Hydrogen production

EN overview of the alternatives for H2 production and reflections on H2 as fuel in the transport sector

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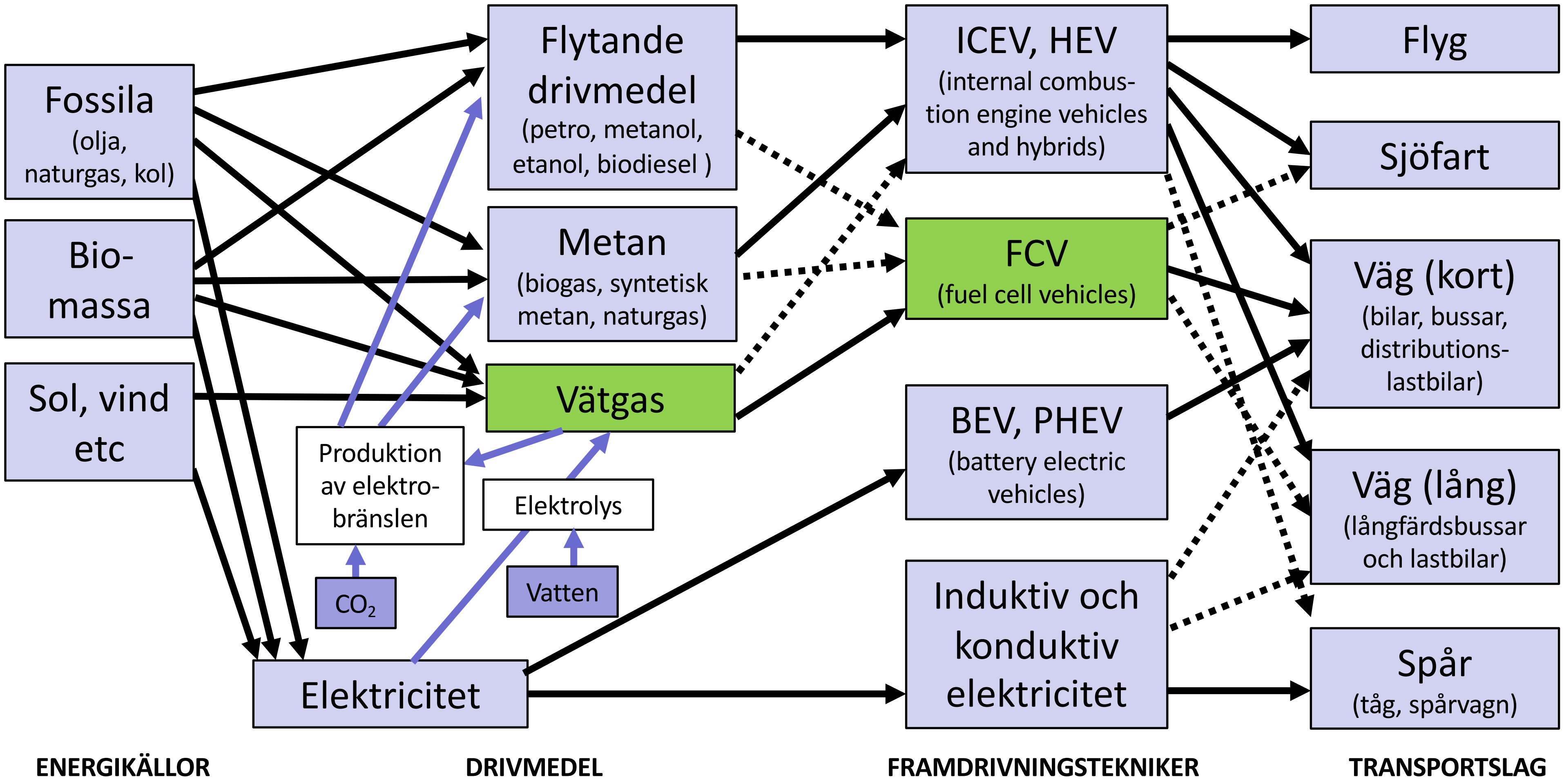
2016-11-29

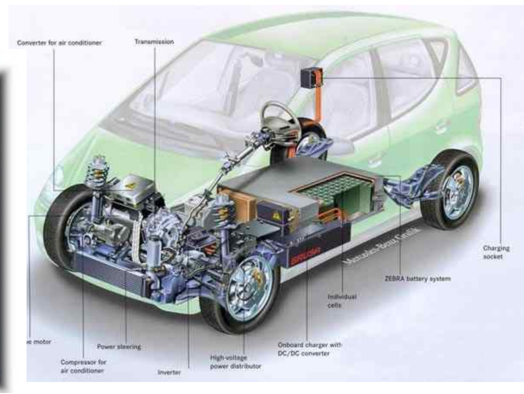
Olika drivmedelsalternativ från olika energikällor lämpar sig olika bra för olika transportslag

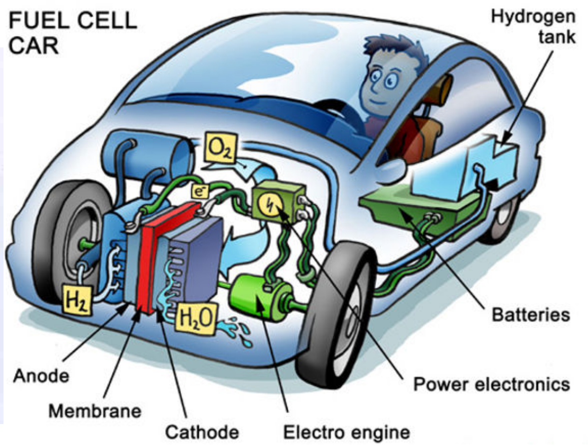


Electricity/Batteries and Hydrogen/Fuel cells

Advantages hydrogen and electricity

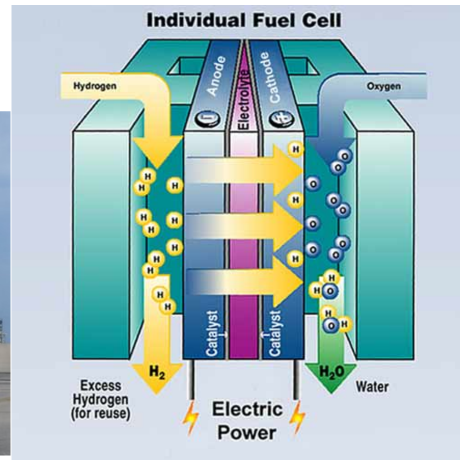
- There are many different options for how to produce electricity and hydrogen with low CO_2-emissions, in future.
- No direct competition with land use issues (food production)
- Fuel cells and batteries have
  - better energy conversion efficiency factors compared to conventional ICEVs.
  - no or low local emissions.
  - lower noise.





