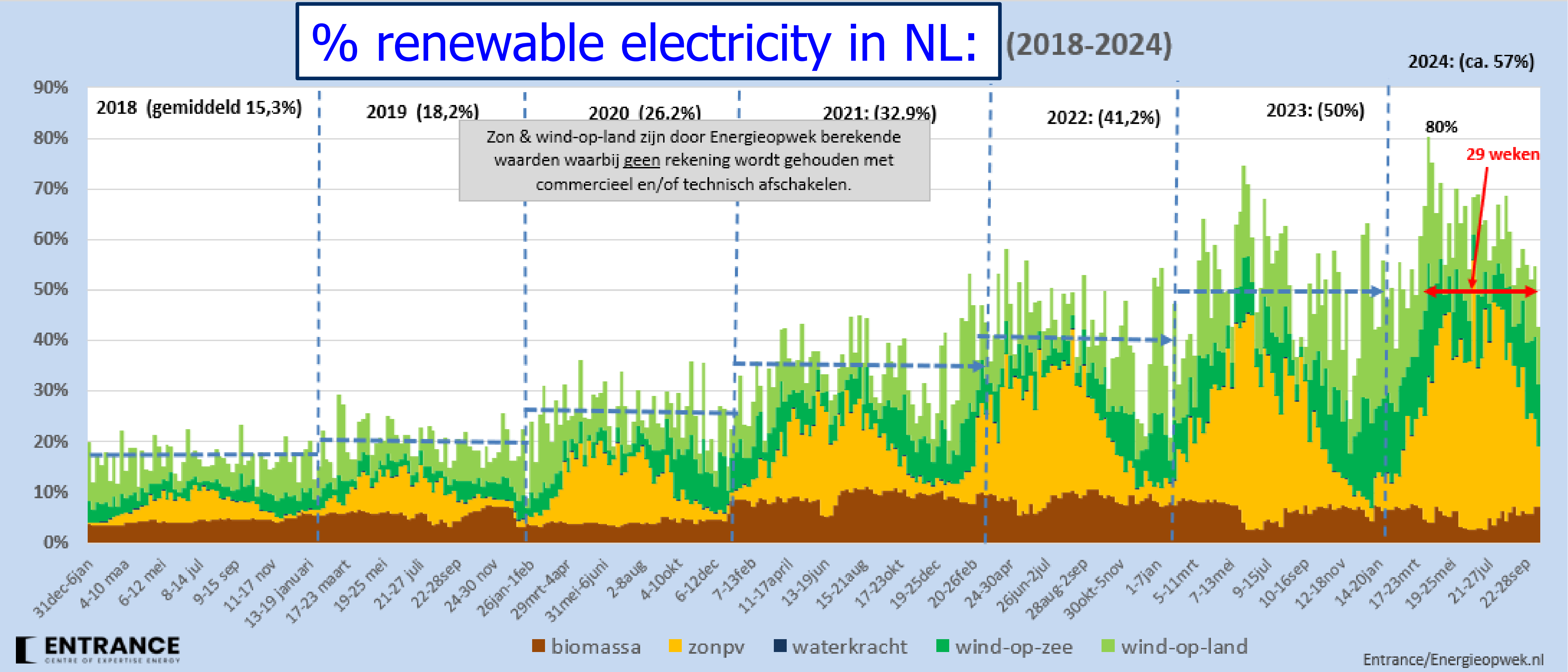
The necessity of energy storage in a renewables-based energy and feedstock system

Prof. dr Fokko Mulder
Faculty Applied Sciences
Delft University of Technology

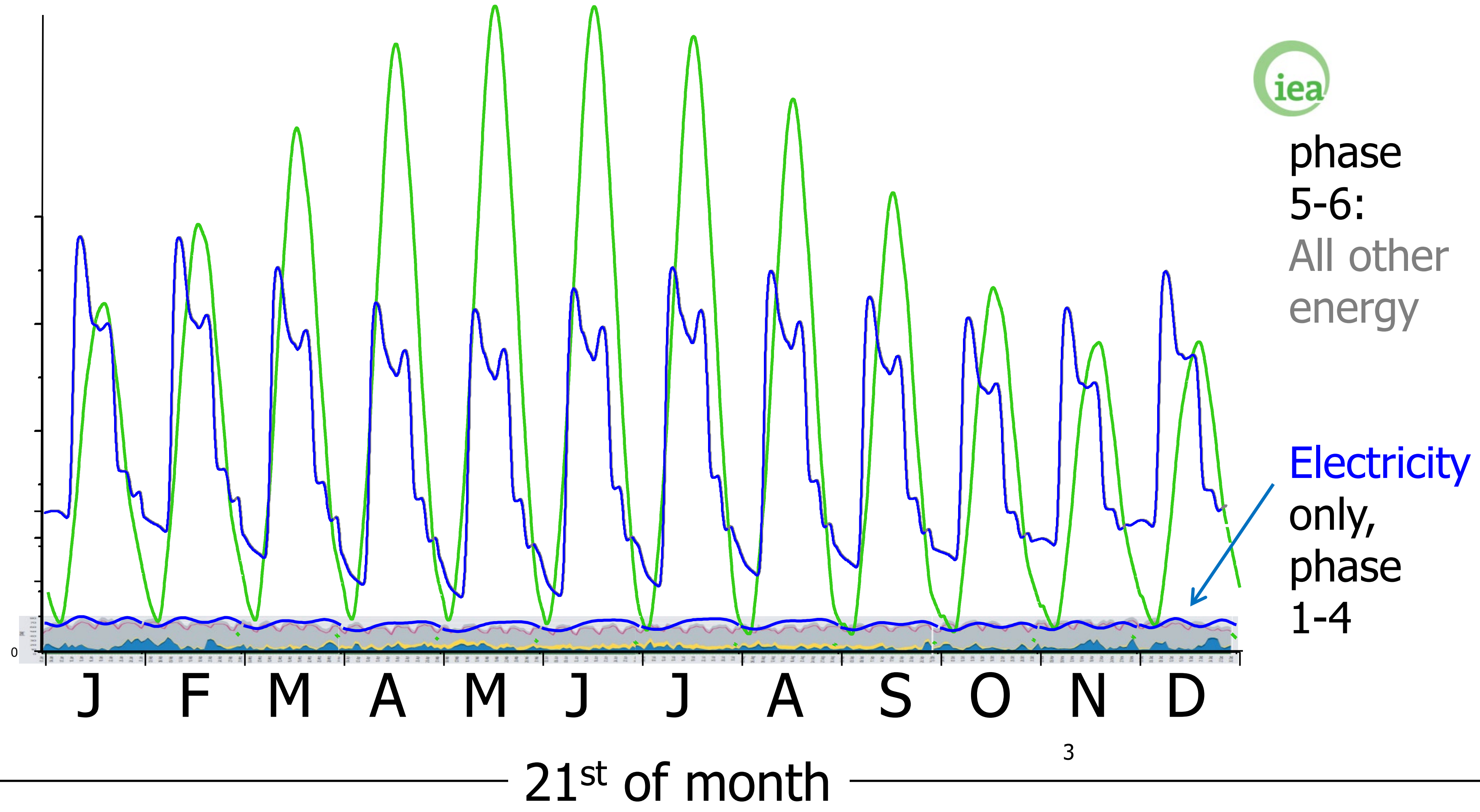
TU Delft

Delft University of Technology


% renewable electricity in NL:
(2018-2024)
2024: (ca. 57%)
2018 (gemiddeld 15,3%)
2019 (18,2%)
2020 (26,2%)
2021: (32,9%)
2022: (41,2%)
2023: (50%)
80%
29 weken
Zon & wind-op-land zijn door Energieopwek berekende waarden waarbij geen rekening wordt gehouden met commercieel en/of technisch afschakelen.
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
31dec-6jan
4-10 maa
6-12 mei
8-14 jul
9-15 sep
11-17 nov
13-19 januari
17-23 maart
19-25 mei
21-27 juli
22-28sep
24-30 nov
26jan-1feb
29mrt-4apr
31mei-6juni
2-8aug
4-10okt
6-12dec
7-13feb
11-17april
13-19jun
15-21aug
17-23okt
19-25dec
20-26feb
24-30apr
26jun-2jul
28aug-2sep
30okt-5nov
1-7jan
5-11mrt
7-13mei
9-15jul
10-16sep
12-18nov
14-20jan
17-23mrt
19-25mei
21-27jul
22-28sep
ENTRANCE
CENTRE OF EXPERTISE ENERGY
biomassa
zonpv
waterkracht
wind-op-zee
wind-op-land
Entrance/Energieopwek.nl

A 100% renewable energy and feedstock system?

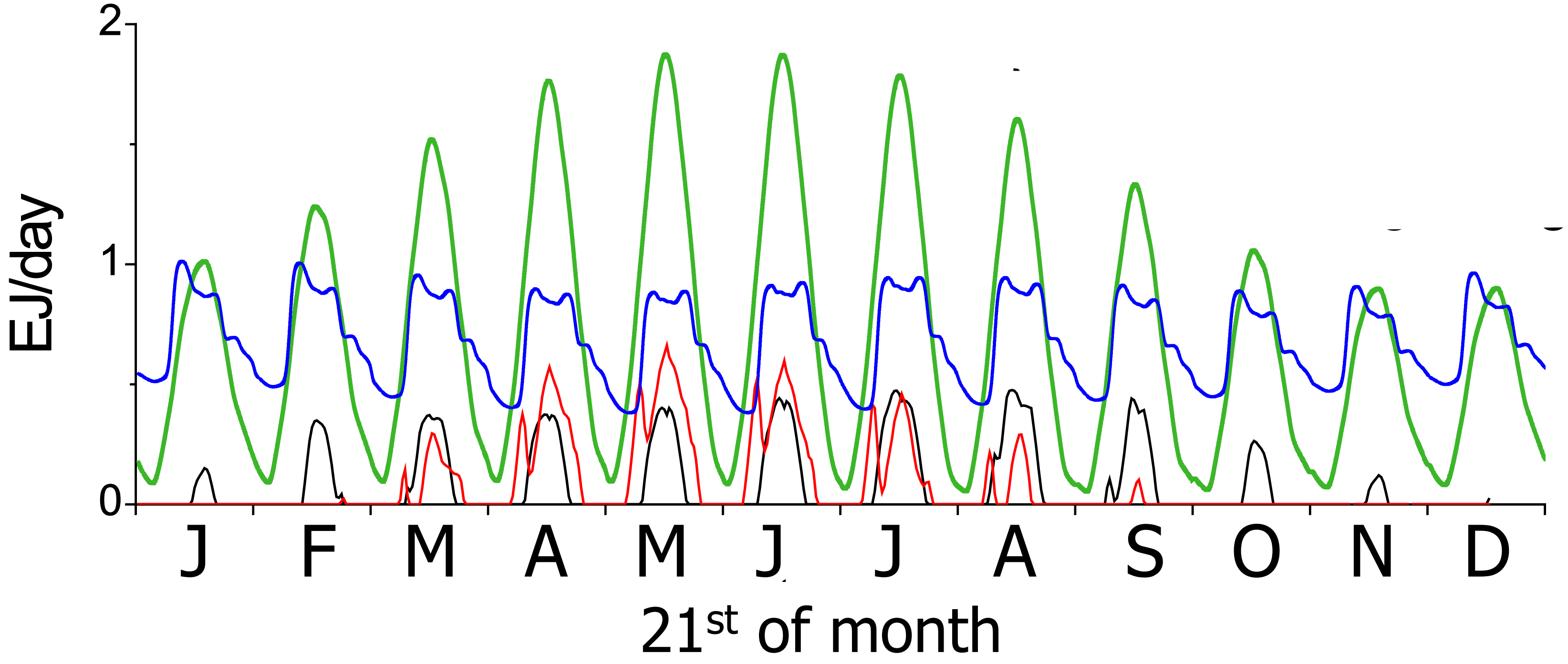
Solar power: dominant in 2050



TU Delft

Systematic mismatch of generation and demand: storage required!

