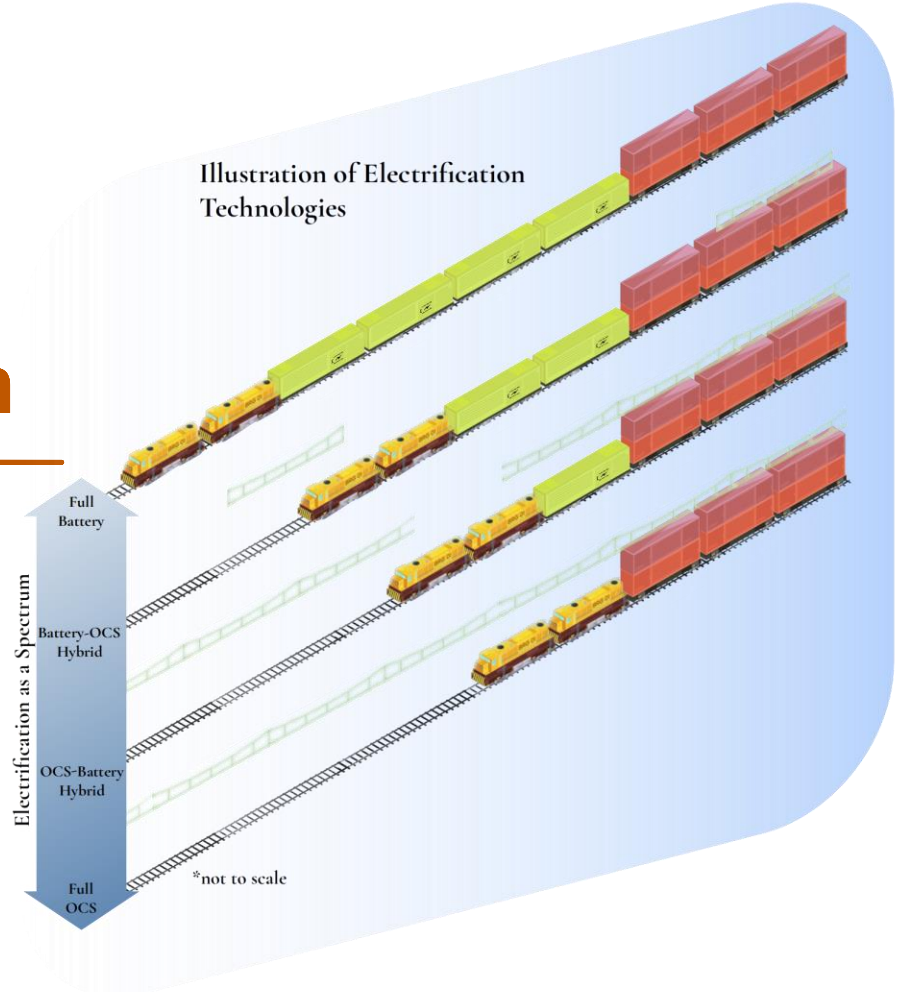
The CURRENT Model for the Economics of Railway Electrification



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REC/NEMA Workshop Q&A
24 October 2024

TRAIN
TEXAS RAILWAY ANALYSIS & INNOVATION NODE

TEXAS
The University of Texas at Austin

Project Objectives

- Holistic understanding of the primary technical and economic barriers to railway electrification

- Identification of innovative technologies and approaches to operations and implementation that will
  - Improve benefits,
  - Reduce cost and risk, and
  - Eliminate or lessen operational limitations and impacts

- Updated benefits and costs of modern electrification options

- New risk-based framework for evaluating the sensitivity of electrification decisions to cost uncertainty, considering:
  - Current railroad operating situation
  - Carbon-focused environmental decision context

Today's Presentation

- Discuss recently concluded FRA-funded project on rail electrification
- Project Objectives & Methodology
- Conclusions from past electrification studies
- New technologies that increase the feasibility of electrification
- Development of the CURRENT Model for economic analysis of rail electrification
- Case Study example using the new CURRENT Model

Tasks & Work Packages

- Task I – Review past/current railway electrification studies
  - Catalog key technologies and their limitations
  - Identify the primary factors influencing costs, benefits, and risks