Challenges for large scale use of hydrogen and fuel cells as well as electricity and batteries

- Large scale CO_2-neutral H_2 and elec production
  - Currently not large scale production of renewable electricity/hydrogen and/or carbon capture and storage (CCS) from fossil fuels.
- Costly H_2-distribution and storage
- Batteries and fuel cells are still rather expensive
  - Improvements are required when it comes to production cost, life time, and dependency on scarce metals.



Some hydrogen production pathways

- Fossil sources
  - Natural gas reforming.
  - Coal gasification (with or without CCS).
- Biomass (resource is globally limited)
  - Biomass gasification and pyrolysis.
  - Biomass-derived liquid reforming.
  - Microbial biomass conversion (dark fermentation).
- Solar (resource is abundant, but intermittent)
  - Solar thermochemical hydrogen (STCH).
  - Photoelectrochemical (PEC).
  - Photobiological.
  - Electrolysis (AEC, PEM, SOEC).

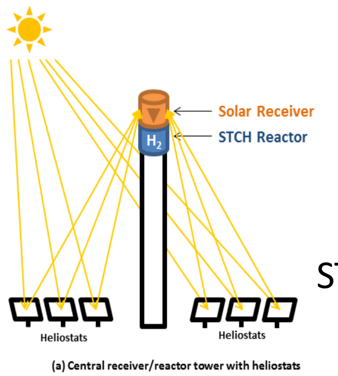
Steam reforming of liquid biofuels+water gas shift into H2.

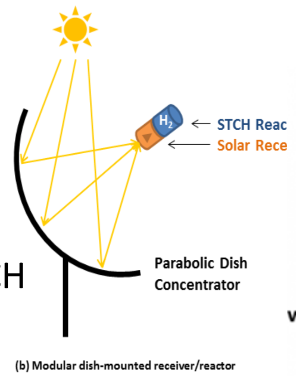
Microorganisms break down organic matter without light.

STCH: Water splitting in high temperatures, e.g. concentrated solar power.

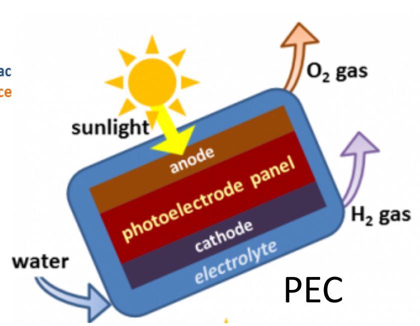
PEC: Semiconductor materials uses sunlight to split water.

Microorganisms (green microalgae or cyanobacteria) use sunlight to split water.

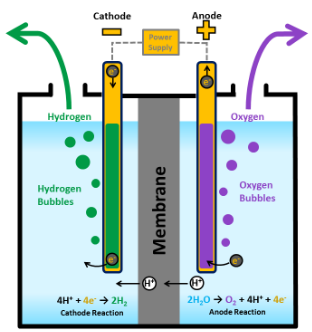




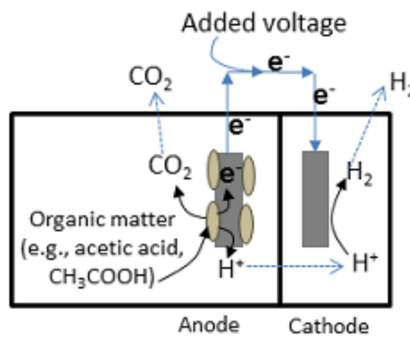
STCH



PEC



Electrolysers

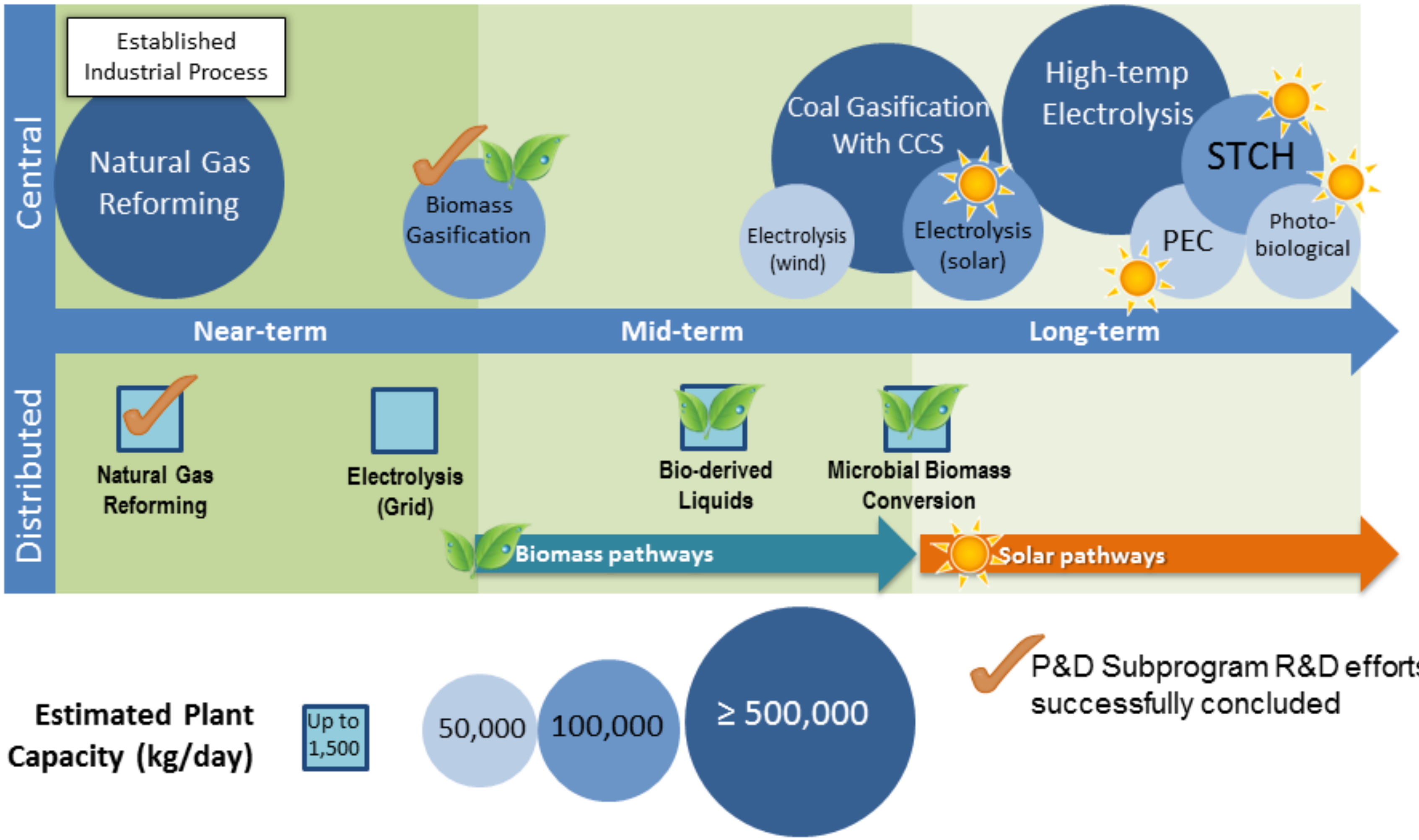


Microbial electrolysis cells (MECs)

