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Hydrogen energy storage
and grid services in microgrids

SINTEF Mathematics & Cybernetics

2 July, 2019
Microgrids Summer School
Belfort, France

Outline

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Hydrogen Technology

Hydrogen and the Grid

The HAEOLUS Project

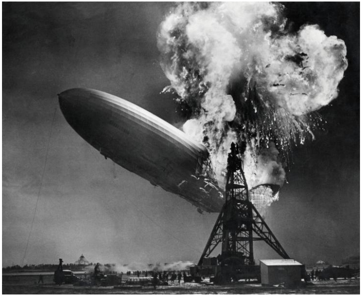
An Arctic Microgrid: Longyearbyen, Svalbard

Hydrogen

- 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 native on Earth: we have to make it!

Safety First

- – Easily ignited
- – No spark necessary, only static charge
- – Invisible and non-radiating flame
- + Light gas will shoot for the sky
- + Composite tanks are very durable
- Safer than diesel and gasoline...
- ... if you know what you are doing!



Do you know how many survived this?

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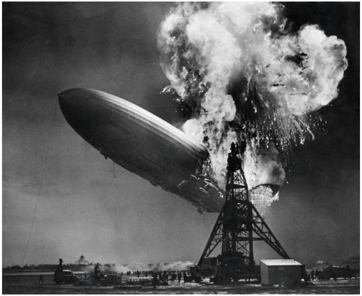
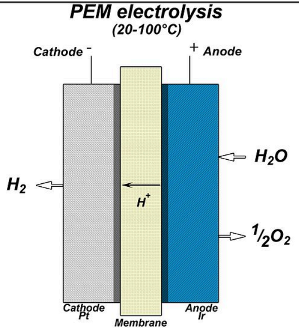


Do you know how many survived this? **62 of 97**

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



$$H_2O \longrightarrow 2H^+ + \tfrac{1}{2}O_2 + 2e^- \quad \text{Anode}$$
$$2H^+ + 2e^- \longrightarrow H_2 \quad \text{Cathode}$$
$$H_2O \longrightarrow H_2 + \tfrac{1}{2}O_2 \quad \text{Total Reaction}$$

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)

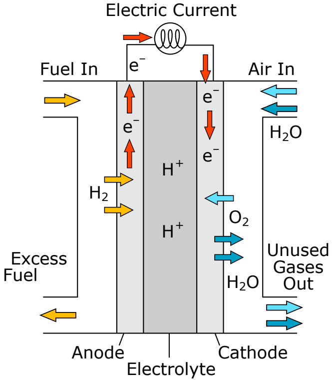
700 bar cH_2 tanks onboard Toyota Mirai

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 %



Caveat on Efficiency

Lies, Damned Lies, Statistics and Efficiency Definitions

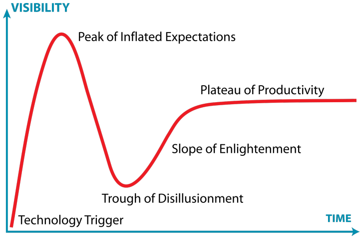
Thermodynamics of the reaction:

$$H_2 + \frac{1}{2}O_2 \longrightarrow H_2O$$

- $\Delta g_l^0 = 237\,\mathrm{kJ/mol}$: maximum obtainable **work**, $V^{\mathrm{rev}} = 1.23\,\mathrm{V}$
- $\Delta h_g^0 = 242\,\mathrm{kJ/mol}$: maximum obtainable **heat** (LHV), $V_\theta^{\mathrm{rev}} = 1.25\,\mathrm{V}$
- $\Delta h_l^0 = 286\,\mathrm{kJ/mol}$: maximum obtainable **heat** (HHV), $V_\theta^{\mathrm{rev}} = 1.48\,\mathrm{V}$
- If converting to power, use Δg ("second-law" efficiency)
- If converting to power and heat, it is debatable
- Some "cheat" by selecting most convenient definition

The Hydrogen Society
Do you remember the early 2000s?

