Catalyzing Power-2-X

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1 W

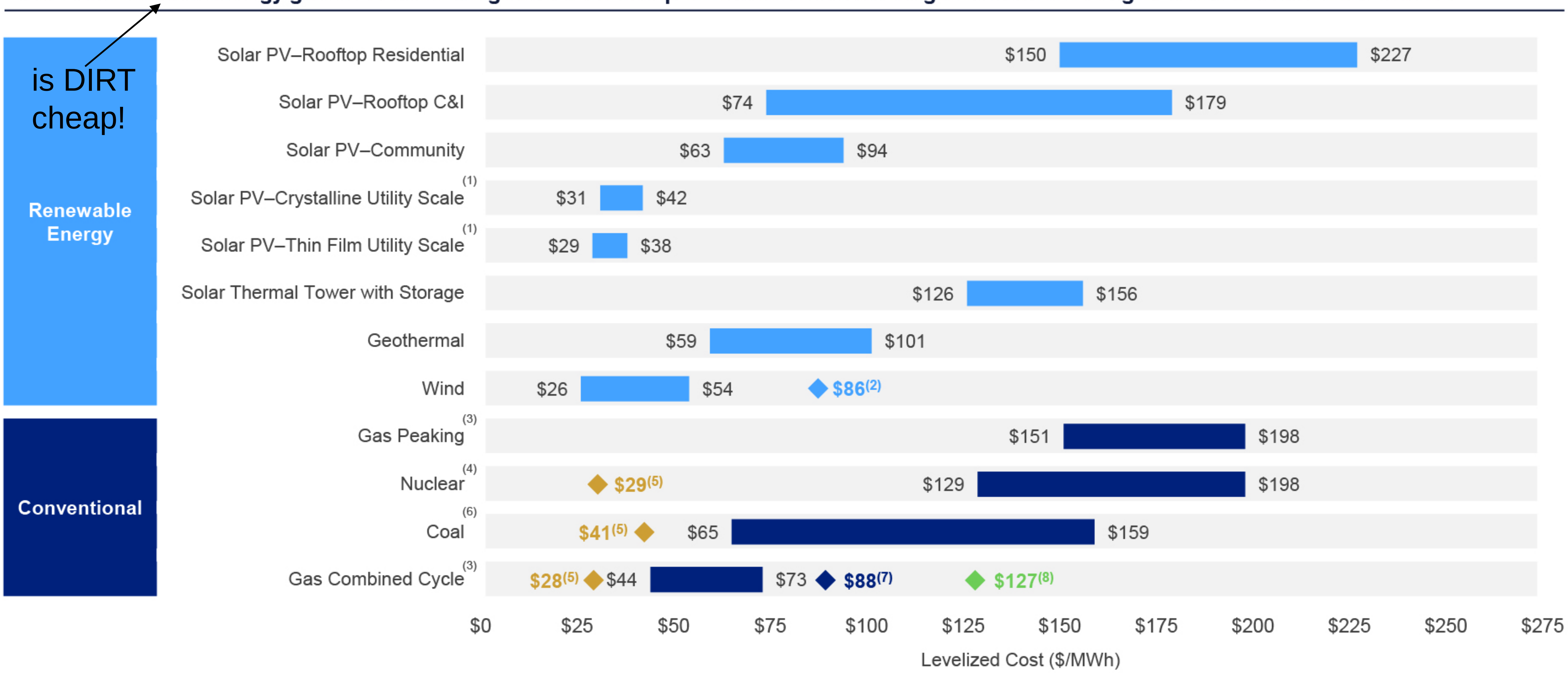
10^3 W
kilo

10^6 W
mega

10^9 W
giga

10^{12}
W tera

Selected renewable energy generation technologies are cost-competitive with conventional generation technologies under certain circumstances



Source: *Lazard estimates.*

Note: Here and throughout this presentation, unless otherwise indicated, the analysis assumes 60% debt at 8% interest rate and 40% equity at 12% cost. Please see page titled "Levelized Cost of Energy Comparison—Sensitivity to Cost of Capital" for cost of capital sensitivities. These results are not intended to represent any particular geography. Please see page titled "Solar PV versus Gas Peaking and Wind versus CCGT—Global Markets" for regional sensitivities to selected technologies.

(1) Unless otherwise indicated herein, the low case represents a single-axis tracking system and the high case represents a fixed-tilt system.

(2) Represents the estimated implied midpoint of the LCOE of offshore wind, assuming a capital cost range of approximately $2,600 – $3,675/kW.

(3) The fuel cost assumption for Lazard's global, unsubsidized analysis for gas-fired generation resources is $3.45/MMBTU.

(4) Unless otherwise indicated, the analysis herein does not reflect decommissioning costs, ongoing maintenance-related capital expenditures or the potential economic impacts of federal loan guarantees or other subsidies.

(5) Represents the midpoint of the marginal cost of operating fully depreciated gas combined cycle, coal and nuclear facilities, inclusive of decommissioning costs for nuclear facilities. Analysis assumes that the salvage value for a decommissioned gas combined cycle or coal asset is equivalent to its decommissioning and site restoration costs. Inputs are derived from a benchmark of operating gas combined cycle, coal and nuclear assets across the U.S. Capacity factors, fuel, variable and fixed operating expenses are based on upper- and lower-quartile estimates derived from Lazard's research. Please see page titled "Levelized Cost of Energy Comparison—Renewable Energy versus Marginal Cost of Selected Existing Conventional Generation" for additional details.

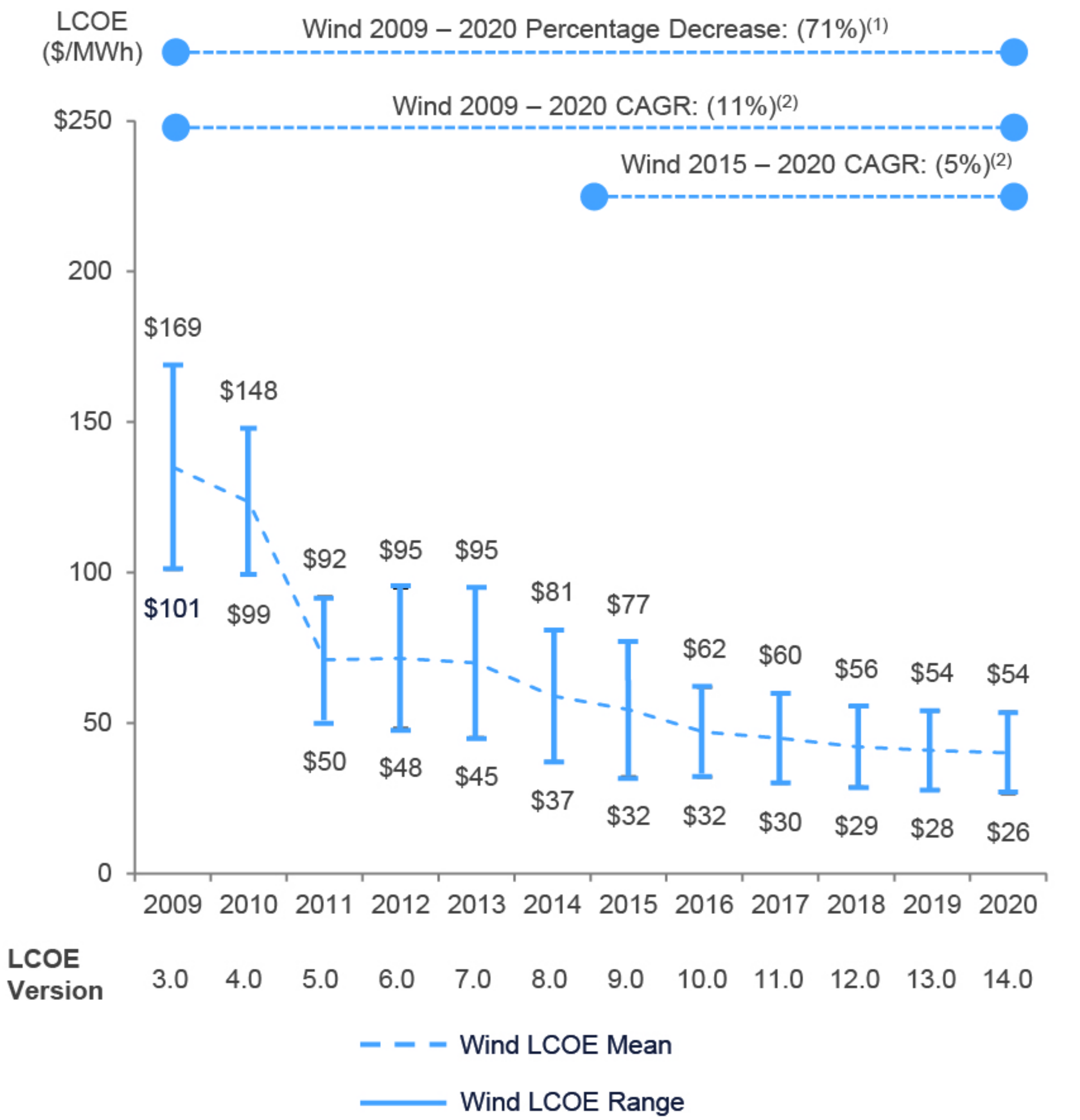
(6) High end incorporates 90% carbon capture and storage. Does not include cost of transportation and storage.

(7) Represents the LCOE of the observed high case gas combined cycle inputs using a 20% blend of "Blue" hydrogen, (i.e., hydrogen produced from a steam-methane reformer, using natural gas as a feedstock, and sequestering the resulting CO_2 in a nearby saline aquifer). No plant modifications are assumed beyond a 2% adjustment to the plant's heat rate. The corresponding fuel cost is $5.20/MMBTU.