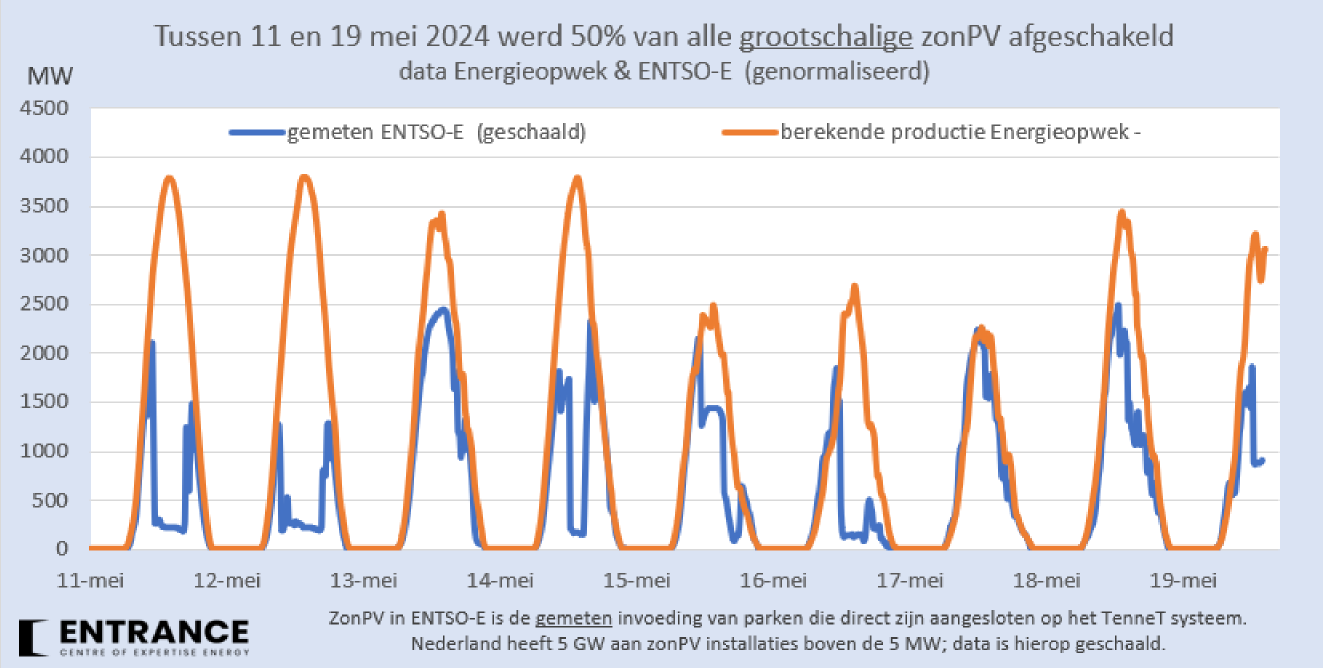
- Short term storage: black line
- Long term storage: red line



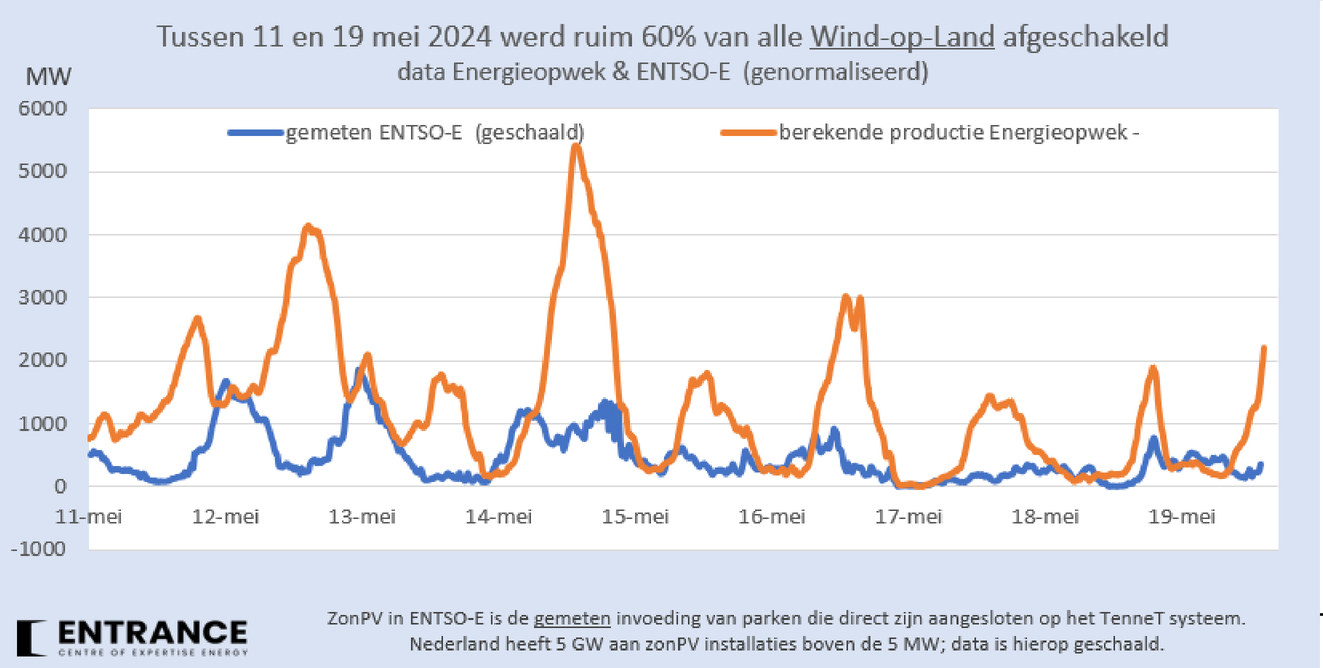
TU Delft [Mulder, J. Ren. Sust. Energy, 2014] https://pubs.aip.org/aip/jrse/article/6/3/033105/285954

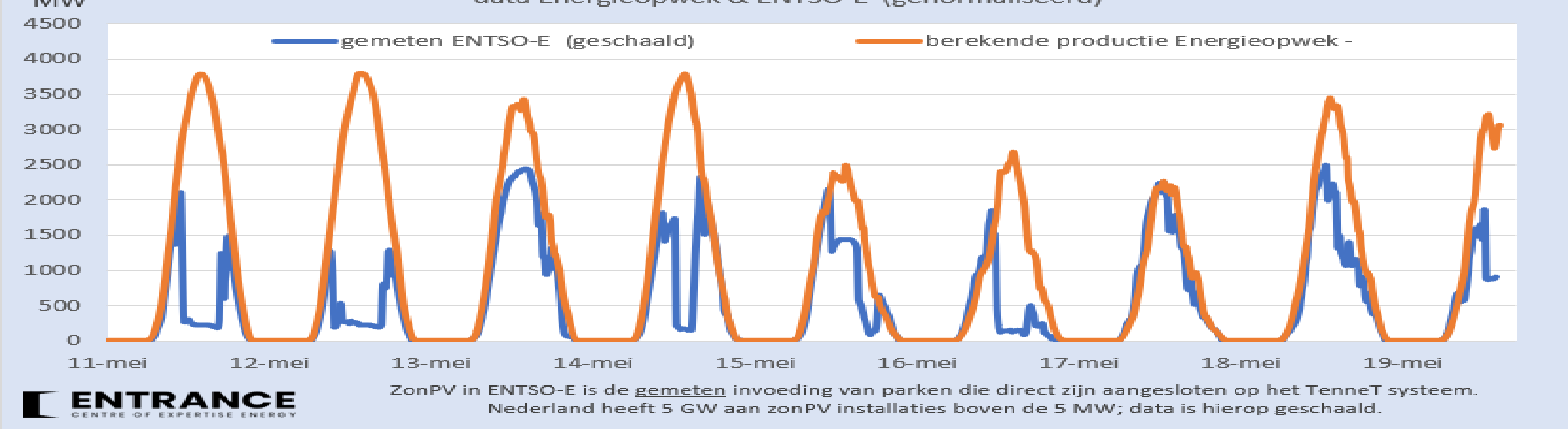
Now: there starts to show up significant oversupply already!

50% large scale PV switched off in May 2024:



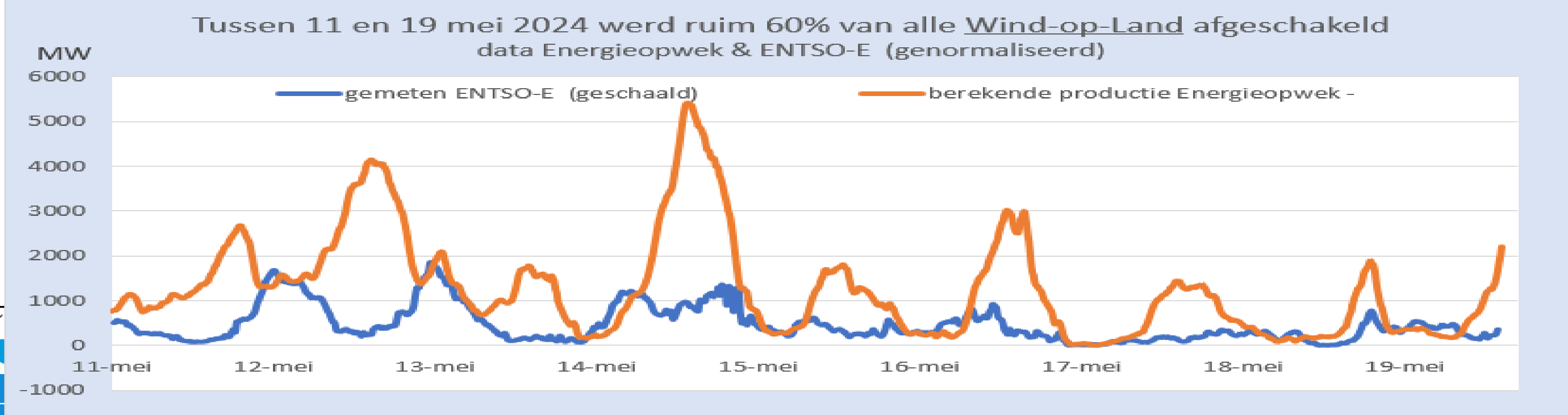
60% wind on land switched off:



