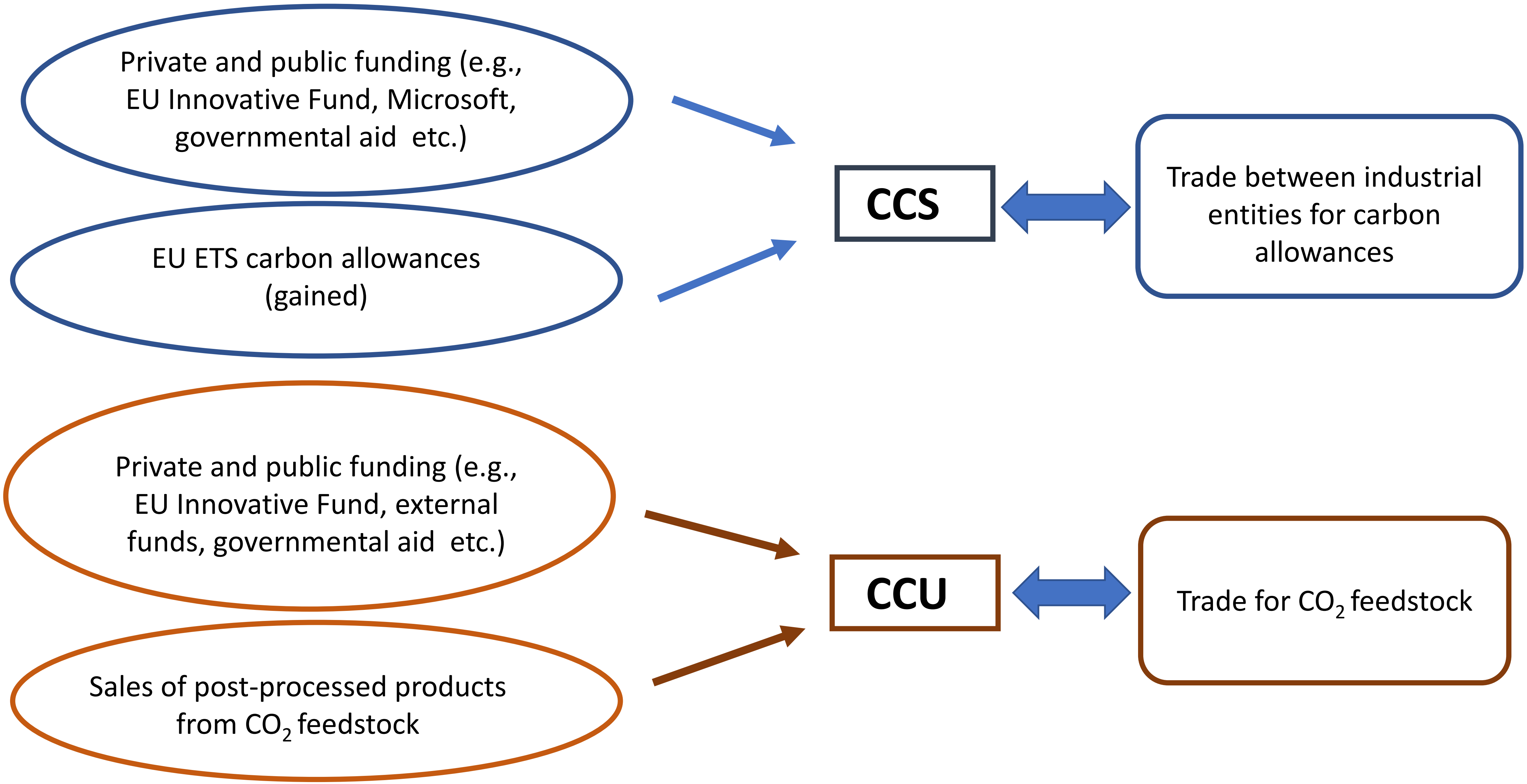
- Electricity and heat generation
- Energy intensive industries: oil refineries, steel works, production of metals, cement, glass, ceramics, aluminum, organic chemicals etc.
- Commercial Aviation within EEA (European Economic Area)
- CCS <u>but</u> no CCU yet (anticipated by the end of 2024)
- Maritime sector (complete inclusion in 1/12/2023)

