METHARC®

zero carbon to surface

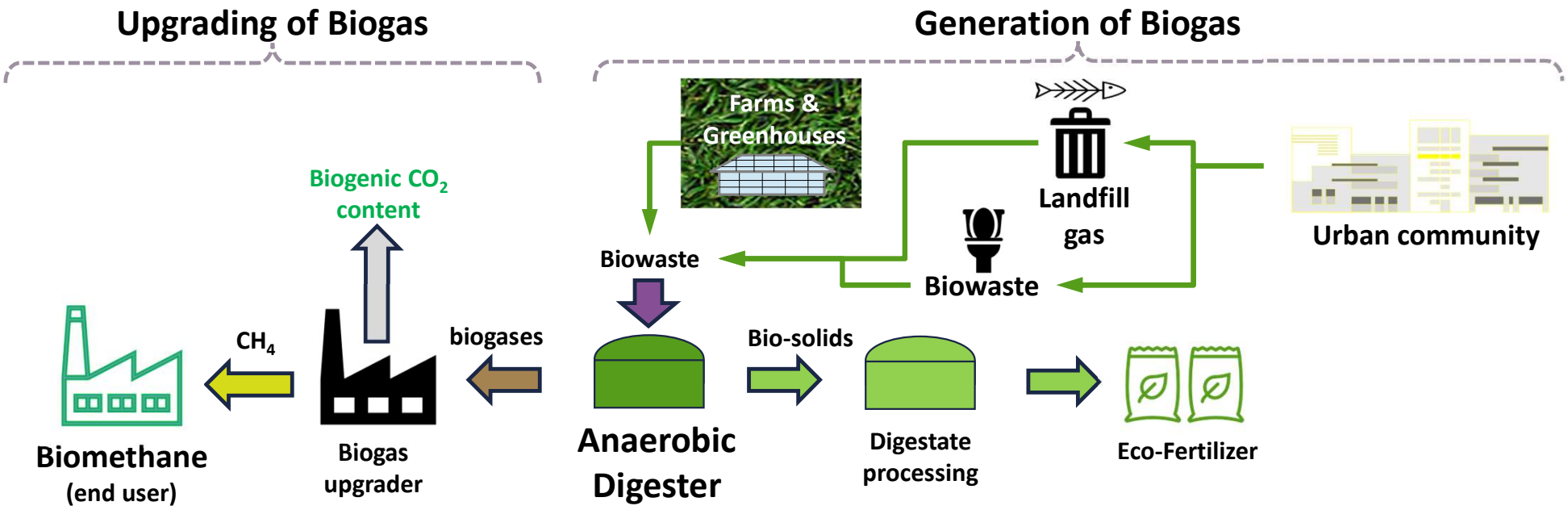
Biogas Reformation in Geothermal Wellbores

- Optimising Heat, H_2 & CCS

The German Geothermal Congress 2025

18th - 20th Nov 2025

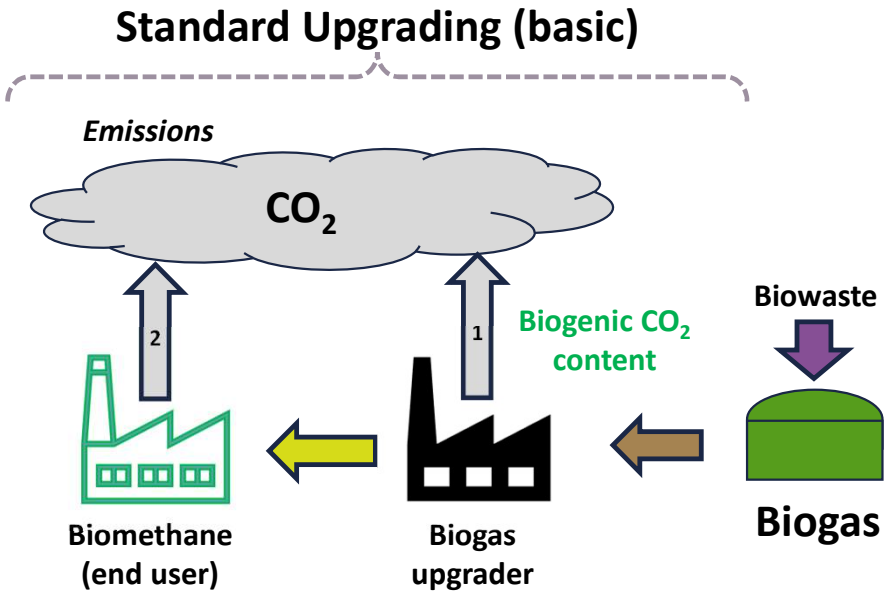
Biogas (CO_2 + CH_4) .vs. Biomethane (CH_4)



Business Optimisation Drivers: Biogas

- Reduce Capex & Opex => **simplify process**
- Increase Production & Optimise subsidies => **eliminate constraints**
- **Reduce risk** => avoid Calorific Value, gas network access & flaring risks
- Increase product value & trading volumes => **create new markets**
- Navigate Carbon Taxation => **capture more CO_2**

Biogas: The CO_2 Dilemma



Two distinct sources of carbon neutral CO_2 emissions

- How do we generate negative emissions, and make a **Greener** product?
- How do we increase CO_2 trading volumes?

How do we account for these 2 separate CO_2 emissions?

- Who is responsible for the CO_2? (i.e., Scope 1, 2, 3 … or 4) *
- EU Carbon Border Adjustment Mechanisms (CBAM) (2026)?

SG

Nov 5th, 2025, the 27 European Energy & Climate ministers agreed a new **EU climate target for 2040** of a **90% reduction in net greenhouse gas emissions** compared to 1990 levels (with 2^0 target of 66.25-72.5% by 2035).

- This aims to amend the European Climate Law of 55% by 2030.

SG3

Note *

Scope 1: **direct emissions** from own sources a company controls, like burning fuel in its vehicles or facilities, or fugitive emissions from leaks
Scope 2: **indirect emissions** from purchased energy: electricity, steam, heat, or cooling
Scope 3: **all other indirect emissions** occurring in the company's upstream and downstream value chain, such as **the transportation, distribution and use of its product**
Scope 4: **avoided emissions** outside a product's value chain, as result of using the product or process (e.g., improved energy efficiency or eliminating process steps)

