FACULTY OF ENGINEERING AND ARCHITECTURE

DE ROL VAN BRANDSTOFFEN IN EEN DUURZAAM ENERGIE- EN TRANSPORTSYSTEEM

Sebastian Verhelst, 20/11/23, AIG

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YOUR SPEAKER

- Prof. Sebastian Verhelst
  - PhD in hydrogen engines, 2005, Ghent University
  - Currently 70% Full Prof. at Ghent University (BE) and 30% Assoc. Prof. at Lund University (SE)
  - Supervising 11 researchers, 2.5 working on hydrogen as engine fuel, 3 on biofuels, and 5.5 on methanol
  - Expertise: internal combustion engines, on alternative/ renewable fuels: methanol (since 2009), ethanol, hydrogen (since 1999), straight vegetable oils, animal fats, biodiesel, alcohol blends, ...
  - Increased focus on marine applications since 2015
    - EU H2020 projects FASTWATER (ongoing, coordinator), LeanShips (WP leader)
    - Collaboration with Belgian medium speed engine manufacturer

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CONTENTS

- Why fuels?
  - &where?

- Which fuels?

- *How shall we convert them (back) to energy?*

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WHY HYDROGEN? (WHY FUELS?)

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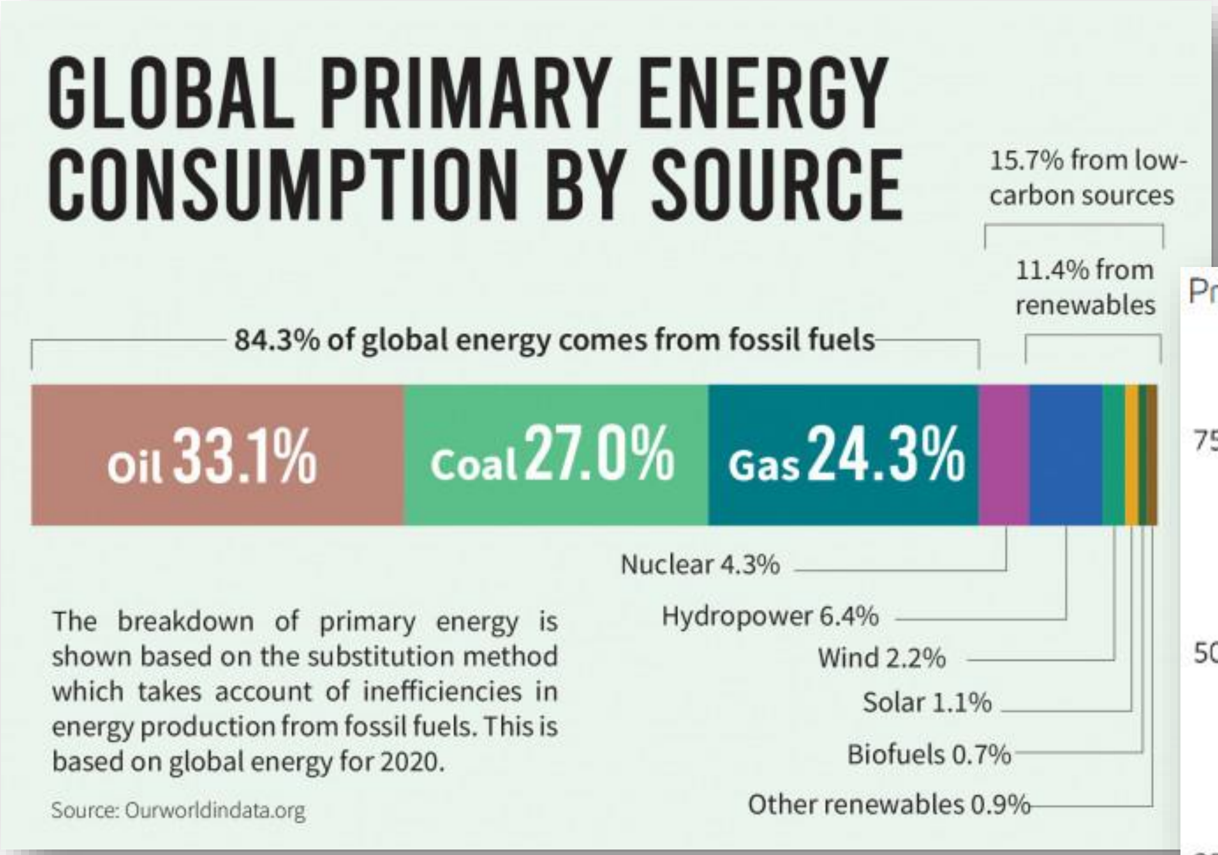
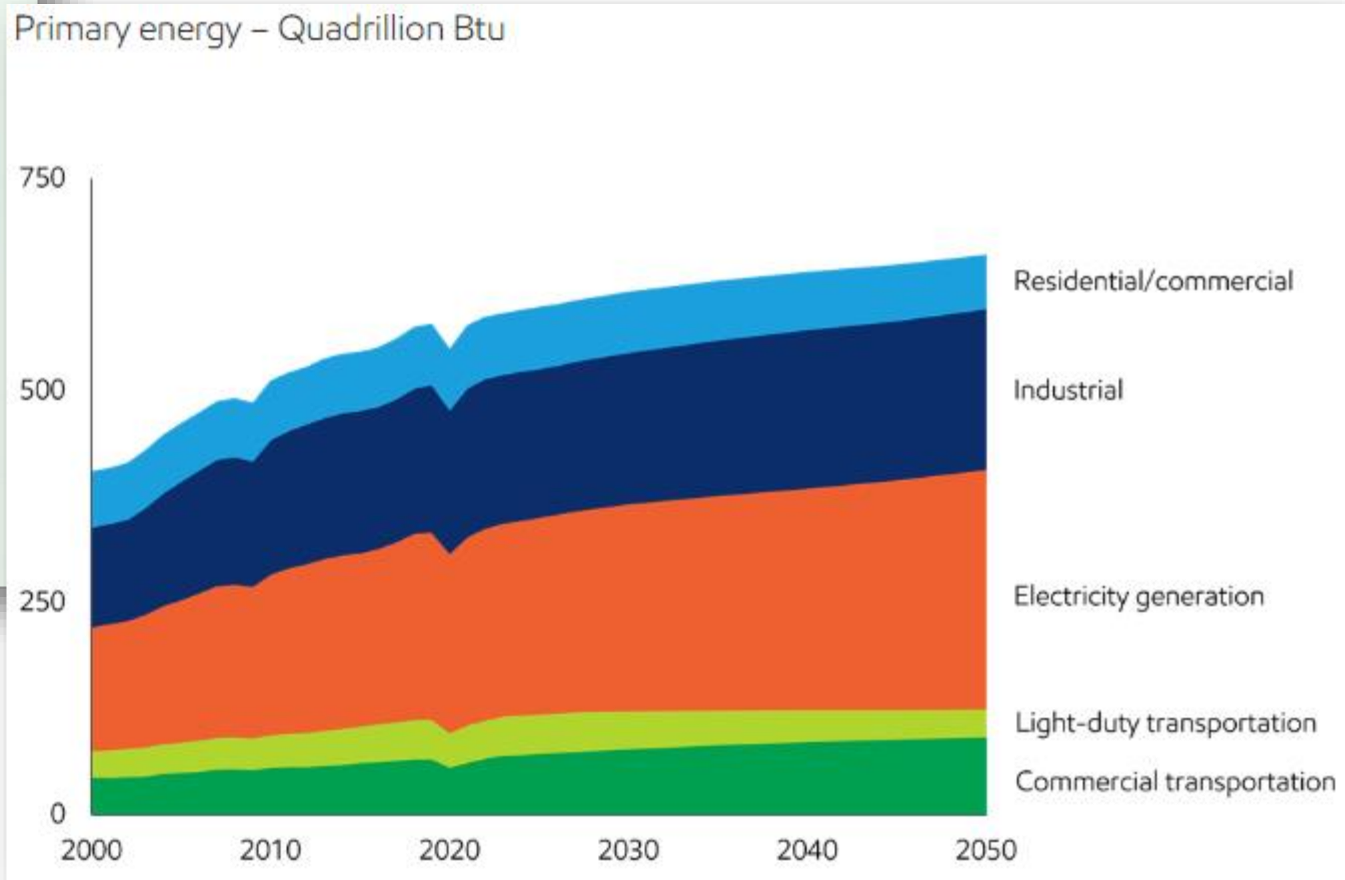
FUELS TODAY





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LIQUID FUELS/MOLECULES USE TODAY

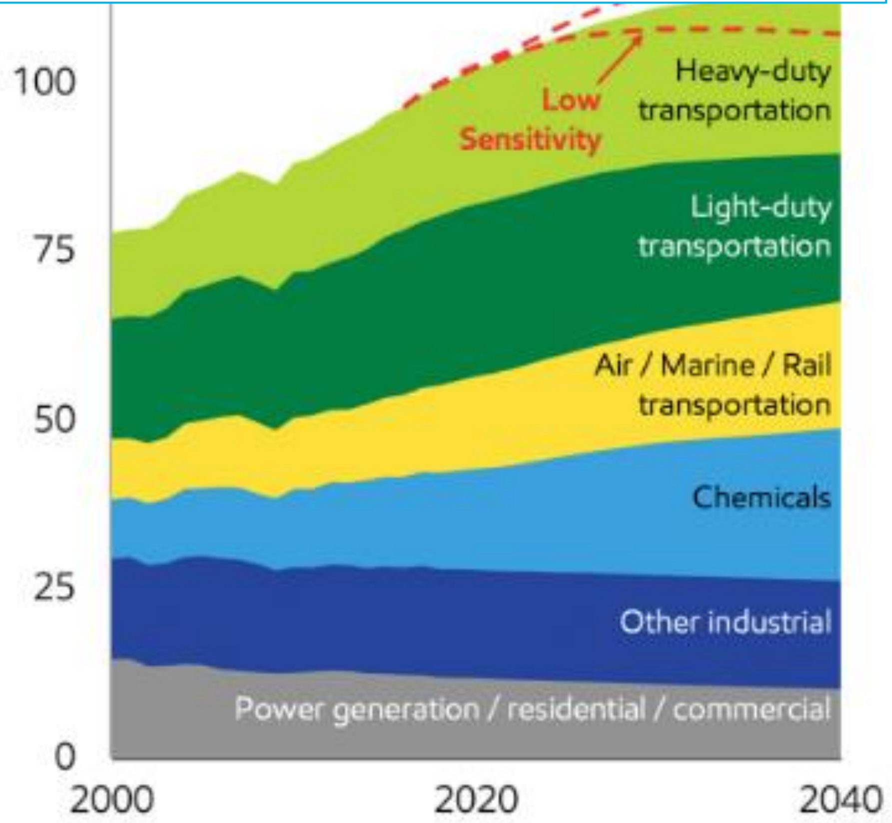
Why so much?

(fossil) (liquid) Fuels are:

- Cheap
- Easy
  - High energy density!
    - E.g. fueling up on gasoline, flow rate corresponds to ~30 MW! (100x EV DC fast charger)
    - See later...
  - Hence easy to distribute, store, buffer
  - Easy to produce
- Compatible with many different applications

FUELS/MOLECULES USE TOMORROW?

World – MBDOE



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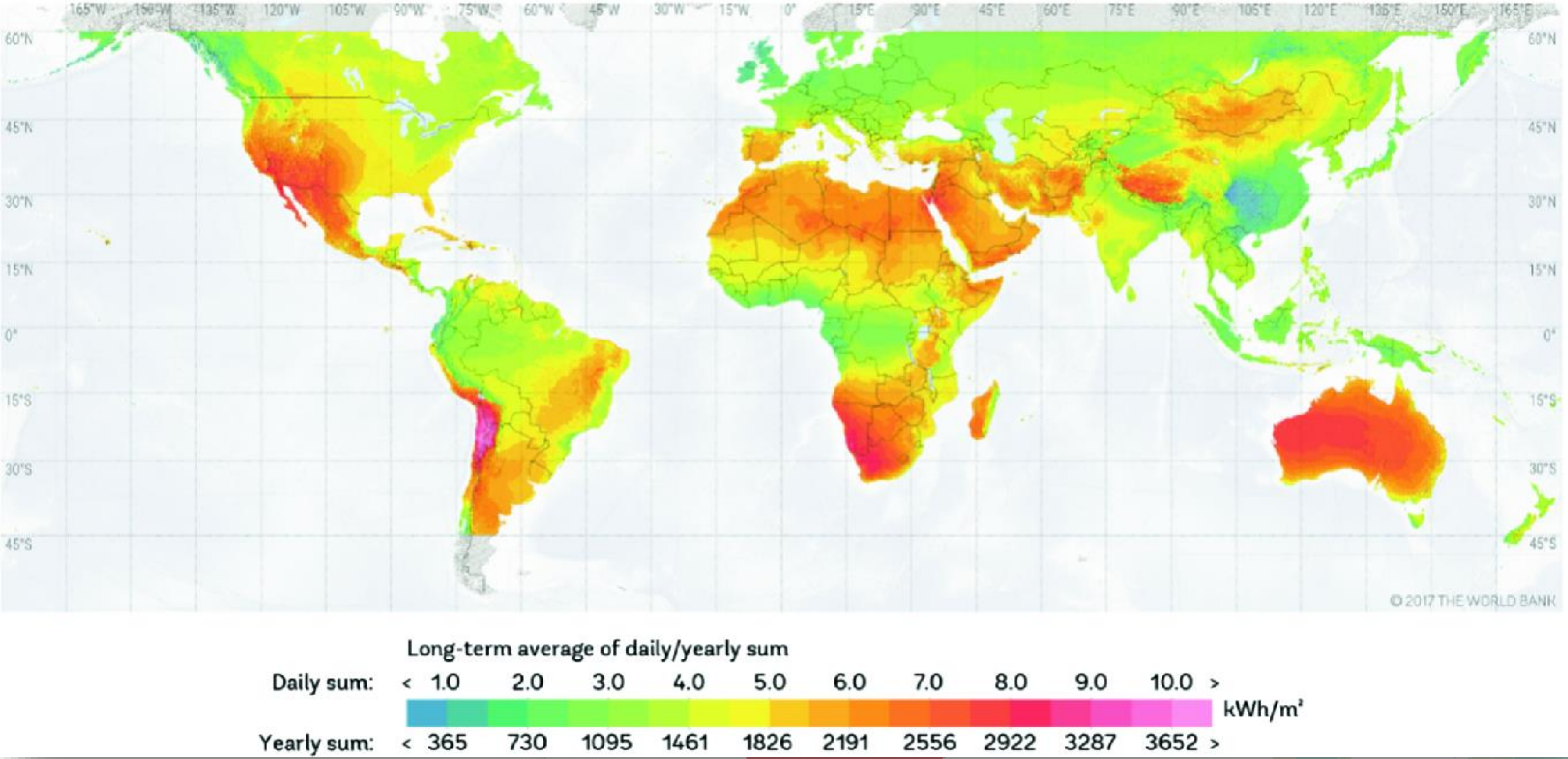
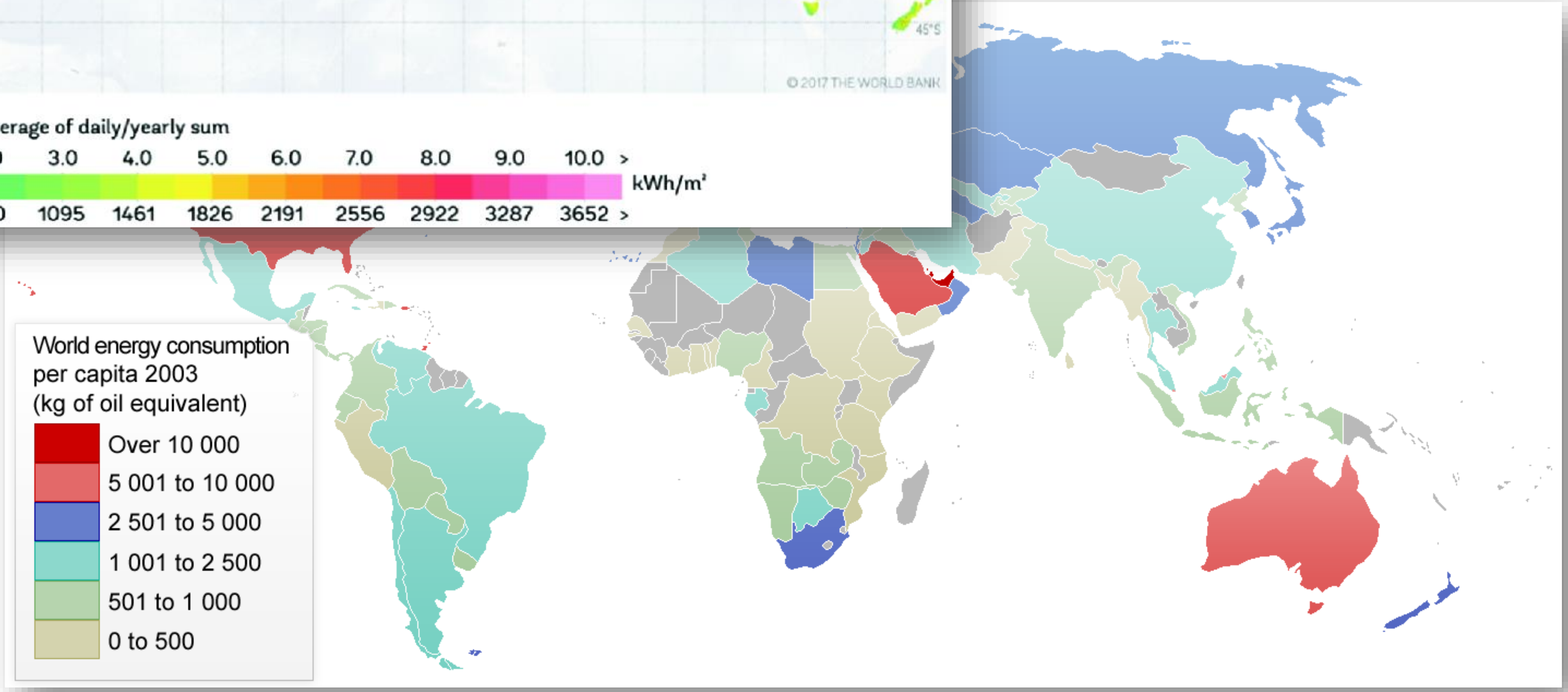


Qiu Z., Li P. (2019) Solar Energy Resource and Its Global Distribution. In: Zhao X., Ma X. (eds) Advanced Energy Efficiency Technologies for Solar Heating, Cooling and Power Generation. Green Energy and Technology. Springer, Cham. https://doi.org/10.1007/978-3-030-17283-1_1



By SG (en.wiki) - Self-made using International Energy Agency (IEA) Statistics Division data; Energy Balances of OECD Countries, 2006 edition and Energy Balances of Non-OECD Countries, 2006 edition. (data.iea.org), CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=2155602

HOW TO MATCH SUPPLY AND DEMAND?