How does it work ? – Key elements:

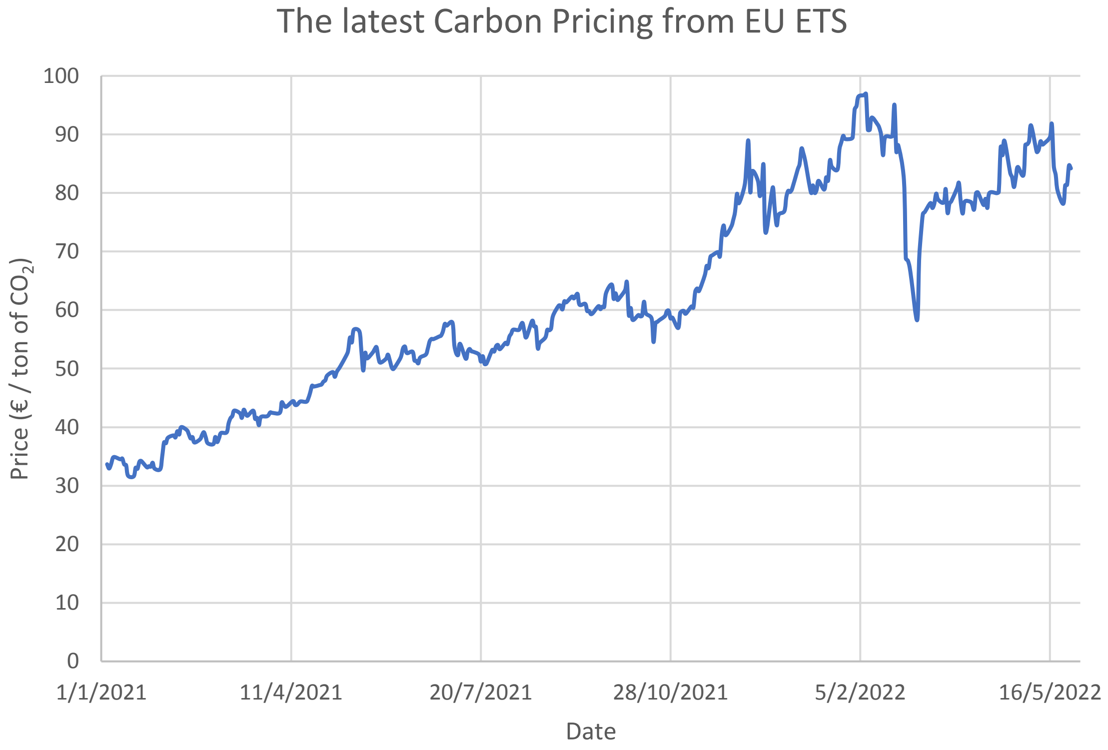
- Works on “cap and trade” principle
- Carbon Credits
- Carbon Allowances
- Penalties for noncompliance

