Federico Zenith

Green Hydrogen from Intermittent Renewables

SINTEF Mathematics & Cybernetics

25 October 2022
Belfort, France

Co-funded by the European Union
Clean Hydrogen Partnership

Outline

Hydrogen Technology

Hydrogen and the Grid

The HAEOLUS Project

Hydrogen Valleys

- Opportunities in Finnmark
- The Svalbard Case

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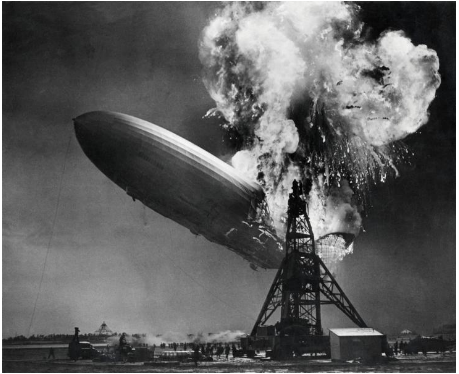
Hydrogen

- 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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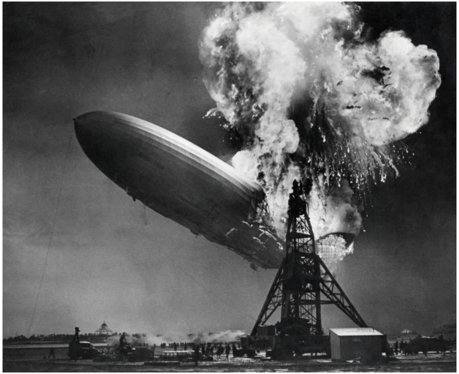
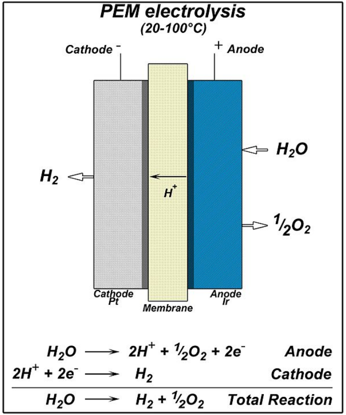


Do you know how many survived this?

62 of 97

Hydrogen Production

- Most produced by NG reforming, but…
- *Electrolysis* is key for renewables: split H_2O with electricity
- 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)– 30 s (cold) start
- Haeolus report: https://www.haeolus.eu/?p=1155



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)

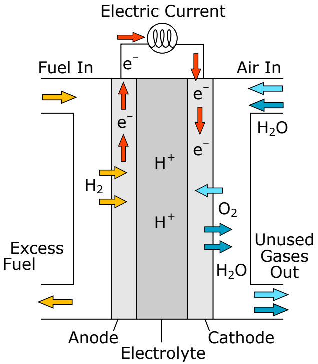
700 bar cH_2 tanks onboard Toyota Mirai

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: *very* high temperature
  - Methanol, formic acid, PAFC, molten carbonate…
- Typical efficiency 50 % to 60 %



Caveat on Efficiency

Lies, Damned Lies, Statistics and Efficiency Definitions

Thermodynamics of the reaction:

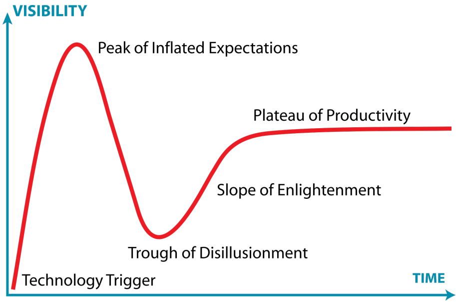
$$H_2 + \tfrac{1}{2}O_2 \longrightarrow H_2O$$

- $\Delta g_l^0 = 237\,\mathrm{kJ/mol}$: 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
- Stick to kWh/kg and you’re safe! (sort of: pressure, part load, purity…?)