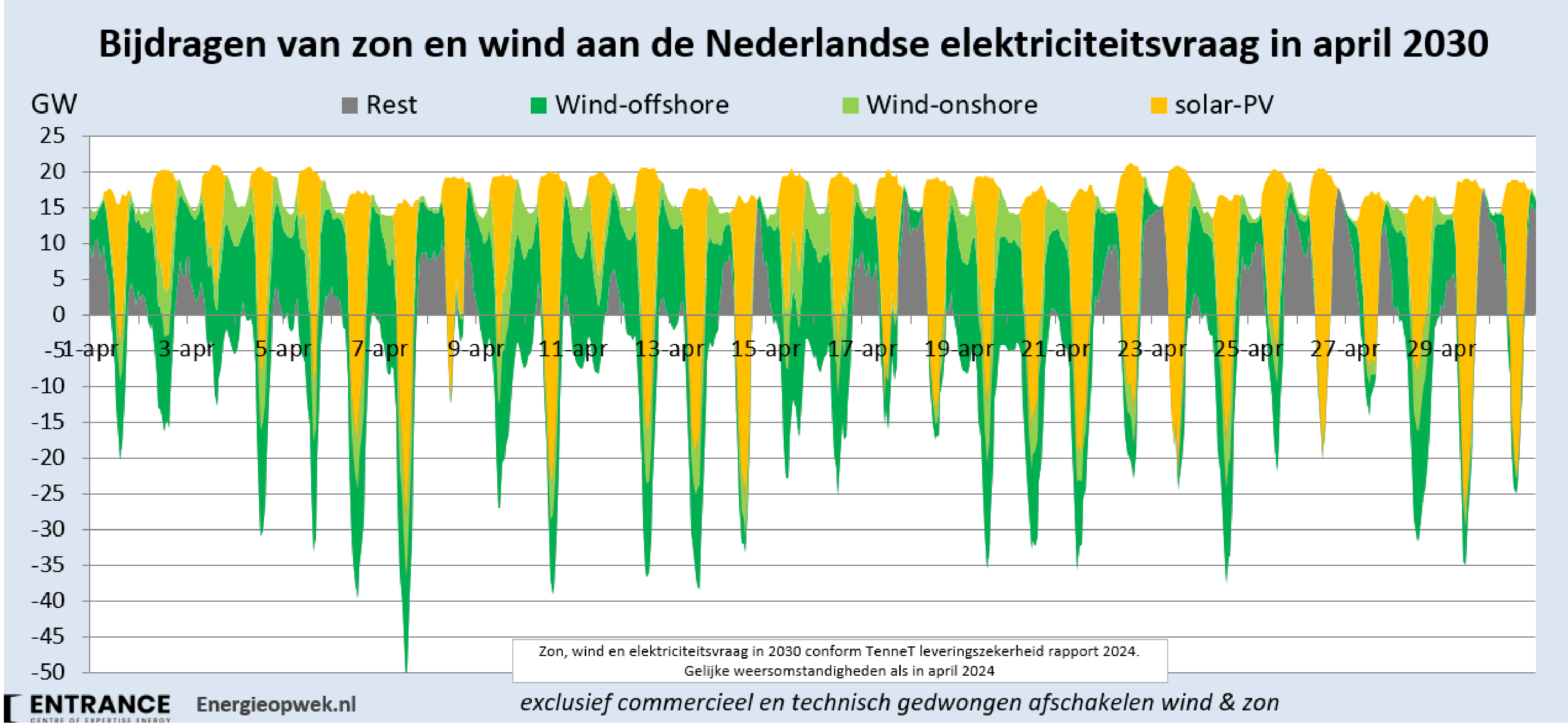


Day ahead market

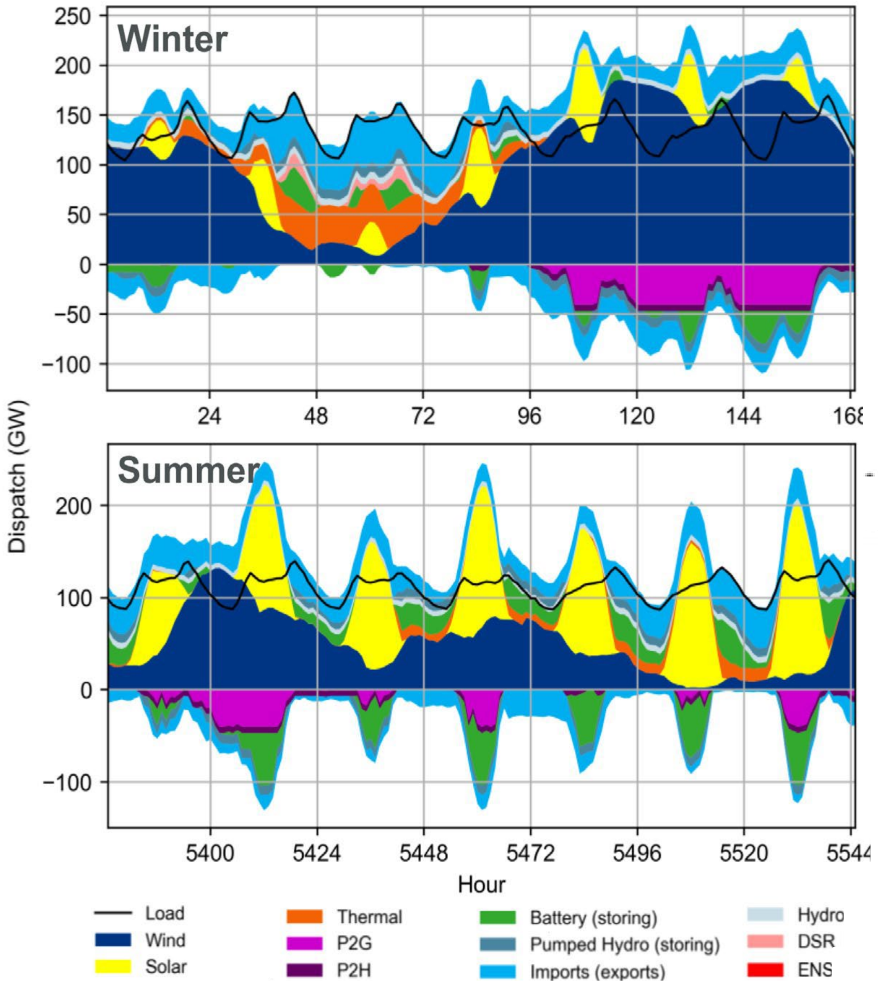
0 Eu/MWh



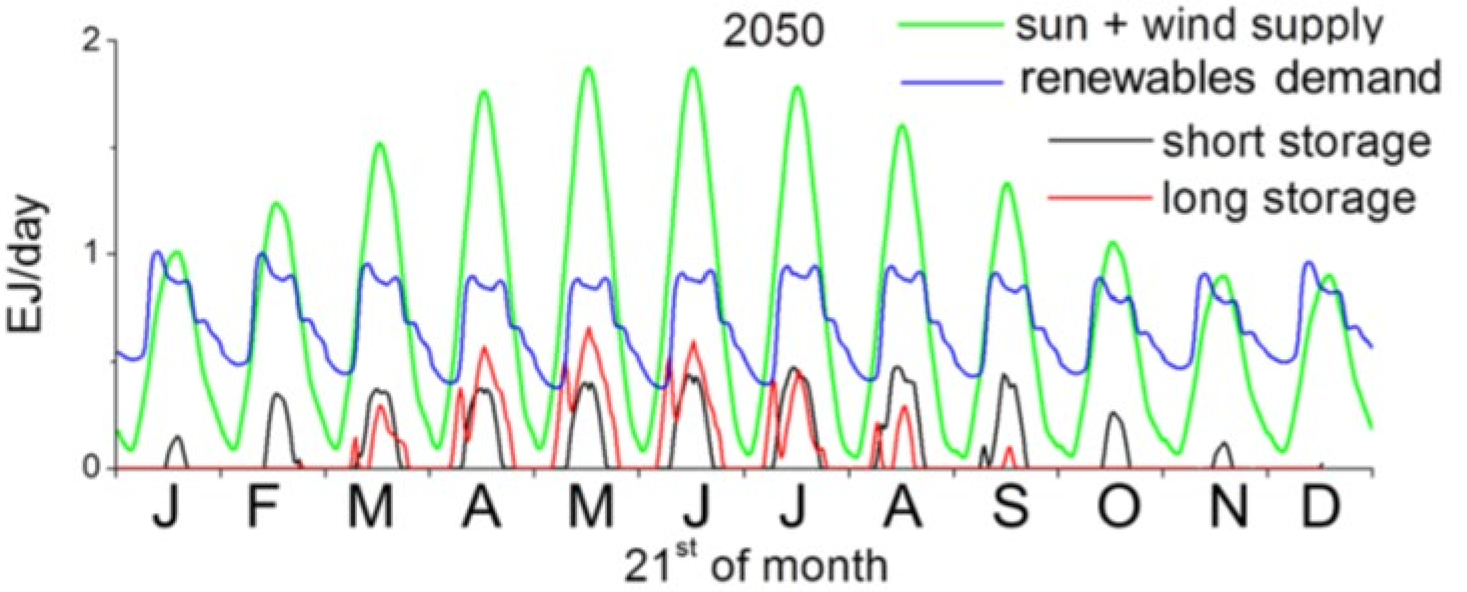
May 2024 weather and 2030 Tennet TSO renewables implementation:
- Most of the time too much generation!



Adequacy outlook, TenneT 2023



Note: here too long and short storage with about equal power



[Mulder, J. Ren. Sust. Energy, 2014]

Note: long and short storage with about equal power

H_2 → 50GW
Battery → 50GW, 200-300GWh

Together: 100GW & 200GWh

TU Delft

What is the role of energy storage?

- security of supply: *get energy also at night and in winter.*

- grid support, congestion management: *don't transport what isn't used anyway at that instant (but store it)*

- security of off-take: *use the energy*
  1) *reduce curtailment*
  2) *reduce price erosion leading to zero revenues for producers*

How did we store electricity until now?

Mostly not! Only power up and down the fossil power.
But that is not enough anymore…

Take-aways when going all-renewable:

There will be either too high or too low instantaneous renewable power availability
→ necessity of storage implementation
→ Low price or high price electricity

We see batteries and electrolysers, at similar power levels.

Capacity factors of electrolysers are limited to 20 - 30% because:
- electricity is too expensive when not in oversupply
- electrolysers switched off when powerplants are burning gas to produce electricity

Capacity factors of batteries are higher because:
- getting preference for short term storage (roundtrip efficiency)
- are also used during discharge

Take-aways when going all-renewable:

Why batteries for short term storage?

- Direct electricity storage
- High round trip efficiency of up to 90% at utility scale
- Could become affordable, but only when cycling daily: 200€/(20y x365)= 0.027 €/kWh

Why hydrogen and gas turbines?

- Batteries too expensive for long-term / seasonal storage
- It is storable and scalable
- Low roundtrip efficiency is a pity, but some losses may be recoverable.