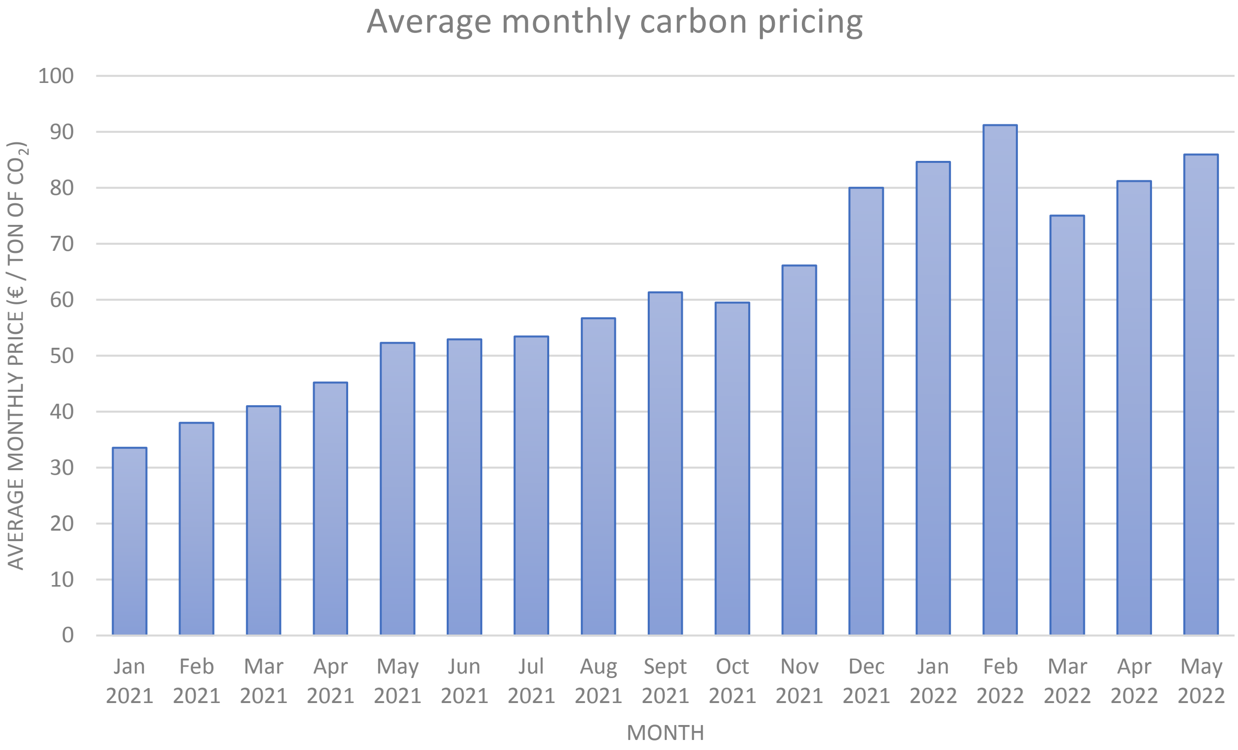


CCUS Revenue Streams



EU ETS Carbon Pricing



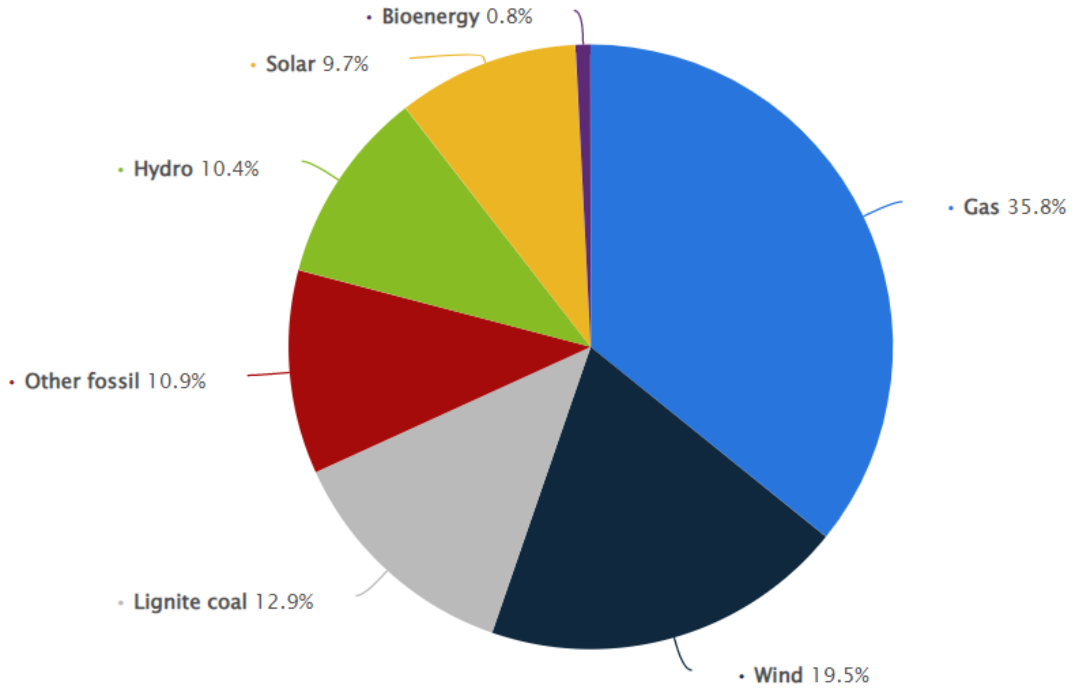


Key Results

- Historically high price on 8/2/2022 at price value of 96,7 €/ t CO_2 (continuous upward price trend until then)
- Moderate scenarios estimate that by 2030 the carbon price will be at least 129 €/ t CO_2
- Financial viability criterion: Levelized cost of Capture or Conversion (€ / t CO_2) < EU ETS carbon allowances (€ / t CO_2) -> not immediately apparent at least for CCU
- Steady maybe even expanded upcoming market share due to inelastic emissions from aviation and maritime sector

