Frankfurt, 27.11.2024

Are e-fuels a beneficial alternative to conventional fuels?

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Bundesministerium für Bildung und Forschung

Prof. Dr.-Ing. Ralf Ehret

Are e-fuels a beneficial alternative to conventional fuels?

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definition

- fuels in generell
  - fuels: combustible substances ➔ chemical energy is converted into mechanical energy through combustion in combustion engines.
- conventionel fuels (gasoline, diesel, kerosene)
  - a mixture of different hydrocarbons (HC) based on crude oil
- e-fuels (electrofuels)
  - synthetic fuels (also HC) that are produced from water and carbon dioxide (CO_2) using electrical energy
  - known as power-to-fuel (PtF or in general PtX)

https://www.bmw.de

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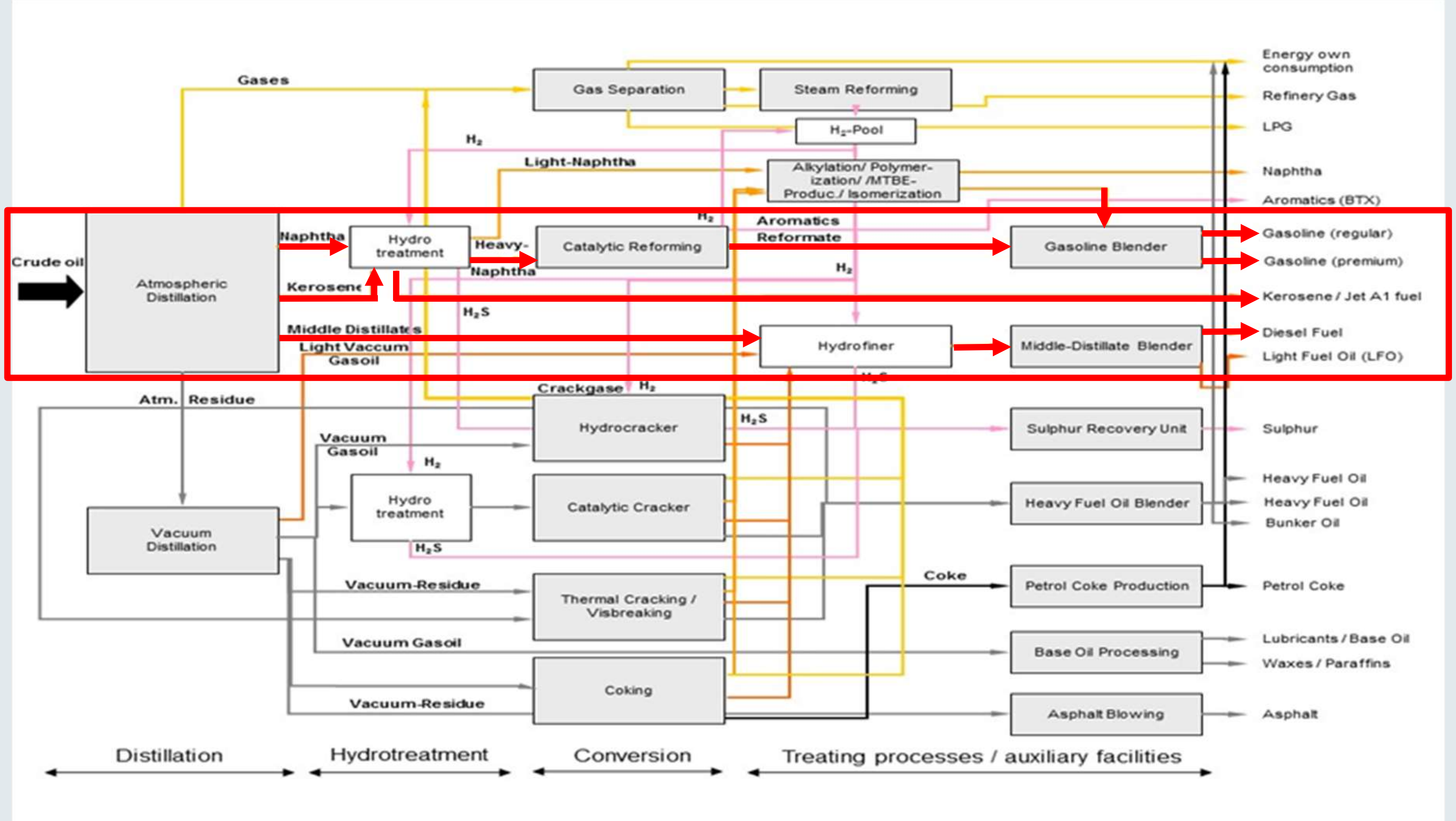
Are e-fuels a beneficial alternative to conventional fuels?

How conventional fuels are produced?



Are e-fuels a beneficial alternative to conventional fuels?

Why do we use hydrocarbons to generate energy?

- easy to handle
- no major hazard potential with careful handling
- high energy density