Slide 3

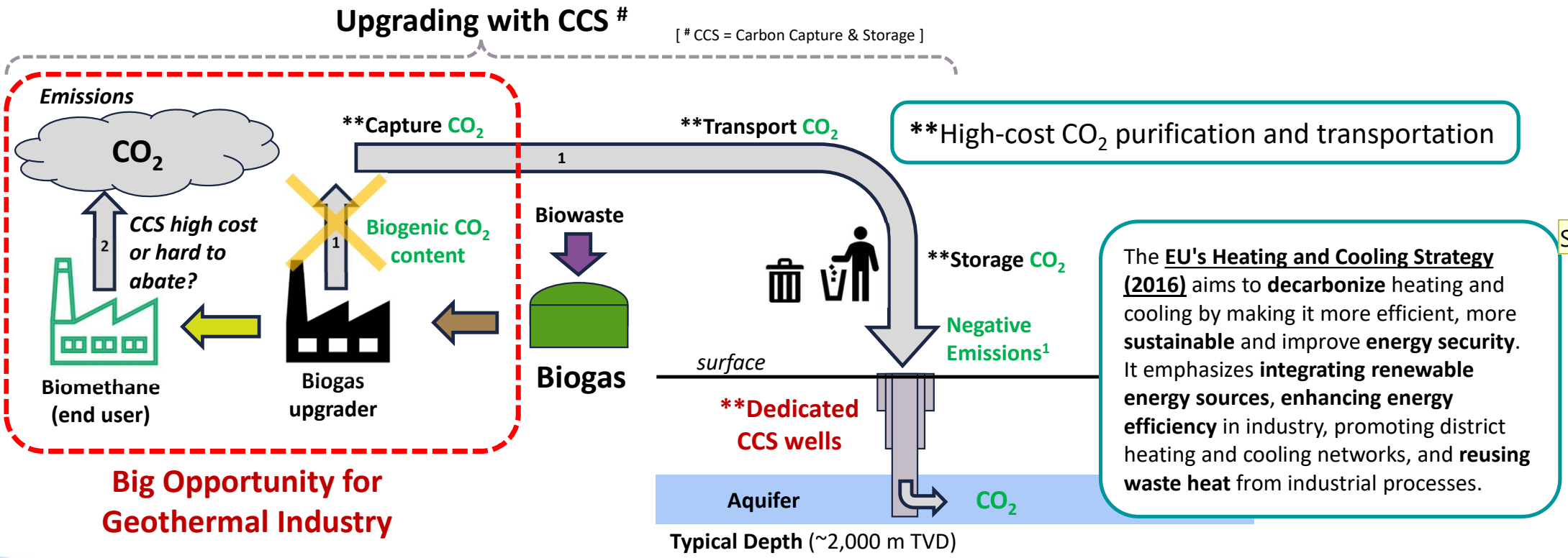
SG1 https://taxation-customs.ec.europa.eu/carbon-border-adjustment-mechanism_en
Stuart Gillick, 2025-11-17T15:23:30.750

SG2 https://climate.ec.europa.eu/eu-action/climate-strategies-targets/2040-climate-target_en
Stuart Gillick, 2025-11-17T15:23:53.838

SG3 https://climate.ec.europa.eu/eu-action/european-climate-law_en
Stuart Gillick, 2025-11-17T15:24:14.208

SG4 https://www.weforum.org/stories/2022/09/scope-4-emissions-climate-greenhouse-business/
Stuart Gillick, 2025-11-17T15:34:15.601

Biogas Upgrading with CCS



We need to **innovate** to **increase sustainability, efficiency** and **energy security**

- **integrate** our **energy generation** and our **carbon management systems**

Slide 4

SG1 https://energy.ec.europa.eu/topics/energy-efficiency/heating-and-cooling_en
Stuart Gillick, 2025-11-17T15:32:49.735

Key Obstacles to Cleaner Energy

Net Zero

Energy security *needs continued commercial exploitation of* ***Biogas***

How we consume *this energy resource and capture its carbon is* ***important***

Sustainability Challenges

Biogas

- carbon fuel (CO_2) - emerging climate restrictions
- sources - agriculture, landfill gas and biowaste (all increase with population)

Geothermal

- limited commerciality
- high upfront capital cost (Wells >50%)
- limited scalability - currently **<10%** * of planet (i.e., zones of shallow 'hot rock')

[Ref * :Duffield, W. A., & Sass, J. H. (2003). Geothermal Energy—Clean Power From the Earth's Heat (Circular) [Circular]. USGS. https://pubs.usgs.gov/circ/2004/c1249/c1249.pdf]

Our Focus: Sector Coupling

Biogas

✓ Geothermal wells provide – a facility for hydrogen production & geological carbon capture (CCS)

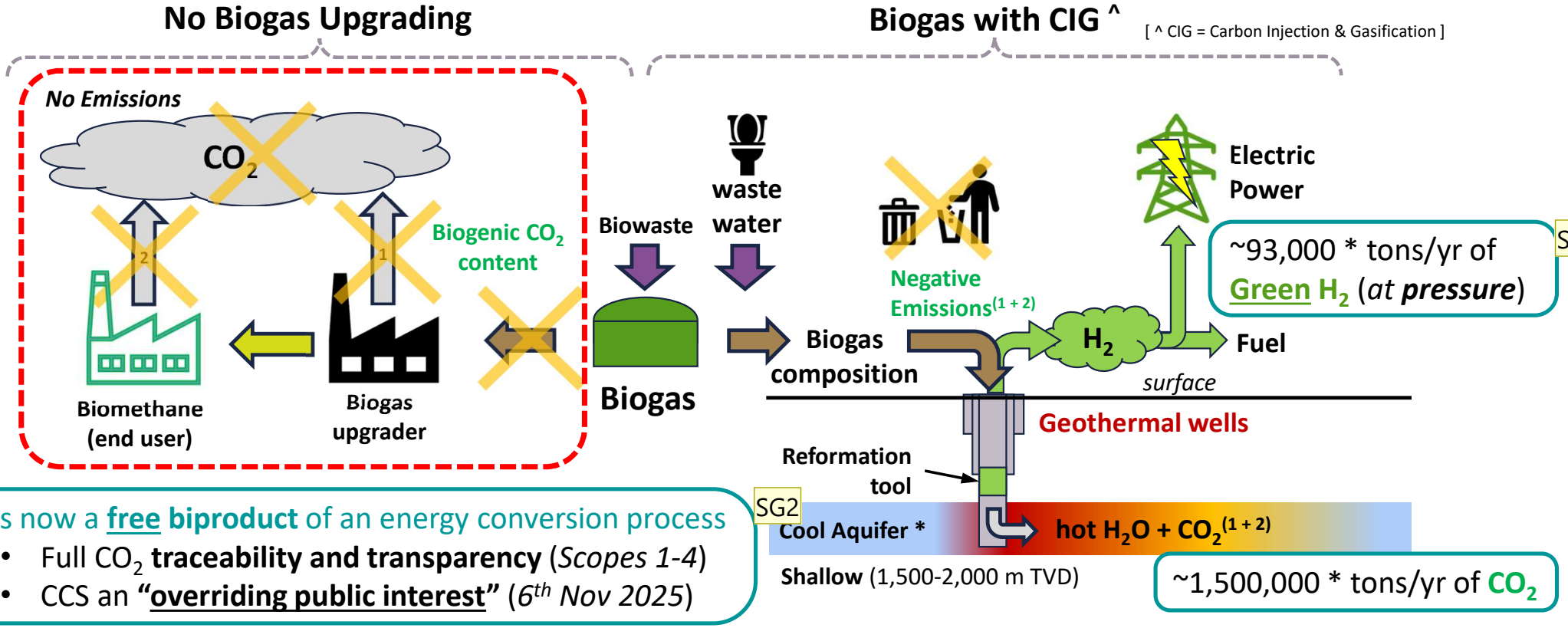
Geothermal

✓ Biogas provides – higher temperature power fluids, power output at lower well costs & heat for storage in reservoir

- **100 % Global geographic scalability** now possible
- **Creates production & commercial growth** in both sectors

A more immediate, direct & effective route to Net Zero

Biogas to Hydrogen (BtH): No Upgrading



CCS is now a **free biproduct** of an energy conversion process

- Full CO_2 **traceability and transparency** (*Scopes 1-4*)
- CCS an **"overriding public interest"** (*6th Nov 2025*)