First Climate Law of Greece (27/5/2022) – Pathway towards carbon neutrality

Distribution of electricity generation in Greece in 2021



Major regulations – goals:

1) Lignite must be phased out gradually until 2028
2) The sale and installation of oil boilers for heating purposes will be entirely prohibited in 2025

RESULT

Energy deficit in electricity and heat generation

SO

Opportunities for the development, expansion and sponsoring of CCUS applications

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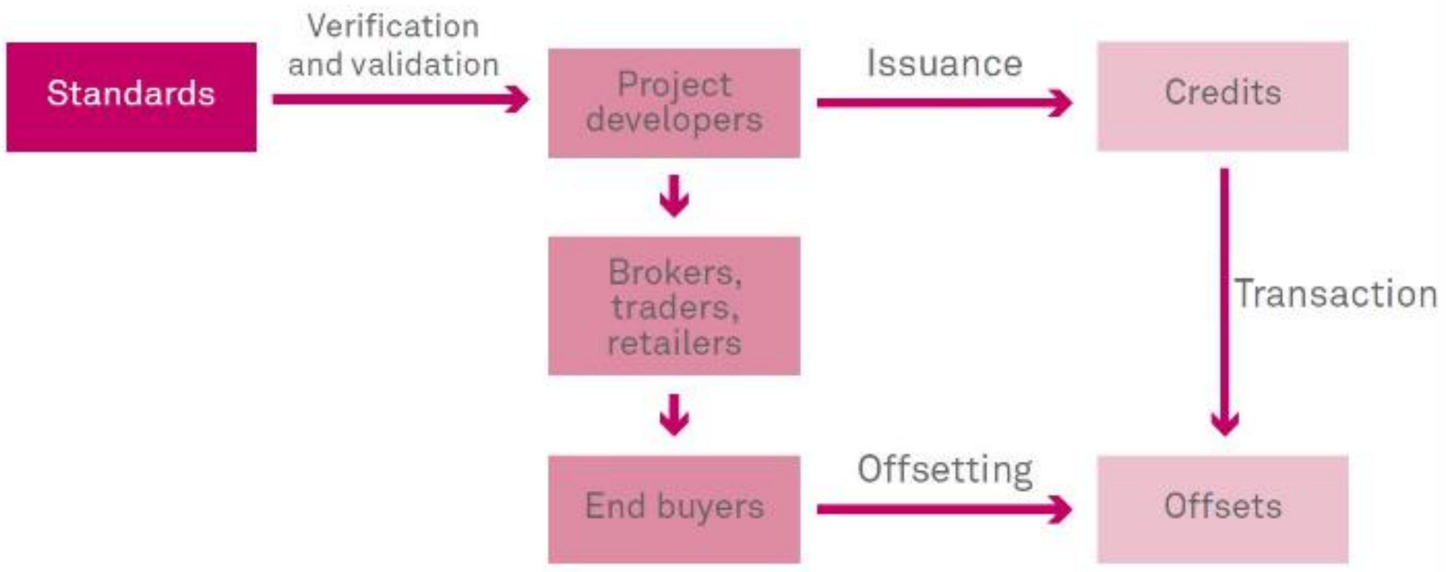
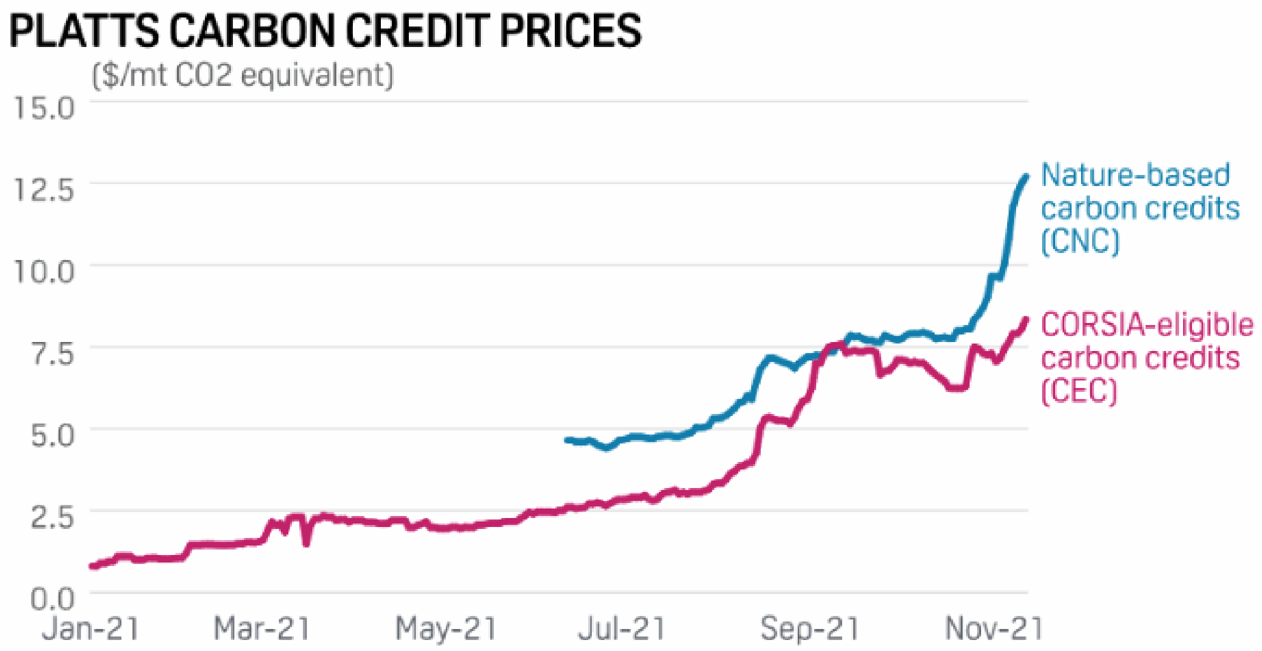
Voluntary Carbon Offset Markets