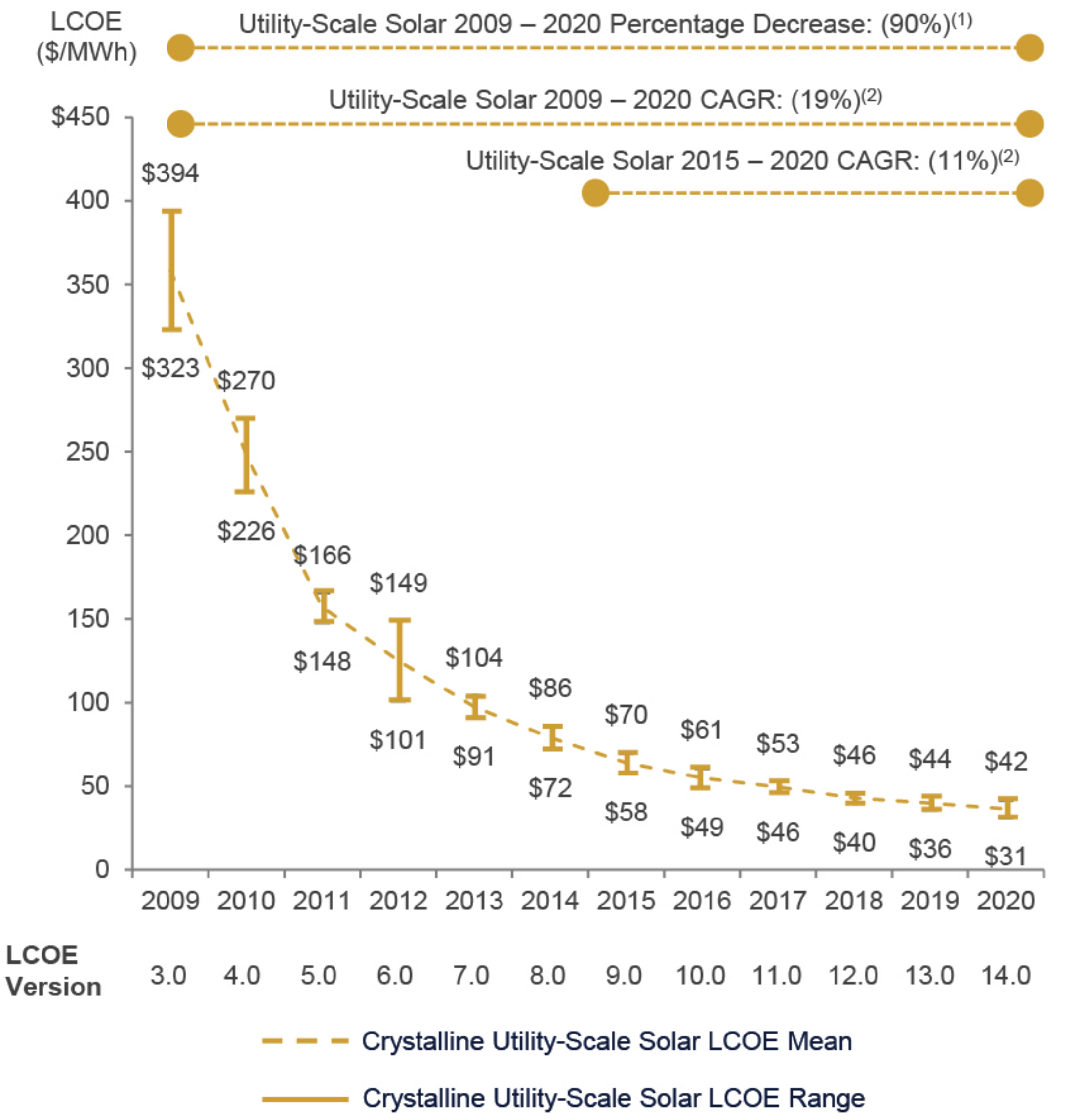
(8) Represents the LCOE of the observed high case gas combined cycle inputs using a 20% blend of "Green" hydrogen, (i.e., hydrogen produced from an electrolyzer powered by a mix of wind and solar generation and stored in a nearby salt cavern). No plant modifications are assumed beyond a 2% adjustment to the plant's heat rate. The corresponding fuel cost is $10.05/MMBTU.

In light of material declines in the pricing of system components and improvements in efficiency, among other factors, wind and utility-scale solar PV have exhibited dramatic LCOE declines; however, as these industries have matured, the rates of decline have diminished

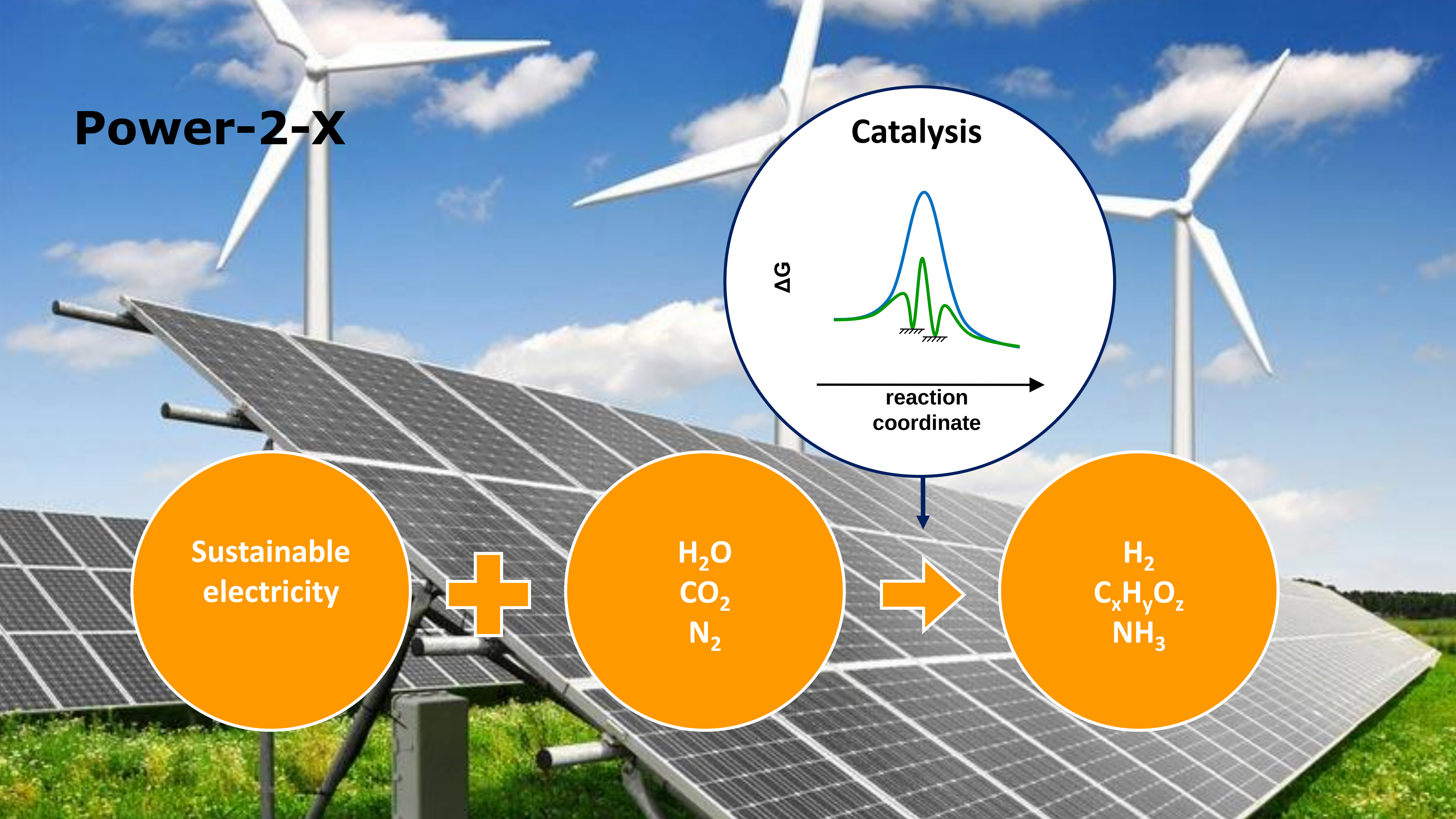
Unsubsidized Wind LCOE



Unsubsidized Solar PV LCOE



Source: Lazard estimates.
(1) Represents the average percentage decrease of the high end and low end of the LCOE range.
(2) Represents the average compounded annual rate of decline of the high end and low end of the LCOE range.



Power-2-X
Catalysis
ΔG
reaction coordinate
Sustainable electricity
H_2O
CO_2
N_2
H_2
$C_xH_yO_z$
NH_3

Key points

- Energy does not equal electricity
- We should **electrify as much as possible** – but not everything can be electrified

- "Fuel without fossil"? (Power-to-X)
- The **oxygen problem** and the role of **hydrogen**

- How we can handle prolonged no-wind situations
- We need much, MUCH more solar power

- This whole energy transition is actually **dirt cheap** and only a small fraction must be paid with tax-money

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Point 1 – Electricity ≠ Energy

Current status in DK

Electricity << Energy
ca 4 GW vs. ca 24 GW

Massive electrification

Possible future

Electricity < Energy
ca 10 GW vs. ca 20 GW

Comment:

Electrification of heating and transportation will increase demand for electricity, but decrease overall energy due to better efficiency
(viz. Heat pump vs. gas boiler)

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Point 1 – Electricity ≠ Energy Recommendations

Goal 1: **Massive electrification** (cars, home heating, commercial building heating, chemical upgrading,…).

Policy suggestion 1: **Electricity** must be **taxed lower** (DKK/GJ) at the consumer level than all other energy forms.

Comment:

Most heating should be done using **heat-pumps** (both central or de-central). Almost all cars and trucks should be **electric (BEV)**.

Goal 2: **Avoid waste** of wind or solar power, and avoid negative electricity prices.

Policy suggestion 2: Any and all initiatives for **using power when it is available** should be actively used. E.g. "smart grids".

This also includes dumping surplus renewable **electricity into the district heating system**.

Comment:

Heat pumps are expensive, but extra capacity from **ohmic heaters** is dirt-cheap (< 0.3 DKK/W) and thus really a "no brainer".

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Point 2 – Fuels without fossil - P2X?
Not everything can be electrified

- Un-electrifiable necessities:
  - Air transport (except very short-haul, perhaps)
  - Heavy industrial equipment such as ships and perhaps some fraction of trucks
  - Chemical industry (agricultural products, textile production, plastics, pharmaceuticals, paints and pigments, lubricants, electrical insulation, etc. etc.)