- Task II – Review alternative technologies and strategic implementation approaches
  - Identify innovative solutions that would improve the cost-benefit-risk assessment of electrification

- Task III – Develop and demonstrate an updated risk-based electrification benefit-cost framework via case study
  - Analyze two representative types of rail corridors
  - Accommodate different policy frameworks, such as Carbon taxes or Carbon reduction commitments
  - Consider variability & uncertainty

Overall Task I Conclusions

- Many past studies, particularly from the 1970's and 1980's do not include detailed economic valuation of public benefits
  - Studies at the time were conducted primarily from the perspective of private railroads, and assumed entirely private financing.
  - Many older studies tend to underemphasize financial risk, compared to modern company practices.
- Many electrification proposals entered advanced stages of engineering design, but do not appear to have reached advanced stages of contractual negotiations.
- Simply adjusting construction costs for inflation leads to a wide range in OCS cost per mile.

Task 1: Summary of Specific Findings

- The cost of public works modifications to accommodate electrification was a large factor in the past that might be mitigated through intermittent electrification

- Shielding signal systems from interference was a significant and highly variable cost – this interaction requires further study with the advent of PTC

- Poor communication between stakeholders (railroads, public agencies, and utilities) stopped some electrification projects

- Multiple railroads independently identified the potential of right-of-way sharing agreements to promote electrification

- Focus needs to shift from “cost of diesel vs electricity” to “what is the most economical way to decarbonize?”

Task II Focus Areas – Technologies & Strategies

- Methods to Streamline Catenary Construction
- Locomotive Technologies
- Intermittent Electrification
- Implementation Strategies

Methods to Streamline Catenary Construction

- Efficiency improvements
  - Better substation spacing
  - Long-term energy savings
- Design improvements
  - Improvements in design costs
  - Savings in materials
- New construction techniques
  - OCS construction trains reduce labor costs as well as line disruption costs
  - Improved project management can reduce scheduling delays
- Alternatives to OCS
  - Third rail electrification is not viable for freight applications
  - Inductive charging requires further development to achieve freight-level power transfers

Locomotive Technologies

- Comparison of electric locomotives to modern diesel-electric locomotives
- Current state of battery-electric locomotives
- Dual-mode locomotives
  - Power limitations
  - Added complexity
  - Ability to accrue project benefits sooner
- Dual-mode locomotives with tenders
  - Comparison with alternatives
  - Can bypass some spatial constraints
  - Can reduce some retrofitting costs

Intermittent Electrification

- Technical aspects
  - Locomotive capabilities
  - Project mobilization uncertainty
- Analysis of potential savings
  - Clearance advantages
  - Moving electrification cash flows forward
- Network effects
  - Reduced cost for sidings
  - Reduced cost for spurs

Implementation Strategies

- Public-private partnerships for rail electrification
  - Monetizing emissions reductions
  - Risk mitigation
- Right-of-Way sharing agreements with electric utility providers
  - Suitability of railroad right-of-way for electricity distribution
  - Construction challenges
  - New revenue streams to support the project
  - Reduced ROW uncertainty for utilities and reduced energy cost uncertainty for railroads

Task III – The CURRENT Model

- Utilizing the knowledge gained throughout the project, the research team developed the Costs, Uncertainties, and Risks of Rail Electrification with New Technologies, or CURRENT Model.
- CURRENT provides a framework to analyze many different electrification strategies along any given railway corridor.
  - Train Performance Function in Python uses a mass strap model to estimate energy consumption for different types of electrification.
  - Cost-benefit analysis model in Microsoft Excel incorporates fifteen categories of costs and benefits to provide rates of return from private and public perspectives.
  - Argo plugin provides risk assessment via Monte Carlo simulations of the cost-benefit analysis.
- CURRENT uses entirely free software. Cost-benefit analysis can utilize independent energy estimates.