$$C_8H_{18} + 12{,}5\ O_2 \rightleftarrows 8\ CO_2 + 9\ H_2O_{(g)} + Energy$$

$$Energy\ =\ 5572\ kJ/mol \equiv 13{,}55\ kWh/kg \equiv 9{,}5\ kWh/L$$

- hard coal 8,3 kWh/kg
- wood ≈ 4 kWh/kg
- natural gas ≈ 12,5 kWh/kg

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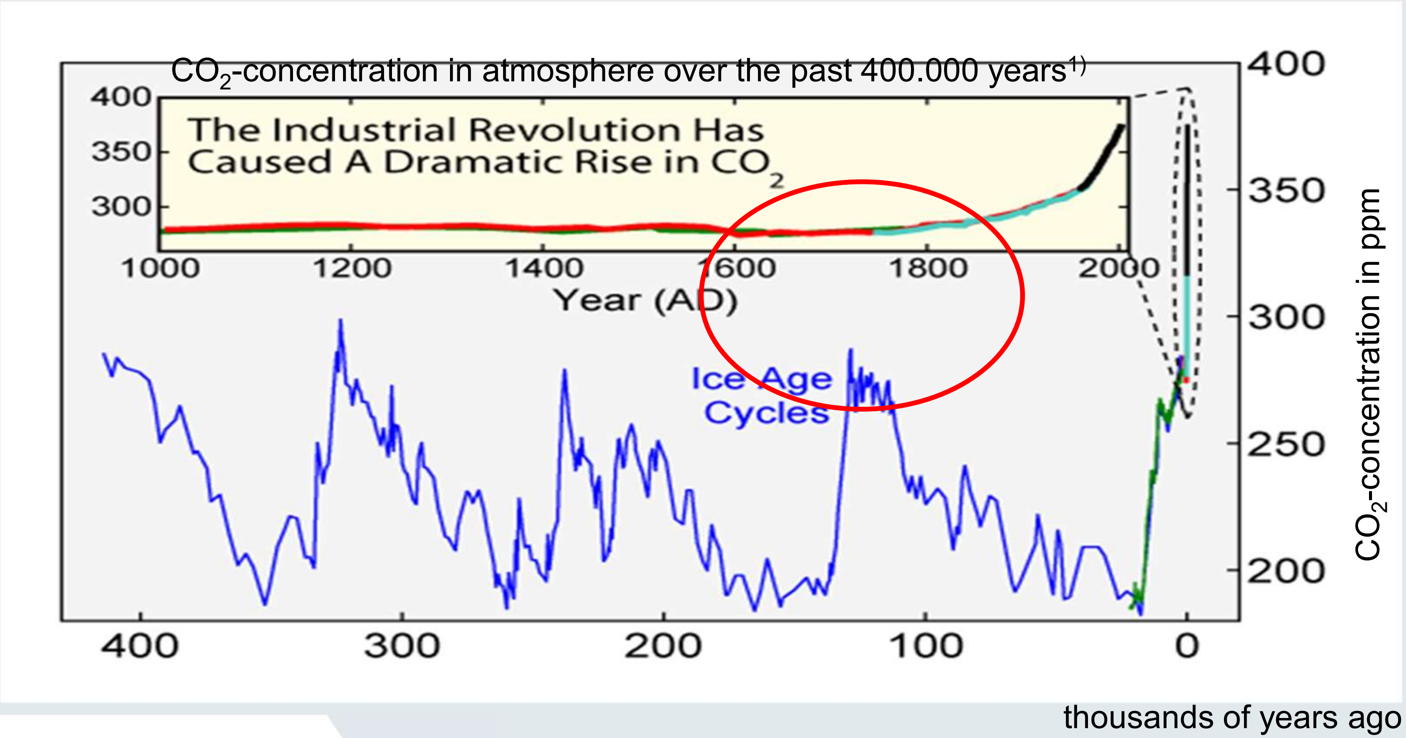
What problems does the combustion of hydrocarbons cause?



1) Hileman B: Ice Core Record Extended: Analyses of trapped air show current CO2 at highest level in 650,000 years. In: Chemical & Engineering News. Band 83, Nr. 48, November 2005, S. 7

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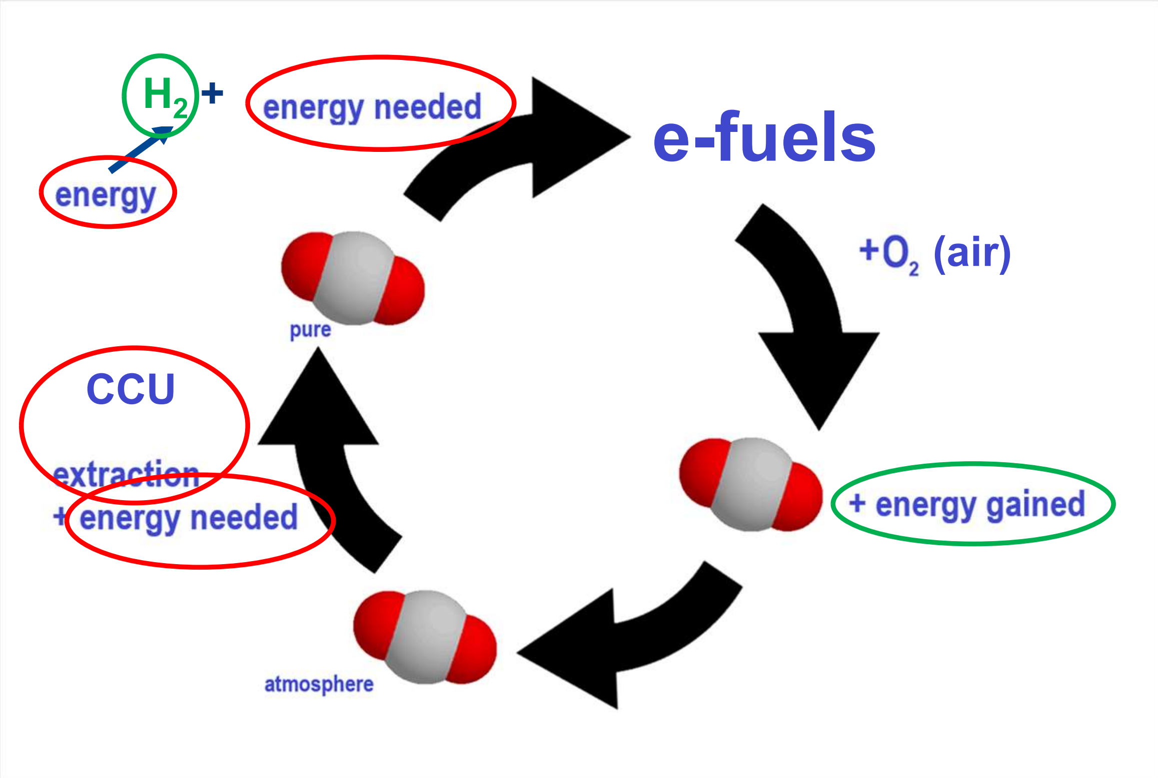
Are e-fuels a beneficial alternative to conventional fuels?