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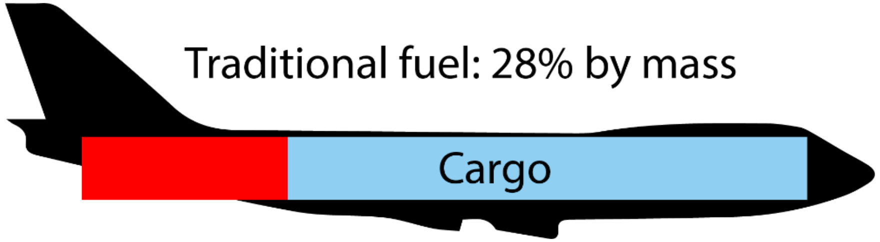
Point 2 – Not everything can be electrified
Battery airplanes? – Probably not…

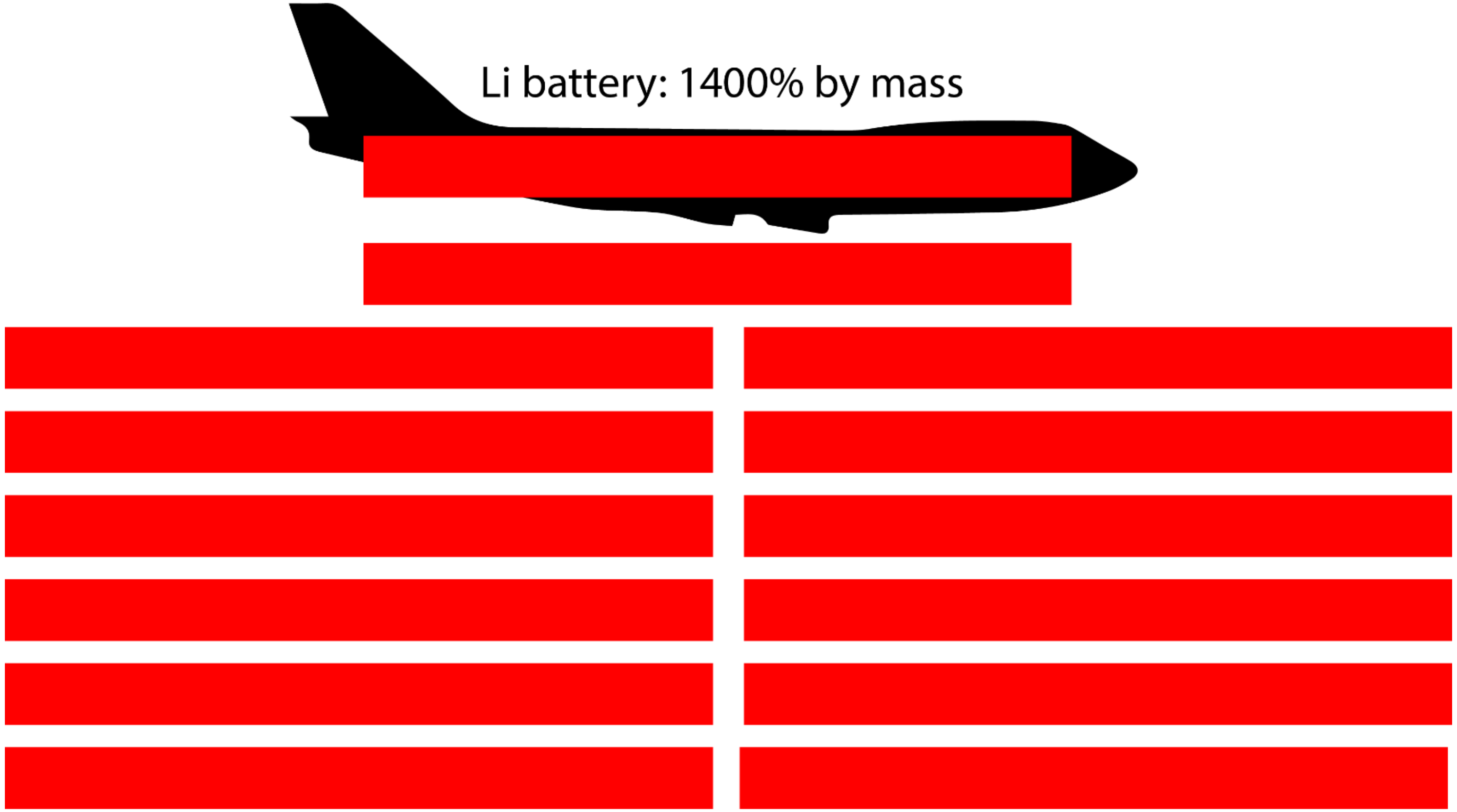
Traditional fuel:

70 ton fuel or 3e12 J



Li ion battery

3500 ton



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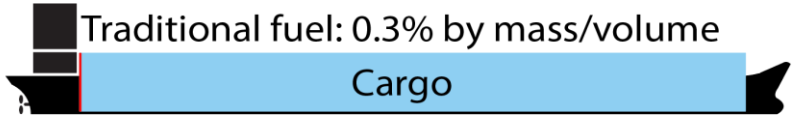
Point 2 – Not everything can be electrified
Battery ships? Maybe one day…

Bulk carrier 205,000 dwt

Traditional fuel:

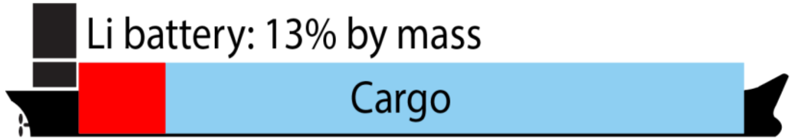
Fuel consumption assuming 50 ton/24hr at 14 knots
(http://mandieselturbo.com)

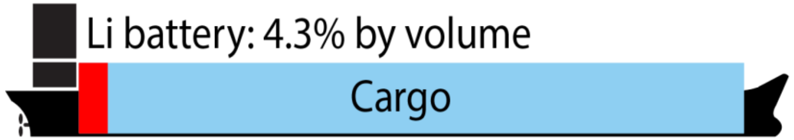
545 ton fuel or 2.3e13 J



Li ion battery

8800 m^3 / 26600 ton





Rotterdam (NL) to Baltimore (USA)

From: https://sea-distances.org/

Result

Direct way

Distance	3670 nautical miles
Vessel speed	14 knots
time	10 days 22 hours

30 battery cycles/yr

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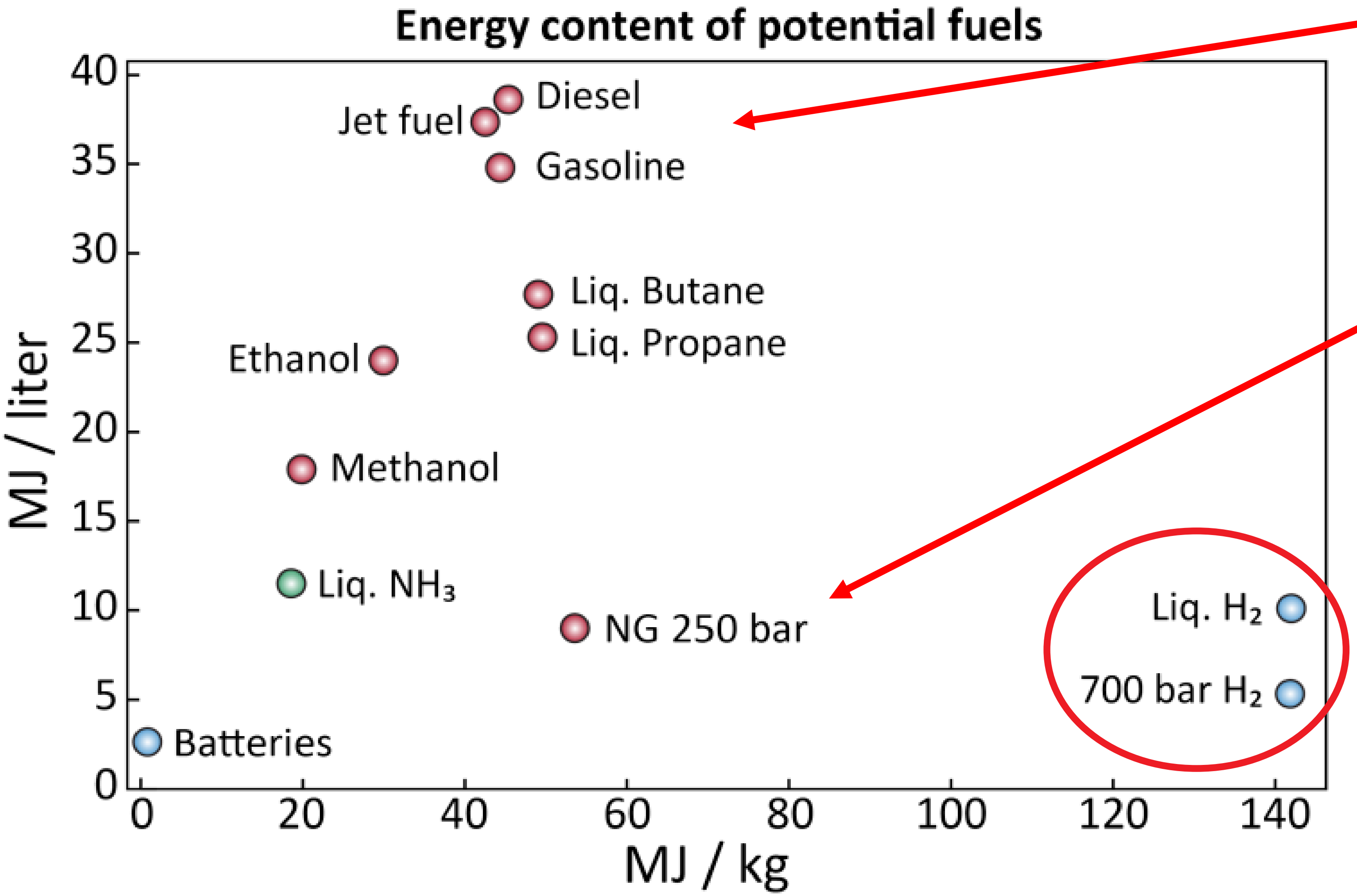
Point 2 – P2X - what X to choose
Fuels are amazing (for some things)



Aviation and long transport (trucks ? & ships ?)

Decentralized long term energy storage ~ months

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Point 2 – P2X

- Bad news: DK does NOT have sufficient waste biomass to cover the missing ”unelectrifiable” demand.