Structure of Benefit-Cost Tool

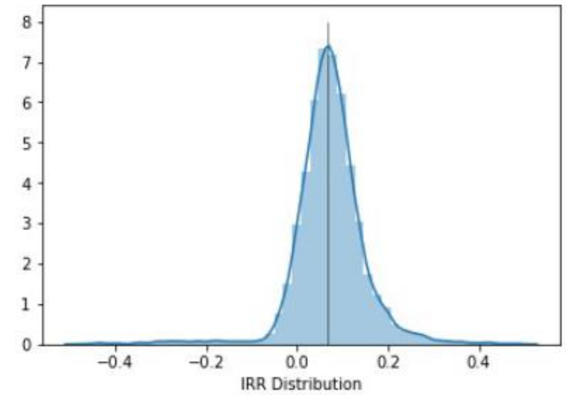
- Results (Overview)
- Capital Costs
- Maintenance Costs
- Energy Costs
- Emissions
- ROW Sharing
- Parameters
- Route Data Input
- Traffic Data Input
- Calculations

Detailed Output

User Input

Monte Carlo Risk/Uncertainty Analysis

- Implemented in Excel using ARGO
  - Free Monte Carlo simulation plug-in
  - Developed by Booz Allen Hamilton
  - Repeats economics calculations 1,000+ times using input distributions to create distribution of output metrics
  - User can select between normal, triangular and uniform input distributions for each parameter

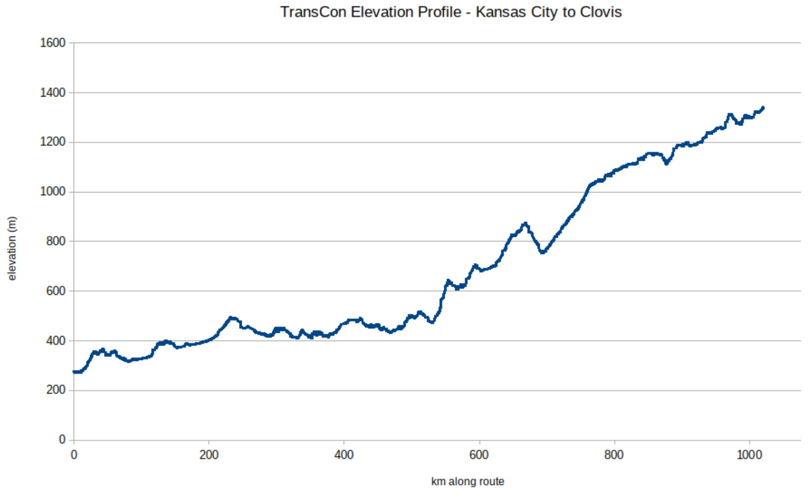


- Partial example of simulation input:

Variable		Unit	Default Value	Distribution	Confidence Level	Normal Distributions Mean	Standard Deviation	normal distribution
Catenary		$1000/km						
	Single Track	$1000/km	403	Normal	95%	403	125	474
	Double Track	$1000/km	737	Normal	95%	737	228	722
	Along Bridge Deck	$/m	1 474	Normal	95%	1 474	188	1 800
Substations		ea ($1000)	7 094	Normal	95%	7 094	2 758	6 100
Substation Spacing		km/substation	50	Normal	95%	50	5	52
Transmission		$1000/km	49	Normal	95%	49	19	69
Public Works*		Lump						
	Track Lowering	ea	50 000	Normal	95%	62 500	19 133	13 593
	Bridge Raising	ea	3 000 000	Normal	95%	3 250 000	892 874	2 557 836
	Tunnel Reconstruction	linear m	300 000	Normal	95%	250 000	51 021	264 568
	Bridge Reconstruction	linear m	100 000	Normal	95%	125 000	38 266	73 124
Signaling and Communications		$1000/km	947	Normal	95%	947	424	1 047
OCS Construction per year		km	250	Normal	95%	250	26	246
Days of Mobilization for a new segment		days	7	Normal	95%	9	3	10
OCS maintenance		$ per km	7 652	Normal	95%	7 652	1 301	7 734
Substation maintenance		ea	73 662	Normal	95%	73 662	12 528	70 973

Mainline Corridor Case Study

- Double-track mainline corridor with dense traffic
  - ~1020 km (635 miles) from Kansas City, KS (Argentine) to Clovis, NM on BNSF
  - Long route requires multiple years of OCS implementation