http://energy.gov/eere/fuelcells/hydrogen-resources#biomass

Timescale for hydrogen production pathways

According to DOE technologies that can produce hydrogen at a target of less than $4/kg



http://energy.gov/eere/fuelcells/hydrogen-production-pathways

Literature review (analysing peer-reviewed publications 2011-2016):

Comparison of cost and performance for different electrolyser technologies

including median of the data found and range in parenthesis

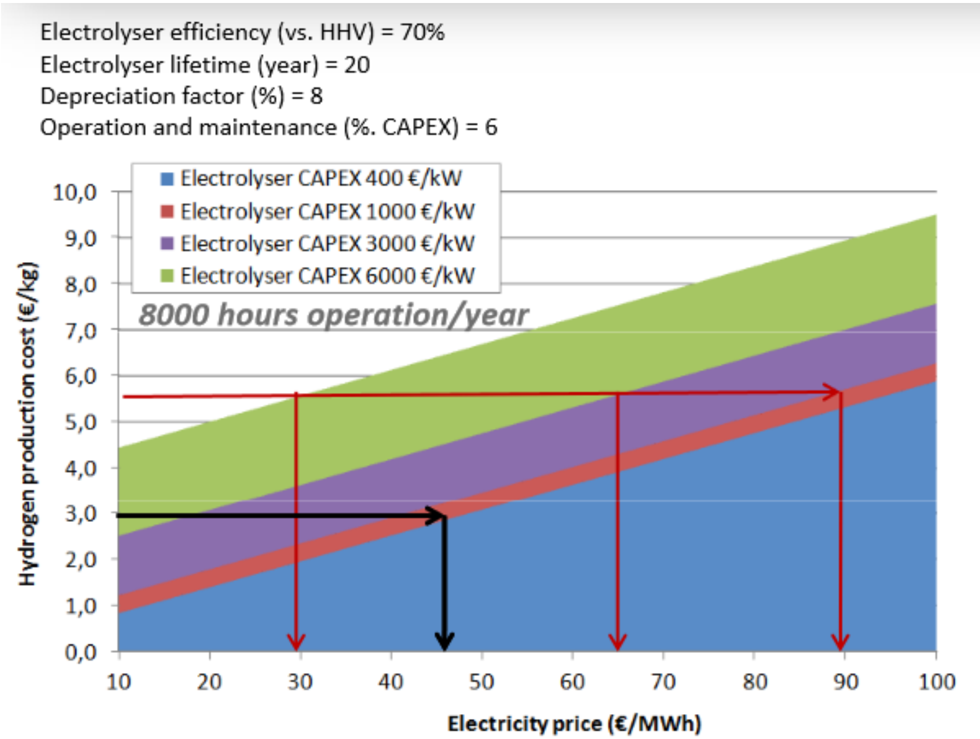
	Alkaline		PEM		SOEC (steam)
	Today	**2030**	**Today**	**2030**	**2030**
Electricity-to-hydrogen$_{LHV}$ efficiency (%)	65 (43-69)	66 (50-74)	62 (40-69)	69 (62-79)	~77
System size (MW)	1.1-5.3	4.9-8.6	0.10-1.2	2.1-90	0.5-50
Stack life span (1000 h)	75 (60-90	95 (90-100)	62 (20-90	78 (60-90)	<90
System life span [years]	25 (20-30)	30	20 (10-30)	30	10-20
Investment cost (€$_{2015}$/kW$_{elec}$)	1100 (600-2600)	700 (400-900)	2400 (1900-3700)	800 (300-1300)	700 (400-1000)
O&M cost	2-5%	2-5%	2-5%	2-5%	2-3%
Stack replacement cost (share of investment cost)	50%	-	60%	-	Included in O&M cost

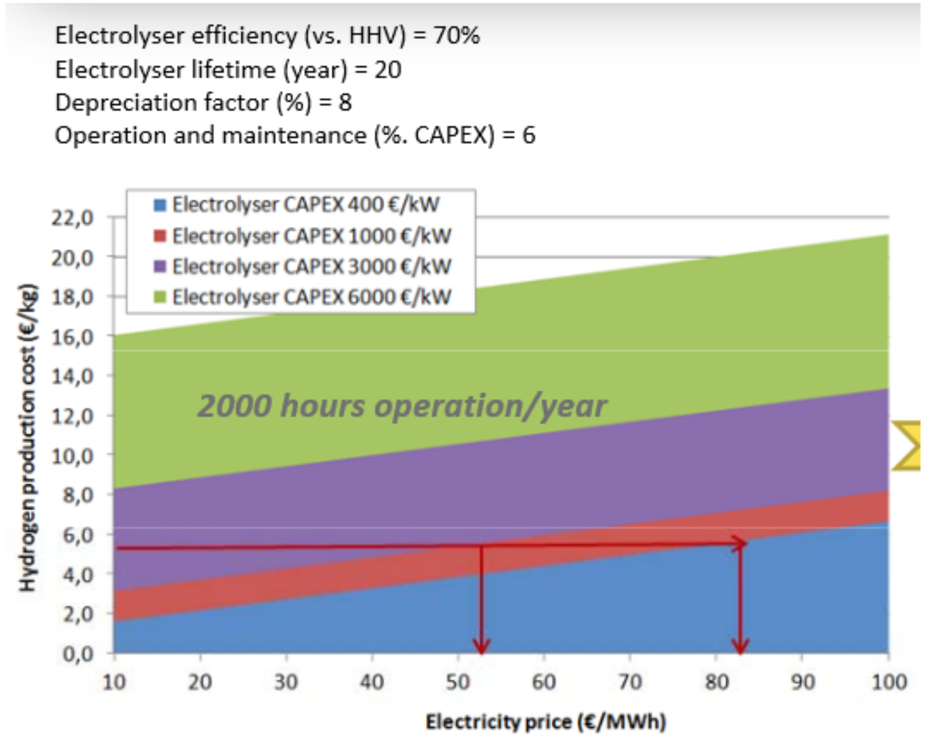
- All types are expected to **improve until 2030**.
- SOEC has the potential to combine low cost with high efficiency (not yet on market).