- An energy *carrier*, not a source
- Take over mobile energy storage
- Produce from renewables
- Use in zero-emission vehicles
- A lot of hype for H_2 cars in early 2000s
- Use in everything from mobile phones to power plants
- Technology was still immature



Hydrogen in Society
Finding what hydrogen is good at

- Batteries have been getting better
  - Private EVs will likely stay on batteries
- Hydrogen will focus on professional and heavy-duty uses
  - Taxis
  - Trucks
  - Ships
  - Trains
  - Planes (short- to mid-range)
  - Energy export

EV traffic jam in Oslo

Hydrogen vs. Batteries

In Numbers & Facts

- CAPEX (note structure)
  - Batteries: 250 $/kWh
  - Fuel cells: 1500 $/kW
    - mass production: 268 $/kW
  - Hydrogen tanks: 20 $/kWh
- Storage efficiency
  - Round-trip batteries: 90 %
  - with fast charging: 80 %
  - Hydrogen: 30 % to 40 %

- Lifetime
  - Batteries: ≈ 1000 cycles
    - Depends on type, usage
  - Fuel cells: up to 30 000 h
  - Hydrogen tanks: 20+ years
- Power tariffs (Norway)
  - Standard: 40 €/kW/y
  - Interruptible: 2 €/kW/y

Hydrogen production can be dispatched, battery charging not

Outline

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Hydrogen and Power Grids

- IEA HIA task 24 for "Wind Energy & Hydrogen Integration" identified 3 roles:
  - Mini-grids
  - Energy storage
  - Fuel production
- IEA HIA task 38 "Power-to-H_2 and H_2-to-X"
  - H_2 downstream uses
  - Grid services

Utsira, experimental minigrid with 50 kW FC and 215 kg hydrogen storage

Flexibility of Power Generation

Baseload (inflexible, constant):

- Coal
- Nuclear

Flexible:

- Gas turbines
- Hydro

New renewables:

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

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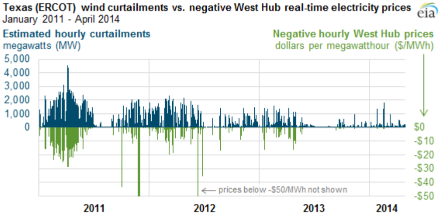
More wind power:

$\Rightarrow$ Less predictable generation

$\Rightarrow$ Negative prices



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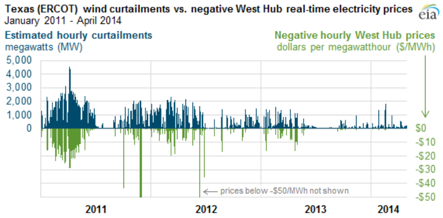
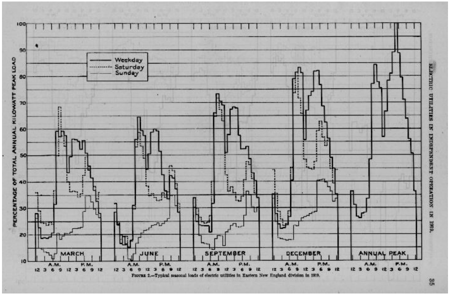


… What about the demand side?

Power Consumption Profiles

- An uncontrollable external input
- Production and import to match
- Periodicity due to:
  - Weekends
  - Power-intensive industry
  - Meal times
- Shape due to characteristics
  - Electricity or gas heating
  - Presence of industries
  - Climate

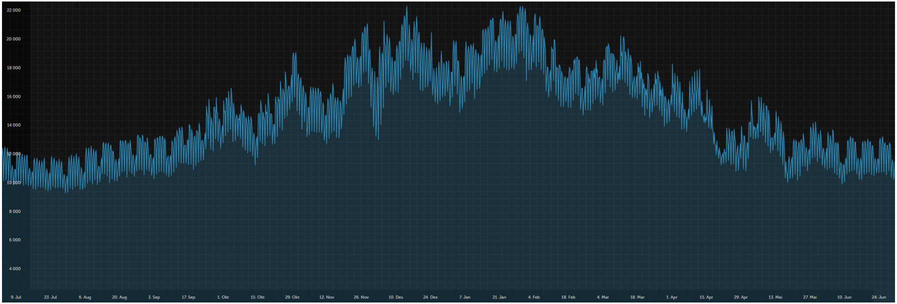


Load profiles for New England, 1919.