How can we solve this problem?



- perfect carbon circle!
- CO_2 balance = 0

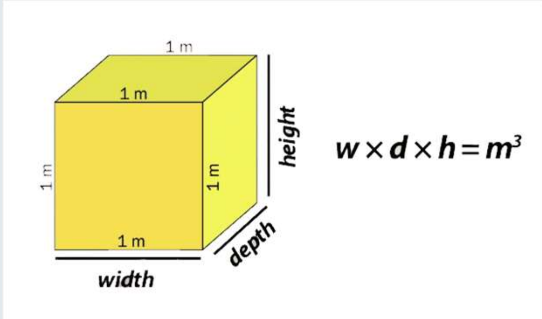
- but….

1. How to extract CO_2?
2. How to produce green hydrogen?
3. How much energy we need?
4. Are we in a position, to generate this energy in a climate-neutral way?
5. At what cost can e-fuels be produced?

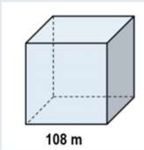
Are e-fuels a beneficial alternative to conventional fuels?

How to extract CO_2 from atmosphere?

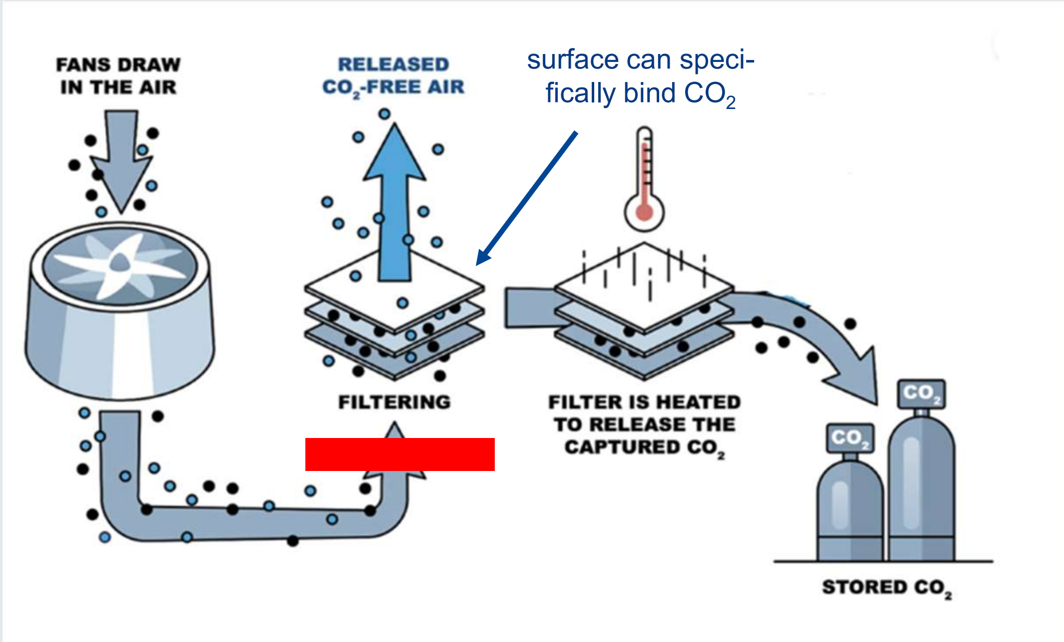
- 400 ppm?
- 1 m^3 air contains: 0,785 g CO_2



- s-DAC ≡ solid-Direct Air Capture
- to extract 1 ton CO_2 ➔ 1,27 mill. m^3 air
- energy needed: ≈ 2 MWh/ton CO_2



- GER released 600 mill. tons CO_2 (2023)[2)]
- renewable energy needed: **1200 TWh**
- total renewable energy in GER: **272 TWh** (2023)[2)]



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1) Mammoth: our newest direct air capture and storage facility (climeworks.com)

2) Umweltbundesamt (2024)

Are e-fuels a beneficial alternative to conventional fuels?

Are there other sources for CO_2 available?

- low concentration of CO_2

- hard coal-fired power station
- up to 15% CO_2 in exhaust gas
- why just 15%?
- purity of the exhaust gas?
- l-DAC ≡ liquid-Direct Air Capture

- energy consumption increases by 30%
- not all CO_2 could be captured
- coal-fired power generation will end in 2038 (Ger)

Kohlekraftwerk Karlsruhe Luftbild Foto & Bild | luftbild rheinneckar, kraftwerk, kohle Bilder auf fotocommunity

➔ not usefull

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Are e-fuels a beneficial alternative to conventional fuels?

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Are there other sources for CO_2 available?