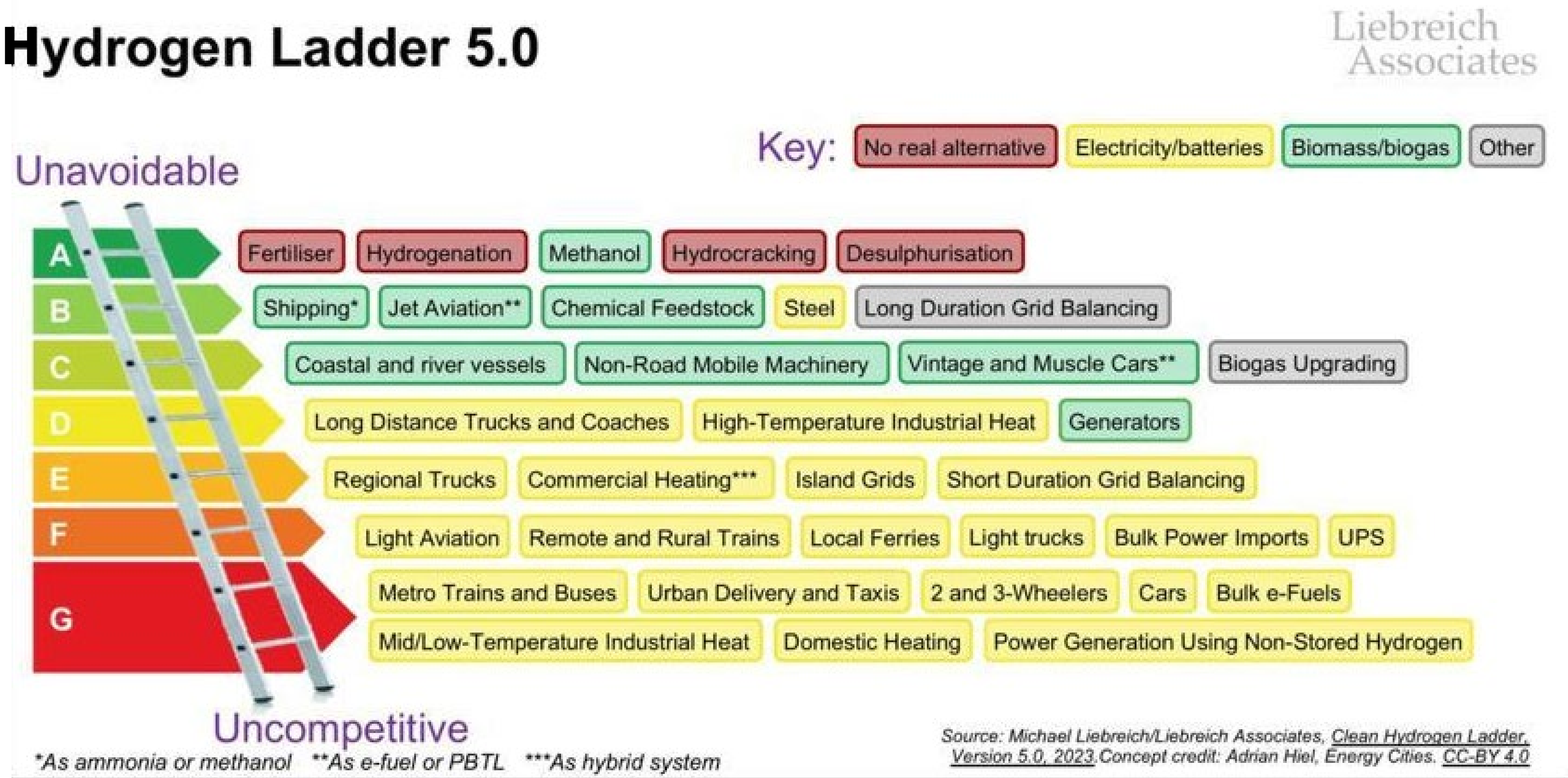
When to use hydrogen and when electricity?

Storage in batteries is more efficient than electricity → H_2 → electricity.
But:

To electrify society electricity needs to be available always: security of supply calls for H_2 as long-term storage.

Electricity for heat pump or EV may come from stored H_2 in a gas turbine, especially in winter.

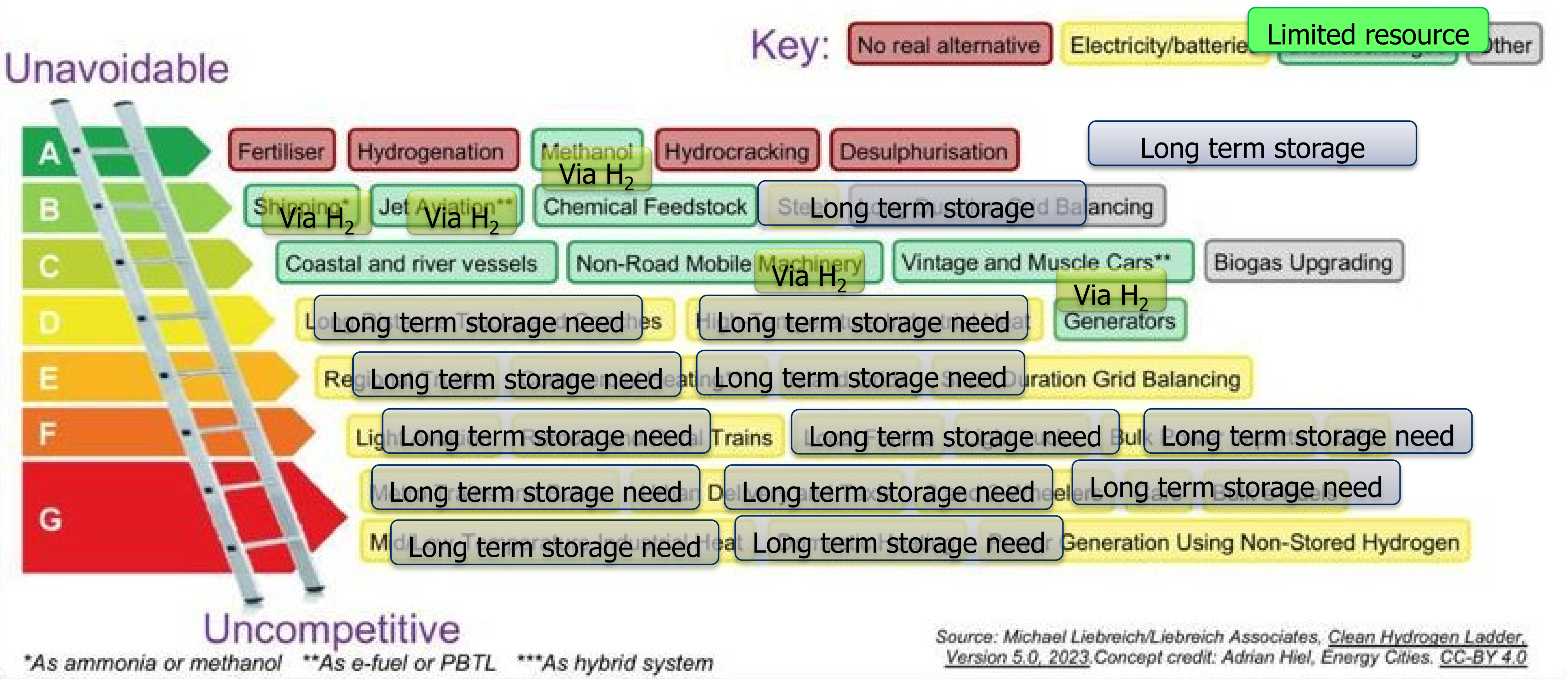
Heavy long-range transport requires higher energy density than batteries, and also fast recharge times.



Hydrogen derived long term storage enables electrification 24/365

But this hydrogen ladder unfortunately does not acknowledge that at all…

Hydrogen Ladder 5.0



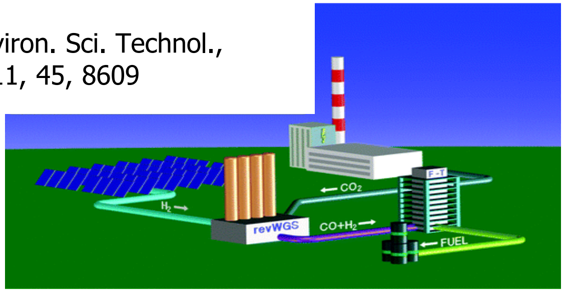
Hydrogen derived long term storage enables electrification 24/365

But this hydrogen ladder unfortunately does not acknowledge that at all…

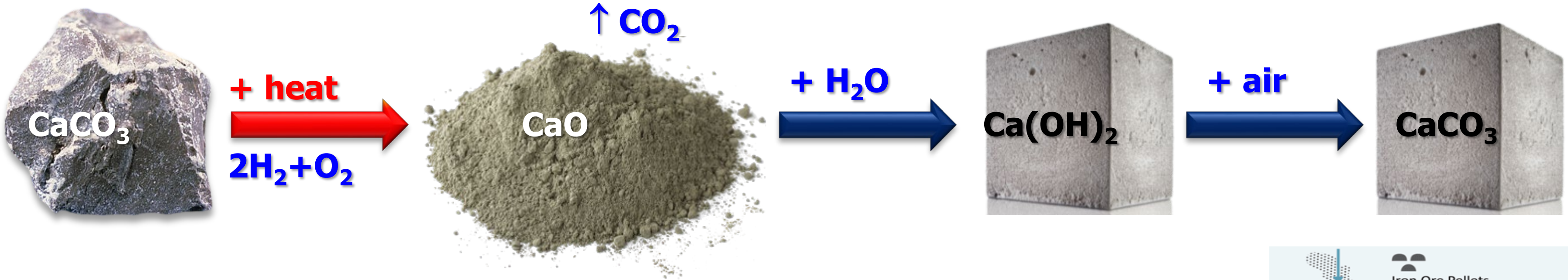
Chemical feedstock transition using H_2

- H_2, power and N_2 for NH_3
- H_2, power and CO_2 for Sabatier (CH_4) or Fischer-Tropsch process (alkanes)