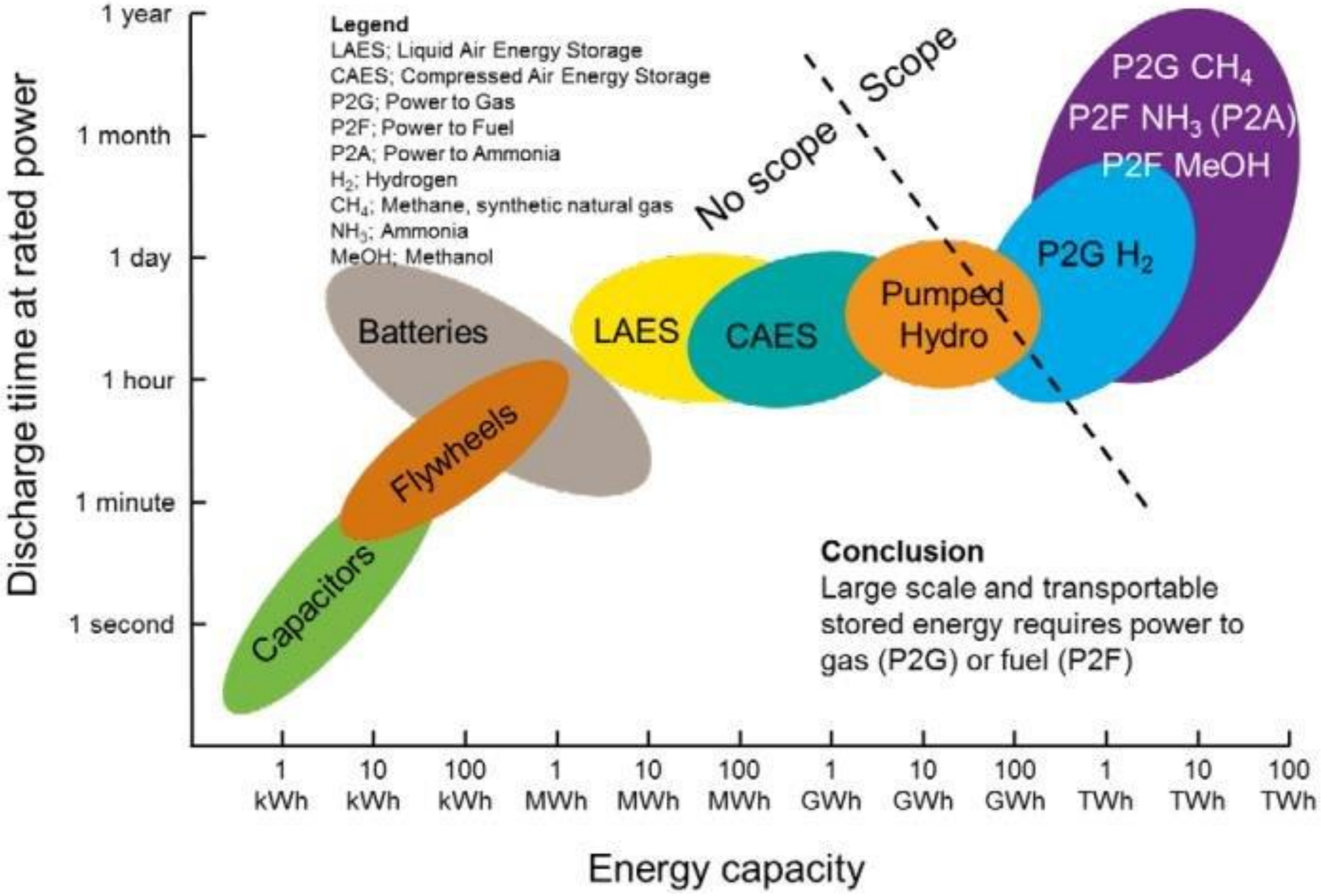
- Now
  - Electricity demand: daily fluctuation
  - Oil demand: weekly fluctuation (~transport)
  - Gas demand: seasonal fluctuation (~heating)
  - Energy easily shipped globally (liquid carrier)
- Versus renewable energy
  - Mismatch timing
    - Daily (“California duck curve”)
    - Seasonally (“Dunkelflaute”)
  - Mismatch geographically
    - E.g. locations heavy industry (energy demand) vs. locations of cheapest renewable energy

WE NEED (MASSIVE) ENERGY STORAGE

Need the energy density of fuels to

- Bridge seasonal fluctuations
- Move large amounts of energy around

i.e. need for molecules, next to electrons



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NEED FOR FUELS/MOLECULES

1. Energy sector: we need (massive) energy storage to make a renewable energy system robust
2. Chemical sector:

   ~10% of petroleum is used to make products
   - Plastics, pharmaceuticals, fibers, foams, paints, …
   - We need non-fossil alternatives
3. Transportation sector: the part that is hard to electrify
   - Limitations of batteries: need the energy density of fuels

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ELECTRIFYING HEAVY TRANSPORT: EXAMPLE

- Yara Birkeland (N) world first electric container ship
- Carries 120 TEU @6 knots over 30 nautical miles
- Diesel container vessels: carry 18000 TEU (x150) over 12000 nm (x400) @20-25 knots (x3-4)
- Assuming 300Wh/kg battery, up to 40% of cargo capacity for Hong Kong → Hamburg
- This is simply basic physics
  - The energy density of batteries is too low for many applications
  - This does not preclude specific niche applications of battery-powered vessels

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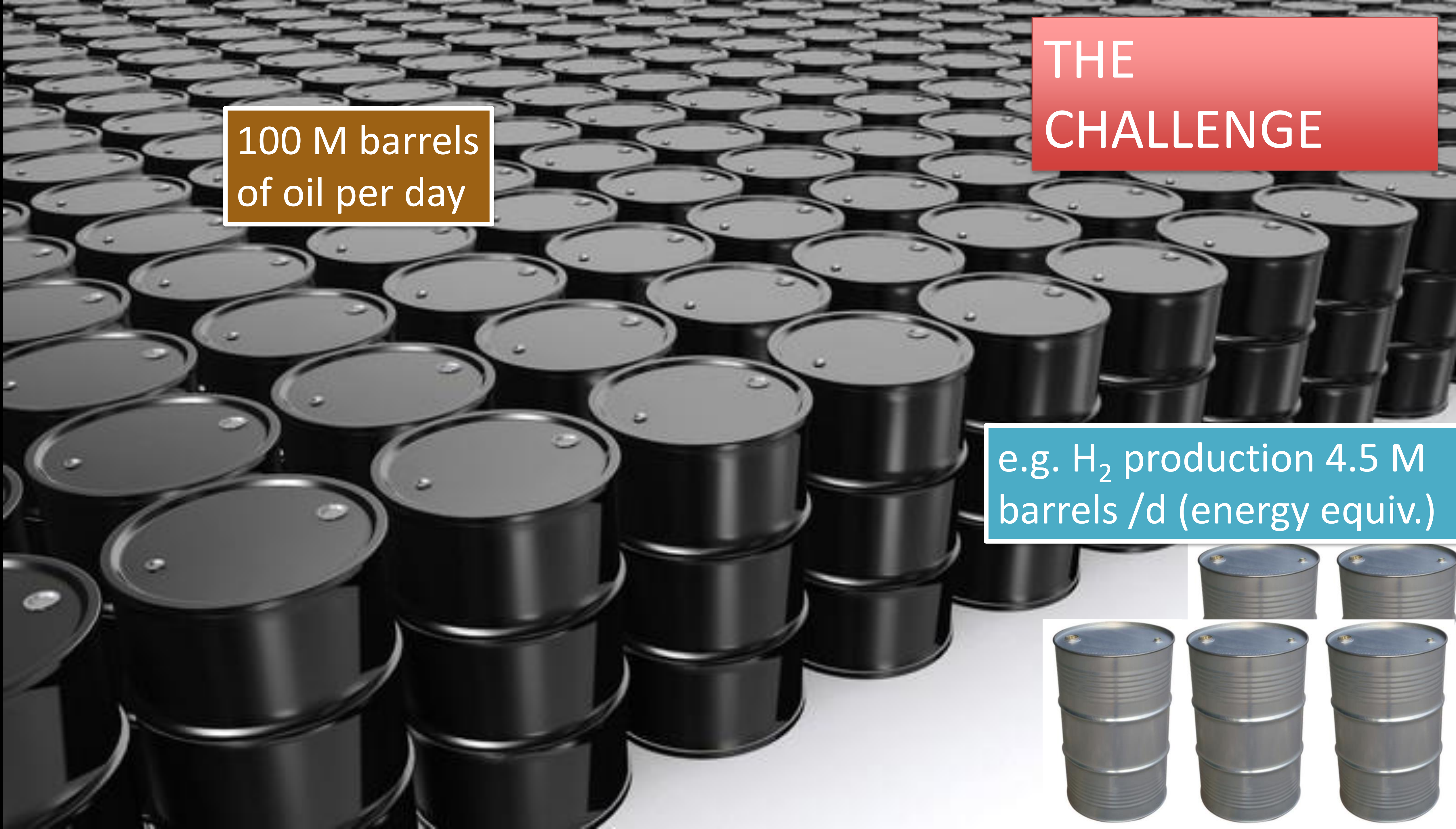
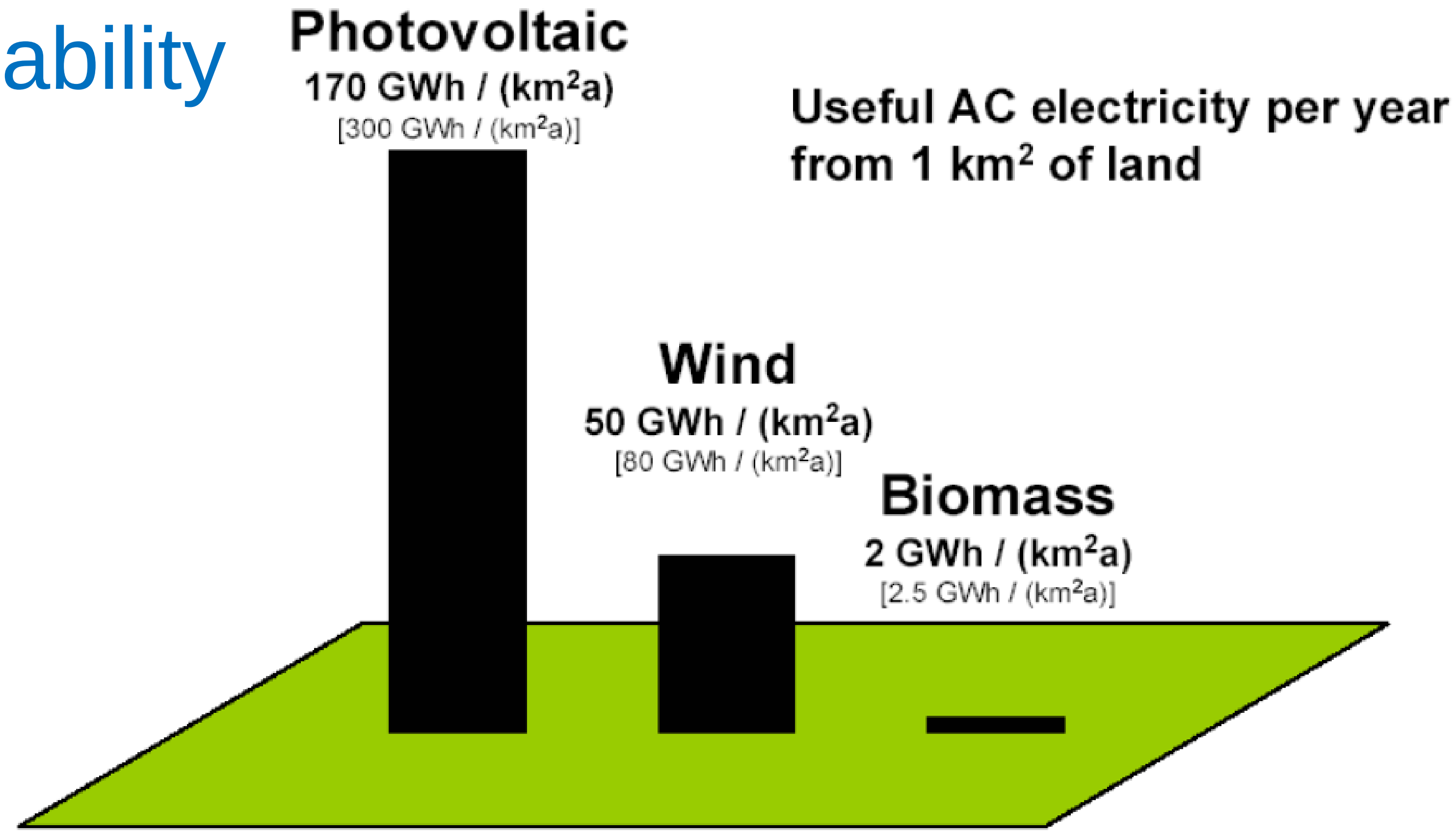
THE CHALLENGE



WHERE TO GET THOSE MOLECULES?

- From fossil-free sources
- We will need a lot, so need to check scalability



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WHERE TO GET THOSE MOLECULES?