- low concentration of CO_2

- cement plant ➔ cement production
  - responsible for 8% of global for CO_2 emissions[1)]
- limestone is indispensable resource
  - responsible for 2/3 of emissions

https://www.rosenheim24.de/rosenheim/rosenheim-land/rohrdorf-ort50271/samstag-offenen-zementwerk-rohrdorf-rosenheim24-2362749.html

- polluted exhaust gas
- l-DAC ≡ liquid-Direct Air Capture
- energy needed: ≈ 2,4 MWh/ton CO_2[2)]

1) https://www.spektrum.de/magazin/klimaneutrale-industrie-neuerfindung-von-zement/2150676

2) geoengineeringmonitor.org (boell.de)

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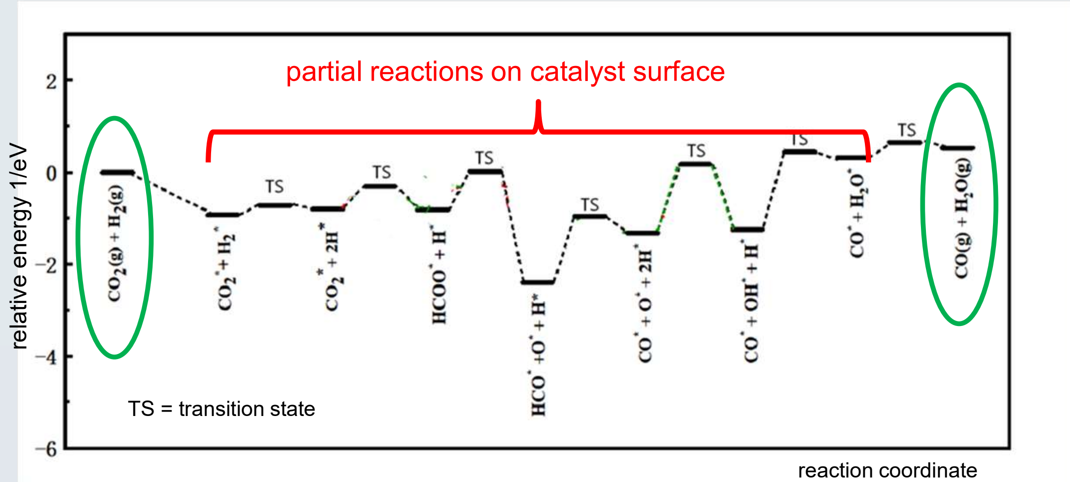
How to produce green hydrogen?

- reverse watergas shift reaction (RWGS)

$$Energy + CO_2 + H_2 \xrightarrow{ca\ .} CO + H_2O_{(g)}$$

- heterogeneously catalysed reaction
- several side reactions (Sabatier-reaction, methanisation, dry-, steamreforming, cocking,…)
- law of conservation of energy
- included in Fischer-Tropsch-reaction
- energy needed: 0,85 MWh/ton CO[1)]



1) REPOSE, unpublishes results

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Are e-fuels a beneficial alternative to conventional fuels?

How to produce green hydrogen?

- RWGS reaction ➔ necessity of green hydrogen

$$Energy + CO_2 + H_2 \rightleftarrows CO + H_2O_{(g)}$$

- H_2O PEM-electrolysis

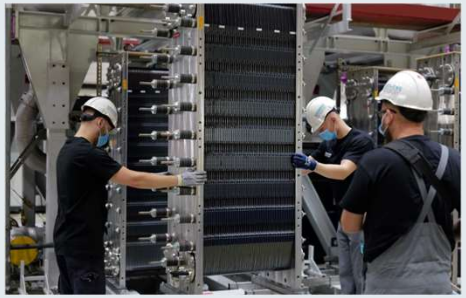
$$Anode: \quad H_2O \rightleftarrows 2H^+ + \frac{1}{2}O_{2(g)} + 2e^-$$

Proton Exchange Membrane

$$Kathode: \; 2H^+ + 2e^- \rightleftarrows H_{2(g)}$$

dc-power source

$$Energy + H_2O \rightleftarrows H_{2(g)} + \frac{1}{2}O_{2(g)}$$



https://www.siemens-energy.com/global/en/home/products-services/product-offerings/hydrogen-solutions.html

- renewable energy needed: 50 MWh/ton H_2[1)]

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1) Frauenhofer IWS (2023)

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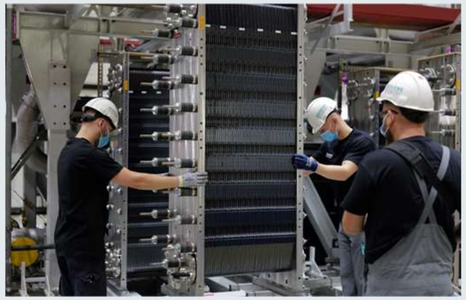
How to produce green hydrogen?

- renewable energy needed: 50 MWh/ton H_2
- current H_2-demand in GER: 10^6 tons ≡ 50 TWh (almost industrial use)
- total renewable energy in GER: 272 TWh (2023)

- expected demand (2050[1)]): $15 \cdot 10^6$ tons ≡ 750 TWh
- necessity of import ➔ H_2 transportation

production site



https://www.siemens-energy.com/global/en/home/products-services/product-offerings/hydrogen-solutions.html

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1) https://www.bmbf.de/bmbf/de/forschung/energiewende-und-nachhaltiges-wirtschaften/nationale-wasserstoffstrategie/nationale-wasserstoffstrategie_node.html#:~:

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How to produce green hydrogen?

- How is the current situation in water electrolysis?
- currently 17 manufacturers worldwide offering 92 different systems (PEM, alkaline, high-temperature)

https://www.refhyne.eu

- 2021: Chemiepark Rheinland (Wesseling) 10 MW PEM-electrolyser REFHYNE[1)] ➔ up to 1.300 tons H_2/y
- 8/2024: Oberhausen, 20 MW PEM-electrolyser TRAILBLAZER, Air Liquide
- 2024 Porsgrunn (Norway), 24 MW PEM-electrolyser (so far biggest in Europe)
- 2024 decision taken: 100 MW PEM-electrolyser REFHYNE II ➔ up to 16.000 tons H_2/y (operational in 2027)
- 2023 Port of Rotterdam ➔ start of construction of 5 plants, total capacity 1 GW ➔ up to 180.000 tons H_2/y (operational in 2025-30)

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1) Shell Deutschland Oil GmbH, SINTEF, Element Energy and Sphera

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How to produce green hydrogen?

