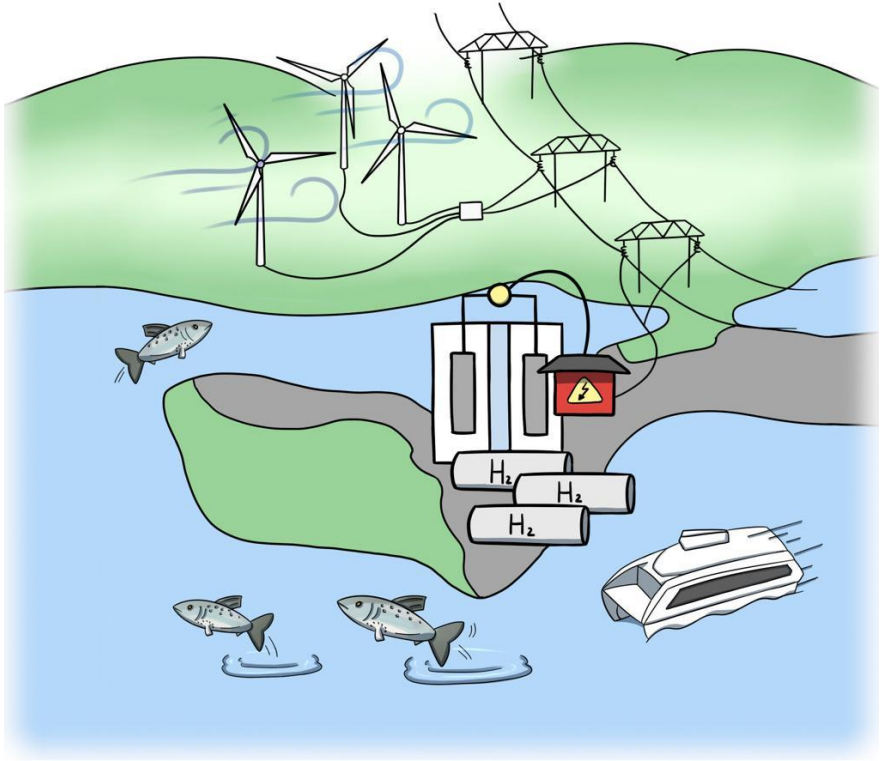
A Feasibility Study of Hydrogen Production at Hitra



Bachelor's thesis in Renewable Energy (Fornybar energi)

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Problem Description

- Task provided by TrønderEnergi

- Is hydrogen production at Hitra feasible?
  - Is it cost competitive?
  - Is there a demand for hydrogen?

Research Question

”Can Hitra — having access to local wind energy — produce competitive hydrogen for the regional maritime sector?”

Key Findings

- Levelized Cost of Hydrogen - LCOH:
  36.4 - 37.8 NOK/kg (3.72 - 3.86 €/kg)
  for alkaline electrolysis (AWE)

- AWE best option

- 10 MW of electrolyzers:
  - Up to 1700 tons/year → 4.7 tons/day

- Competitive hydrogen
  due to costs & environmental benefits

Introduction and Background

Hydrogen (H) - Hydrogen gas (H_2)

- Good energy carrier
- Energy storage
- Environmentally friendly
- Transport: used as fuel

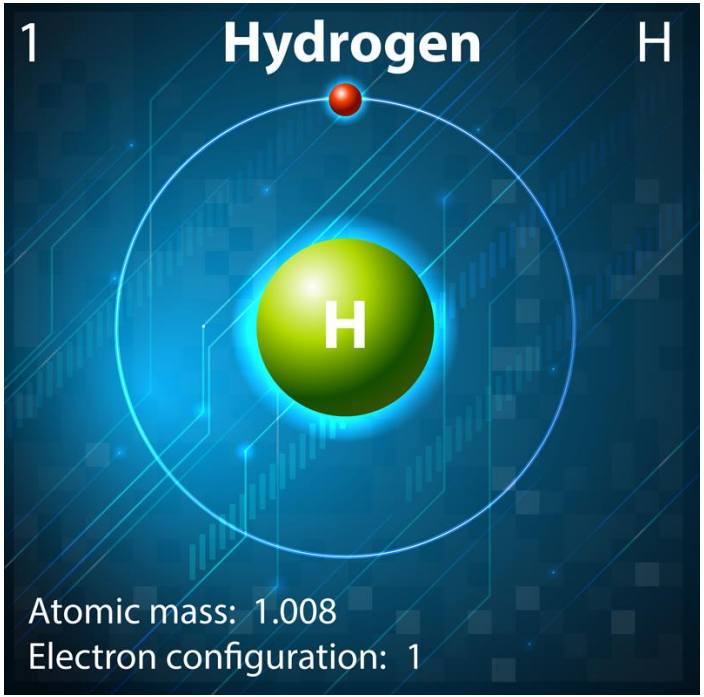


Illustration from: https://www.alkaway.com.au/learning-centre/molecular-hydrogen/

→ Hydrogen: a Good Energy Carrier

(Marin Gas Oil)

Diesel/MGO: 11.8 kWh/kg

H_2: 33.3 kWh/kg

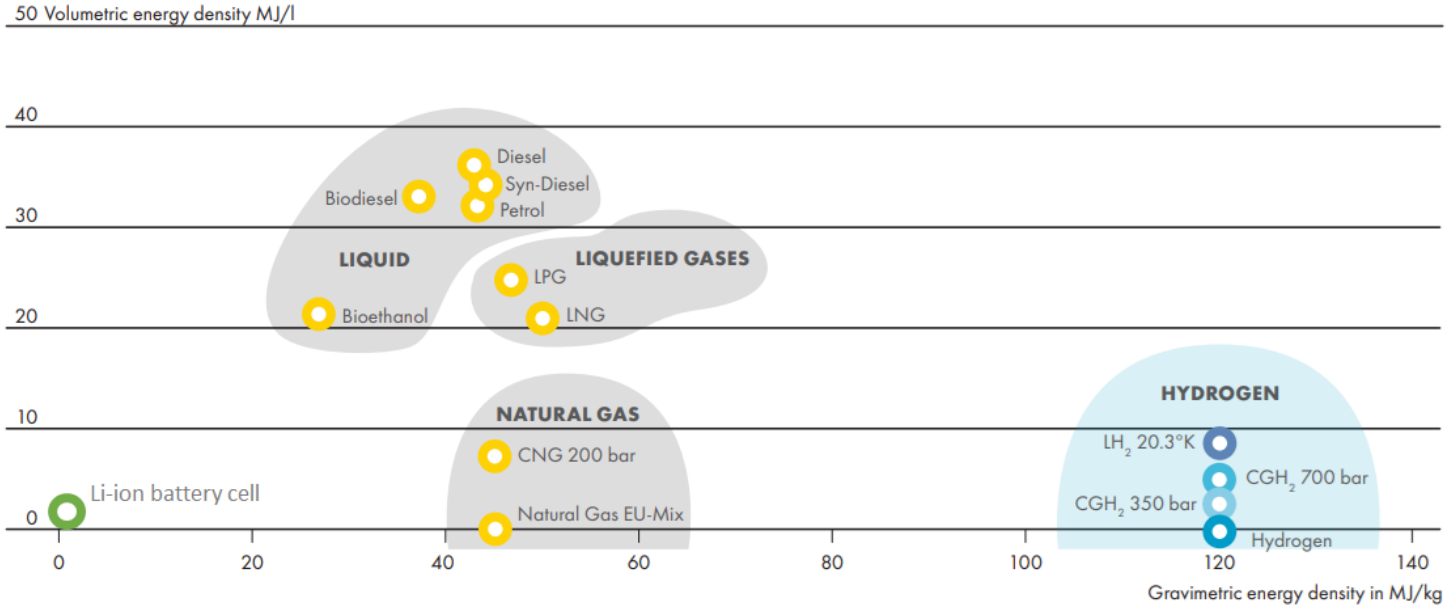
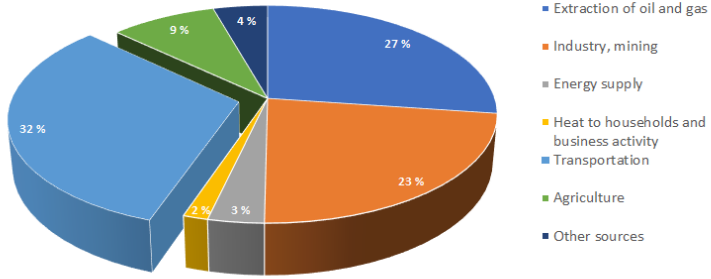