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
- 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

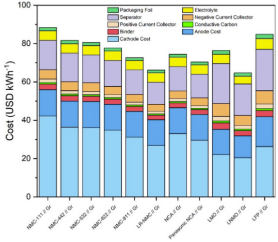
In Guesstimated Numbers & Factoids

- CAPEX (note structure)
  - Batteries: 200 \$/kWh
    - Lithium price *decuplicated* since 2021!
  - Fuel cells: 1500 \$/kW
    - mass production: 268 \$/kW
  - Hydrogen tanks: 10–20 \$/kWh
- Storage efficiency
  - Round-trip batteries: 90 %
  - with fast charging: 80 %
  - Hydrogen: 30 % to 40 %
- Lifetime
  - Batteries: ≈ 1000–2000 cycles
    - Depends on type, usage
  - Fuel cells: up to 30 000 h
  - Hydrogen tanks: 20+ years
- Power tariffs
  - Standard: full power always available
  - Interruptible: power company can throttle

Hydrogen production can be dispatched, battery charging cannot

Note on Battery Prices

- Long followed Moore's law with −20 %/year
- Improvements focused on manufacturing
- No new technologies on the market (maybe solid-state?)
- Battery price cannot fall below raw material's!
- Not much improvement in raw material supply
  - Li, Co, Ni, Mn…
- Li is not main cost in batteries, but its main use is batteries



(Wentker & al., 2019)

Heavy vs. Light Duty Fuel Cells

Why we are so interested in heavy duty

- Increasing interest in hydrogen for HD applications
- There are also batteries, what is the case for hydrogen?
- Batteries have established an advantage in the car sector
- Cars vs. heavy-duty vehicles:
  - 95 % parked vs. maximised operation time
  - Distributed vs. focused/dedicated infrastructure
  - Disposable income vs. cost minimisation
  - Free time vs. salaried time
- All these factors push towards hydrogen

Outline

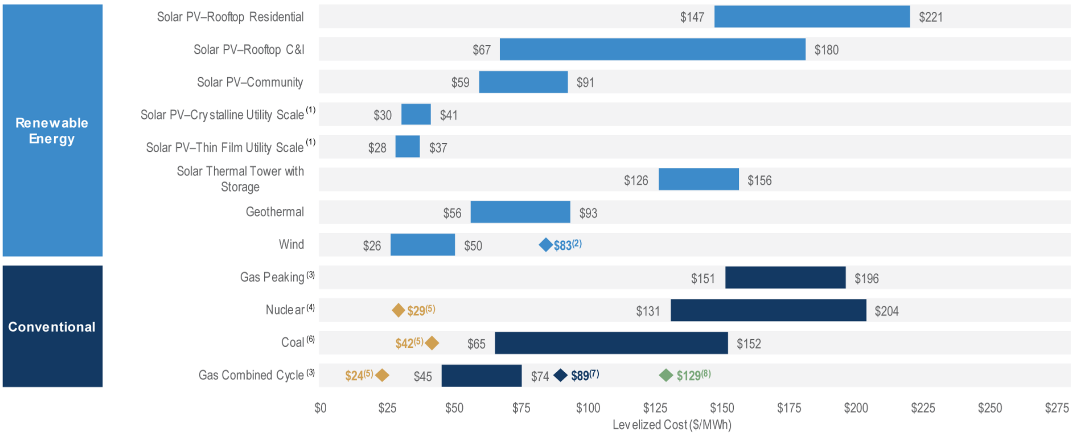
Hydrogen and Power Grids

- 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 (2004–2008)

Renewables are now the cheapest energy sources

Source: Lazard LCOE Analysis 2021



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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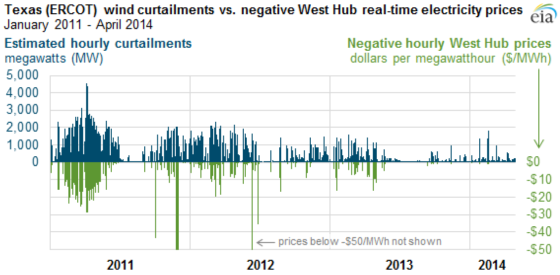
More wind power:

$\Rightarrow$ Less predictable generation

$\Rightarrow$ Negative prices



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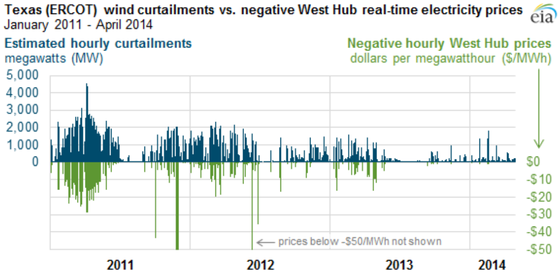
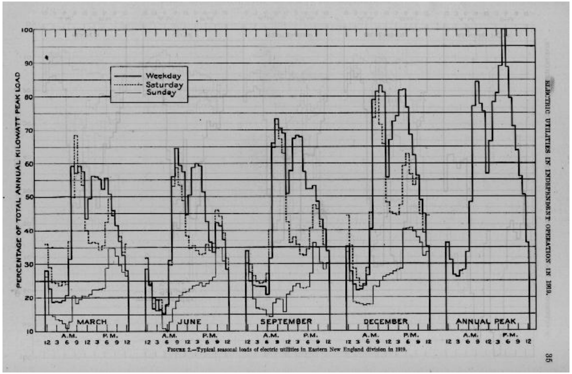


… What about the demand side?

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

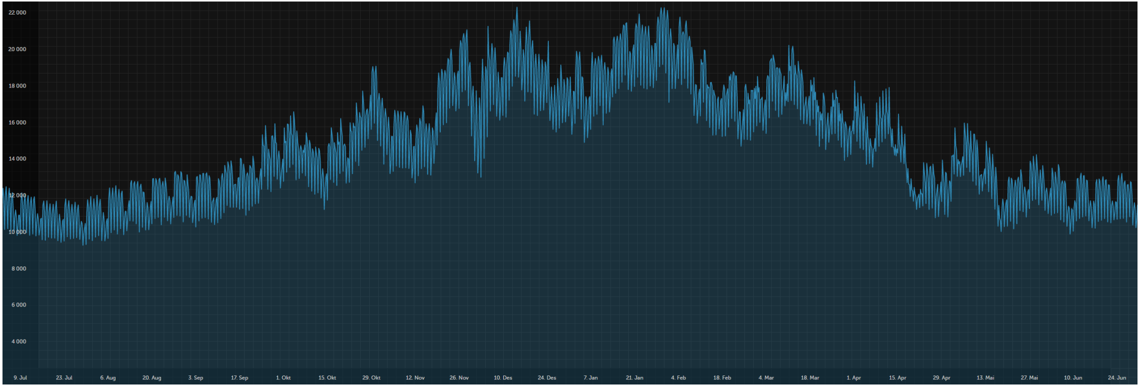


Load profiles for New England, 1919.

Norwegian Consumption Profile

July 2018–June 2019

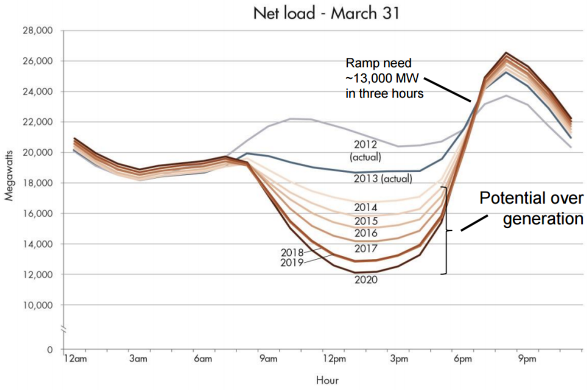
- Small weekly oscillations (electric heating)
- Significant seasonal oscillation (cold winter 2018–2019)