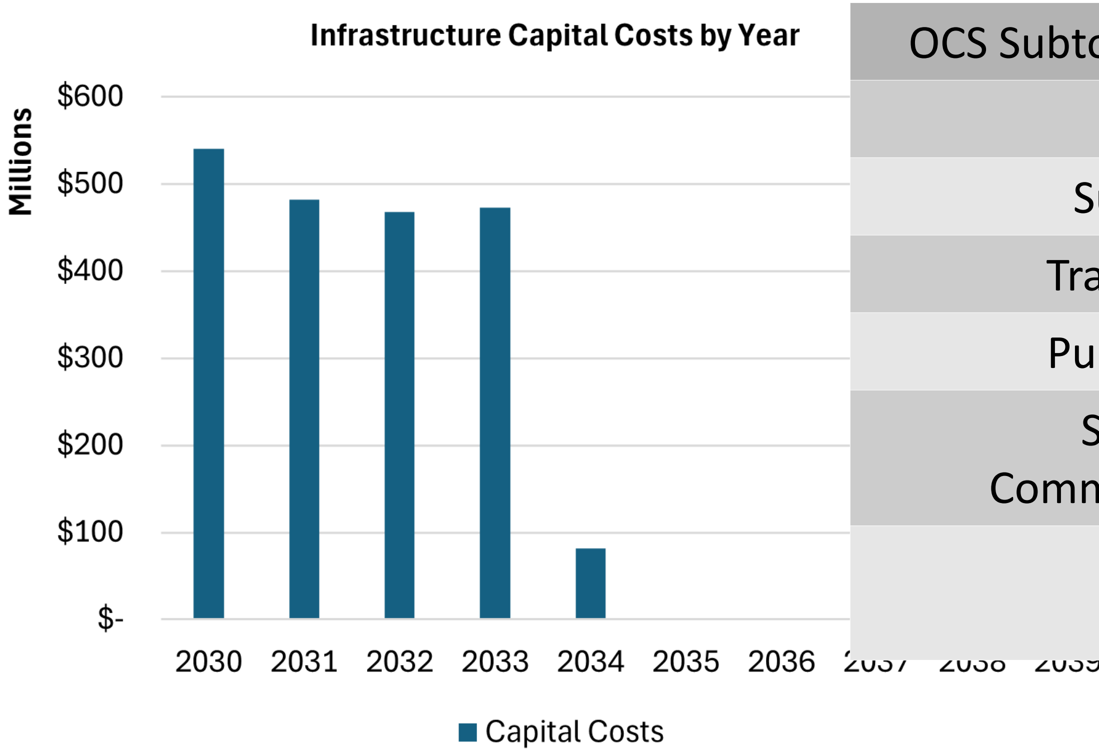
- Traffic Parameters
  - 60 trains per day
    - Intermodal: 150 platforms
    - Bulk: 125 cars, 286k GRL
    - Manifest: 77 loads, 38 empty (286 GRL)
    - 3 or 4 locomotives per train

Mainline Corridor: OCS costs

- Analyzed four electrification scenarios:
  - Full conventional electrification
  - OCS with short gaps at public works and last-mile batteries
  - Intermittent electrification via battery tenders and OCS recharging segments
  - Progressive electrification via dual-mode locomotives
- Short gaps scenario is assumed to avoid all public works costs
- Intermittent electrification scenario included broad analysis of different combinations of OCS power and OCS coverage
- Progressive electrification scenario starts electric operations as the infrastructure is built in the initial years of the project