Illustration: Dr. Jorg Adolf with several (Shell) https://preview.tinyurl.com/v4u7ess

→ Reduce Emissions in Transport Sector

Transport sector in **Norway**:

- Huge GHG emissions (32 %)[1]



Transport sector in **Trøndelag**:

- 90 % of direct GHG emissions
- 50 - 60 % by sea

Hydrogen: a solution

- No CO_2 emissions (only water)
- Fuel cell: H_2 → electricity → motor

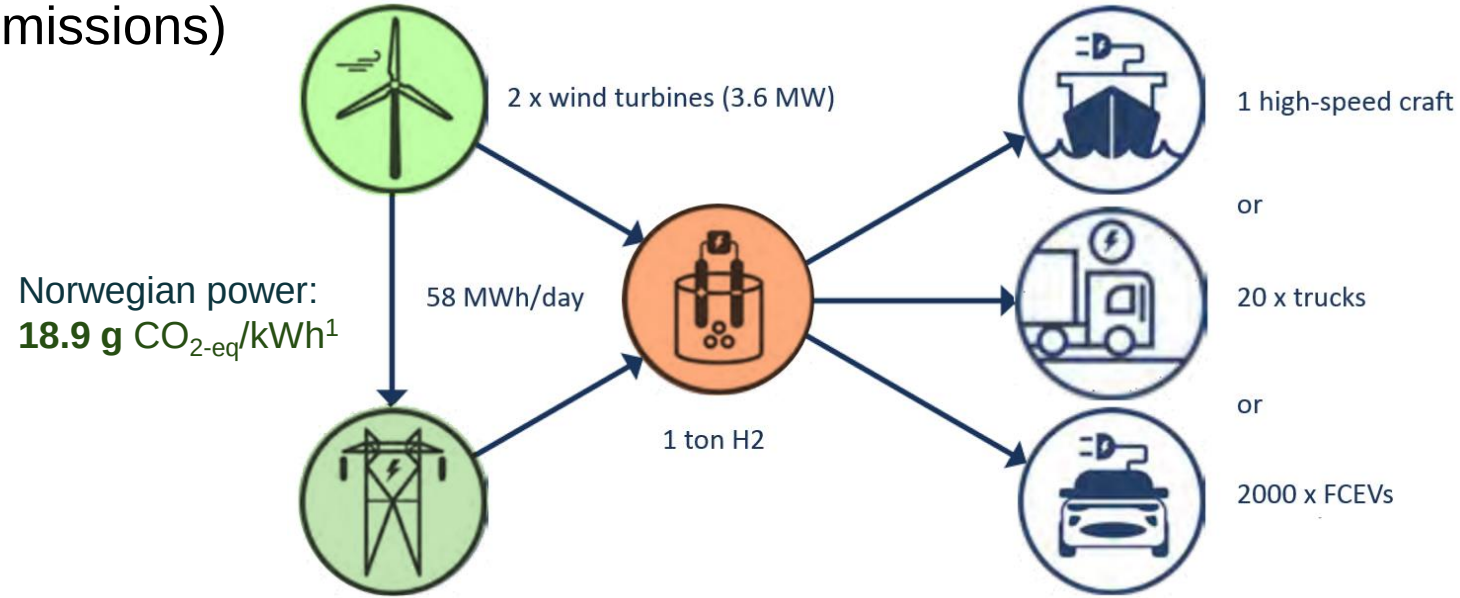
$$2H_2 + O_2 \longrightarrow 2H_2O + \text{Electricity} + \text{Heat}$$

[1]: SSB. Utslipp til norsk luft (2018). https://www.ssb.no/klimagassn
Illustration: https://www.skipsrevyen.no/batomtaler/m-s-terningen/

→ **Renewable Hydrogen**
Produced From Water Electrolysis

Water + Electricity → **Hydrogen (g)** + Oxygen (g)

(Low emissions)



Alkaline Water Electrolysis (**AWE**) & PEM Water Electrolysis (**PEMWE**)

[1]: NVE: https://www.nve.no/energiforsyning/varedeklarasjon/nasjonal-varedeklarasjon-2018/
Illustration: Fornybarklyngen. https://fornybarklyngen.no/prosjekter/veikart-hydrogen/

→ The Norwegian Hydrogen Market

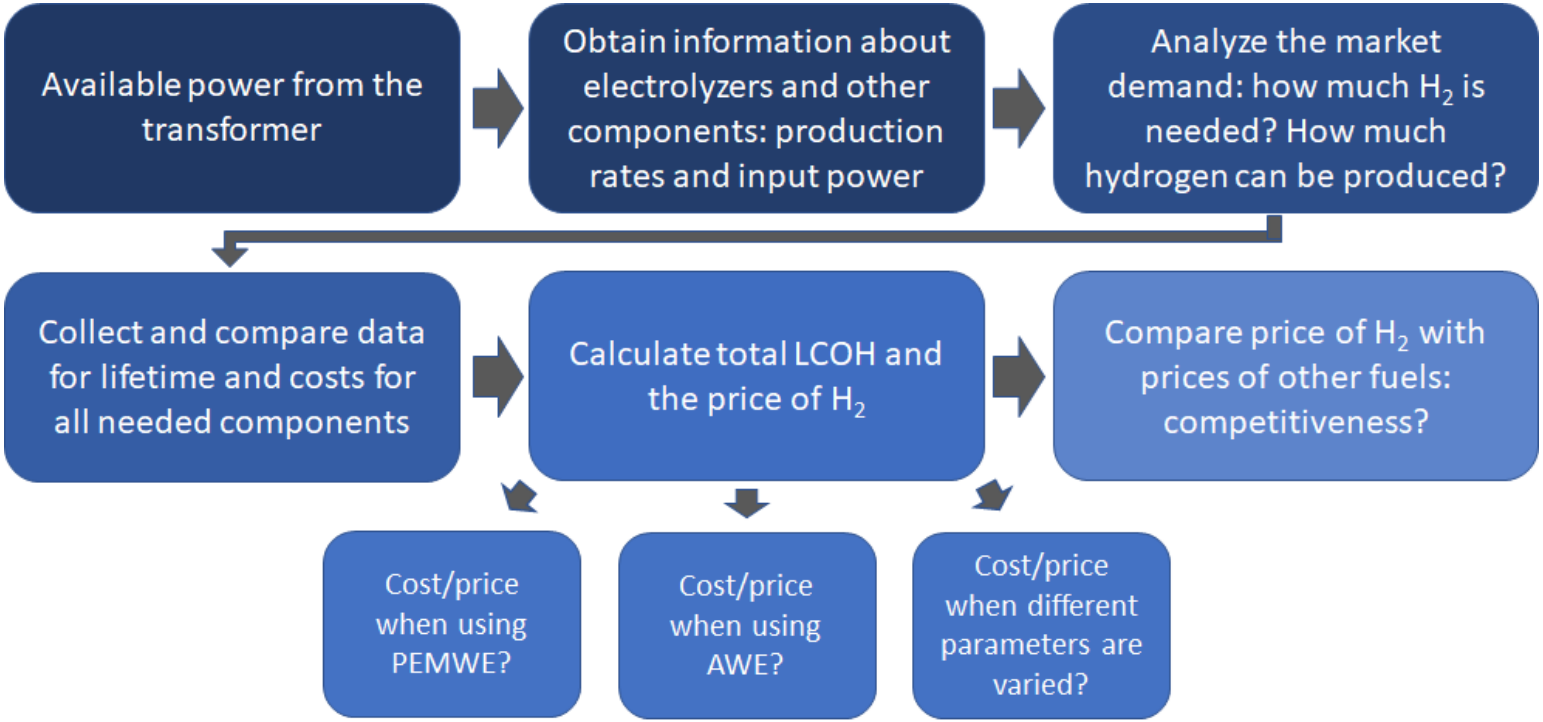
- 225 000 tons of hydrogen
  - Methanol and ammonia production
- Wind potential: 1000 TWh/y onshore
  - Haelous, Raggovidda

Why Hitra?

