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Hydrogen-energy systems, production and grid services

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Outline

Motivation

Hydrogen as Energy Storage

The Haeolus Project

Grid Services and Hydrogen

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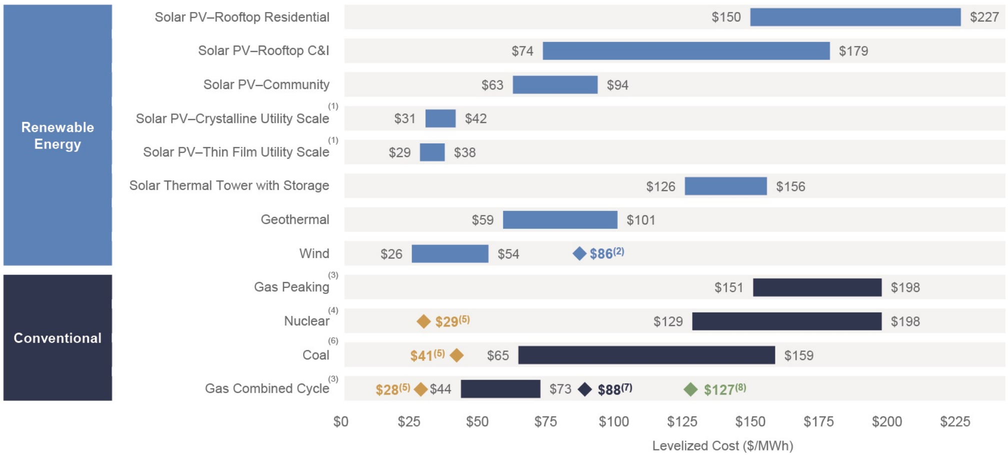
Renewables are now the cheapest energy sources

Source: Lazard LCOE Analysis 2020



Flexibility of Power Generation

Uncontrollable renewable power causes dispatching problems

Baseload (inflexible, constant):

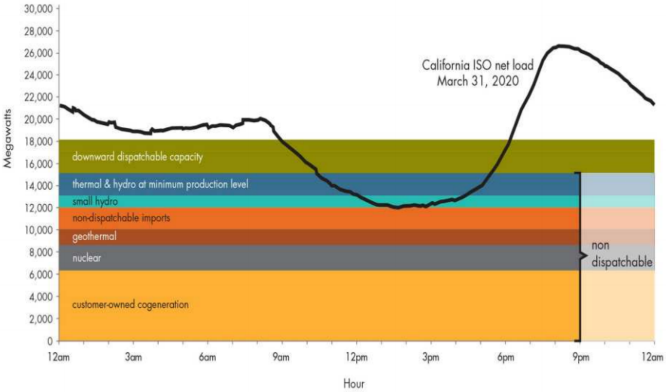
- Coal
- Nuclear

Flexible:

- Gas turbines
- Hydro

New renewables:

- Tidal (scheduled)
- Solar (≈ predictable)
- Wind (almost random)



The California Duck Curve

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Hydrogen's Role

- Production of hydrogen is highly flexible
- Hydrogen demand can become significant
- Focus on professional and heavy-duty uses
  - Taxis
  - Trucks
  - Ships
  - Trains
  - Planes (short- to mid-range)
  - Energy export
- Private EVs will likely stay on batteries

Alstom's iLint hydrogen train

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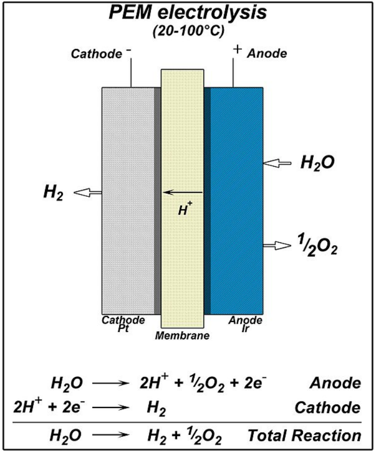
Key Hydrogen Properties

- The lightest element in nature: one proton, one electron
- In native state, H_2 is a *very* light gas: 12 Nm^3/kg
- Very reactive with a weak H–H bond
- Wide explosion range in air, 4 % to 75 %; can ignite w/o spark
- High energy density: **33 kWh/kg** for reaction with oxygen to give water
- The most common element in the universe…
- Yet, not to be found natively on Earth: we have to make it!

