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bio-energy based CO_2 for polyols and fuels

WP1 Feedstock integration
Hydrogen supply for BECCU concepts

1 **Mapping of state-of-the-art and near future** water electrolysis developments

2 **By-product hydrogen from industrial sources** Possibilities and limitations for by-product hydrogen utilization in BECCU concepts

3 **Hydrogen assisted biogas upgrading is tested in co-operation with Metener**

State of the art of water electrolyser technologies

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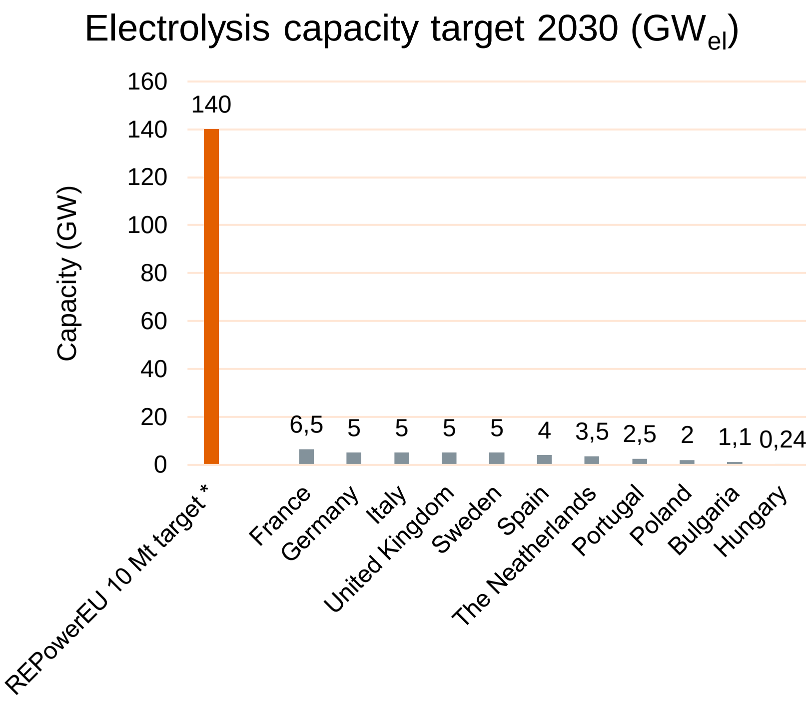
Hydrogen production targets

- **REPowerEU** plan targets annual **10 Mt production** of renewable H_2 in the EU and additional **10 Mt imports** by 2030
- **Scale-up** in the green hydrogen production is needed to reach high targets and to achieve competitive price
- Several countries have released **National hydrogen strategies** and targets for electrolyser capacities by 2030



* Electricity input, utilization factor 43 %, efficiency 70 %, LHV

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1

Scale-up of manufacturing

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Company	Country	Technology	Production capacity
McPhy	France	Alkaline	300 MW/a 1 000 MW/a planned
Nel hydrogen	Norway	Alkaline	500 MW/a potential to 2 000 MW/a
thyssenkrupp nucera	Germany	Alkaline	1 000 MW/a 5000 MW/a planned
Green Hydrogen Systems	Denmark	Alkaline	75 MW/a 400 MW/a by 2023 planned
John Cockerill	Belgium	Alkaline	200 MW/a 1 000 MW/a planned
Teledyne Energy Systems	USA	Alkaline	N/A
Cummins (Hydrogenics)	Canada	Alkaline/PEM	PEM: 500 MW/a potential to 1 000 MW/a
GTT/Elogen (Areva H2Gen)	France	PEM	160 stacks and 40 electrolysers
Siemens Energy	Germany	PEM	250 MW/a 1 000 MW/a planned
MAN Energy (H-TEC Systems)	Germany	PEM	N/A
ITM Power	United Kingdom	PEM	1 000 MW/a (UK) Future: 1 500 MW/a (UK) + 2 500 MW/a (overseas)
NEL (Proton On-Site)	USA	PEM	> 50 MW/a
Plug Power (Giner elx)	USA	PEM	500 MW/a
Sunfire (IHT)	Germany	SOE/Alkaline (IHT)	Alkaline: 500 MW/a by 2023 1 000 MW/a planned
Haldor Topsoe	Denmark	SOE	500 MW/a by 2023 potential to 5 000 MW/a
Enapter	Germany	AEM	1 200 units/a x100 production planned 2022

- Electrolyser production cost reduction through:
  - Manufacturing **volume increase**
  - Increased **automation**
  - **Stack design** and **assembly**
  - **Balance of Plant cost** reductions

1 NEL Production capacity expansion
2 ITM Power Production capacity expansion

Table lists western companies, but Chinese companies have large share of alkaline electrolyser production

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State-of-the-art and future electrolyser KPIs