Brynolf S, Taljegard M, Grahn M, Hansson J. (2016). Electrofuels for the transport sector: a review of production costs. *Submitted to Renewable & Sustainable Energy Reviews*.

Hydrogen production cost

depends on electricity price, investment cost for the electrolyser and hours operation per year (note that scale on y-axis differ)





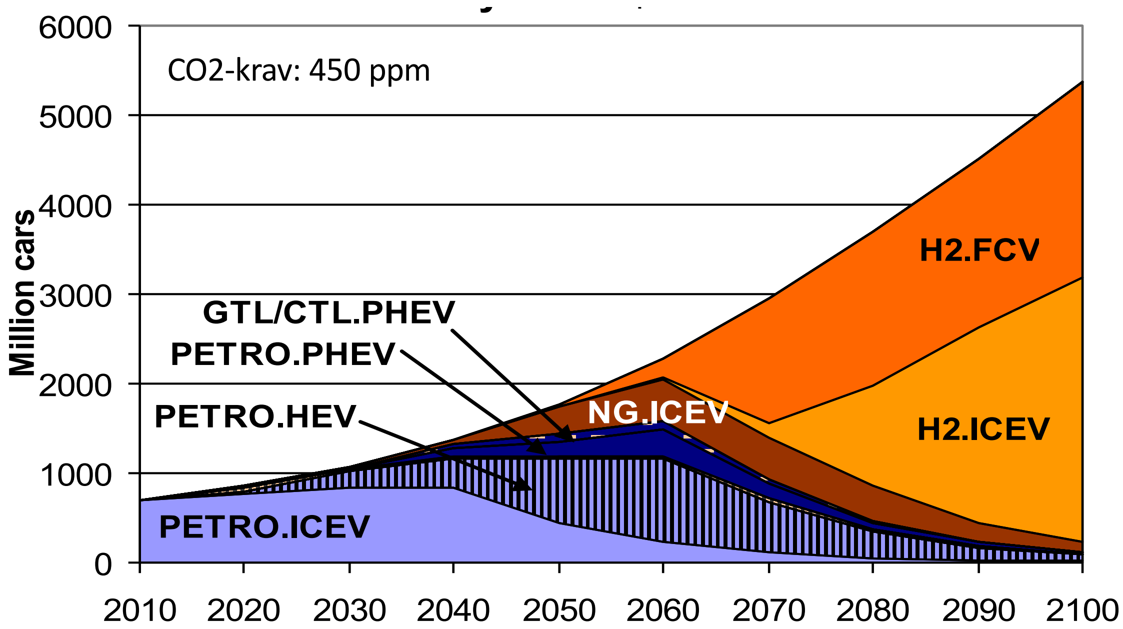
Likely that hydrogen can be produced less than $4/kg

From presentation by
Annabelle Brisse, brisse@eifer.org
Conference, Iceland, June 2013

Results and insights from my research

Resultat från kostnadsminimering. Global energisystemmodell.

Analys av bränsleval för världens bilflotta när ambitiösa klimatmål ska nås till lägsta kostnad.



PETRO = Bensin/Diesel
BTL= Biodrivmedel
CTL= Bränslen baserade på kol
GTL= Bränslen baserade på naturgas
NG = Naturgas
H2 = Vätgas

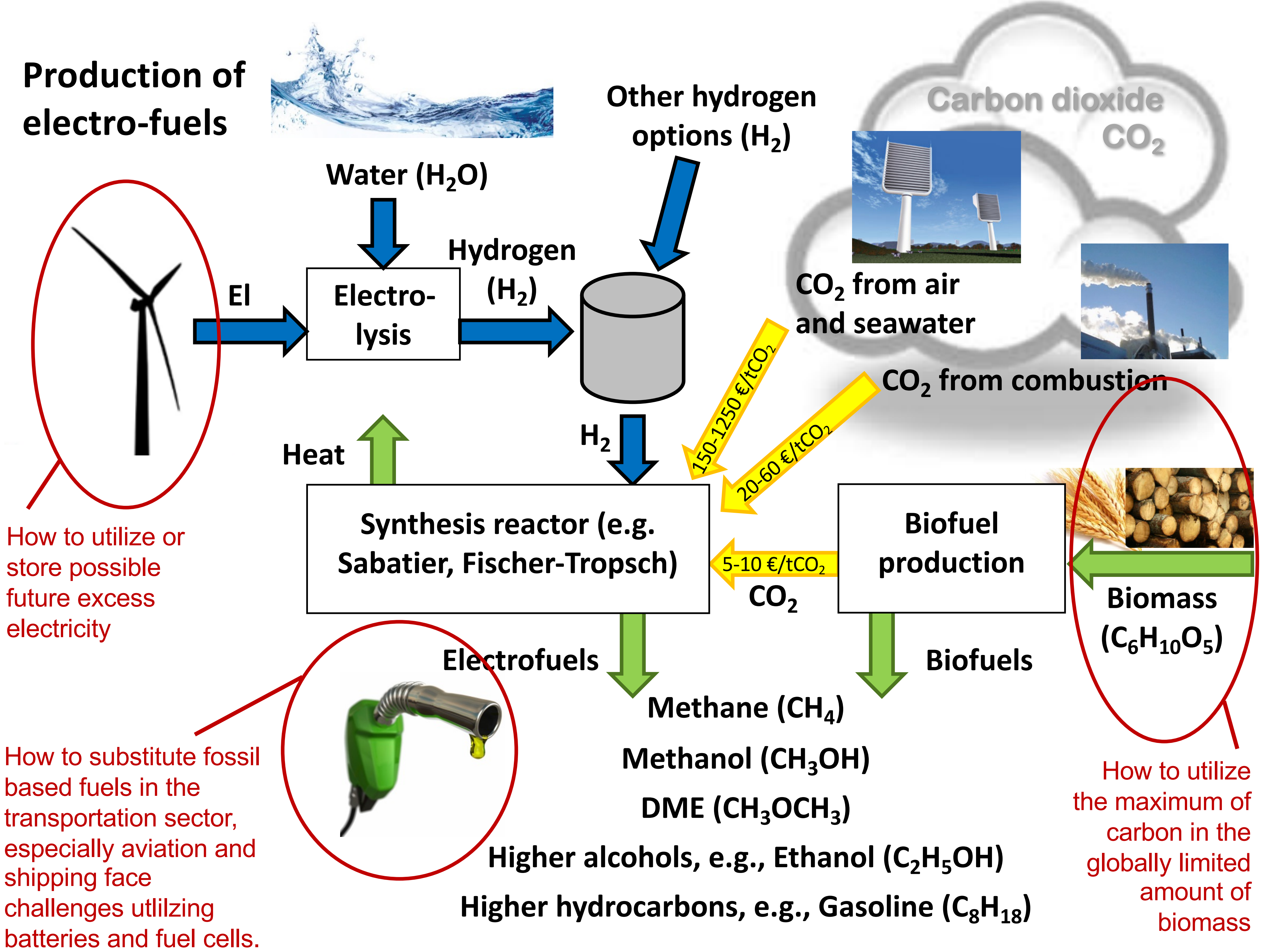
ICEV = Internal Combustion engine
FCV = Fuel cell vehicle
HEV = Hybrid electric vehicles
PHEV = Plug-in electric vehicles