- Most scalable (i.e. affordable) renewable energy sources: PV, wind
  - So, available as ("green") electricity
- How to convert electricity to fuels?
  - "Electrofuels", "e-fuels"
  - Simplest e-fuel: hydrogen

HYDROGEN SENSE AND NON-SENSE

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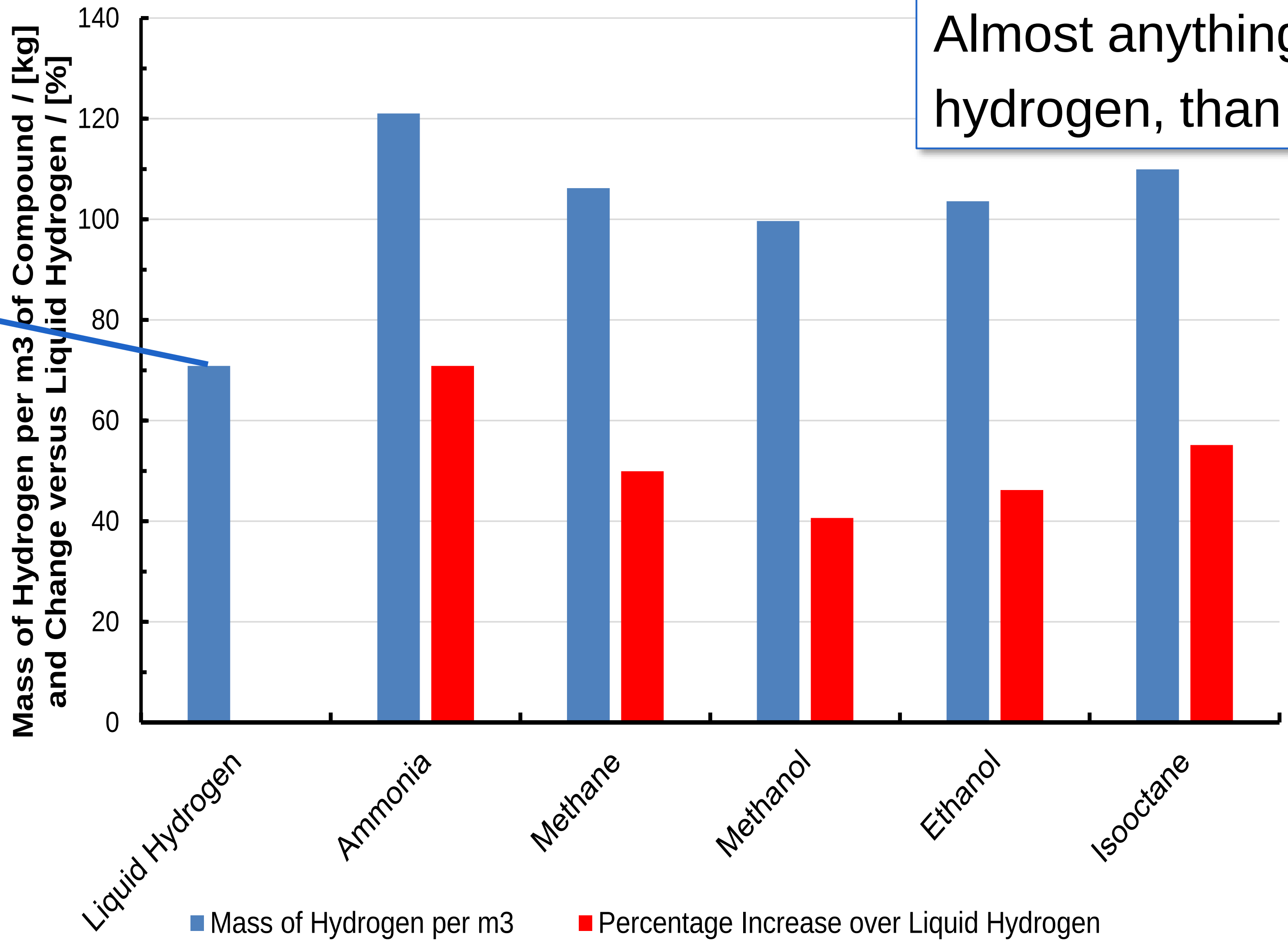
HYDROGEN PROPERTIES

- Very low density at atmospheric conditions
  - 14 times lighter than air (ρ_{H2}: 0.08 kg/m³)
  - 1 kg of H_2 contains a lot of energy (LHV 120 MJ)
    - energy equivalent to 3.6 liter of gasoline
  - But still: very low density!
    - i.e. 3.3 m³ H_2 for same energy as 1 liter of gasoline
- Solutions
  - Compressed, @700 bar: 6 liters (net), 12 liters (system) for 1l gasoline eq.
  - Liquified, -253°C: 3.5 liters (net), 8 liters (system) for 1l gasoline eq.

H_2: VERY BAD AT STORING HYDROGEN!

Almost anything is better at storing hydrogen, than hydrogen itself!

70kg/m³
The density of styrofoam!



Progr Energ Comb Sci 70:43

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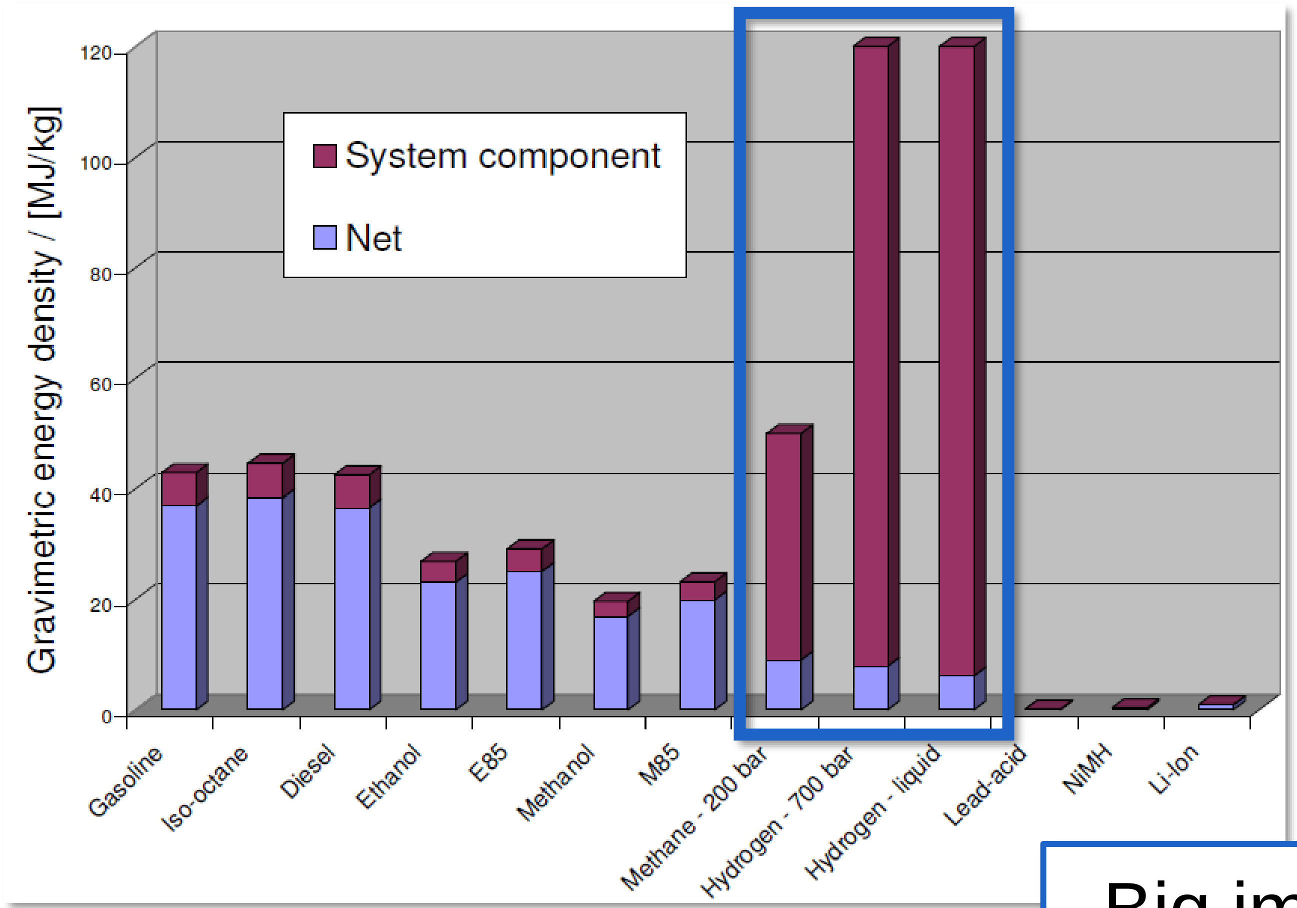
DON'T FORGET STORAGE SYSTEM!



Big impact for gases

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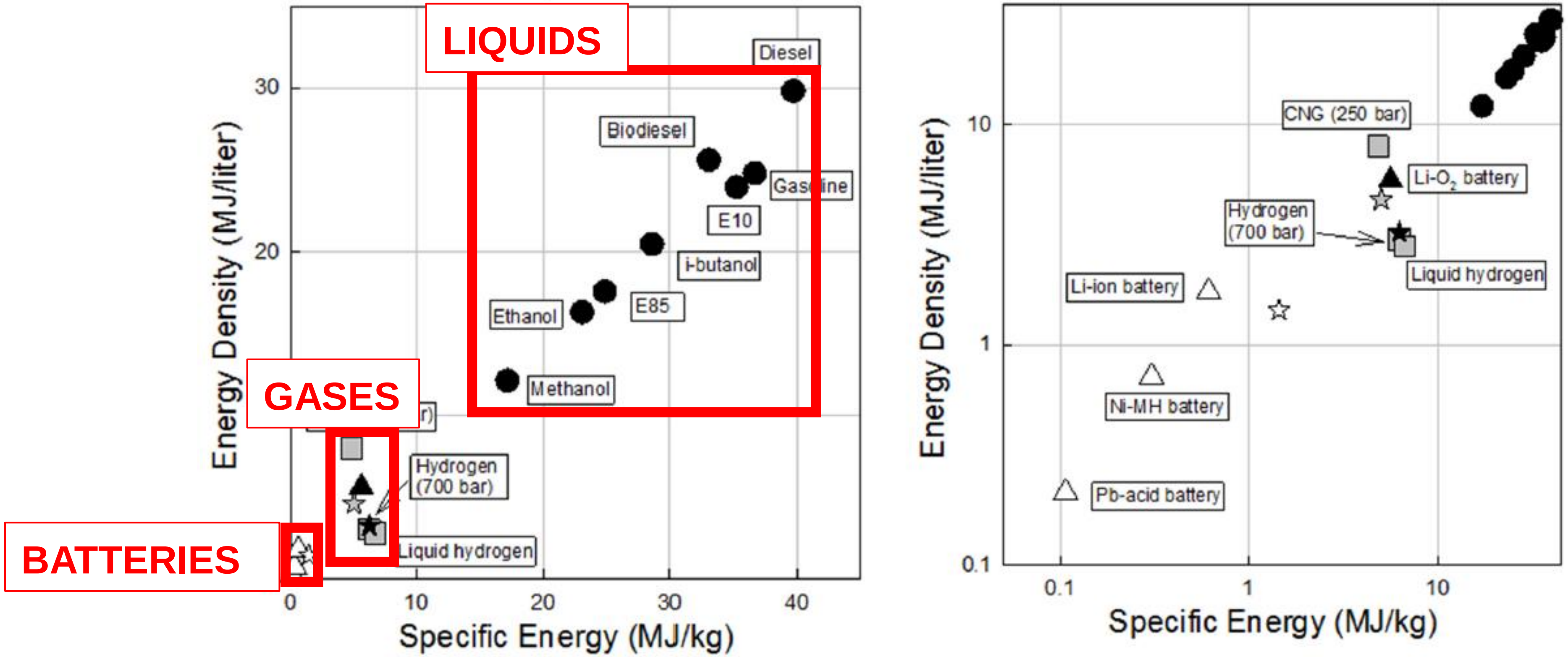
NET ENERGY DENSITY AND SPECIFIC ENERGY FOR SELECTED ENERGY CARRIERS



Volume and weight are important for (heavy) transportation:

- Weight → rolling resistance (+ road limits)
- Volume → competition with cargo (money maker) or machinery

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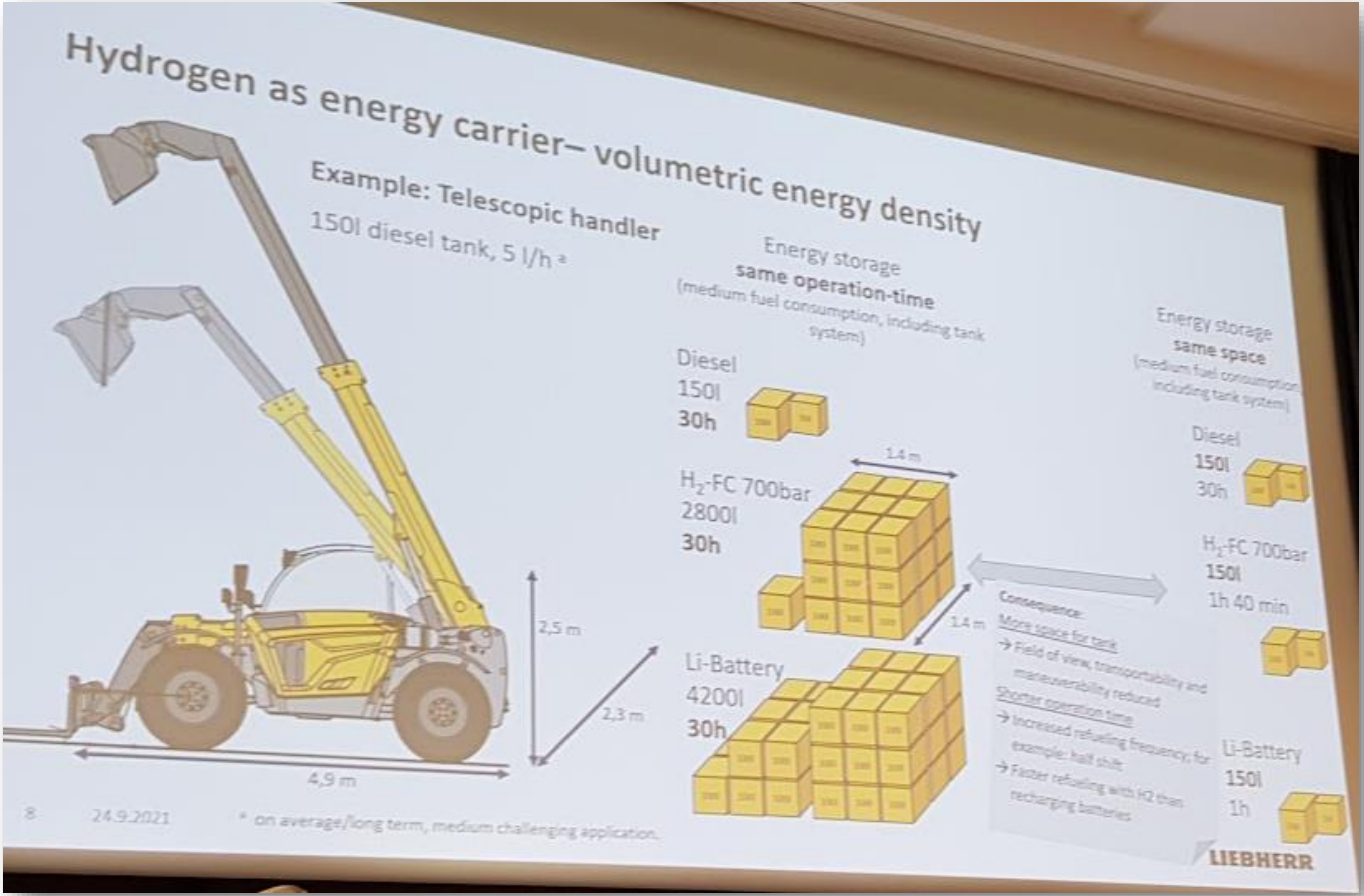
Wallington TJ et al. DOI:10.1021/ed3004269



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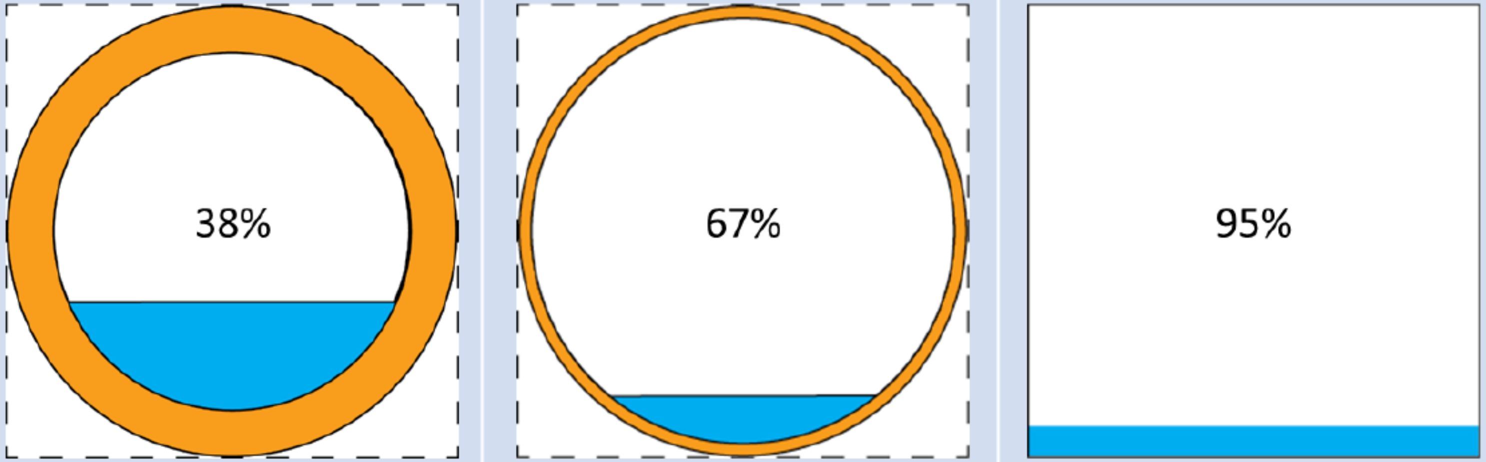
EXTRA: “PRACTICAL” STORABILITY

ALTERNATIVE FUELS

STORAGE SYSTEM

	LH_2	NH_3	MeOH
State	20 Kelvin, 1 bar	240 Kelvin, 1 bar	298 Kelvin, 1 bar
Shape	Round	Round	Rectangular
Effective volume [%]	38%	67%	95%



RULES OF THUMB ENERGY STORAGE

€ 250

x10

€ 2.500

x10

€ 25.000

Scalability also means affordability!