Key players:

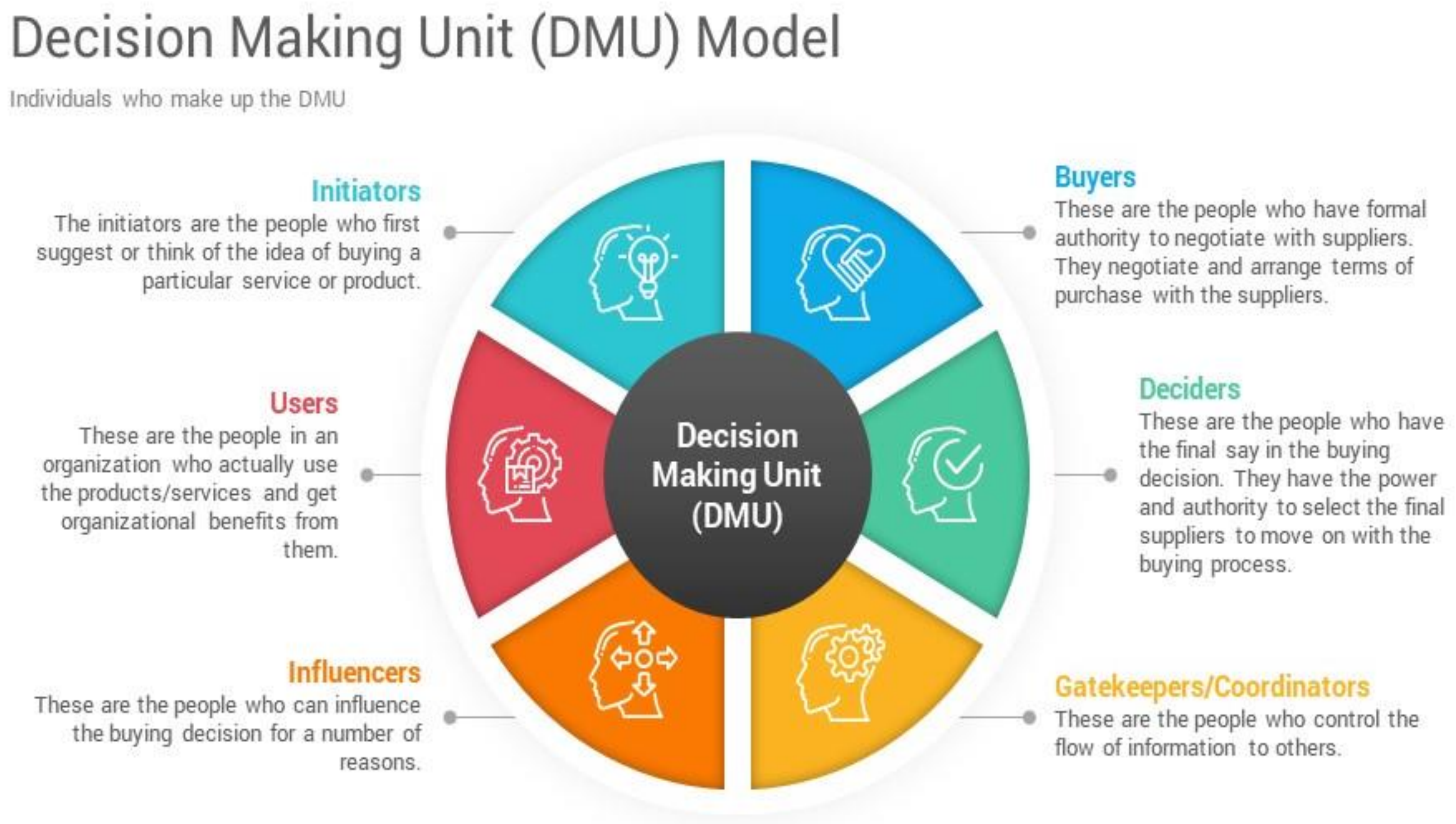
- ✓ Project developers of CCUS applications
- ✓ End buyers – funding examples of Microsoft and BCG towards Climeworks
- ✓ Brokers, traders, retailers
- ✓ Standards



Key elements of this market:

- ✓ Prices follow the trend of EU ETS
- ✓ Absence of mandatory trading of carbon emissions
- ✓ Based on the influence of the evaluators for the amount of grants given as carbon offsets
- ✓ Offers good reputation of environmental awareness to end byers

Decision Making Model



Players:

- ✓ Initiators
- ✓ Buyers (responsible for the purchase negotiations with the suppliers)
- ✓ Users (both employees and customers)
- ✓ Influencers
- ✓ Deciders
- ✓ Gatekeepers/Coordinators (they control the flow of information between initiators and buyers)