(Elektrobränslen är inte inkluderat i modellen)

Generella resultat:

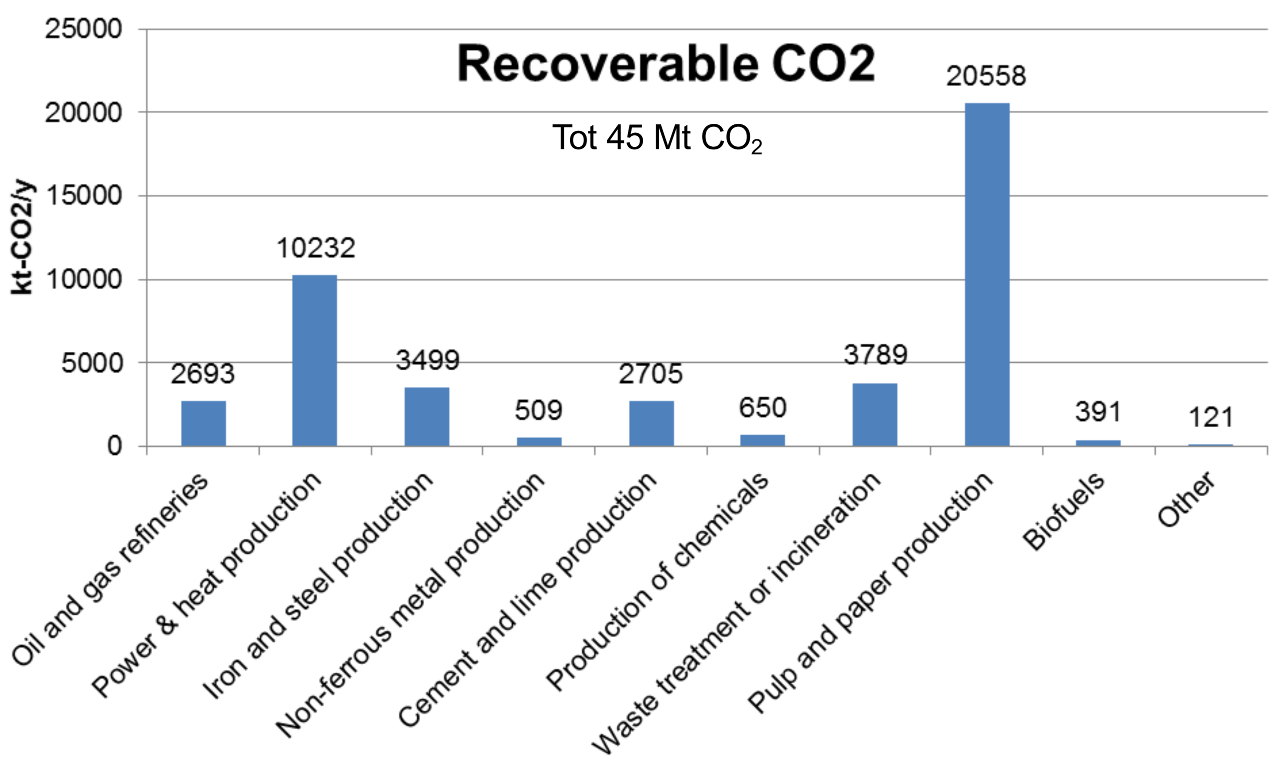
- Det är osannolikt att en enda bränsle- och tekniklösning kommer att ersätta dagens användning av bensin och diesel. Mer sannolikt att vi får se en mix av olika lösningar.
- Hybrider och plug-in-hybrider är lösningar som har potential att spela störst roll i en nära framtid.
- **Vätgas** är den dyraste tekniken men ändå den som kan dominera en framtida lösning när olja, naturgas och bioenergi är mycket knappa resurser.
- Den begränsade mängden biodrivmedel kan minska utsläppen till lägre kostnad om den ersätter fossila bränslen i el, värme och kemikalieproduktion (istället för som transportbränsle).

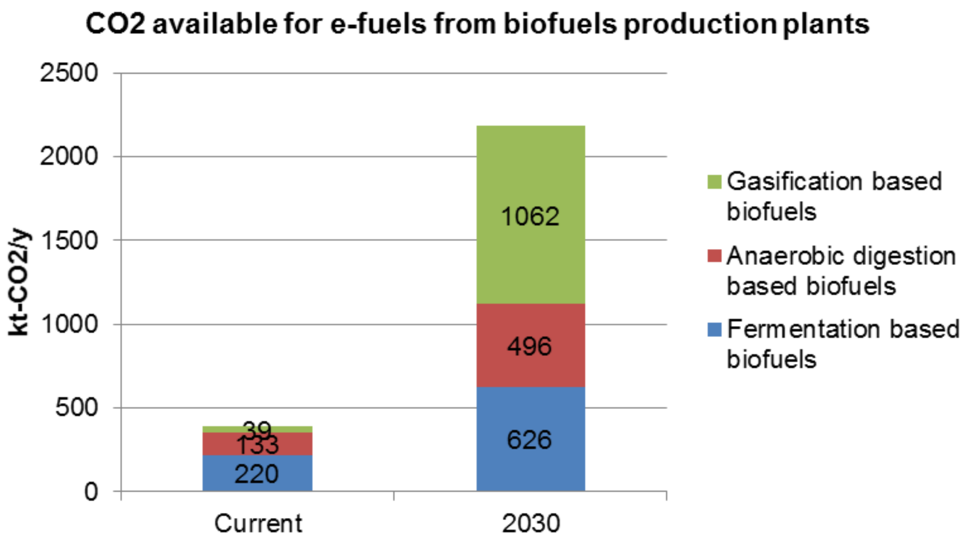
Source: Grahn M, Azar C, Williander MI, Anderson JE, Mueller SA and Wallington TJ (2009). Fuel and vehicle technology choices for passenger vehicles in achieving stringent CO_2 targets: connections between transportation and other energy sectors. *Environmental Science and Technology* 43(9): 3365–3371.