Environ. Sci. Technol., 2011, 45, 8609

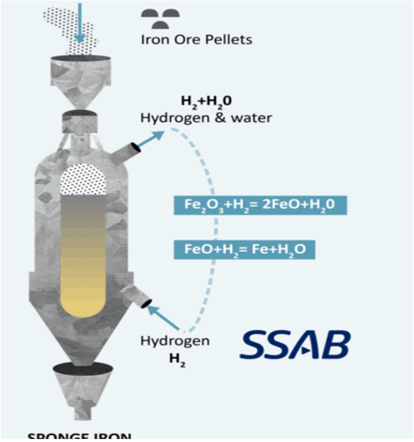


- H_2 & power for concrete production and CO_2 harvesting



- H_2 & power for fossil free iron reduction

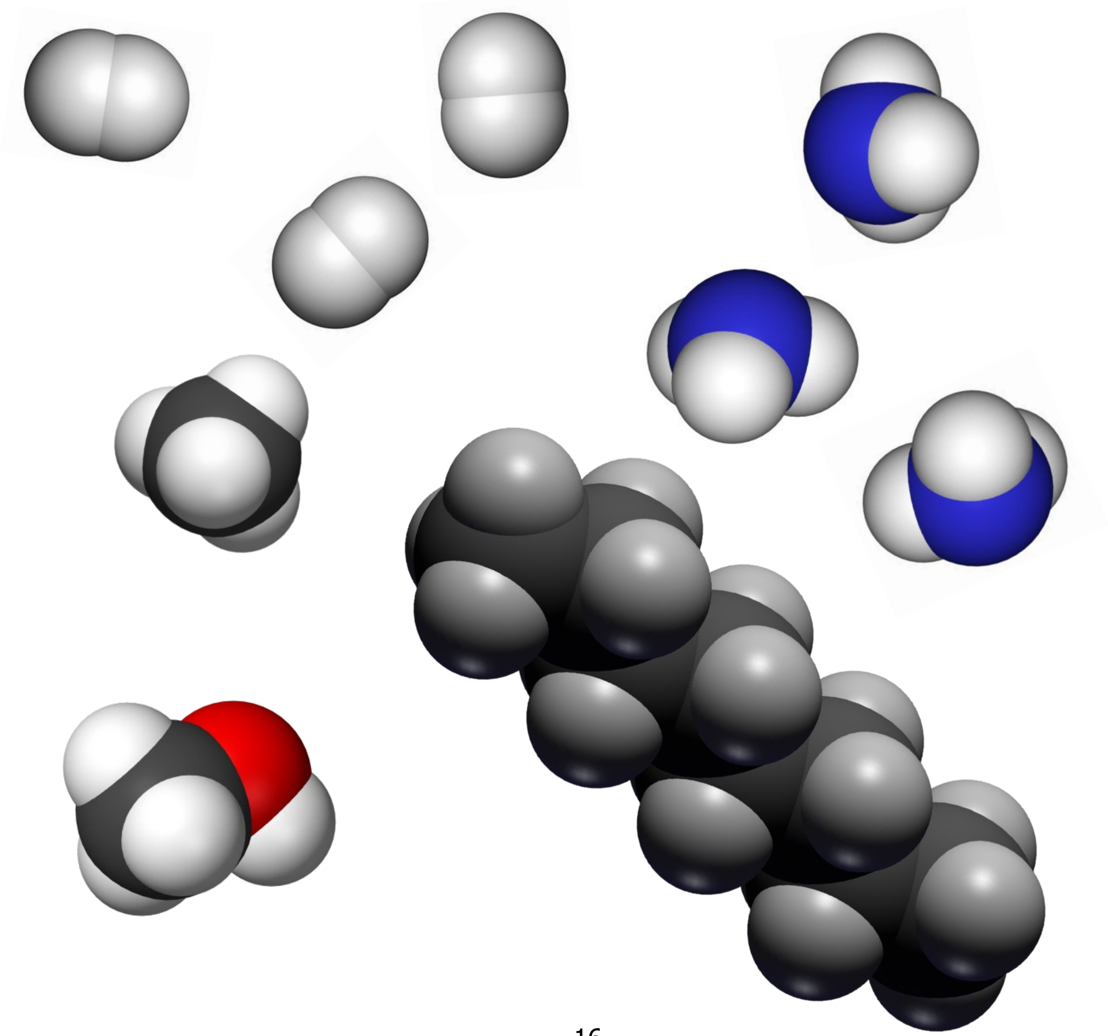
$$Fe_2O_3 + 3H_2 \rightarrow 2Fe + 3H_2O$$



Fuels are often the same chemical commodities as feedstocks

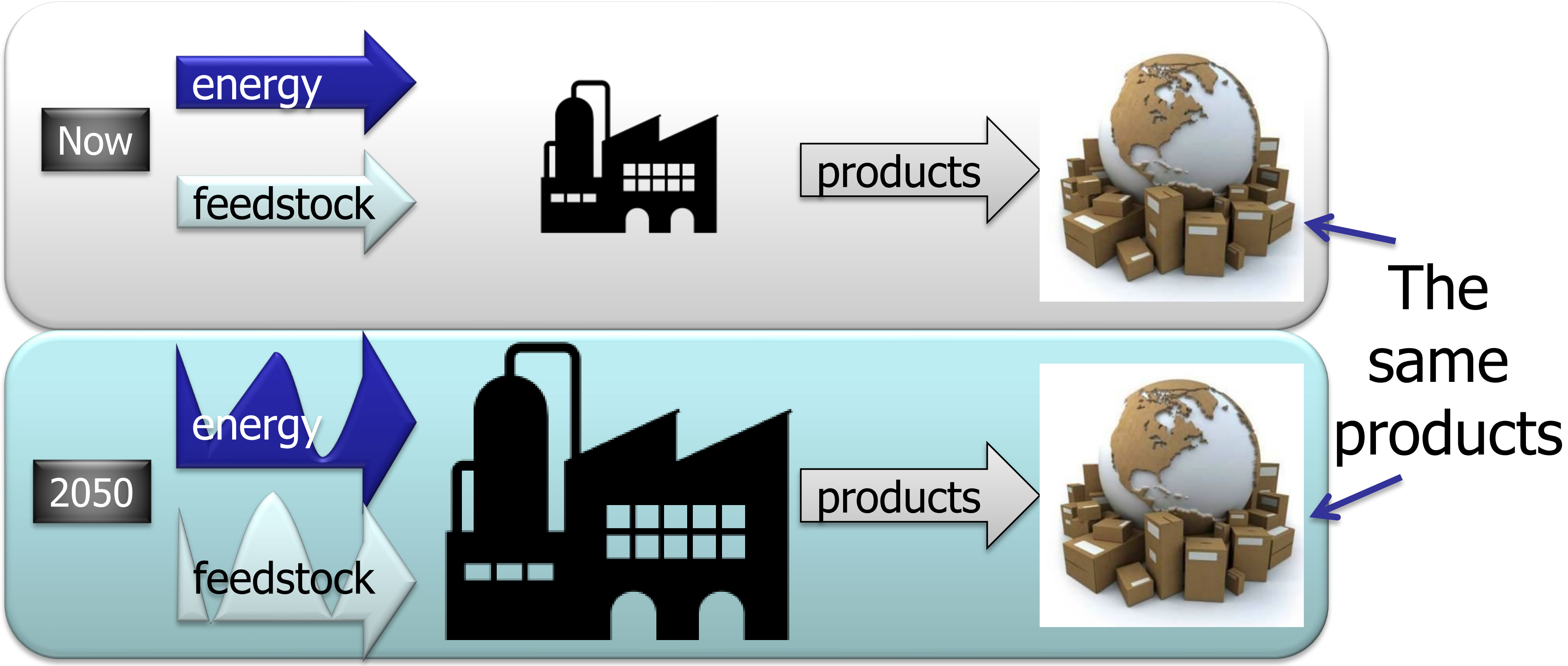
Examples?

- H_2
- NH_3
- C_nH_{2n+2}
- $C_nH_mO_p$



TUDelft

➢ Energy & feedstock transition:

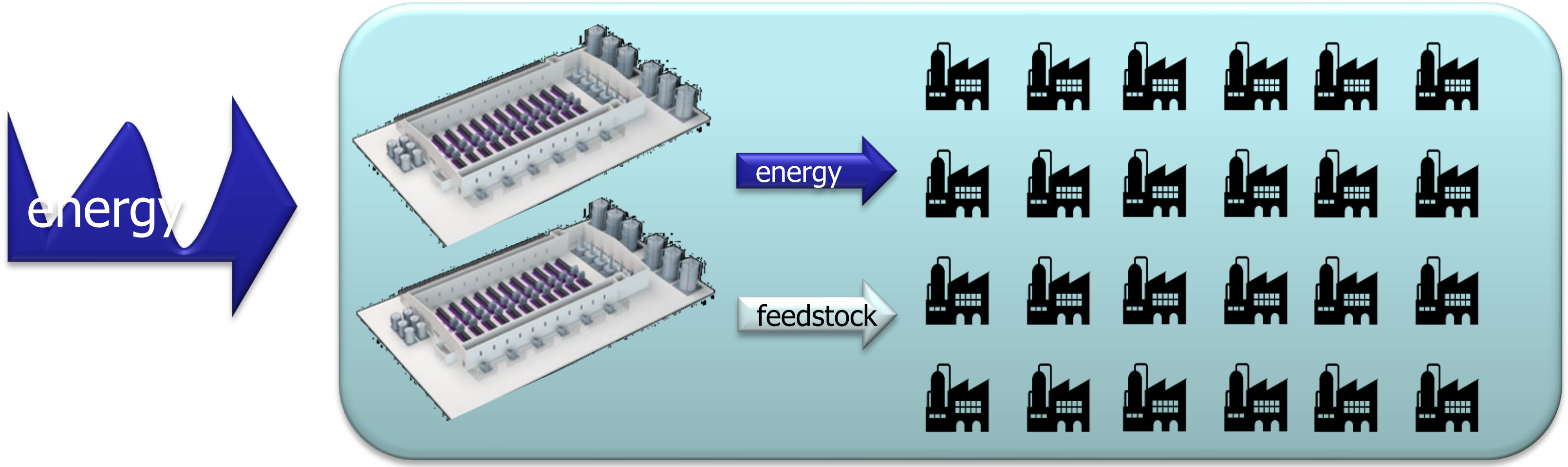


Demand side management

Larger capacity to handle intermittency, but lower capacity factor.

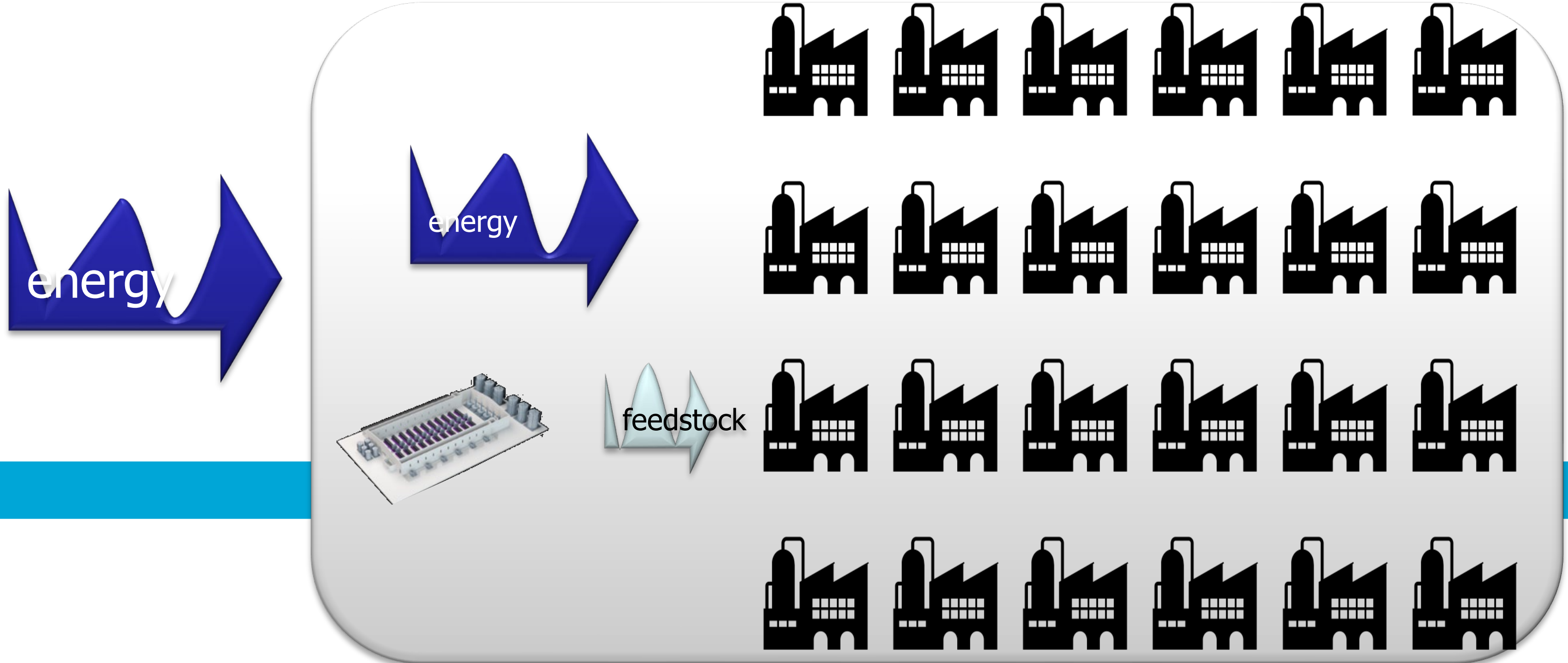
TU Delft

System choice: - invest in energy storage and conversion - keep the rest at high capacity factor