May 21st, 2025, the EU Commission adopted the **Net-Zero Industry Act (NZIA)** EU-wide target of **50 Mt/yr CO_2 injection capacity by 2030 for permanent geological CO_2 storage** (arts. 36-39) SG3

[Note * : Equivalent based on total Danish biogas production of 32 PJ/yr in 2023 - Danish Energistyrelsen Energy figures for biogas 2023 **]**

Slide 6

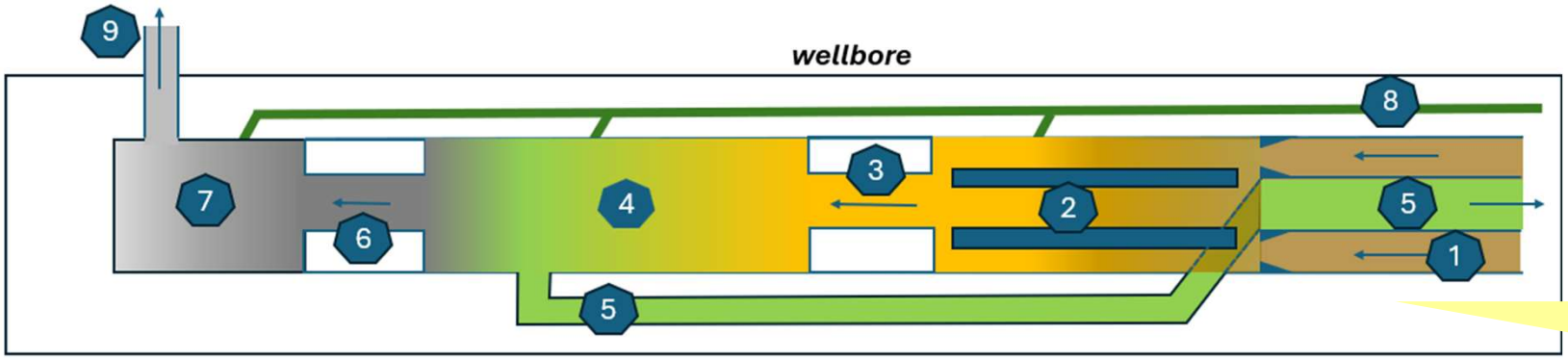
SG1 https://www.europarl.europa.eu/RegData/etudes/BRIE/2023/747085/EPRS_BRI(2023)747085_EN.pdf
Stuart Gillick, 2025-11-17T15:27:56.074

SG2 https://www.reuters.com/sustainability/climate-energy/german-bundestag-passes-law-allow-underground-carbon-storage-202
Stuart Gillick, 2025-11-17T15:28:27.348

SG3 https://eur-lex.europa.eu/eli/reg/2024/1735/oj/eng
Stuart Gillick, 2025-11-17T15:32:06.035

CH_4 Reformation and H_2 Separation

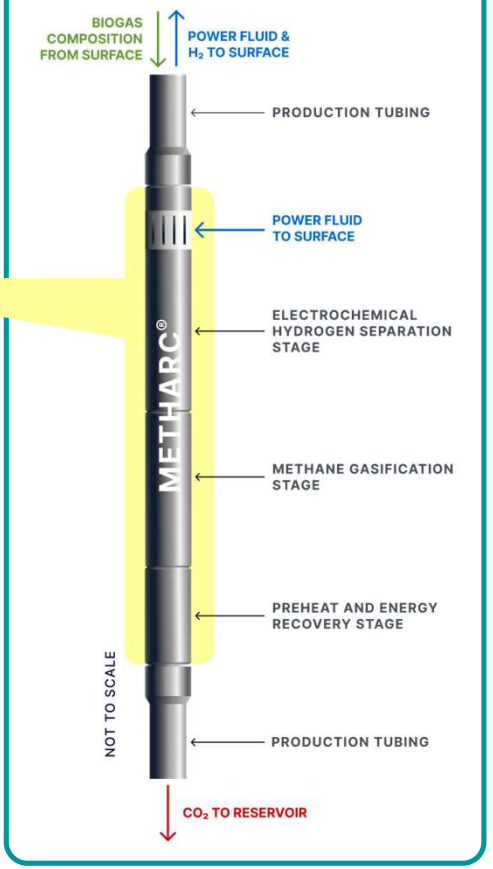
high temperature > 150 °C



1. Biogas stream + air + water from surface
2. Reformation section
3. High pressure/temperature H_2 + CO_2 + Impurities (reformer product stream)
4. Ceramic-metallic electrochemical H_2 separation (EHS) membrane
5. H_2 under high pressure/temperature (towards surface)
6. CO_2, water + Impurities at high pressure/temperature (EHS waste/exhaust stream)
7. Energy recovery module (turbo-booster or turbine – electricity generation)
8. Electrical cable to/from surface (to each module)
9. CO_2, water and impurities into the subsurface reservoir

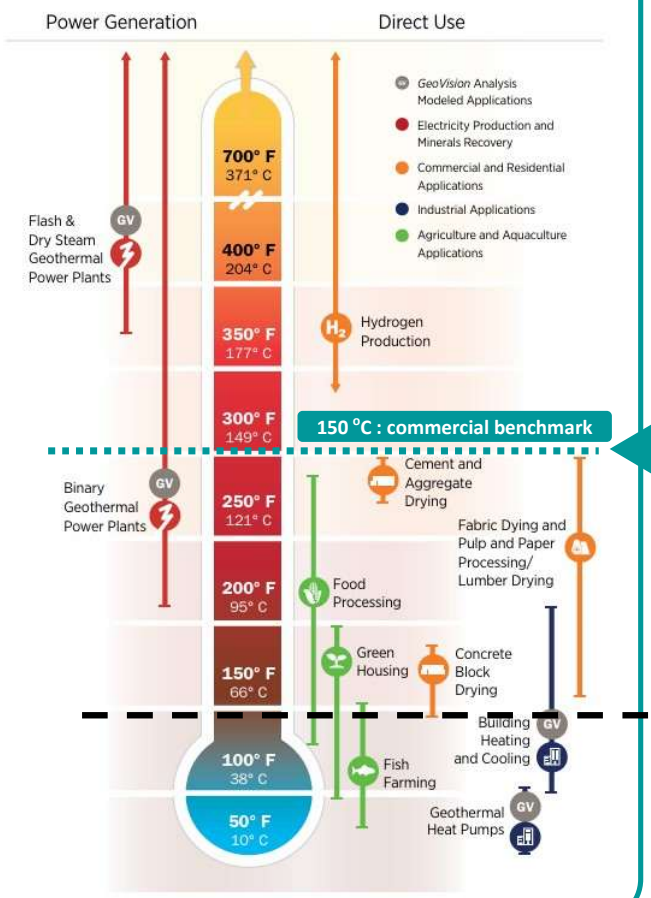
CH_4 Reformation: a high temperature process > 600 °C