Interplay of Consumption and Renewables

The California Duck Curve

- Increasing solar power
- Daily demand dip



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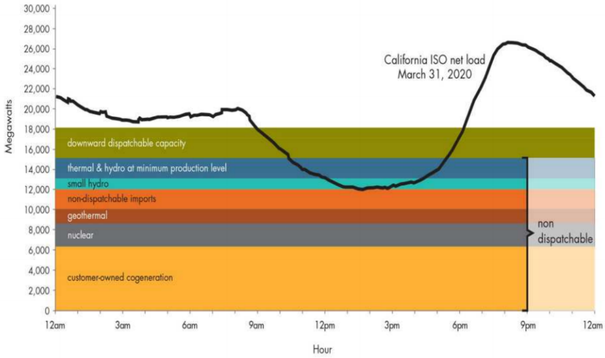
- Risk of curtailing



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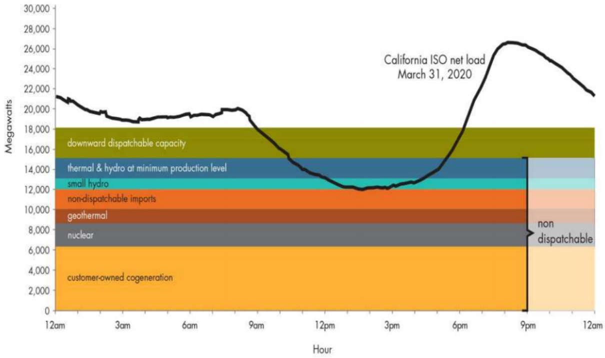

Generation is becoming less flexible: what about flexible *consumption*?

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€

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 (rectifiers at part load)

Hydrogen in the Small Picture

Application 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

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
  - Regulations change *a lot* among countries
- 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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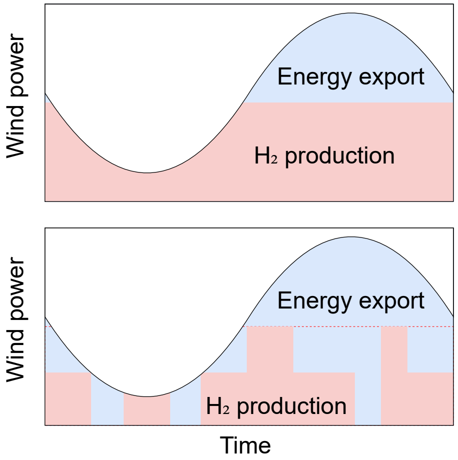
- FCR/aFRR can be
  - Procured (Norway, Germany)
  - Mandatory (Italy, France)
- Remuneration based on
  - Capacity (Denmark)
  - Activation (Italy)
  - Both (Norway)
- Direction
  - Symmetric
  - Up- or down-regulation
  - Asymmetric with set ratio (Spain)

Hydrogen Production with Grid Services

- Electrolyser within a wind park
  - No power import (user fees)
  - Electrolyser power is controllable
- Nominal operation
  - Electrolyser at full power
  - 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

Measuring the value of grid services—and only that

- 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

$$v_{H_2} = \frac{I - I_0}{H_0 - H}$$

"Value of hydrogen we did not produce because of grid services"

- Same electrolyser
- Same OPEX/CAPEX
- Easily computable

Data and Method

- Data for wind power from several countries (2017), scaled to Raggovidda's 45 MW
- Data for spot prices, FCR/aFRR capacity and activation for same year from grid operators
- Data gathered for Norway (NO4), Spain, France, Italy (CSUD)
- Electrolyser sizes: Haeolus (2.5 MW) and Raggovidda full scale (45 MW)
- Minimum power 0.3 MW, minimum bid 1 MW
- Symmetric and asymmetric services
- Calculate I and H and compare