- High-speed craft (HSC) connection Tr-Kr
  - Likely to need H_2
- Maritime industry
  - ➢ Future H_2 demand
  - Well-boats
  - Trucks

Illustration: Rambøll. Infrastruktur for fremtidens hurtigbåt. https://bit.ly/2TQj4T9

Methodology

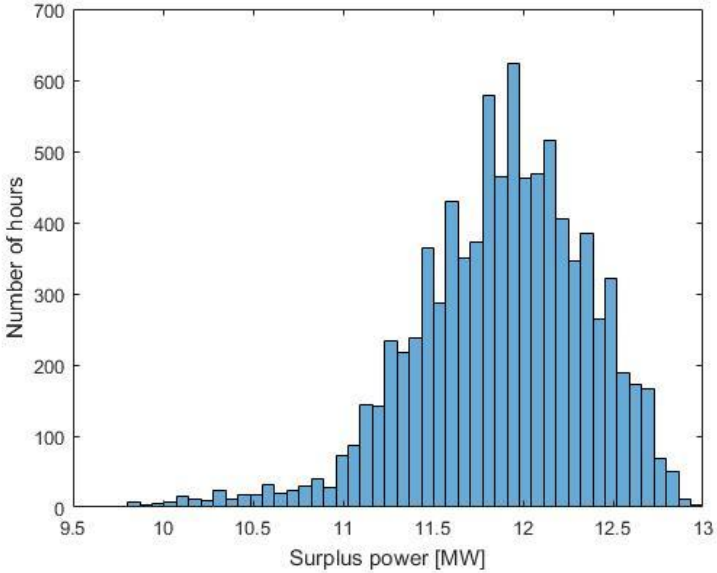


→ Available Power

- Transformer at Hitra Harbor: 25 MVA
- Available power ~ 12 MW

Processing of raw data:

- Histogram
- Average week per month



→ Selecting Electrolyzers

10 MW: Electrolyzers

2 MW: Compressor/filling and other losses

Electrolyzers from Nel Hydrogen:

- Alkaline and PEM electrolysis

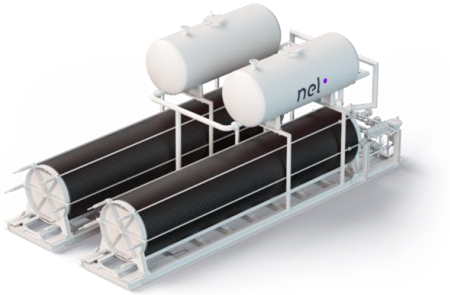


Illustration: Nel Hydrogen. https://nelhydrogen.com/water-electrolysers-hydrogen-generators/

→ Electrolysis Technologies

Water Electrolysis: $Energy + H_2O \rightarrow H_2 + ½\ O_2$

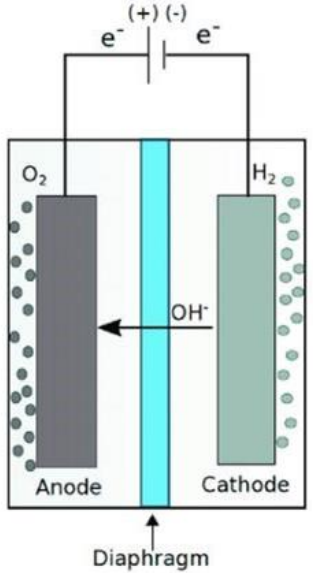
AWE: Alkaline water electrolysis

- Liquid electrolyte and diaphragm

PEMWE: Proton exchange membrane water electrolyzer

- Solid membrane

→ PEMWE is more suited for load-following operations



Cost difference: PEMWE > AWE

Illustration: https://www.researchgate.net/figure/Mechanism-of-different-electrolyzers-for-hydrogen-production_fig3_327818654

→ Producing Hydrogen

Alkaline electrolysis: 1700 ton/year → 4.7 ton/day

PEM electrolysis: 1580 ton/year → 4.3 ton/day

→ Hydrogen Demand

High-speed crafts (HSCs):

- 400 kg one crossing Tr - Kr
- Three crossings per day (x2) → 2500 kg per day

Well-boats:

- 5.25 tons per week
- Refueling two times per week

Illustration: https://www.nordlaks.no/nyheter-fra-nordlaks/2018/12/17/nordlaks-gjr-innhugg-i-klimautslippene-bestiller-enda-en

Trucks:

- 1 ton hydrogen → 20 trucks[1]
- 63 trucks per day Monday - Friday
  - Total demand: 3.15 tons per day

- 20% of total demand → 0.63 tons per day

[1]: Fornybarklyngen. https://fornybarklyngen.no/prosjekter/veikart-hydrogen/
Illustration: https://www.tungt.no/transportmagasinet/scania-over-pa-hydrogen-na-i-trondheim-6869919

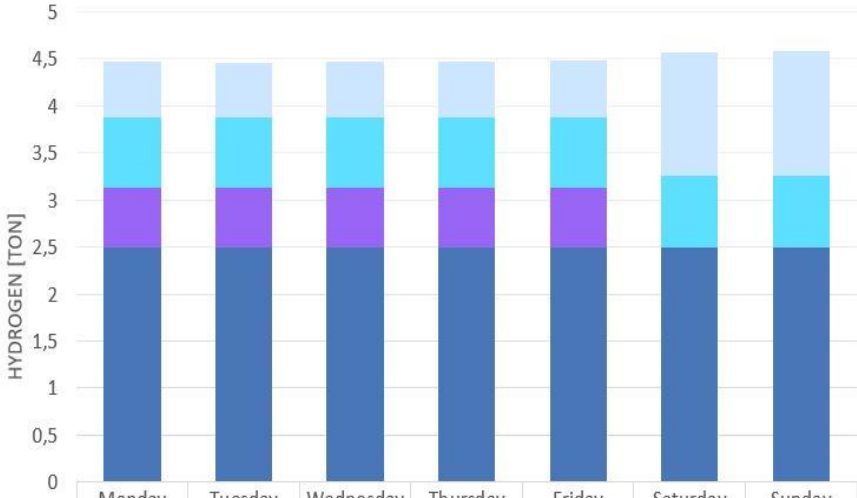
→ Hydrogen Distribution

Average week

~ 4.5 tons per day

Main case:

- 2 HSCs per day
- 1 well-boat per week
- 63 trucks per week



	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Residual	0,5959	0,5745	0,5883	0,5918	0,6072	1,324	1,3291
Well boat	0,75	0,75	0,75	0,75	0,75	0,75	0,75
Trucks	0,63	0,63	0,63	0,63	0,63		
HSC	2,5	2,5	2,5	2,5	2,5	2,5	2,5

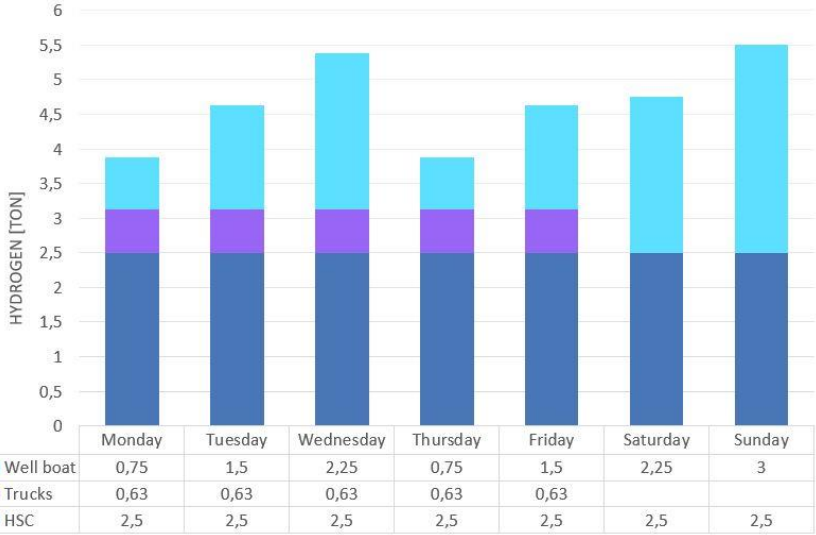
→ Storage

Stationary storage: 8.0 tons

- Steel tanks

Mobile storage: 2.0 tons

- Composite tanks
- Hexagon



	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Well boat	0,75	1,5	2,25	0,75	1,5	2,25	3
Trucks	0,63	0,63	0,63	0,63	0,63		
HSC	2,5	2,5	2,5	2,5	2,5	2,5	2,5