BIOGAS TOOL INSTALLED IN A GEOTHERMAL WELL



Economic Benchmarks: Geothermal

Ref. p22: US DoE GeoVision Report SG1



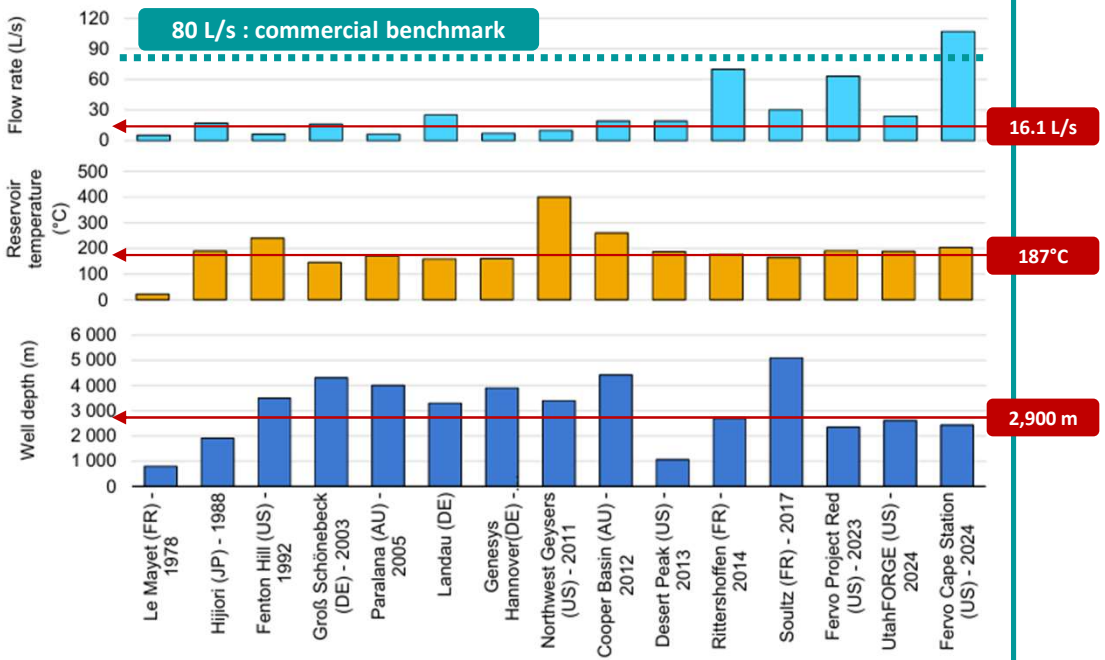
(** *Reservoirs* are artificially created in deep basement rock - a finite, fractured volume of low L/s)

Reservoirs ** at T > 150°C at economic depths are not abundant across the planet.

Shallow (< 2,000 m), natural, sedimentary reservoirs at T ~ 60° C are!

Ref. p38: IEA The Future of Geothermal (Dec 2024) * SG2

Vertical well depths, reservoir temperatures and maximum sustained flow rates of selected enhanced geothermal projects



*** Well costs are typically ~50% of Geothermal project costs**

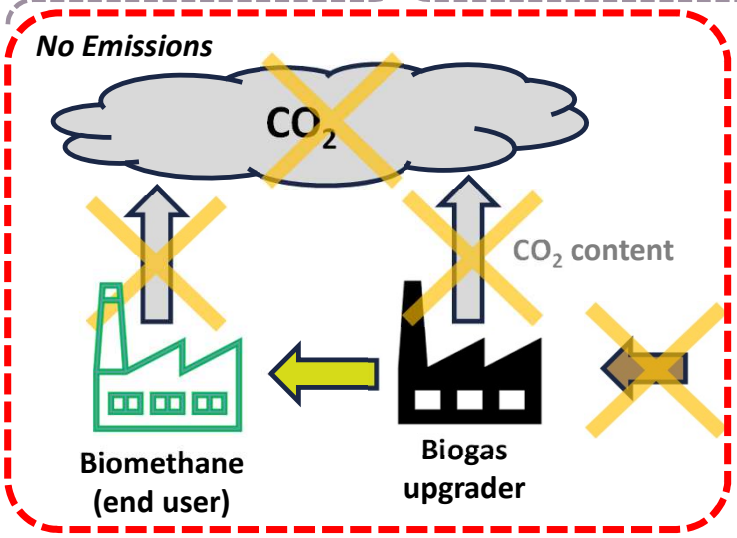
Slide 8

SG1 https://www.energy.gov/sites/prod/files/2019/06/f63/GeoVision-full-report-opt.pdf
Stuart Gillick, 2025-11-17T15:30:30.590

SG2 https://www.iea.org/reports/the-future-of-geothermal-energy
Stuart Gillick, 2025-11-17T15:30:47.819

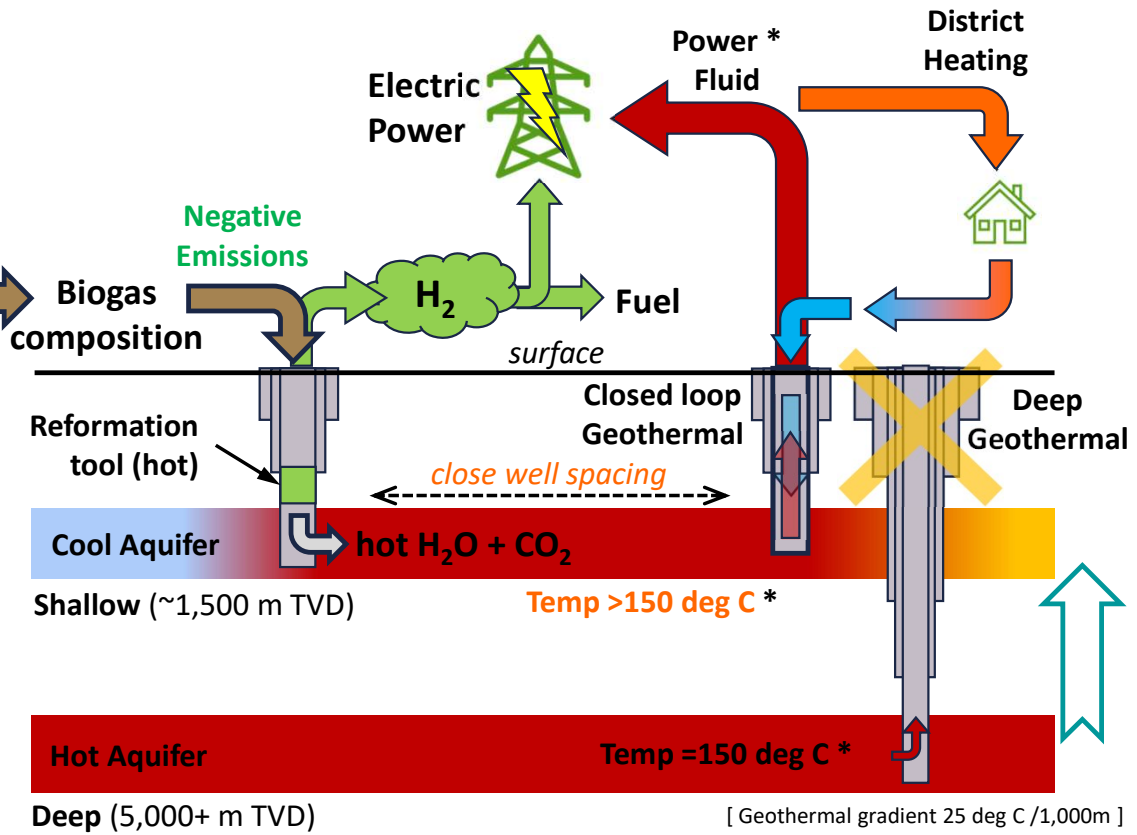
Geothermal-Biogas Coupling: Heat Recovery

