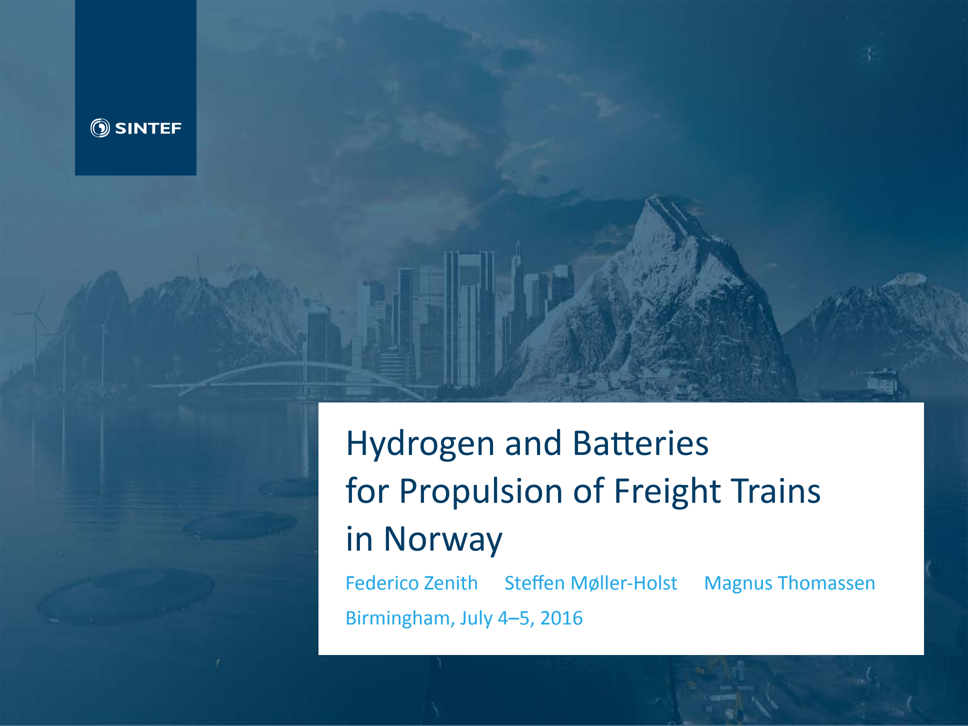

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# Hydrogen and Batteries for Propulsion of Freight Trains in Norway

Federico Zenith    Steffen Møller-Holst    Magnus Thomassen

Birmingham, July 4–5, 2016

# Outline

Non-Electrified Railways in Norway

Alternatives for Electrification

Techno-Economical Analysis

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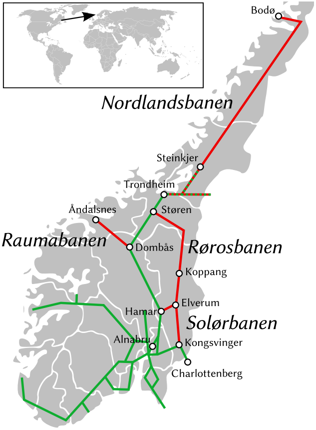
# Norwegian Railway Network

## Focus on non-electrified lines (in red)

- Røros and Solør lines (381 km, 94 km)
  - Catenary officially proposed
  - "Backup" for Dovre line
- Rauma line (111 km)
  - Scenic line for tourists
  - Catenary not desirable
- Nordland line, 731 km
  - To be partly electrified (130 km)
  - Up to 19 ‰ slope
- Politicians: *"Please electrify everything"*
- Railway authority asked SINTEF



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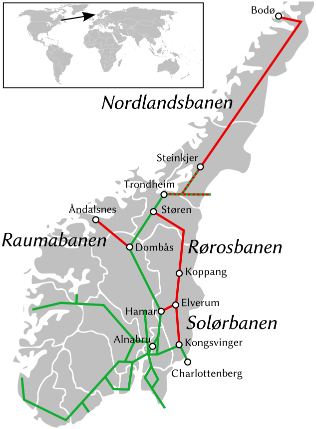
# Alternatives for Railway Electrification in Norway