Target pressure: 250 bar

Storage pressure: 300 bar

→ Additional Scenario: High-speed crafts only

First end user of hydrogen at Hitra Harbor

Production:

- 2500 kg per day
- 5.5 MW electrolysis

Storage:

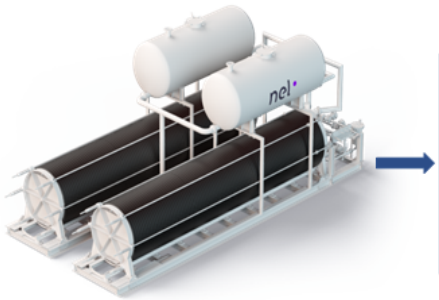
- < 5 tons in stationary steel tanks
- Avoids the regulation for major accident

→ Regulations for Major Accidents

- Exceeds 5 tons: *Notifiable business*
  - Report every third year
- No specific safety distance table for hydrogen

Illustration: https://insideevs.com/news/354223/hydrogen-fueling-station-explodes/

Summary: This is the Case



Electrolyzer ≈ 200 (100) kg/h
PEM: p_{out} = 30 barg
Alkaline: p_{out} = 1 bar

Compressor

p_{out} = 300 barg

Storage
(300 bar)

Stationary/mobile storage
at 300 bar

Filling eqp. for trucks
(extra compressor needed)

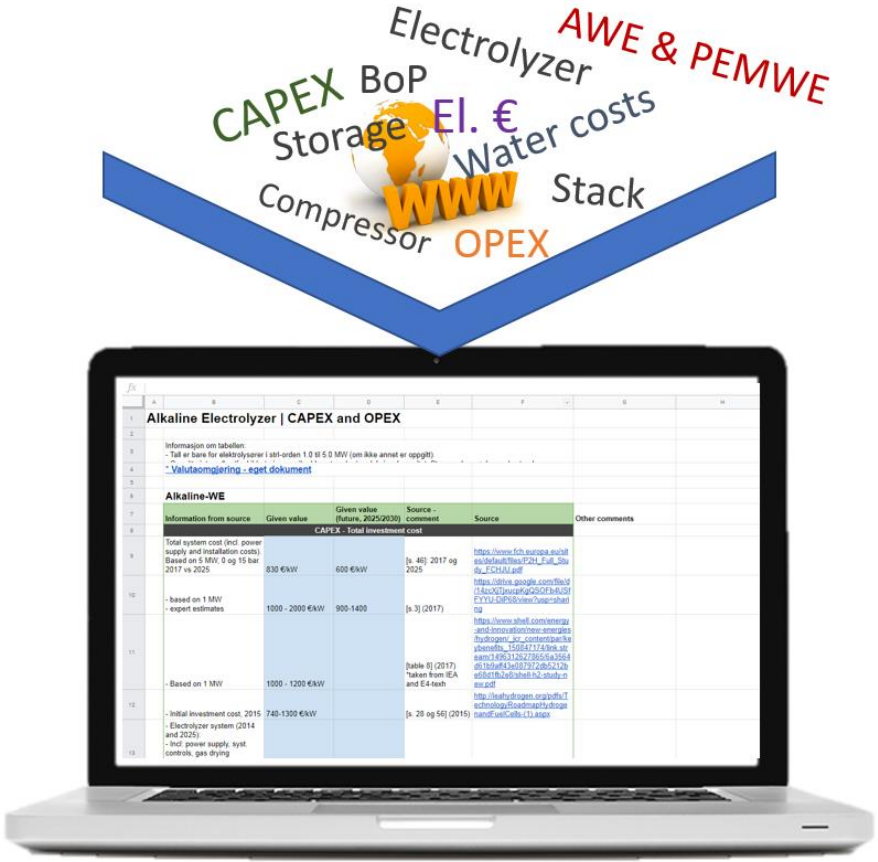
Filling eqp. for high-speed
crafts/well-boats
(e.g. overflow filling to 250 bar)

Hydrogen transport by trucks
(mobile storage tanks, 300 bar)

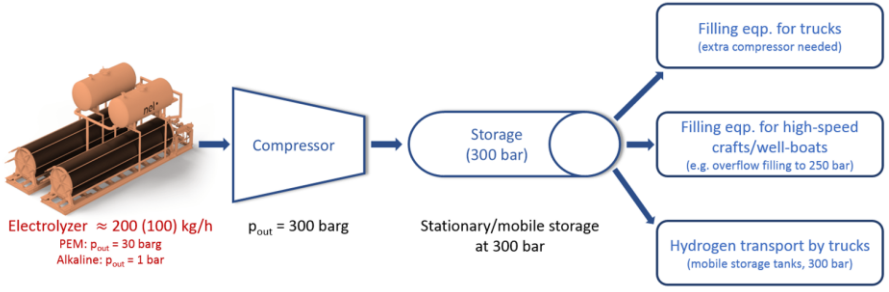
→ Obtaining Cost Data from Literature

- Data collected and compared
- Categories:
  - CAPEX (eqp. investment)
  - OPEX (maintenance, yearly)
  - El. & water costs

- Adapting to Scenario at Hitra
- Assumptions

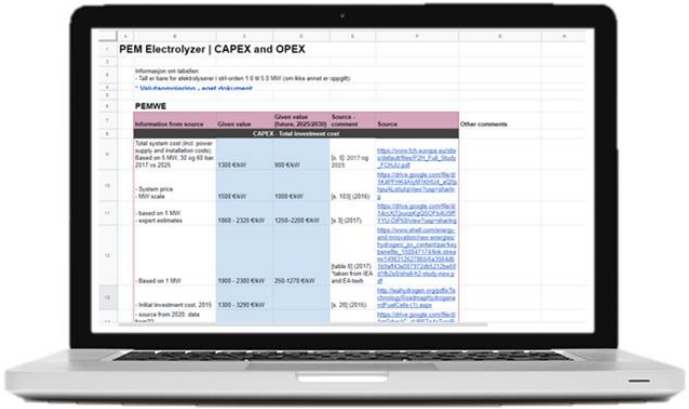


→ Electrolyzer Costs



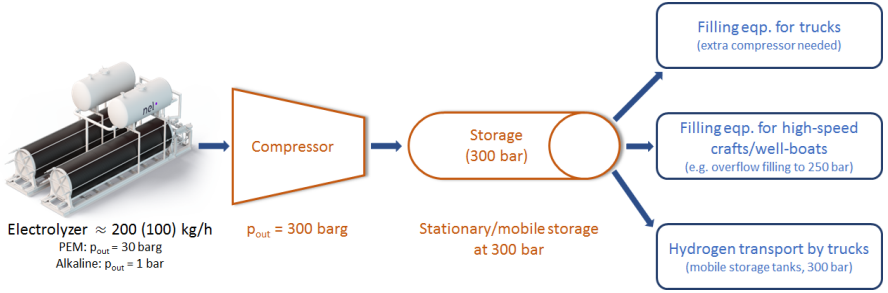
AWE & PEMWE

- CAPEX for **system**
- OPEX
- Stack Replacement
- Excl. “Other costs”
  (installation, building, engineering, administration)
- Using average values



X €/kW

→ Costs for Compr. & Storage



- Storage at 300 bar:
  - 8 ton: steel containers
  - 2 ton: composite
- Average costs from literature
  - \+ Hexagon

- Compression to 300 bar

- Assumptions, adapting data

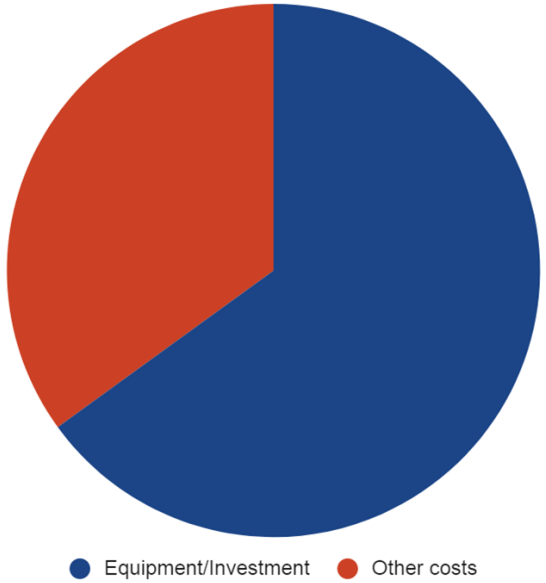
Illustration: https://www.indiamart.com/proddetail/hydrogen-gas-20875738973.html