- Good news, Denmark DOES have sufficient waste biomass, *provided* that it is **upgraded by hydrogenation**. This requires (among other things) **electrolysis** to **make H_2 on a GW scale**.
  - This probably won’t be cheap, but that’s fine since in the future any ”fuel”/chemical energy bearer should be expensive to discourage overuse.

- Long term we probably need to develop the technology to **harvest CO_2 directly** out of the atmosphere in order to have sufficient carbon atoms to have adequate synthetic fuels.
  - <u>Research needs for “Electrofuels”</u>:
    - **Electrolysis** – in particular oxygen evolution electrocatalysis, but also engineering
    - **Direct CO_2 capture** and recycling
    - **Electrochemical N_2 reduction** (to ammonia) – fundamentally unsolved problem!

Point 2 – P2X - some recommendations

Goal 3: **GW-scale electrolysis** and better use of waste biomass resource.

Policy suggestion 3: Some sort of **subsidy program** is needed to encourage build-out of electrolyzers and biomass upgraders. Power companies should pay less taxes for synthetic/upgraded fuels than fossil fuels.

Comment:

This is highly relevant in the medium-long term, so we better start on a small scale now.

Goal 4: **Electrofuels** other than hydrogen are needed. I.e. either electricity derived ammonia – or air-captured CO_2 converted to a hydrocarbon.

Policy suggestion 4: There is a massive **research need** for both the electrochemistry, the electrolyzer engineering and the CO_2 capture technology.

Comment:

This should really be a massive global research effort. We need this ready to scale within two decades (maximum) – and right now we have just small lab experiments.

How to jump from lab to market?

EU is in pole position!

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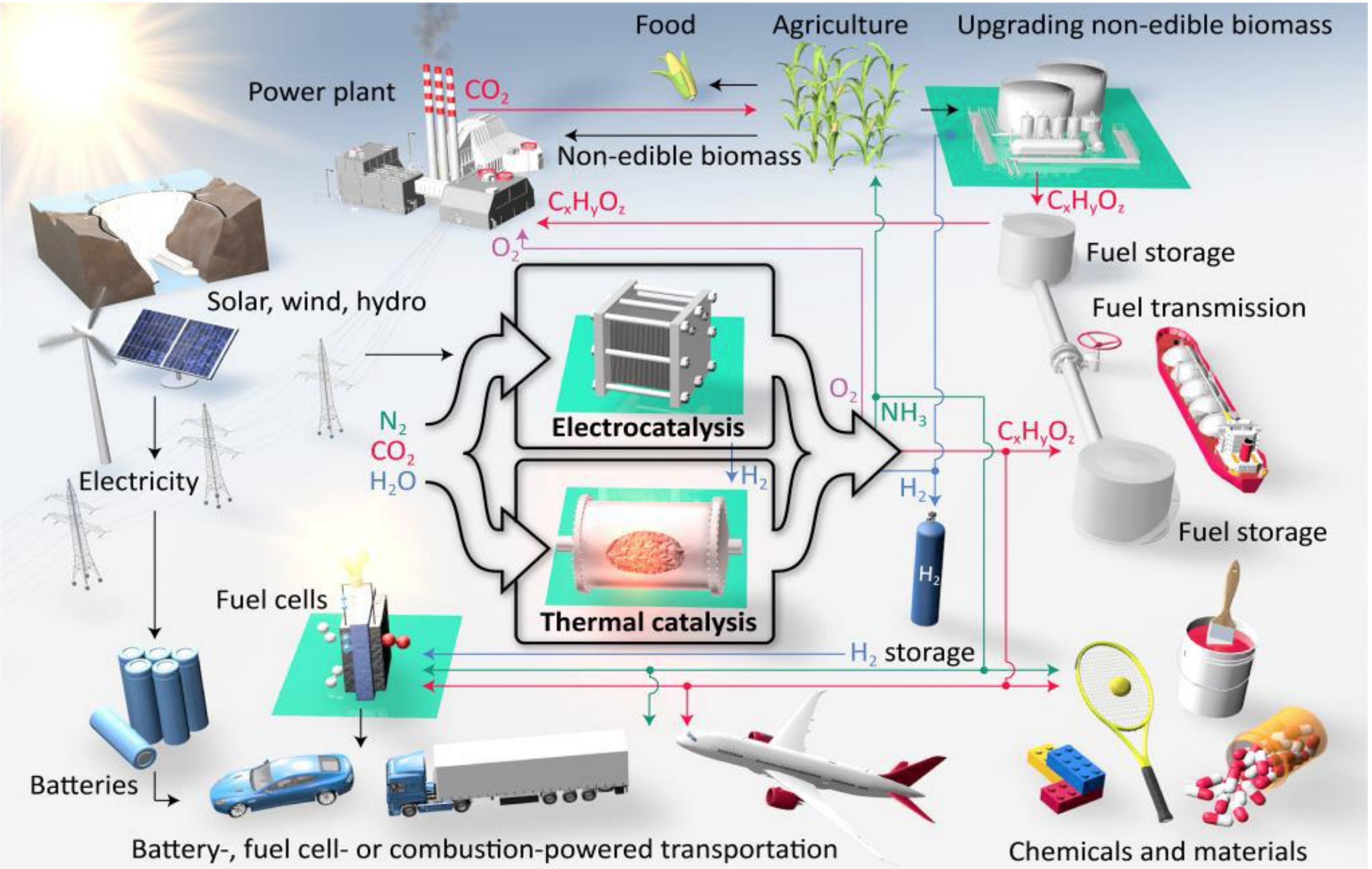
Point 3 – P2X:
Research needs for a fossil free future



Europe uses:
Total 2.2 TW

~ 5 % for Chemicals

~ 5 % for Steel prod.

~ 3 % for Aviation fuel

~ 3 % for Shipping

Where will the CO_2 come from?

- Concrete production
- Biomass using O_2 from Electrolysis
- Direct air caputure?

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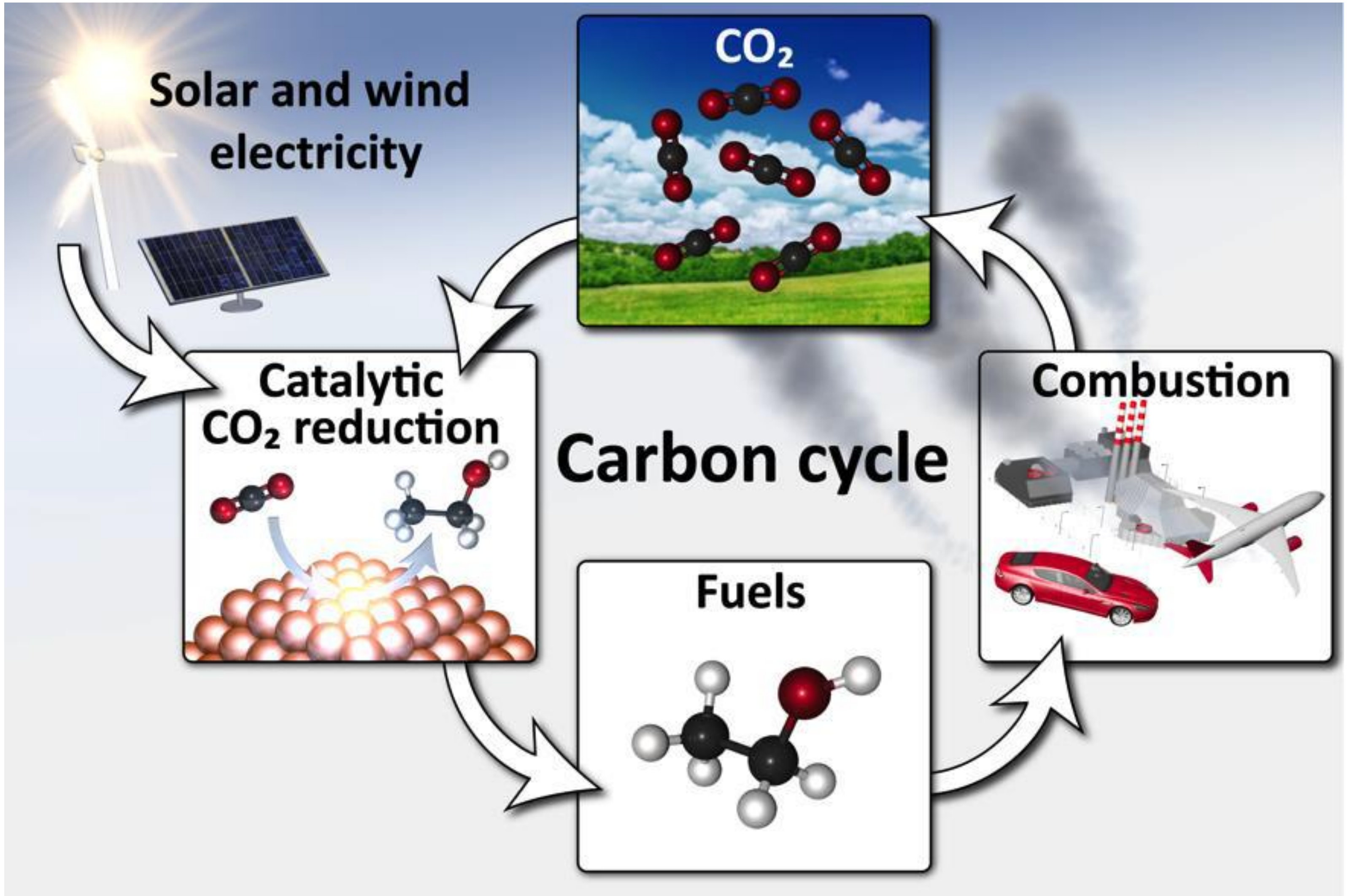
Point 3 – P2X: A circular CO_2 economy



This could perhaps be done – even better – with ammonia.