Investment in storage & conversion

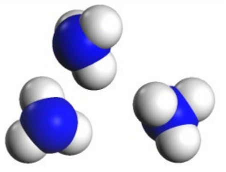
versus



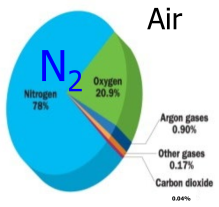
Investment in 'down stream' production capacity

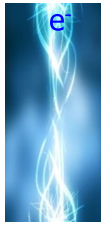
TU Delft

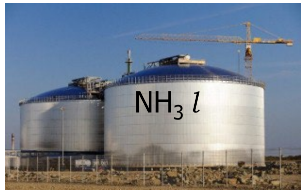
Ammonia NH_3 for large scale H_2 / energy storage? → Stabilizing the energy and feedstock system



Energy future	➢ Renewables implementation needs storage.
Production	➢ based on abundant elements N, H, and cheap catalysts: scalable. ➢ can be produced using abundant renewable electricity and CO_2 free.
Storage	➢ energy density NH_3: 22.5 MJ/kg (HHV) ➢ liquid at 10bar, 20ºC and 1bar, -35ºC ➢ current containers can contain 100000 ton NH_3~ 625 GWh.
Use	➢ clean use in fuel cell, combustion engine, gas turbine. No CO_2. ➢ fertilizer industry: CO_2 neutral fertilizers
Acceptance	➢ poisonous, but 100⁺ yr industrial know-how ➢ current NH_3 production costs >1.5% of world energy use >5 EJ/yr ➢ Biodegradable (fertilizer)





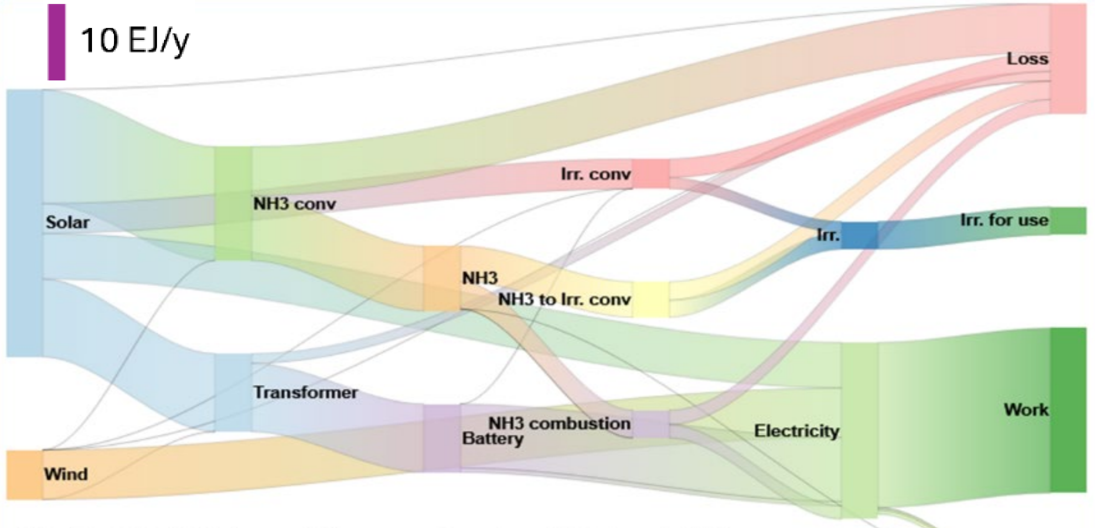


NH_3 today:
1.5% worlds energy use

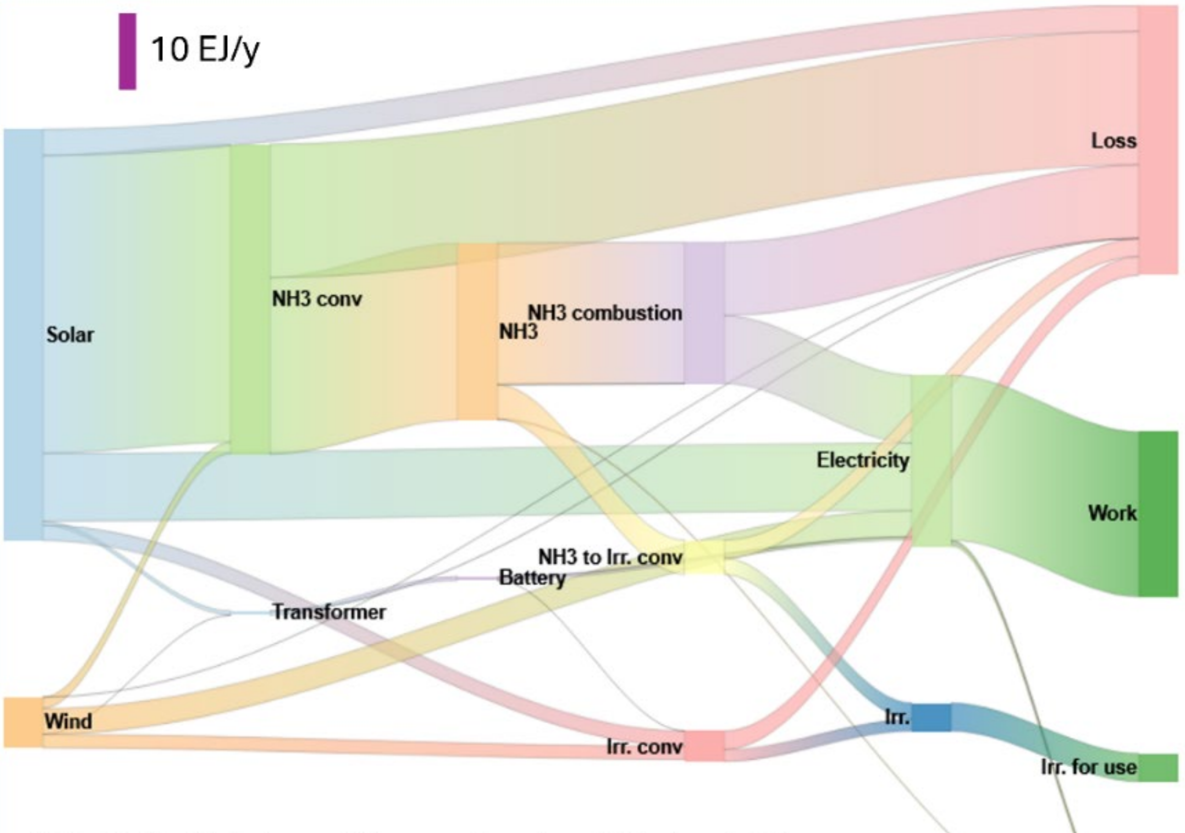
NH_3 2050:
use for long term storage & H feedstock
→ 30% energy, 20 x today

But at ~20-25 % capacity factor
→ x 4

The whole EU energy and feedstock system in a Sankey diagram, Example scenario's that use NH_3 as large scale storage



Scenario 6: Solar and Biomass, Restricted Wind, only NH_3 storage



Scenario 7: Solar and Biomass, Restricted Wind, only NH_3 storage, Scaled

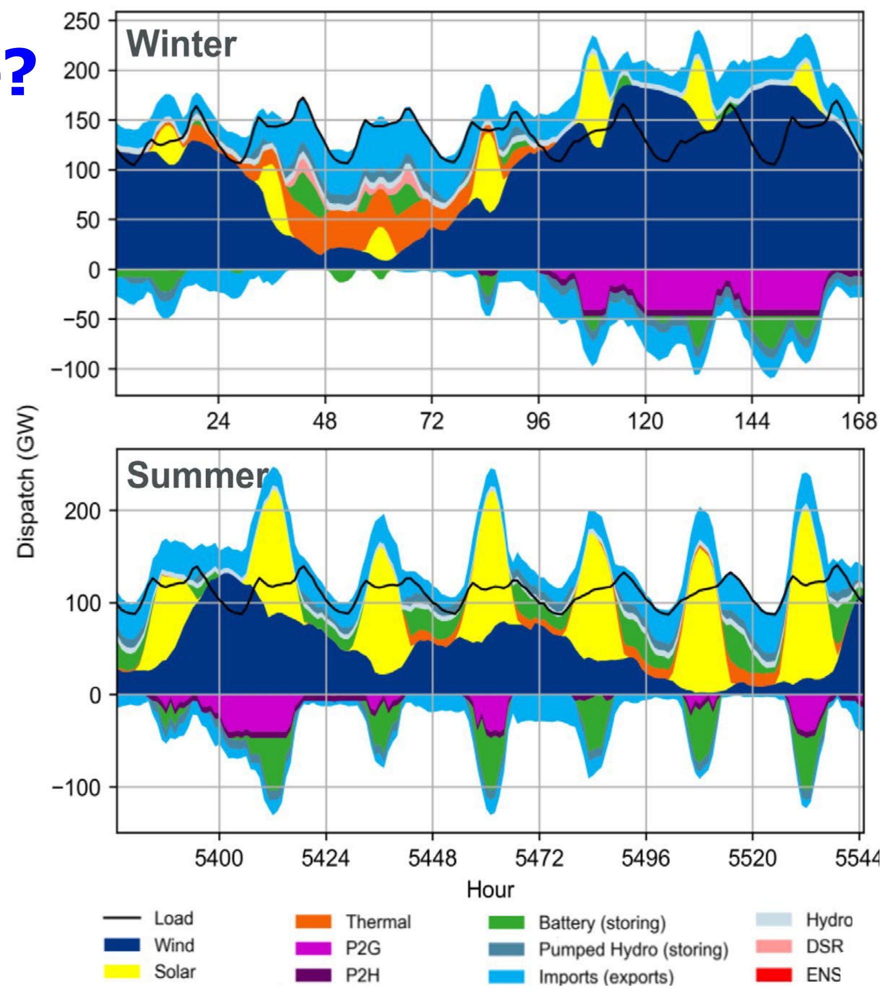
Weijers et al., under review

So we need very large scale battery and electrolysis. How to limit raw materials use?