Production of electro-fuels
Water (H_2O)
Other hydrogen options (H_2)
Carbon dioxide CO_2
El
Electro-lysis
Hydrogen (H_2)
CO_2 from air and seawater
CO_2 from combustion
150-1250 €/tCO_2
20-60 €/tCO_2
Heat
H_2
Synthesis reactor (e.g. Sabatier, Fischer-Tropsch)
5-10 €/tCO_2
CO_2
Biofuel production
Biomass ($C_6H_{10}O_5$)
Electrofuels
Biofuels
Methane (CH_4)
Methanol (CH_3OH)
DME (CH_3OCH_3)
Higher alcohols, e.g., Ethanol (C_2H_5OH)
Higher hydrocarbons, e.g., Gasoline (C_8H_{18})
How to utilize or store possible future excess electricity
How to substitute fossil based fuels in the transportation sector, especially aviation and shipping face challenges utlilzing batteries and fuel cells.
How to utilize the maximum of carbon in the globally limited amount of biomass

Results on available CO_2 sources in Sweden





How much fuel can be produced?

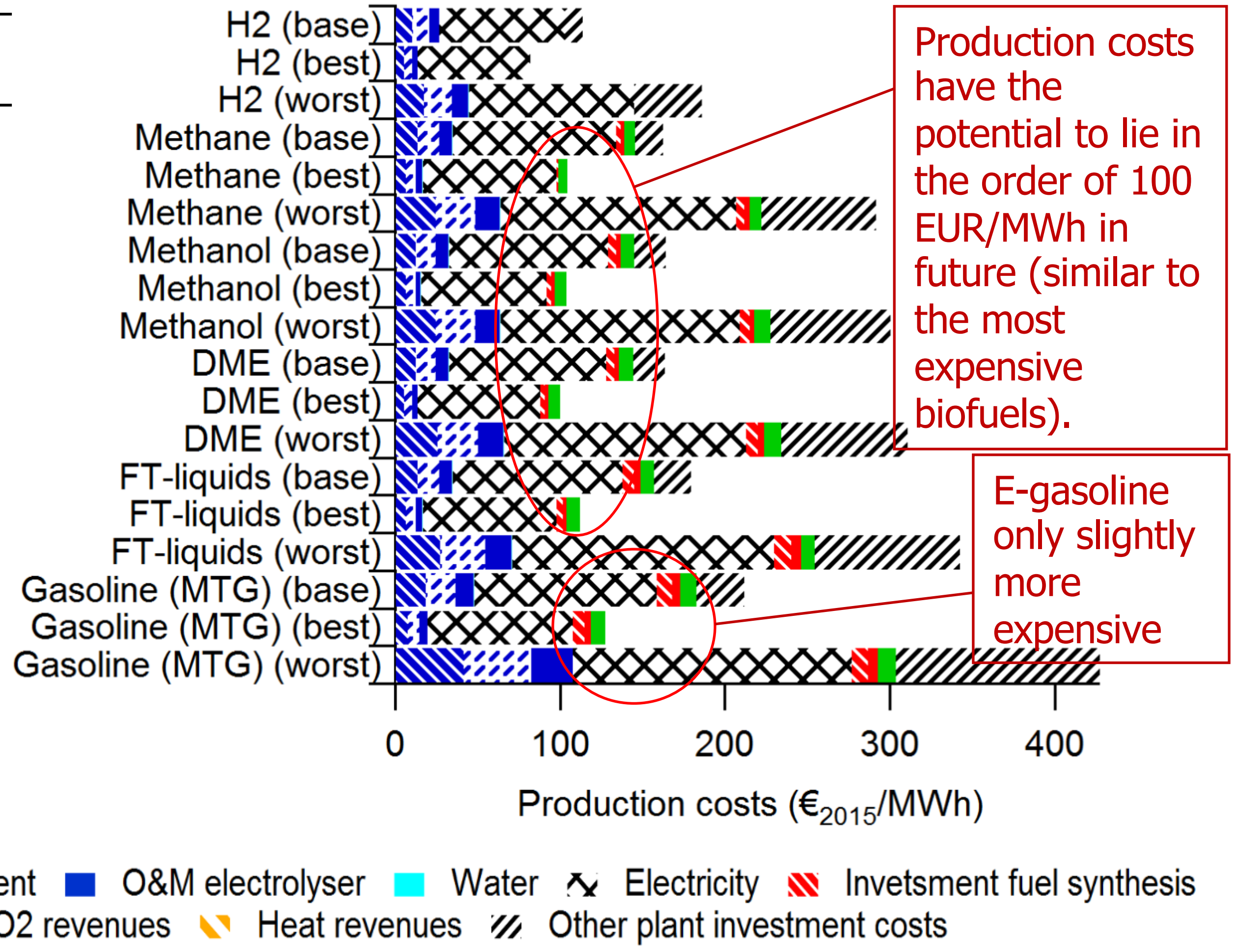
- 45 $MtCO_2$/yr (fossil+renewable)
- 30 $MtCO_2$/yr is recoverable from biogenic sources =>**110 TWh/yr e-methanol**

	Sweden
Assuming replacing all **bunker fuel** (TWh)	22
Electricity demand (TWh)	42
Carbon dioxide (Mton)	6
Current electricity use in Sweden (TWh)	*140*
RE generation goal 2020 (TWh)	*30*

Production cost different efuels, 2030

assuming most optimistic (best), least optimistic (worst) and median values (base)