0.04% CO_2 vs

79% N_2

in the atmosphere

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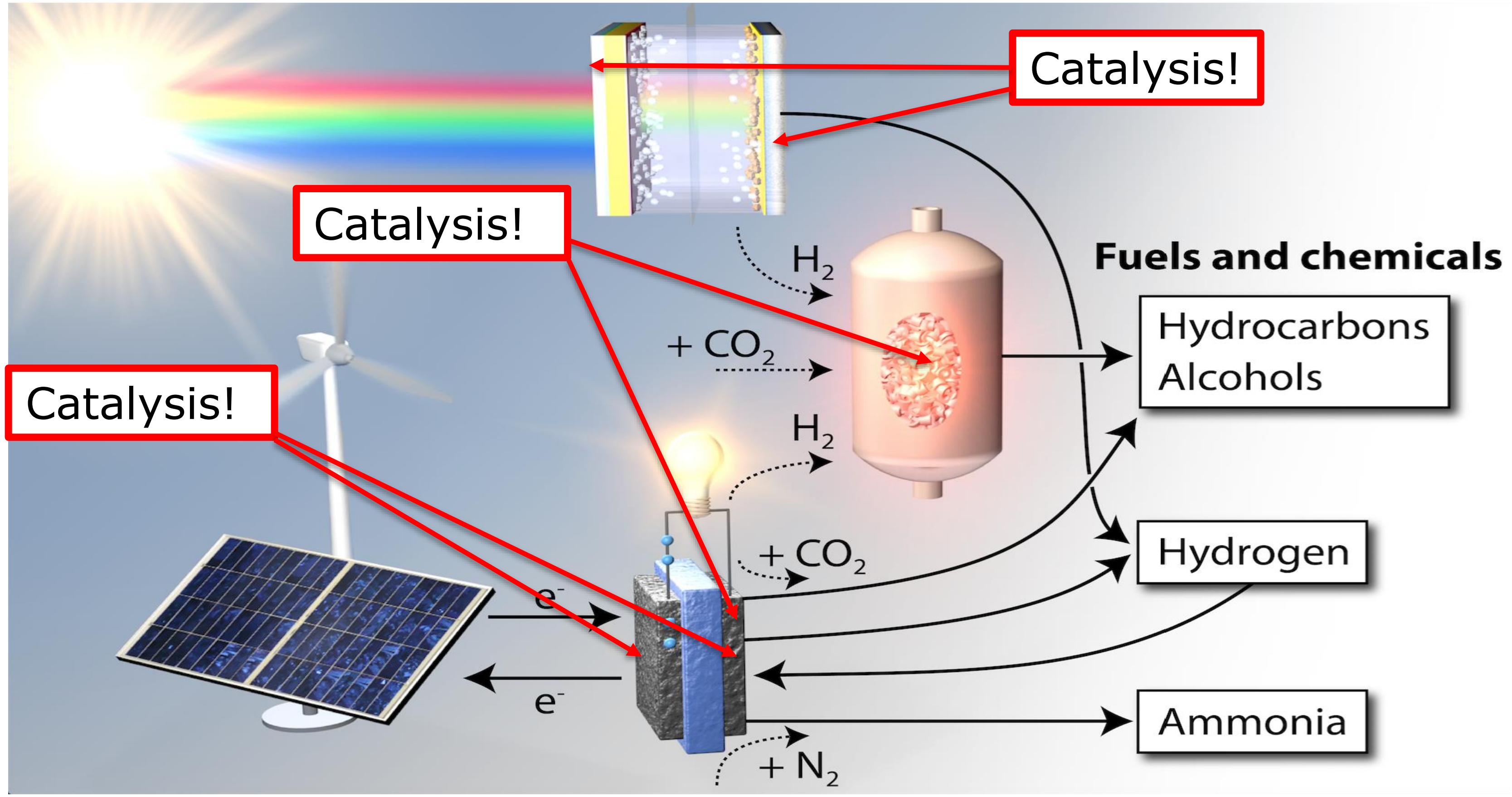
Point 3a – P2X:
Research needs for a fossil free future



The challenge:
We need new catalysts with:

- High efficiency
- High selectivity
- High stability
- Abundantly available elements

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Point 3a – P2X: Sub projects

2. Photo-Electro-Catalysis for hydrogen and oxygen evolution(HER and OER)

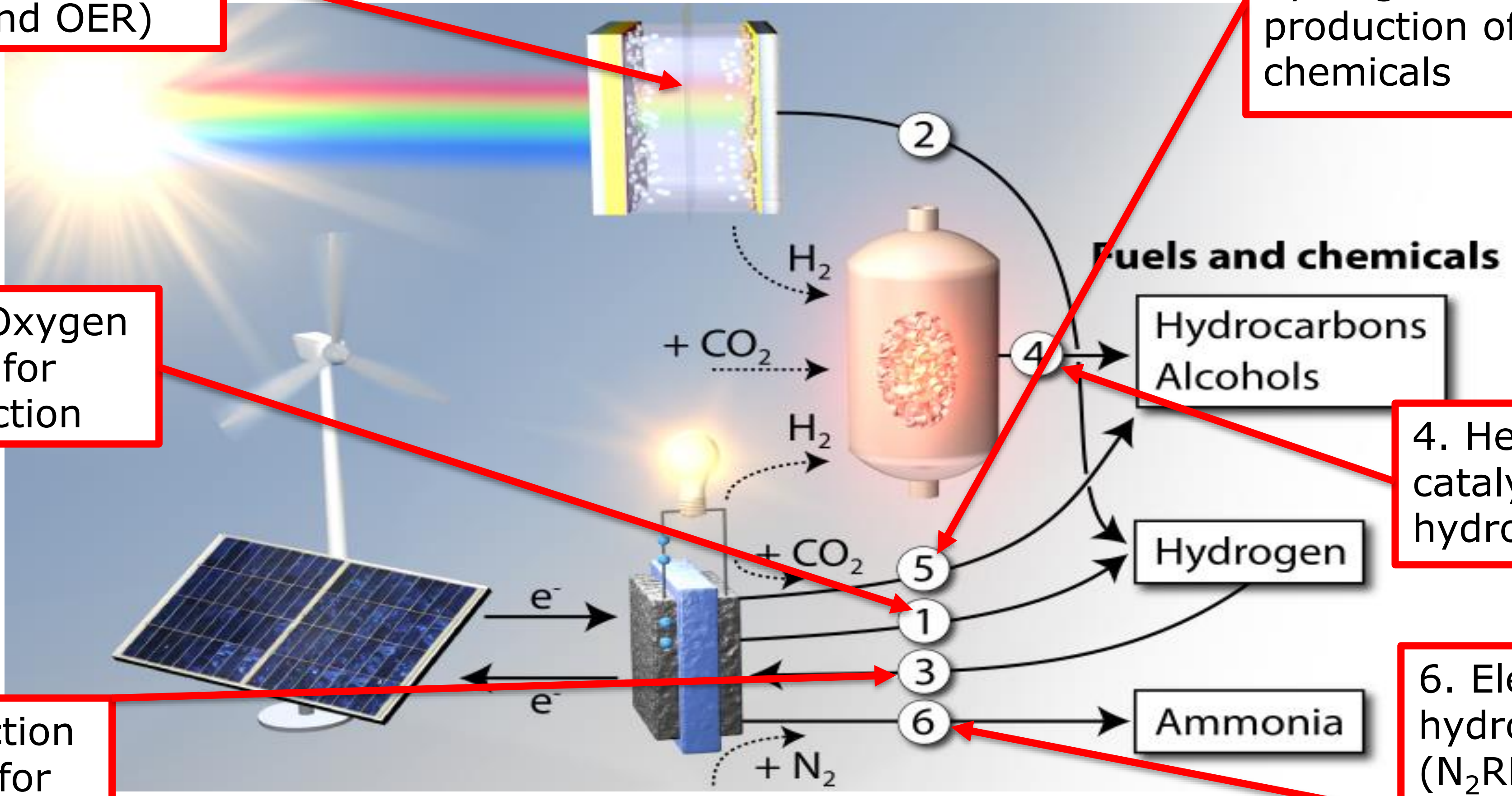
5. Electrochemical CO_2 hydrogenation (CO_2RR) for production of fuels and base chemicals