Mainline Corridor: OCS costs

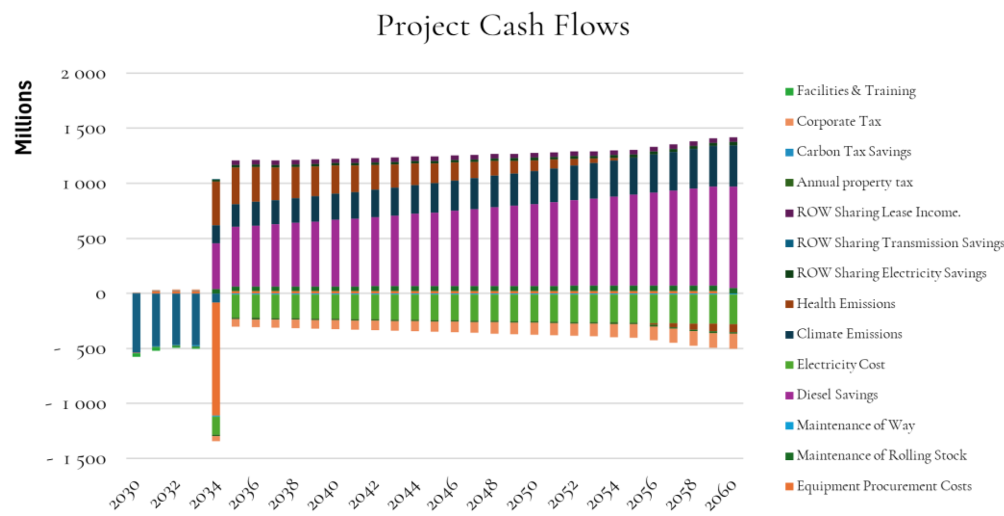
- Signaling & Communication is the largest expense, highlighting the need for more research in this area.
- Public Works cost shows the potential savings for intermittent electrification



OCS Subtotals ($ millions):	
Catenary	754
Substations	149
Transmission	25
Public Works	149
Signaling & Communication	969
Total	**$2,046**

Mainline Corridor: Conventional Electrification

- Conventional electrification produces positive returns, but requires significant upfront investment that creates a negative position.
- Public support might be necessary to bring-about private investment.

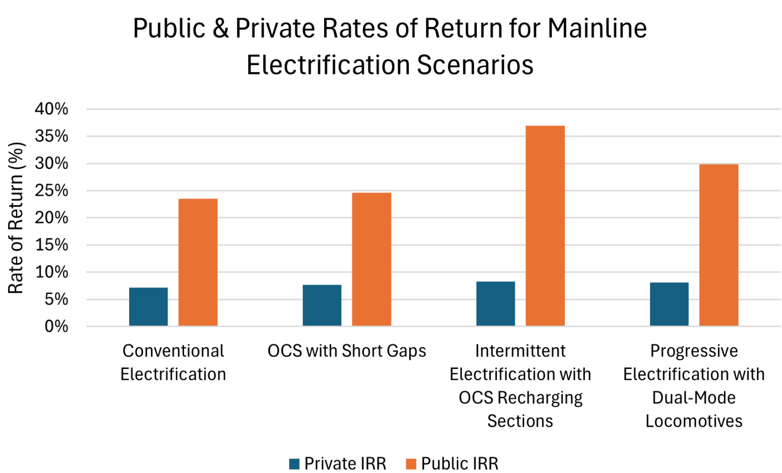


Perspective	Net Present Value ($ millions)			Internal Rate of Return	Benefit-Cost Ratio		
Discount Rate:	3%	7%	18%		3%	7%	18%
Purely Private RR Investment	1320	48	-1170	7.2%	1.4	1.0	0.5
Private Investment with ROW Sharing	2060	538	-975	9.3%	1.7	1.2	0.6
Private investment with ROW sharing and public support	7870	4440	643	22.9%	3.7	2.7	1.3
Public Perspective	8280	4700	728	23.5%	4.0	2.8	1.3