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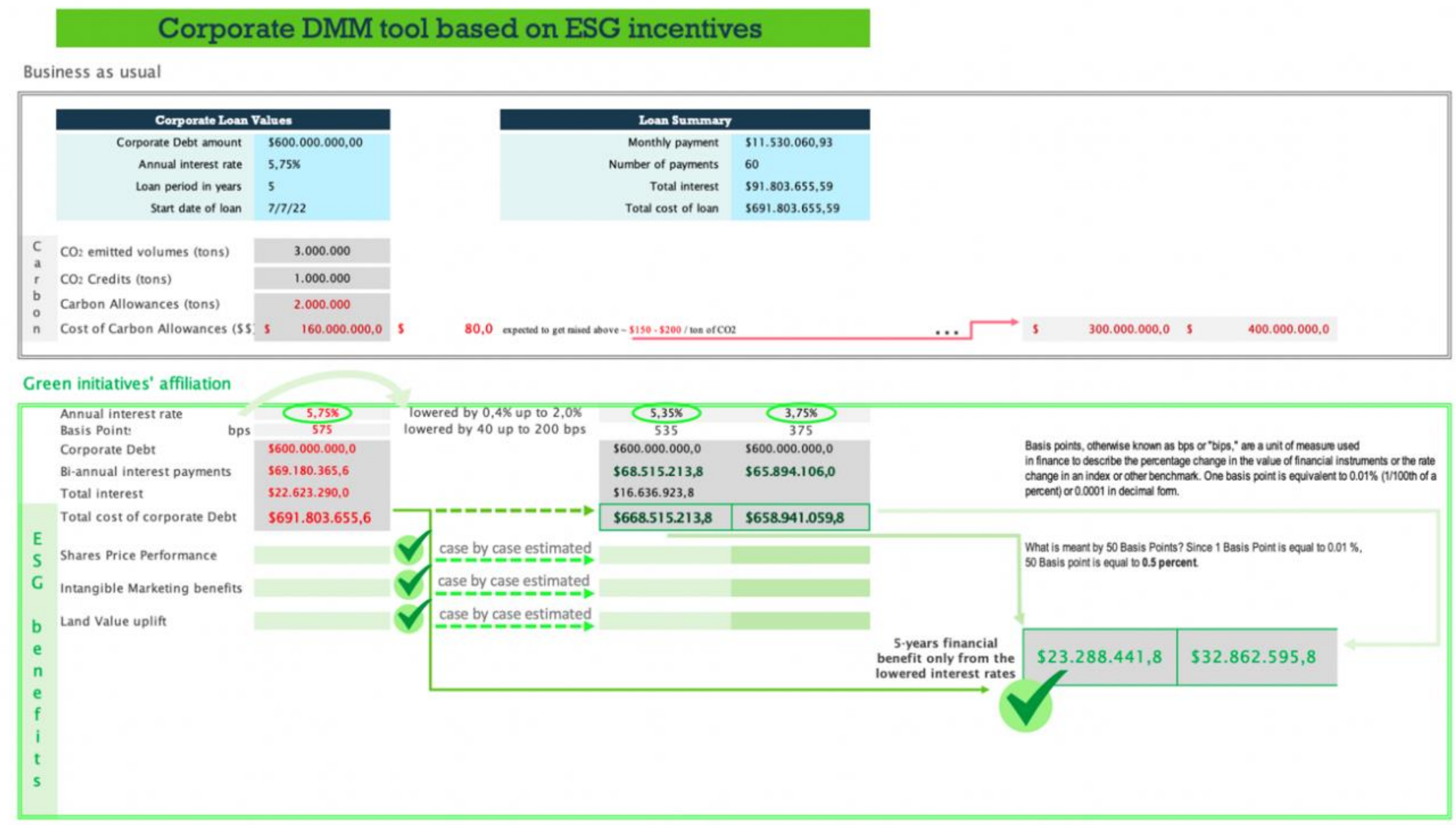