- projekt: OffsH2ore[1)]
- feasibility study
  - off-shore wind farm
  - 500-MW platform for H_2O-PEM-electrolyses
  - capacity: 50.000 tons/y H_2
  - modular concept ➔ easy scalability
  - energy: reversed osmosis ➔ waste heat from electrolyses
  - clean and dry H_2 ➔ compressed to 500 bar
- transportation:
  - via pipeline
  - via ship (max load 400 tons)

Gefördert durch:
Bundesministerium für Wirtschaft und Klimaschutz
aufgrund eines Beschlusses des Deutschen Bundestages

Schematic illustration of an offshore concept for hydrogen production and pressurised gas transport (ship or pipeline)

	ecology (LCA)	economy (TEA)
pipeline	+	-
ship	-	+

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1) PINE AG, Fraunhofer-Institut für Solare Energiesysteme ISE, SILICA Verfahrenstechnik GmbH, KONGSTEIN GmbH

Are e-fuels a beneficial alternative to conventional fuels?

How to produce e-fuels?

- syn gas: CO (from CO_2 via RWGS) + H_2
- Fischer-Tropsch-reaction:
- developed 1920 ➔ commercialized in 1930s
- historical: coal liquefaction (2 steps)
- per kg HC ➔ 1,25 kg H_2O ➔ loss of H_2
- side products (CA, alcoholes, aldehydes, ketons, …)

$$n\,CO + 2n\,H_2 \xrightarrow{cat.} HC + m\,H_2O_{(g)} + Energy$$

www.wikipedia.de

SASOL - Slurry phase distillate reactor[1)]

1) https://websites.umich.edu/~elements/fogler&gurmen/html/01chap/html/reactors/sasol.htm

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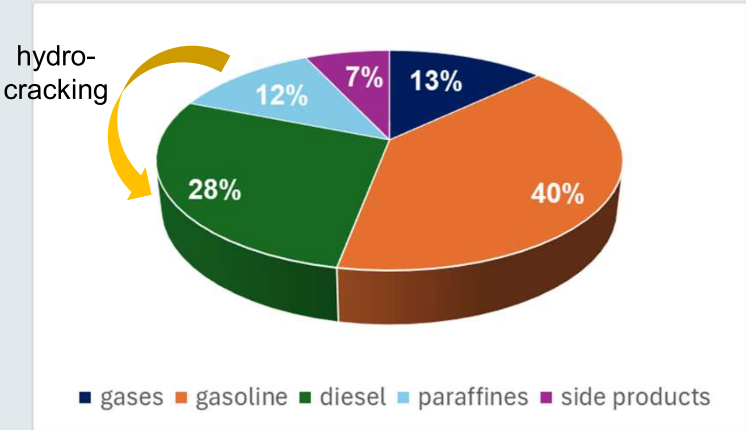
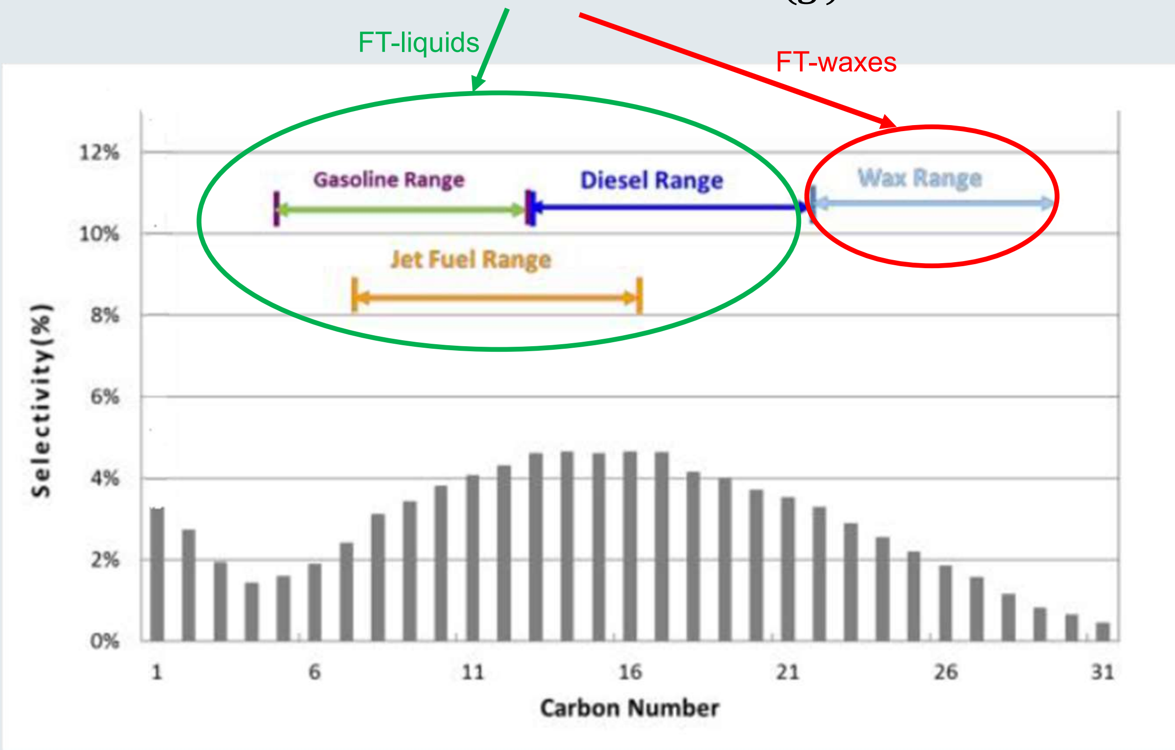
$$n\ CO + 2n\ H_2 \xrightarrow{cat.} HC + m\ H_2O_{(g)} + Energy$$

How to produce e-fuels?