No Biogas Upgrading



Biogas with CIGG $

[$ CIGG = Carbon Injection & Gasification Geothermal]

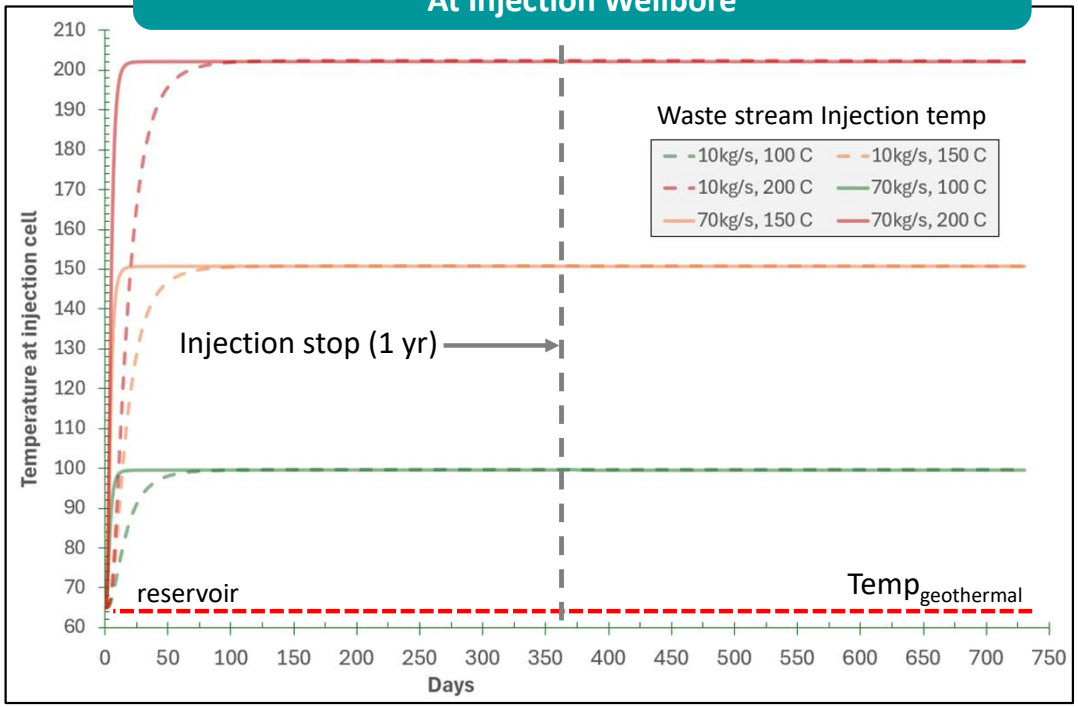


Geothermal (GT) Heat Recovery from reservoir

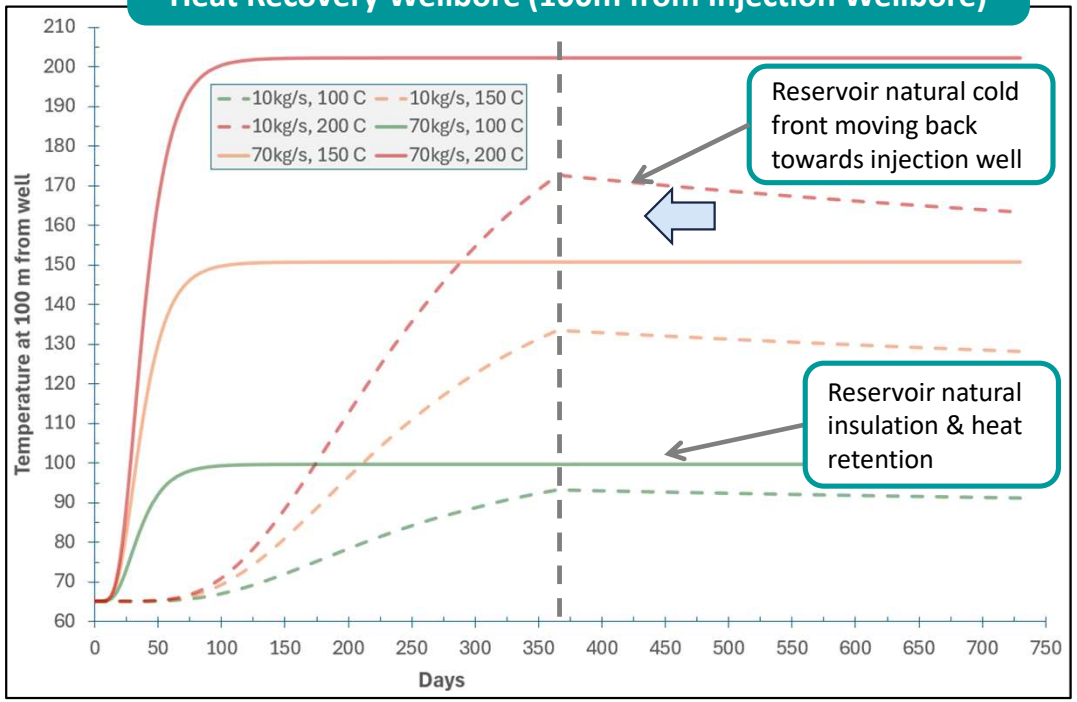
- ✓ Creates **fluid temp** equivalent to **deeper reservoirs**
- ✓ **Shallower**, high-quality reservoir are used **(No. wells?)**
- ✓ **Less fluid temp loss** in production to surface
- ✓ **NO Thermal Depletion**, in the cooler reservoirs
- ✓ **CCS** – as no GT fluid exchange with reservoir (CO_2)
- ✓ **District Heating** fluid now also a **free** biproduct GT power, …. a large reduction in "***strategic cost***"

Geothermal Reservoir: Injected Heat Retention

At Injection Wellbore



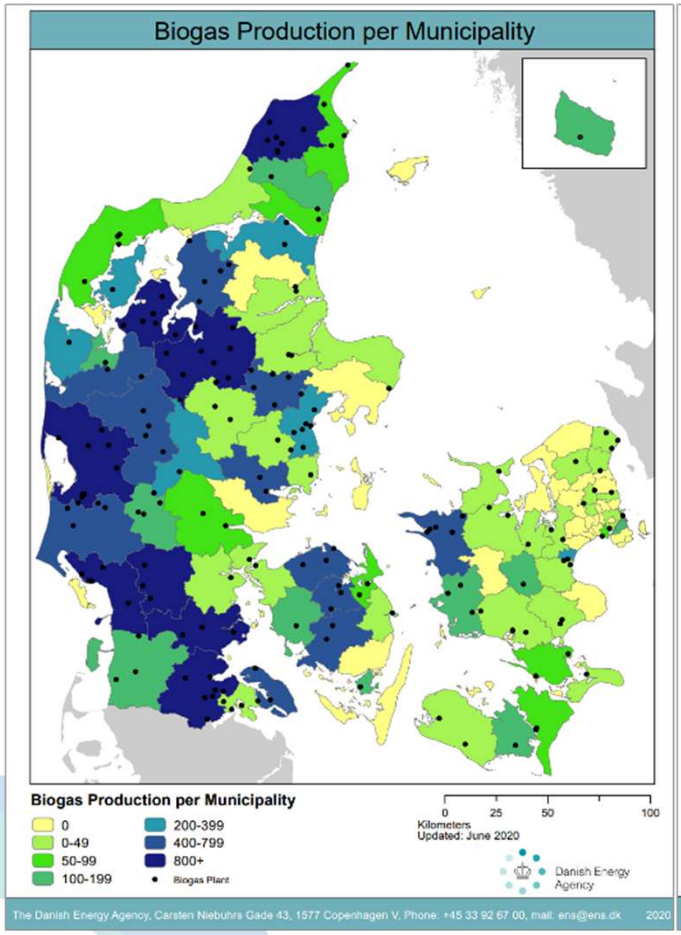
Heat Recovery Wellbore (100m from Injection Wellbore)