→ Defining “Other Costs”

(Installation, building, engineering, administration)

Two models:

- NVE: **35 %** of total investment[1]
- FCH: **38 %** av equipment costs[2]



[1]: NVE – kostnader i energisektoren. http://publikasjoner.nve.no/rapport/2015/rapport2015_02a.pdf
[2]: FCH JU: https://www.fch.europa.eu/sites/default/files/P2H_Full_Study_FCHJU.pdf

→ Costs for Water & Electricity

- For Hitra, specifically
- Based on estimated consumption
  - Energy price: 24 øre/kWh (24.57 EUR/MWh)

Electricity costs: **50 - 70 %** of total H2 costs

Results

- Lifetime: 20 years
- Stack replacements
  - → AWE: 10 years
  - → PEMWE: 7 years

Scenario	Electrolyzer size	Storage Capacity	Production per year
Full production	10 MW	10 tons	1700 tons
HSCs only	5.5 MW	< 5 tons	913 tons

(High-speed crafts)

→ CAPEX and OPEX (Full Production)

CAPEX

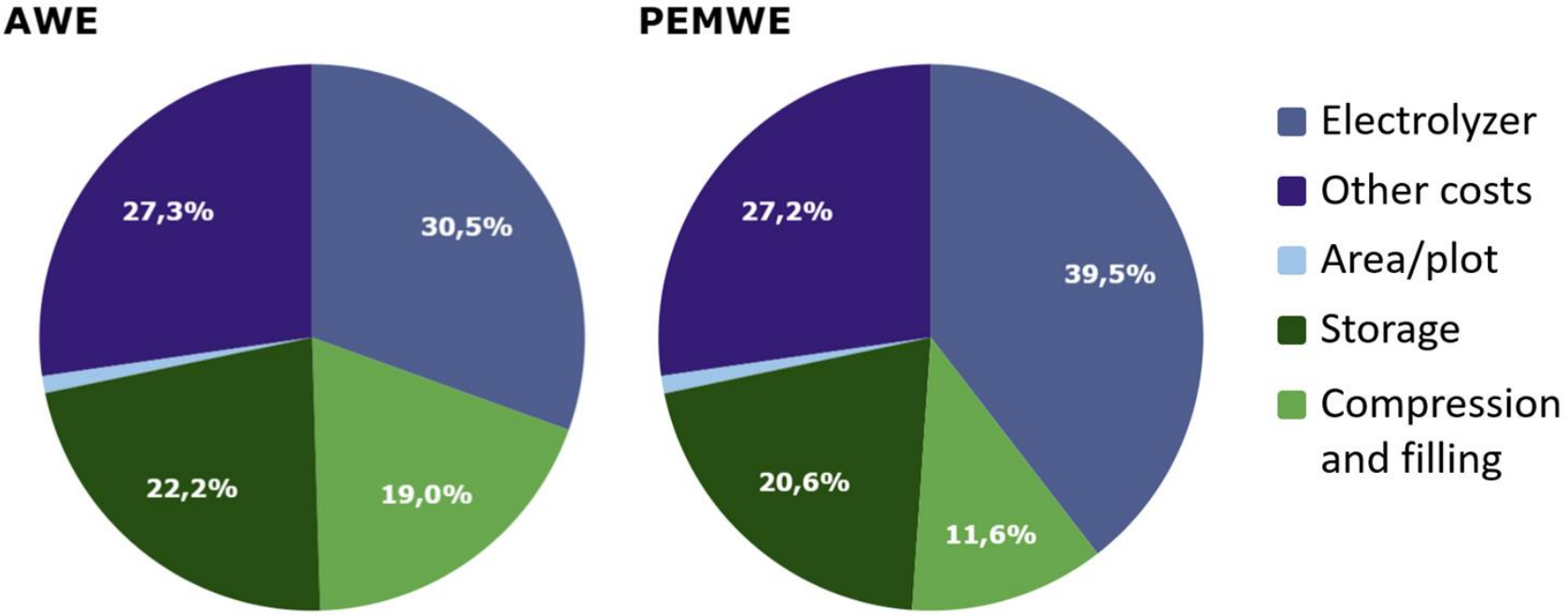
		Electrolyzer	Compression and filling	Storage	Building plot	"Other costs"		Total CAPEX	
						FCH	NVE	FCH	NVE
AWE	[M€]	5.03	3.14	3.66	0.170	4.50	6.37	16.5	18.4
	[MNOK]	49.2	30.7	35.8	1.66	44.0	62.3	161	180
PEMWE	[M€]	7.03	2.06	3.66	0.190	4.84	6.84	17.8	19.8
	[MNOK]	68.8	20.1	35.8	1.90	47.3	66.9	174	194

OPEX

		Electrolyzer	Stack replacement	Compression and filling	Storage	Electricity	Water	Total OPEX[a]
AWE	[k€]	151.0	3 079	63.00	73.00	3 978	40.00	4 305
	[MNOK]	1.477	30.11	0.616	0.714	38.90	0.3912	42.10
PEMWE	[k€]	211.0	3 267	41.00	73.00	3 978	38.00	4 340
	[MNOK]	2.064	31.95	0.401	0.714	38.90	0.3716	42.44

[a] Stack replacement is excluded in Total OPEX

→ CAPEX


AWE
27,3%
30,5%
22,2%
19,0%
PEMWE
27,2%
39,5%
20,6%
11,6%
Electrolyzer
Other costs
Area/plot
Storage
Compression and filling

→ LCOH

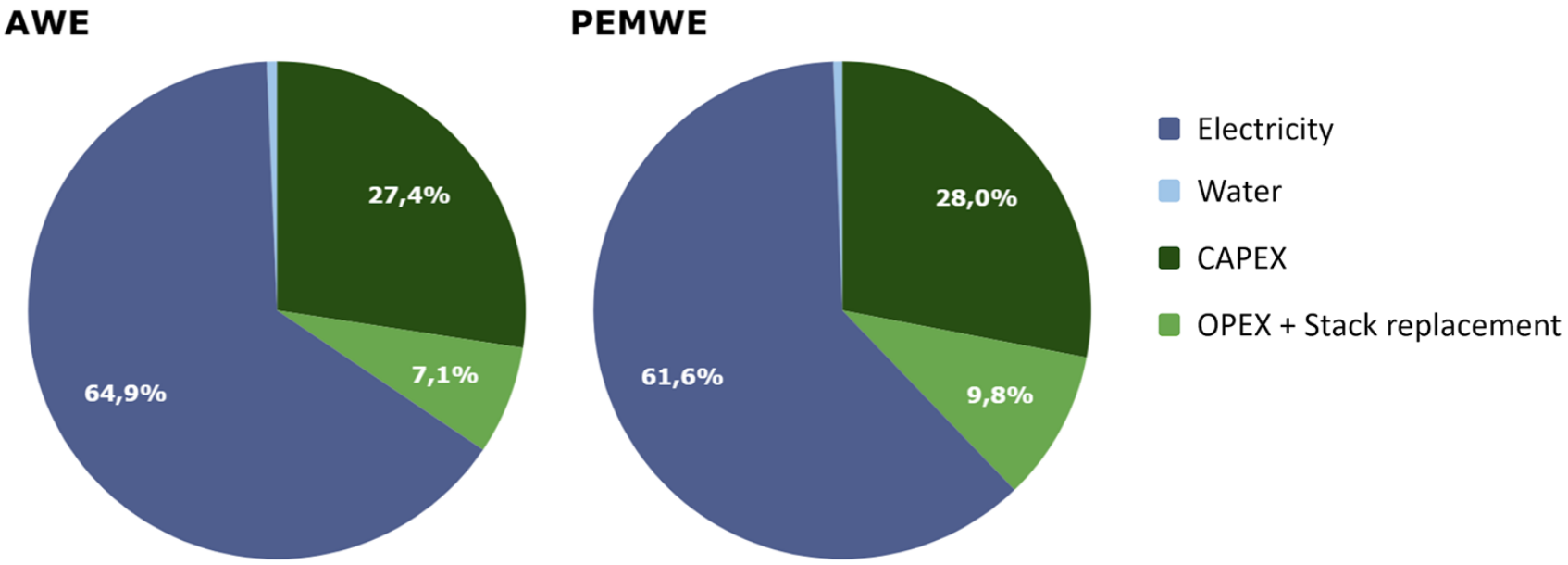
- Levelized cost of Hydrogen (LCOH)

$$LCOH = \frac{CAPEX + \sum_{k=1}^{n} \frac{OPEX}{(1+r)^k}}{\sum_{k=1}^{n} \frac{m_g}{(1+r)^k}}$$