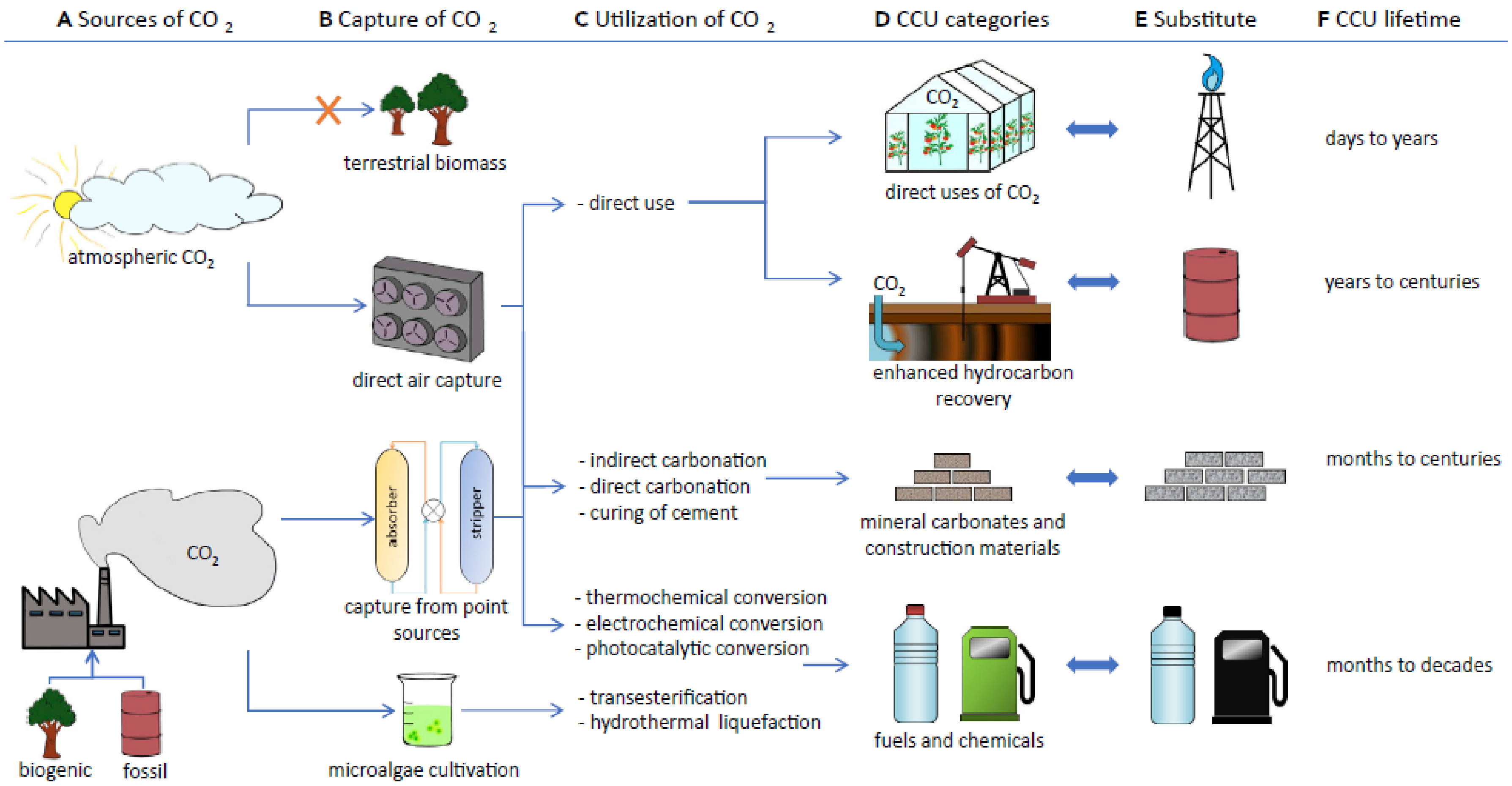
Case Study Scenario for an oil refinery (ESGs Influence)