Remember: on Dutch scale:
H2 → 50GW
Battery → 50GW, 200-300GWh

Together: 100GW & 200GWh

In battery terms: C/2 charge & C/4 discharge



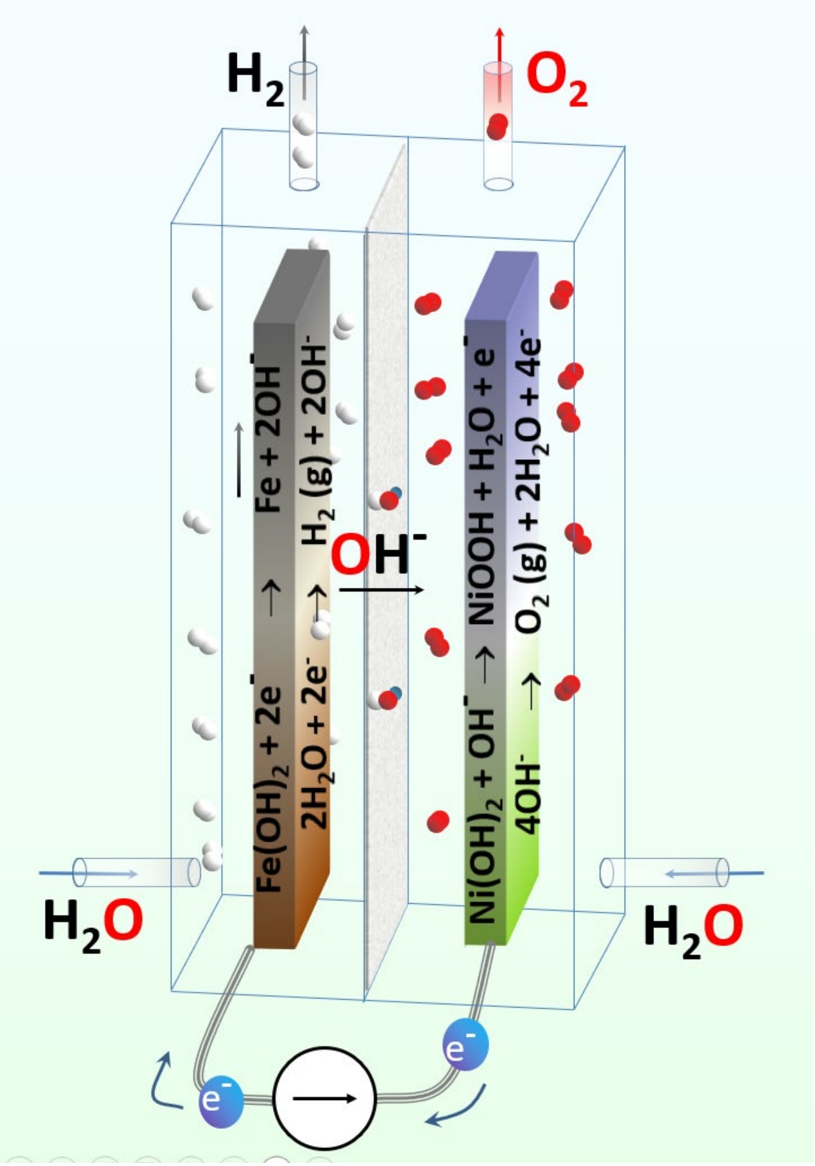
Adequacy outlook, TenneT 2023

Integrate storage applications to reduce materials demand:

1. Short term storage in batteries very efficient
2. Long term storage in H_2 fuels less efficient

Battolyser:

integrate short- & long-term storage
in one device



Battery-electrolyser:

Negative electrode:

$$Fe(OH)_2 + 2e^- \leftrightarrow Fe + 2OH^-$$

$$2H_2O + 2e^- \rightarrow H_2 (g) + 2OH^-$$

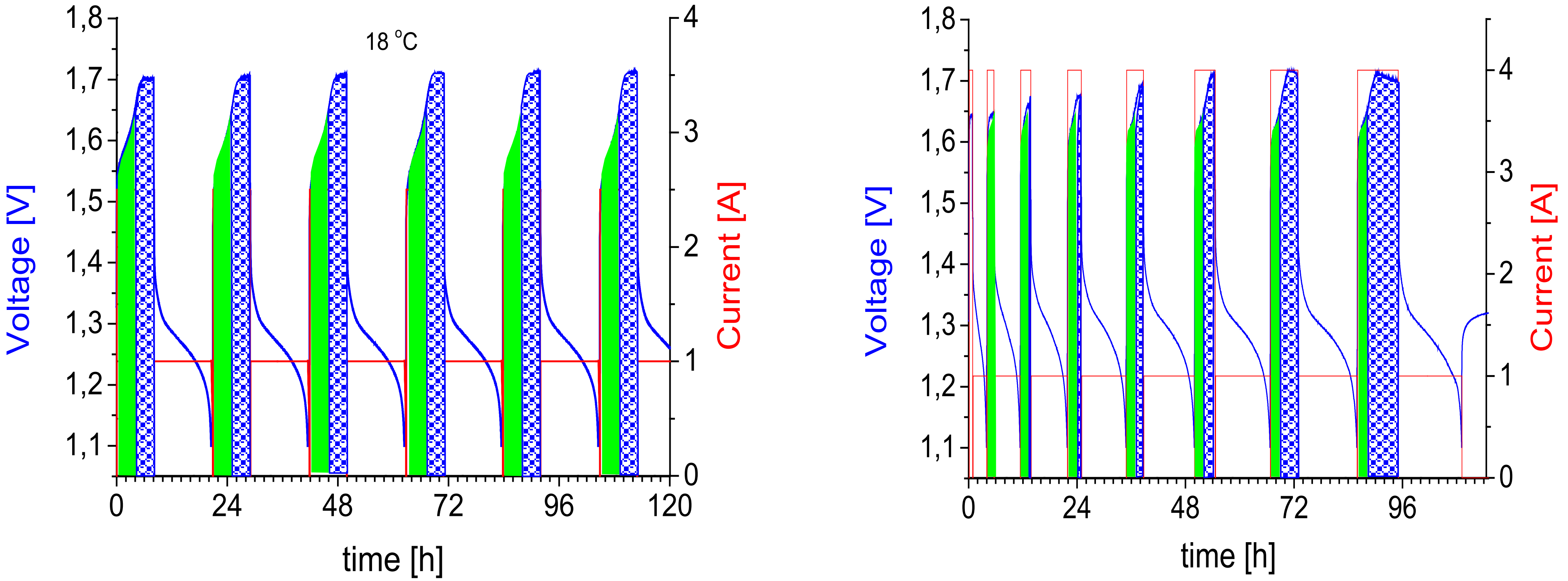
Positive electrode:

$$Ni(OH)_2 + OH^- \leftrightarrow NiOOH + H_2O + e^-$$

$$4OH^- \rightarrow O_2 (g) + 2H_2O + 4e^-$$

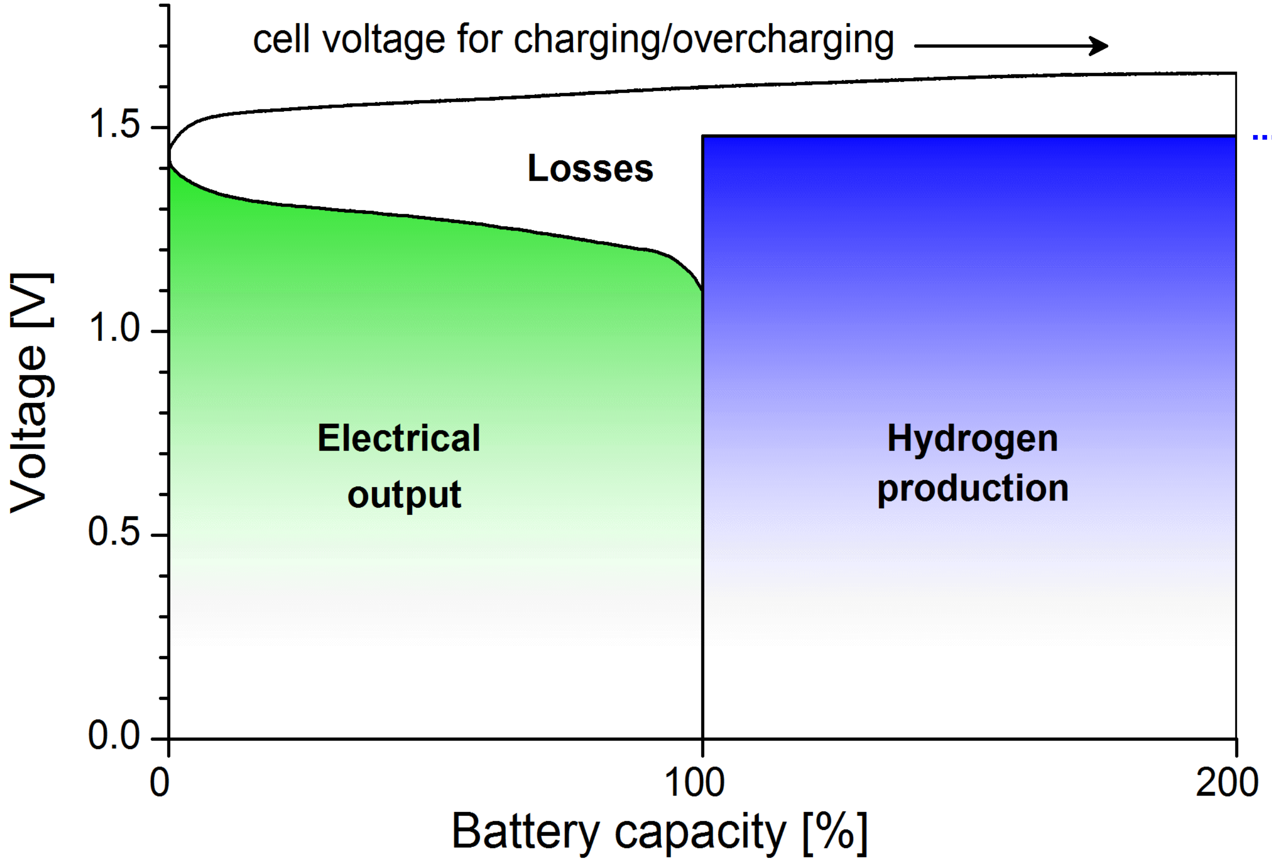
Mulder et al. Energy & Env. Science 2017
Mőller-Guland et al, Cell Rep. Phys. Scie. 2024

Charge (green) + electrolysis (bubbles) and discharge (white)



Current: applied currents during charge, electrolysis, and discharge
Voltage: that is the voltage that results when using these currents
Several cycles with constant (left) or increasing (right) current insertion.