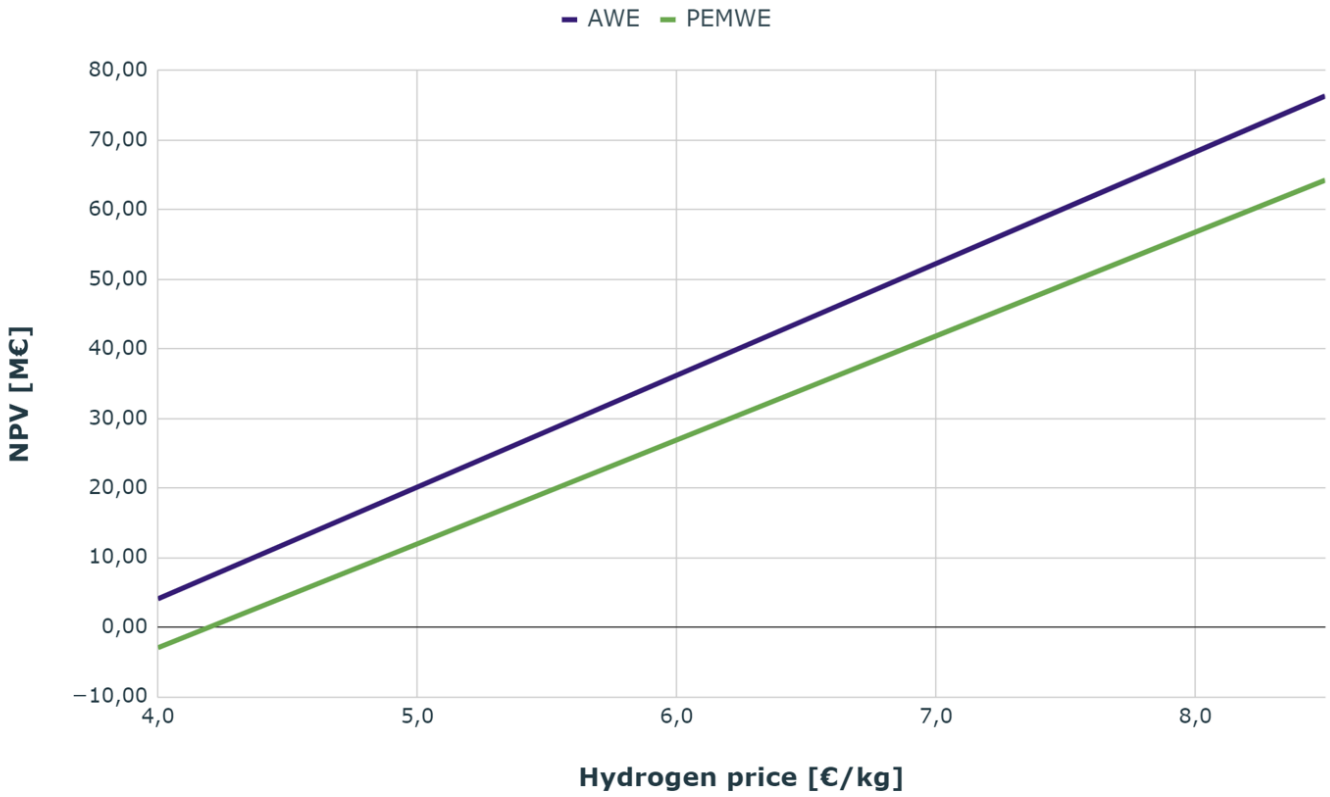
- Discount rate → 8 %

Electrolyzers	Full production, NOK/kg (€/kg)	HSCs only, NOK/kg (€/kg)
AWE	36.7 - 37.8 (3.75 - 3.86)	36.4 - 37.6 (3.72 - 3.84)
PEMWE	41.6 - 42.8 (4.25 - 4.38)	39.9 - 41.1 (4.08 - 4.20)

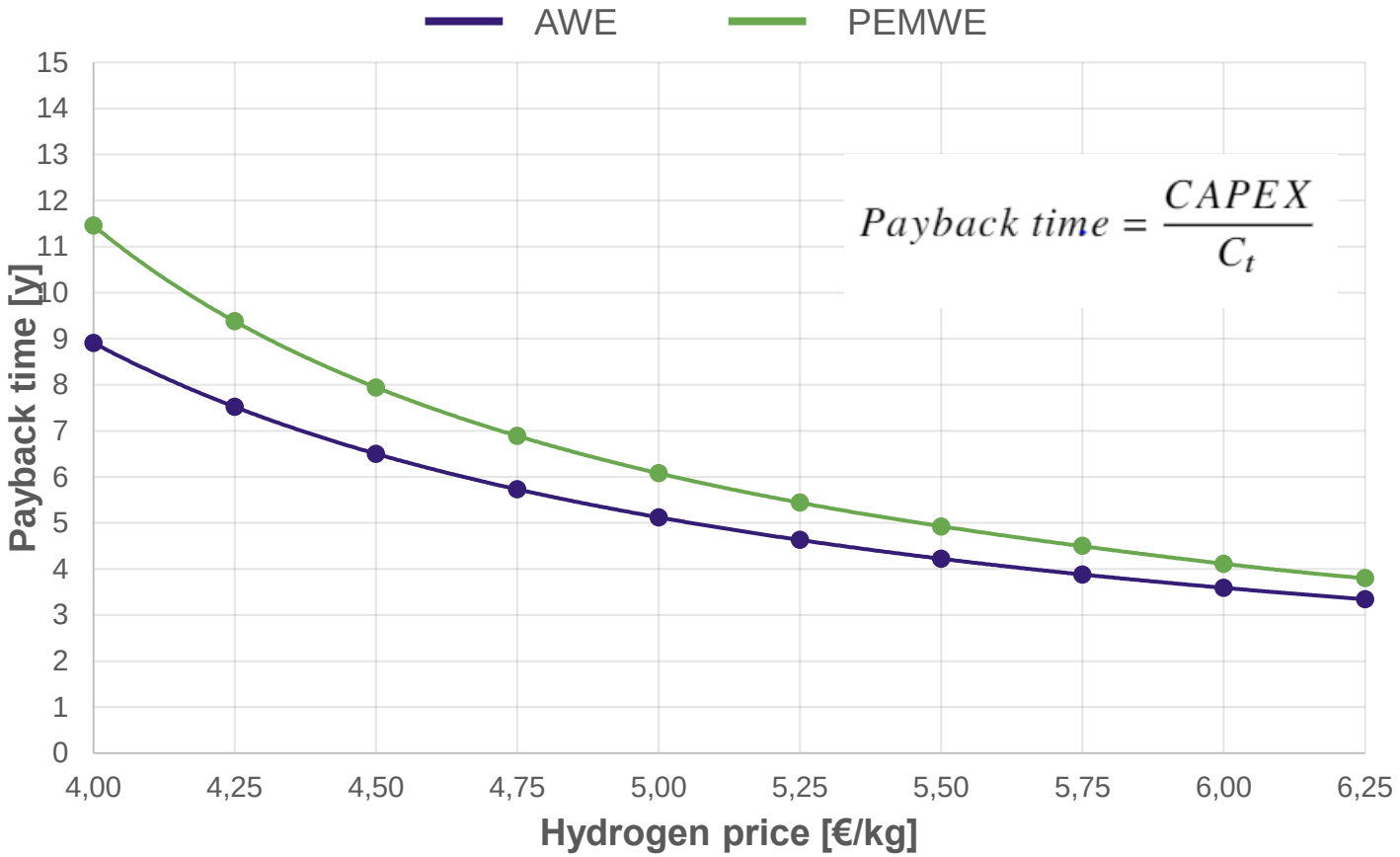
→ LCOH Shares


AWE
27,4%
7,1%
64,9%
PEMWE
28,0%
9,8%
61,6%
Electricity
Water
CAPEX
OPEX + Stack replacement