Results

https://doi.org/10.1016/j.ijhydene.2022.08.152

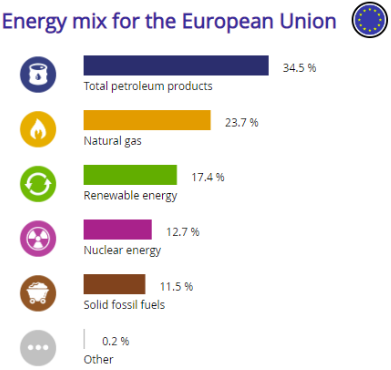
- Not so good results with lots of hydro (Norway)
  - Hydro is fast to control, little need of balancing
  - Wind, solar are increasing worldwide: demand will pick up
- Electrolyser size does not matter much
- Up-regulation most profitable
- Wind subsidies help a lot, but not decisively
- 2030 hydrogen price targets: 1.8 €/kg (EU), 1 $/kg (USA)
- A lot of electrolysers will flood the market
- Use: "catapult" effect for early units

[€/kg]	Up-regulation	Symmetric regulation	Down-regulation
France			
Energy	2.27	2.28	2.29
Capacity	7.92	0.76	0.40
Incentives	3.38	3.38	3.38
Total	13.57	6.43	6.07
without incentives	10.19	3.05	2.69
Italy			
Energy	2.74	2.54	2.45
Net activation	3.32	2.75	2.27
Incentives	5.72	5.72	5.72
Total	11.79	11.00	10.45
without incentives	6.07	5.28	4.73
Norway			
Energy	1.35	1.34	1.34
Capacity	0.52	0.20	0.13
Net activation	0.08	0.03	0.02
Tariffs	−0.08	−0.08	−0.08
Incentives	0.70	0.70	0.70
Total	2.56	2.20	2.11
without incentives	1.86	1.50	1.41
Spain			
Energy	2.48	2.60	2.63
Capacity	3.44	1.50	0.96
Net activation	0.31	0.21	0.19
Total	6.23	4.32	3.78

Outline

Motivation

- EU 2030 target: 40 % renewable energy mix
  - Up from previous target 27 %
  - In 2015 it was 13 %, in 2020 17 %
  - *Production* is already over 40 % (2020)
  - … up from 26 % in 2015
  - No renewables in energy imports
- Most renewables produce electricity
- Several are not controllable
- Some are unpredictable



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!
- Beyond 20 % wind share, value plummets
- Hydro is rarely possible to combine

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 2018–2023
  - Capacity 1 t/d
  - Production start: June 2021

The Haeolus plant in Berlevåg (video)

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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  - Neighbour Hamnafjell: 50 MW / 120 MW
  - Bottleneck to main grid is 95 MW
  - 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 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:

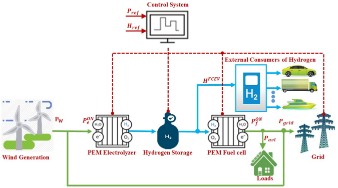
HYDROGENICS
SHIFT POWER | ENERGIZE YOUR WORLD

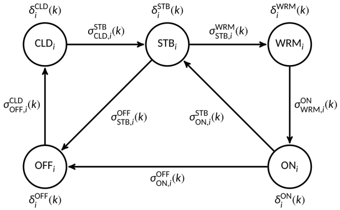
View of Berlevåg, site highlighted

Control System

- Mixed-Integer Dynamical model
- Model-Predictive Control (MPC) on multiple time scales
- Model with 5 discrete states
- Cost of state change
- Load tracking
- Application to current practice?
- Partner university:

  University of Sannio





Other Activities

- Techno-economic analysis
- Life-cycle analysis

tecnalia

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

UBFC
UNIVERSITÉ
BOURGOGNE FRANCHE-COMTÉ

- Execution of demonstration

University of Sannio

- Remote control and implementation
- Integration with smart grids
- H_2 valorisation plan

SINTEF KES Knowledge Environment Security Srl

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

How to Start a Hydrogen Valley

Hydrogen producers want:

- to sell hydrogen regularly
- to have a reliable income
- not to go broke in the "Valley of Death"

Hydrogen users want:

- to be sure hydrogen will stay available
- a reliable supply chain
- a predictable hydrogen cost
- readily available maintenance

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Regional strategy in Troms & Finnmark

- Solid, known producer (Varanger Kraft)
- Identify key 1st movers on demand side
- Coordinate with local authorities
- Disseminate to local businesses

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?