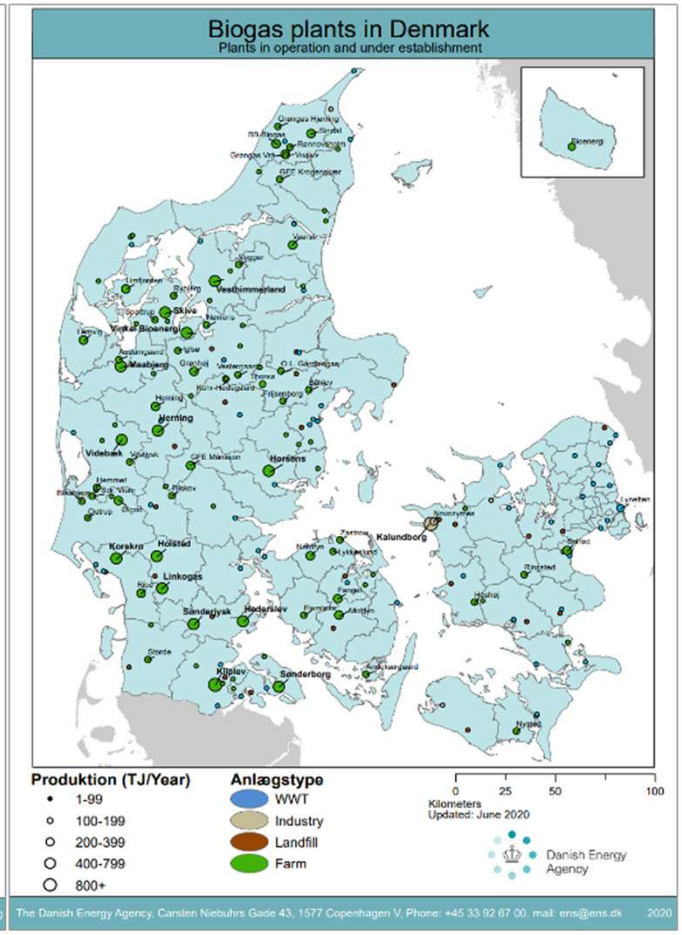


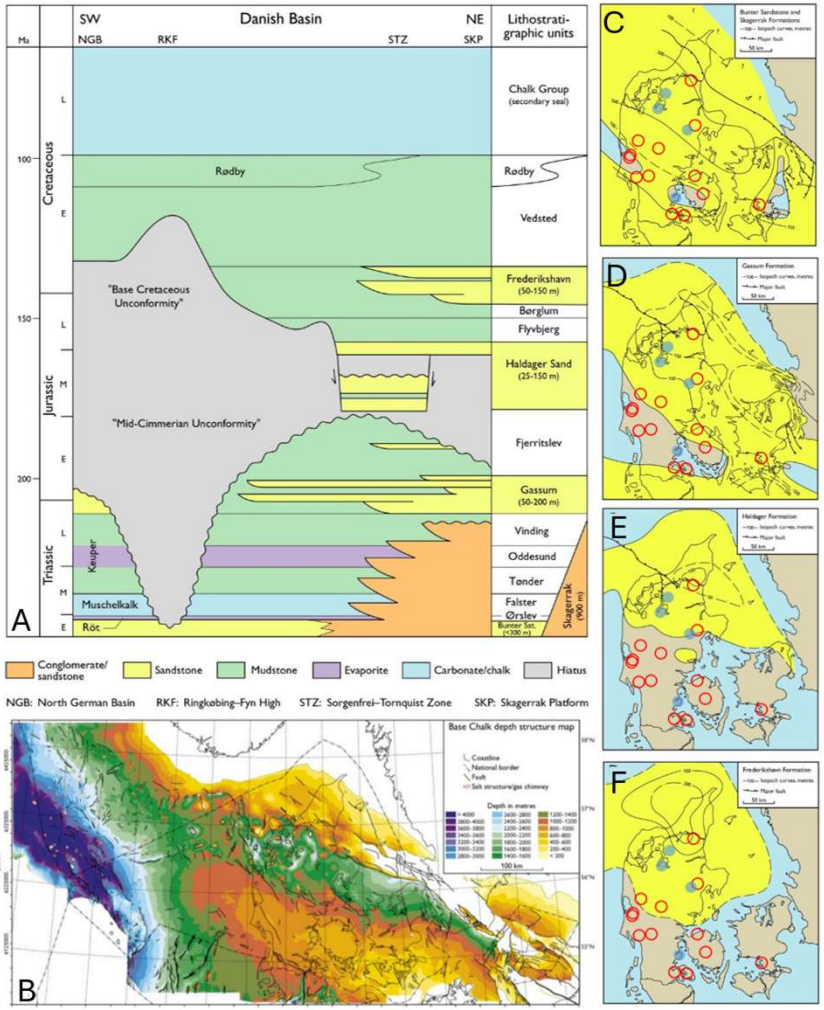
The simulations were performed using SLB ECLIPSE E300 (a compositional thermal simulator). The domain is homogeneous and cylindrical. The simulation accounts for radial flow and heat transport in a single-phase water or two-phase (steam and water) condition. It considers one well and assumes a semi steady-state flow field is set up very rapidly. The purpose is to test heat conduction, convection and insulation-retention in a single-phase compressed water reservoir. No production occurs after injection stops.

Key assumptions: Reservoir depth = 2000 m TVD, reservoir thickness, h = 10 m, radius = 400 m, boundaries: open in radial direction to analytical aquifers with similar permeability and temperature, geothermal temp gradient = 25 ^{o}C/1000m, surface temp = 15 ^{o}C, Horizontal permeability K = 1000 mD, Vertical permeability = 100 mD, Porosity = 20 %, Injection flow rates, Q = 10 & 70 kg/sec (L/s), grid discretization: 40 in radial direction, 1 in angular direction and 10 in z-direction. Rock conductivity 10 W/m.K (Ref.: p23 THERMAL PROPERTIES OF ROCKS).