Norwegian Consumption Profile

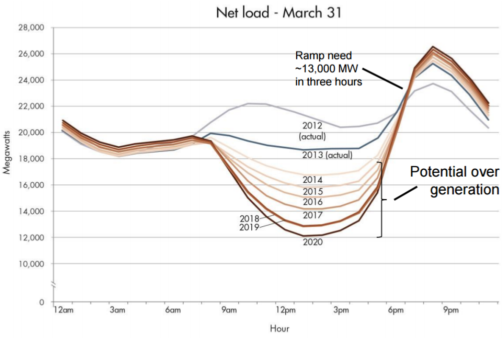
July 2018–June 2019

- Small weekly oscillations (electric heating)
- Significant seasonal oscillation (cold winter 2018–2019)



Interplay of Consumption and Renewables
The California Duck Curve

- Increasing solar power
- Daily demand dip



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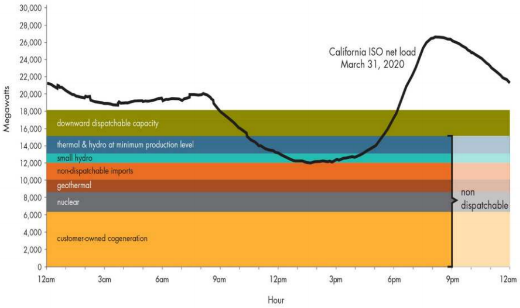

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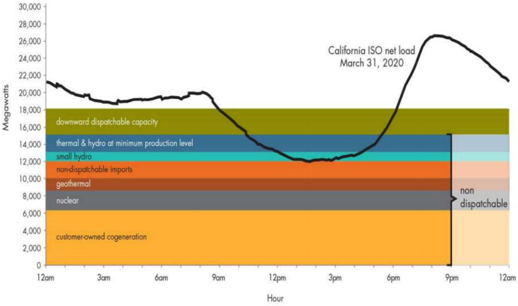

Generation is becoming less flexible: what about flexible *consumption*?

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Demand Flexibility

Hydrogen and 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€

Grid Services

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

Prices in some European countries (June-July 2019)

- FCR
  - Northern Norway: 6–38 €/MW/h
  - Germany: 8 €/MW/h
  - France: 4 €/MW/h
- FRR-A
  - Northern Norway: 0–10 €/MW/h
  - Germany: 1–7 €/MW/h
  - France: 20 €/MW/h
- `transparency.entsoe.eu`

Hydrogen in the Big Picture

Stabilising the Grid by Dispatching Production

- Electrolysers are large consumers with fast dynamics (ms)
- Hydrogen production is not time-critical
- Re-electrification is (usually) not economical
- Money-makers:
  - Hydrogen sales
    - Hydrogen is an energy carrier for mobile applications
    - Over 25 % of energy worldwide is used for transport
  - Interruptible power supply tariff
  - Grid services in all time scales
  - Reactive power compensation

Hydrogen in the Small Picture

How does it Apply to Microgrids?

- Centralised control vs. market economy
- Power constraints instead of pricing
- Direct automatic frequency support
  - No contracts, bids, etc.
- Re-electrification with fuel cells
- Different criteria for hydrogen storage sizing & security of supply

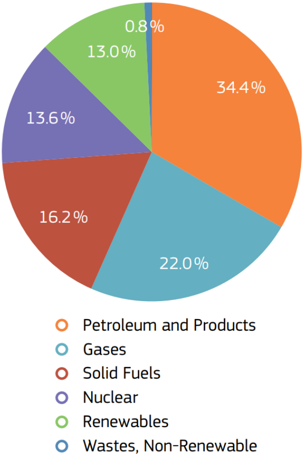
Longyearbyen, Svalbard: 2000 inhabitants and a microgrid

Outline

Motivation

- EU 2030 target: 27 % renewable energy consumption
  - In 2015 it was 13 %
  - *Production* is already 26.2 % (2015)
  - No renewables in energy imports
- Most renewables produce electricity
- Several are not controllable
- Some are unpredictable

2015 EU consumption



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Constraints of Wind Power

- Hard to predict production
- Capacity factor about 33 %
- Need reserve capacity
- Often, good wind power is found where:
  - there is little hydro potential
  - few people live
  - the grid is weak
  - accessibility is difficult
- All this even more true for offshore wind!

