NUFRIEND Insights

RANGES OF BATTERY-ELECTRIC LOCOMOTIVES (BELS)

Northwestern University Freight Rail Infrastructure & Energy Network Decarbonization (NUFRIEND) is a comprehensive industry-oriented tool to simulate the deployment of new energy technologies across U.S. freight rail networks. Scenario-specific simulation and optimization modules provide estimates for carbon reductions, capital investments, costs of carbon reductions, and operational impacts for any given deployment profile.

WHY DO BEL RANGES MATTER?

- The ranges of BELs are much more limited compared to existing diesel-electric locomotives.
- They require charging stations between terminals for linehaul shipments, incurring significant capital costs.

This NUFRIEND Insights models future BEL deployment in an aggregated U.S. Class I railroad network under 200-mile vs 800-mile ranges, to analyze their costs and emissions.

<table>
<thead>
<tr>
<th>BEL Range</th>
<th>200-mile</th>
<th>800-mile</th>
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<tbody>
<tr>
<td>Cost of Avoided Emissions</td>
<td>$0.9/kgCO2</td>
<td>$0.1/kgCO2</td>
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<tr>
<td># of Charging Facilities</td>
<td>143 out of 544</td>
<td>7 out of 544</td>
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<tr>
<td>Emissions Reduction</td>
<td>7.18%</td>
<td>29.06%</td>
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Optimization results of an aggregated transcontinental U.S. rail network where 20% shipments are served by BELs.

HOW DO BEL RANGES AFFECT RAIL DECARBONIZATION?

Range is critical, as deploying charging stations in locations with no proximal railyards may be economically infeasible.

200-mile Range:
- Mass deployment of charging stations limited to regions with existing railyards.
- Limited linehaul corridor options to deploy BELs.
- High cost of avoided emissions from capital investment to build a lot of charging facilities.

800-mile Range:
- Few charging stations needed to decarbonize the high-volume linehaul routes.
- Flexibility to deploy BELs on easy-to-decarbonize routes.
- Cost of avoided emissions in line with potential U.S. carbon credit pricing.

SUMMARY

- Longer-range BELs require a smaller capital investment while attaining a higher carbon reduction.
- Longer ranges mean more flexibility for railroads to deploy BELs and leverage economies of scale in heavily trafficked corridors.
- For individual railroads and different BEL ranges, the NUFRIEND tool can optimize the deployment of charging infrastructure and offer more pointed insights.

1 The cost of avoided emissions measures the average cost required to reduce emissions by one kg of CO2 and serves as a strong evaluation and policy metric.

NUFRIEND Insights for:

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<th>RAILROADS</th>
<th>OEMS</th>
<th>ENERGY PROVIDERS</th>
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<tbody>
<tr>
<td>BEL charging time causing high delay costs</td>
<td>Value of range improvements</td>
<td>Coordination to ensure adequate electricity supply for connected charging infrastructure</td>
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<tr>
<td>Significant benefits attainable from advanced rollout planning</td>
<td>Innovations in charging speeds</td>
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<tr>
<td>Potential gains from easy-to-decarbonize routes</td>
<td>Need for cost-competitive manufacturing relative to other fuel technologies</td>
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<td>Value of accurate range estimates and forecasts</td>
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