Bit more complicated…

450 kWh, 900km

90 kWh, 450km

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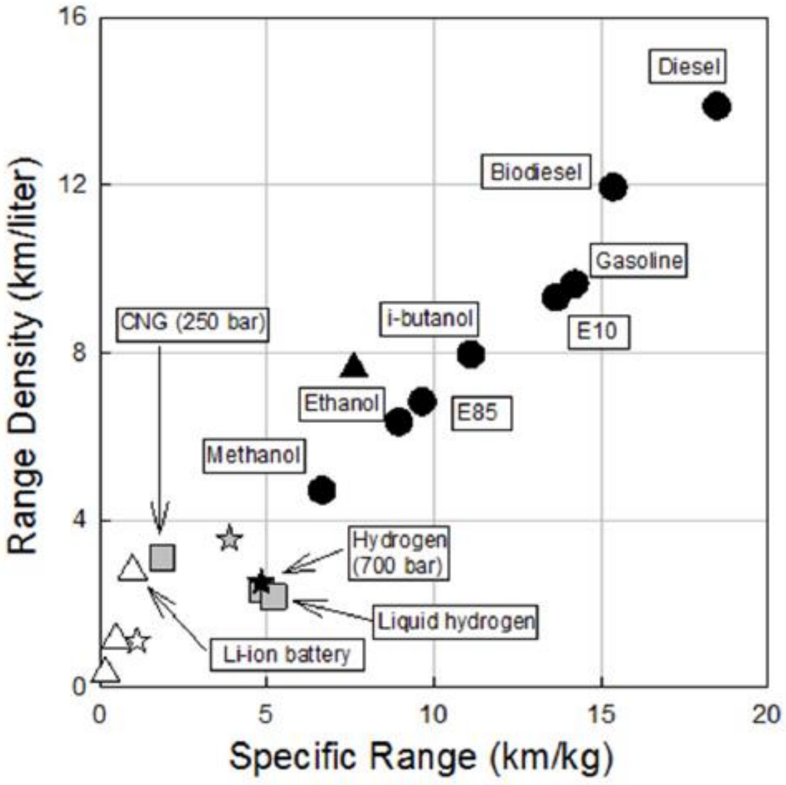
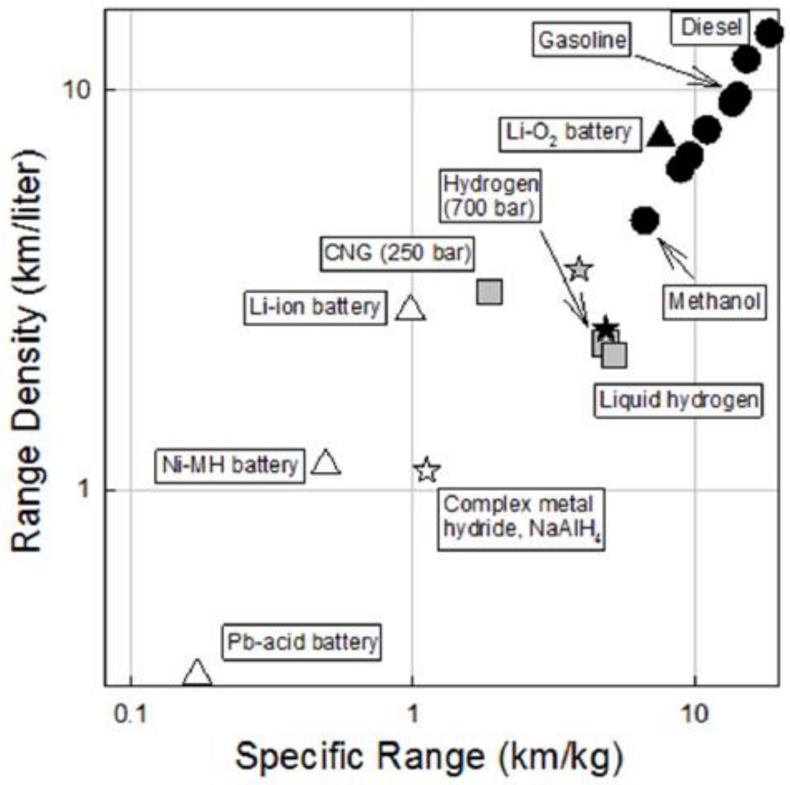
VOLUMETRIC AND GRAVIMETRIC **RANGE DENSITIES** FOR SELECTED FUELS

Counting conversion efficiency (EV vs. FC vs. ICE)





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HYDROGEN?

- Needed to talk about hydrogen

  … to explain

  … why I’m not going to talk about hydrogen!
- It’s simply not energy-dense enough

  for many applications
  - Even if it’s technically feasible, it’s either not practical or economical to use it

WHICH FUELS THEN?

WHICH FUELS THEN? BIO?

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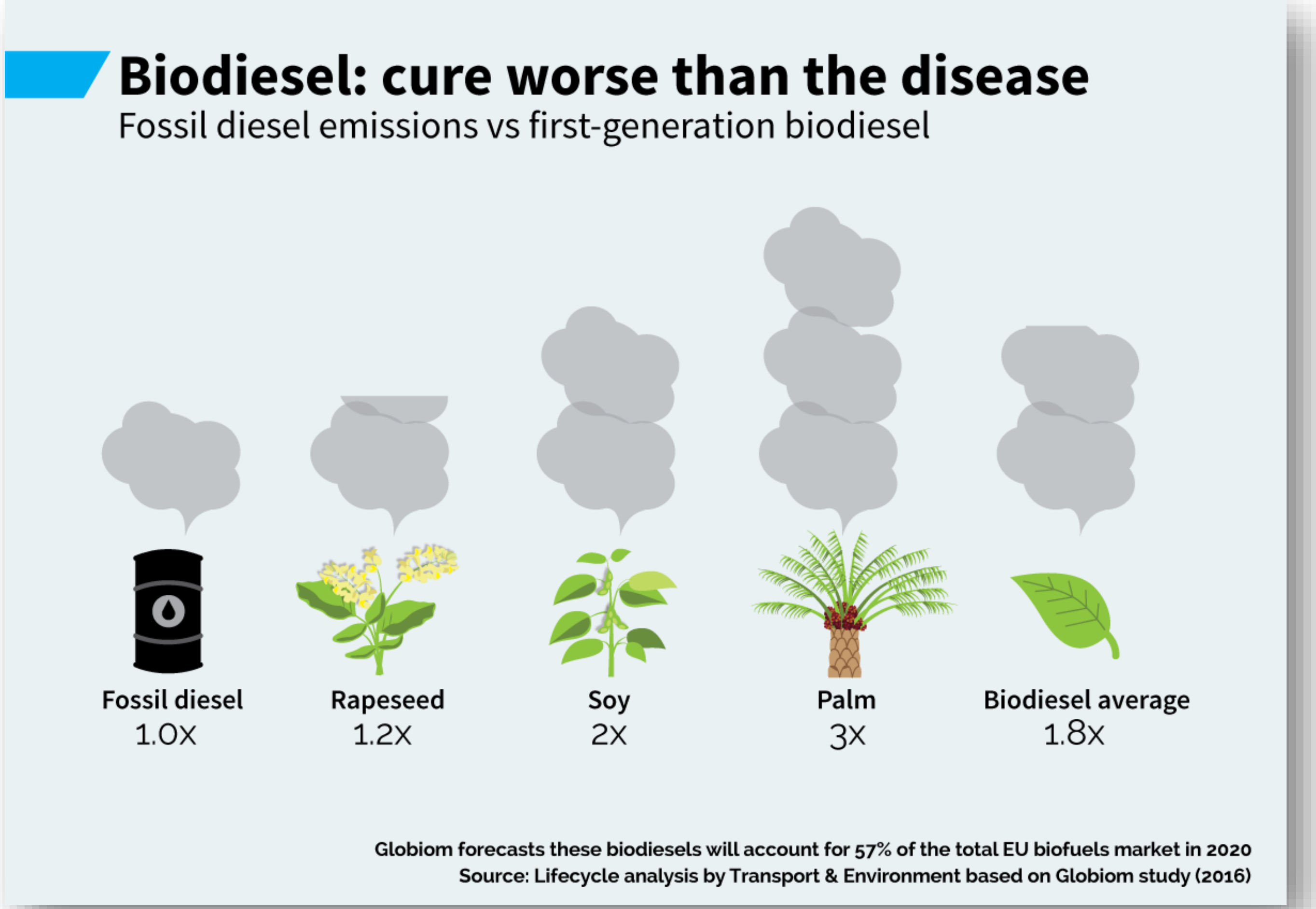
RENEWABLE FUELS AVAILABLE TODAY: BIO

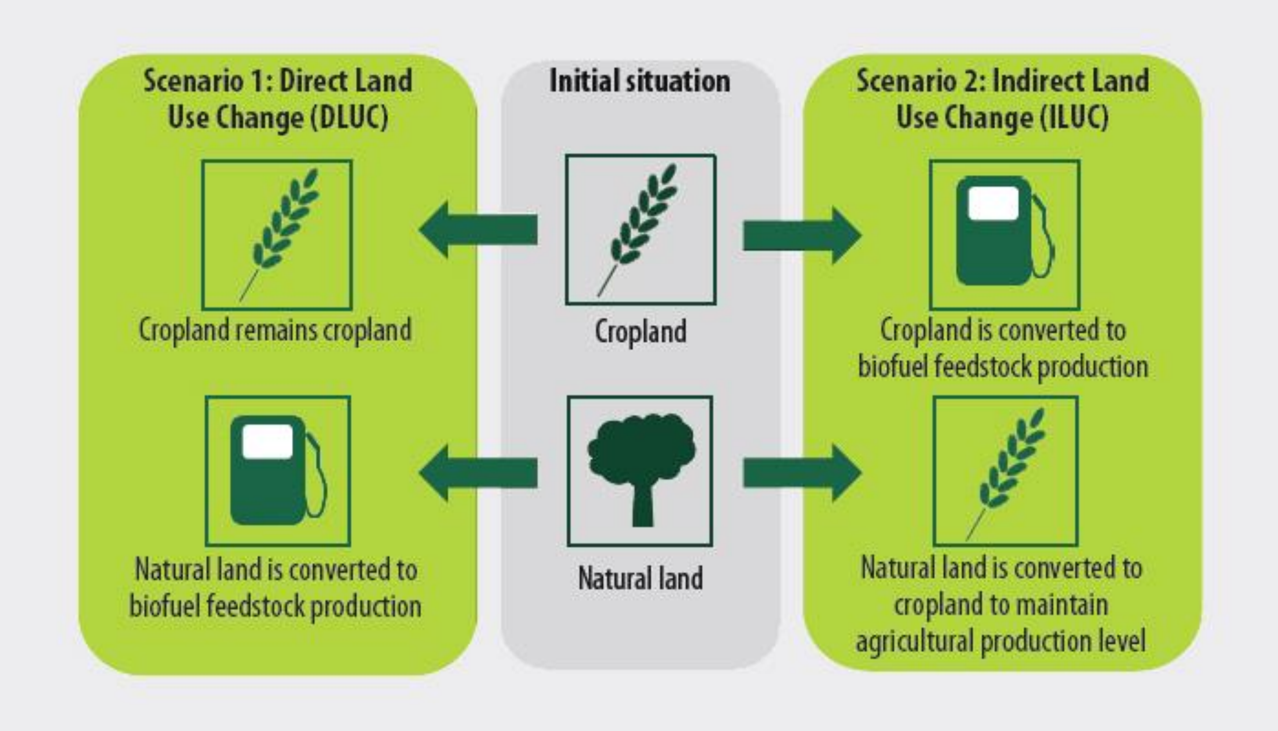
- You know this
  - Fueling a gasoline car: up to 10vol% is bio-ethanol
    - From sugar beet/cane, maize, corn, …
    - 2022: 84Mton produced (56Mton gasoline equivalent
      - 7% of annual gasoline consumption)
  - Fueling a diesel car: up to 7vol% is biodiesel
    - From rape seed oil, soy, palm, …

BIOFUELS: WORSE THAN FOSSIL FUELS?



HOW COME?

- Fossil fuel use for farm equipment, transport
- Indirect land use change!
  - “unintended consequence of releasing more carbon emissions due to land-use changes induced by the expansion of croplands for biofuel production”
  - Extreme example:
    burn down rainforest
    (carbon sink → emission)
    to grow palm



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BIOFUELS VS. GHG

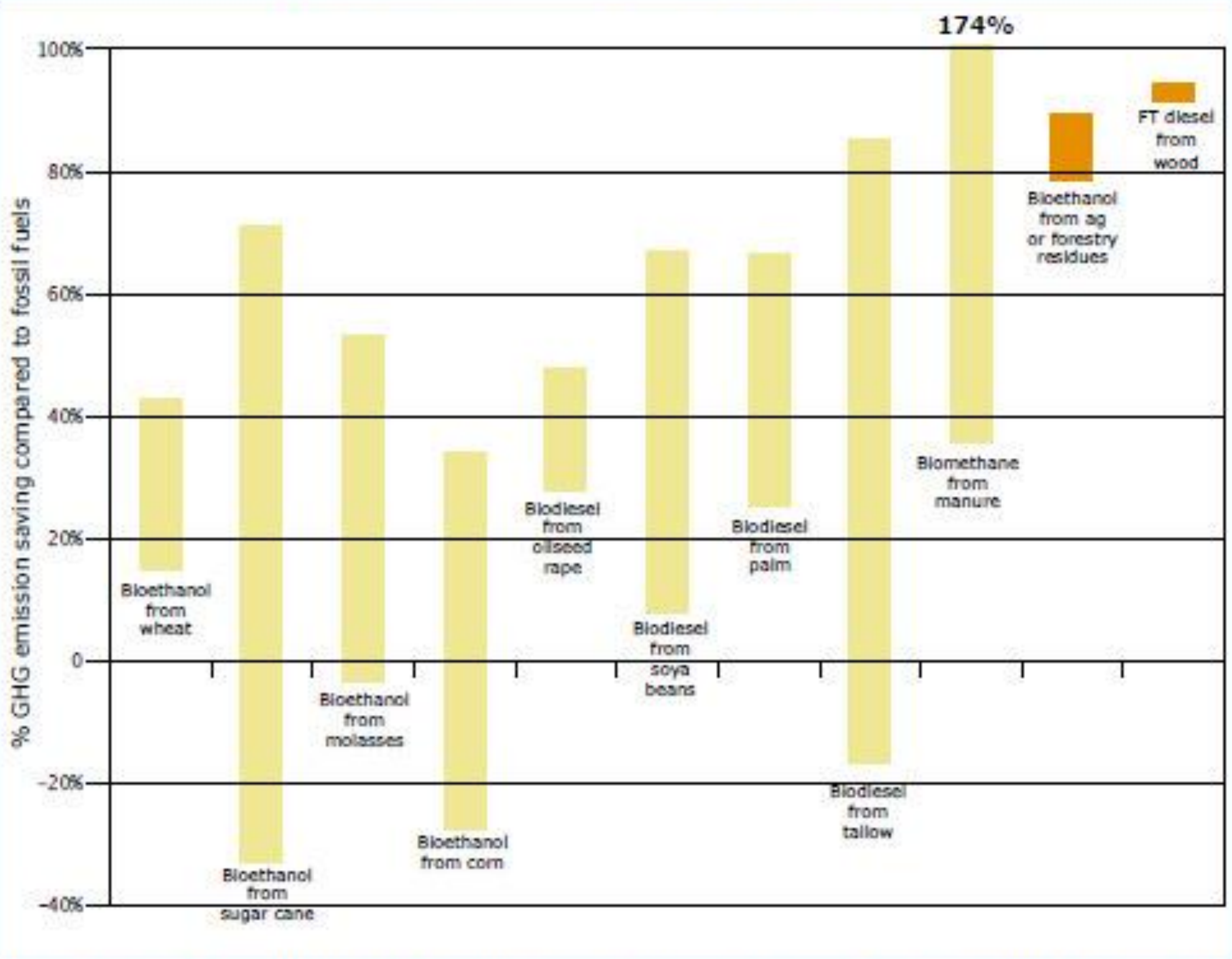
Complex!