Reservoirs & Biogas Production (Denmark)







(Ref.: DEA, Bertelsen 1980, Michelsen & Clausen 2002; Michelsen et al. 2003, www.geus.dk/om-geus/nyheder/nyhedsarkiv/2007/nov/kort-over-kalken-i-danmark-nu-tilgaengelig-paa-nettet, Modified from Michelsen et al. (1981) and Haenel & Staroste (1988))

Key Value Drivers: Geothermal-Biogas

METHARC®

Enhanced Revenue Streams

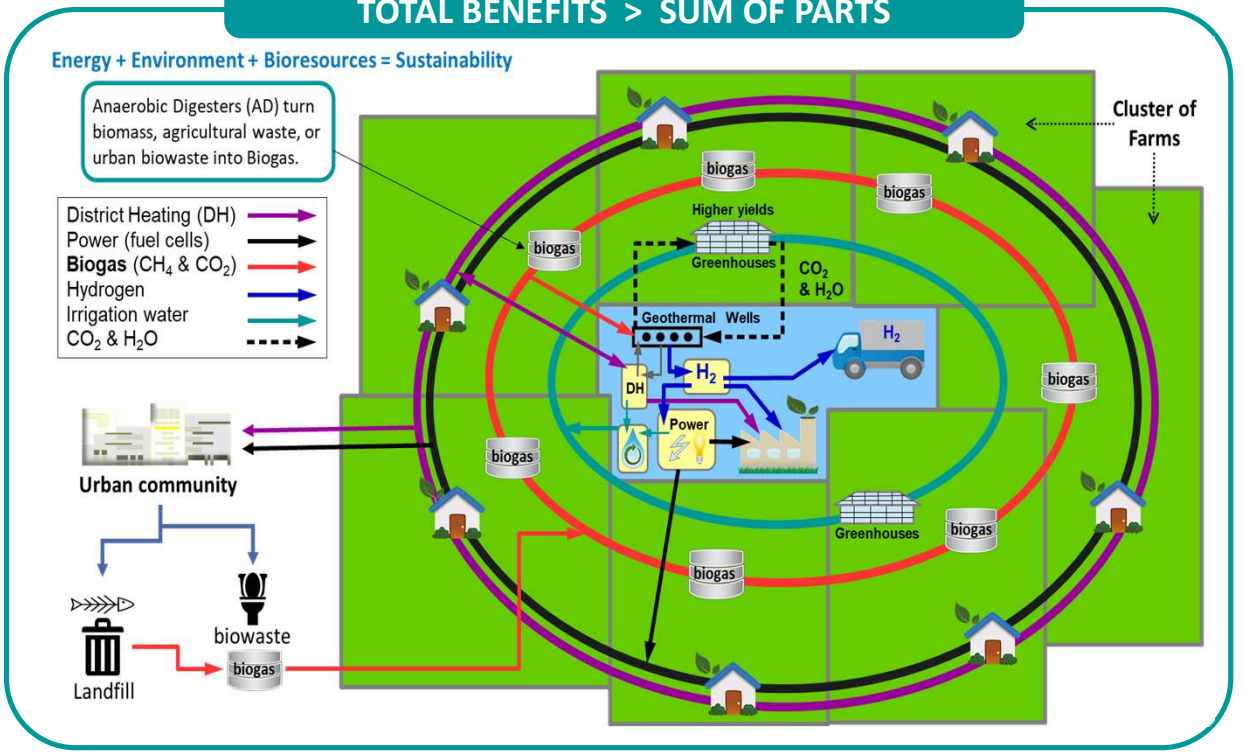
- Sales values: Biogas or **Green Hydrogen**, Electricity, Digestate (eco-fertilizer), Water
- Secondary Biogas market (as H_2): removes biogas production constraints, higher production
- Subsidies: Biogas prod, Green-H_2 , Biogenic CO_2
- Negative Emissions (CCS): Carbon Trading
- Enhanced Power generation + District Heating
- Geothermal incentives: feed-in tariffs

Savings: Processes, Energy & Cost

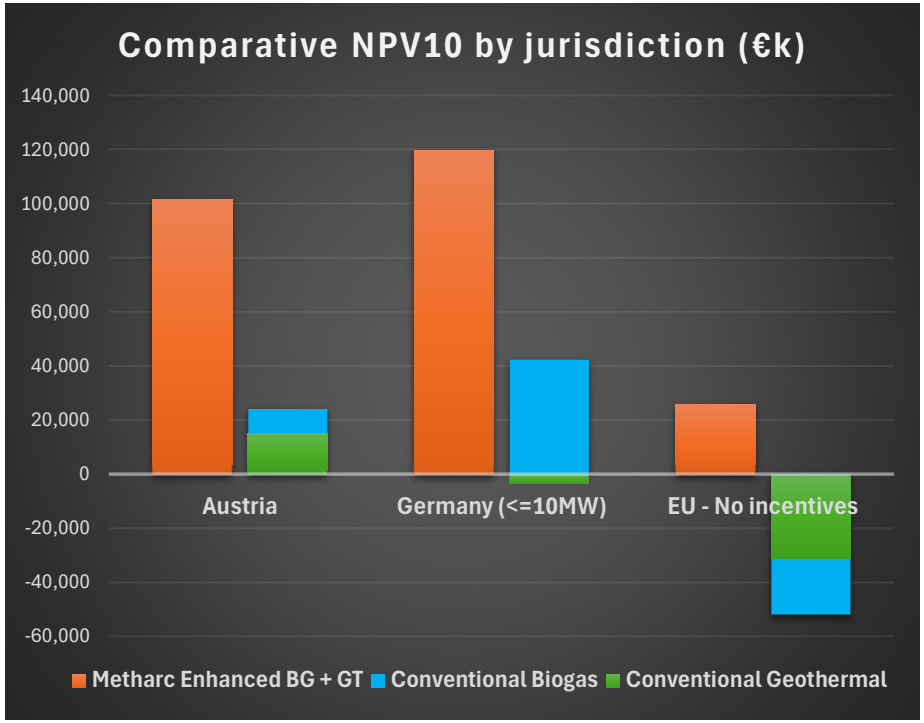
- No Biogas Upgrade to Biomethane
- Geothermal wells: Shallower = cheaper
  => in better quality reservoirs (Perm & Porosity)
  => higher flowrates (more power) > 80 L/s
- Integrated process: Less steps => less energy
- 100% Carbon Capture => as a free bi-product
- Better navigation of CO_2 Taxation
- No GHG transportation or off-site storage

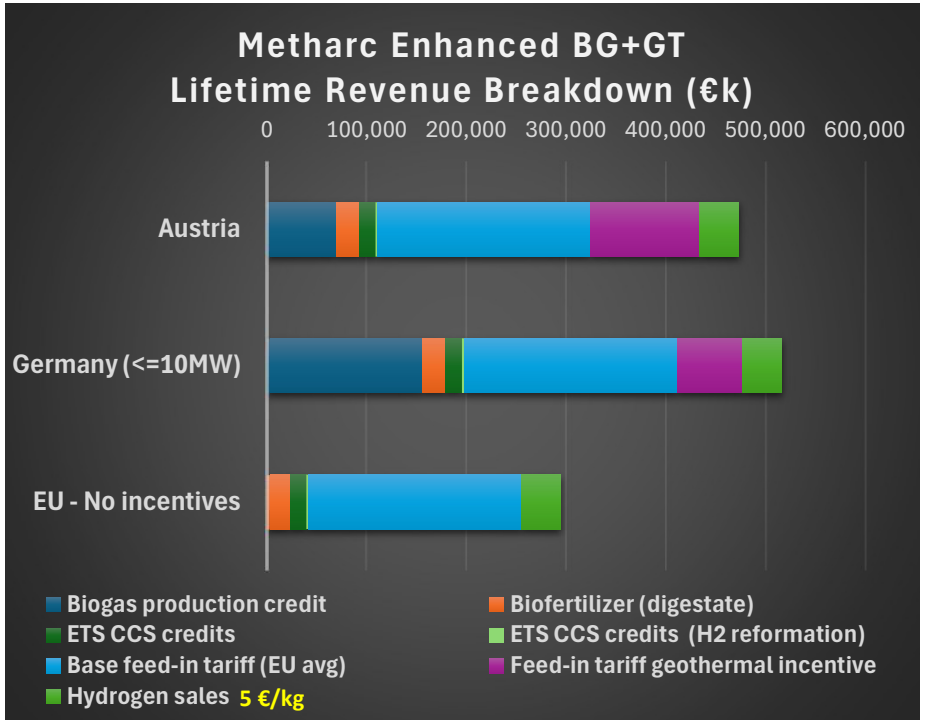
'Behind-the-meter' independence **decentralizes** hydrogen and power production, moving it closer to local Biogas production, where **energy & water requirements are better serviced** with excess power fed into the national grid and hydrogen into the gas network