## As considered in SINTEF's study

- Alternatives considered:
  - Biofuels
  - Natural gas
  - Hydrogen
  - Batteries
  - Diesel
  - Catenary
  - Hybrids
- Evaluation criteria
  - Environment
  - Technology readiness
  - Regulatory framework
  - Economy
  - Flexibility & robustness



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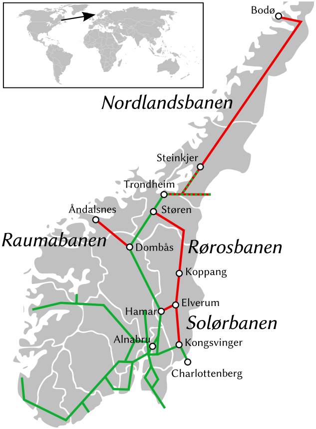


Freight on Nordland line



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# The Nordland Line

- Single-track line
- Passing loops: 600 m
- Vossloh Euro 4000 locomotives
  - Diesel-electric
  - 400 kN, 3.15 MW
- 19 ‰ slope at Saltfjellet
  - Freight trains at 40 km/h


Freight train at Trondheim



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- Strong winds (few or no trees)
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Freight train at Saltfjellet

10-hour cab rides on Youtube ("Nordlandsbanen minutt for minutt")

# Outline

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# Current Options

## Diesel and Catenary

| | Diesel | Catenary |
|---|---|---|
| Extra infrastructure | None | Large |
| Energy cost | High | Low |
| Pollution | Local & Global | None Direct |
| Tractive effort | High | Low |
| Power | Low | High |
| Appropriate traffic volume | Low | High |
| Appropriate population | Sparse | Dense |
| Appropriate inclination | High | Low |
| Appropriate speed | Low | High |

# Current Options

## Diesel and Catenary

| Characteristics of Nordland line | Diesel | Catenary |
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# Alternatives

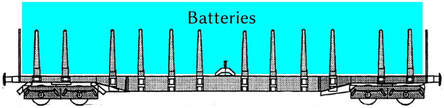
## Biodiesel, Hydrogen, Batteries

- Biodiesel
  - "Quick fix"
  - Less global, same local pollution

# Alternatives

Biodiesel, Hydrogen, Batteries

- Biodiesel
  - "Quick fix"
  - Less global, same local pollution
- Batteries
  - Heavy and cumbersome
  - 1 battery wagon: 5.7 MWh
  - 3 wagons for Nordland line
  - Option to charge midway
    - » At station
    - » With short catenary



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# Alternatives

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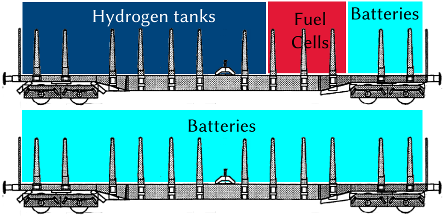
  - Less global, same local pollution
- Batteries
  - Heavy and cumbersome
  - 1 battery wagon: 5.7 MWh
  - 3 wagons for Nordland line
  - Option to charge midway
    - » At station
    - » With short catenary
- Hydrogen
  - 1 "$H_2$ wagon": 182 MWh
  - Require hydrogen refuelling
  - Fuel cells: 15 t for 5.6 MW
  - Hybridisation with batteries



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# Outline

Non-Electrified Railways in Norway

Alternatives for Electrification

Techno-Economical Analysis

# Equivalent Annual Cost

## Comparison Criterion

- Very different lifetimes
  - Batteries: 2–3 years
  - Catenary: 75 years
- Use Equivalent Annual Cost *A*, equivalent to Net Present Value

$$I \equiv NPV = \sum_{i=1}^{n} A\,(1+r)^{-i}$$

**!** Disregards opportunity costs

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! Disregards opportunity costs

**Example**

- CAPEX $I$: 1 million €
- Lifetime $n$: 20 years
- Interest rate $r$: 4 %
- Annualised CAPEX $A$: 73 582 €
- OPEX 15 000 €
- Equivalent annual cost: 88 582 €