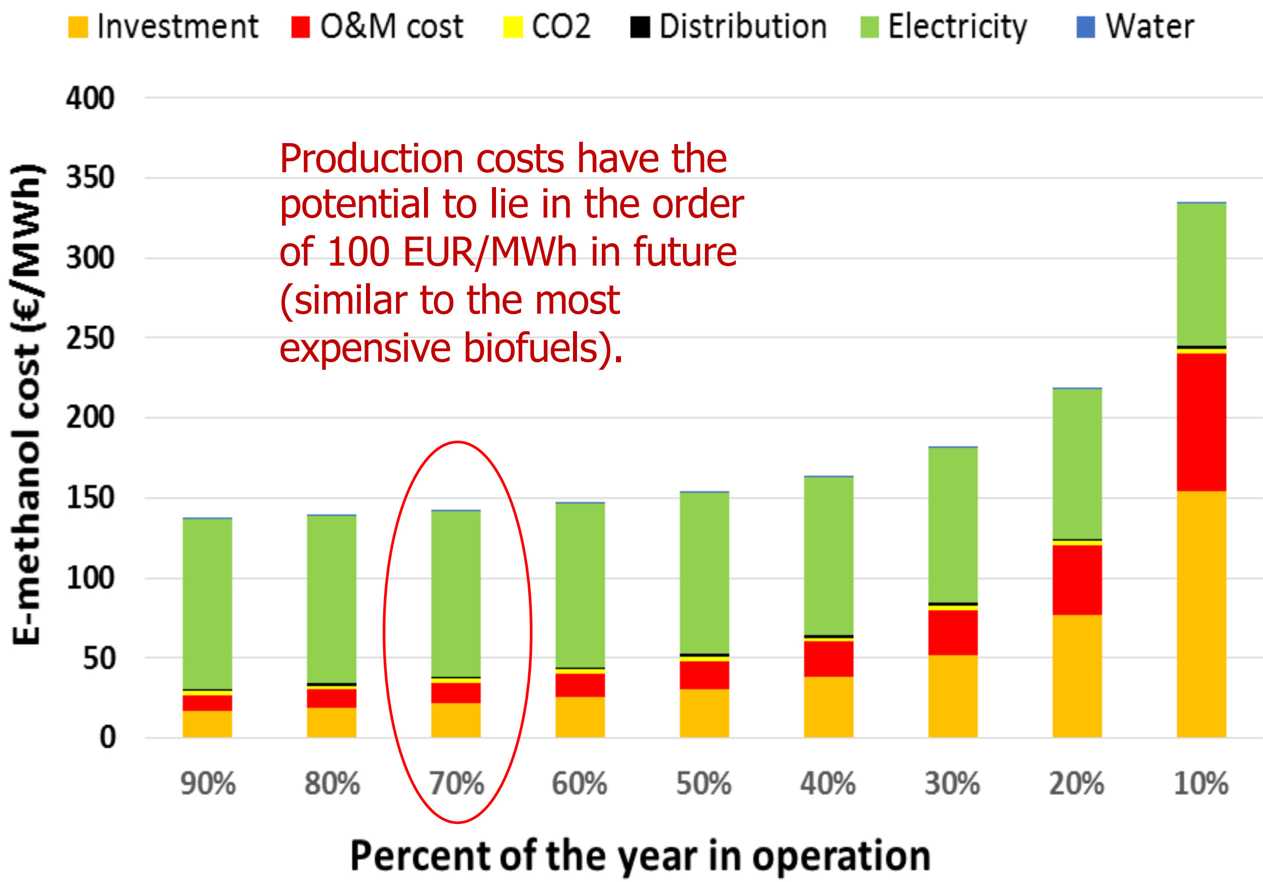
Parameters assumed for 2030, 50 MW reactor, CF 80%.	
Interest rate	5%
Economic lifetime	25 years
Investment costs:	
Alkaline electrolyzers €/kW_{elec}	700 (400-900)
Methane reactor €/kW_{fuel}	300 (50-500)
Methanol reactor €/kW_{fuel}	500 (300-600)
DME reactor €/kW_{fuel}	500 (300-700)
FT liquids reactor €/kW_{fuel}	700(400-1000)
Gasoline (via meoh) €/kW_{fuel}	900(700-1000)
Electrolyzer efficiency	66 (50-74) %
Electricity price	50 €/MWh_{el}
CO_2 capture	30 €/tCO_2
O&M	4%
Water	1 €/m³



Brynolf S, Taljegard M, Grahn M, Hansson J. (2016). Electrofuels for the transport sector: a review of production costs. *Submitted to Renewable & Sustainable Energy Reviews.*

The production cost of e-methanol for different reactor capacity factors

Parameters assumed in the cost calculation (base case)	
Interest rate	5%
Economic lifetime	25 years
Investment cost	1900 €/kW$_{fuel}$
Electricity price (at CF 70%, Swe 2014, incl. tax and net tariff)	56 €/MWh$_{el}$
CO_2 capture	10 €/tCO_2
O&M	4%
Water	0.7 €/m^3
Distribution of methanol	1.6 €/MWh
Heat (120°C)	0.04 €/kWh$_{heat}$