But no reason to abandon this option altogether?

Table 2.1: Illustrative GHG savings and payback times for biofuel feedstock causing land change[13]

Fuel chain	Assumed country of origin	GHG saving excluding the impacts of land-use change	Carbon payback (years)	
		%	Grassland	Forest
Palm to biodiesel	Malaysia	46%	0 – 11	18 – 38
Soya to biodiesel	USA	33%	14 – 96	179 – 481
Sugarcane to bioethanol	Brazil	71%	3 – 10	15 – 39
Wheat to bioethanol	UK	28%	20 – 34	80 – 140

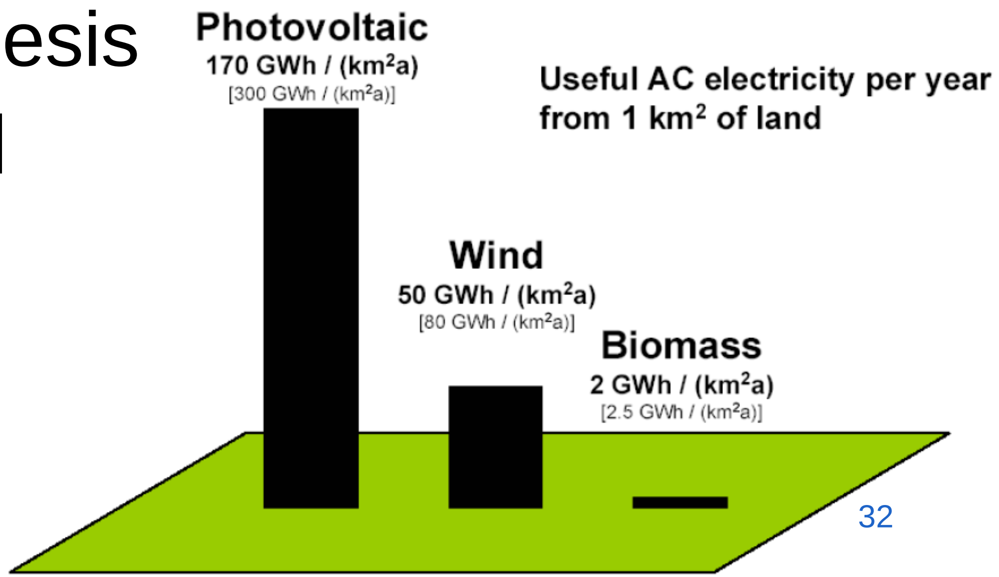
Figure 2.2: Estimated GHG savings of current biofuels



Note: current technologies are shown in yellow, advanced technologies in orange

POTENTIAL OF BIOMASS?

– "Biomass limit": amount of sustainable biomass available worldwide, for energy
  – Very large geographical spread
    – E.g. Belgium versus Sweden
  – Consensus: biomass is insufficient for meeting our energy demand
    – Cause: low efficiency photosynthesis
  – No consensus on actual potential
    – Varies – 20% EU, to 50% world?



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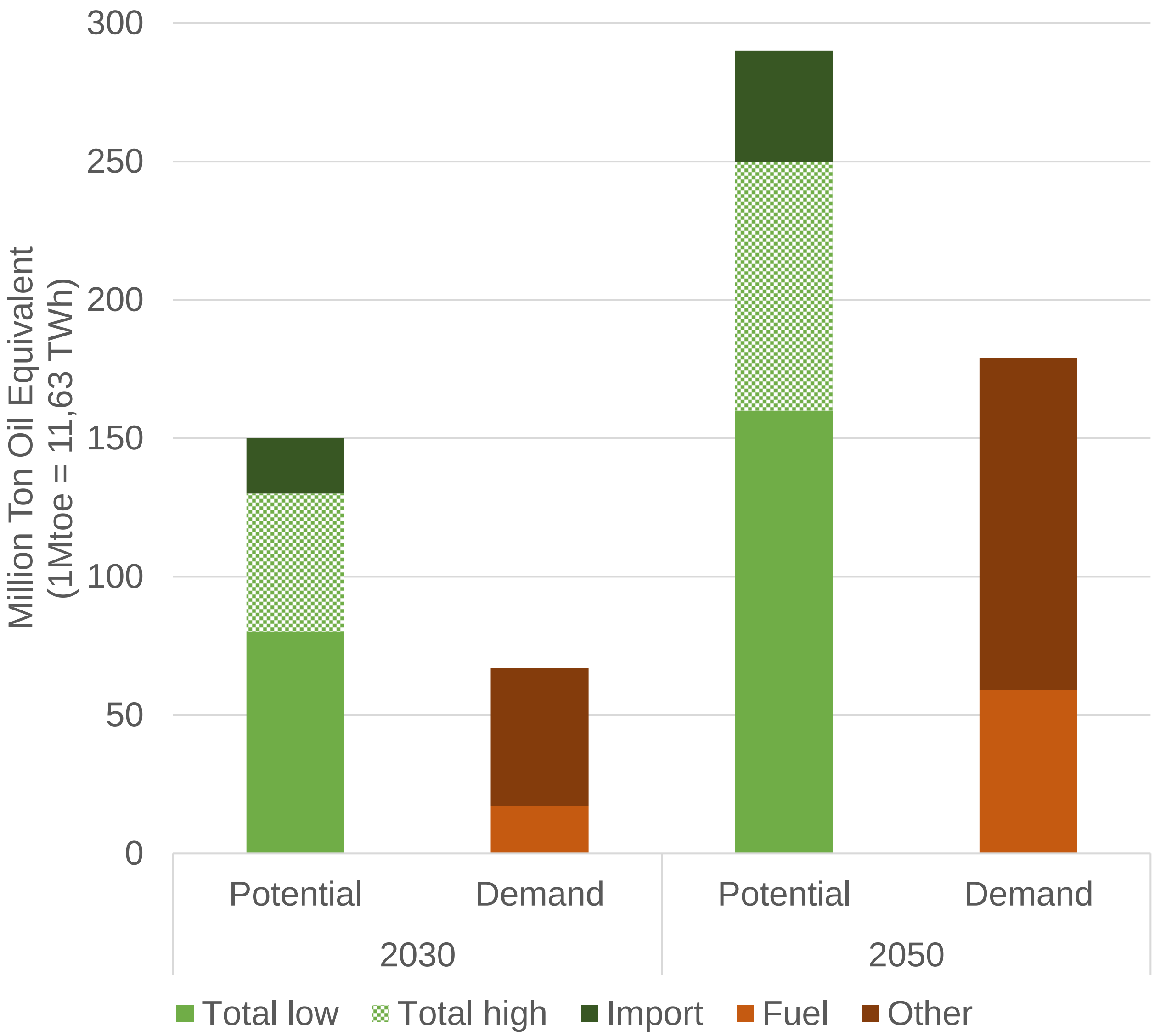
BIOMASS AVAILABILITY IN EU?



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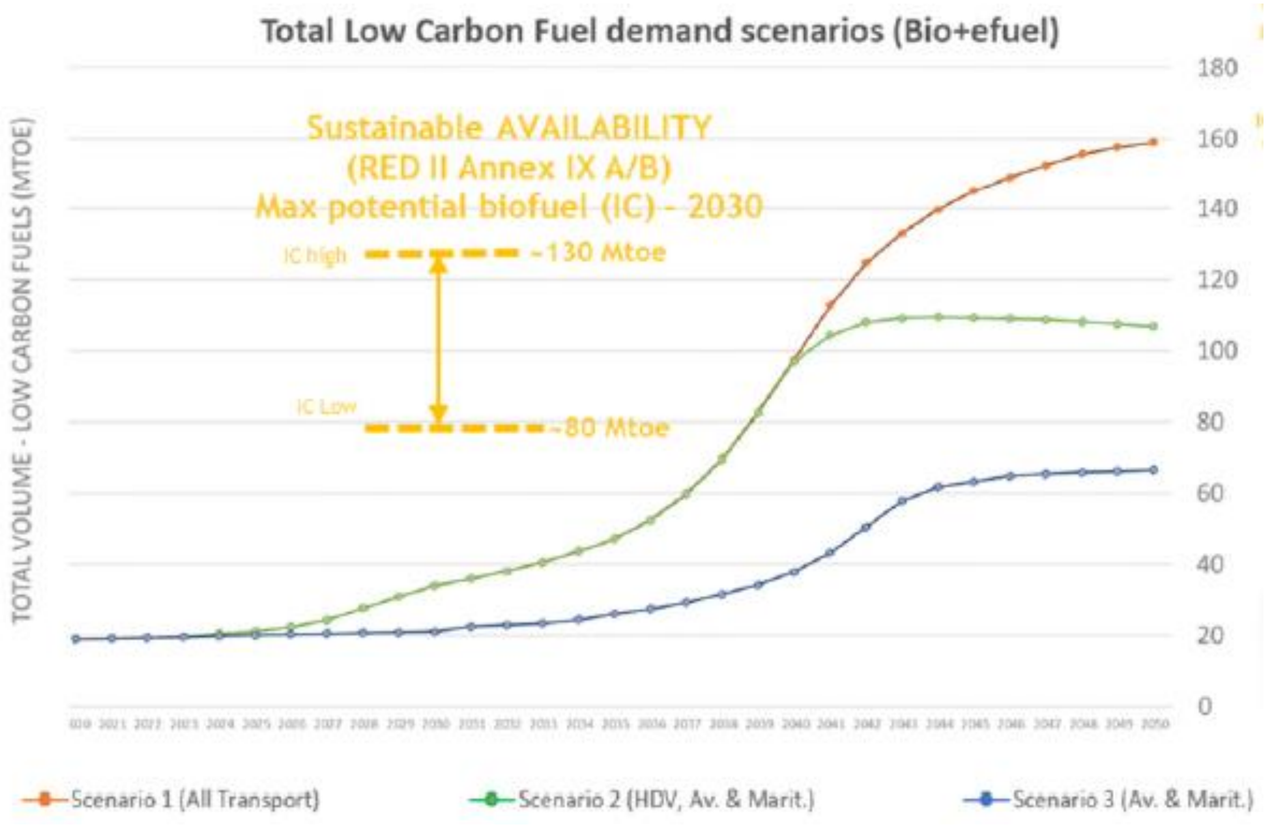
BIOMASS ASSUMPTION

Availability

Biofuel equivalent (MAX YIELD SCENARIO)	Feedstock	Max potential adv biofuel availability (2030)	Max potential adv biofuel availability (2050)
HVO	Waste oil and fats	2	2
	UCO	3	6.5
Cellulosic ethanol	Agricult.residues (straw-like)	21-26	N/A
	Lignocellulosic crops	5.5-16	6.5-19.6
Gasification + FT	Biowaste	9-17	13-24
	Solid industrial waste	28-40	57-84
	Agricult residues (straw-like)	0	54-62
	Agricult residues (woody)	1	2-3
	Lignocellulosic crops (woody)	8-23	17-51
	TOTAL liquid biofuels - All bioenergy	**80-130**	**160-250**



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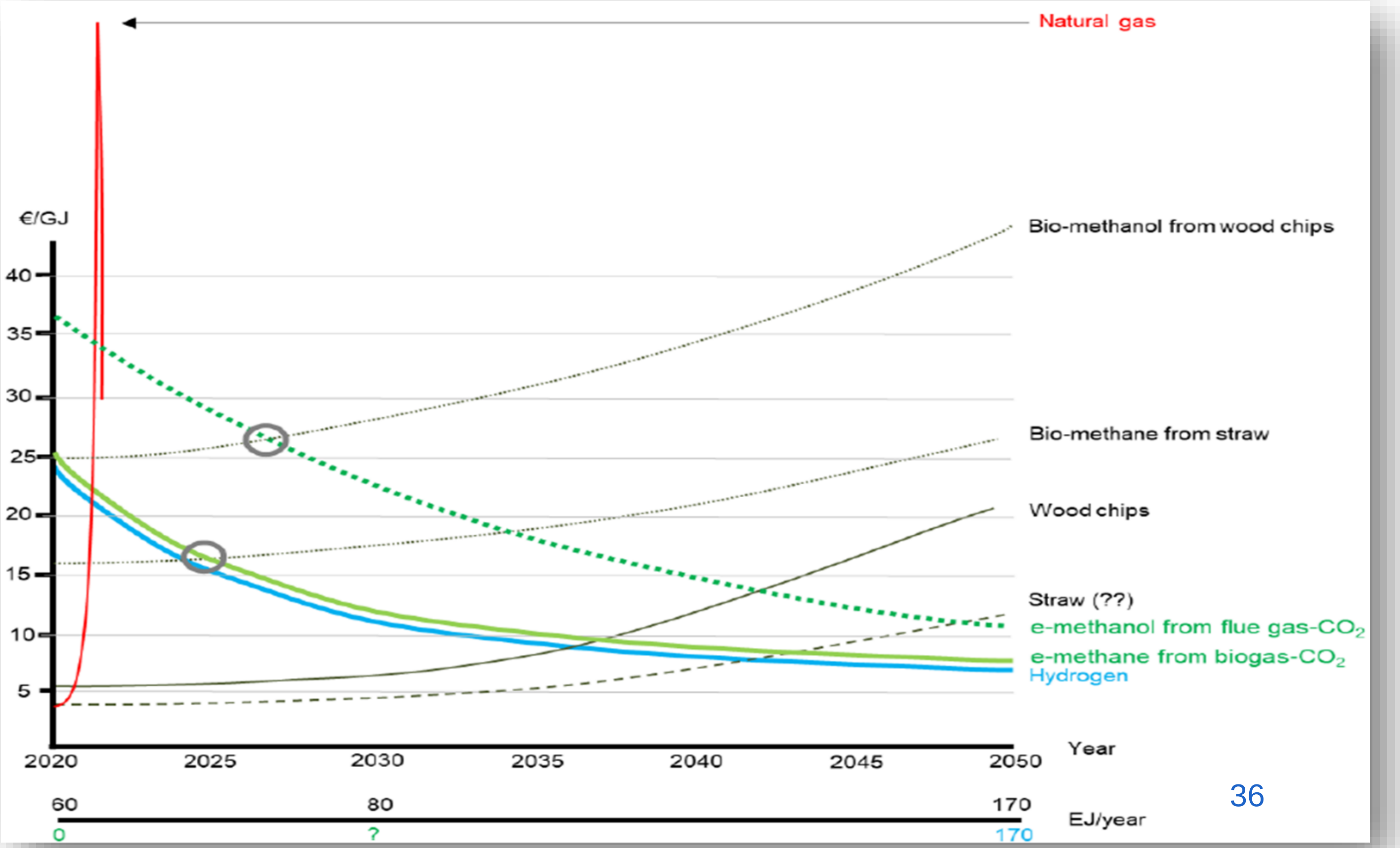
Source: (Panoutsou et al., 2021, Soler, 2021, Yugo, 2021)

“BIO” VS. “E”

- Short-term, molecules from biomass most interesting (~developed market)
- Long term, the expectation is that the “e-route” takes over
  - No “biomass limit”: more scalable
  - Hence, likely to become cheaper



WHICH FUELS THEN? “ELECTRO”?