1. Electrolysis: Oxygen evolution (OER) for hydrogen production

4. Heterogeneous catalysis for CO_2 hydrogenation

3. Oxygen reduction reaction (ORR) for fuel cells

6. Electrochemical hydrogenation of N_2 (N_2RR) for production of ammonia



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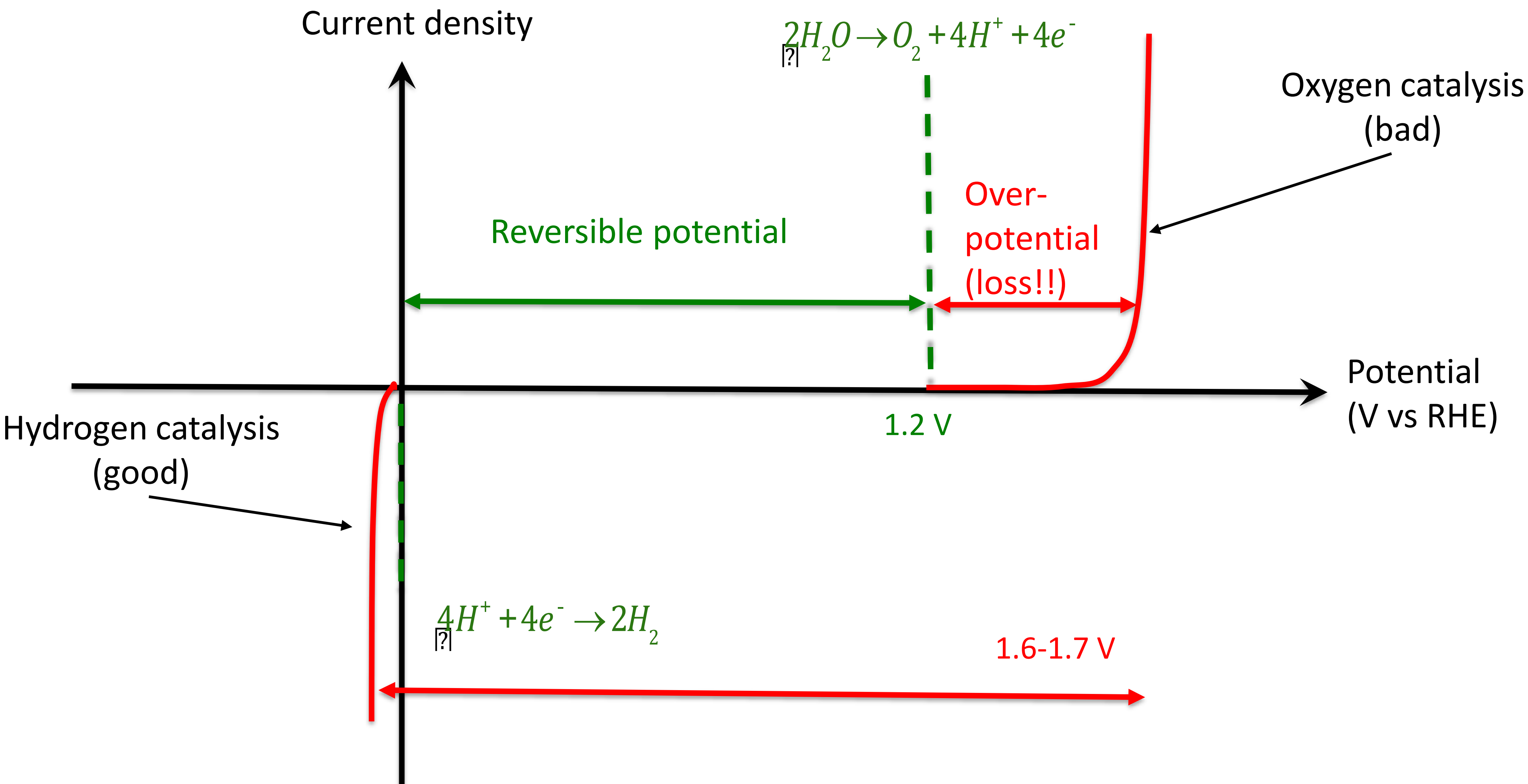
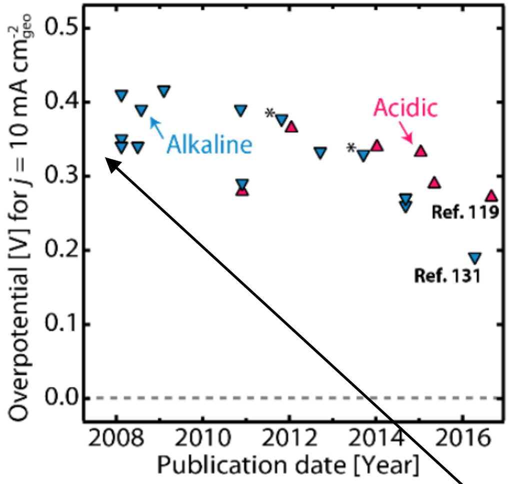
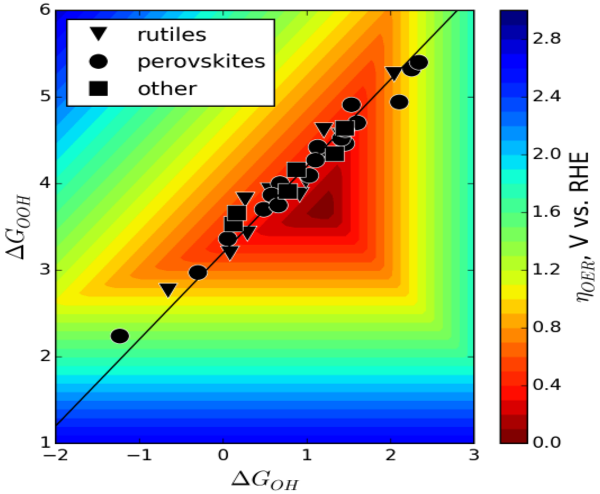
Point 3b – P2X:
The oxygen problem (affecting all X incl H_2)



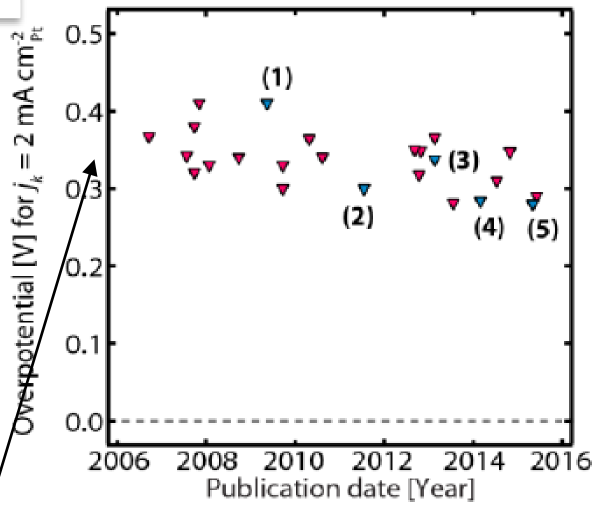
Point 3b – P2X:
The oxygen problem (affecting all X incl H_2)

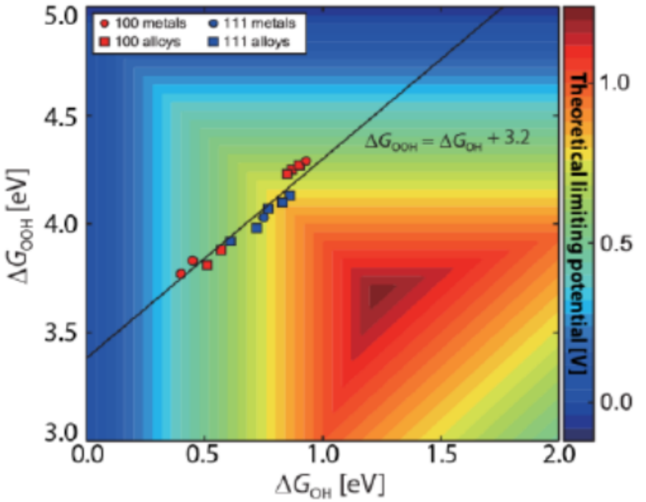
Water splitting catalysts (OER)





Fuel cell catalysts (ORR)





25% loss *making* hydrogen (caused by oxygen)

25% loss *using* hydrogen (caused by oxygen)

These loss(es) are caused by the "scaling relations" which are *very* hard to get around...
Conclusion - avoid oxygen reactions whenever possible => electrify everything instead.

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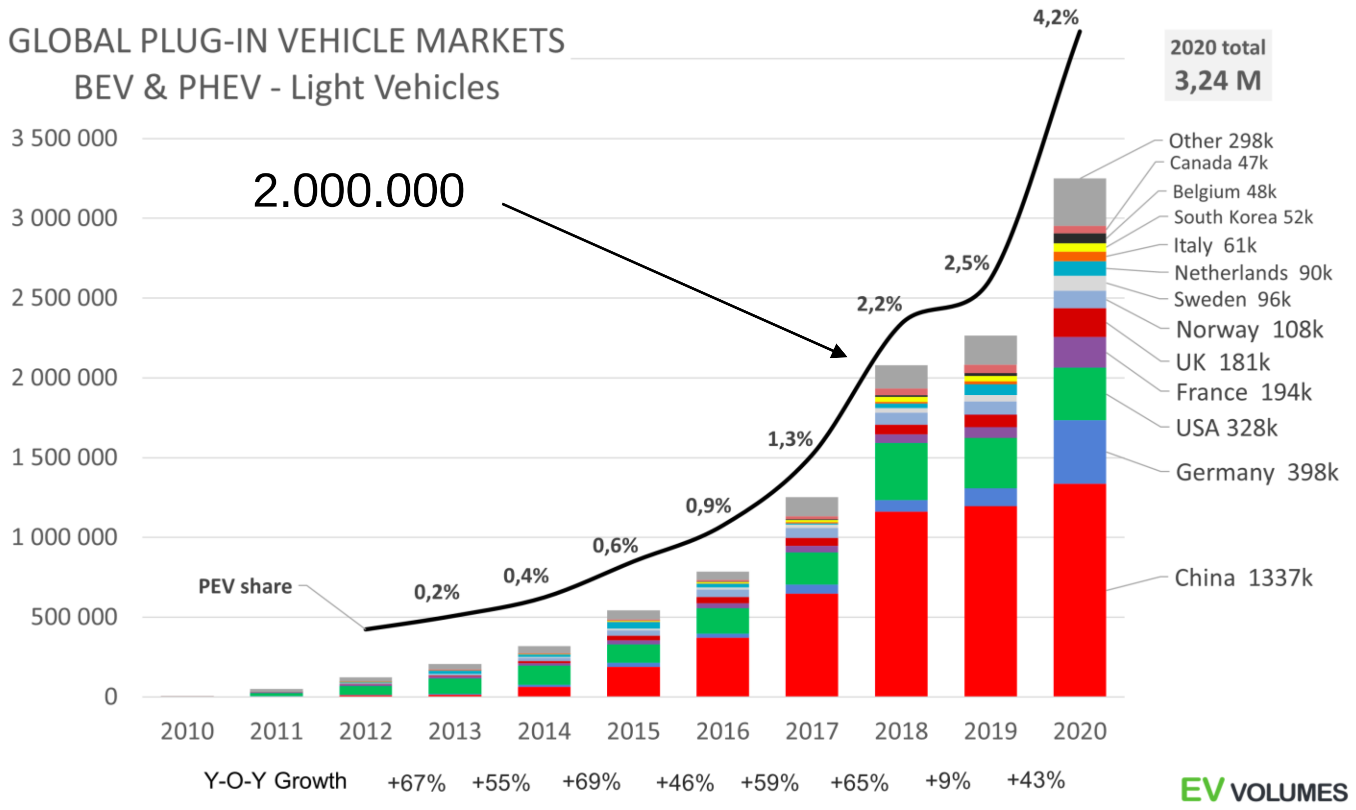
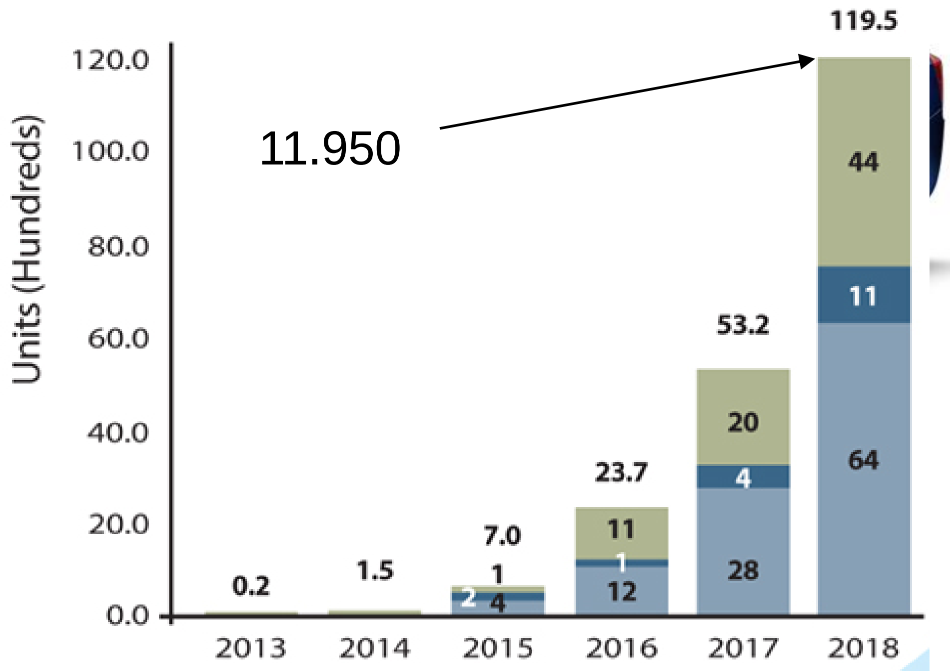
Point 3b – P2X: Why hydrogen cars failed