Hydrogen Production

- Most produced by NG reforming, but. . .
- *Electrolysis* is key for renewables: split H_2O with electricity into H_2 and O_2
- Two commercial technologies:

  Alkaline mature, efficient, proven
  PEM flexible, fast, compact
- Solid oxide: high-temperature, in research
- 2020 targets: 52 kWh/kg, 2 M€/(t/d), 2 s hot start, 30 s cold start



Hydrogen vs. Hydro Power

- Hydroelectric dams
  - Large-scale plant and investment
  - Major impact on local geography, can cause protests
  - LCOE 20–50 US$/MWh
  - High efficiency, fast response
  - ⇒ Use whenever possible
- Hydrogen
  - Can be deployed anywhere
  - Can export power as hydrogen
  - Lower efficiency, but still fast response
  - ⇒ Use when hydro is unfeasible
    - » it's actually a lot of cases

Hydrogen vs. Batteries

- Batteries
  - Store excess energy
  - Compensate for wind
  - Smooth power output
  - High efficiency
  - ⇒ Re-electrification
- Hydrogen
  - Store excess energy
  - Modulate production
  - Export hydrogen
  - High storage capacity
  - ⇒ Large scale

Hornsdale Power Reserve
129 MWh, 100 MW, 56 M€

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Raggovidda Wind Park

Berlevåg municipality, **Varanger** peninsula, **Troms & Finnmark** county

- The Raggovidda wind park:
  - 45 MW built of 200 MW concession
  - Neighbour Hamnafjell: 50 MW / 120 MW
  - Bottleneck to main grid is 95 MW
  - Total Varanger resources about 2000 MW

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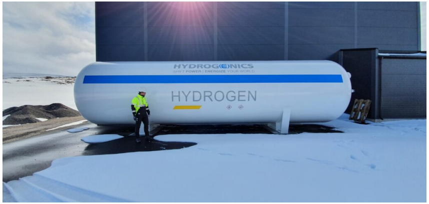
  - Total Varanger resources about 2000 MW
- Capacity factor 50 %
- Local consumption max. 60 MW
- Local economy based on fishing
- Partner operator of park & grid:

VARANGER KRAFT

The Haeolus Project

- EU project, budget 7.6 M€
- Electrolyser beside Berlevåg harbour
- Capacity: 2.5 MW or 1 t/d @ 30 bar
- Production started in June 2021
- New 10 km power line from Raggovidda
- Virtually “inside the fence”
- Accessibility by road or sea
- Partner electrolyser manufacturer:

HYDROGENICS
SHIFT POWER | ENERGIZE YOUR WORLD



The hydrogen tank
outside the containment building

Prospective Uses

What should we do with our hydrogen?

- Cars
- Boats
- Ships
- Planes
- Export to Svalbard
- Ammonia
- Biogas upgrade






Main problem: investment deadlock

Breaking the Deadlock

Also known as the “chicken-and-egg” problem

- Hydrogen suppliers
  - Energy companies
- Hydrogen users
  - Transport companies
  - Shipping companies
  - Public authorities
  - Industry
  - Private citizens
- Suppliers need demand to make money
- Users need offer for their equipment
- Is the other side going to hold out?

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- We *must* start with infrastructure
- How do we make it viable?
  - Identify key niche
  - Find one big customer
  - Find a “side hustle”
- Involve the authorities
  - Guarantee demand with buyback of hydrogen equipment
  - Guarantee supply with buyback of hydrogen fuel

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Grid Services

A viable side income for hydrogen production plants

- Balancing markets
  - Keep frequency between 49.9–50.1 Hz
  - Add-remove power to adjust
- Primary reserves (FCR)
  - Automatic
  - Few seconds to start
- Secondary reserves (aFRR)
  - Automatic
  - 30 seconds to start
- Tertiary reserves (FRR-M)
  - Manual
  - Up to 15 minutes to start

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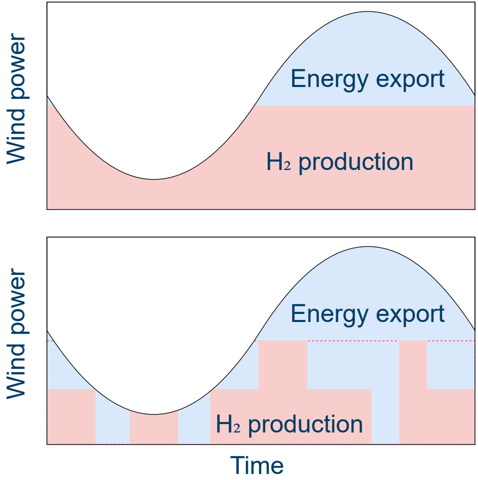
- FCR/aFRR can be
  - Procured (e.g. Norway, Germany)
  - Mandatory (e.g. Italy, France)
- Remuneration based on
  - Capacity (e.g. Denmark)
  - Activation (e.g. Italy)
  - Both (e.g. Norway)
- Minimum bid sizes
  - 1 MW (Norway FCR)
  - 5 MW (Spain aFRR)
- Direction
  - Symmetric
  - Up- or down-regulation