→ NPV Analysis



→ Payback time



Competitiveness

Two factors to consider:

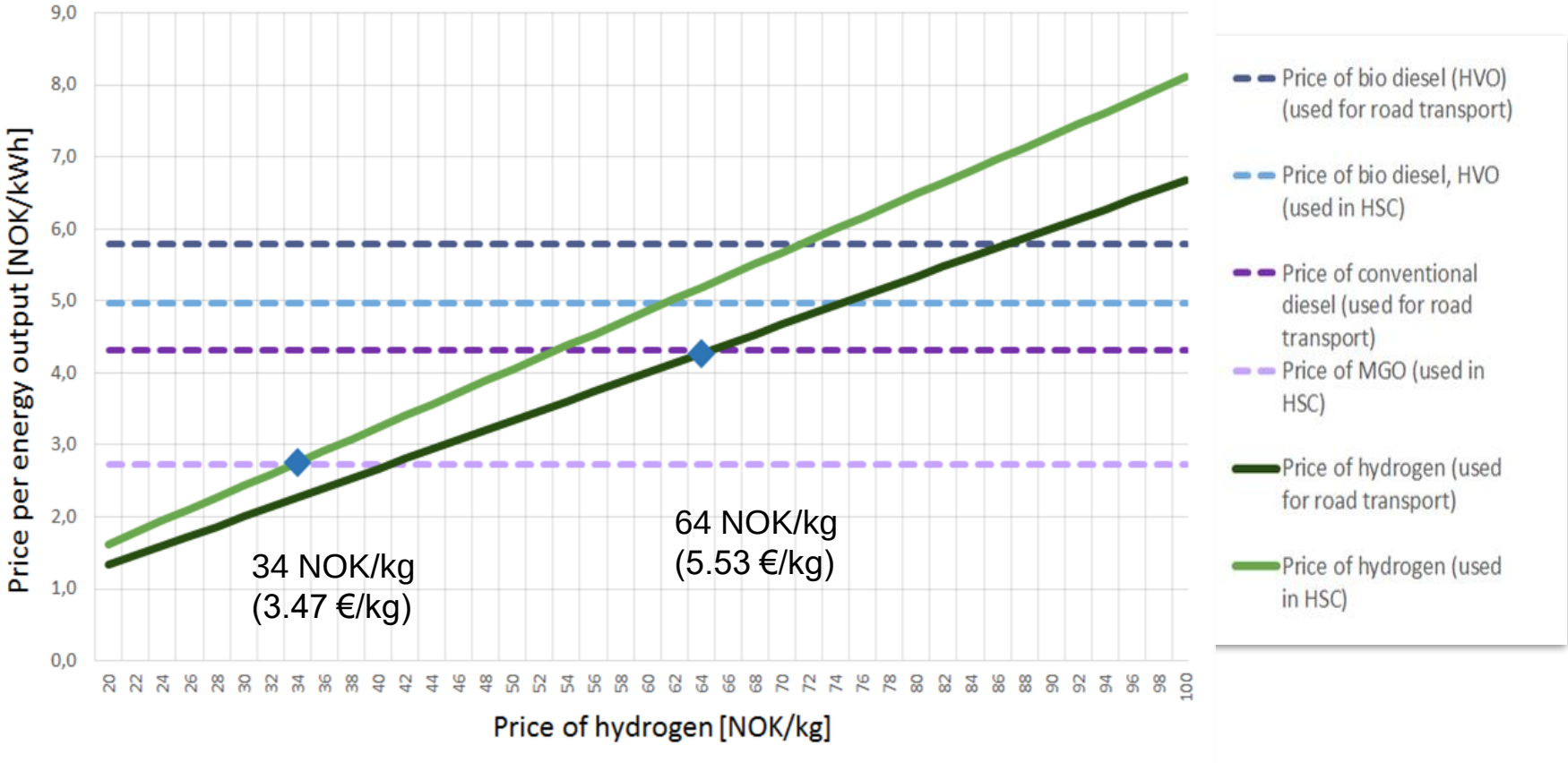
1. Costs / prices for hydrogen.
   Compared to other fuels / other available H2

€

2. Environmental benefits

Illustration: https://internetofbusiness.com/zero-emissions-uk-launches-25m-competition-for-new-battery-tech/

→ Competitiveness Due to Costs/Prices



NTNU

Battery

$18.9 \frac{g\ CO_{2-eq}}{kWh_{el}}$

El. Engine

$28.1 \frac{g\ CO_{2-eq}}{kWh}$

$\eta_{transmission} = 99\ \%$ $\eta_{charging} = 99\ \%$ $\eta_{el.\ engine} = 94\ \%$ $\eta_{propeller} = 73\ \%$

Hydrogen

$18.9 \frac{g\ CO_{2-eq}}{kWh_{el}}$

Fuel cell

El. Engine

$78.7 \frac{g\ CO_{2-eq}}{kWh}$

$\eta_{electrolyzer} = 72\ \%$ $\eta_{FC} = 54\ \%$ $\eta_{el.\ engine} = 94\ \%$ $\eta_{propeller} = 73\ \%$

Diesel/MGO

$263 \frac{g\ CO_2}{kWh_{Fuel}}$

Internal Combustion Engine

$900 \frac{g\ CO_{2-eq}}{kWh}$

$\eta_{combustion} = 40\ \%$ $\eta_{propeller} = 73\ \%$

Conclusions

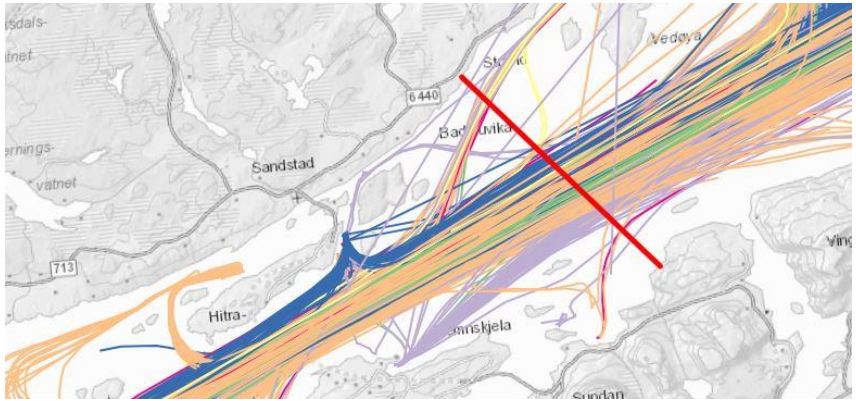
”Can Hitra — having access to local wind energy — produce competitive hydrogen for the regional maritime sector?”

→ Yes, it is possible to produce competitive hydrogen for the maritime sector at Hitra.

- AWE is the cheapest option for hydrogen production
- Electricity constitutes a large share of the costs
    - El. needs to be cheap

- No tailpipe emissions: Environmentally friendly
    - Green transformation ⇒ H_2 > MGO/Diesel
    - Green production at Hitra

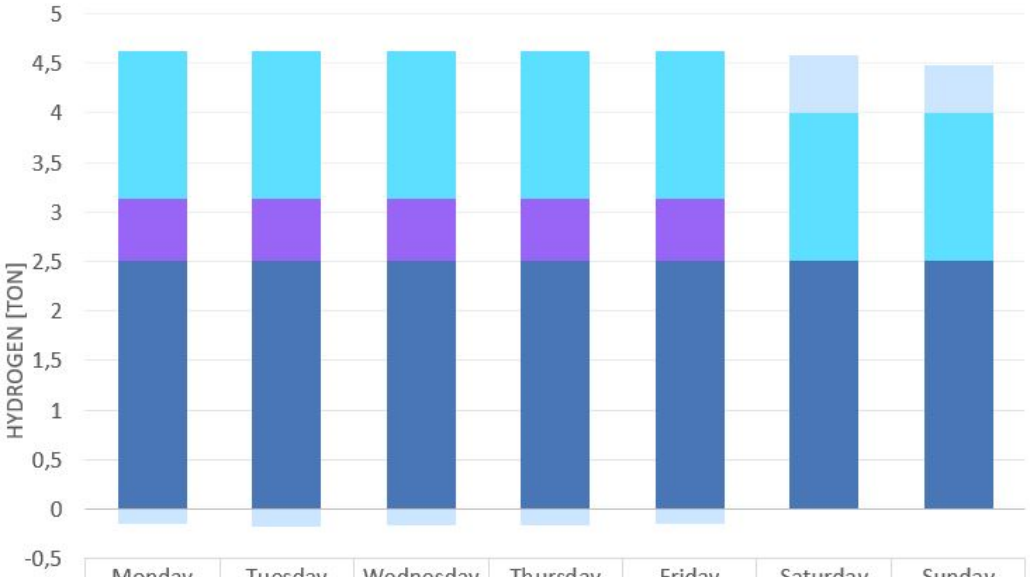
Future Work



- Building plot
- Logistics for refueling
- Analysis of the shipping lane outside of Hitra
- Environmental aspect: LCA analysis