Battery Electric Vehicles



Fuel Cell Electric Vehicles



		647 km
		5 kg H2 (700 MJ)
Efficiency	**6.58 km/kWh**	**3.33 km/kWh**

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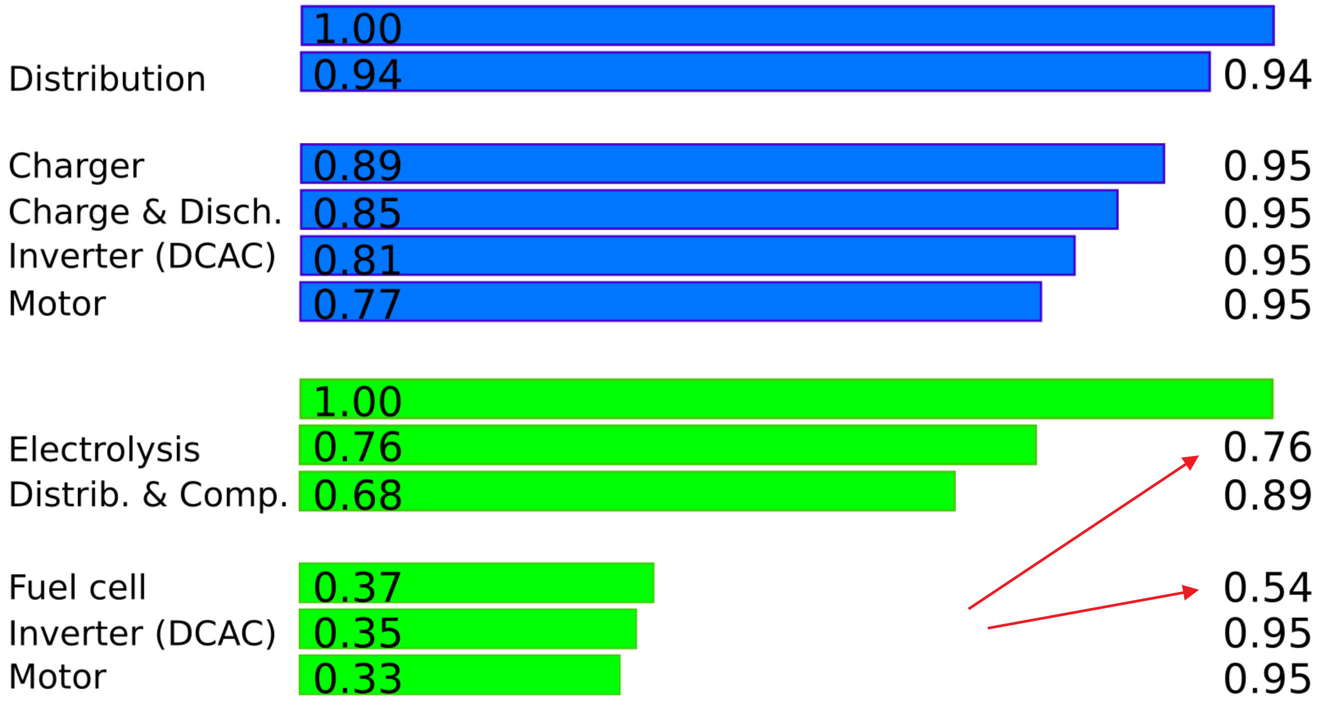
Point 3b – P2X:
Why hydrogen cars failed



Solar to wheel:
77%

Solar to wheel:
33%

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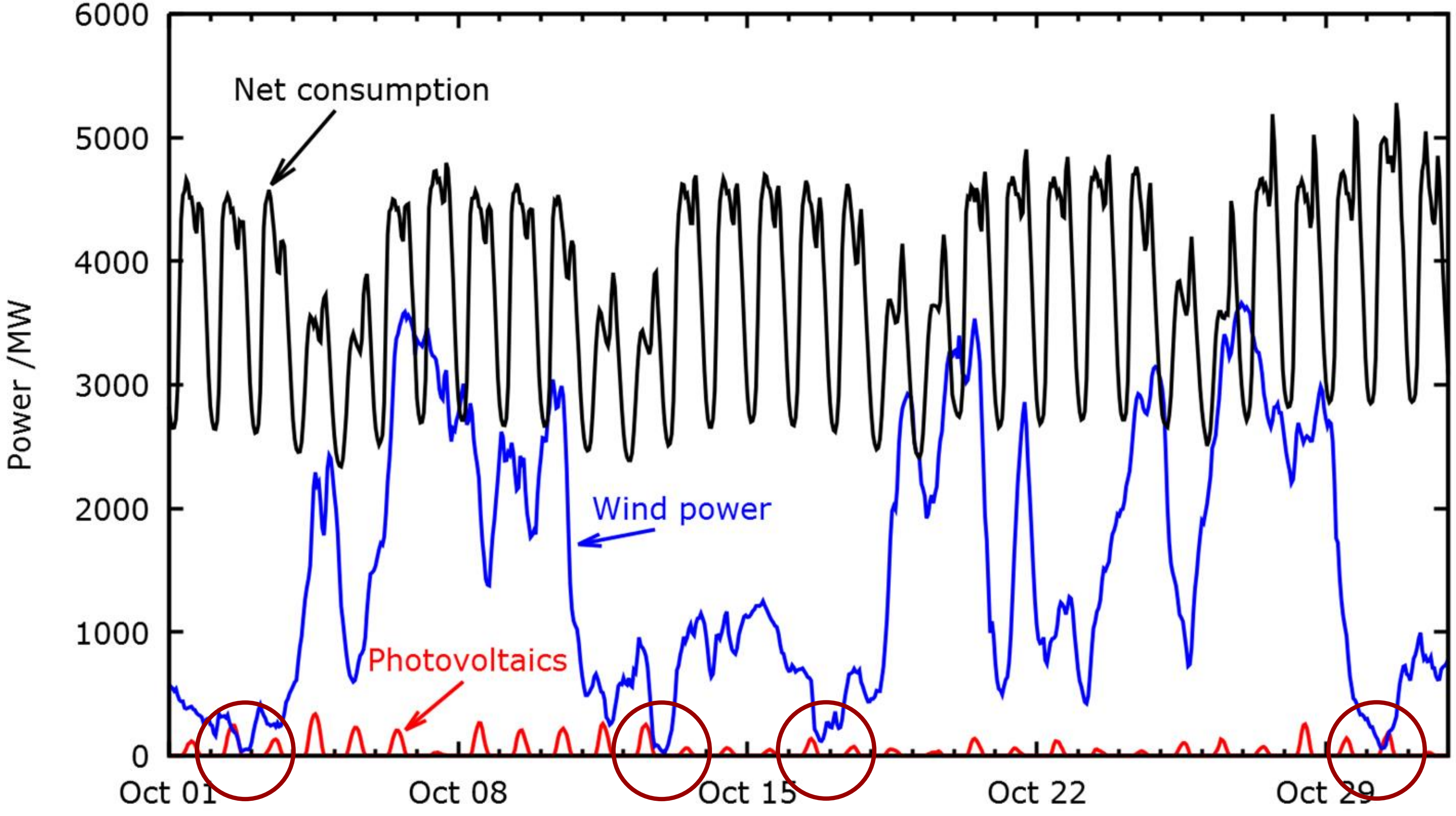
Point 4 – The "night and no wind" problem



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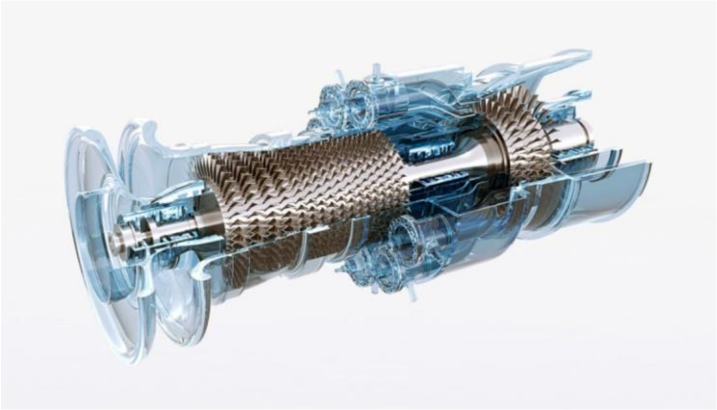
Point 4 –
How to handle the ”night and no wind” problem

- **Interconnectors** are OK – but not cheap* AND it is often low/no wind (or sunlight) all over northern Europe at the same time.
  => We NEED backup capacity corresponding to nearly peak demand



- Cheap and versatile **solution**: Install 5 – 8 GW capacity of **Gas Turbines**
  - They are not too expensive (ca 7 DKK/W)
  - They are flexible – quick start-stop time
  - They are compact and have great efficiency
  - They can run on many kinds of fuel – including many biofuels and hydrogen
  - Perfect complement for grid batteries which are good for hour-scale backup capacity (e.g. Tesla Megapack)

* Viking link: 11 mia DKK for 1.4 GW = 7.8 kr/W

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Point 4b – Why batteries alone won't solve the ”night and no wind” problem - P2X needed

- Batteries are GREAT for hour-to-hour fluctuations, but CANNOT handle days of ”no wind”.

- Because it’s unlikely we can have enough batteries!