The Connection between Hydrogen and Wind

- Beyond 20 % wind share, value plummets
  - *Gonzalez et al., Ren. Ener., 29.4 (2003), 471–489*
- Hydro is rarely possible
- Batteries are too expensive
- Hydrogen has lower efficiency
- IEA's HIA task 24 identified 3 main cases:
  - Energy storage
  - Mini-grid (e.g. islands)
  - Fuel production
- Grid services, reserves, target matching...

Utsira, Norway (2004)

The HAEOLUS Project

http://haeolus.eu - @HaeolusProject

- A FCH2 JU Innovation Action
- Objectives:
  - Enable more wind power
  - Test multiple use cases
  - Demonstrate a 2.5 MW system
  - Demonstrate remote operation
  - Report & disseminate
- Key figures:
  - Budget: 7.6 M€ (5 M€ from EU)
  - Time frame 2018–2021
  - Capacity 1 t/d
  - Production start: early 2020

Kick-off in Oslo, January 2018

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The Wind Park

Raggovidda wind park, **Berlevåg** municipality, **Varanger** peninsula, **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

H2AEOLUS

The Electrolyser System’s Site

Raggovidda wind park, **Berlevåg** municipality, **Varanger** peninsula, **Finnmark** county

- Located beside Berlevåg harbour
- Compact 2.5 MW PEM electrolyser
- 100 kW fuel cell for re-electrification
- New 10 km power line from Raggovidda
- Virtually “inside the fence”
- Accessibility by road or sea
- At least 120 t over 2.5 year
- Partner electrolyser manufacturer:

HYDROGENICS
SHIFT POWER | ENERGIZE YOUR WORLD

View of Berlevåg,
site highlighted

Grid Services

- Wind energy production target match
  - Currently: prediction outsourced
  - 3rd party paid in % of production
  - Easily quantifiable potential
  - Adjust electrolyser to fulfil target
- Primary, secondary & tertiary reserves
  - Electrolysers are easily ramped
  - Can acquire slots in all reserves
- Project partner:

tecnalia

Hour	Price NOK/MW	Volume MW
1	180	33
2	139	34
3	139	34
4	139	34
⋮	⋮	⋮
18	18	34
19	18	25
20	17	48
⋮	⋮	⋮

Price for primary reserves on Oct. 3, 2018, northern Norway.

Other Activities

- Remote operation
  - Relevant for many wind parks
  - Run demonstration from Italy
- Partner software developer:

Knowledge Environment Security Srl

- System prognostics
  - Reduce on-site inspections
  - Optimise maintenance
  - Avoid unscheduled stops
- Partner university:

UBFC UNIVERSITÉ BOURGOGNE FRANCHE-COMTÉ

- Dynamic modelling
  - Process model & optimisation
  - Control synthesis
- Partner university:

University of Sannio

- Control implementation
- Integration with smart grids
- H_2 valorisation plan
- Coordinator:

SINTEF

Expected Impact
From Short to Long Term

- Convince Varanger Kraft to expand hydrogen production
- Export model to other sites in Europe (other EU projects?)
- Allow deployment of wind power beyond 20 %
- Push hydrogen utilisation in the area
  - Mobility, industry, etc.
- Contribute to EU renewable targets & energy independence

Public Deliverables

Reports (18):

- Raggovidda energy analysis
- Dynamic model & control
- Impact on energy systems, RCS
- Valorisation plan
- Business case analysis
- Road to MAWP 2023 targets
- Techno-economic analysis
- Environmental performance
- Demonstration protocols & data

Other (15):

- Workshop at ECC2019 Naples
- Real-time demo on website
- Plant visit
- Academic seminars
- Student internship
- Presence at industrial fair

What to Do with the Hydrogen?