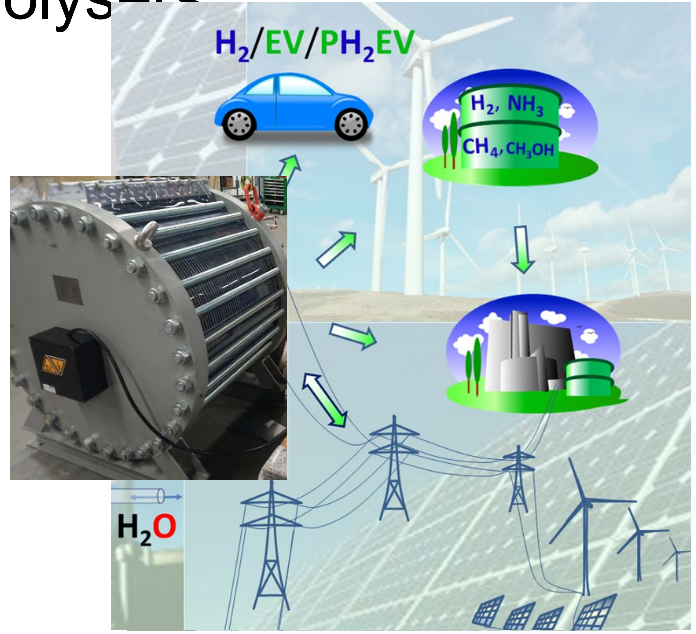
Energy efficiency:



1.48V Thermo-neutral potential = HHV

Battery - electrolyser tests

- Energy efficiency > 82-92%
- Scalable, no platinum group metals
- Highly robust
- Switches instantly
- Competitive with static batteries and electrolysers
- Non-flammable electrolytes



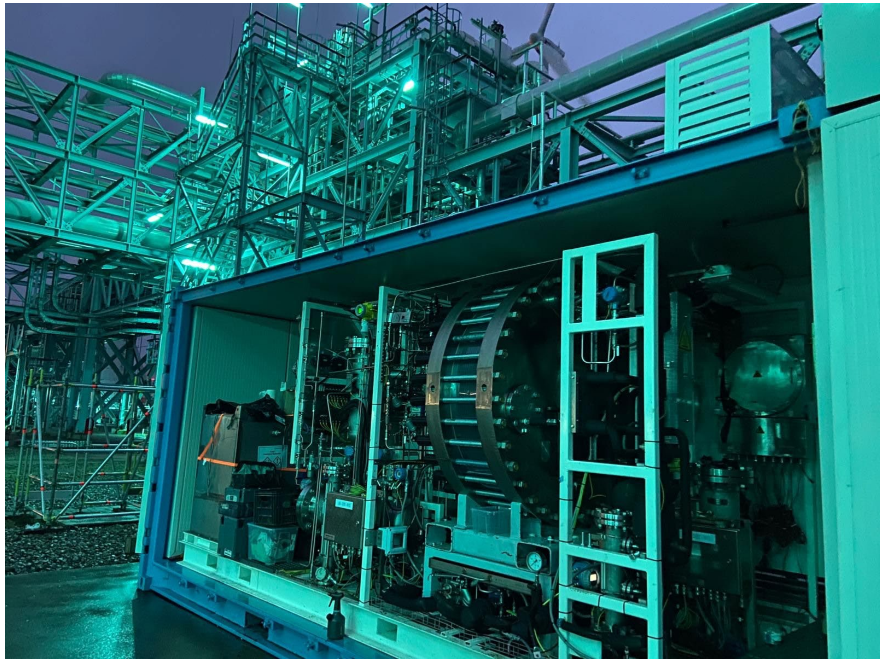
NWO Applied and Engineering Sciences

& industrial partners

www.battolysersystems.com

waddenfonds

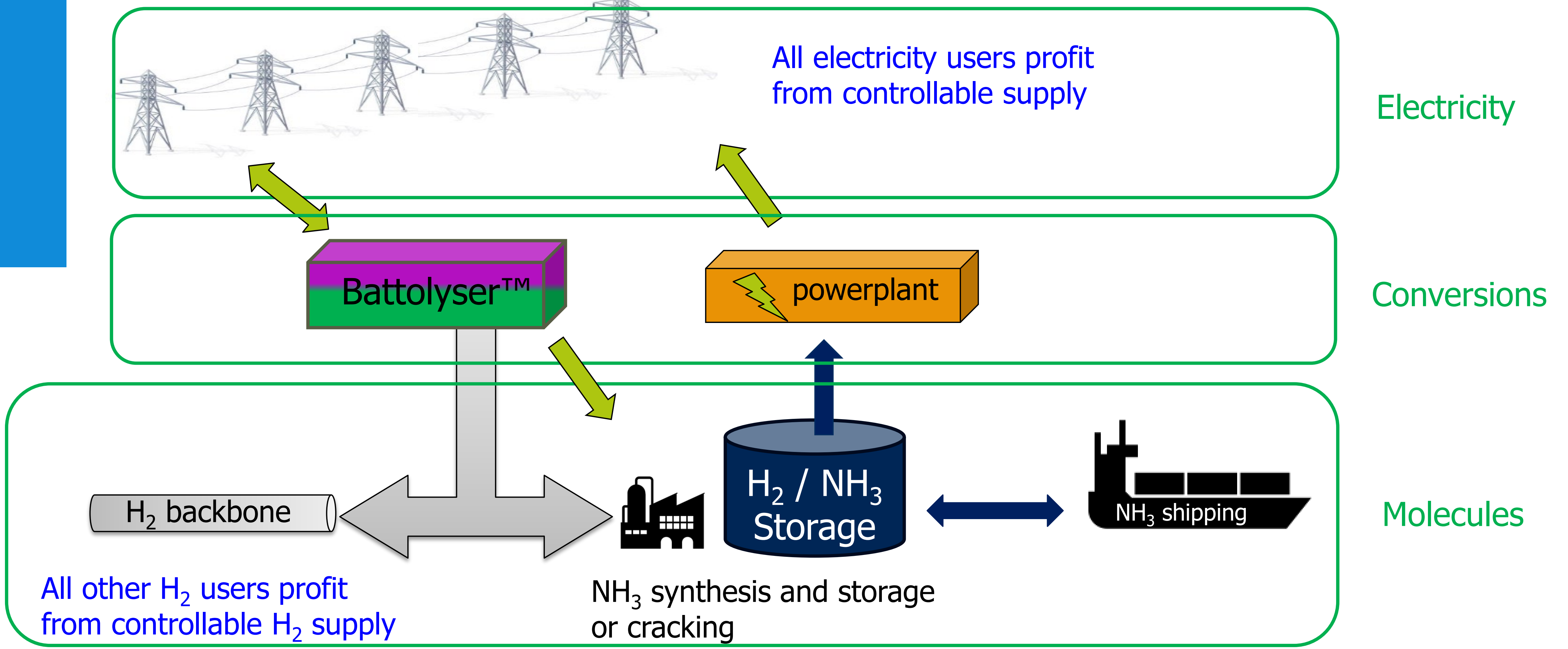
From TUD lab-scale to pilot scale at Magnum powerplant:
→ Factor ~1000 scale increase.

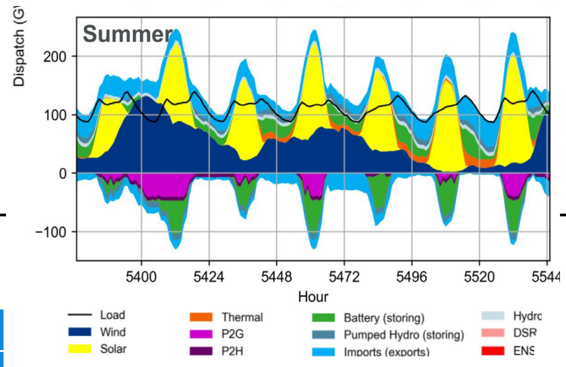


Battolyser compared to Alkaline electrolyser + Li-ion battery

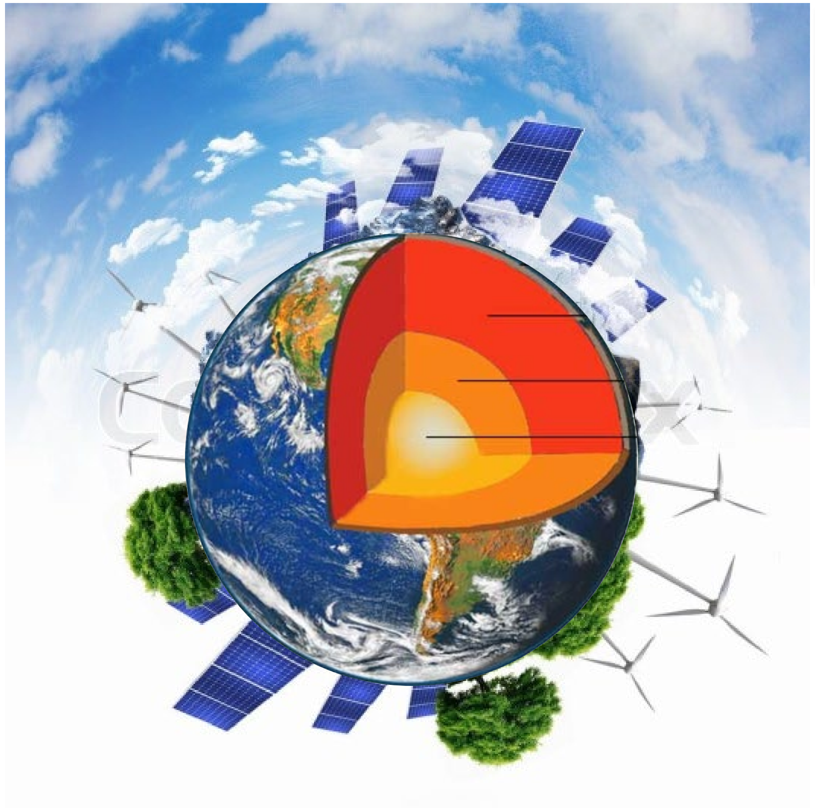
Battolyser™	Power BMS	Housing + cooling	Gas & electrolyte	Stack materials	Electrode mass	Space 20ff / GW
Alkaline electrolyser	Power BMS Min load	Housing + cooling	Gas & electrolyte	Stack materials	Electrode mass	Space 20ff / GW Eneco R'dam
Li –ion LFP battery	Power BMS	Housing + cooling	Modules racks	Separators current coll.	Electrode mass	Gigastorage Eemshaven Space 15ff /GWh

ff = 50 x 100 m^2


All electricity users profit
from controllable supply
Electricity
Battolyser™
powerplant
Conversions
H_2 backbone
H_2 / NH_3
Storage
NH_3 shipping
Molecules
All other H_2 users profit
from controllable H_2 supply
NH_3 synthesis and storage
or cracking


Summer
Dispatch (G
200
100
0
−100
5400
5424
5448
5472
5496
5520
5544
Hour
Load
Wind
Solar
Thermal
P2G
P2H
Battery (storing)
Pumped Hydro (storing)
Imports (exports)
DSR
ENS

For a TW storage challenge: better use abundant materials!



Planet Earth:
- Fe-Ni alloy core
- 70% H_2O surface
- 78% N_2 in air

Short term storage:
- Ni-Fe battolyser

Long term storage, transport, feedstock:
- H_2 from battolyser
- NH_3 using Fe catalyst and reactor