- Batteries also may have fundamental supply limits to global implementation (reserve for cars)

- Example: Best case scenario, we have 2.5 million EVs in DK each with a 60 kWh battery.
  - Assume that all these cars take part in some clever vehicle-to-grid scheme.
  - Assume that when the wind stops, they are on average 80% charged.
  - Assume that the consumers will unplug them when they drop below 30% charge.

  - This gives a useful energy of V2G=(2.5 million x 60 kWh x (0.8-0.3)) = 75 GWh.
  - Right now, that would **run the DK grid for less than 20 hours!** (75 GWh/ 4 GW = 18.8 h).
  - For Eu (or USA) the same calculation gives less than 10 hours.

- In the (hopefully more electrified) future, where DK uses perhaps 10 GW electricity instead of 4 GW currently, this calculation gets even worse.

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Point 4b –
Batteries for the ”night and no wind” problem?

2.5 million cars in V2G

19 hours of backup

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Point 4c – Why "smart grid" alone solve the ”night and no wind” problem - P2X needed

- Smart grid technology enables demand response – i.e. that the consumption can be ”turned” up or down depending on the grid’s ability to deliver the electricity.

- This has great potential for increased efficiency (both energy- and economic efficiency)
- It is perfectly suited for building mass heated using heat pumps!

- BUT there are limits to what can be achieved. My GUESS is that less than 25% of the average load could be steered right now (ca 1 GW) – perhaps 2 GW with massive implementation of electric cars.
  - Since 1 GW << 4 GW smart grid alone cannot solve the ”no wind” problem – but it can help.

- Also – there are serious security implications to this!
  - Privacy
  - Terrorism & WAR
  - EMP/MCD (solar storm)
  - …resilience are all very difficult, but critical questions which MUST have good answers.

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Point 4 – ”night and no wind” Recommendations

Goal 5: Achieve a **stable grid** – even under prolonged adverse weather conditions

Policy suggestion 5: Install the necessary capacity of **gas turbines** (perhaps “combined cycle” for higher efficiency) in the grid.
Run them as needed on electrolyzed hydrogen or upgraded biomass.

Comment:

This may well be cheaper than a massive very-long distance network of interconnectors – and it is much more reliable.

Perhaps combined with grid-tied battery systems (for the hour timescale).

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Point 5 – DK needs WAY more solar power (10x)

- The current mix is ca 15% solar/85% wind (nameplate capacity)
- Depending on exactly what you optimize for, the optimal mix in DK is closer to **40% solar/60% wind** (fossil-free DK requires ca: **13 GW solar** + **20 GW wind**)

Goal 6: We need to build BOTH more wind, but especially **more solar**. Preferably cheap (ground mounted) large scale solar.

Policy suggestion 6: Eliminate ”fixed rate”/feed in tariffs for wind and solar.
Instead, let the utilities buy electricity **at some multiple of the Nordpool spot price**.

Comment:

Let the owners choose whether or not to sell to the grid. (Market force)

Bonus: The value of the multiple can be used as a long term political steering tool.

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Point 5 – DK needs WAY more solar power (10x) Land requirements

Sustainable Energy in Denmark

In Denmark we use 0.6 W/m^2 per capita

but we get ~120W/m^2 of sunlight

13 GWp requires ca 100 km^2
= **0.24% of DK area**

Amager: 96 km^2
Læsø: 113 km^2
Møn: 218 km^2

Is it too expensive?

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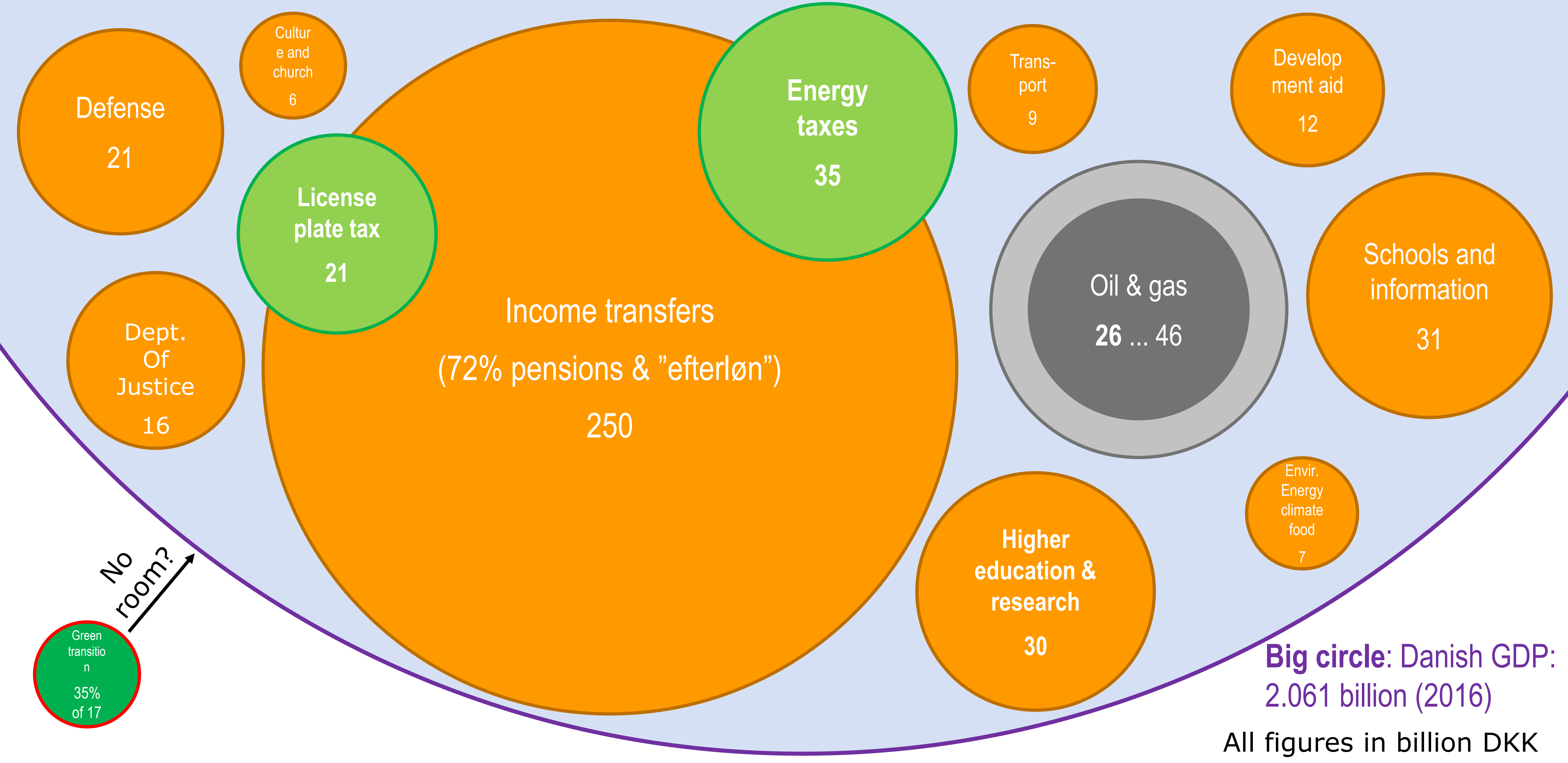
Point 6 – it's very doable!
Rough cost estimate: 17 billion DKK/year

- Investment need (VERY rough estimates):
  - 13 GW solar + 20 GW wind (nameplate capacity) < 125 bDKK Corporate
  - 8 GW gas turbine backup capacity ~ 52 bDKK Public (mostly)
  - **4 GW electrolyzer capacity** (guesstimate) ~ 80 bDKK Public
  - Biomass upgrader units (rough guess) ~ 50 bDKK Public
  - Smart grid (Dansk Energi estimate) ~ 4 bDKK Private+Corporate
  - 10 GWh grid-tied batteries ~ 6 bDKK Corporate + Public
  - Grid expansion (5 GW -> 10 GW capacity – my guess) ~ 45 bDKK Corporate+Public
  - Heat pumps (1.5 million home units + 50.000 industrial units) ~ 150 bDKK Private+Corporate
  - 20 GW Ohmic heaters (no energy wasted!) ~ 6 bDKK Corporate

  - **Total** investment (**NB**: *much of this would be needed anyway*) **~ 518 bDKK**
    518 bDKK/30 yr ~ **17 bDKK/yr** (of which around 35% must be tax financed)

Perspective:
Selected Danish budget items in 2015



Big circle: Danish GDP: 2.061 billion (2016)

All figures in billion DKK

Final thoughts…

We need to make Sustainable Energy cheaper than Fossil Fuels

- What can be electrified should be electrified.
- What is definitively needed: Better electrolysis catalysts
  - plenty of hydrogen; also other P2X technologies.
- We should consider new processes for delocalized production, whether it is Thermal or Electrochemical does not matter as long it is efficient and selective
- This provides new opportunities: SurfCat has started three spin-off companies since 2014.

SpectroInlets
Enabling real-time analysis

HPNow

RenCat

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- **Fossil free future**
  - We need a comprehensive electrification effort, but
    - Why does Denmark tax (green) electricity more than Diesel and natural gas?
    - How do we ensure a complete transition from burners and to heat pumps (inspiration Sweden)?
    - How do we get to 100% electric cars (inspiration Norway, Netherlands)?
    - Why are solar cell rules abruptly changed time and again? (We need 10 times more solar in Denmark)

- **Research needs**
  - Power-to-X "Electrofuels" is an essential technology - and everything starts with hydrogen
    - We need a massive global research effort. Europe is (still) in a leading position...
  - Crypto currency/blockchain technology holds great promise for the green transition (in spite of their reputation).

- **Research conditions**
  - EU should make a huge (+10 year, +2 bEUR) electrofuels/Power-to-X research initiative to stay ahead and lead the World. European industry needs to be closely involved!
  - We must not forget resources for non-targeted, blue-sky research. In Denmark:
    - DFF's "Research project 1, 2 need a boost and 3 should be resurrected
    - *The Sapere Aude* programme should be lifted back to former glory

- **Start-up conditions**
  - All companies should have a legal right to get a bank account (presently, the banks kill start-ups *en masse*)
    - This is due to poorly thought out Anti-Money Laundering legislation. This needs an overhaul.
  - The *De minimis* rules are poison for start-up companies, *e.g.* in the Danish EUDP programme.
    - This is due to poorly thought out European anti-government subsidy rules. This needs an overhaul.

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