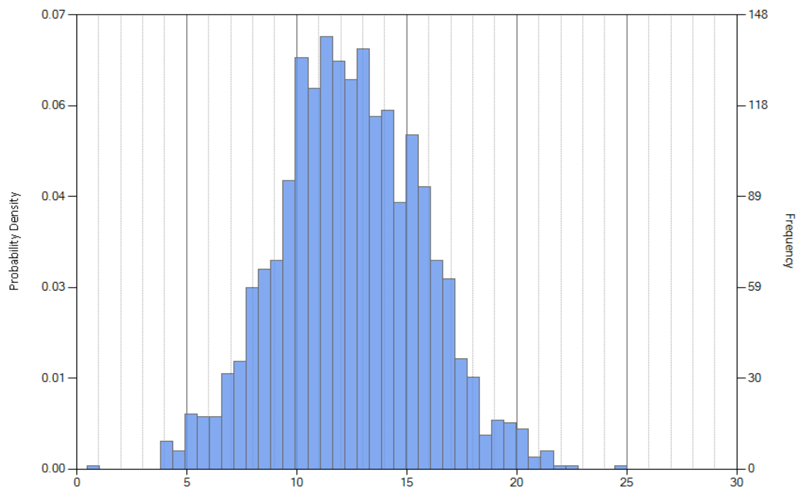
Mainline Corridor: Scenario Comparison

- Each of the technologies tested improved the project's economic performance
- Some internalization of public benefits might be necessary to bring about large enough returns for investment

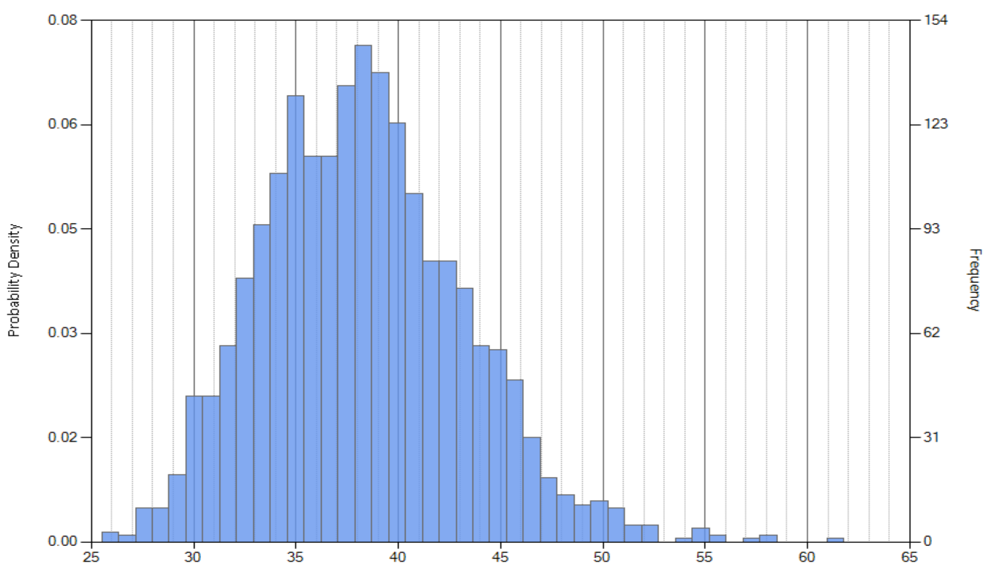
Scenario	Private Internal Rate of Return	Public Internal Rate of Return
Conventional Electrification	7.2%	23.5%
OCS with Short Gaps	7.7%	24.6%
Intermittent Electrification with OCS Recharging Sections	8.3%	36.9%
Progressive Electrification with Dual-Mode Locomotives	8.1%	29.8%



Risk and Uncertainty – Intermittent Electrification case



Private Rate of Return



Public Rate of Return

Thank you for your attention!

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Task I – Historical Studies

Q&A Slides

Task I Materials

Tasks & Work Packages

- **Task I – Review past/current railway electrification studies**
  - **Catalog key technologies and their limitations**
  - **Identify the primary factors influencing costs, benefits, and risks**