- Fischer-Tropsch-(FT)-reaction
- what means „HC“?
- product distribution = f (T, p, cat., reactor system, t)
- distribution for L(ow)T(emp.)-FT:





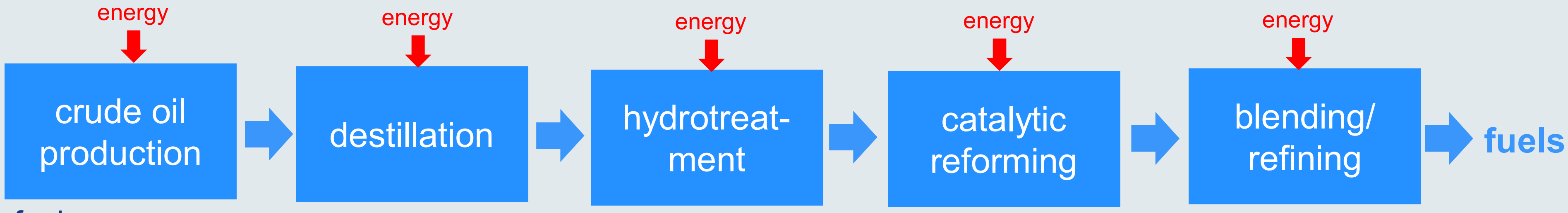
product distribution of LTFT (200 - 250 °C)[1)]

1) Rui Xu, Departement of Chemical Engineering, Auburn Univ, 2013

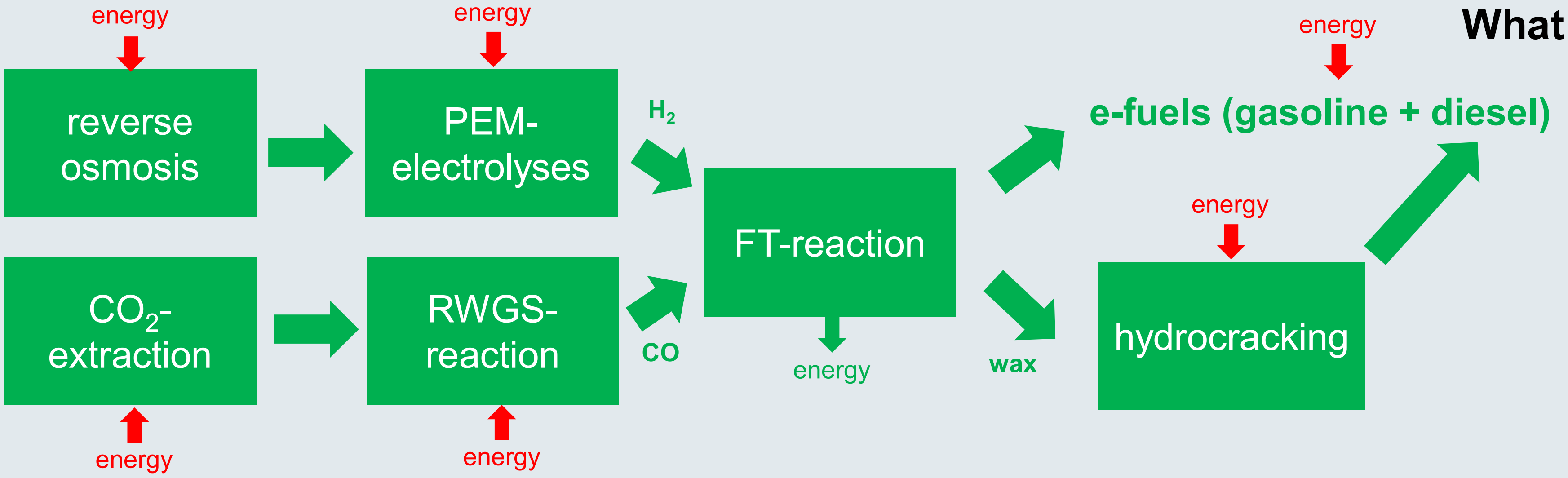
Are e-fuels a beneficial alternative to conventional fuels?

Interim summery

- conventional fuels:



- e-fuels:



What‘s better?

Are e-fuels a beneficial alternative to conventional fuels?

Energy needed?

- to produce 1 L fuel (gradle to tank)
- conventional fuel 1,6 - 1,8 kWh[1)] ≈ 2 kWh
- e-fuel 18 - 25 kWh[1)] ≈ 22 kWh
- fuel consumption in GER 2023[2)]

fuel	quantity [tons]	density [kg/L]	volume [m^3]
diesel	$36*10^6$	0,84	$42,9*10^6$
gasoline	$18*10^6$	0,74	$24,3*10^6$
kerosene	$9*10^6$	0,80	$11,3*10^6$
total	$63*10^6$		

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1) Frauenhofer IWS 2020, Deutsches Zentrum für Luft- und Raumfahrt, 2021

2) Bundesministerium für Wirtschaft und Klimaschutz, Arbeitsgemeinschaft Energiebilanzen e.V.

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Additional energy needed?

$$Energy = 78{,}5 \cdot 10^9 L \cdot 20\ kWh/L = 1.570 \cdot 10^9\ kWh \equiv 1.570\ TWh$$

- renewable energy available in GER[1)]

$$Energy\ (2023) = 513\ TWh \Rightarrow 53\%\ renewable \Rightarrow 272\ TWh$$

-  ?

$$\frac{152\ TWh}{30782\ wt} \approx 5\,\frac{GWh}{wt} \qquad \Longrightarrow \frac{1570\ TWh \cdot wt}{15\ GWh} \approx 105.000\ wt$$

- but…..