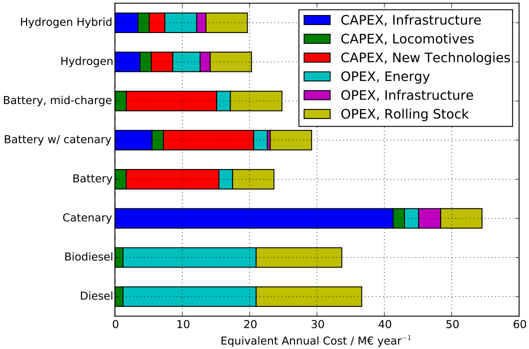
# Selection of Input Data

## Costs, Lifetimes and Traffic

- US DoE state of art / near targets
  - Batteries: 500 $/kWh, 1500 cycles
  - Fuel cells: 300 $/kW
    - Dynamic operation: 12 000 h
    - Static operation: 50 000 h (hybrid)
  - Hydrogen storage: 12 $/kWh
  - Hydrogen station: 4400 $/kg d, 10 years
- Norwegian Railway Authority
  - Catenary: 1.5 M€/km
  - Power price: 33 €/MWh
- Diesel: 1.4 €/L
- Traffic on Nordland line
  - 6 locomotives
  - 3000 train movements a year

# Results – At a Glance

- Hydrogen is cheapest
- Battery very close second
- Mid-charging not attractive
- Catenary most expensive



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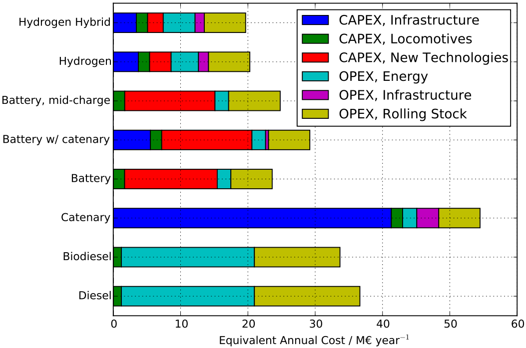
# Results – Diesel

## Current Technology

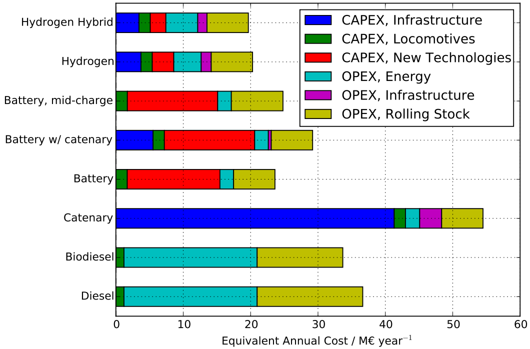
- Dominating energy costs
  - High diesel cost
  - Lower efficiency
  - Excise taxes (Europe)
- High other OPEX
  - High maintenance
  - Lower for biodiesel ($CO_2$ taxes)



# Results – Catenary

## Traditional Alternative

- Dominating infrastructure costs
  - Investment *1 billion €*
- Long-term commitment: 75 years
- Lowest energy costs



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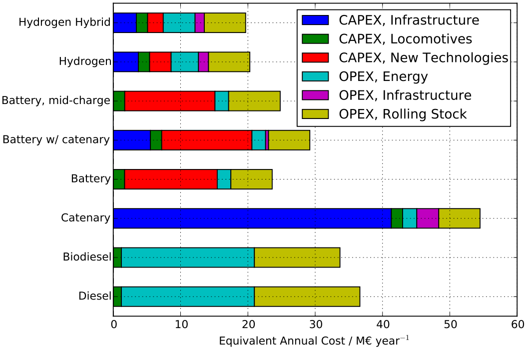
# Results – Batteries

- Dominating battery costs
  - High CAPEX
  - Low lifetime
- Lowest energy costs
- Midway charging not attractive
  - Same battery costs
  - More infrastructure