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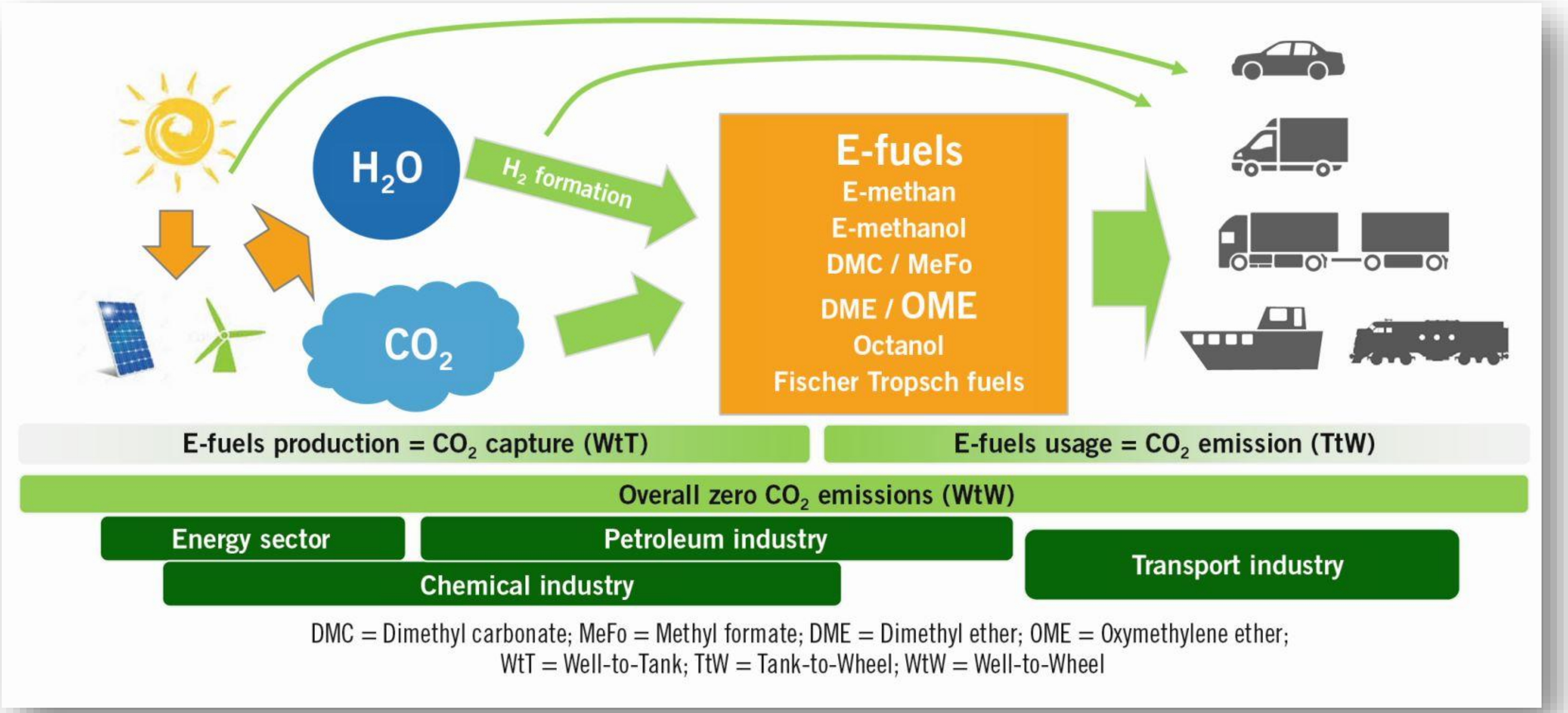
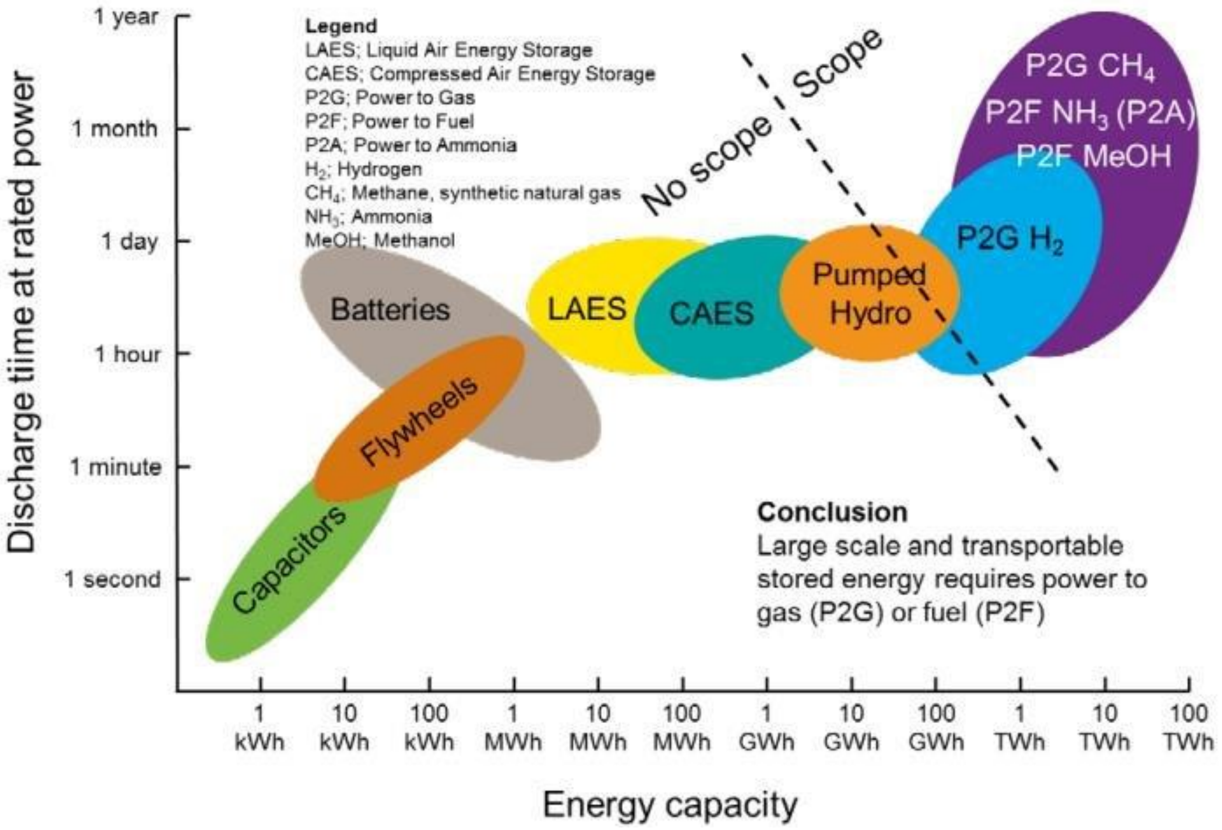
RENEWABLE FUELS

- Solar fuels, e-fuels, “liquid electricity”, …
- Making sustainable energy storable



POWER TO…

- Renewable power P to
  - Gas: PtG
  - Liquids: PtL
  - General: PtX, power-to-X
- Round trip: X-to-power
  - Hence PtXtP, P2X2P etc.



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WHICH FUELS?

- So, we need fuels... let's make what we want then:
  - Sufficient energy density & preferably simple molecules
    - Production is more efficient (Well To Tank energy use)
    - Conversion is more efficient (Tank To Well energy use)
- Abundantly available building blocks: C, H, O, N, …
- Thus, most simple fuels:
  - Hydrogen, H_2 (at p_{atm}, liquid at 20K)
  - Methane, CH_4 (at p_{atm}, liquid at 91K)
  - Ammonia, NH_3 (at T_{atm}, liquid at 8.6 bar)
  - Methanol, CH_3OH (liquid)
  - Dimethylether (DME), CH_3OCH_3 (liquid at 5.3 bar)
  - …

Why not stop at hydrogen?

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H_2 STORAGE: ENERGY IMPLICATIONS

- Making hydrogen liquid, or compressing it to 700 bar, takes as much energy as making e.g. methanol from it
  - Between 10% (CH_2) and 40% (LH_2) of the heating value
- E.g. methanol is using CO_2 to carry H_2 more efficiently!

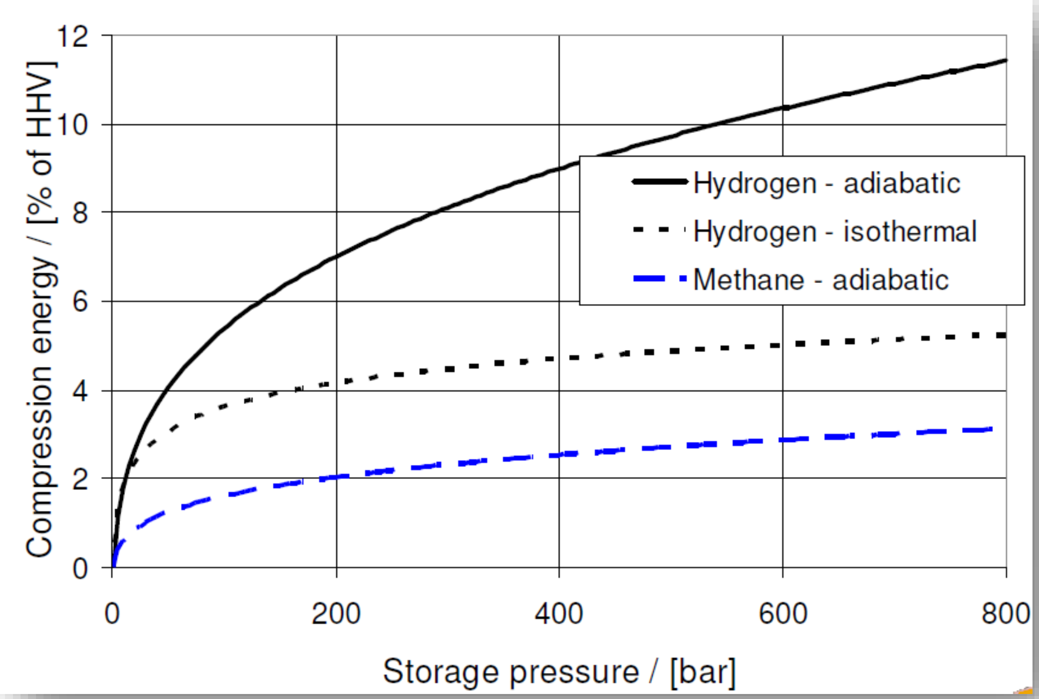

Fig. 6. ***Energy needed for the road delivery of fuels relative to their HHV energy content.***

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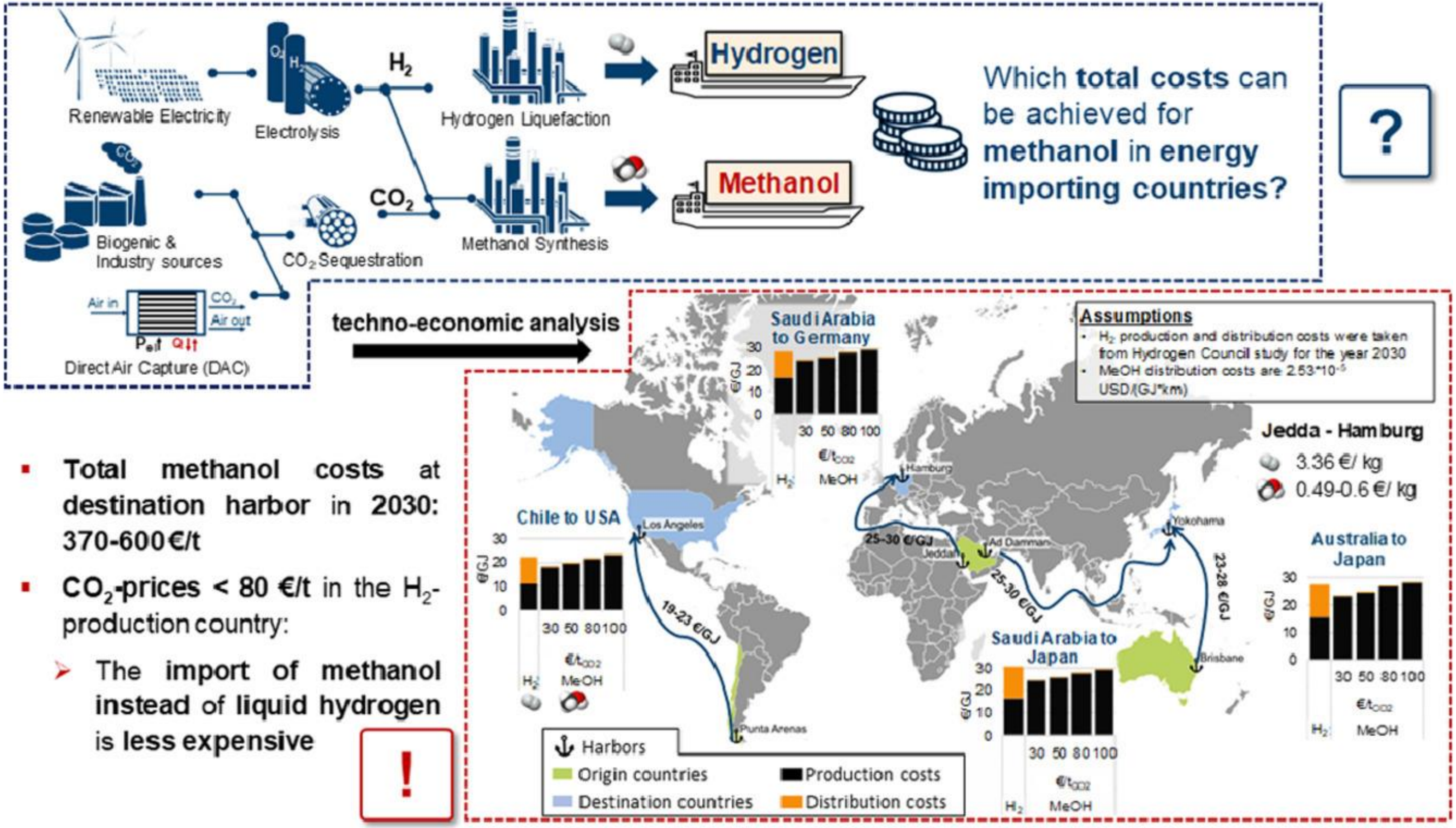
Methanol as a Renewable Energy Carrier: An Assessment of Production and Transportation Costs for Selected Global Locations

F. Schorn, J. L. Breuer, R. C. Samsun, T. Schnorbus, B. Heuser, R. Peters, D. Stolten



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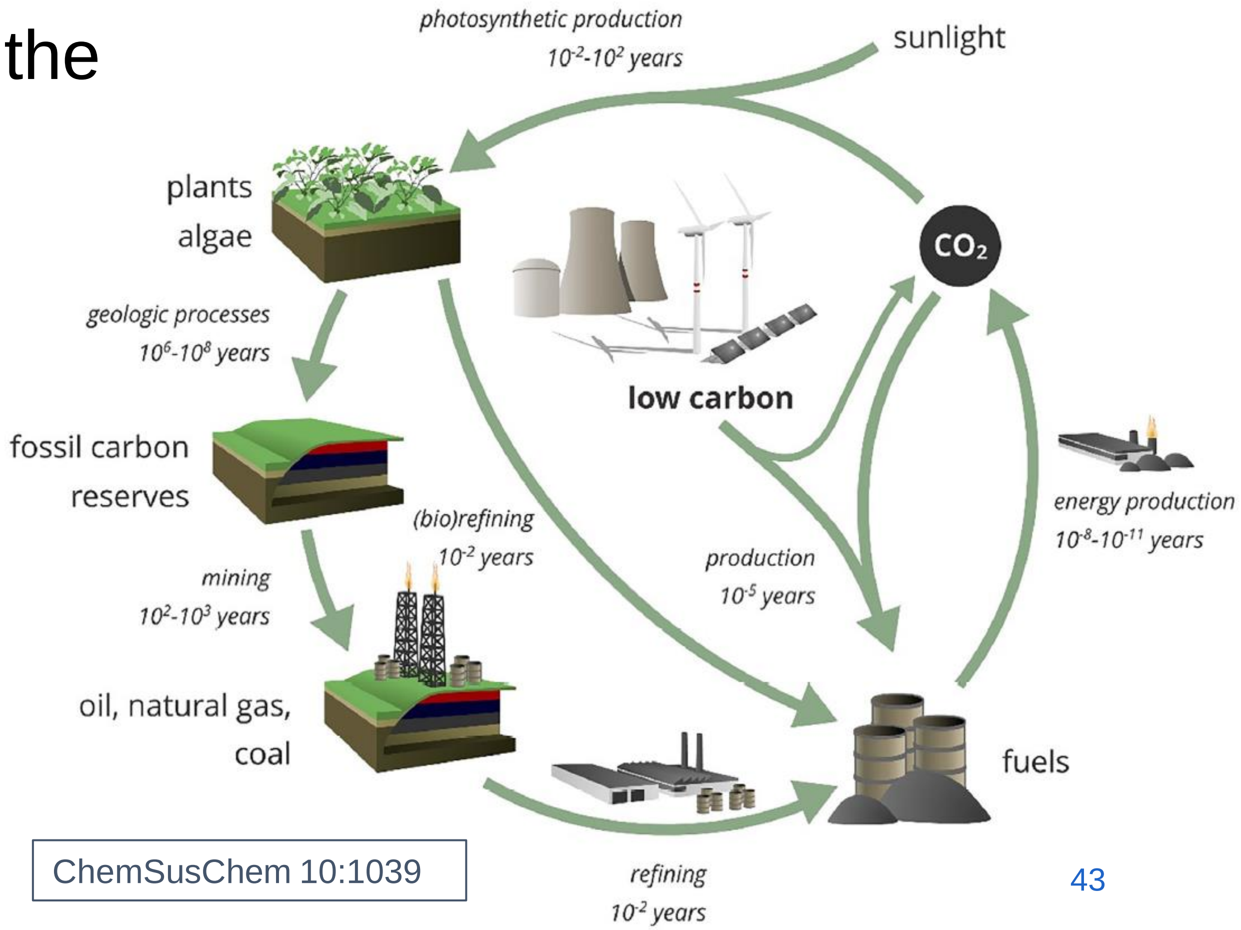
CAN WE USE CARBON?