Breaking the Deadlock

Also known as the "chicken-and-egg" problem

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  - Shipping companies
  - Public authorities
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- Suppliers need demand to make money
- Users need offer for their equipment
- Is the other side going to hold out?

- 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

Core Distribution System

- Pressurised tanks at 350 bar
- Commercial containers
  - 20’ or 40’ (resp. ca. 350 and 700 kg)
  - Cost 150–300 k€ each
- Compressor in Berlevåg
  - Advantage to start from 30 bar
  - Cost about 350 k€
- Minimal distribution system
  - 1 compressor and 2 containers
  - 0.7–1 M€ in investment
  - Container leasing? Smaller compressor?

Specific minimum cost mode for hydrogen transport LD

Production volume (tpd) \ Distance (km)	10	50	100	250	500	750	1000	2000	3000
1	CT	CT	CT	CT	CT	LT	LT	LT	LT
5	CSP	CT	CT	CT	LT	LT	LT	LT	LS
10	CSP	CT	CT	LT	LT	LT	LT	LS	LS
20	CSP	CSP	CSP	LT	LT	LS	LS	LS	LS
30	CSP	CSP	CSP	CSP	CS	CS	CS	CS	LS
40	CSP	CSP	CSP	CSP	CS	CS	CS	LS	LS
50	CSP	CSP	CSP	CSP	CS	CS	CS	LS	LS
60	CPP	CSP	CSP	CSP	CS	CS	CS	LS	LS
70	CPP	CSP	CSP	CSP	CS	CS	LS	CS	LS
80	CPP	CSP	CSP	CSP	CS	CS	CS	LS	LS
90	CPP	CSP	CSP	CSP	CS	CS	CS	LS	LS
100	CPP	CSP	CSP	CSP	CS	CS	CS	CS	LS

(Project work by Simen A. Madsen)

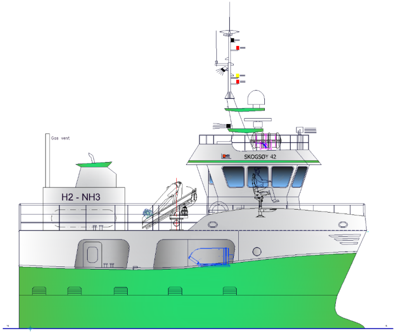
Liholmen Biogas Plant

- Newly opened in “neighbouring” Båtsfjord
  - Produce biogas, burn in turbine, sell power
- Methanation of biogas ($CH_4 + CO_2$)
  - $CO_2 + 4\,H_2 \longrightarrow CH_4 + 2\,H_2O$
  - Biomethane more valuable as marine fuel
- Potential regular customer
  - Steady need for hydrogen
  - Long-term agreement possible
- Båtsfjord biogas plant
  - Right distance (90 km)
  - Right size (80 t/year)

Liholmen Biogass plant in Båtsfjord

Fishing Boats

- Main activity in region is fishing
- Battery-driven boats already operate
  - *Karoline, Angelsen Senior*
  - Diesel remains for propulsion
  - Battery-only on fishing field
- Hydrogen can remove *all* emissions
- Several Berlevåg fishermen interested
- FHF-sponsored SINTEF report (2021:00632)
- Quota system hampers zero-emission propulsion



Design of a zero-emission coastal fishing boat

Fast Passenger Ferries

- Three consortia developing ferries
  - ESNA (Kristiansand)
  - Brødrene Aa (Hyen)
  - TECO 2030 (Narvik)
- Interest in counties Vestland, Trøndelag, Nordland and Finnmark
- Pilot scheduled for 2025
- Kirkenes–Vadsø a possible case
  - Currently: 15 min plane or 2 hour drive
  - 40 km over the Varangerfjord

Brødrene Aa's H_2 ferry concept

Coastal Express

- The Coastal Express already stops in Berlevåg
  - Electrolyser is right by the dock
  - Visible application for tourists
- New competitor *Havila* seeks green profile
- 4 new ships (two operational)
- New ships are ready for hydrogen and ammonia
- Retrofit planned with 2.3 MW fuel cells
- Storage based on liquid hydrogen
- Approval granted by DNV in May 2022

Cars

- 1 t/d is enough for 3000 cars, not realistic but…
- Lighthouse effect (“world’s northernmost H_2 station”)
- Finnmark has fewest electric cars in Norway
- Users: local municipalities, Varanger Kraft, taxis…
- Hydrogen cars can drive & return anywhere in East Finnmark from Berlevåg
- All mayors in Varanger want hydrogen stations!