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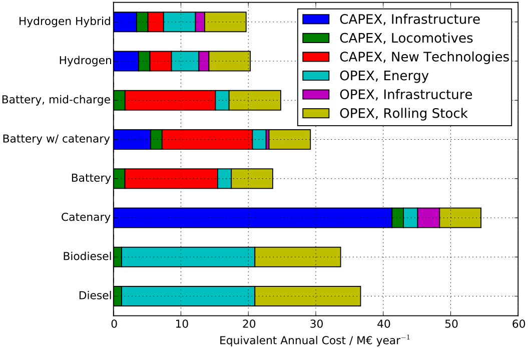
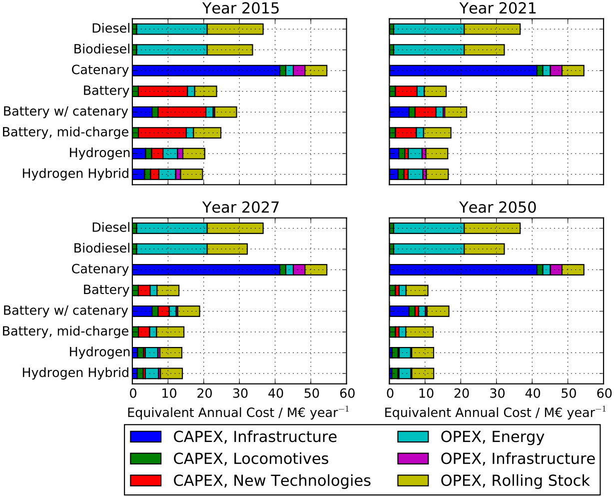
# Results – Hydrogen

- Low energy costs
- CAPEX/OPEX for refuelling station
- Fuel cells cheaper than batteries
- Hybrid layout
  - 1.5 MWh batteries
  - Regenerative braking
  - Stationary fuel cells



# Results towards 2050



# Extended Analysis for Norwegian Railway Authority

## Development towards 2050

Short term Natural gas and partial catenary are easiest to implement

Medium term Battery electrification and biodiesel increase readiness

Long term Hydrogen and batteries dominate

| Technology | **2015** | 2016 | 2017 | 2018 | 2019 | 2020 | **2021** | 2022 | 2023 | 2024 | 2025 | 2026 | **2027** | 2030 | **2050** |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Diesel-electric** | 6 | 5 | 5 | 5 | 5 | 4 | 4 | 4 | 4 | 3 | 2 | 2 | 1 | 1 | 1 |
| **Catenary** | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 5 | 4 | 4 | 4 | 4 | 4 |
| **Partial catenary** | 3 | 3 | 4 | 5 | 5 | 6 | 7 | 8 | 8 | 8 | 7 | 7 | 7 | 7 | 7 |
| **Battery** | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 8 | 8 | 8 | 8 | 8 | 8 | 9 | 9 |
| **Biodiesel** | 2 | 4 | 5 | 6 | 6 | 6 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 7 |
| **Natural gas** | 3 | 3 | 4 | 4 | 4 | 4 | 5 | 4 | 4 | 4 | 4 | 4 | 4 | 2 | 1 |
| **Hydrogen** | 1 | 2 | 2 | 3 | 4 | 5 | 6 | 6 | 8 | 8 | 9 | 9 | 9 | 9 | 10 |

Full report (A27534) available online at sintef.no.

# Conclusions

- Hydrogen and batteries have strong potential for powering trains…
  - … but catenary will be always cheaper with enough traffic
- Advantages:
  - Lower energy costs (like catenary)
  - Little or no infrastructure (like diesel)
- Disadvantages:
  - Batteries: high battery CAPEX
  - Hydrogen: low technology readiness, missing regulations
- Relevant environments beyond Norway:
  - USA (over 200 000 km, almost none electrified)
  - Canada (almost 50 000 km, almost none electrified)

# Acknowledgements

Research performed with the support of
**Jernbaneverket**, the Norwegian Railway Authority.

*Thank you for your attention!*

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Technology for a better society