- A carbon bond outperforms most others, in terms of energy densities
- Note carbon in itself is not a problem – the whole biosphere works on it!
- But: we need to restore the carbon balance
  → close the carbon cycle, increase the speed at which carbon is captured
  - Can't rely on fossilization,
    can't rely on biomass: too slow
  - Must use chemistry, driven by renewable energy, to capture carbon



ChemSusChem 10:1039

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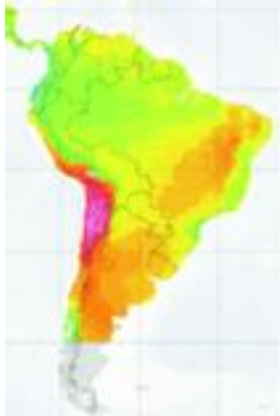
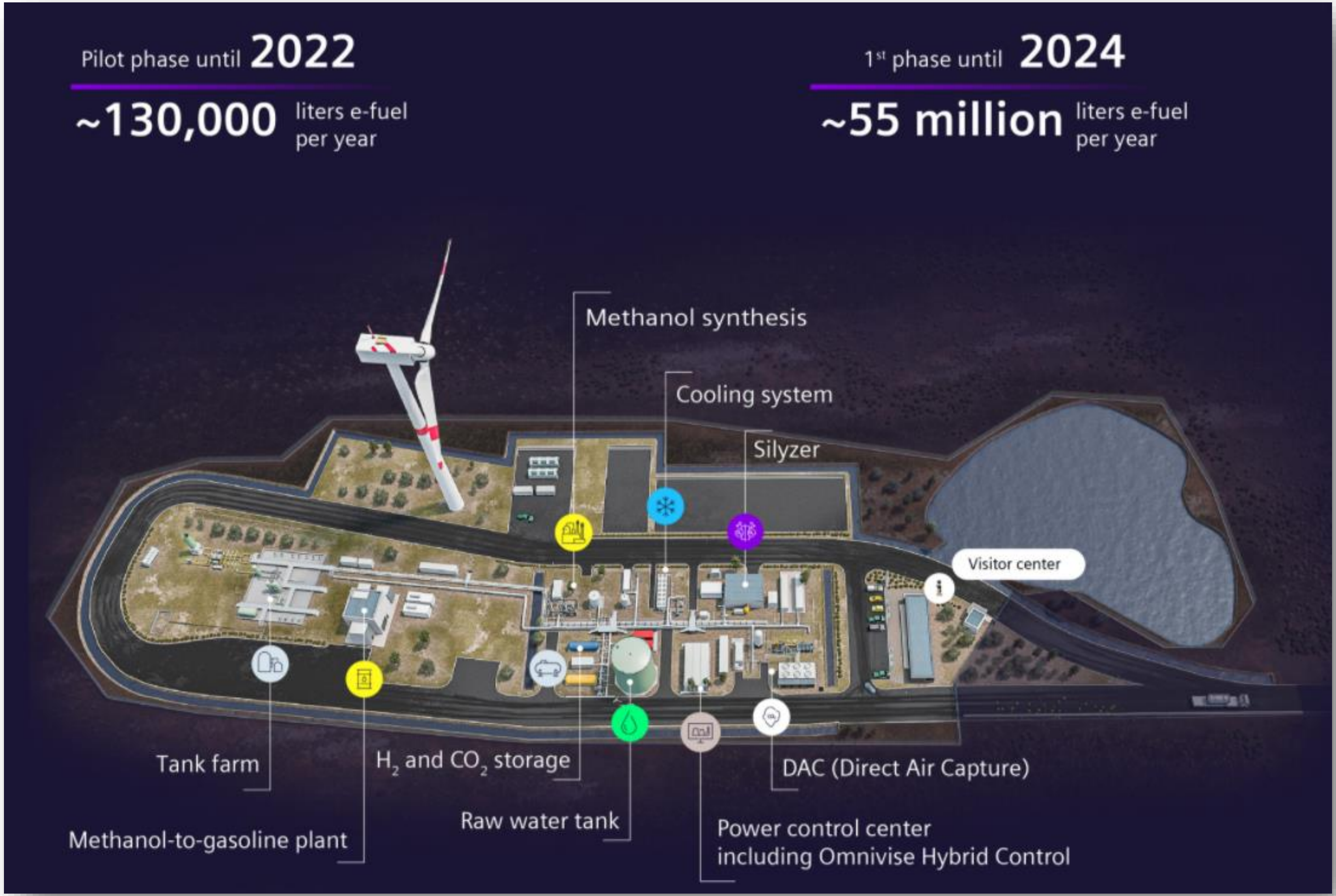
CARBON: WHICH?

- Could/should start with point sources
  - 50% of carbon emissions are from those “point sources” (emitting > 100kton/y) – with high CO_2 concentration
- Waste sources
  - E.g. black liquor (paper industry)
  - E.g. waste-to-methanol plants (municipal waste)
- Bio-carbon
  - Hybrid production processes: “e-H” with “bio-C”
- Direct air capture (DAC): capturing CO_2 from the air
  - Currently just 10.000 ton/y
  - Intensive R&D (might also need it for negative-carbon schemes)
  - Final option (most energy-demanding: lowest carbon concentrations)

PORSCHE – SIEMENS E-FUEL PROJECT CHILI





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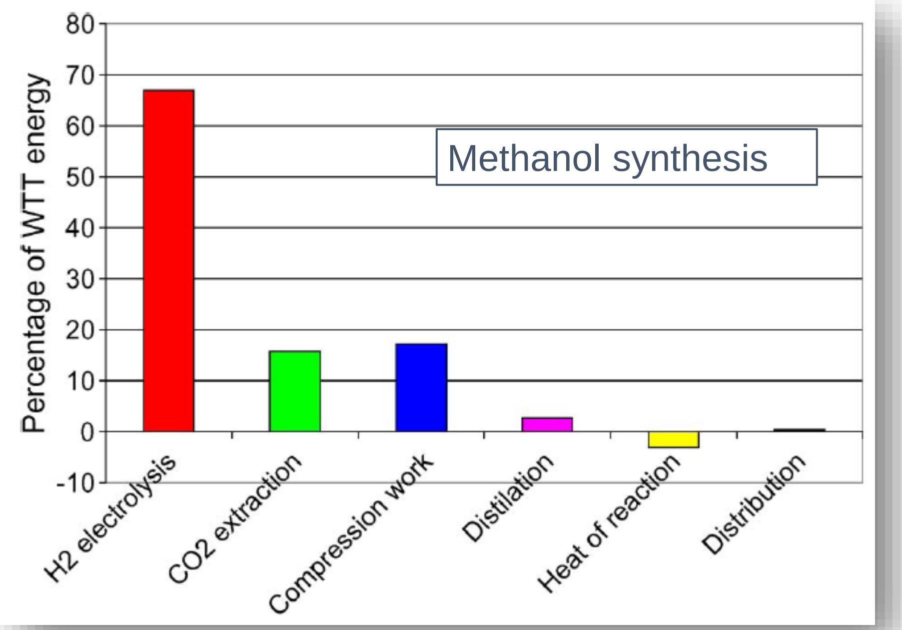
PRODUCTION EFFICIENCIES?

- Some surprises
  - Carbon capture does not come for free, but it's producing hydrogen that is the biggest energy chunk
  - Example: methanol production
  - Ammonia production: splitting nitrogen is also energy intensive: N≡N
  - Thus, there are differences (and there is a range of numbers in the literature), but it's not that big



PIEEE 100(2):440-460

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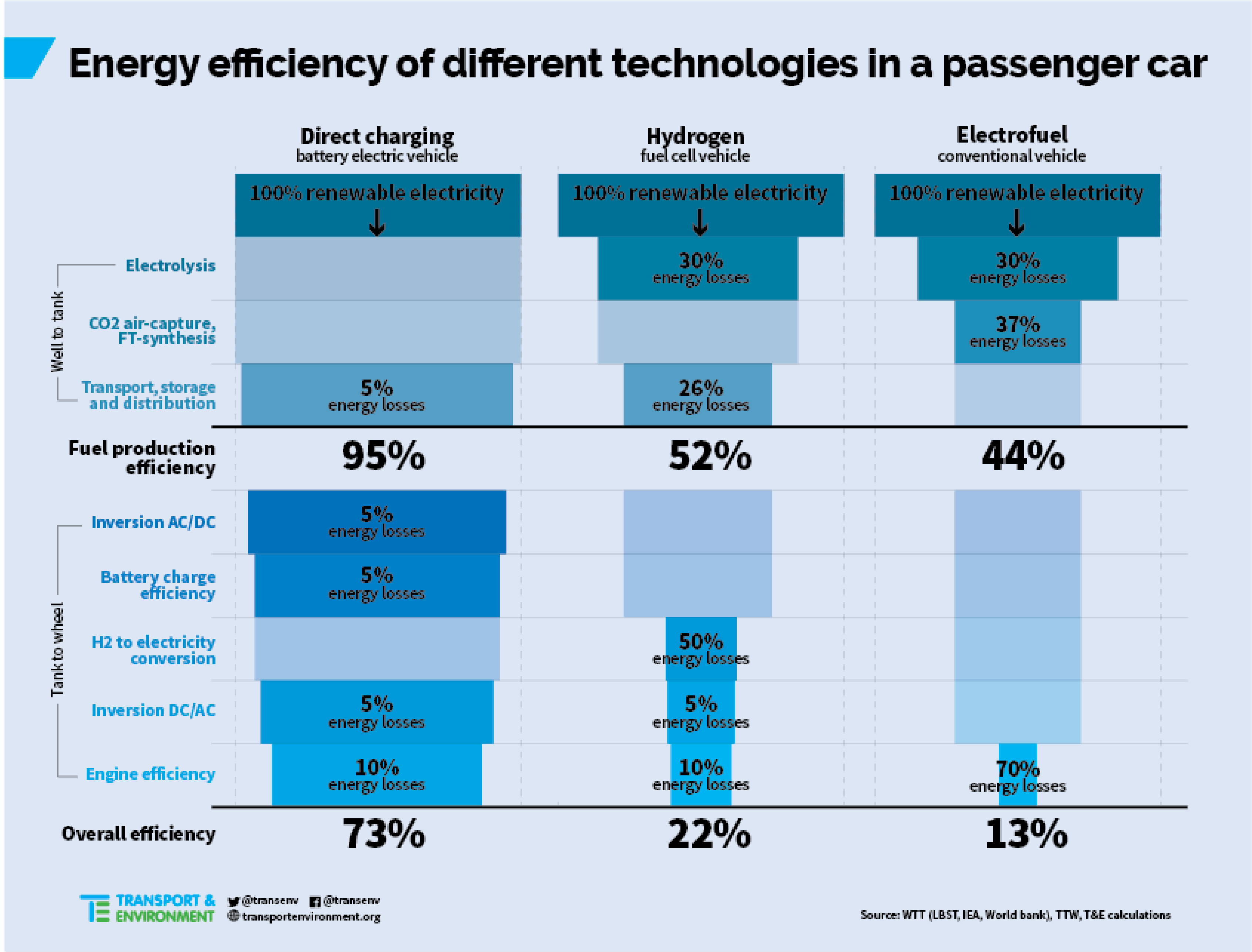
GO E-FUELS!

- Or not?
- Overall efficiency explains heavy opposition
- But ignores lifecycle perspective, and that energy efficiency is not the only criterion



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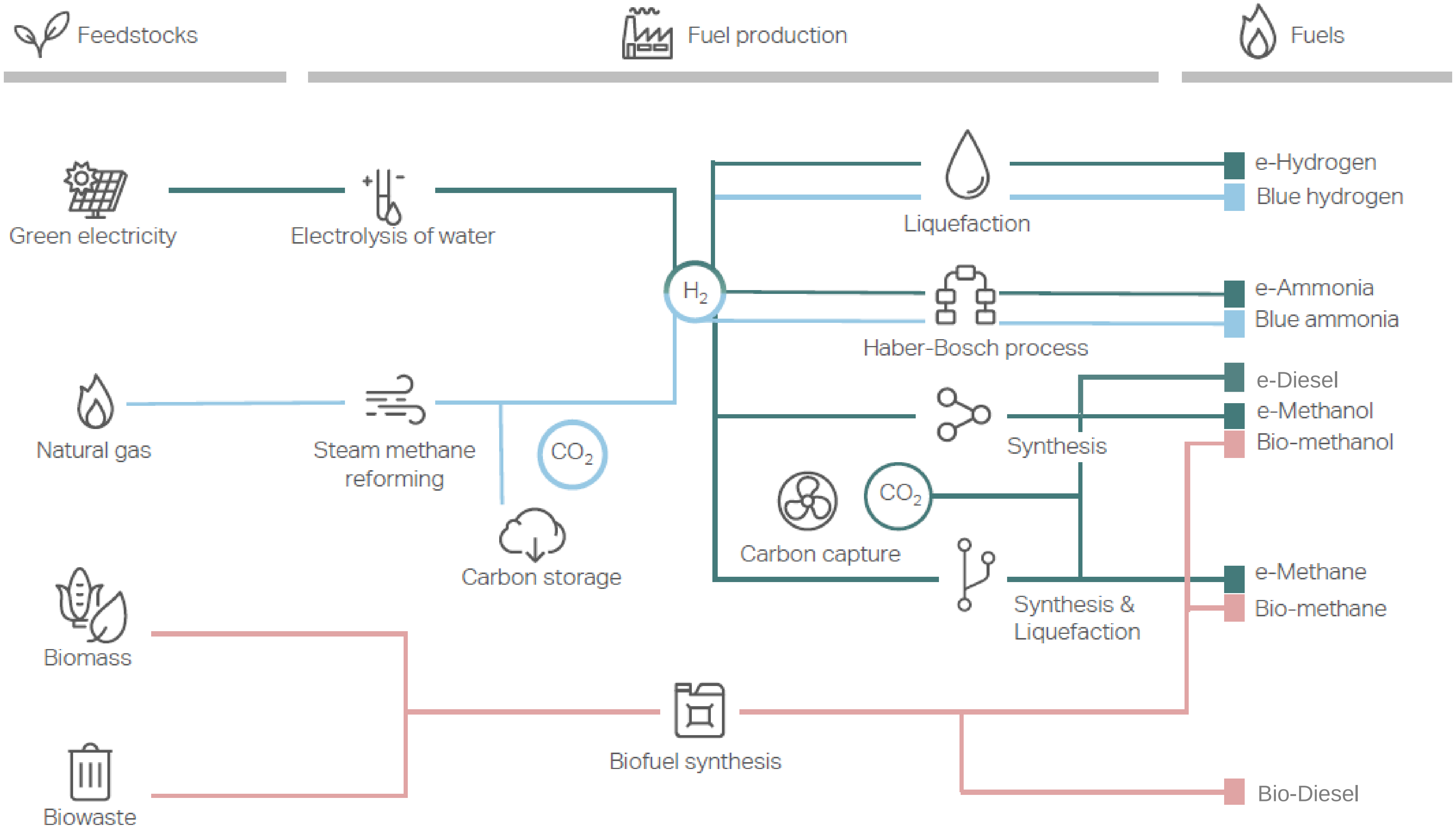
PRODUCTION PATHWAYS