	Alkaline		PEM		SOEC	
	SOTA	**2050**	**SOTA**	**2050**	**SOTA**	**2050**
System electrical efficiency (kWh/kg H_2)	50 – 56	< 45	50 – 65	< 45	45 – 50	< 40
Stack lifetime (h)	60 000	100 000	50 000 – 90 000	100 000 – 120 000	< 20 000	80 000
Operating temperature (°C)	70 – 90	> 90	50 – 80	80	700 – 850	< 600
CAPEX system (USD/kW_e)	500 – 1000	< 200	600 – 1400	< 200	> 2000	< 300

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By-product hydrogen for BECCU concepts

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By-product H_2 for BECCU concepts

- **Fischer-Tropsch (FT) synthesis and reverse-water-gas-shift reaction based on catalytic partial oxidation** of H_2/CO_2 feed (CPOX/rWGS)
  - **Cl_2/HCl** and other chlor compound impurities need to be removed from the H_2 gas to avoid **catalysts deactivation** preferably < 0.1 ppm level
- **Biogas upgrading**
  - Anaerobic, oxygen free process requires **< 1.5 vol-% O_2** concentration
  - **Low Cl_2 levels** are assumed to be required due to **inhibitory effect of chloride on the methanogenesis process**

Plant	Annual hydrogen production (estimate)	Annual hydrogen surplus (estimate)	Hydrogen production process
Äetsä $NaClO_3$	6 000 t/a	1 500 t/a	Chlorate electrolysis
Joutseno $NaClO_3$ NaOH	8 500 t/a 2 000 t/a	2 200 t/a	Chlorate + chlor-alkali electrolysis

Impurity	Cl_2	O_2	CO_2
Basic purification	< 2 ppm	2 – 3 %	Few 10s of ppm
Extra purification	< 0.2 ppm*	< 20 ppm	< 30 ppm

* Cl_2 < 50 ppb possible

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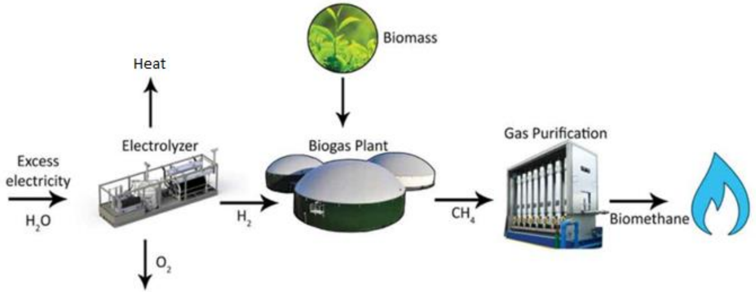
H_2 supply for biogas in-situ upgrading

Hydrogen assisted biogas upgrading

- Biogas upgrading into biomethane via **in-situ conversion** is process where microbial community **methanogens** utilize H_2 and CO_2 to produce CH_4 under anaerobic conditions inside the biogas reactor
- Integration with **existing anaerobic digestion reactors** offers **low investment costs** but several barriers in the upgrading process need to be solved:
  - H_2 supply method for high conversion rate
  - Balancing the H_2 feed amount to not disturb other microbial processes inside the reactor
  - Cost of green hydrogen

Biological methanation

$4\ H_2 + CO_2 \rightarrow CH_4 + 2\ H_2O$, $\Delta G° = -165$ kJ/mol



In-situ biogas upgrading experiments

- **Laboratory scale 60 dm^3 biogas reactor**
  - At optimal conditions, hydrogen injections increased methane yield by **factor of 1.5**
- **Full-scale tests in 720 m^3 biogas reactor**
  - Biomass height in larger reactor offered **longer residence time** and assumably **better conversion rate** than in smaller scale unit
  - Hydrogen **conversion rate of 83 %** was monitored, when the injected H_2 amount corresponded to around 20 – 30 % of product methane's energy content
  - Higher H_2 supply amounts would not convert to methane in sufficient rate leading to over 1 vol-% H_2 concentration in the product gas
  - Additionally, some **heavier hydrocarbons**, namely **propane**, was observed in the product biogas, which is assumably result of the in-situ upgrading as propane has not normally occurred in normal biogas process.

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In-situ biogas upgrading future steps

- Tests showed potential for the in-situ upgrading in larger scale reactor by **increasing the methane yield** in the product gas
- **CO_2 concentration remained relatively high** and therefore **biogas purification is still needed** to achieve required purity for biomethane applications. In addition, the hydrogen supply is likely to be intermittent if no storage capacity is available.
- On-site electrolysers could additionally produce **heat and oxygen** for the **process heating** and **hydrogen sulfide removal**
- Follow-up is needed for **electrolyser system investment costs** in **smaller scale systems** for local hydrogen production or **hydrogen transportation cost** from centralized plants

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