"Hydrogen and Batteries for Propulsion of Freight Trains in Norway"
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SINTEF - Scandinavia's largest independent research organization

- 2000 Employees
- 70 Nationalities
- 3800 Customers
- NOK 3.2 billion Revenues
- NOK 500 MILL International sales

Key player in low & 0-emission transport both in R&D and demonstration:
- development of combustion-, battery- as well as H₂ and FC-technologies
- interdisciplinary approach: technology, economy & societal aspects
Outline

• Non-Electrified Railways in Norway
• Alternatives to Electrification with Over-Head Lines (OHL)
• Techno-Economical Analysis
Norwegian Railway Network

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

- Alternatives considered:
  - Biofuels
  - Natural gas
  - Hydrogen
  - Batteries
  - Diesel
  - Over-Head Lines
  - Hybrids

- Evaluation criteria
  - Environment
  - Technology readiness
  - Regulatory framework
  - Economy
  - Flexibility & robustness

- Focus on Freight Trains
The Nordland line

- Single-track line
- Passing loops: 600 meters
- Vossloh Euro 4000 locomotives
  - Diesel-electric
  - 400 kN, 3.15 MW
- 19 ‰ slope at Saltfjellet
  - Freight trains at 40 km/h (up-hill)
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  - Freight trains at 40 km/h (up-hill)
- Crosses polar circle
- Strong winds (few or no trees)
- Ice formation on infrastructure

Freight train at Trondheim
Freight train at Saltfjellet
Outline

- Non-Electrified Railways in Norway
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## Current options

<table>
<thead>
<tr>
<th>Characteristics of Nordland Line</th>
<th>Diesel</th>
<th>OHL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extra infrastructure</td>
<td>None</td>
<td>Large</td>
</tr>
<tr>
<td>Energy cost</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Pollution</td>
<td>Local &amp; Global</td>
<td>None Direct</td>
</tr>
<tr>
<td>Tractive effort</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Power</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Appropriate traffic volume</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Appropriate population</td>
<td>Sparse</td>
<td>Dense</td>
</tr>
<tr>
<td>Appropriate inclination</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Appropriate speed</td>
<td>Low</td>
<td>High</td>
</tr>
</tbody>
</table>
Alternatives

- 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

- Hydrogen
  - 1 “H₂ wagon”: 182 MWh
  - Require hydrogen refuelling
  - Fuel cells: 15 t for 5.6 MW
  - Hybridisation with batteries
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Equivalent Annual Cost (A)

• Very different lifetimes
  • Batteries: 2-3 years
  • Over-Head Lines: 75 years

• Use equivalent Annual Cost A, equivalent to Net Present Value:

  \[ I \equiv NPV = \sum_{i=1}^{n} A \left(1 + r\right)^{-i} \]

  ! 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

- US DoE state of art (2015)/ 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 – Freight trains Nordland line

• Hydrogen is cheapest
• Battery very close second
• Mid-charging not attractive
• OHL most expensive
Results – Freight trains Nordland line

Diesel
- Dominating energy costs
  - High diesel cost
  - Lower efficiency
  - Excise taxes (Europe)
- High other OPEX
  - High maintenance
  - Lower for biodiesel (CO₂ taxes)
Results – Freight trains Nordland line

Over-Head Lines (Catenary)

- Dominating infrastructure costs
  - Investment 1 billion €
- Long-term commitment: 75 years
- Lowest energy costs
Results – Freight trains Nordland line

Batteries
- Dominating battery costs
  - High CAPEX
  - Low lifetime
- Low(est) energy costs
- Midway charging not attractive
  - Same battery costs
  - More infrastructure
Results – Freight trains Nordland line

Hydrogen / fuel cells

- Low energy costs
- CAPEX/OPEX for refuelling station
- Fuel cells cheaper than batteries
- Hybrid layout
  - 1.5 MWh batteries
  - Regenerative braking
  - Stationary fuel cells
Solutions' actuality towards 2050

Evaluation Criteria:
- Environment
- Technology readiness
- Regulatory framework
- Economy
- Flexibility & robustness
Source and Acknowledgement

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

Full report (A27534) available online at SNTEF’s website: www.sintef.no
Thank you for your attention!

Technology for a better society