Extra slides

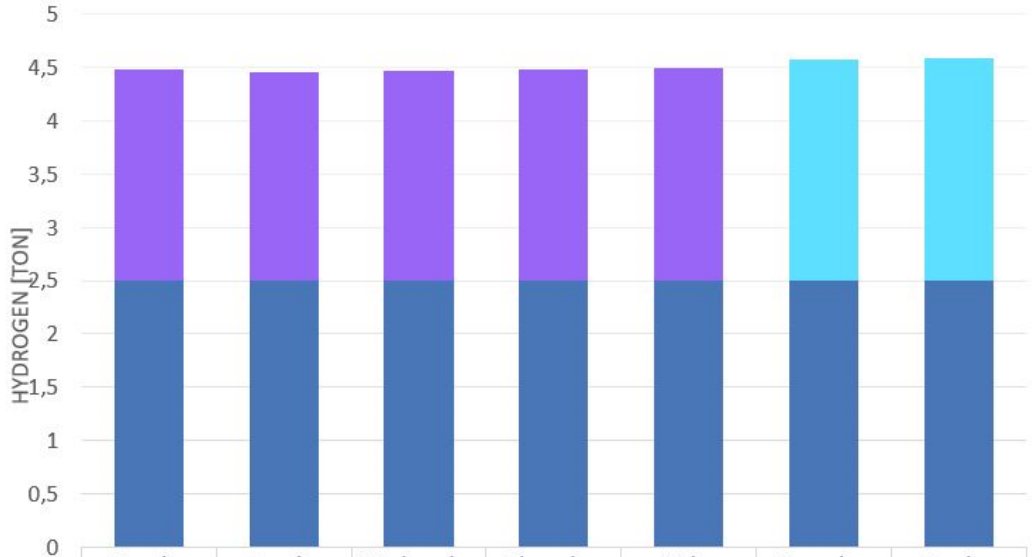
Option two: Additional well-boat



	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Residual	-0,1541	-0,1755	-0,1617	-0,1582	-0,1428	0,574	0,4791
Well boat	1,5	1,5	1,5	1,5	1,5	1,5	1,5
Trucks	0,63	0,63	0,63	0,63	0,63		
HSC	2,5	2,5	2,5	2,5	2,5	2,5	2,5

→ Low delivery reliability

Option three: Cover more of the total demand for trucks



	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Residual						2,074	2,0791
Trucks	1,9759	1,9545	1,9683	1,9718	1,9872		
HSC	2,5	2,5	2,5	2,5	2,5	2,5	2,5

Total demand: 15.75 ton/week

10 tons per week
→ 63% of total demand

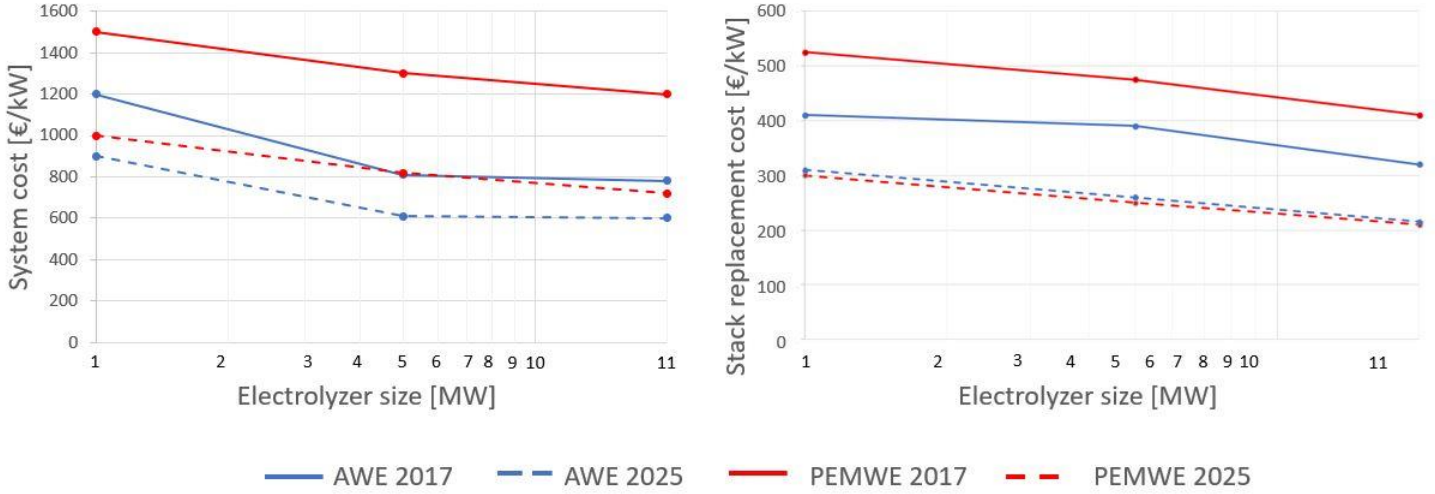
12 tons per week
→ 76% of total demand

Compressed vs Liquid Hydrogen

Favor of Compressed	Favor of Liquid
Cheapest	Store greater mass with the same volume
Requires less energy	Best when producing large amounts
Most common	The future

→ Hydrogen production at Hitra: Compressed Hydrogen

Cost Reduction & Inflation



⇒ Cost in **2020**:

	Electrolyzer	Stack replacement
AWE	503 €/kW	308 €/kW
PEMWE	703 €/kW	326 €/kW

OPEX: 3.0 % of CAPEX per year

Illustration: https://www.fch.europa.eu/sites/default/files/P2H_Full_Study_FCHJU.pdf

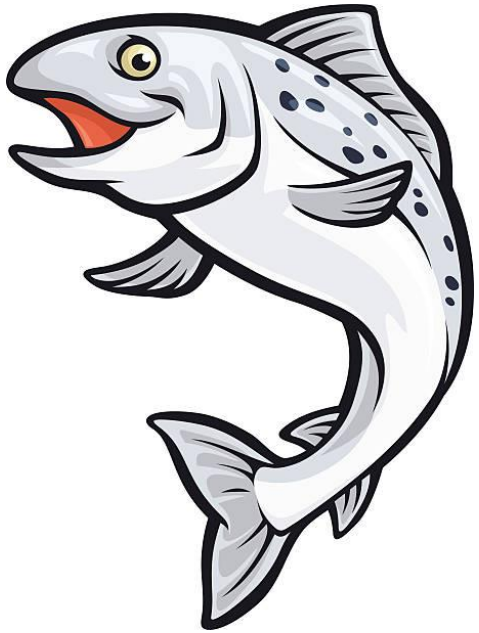
Electricity & Water Costs

Category	Price [excl. VAT]
Fixed price, grid tariff	20 800 NOK/year
Energy price, grid tariff	2.8 øre/kWh
Power price - winter, grid tariff	38 NOK/kW (per month)
Power price - summer, grid tariff	28 NOK/kW (per month)
Energy price, average 2021 - 2030	24 øre/kWh (24.57 EUR/MWh)
Water: subscription fee	65 782.96 NOK
Water: consumption price	14.93 NOK/m^3

Advantages with Hitra as Location

Growing hydrogen market:

- Norway
- Green hydrogen
- High-speed crafts



Salmon industry:

- Require a lot of energy
- Unique opportunity for Hitra
- Hydrogen, oxygen and waste heat