TOTAL BENEFITS > SUM OF PARTS



Coupling Lowers Barriers to Commerciality





The charts compare NPV and Revenue breakdown, for country specific sector incentives, when retrofitting the Metharc tool in a coupled biogas-geothermal (BG+GT) project versus standalone biogas and geothermal projects

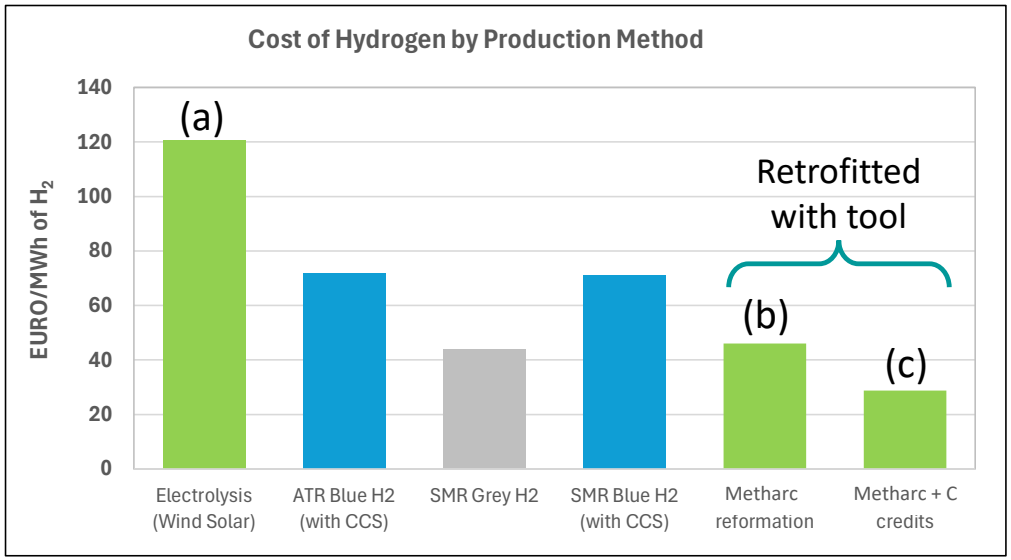
Key value drivers include the benefits of shallower and fewer higher flow geothermal wells, integrated CCS and removal of the Capex and Opex of biogas upgrading

Key assumptions:

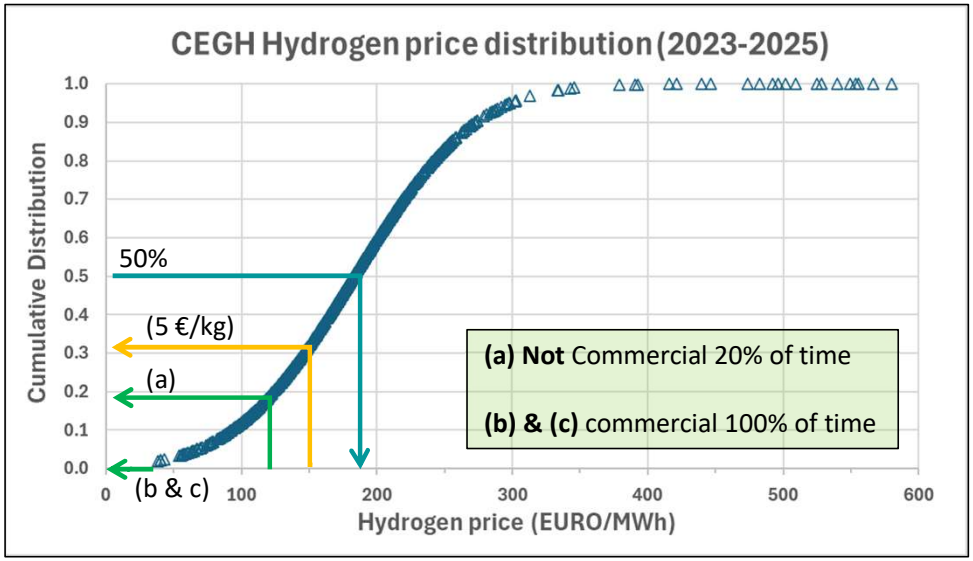
- Biogas plant capacity: 1,000,000 SCF/d (at 40% CO_2 content)
- Geothermal plant gross power output = 10 MW

Geothermal-Biogas: Hydrogen Sales

Sector coupling creates a true Circular Economy, where all biogenic-CO_2 is captured (negative emissions) and fossil-free agriculture is achieved, adding increased value to waste and reducing reliance on imported energy



Cost of hydrogen by production method The 'Metharc with carbon credits' (c) hydrogen cost includes a 61 EURO/ton CO2 carbon credit, which lowers the hydrogen price by a corresponding 0.68 EURO/kg H2, based on a CO2/H2 weight ratio of 11.2 for the final production stream
Based on; www.icf.com/insights/energy/comparing-costs-of-industrial-hydrogen-technologies, www.burnertec.com/hydrogen-plant-cost-analysis/, A geothermal energy techno-economic analysis for downhole wellbore hydrogen production from biogas with subsurface carbon retention - Gillick 2025 https://pubs.rsc.org/en/content/articlelanding/2025/se/d5se00186b



Ref.: Green Hydrogen market price distribution from Jan 2023 to Jul 2025, based on the CEGH (Central European Gas Hub) GreenHydrogen Index. Cumulative probability curve of actual prices showing a mean price of 182 EURO/MWh, a 10% chance of prices exceeding 270 EURO/MWh and a 10% chance of prices being lower than 95 EURO/MWh

[Note: 30 kg of hydrogen contains 1.0 MWh of energy **]**

Summary: Accelerate Energy Security

The global energy transition is being held back by a dichotomy;
a challenging geo-political environment around carbon fuels on one hand,
and the difficult financial metrics around renewables on the other

Change how we use biogas energy assets, infrastructure and workforce (human capital) - adapt existing energy generation to incentivize **biogenic green hydrogen** production

Convert methane in the wellbore to **increase green H_2** volumes, with wells **capturing carbon at point-of-use**. Create a decentralized, secondary biogas market

Promote local, upstream, **sustainable carbon capture**. Reduce the huge cost and subsidies of GHG transportation - minimize downstream CO_2 capture infrastructures

Couple **Biogas, Geothermal, Hydrogen, Carbon Management** and **District Heating** to improve the 4Ps (Profit, Power, Planet, People), energy efficiency and energy security. **Reduce energy volatility** - **provide long-term price & supply stability** (20+ yrs)

METHARC®

zero carbon to surface

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https://www.youtube.com/watch?v=CTQxCSCcXTQ

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