Snowmobiles

- Great lighthouse potential
- Prototype developed in Austria
- Interest from Nordkapp municipality
- Zero-emission day trips for North Cape tourists
- Also relevant for Varanger Kraft to access Raggovidda

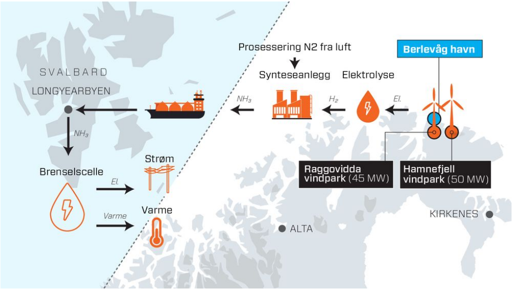
The Rotax HySnow prototype

Hydrogen Planes

- Batteries are and will remain inadequate for commercial planes
- Airbus announced grand hydrogen strategy
- Large STOLport network in Northern Norway
- “Milk route” between Tromsø and Kirkenes
- No replacement for current Dash 8 after 2030
- High-activity area (Airbus, Schiphol, ZeroAvia…)

Ammonia Production

- “Grand plan” of Varanger Kraft
- *Green ammonia* from electrolysed hydrogen
- Extension to over 100 000 tons NH_3
- Electrolyser capacity 40–50 times HAEOLUS
- Key markets:
  - Shipping industry (ZEEDS groups: Aker Solutions, Wärtsilä, Equinor, . . .)
  - Export to Svalbard and similar communities



Energy Supply to Svalbard

- 2100 inhabitants in Longyearbyen
- Old coal power plant, planned to be shut down
- LNG would be cheapest, but zero emission has support
  - Politicians, organisations and companies (Statkraft, NEL)
- Hydrogen import or NH_3 as energy carrier?
- µCHP is an off-the-shelf technology
- Gradual introduction of hydrogen into the energy system

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

Last Holdout of Coal in Norway

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- 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: 21.5 €/MWh[1]
- Electrolyser: 0.93 M€/MW
  - OPEX 7 % thereof[2]
- Compressors: 0.6 M€/MW_{H_2}
  - OPEX 4 % thereof[2]
- 40’ container, 780 kg_{H_2}: 0.3 M€
- Transport logistics: 1 €/kg_{H_2}
- CHP fuel cells: 2.5 k€/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	88.2 M€
30 MW Electrolysers	27.9 M€
Electrolyser OPEX	30.4 M€
Compressors	15.8 M€
Compressor OPEX	7 M€
243 H_2 containers	72.9 M€
Logistics (25 years)	78.9 M€
FCs in Longyearbyen	21.2 M€
Total	**342.3 M€**
Energy cost	0.09 €/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 200 M€

Pilot Deployment in Conjunction with HAEOLUS

Adapted to a 1 t/d production in Berlevåg

Investments	
Compressor	0.8 M€
Fuel cells	1.6 M€
10 containers	3 M€
Total investments	5.4 M€
Yearly OPEX	
Energy	0.41 M€/y
Logistics	0.36 M€/y
Compressor OPEX	0.03 M€/y
Total OPEX	0.8 M€

- 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 is best suited for heavy-duty mobility
- Electrolysers and renewables can "solve each other's problems" through grid services
- Many opportunities, but need coordination between supply and demand
- The main issue is now politics and economy—the technology is here

Conclusion

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Thank you for your attention!

Co-funded by the European Union
Clean Hydrogen Partnership

H2AEOLUS

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

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Clean Hydrogen Partnership

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