Source: MMMCZCS, 2021

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CAREFUL WITH DEFINITIONS

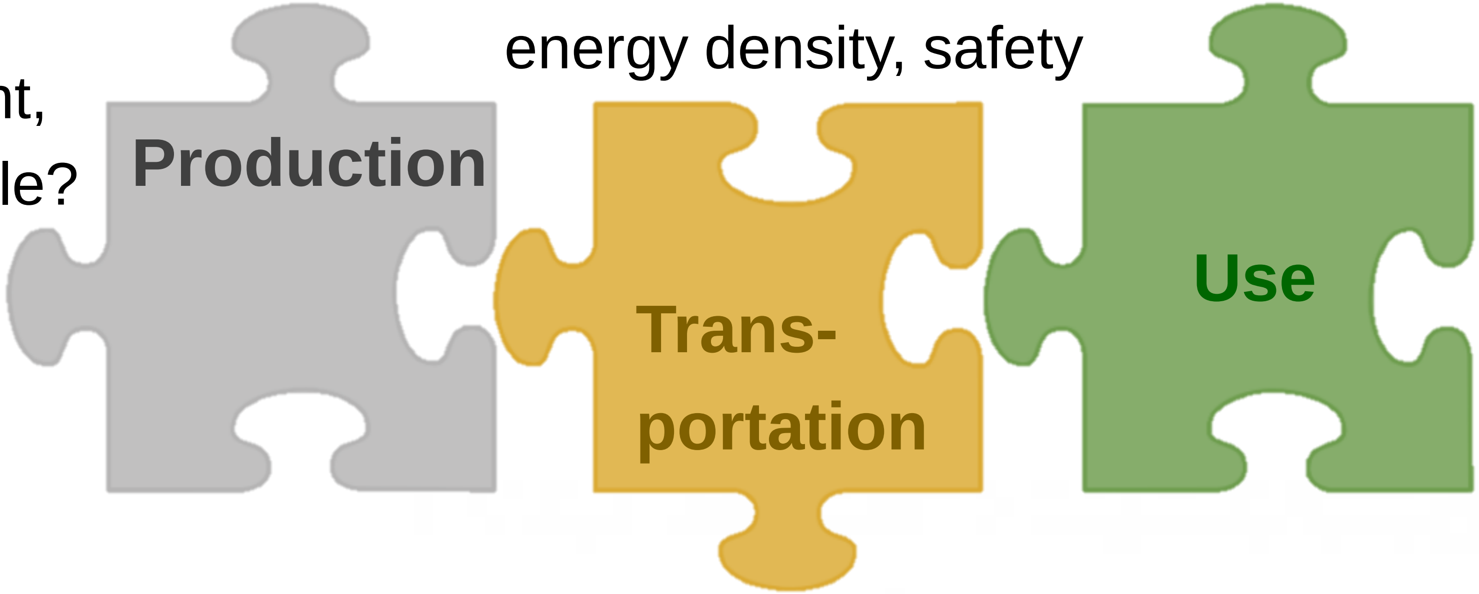
- E-fuels can mean several things
  - The shipping sector lists
    e-hydrogen, e-methane, e-methanol, e-ammonia
    - As fuel cost is a large part of the lifecycle cost
  - The (fossil) fuel and car industry means synthetic gasoline & diesel
    - As “drop-in” capability is very attractive
  - The aviation industry means synthetic kerosene
    - Sustainable Aviation Fuels (SAFs) (includes bio-route)

- Keep in mind producing more complex molecules (MTO/FT) demands more energy, leads to lower efficiency@use and higher emissions

WHICH FUELS?

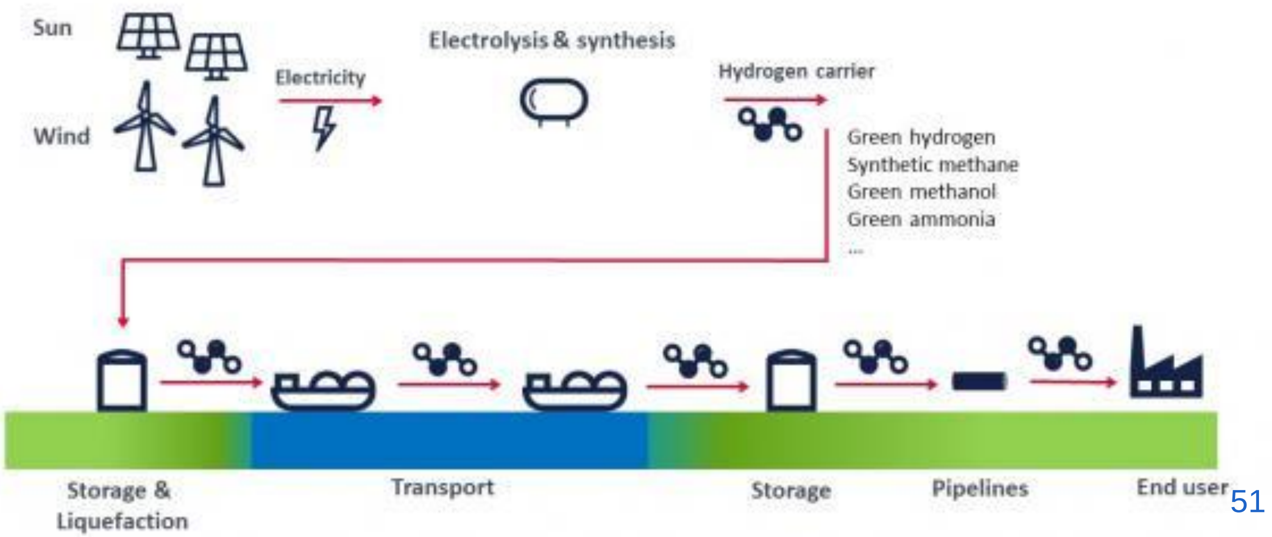
how efficient,
how scalable?

from production location
to point of use:
energy density, safety



energy
density,
how efficient,
how safe,
how clean?

Need to look at all parts of the energy carriers' "life"



EXAMPLE

++	+	neutral	-	--

Energy Carriers				Hydrogen		Methanol		Ammonia		Methane			Diesel		
				E-	Blue-	E-	Bio-	E-	Blue-	E-	Bio-	Grey-	E-	Bio-	Grey-
Availability/ Production	Short term	Local		-	+	-	+	-	+	-	+	++	-	+	++
		Import		--	--	neutral	neutral	neutral	neutral	neutral	neutral	++	neutral	neutral	++
	Long term	Local		neutral	-	neutral	neutral	neutral	-	neutral	neutral	++	neutral	neutral	++
		Import		--	--	+	+	+	neutral	+	+	++	+	+	++
Total Cost of Ownership	OPEX	Fuel production cost	Short term	--	neutral	--	neutral	-	neutral	--	neutral	++	--	neutral	++
			Long term	+	neutral	neutral	+	+	+	neutral	+	++	neutral	+	++
		Infrastructure cost		--		+		neutral		-			++		
		Engine efficiency		+		++		neutral		+			++		
	CAPEX	Propulsion cost		-		+		neutral		-			++		
		Storage cost		--		+		neutral		-			++		
		Cost of reduced cargo space		--		neutral		-		+			++		
	Overall	Short term		--	--	-	neutral	-	neutral	--	neutral	++	--	neutral	++
		Long term		--	--	-	neutral	neutral	neutral	-	neutral	++	-	neutral	++
Environmental issue	GHG emission	Well-to-Tank		++	-	++	+	++	-	++	+	+	++	-	+
		Tank-to-Wake		++	++	++	++	neutral	neutral	-	-	--	++	++	--
		Well-to-Wake		++	-	++	+	++	-	+	neutral	--	++	-	--
	Pollutant emission			-		+		-		+			--		
	Bunkering/Onboard safety			-		+		--		-			++		

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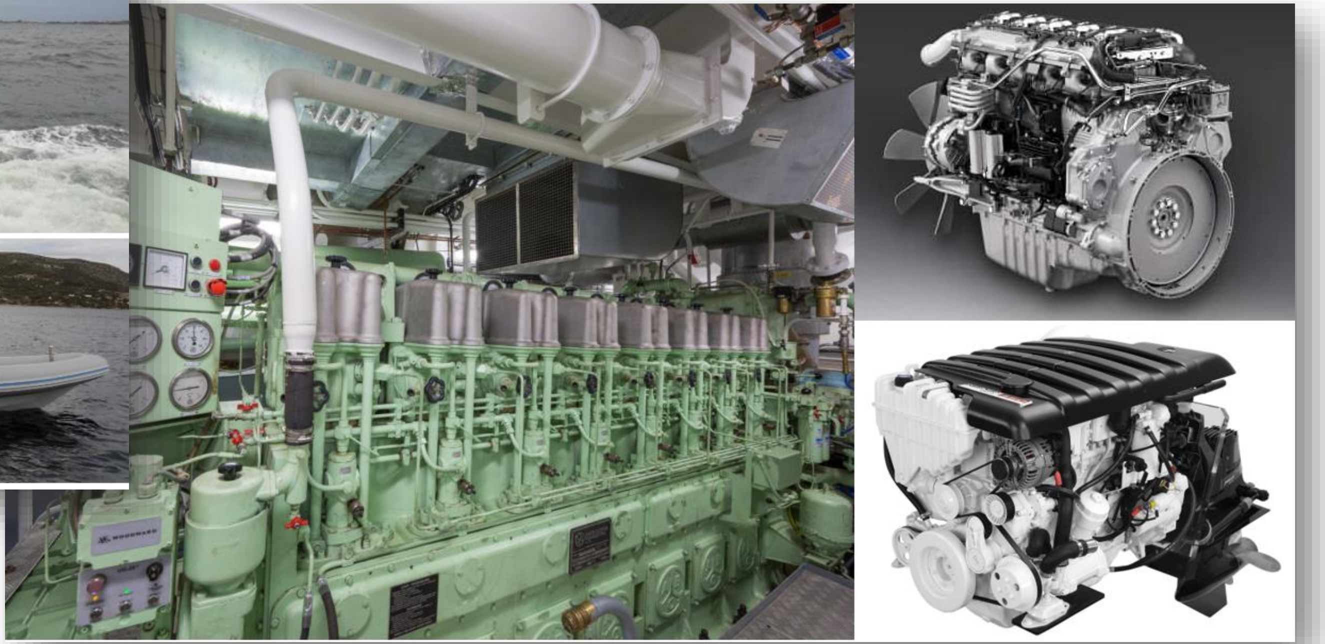
FASTWATER

FAST Track to Clean and Carbon-Neutral WATERborne Transport

June 2020 – May 2024

The project has received funding from the European's Horizon 2020 research and innovation programme (Contract No.:860251)

fastwater.eu



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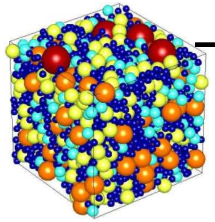
DISCUSSION / CONCLUSIONS

1. WE WILL ALWAYS NEED FUELS

- We want to set out the path to sustainable transportation
- That means: aiming, long-term, for a chain
  energy source – energy carrier – energy converter that is

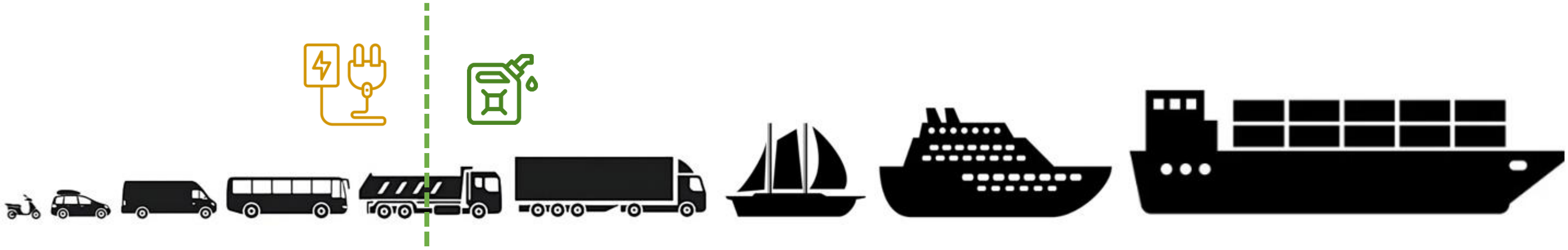
  - Sustainable
    - Source: solar, wind, bio, …
    - Closed cycle for energy carrier and converter materials

  - Scalable
    - Use abundantly available resources
    - Also implies affordable



  - Storable
    - High energy and power density: need range & payload

At least 3 sectors need **molecules**
- Energy (buffering/storage)
- Chemical
- (heavy) Transport



Main catch:
which fuel(s)?

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2. CHOOSE SIMPLE FUELS

- RES: primarily available in the form of green electricity
  - Biomass also interesting, depending on where you are
- If we need to synthesize fuels, let's make what we want
  - Sufficient energy density
  - Preferably simple molecules
    - Production is more efficient → Well-to-tank (WTT) part of the equation
- Scalable? Needs abundantly available building blocks: C, H, O, N…
  - Thus, most simple fuels:
    - Hydrogen (gas); methane (gas); ammonia (gas); methanol (liquid); …

The base building block… so cheapest to produce, but expensive to handle

Higher energy density, comparable production cost

Eliminate emission formation mechanism – benefits **TTW** efficiency

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TAKEAWAYS

- We will always need fuels
- Those can be carbon-based
  - We should “defossilize”, not “decarbonize”
- We need to find out how to make them affordable, at scale
  - But they’re not going to be cheap, so we should only use them were necessary

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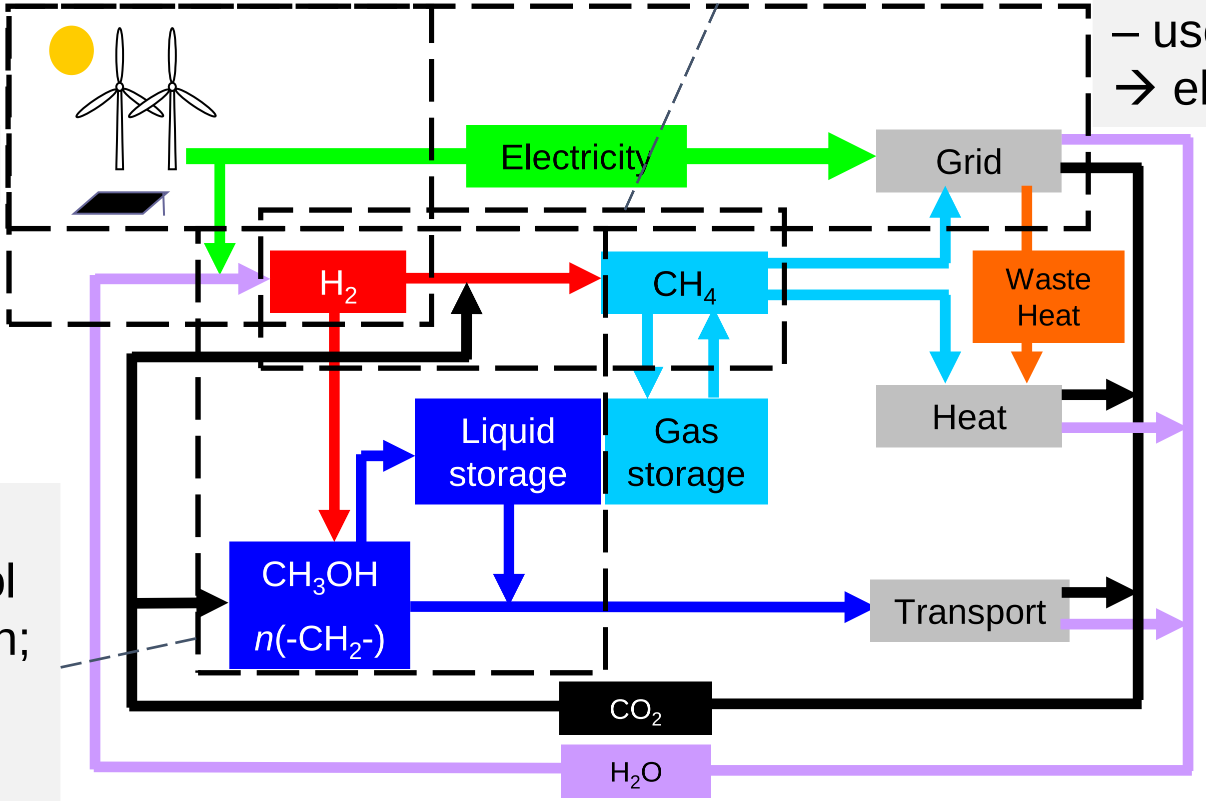
AN INTEGRATED SYSTEM

Hydrogen to buffer renewables
Balance electricity grid
Methanation / e-gas: increase energy density
Make use of existing gas grids

Most efficient route
– use whenever possible
→ electrify

Electrolysis



When energy density needs require liquid fuels: methanol synthesis or Fischer-Tropsch;
Balance seasons,
import energy;
Serve transport needs

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R. J. Pearson et al. "Energy storage via carbon-neutral fuels made from CO2, water, and renewable energy," Proc. IEEE, vol. 100, no. 2, pp. 440–460, Feb. 2012.

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Thanks for listening!

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