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1) Umweltbundesamt, 2023

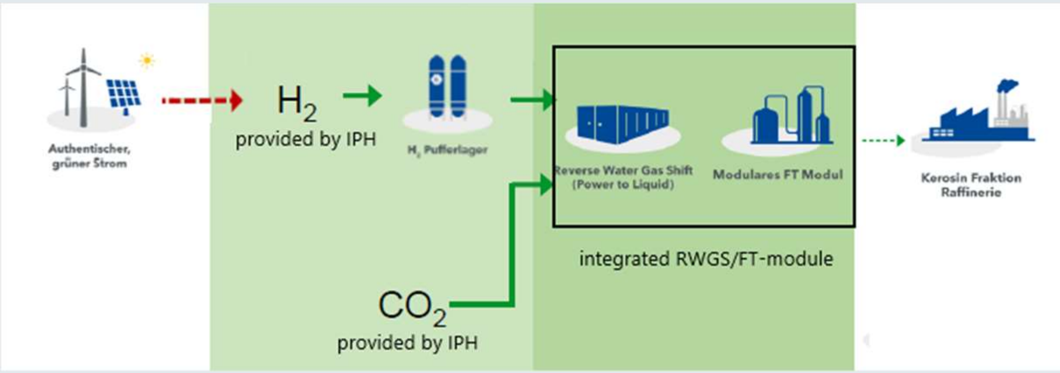
Are e-fuels a beneficial alternative to conventional fuels?

Use of excess energy!

$$Energy\ lost\ (2023)^{1)} = 8.6\ TWh \equiv 430.000\ m^3\ fuel$$

- large scale FT-plants in Germany? ➔ small scale
- REPOSE[2)] ≡ Renewable Power Supply for e-fuels
- capacity: 2.500 tons/y fuel

Bundesministerium für Verkehr und digitale Infrastruktur



INERATEC plant at IPH
(operational Dec. 24)

1) PV- and wind energy, Umweltbundesamt, 2023, Statistisches Bundesamt 2023   2) CENA, Provadis Hochschule, Ineratec, Frauenhofer Institut

Are e-fuels a beneficial alternative to conventional fuels?

Transportation

- fuels (diesel, gasoline, kerosene) and $CO_{2(sc/l)}$ ➔ pipelines oder ships ➔ established technology
- H_2?

energy source	calorific value [kWh/kg]	density [kg/m³]	volume [L]	in relation to cv
H_2	33	0,09	11.200	3735
gasoline	11	750	1,3	1,3

- liquification

energy source	calorific value [kWh/kg]	density [kg/m³]	volume [L]	in relation to cv
H_2 (liquid)	33	71	14,1	4,7
gasoline	11	750	1,3	1,3

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Are e-fuels a beneficial alternative to conventional fuels?

https://www.chemie-master.de/FrameHandler.php?loc=https://www.chemie-master.de/pse/pse.php?modul=O

Transportation

- boiling point H_2?
- storage, loading, loss of H_2 during transportation via ship…..?
- compression?

energy source [600 bar]	calorific value [kWh/kg]	density [kg/m^3]	volume [L]	in relation to cv
H_2	33	48	18,7	6,2
gasoline	11	750	1,3	1,3

- hydrogen induced embrittlement ➔ cracking

increases with temperature and pressure

➔ specific steel alloys or composite reinforced pipelines

- transportation of H_2 is a major challenge!

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Are e-fuels a beneficial alternative to conventional fuels?

Other possibilities für H_2-transportation?

- as a chemical compound ➔ e.g. NH_3
- March 2023: Signing of feasibility and implementation agreement between Namibia and Hyphen Hydrogen Energy[1)]
- to proof within 2 years the possibilty to install that:
- total invest: 10 billion $ ➔
  - desaltination plant
  - H_2O-electrolyses ➔ H_2
  - Linde air separation plant ➔ N_2
  - Haber-Bosch-ammonia plant ➔ NH_3
  - new harbour at Lüderitz bay + infrastructur
- capacity/year: 2 million tons ammonia, 350.000 tons H_2, 7.000 MW PV-electricity (total Namibia: 600 MW)
- transportation on liquid NH_3 ➔ boiling point: -33 °C (H_2: -252 °C)
- conversion into H_2 ➔ via thermal catalytic cracking


model of the planned plant in Namib Desert[1)]

https://www.google.de/maps

1) joint venture between Nicholas Holdings Limited and ENERTRAG AG

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Are e-fuels a beneficial alternative to conventional fuels?

The life cycle assessment view

- kg CO_2-equivalents for 1 L fuel

	conventional fuels		e-fuels	
	gasoline	diesel	gasoline	diesel
well to tank (WTT)[1)]	0,5 - 1	0,6 - 1,2	0 - 2,4	0 - 2,7
tank to wheel (TTW)[2)]	2,4	2,7	0	0
total (WTW)	2,9 - 3,4	3,3 - 4,5	0 - 2,4	0 - 2,7

1) indirect emissions → extraction, production + rafination, transport

2) direct emissions → combustion

- 100% renewable energy is a necessity

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Are e-fuels a beneficial alternative to conventional fuels?

only costs for e-fuel production

The techno-economic view

- tax & OPEX values for 1 L gasoline

	conventional fuel		e-fuel
	1,60 €		3,18 €
mineral oil tax[1)]	65 ct	mineral oil tax[1]	65 ct
CO_2 tax	10 ct	CO_2 tax	-
	85 ct		**253 ct**
crude oil		electricity + CO_2	20 ct
refinery		hydrogen	180 ct
transportation		transportation	11 ct
margin		margin	15 ct
VAT		VAT	27 ct

1) fix amount, no percentage, diesel mineral oil tax: 47 ct
2) Promotionsarbeit S. Schemme, FZ Jülich 2020

Are e-fuels a beneficial alternative to conventional fuels?

Current situation?