Hydrogen Production with Grid Services

- Electrolyser within a wind park
  - No power import
  - Energy producer at all times
  - Electrolyser power is controllable
- Nominal operation
  - Full electrolyser operation
  - Use all wind power for H_2
  - Income for exported power
- Grid-service operation
  - Throttle electrolyser as needed
  - Reduce hydrogen production
  - Income for exported power
  - Income for grid services



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Value of Curtailed Hydrogen

- Price of sold hydrogen is unknown or volatile
  - Often agreed “politically” rather than set by market
  - Agreed-upon quantity may be limited
- Keep spare capacity
  - Ready for market expansion
  - Deployment of new electrolysers takes time
- Monetise this spare capacity
  - Operational income I
  - Hydrogen production H
  - H_0, I_0 for nominal, “full power” case
  - H, I for grid-service case

$$v_{\mathrm{H}_2} = \frac{I - I_0}{H_0 - H}$$

“Value of hydrogen we did not produce because of grid services”

- Same electrolyser
- Same OPEX/CAPEX
- Easily computable

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Data and Method

- Data for wind power from Raggovidda (2017), 0–45 MW
- Data for spot prices and FCR capacity for NordPool, same year
- Data for activated capacity from Statnett
- Electrolyser sizes: Haeolus (2.5 MW) and Raggovidda full scale (45 MW)
- Minimum power 0.3 MW, minimum bid 1 MW
- Symmetric FCR (real) and hypothetical asymmetric FCR
- Calculate *I* and *H* and compare

Preliminary Results

With data from Norther Norwegian grid subdivision (NO4)

	Haeolus (2.5 MW)		Raggovidda (45 MW)	
	Production (t/y)	v_{H_2} (€/kg)	Production (t/y)	v_{H_2} (€/kg)
Reference	362	—	3668	—
Up	308	4.05	3032	3.98
Symmetric	226	2.47	2526	2.86
Down	138	2.32	888	2.29

- EU estimate for green hydrogen: 2.5–5.5 €/kg
- EU 2030 target for green hydrogen: 1.1–2.4 €/kg
- US 2030 target for clean hydrogen: 1 $/kg

Initial Observations

- All values comparable to production targets for hydrogen cost
  - No large loss, or even profit, by curtailing hydrogen
- Only up-regulation has significantly higher value than spot price (1.75 €/kg)
  - It is not even a “real” FCR service
- Norway has a very small and unprofitable capacity market
  - Rationale: large hydro providing balance
  - Increase in wind power and interconnection may change this
- Spain, France can prove more interesting—Analysis ongoing

Conclusions

- Flexible hydrogen production can ease adoption of renewable energy sources
- Hydro, hydrogen and batteries serve different purposes
- Introducing the “hydrogen economy” is a mostly a coordination problem
- Delivering reserve services to the grid can give idle hydrogen infrastructure something to do while the demand builds up

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Thank you for your attention!

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Technology for a better society

Hydrogen Storage (1/2)

Mobile & On-Board Storage

- Compressed gas (cH_2), 350 bar to 700 bar
  - No self-discharge, resilient
  - Requires compressor, 2 kWh/kg
  - Good for minor amounts
- Liquid hydrogen (LH_2)
  - Critical point 33 K@13 bar
  - Large plant required, 5 to 10 kWh/kg
  - Boil-off and large ATEX zone
  - Good for large amounts, maritime
- Metal hydrides (MH)
  - Volume as LH_2, no odd p or T
  - High weight and cost
  - Only special applications (submarines)

700 bar cH_2 tanks onboard Toyota Mirai

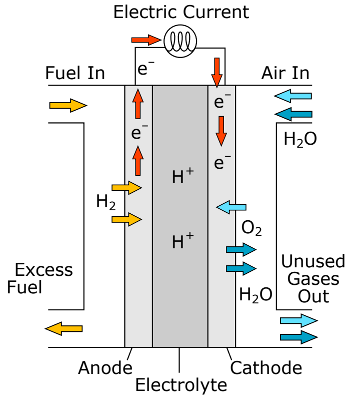
Hydrogen Storage (2/2)

Stationary and Large-Scale Storage

- Low-pressure or cryogenic spheres
- PEM electrolysers produce at 30 bar
  - Can avoid compressor
- Bulk ships for long-range LH_2 export
- Chemical carriers (LOHC, NH_3, . . .)
- Salt caverns (geology-dependent)

Hydrogen Use

- Fuel cells: opposite of electrolysers
- Many types (also other fuels):
  - **LT-PEM**: most developed
  - HT-PEM: (a little) higher temperature
  - Alkaline: good, but CO_2-intolerant
  - Solid-oxide: high temperature
  - Methanol, formic acid, PAFC, ...
- Typical efficiency 50 % to 60 %



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