Valorisation Plan: Identified Opportunities

Action	Realism	Size	Gimmick
Svalbard energy supply	✓	✓	✓
Coastal ships	(✓)	✓	✓
Fishing boats	(✓)	✓	
Ammonia production	✓	✓	
Aquaculture	(✓)	✓	
Fast passenger boats	(✓)	✓	
Cars	✓		✓
Regional mini-buses	✓		
Waste collection trucks	✓		
Backup generators	✓		
Snowmobiles			✓
Regional planes		✓	✓
ZE steel production		✓	
Mining and ore processing		✓	

Outline

Last Holdout of Coal in Norway

- Uses about 120 MWh/year
- Wasteful with district heating
- Max electrical load 8 MW
- 2 coal boilers, 6 diesel gensets
- Old coal plant should be replaced...
- Multiconsult: LNG is cheapest

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- 2 coal boilers, 6 diesel gensets
- Old coal plant should be replaced…
- Multiconsult: LNG is cheapest
- Svalbard is a hot spot for climate change, common example
- Installing fossil generation is not politically viable

Hydrogen Import to Svalbard

- Not considered in Multiconsult's report
- Can exploit better green H_2 sources
  - Wind in Finnmark
- H_2 can be readily imported
  - Container solutions available
  - (Initially) also non-green H_2?
- Combined heat & power fuel cells
  - High efficiency (45 %+45 %)
  - Market ready

Flexibility & Scalability in Deployment

- Fuel cells are modular
- Can be introduced gradually
  - Start with smaller pilot
  - Extend later: future-proof
  - LNG needs MW investment
- Can add local renewables later
- Distributed generation
  - Same efficiency
  - E.g. replacing boilers FH1–6
  - Better reliability and redundancy
- Can replace diesel generators

Hydrogenics “closet” with 4×33 kW fuel cells systems.
Each can be replaced individually.
Already deployed in 1 MW unit i Kolon, Korea (in a 40’ container).

Data Sources

- Finnmark energy cost: 215 NOK/MWh[1]
- Electrolyser: 9.3 MNOK/MW
  - OPEX 7 % thereof[2]
- Compressors: 6 MNOK/MW_{H_2}
  - OPEX 4 % thereof[2]
- 40’ container, 780 kg_{H_2}: 3 MNOK
- Transport logistics: 10 NOK/kg_{H_2}
- CHP fuel cells: 25 kNOK/kW, 22 years[3]

Sources:

1. Multiconsult LCOE calculation for Davvi wind power plant
2. Noack et al. (DLR, LBST, Fraunhofer, KBB)
3. FCH JU’s Multi-Annual Implementation Plan

Full Deployment with only Imported Hydrogen

All Items are NPV over 25 years with 4 % Discounting Rate

Energy costs	882 MNOK
30 MW Electrolysers	279 MNOK
Electrolyser OPEX	304 MNOK
Compressors	158 MNOK
Compressor OPEX	70 MNOK
243 H_2 containers	729 MNOK
Logistics (25 years)	789 MNOK
FCs in Longyearbyen	212 MNOK
Total	**3423 MNOK**
Energy cost	0.91 NOK/kWh

- Reasonable kWh price
- Extra 60 MW @ Raggovidda
- Burning some H_2 for heat
- What can improve in time?
  - Fuel cell cost
  - Electrolyser cost
  - Cheaper H_2 storage
  - Heat savings (−40 %)
- It can land at about 2000 MNOK

Pilot Deployment in Conjunction with HAEOLUS

Adapted to a 1 t/d production in Berlevåg

Investments	
Compressor	8 MNOK
Fuel cells	16 MNOK
10 containers	30 MNOK
Total investments	54 MNOK
Yearly OPEX	
Energy	4.1 MNOK/y
Logistics	3.6 MNOK/y
Compressor OPEX	0.3 MNOK/y
Total OPEX	8 MNOK

- Budget within range of an EU project
- Proceed in steps:
  - Replace diesel gensets
  - Supplement local renewables
  - Combine with battery storage
  - Gradually expand capacity
- Optimise battery+hydrogen+import
- Finally, take coal plant offline

Conclusion

- Hydrogen can store large quantities of (renewable) energy
- It can cooperate with batteries, different tasks
- Grid services are critical for economy of electrolyser plants
- Can ramp up and down fast in a microgrid
- Exploiting produced hydrogen is better than re-electrifying it

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Thank you for your attention!

Hydrogen-**A**eolic **E**nergy with **O**ptimised e**L**ectrolysers **U**pstream of **S**ubstation

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