Parameters affecting the model:

- ✓ CO_2 emissions
- ✓ CO_2 credits
- ✓ CO_2 allowances
- ✓ Land Value
- ✓ ESGs
- ✓ Corporate bond / debt
- ✓ Tangible and intangible benefits
- ✓ Basic Points (interest rates index)
- ✓ National and European index of economic growth and necessity

Summary of the examined CCUS technologies that were covered in this diploma thesis



Conclusions

Opportunities for the expansion of CCUS:

a. Legal and Financial environment
b. Promotion of circular economy
c. Contribution to global sustainable environmental longevity
d. Public environmental awareness

Achieving goals criteria for attracting potential investors:

a. Geological Constraints
b. Technology readiness - Scalability
c. Investment and Operational Costs
d. Quality and quantity of benefits from the operations of CCUS
e. Public acceptance and support
f. Targeted Decision Making Model

Barriers for the expansion of CCUS:

a. Yet low technology readiness - scalability
b. Possible need for the creation of new infrastructure
c. Hazard from high re-emission percentage that cancels out the whole carbon capture process
d. Non inclusion of CCU in EU ETS legal framework
e. Absence of sufficient standards and certifications for the cultivation of trust among the majority of the society for the beneficial outcomes of the implementation of CCUS

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Thank you very much for your attention !

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