"Ørsted scraps flagship European green fuels project"

- 201 mil. € investment
- 55.000 tons green Methanol (MeOH)
- CO_2 ➔ combined heat and power plant + green H_2
- cancelled in 8/2024
- MeOH price to high

"Fulcrum BioEnergy abandons trash-to-fuel plant in Nevada. The waste gasification start-up abruptly laid off most staff in mid-May" (2024)

- capacity 42 million L of e-fuel per year
- employed about 120 people.
- permits no extended and technical problems

https://cen.acs.org/energy/Fulcrum-BioEnergy-abandons-trashfuel-plant/102/web/2024/06

Shell Nederland Raffinaderij B.V is to temporarily pause on-site construction work at its 820,000 tonnes a year biofuels facility at the Shell Energy and Chemicals Park Rotterdam in the Netherlands to address project delivery and **ensure future competitiveness given current market conditions** (July 2024).

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Are e-fuels a beneficial alternative to conventional fuels?

Current situation in Ger?

	Projekt	Hauptprodukt	Kapazität	Standort	Produktionstechnologie	Angekündigte Inbetriebnahme	CO_2-Quelle	Geplantes Einsatzfeld
1	Solarbelt	Kerosin	360 t/a	Werlte	Fischer-Tropsch	Seit 2021	Punktquelle Biomethan	Luftfahrt
2	NextGate	eFuels und Wachse	200 t/a	Hamburg	Fischer-Tropsch	Seit 2022	Biogenes CO_2 per Tankwagen	Keine Angabe
3	Reallabor Westküste 100/ KeroSyn100	Kerosin	600 t/a	Demonstrationsanlage Raffinerie Heide	Methanol-to-Jet	2023/2024	Punktquelle Zementwerk	Luftfahrt
4	Ineratec	eFuels	3.500 t/a	Industriepark Hoechst	Fischer-Tropsch	2024	Biogas	Keine Angabe
5	Shell Rheinland Raffinerie	Kerosin	100.000 t/a[1]	Köln	Nicht bekannt	2025	Altholz	Luftfahrt
6	HyKero	Kerosin	42.000 t/a	Böhlen- Lippendorf	Fischer-Tropsch	2026	Punktquelle Biomethan	Luftfahrt u.a.
7	Jangada	Kerosin	34.000 t/a	ehemaliger Flugplatz in Drewitz (GRAL)	Fischer-Tropsch	2027	Biogene Punktquelle	Luftfahrt
8	Reallabor Westküste 100/ KeroSyn100	Kerosin	20.000 t/a	Demonstrationsanlage Raffinerie Heide	Methanol-to-Jet	2027	Punktquelle Zementwerk	Luftfahrt
9	reFuels – Kraftstoffe neu denken	Raffination Syn-Crude	Bis zu 50.000 t/a	MiRO Karlsruhe	Fischer-Tropsch	2027	Nicht bekannt	Nicht bekannt
10	OMV Burghausen	Kerosin	50.000 t/a	Voraussichtlich im Raum Burghausen (Bayern)	Nicht bekannt	Ende der 2020er-Jahre	Nicht bekannt	Luftfahrt
11	Concrete Chemicals	Kerosin u.a.	30.000 t/a SAF	Rüdersdorf	Fischer-Tropsch	2028	Punktquelle Zementwerk	Luftfahrt u.a.
12	DAWN	Kerosin	3.500 t/a	Jülich	Fischer-Tropsch	Nicht bekannt	Sun to liquid	Luftfahrt
13	E-Kerosin-aus-der-Luft	Kerosin	274 t/a	Rostock- Laage	Fischer-Tropsch	Nicht bekannt	Nicht bekannt	Luftfahrt u.a.
14	Technologie-Plattform (TPP)	SynCrude, Kero-sin, Methanol u.a.	10.000 t/a	Leuna	Diverse Forschungsmodule	Baubeginn: 2024	Nicht bekannt	Keine Angabe
15	Green Fuels Lausitz	Methanol und Kerosin	200.000 t/a	Industriepark Schwarze Pumpe (Lausitz)	Methanol-Synthese/Fischer-Tropsch	Nicht bekannt	Abfallverwertung	Keine Angabe
16	Green MeOH	Methanol	200.000 t/a	Chemiepark in Stade	Methanol-Synthese	Nicht bekannt	Punktquelle Gaskraftwerk	Seefahrt
17	PtX 1.0	Kerosin	274 t/a	Böhlen- Lippendorf	Nicht bekannt	Nicht bekannt	Nicht bekannt	Luftfahrt
18	PtX Lab Lausitz	Kerosin	10.000 t/a	Lausitz	Fischer-Tropsch	In Planung	Biogene Punktquelle/DAC	Luftfahrt
19	SAF@STR	Kerosin	120.000 t/a	Stuttgart	Nicht bekannt	Nicht bekannt	Punktquelle Zementwerk	Luftfahrt

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Are e-fuels a beneficial alternative to conventional fuels?

summary

- extreme amounts of renewable electrical energy required
  - so far not available ➔ heavy investment necessary
- an overnight changeover is not feasible
  - stepwise approach ➔ blending of e-fuels via a quota system and/or taxes
- challenging H_2 transportation
  - no sufficient solution so far ➔ more research needed
- economy vs. ecology
  - politics can set the framework conditions through taxes
- fully integrative systems (DAC + elektrolyses ➔ e-fuels) necessary
  - outside GER ➔ continued dependencies
- economy of scale

E-fuels as an interim solution?

Why e-fuels at all?

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BEGLEITFORSCHUNG P2X-RINGVORLESUNG

Your opinion is important - We look forward to your participation!

Ihre Meinung ist wichtig - Wir freuen uns über Ihre Teilnahme!

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SCAN ME

www.soscisurvey.de/P2X-Ringvorlesung/

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PARTICIPATION CERTIFICATE

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Participation Certificate Request
VL4

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THANK YOU FOR YOUR PARTICIPATION – SEE YOU NEXT WEEK

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