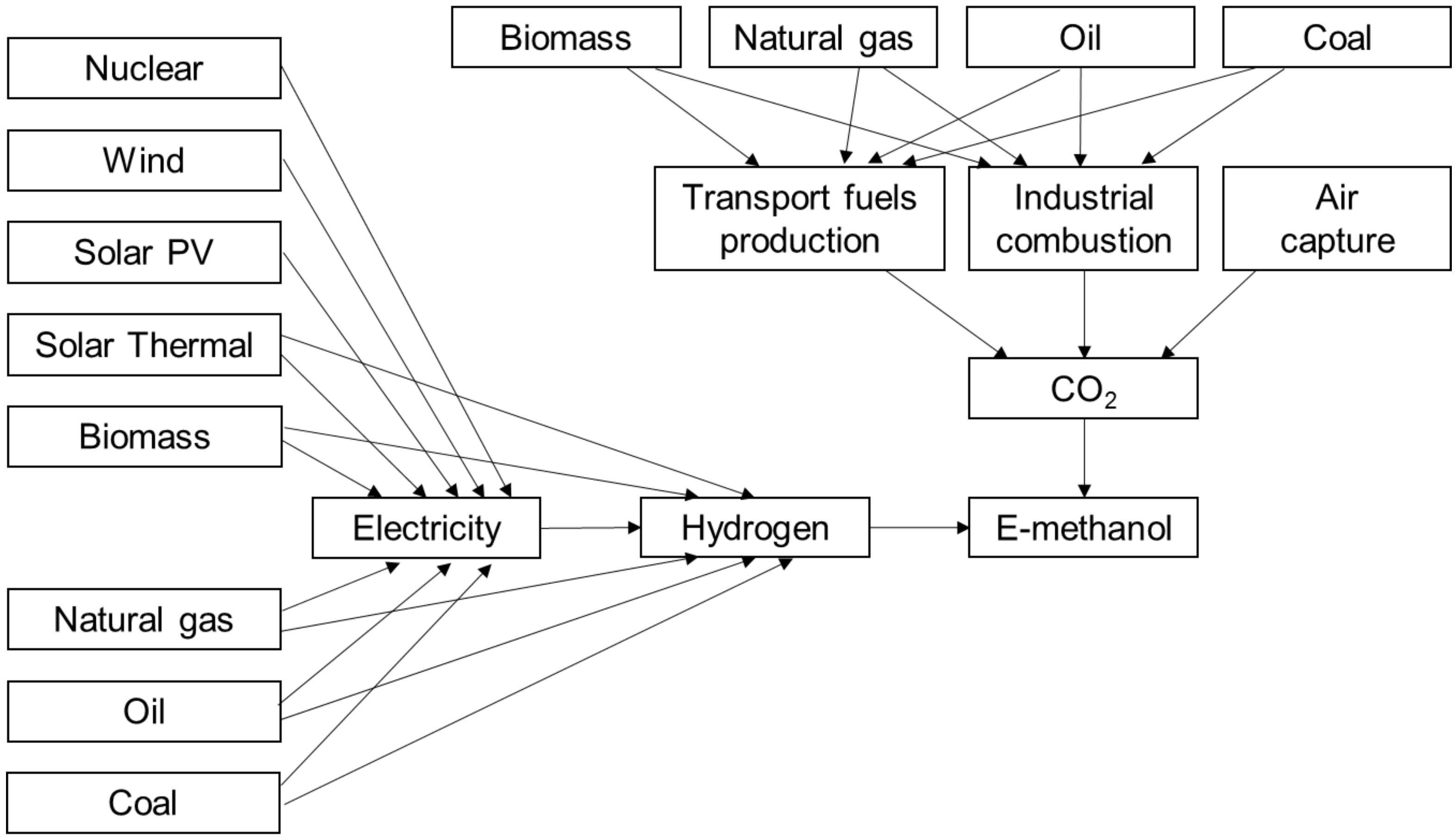


Comparison other alterantive fuel options (from literature review)	€/MWh
Heavy fuel oil	17-43
Marine gas oil	32-68
Gasoline/Diesel	39-140
Rapeseed/soy/palm methyl ester	50-210
BTL (gasification of lignocellulose)	80-655
HVO (palmoil)	134-185
SNG (gasification of lignocellulose)	70-90
Biogas (anaerobic digestion)	40-180
Liquefied natural gas	11-43
Liquefied biogas	40-180
Methanol (from natural gas)	18-54
E-methanol	**80-140**
Hydrogen gas (from electrolysis)	75-90

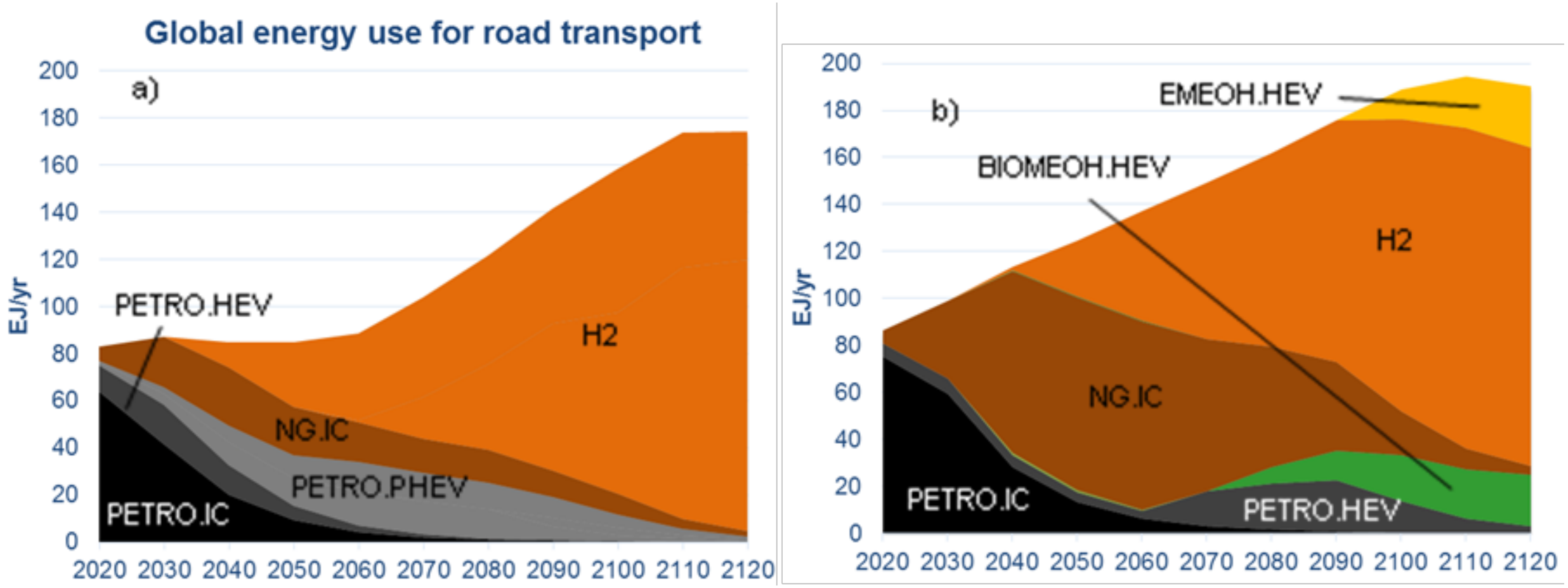
Taljegård M, Brynolf S, Hansson J, Hackl R, Grahn M, Andersson K. (2015). Electrofuels: a possibility for shipping in a low carbon future. *Conference proceedings to Shipping in changing climates*, Glasgow, Nov 2015.

Brynolf S, Taljegard M, Grahn M, Hansson J. (2016). Electrofuels for the transport sector: a review of production costs. *Submitted to Renewable & Sustainable Energy Reviews*.

Possible pathways for the production of electrofuels, in the form of e-methanol, in GET-R 6.4.



Preliminary results



Cost-effective fuel choices for global road transport when CO_2-concentration is stabilized on 400 ppm for the (a) base case scenario and (b) an alternative scenario assuming lower costs and higher conversion efficiency for e-methanol synthesis as well as higher costs for batteries and fuel cells.

Acronyms used are: PETRO= petroleum-based fuels e.g. gasoline and diesel, NG= natural gas, H2= hydrogen, BIOMEOH= biomass-based methanol, EMEOH= electrofuels as e-methanol, FC= fuel cell, IC= internal combustion engine, HEV= hybrid electric vehicle, PHEV= plug-in hybrid electric vehicle (assumed to run 65% of the distances in electric mode).

Ref: Grahn M, Brynolf S, Hansson J, Taljegård M (2016). The cost-effectiveness of electrofuels in comparison to other alternative fuels for transport in a low carbon future. Conference proceedings, EUBCE, Amsterdam, June 2016.

Sammanfattning

- Mycket flexibel råvarubas för produktion av vätgas.
- Även om biomassa är en globalt begränsad resurs så finns flertalet sätt att producera vätgas från fossila källor med CCS, från sol eller förnybar el.
- Prognos för både effektivare och billigare vätgasproduktion i framtiden.
- Produktion av vätgas kan förutom att bidra till lösningar för transportsektorn också bidra till lösningar för lagring av intermittent överskottsel.
- Vätgas i bränsleceller kan under olika förutsättningar kostnadsmässigt konkurrera andra framtida alternativ.