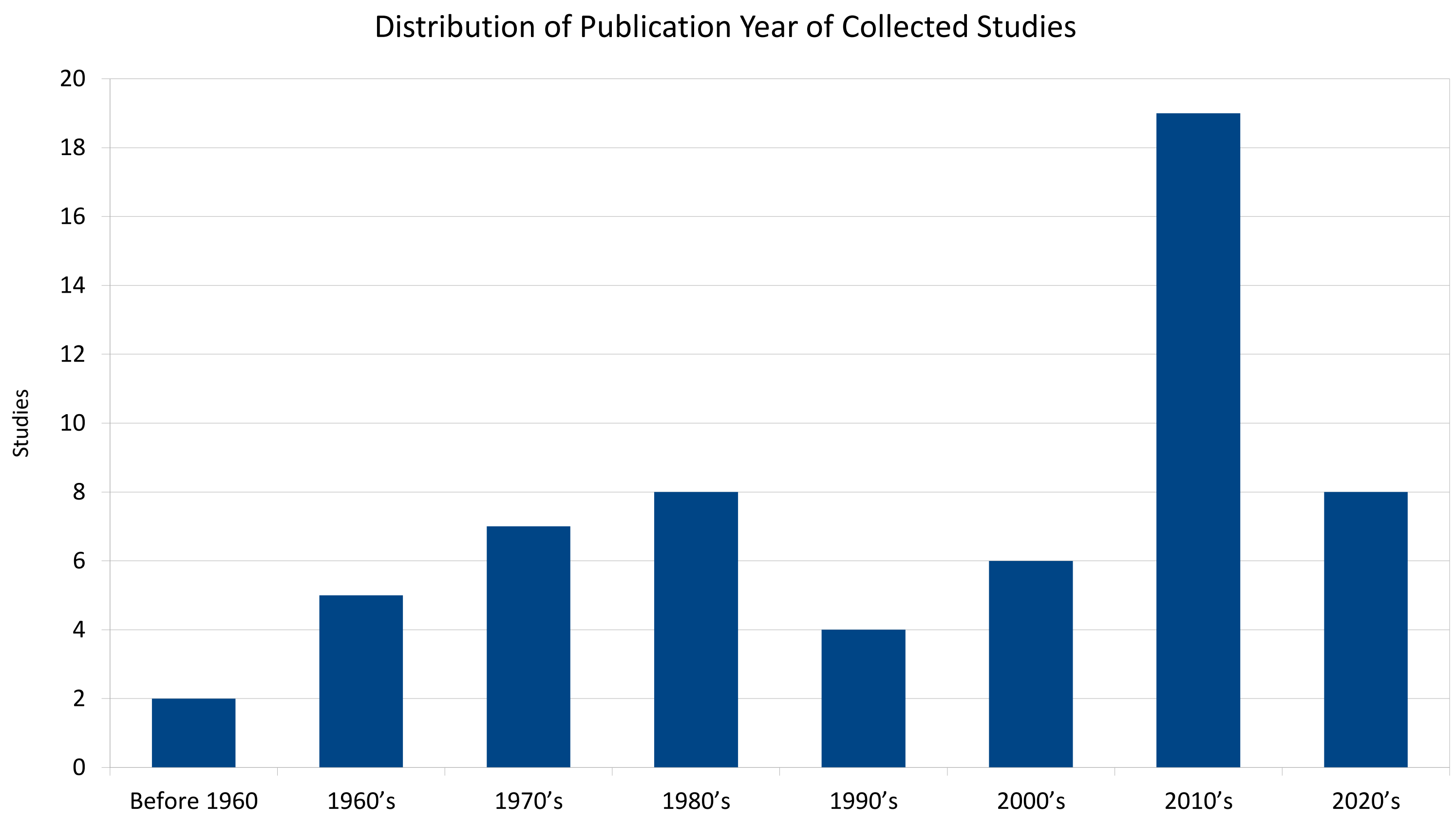
- Task II – Review alternative technologies and strategic implementation approaches
  - Identify innovative solutions that would improve the cost-benefit-risk assessment of electrification

- Task III – Develop and demonstrate an updated risk-based electrification benefit-cost framework via case study
  - Analyze two representative types of rail corridors
  - Accommodate different policy frameworks, such as Carbon taxes or Carbon reduction commitments
  - Consider variability & uncertainty

Studies Analyzed

- 53 Studies Analyzed as part of Task I
- Broad geographic range and time range
  - US studies come from different regions and railroads
  - International studies included from a wide range of countries
  - Recent studies mixed with reports from the 1970’s and 1980’s

Studies Analyzed



Specific Findings

- The cost of public works modifications to accommodate electrification was a large factor in many studies
  - The research team made this a point of emphasis moving into Task II, as we examined the potential for intermittent electrification.
- Shielding signal systems from interference was a significant and highly variable cost.
  - One research gap identified was in the overall effect PTC would have on this cost.
- Some projects seemed to suffer from poor communication between the railroads and the utility companies.

Task 1: Overall Conclusions

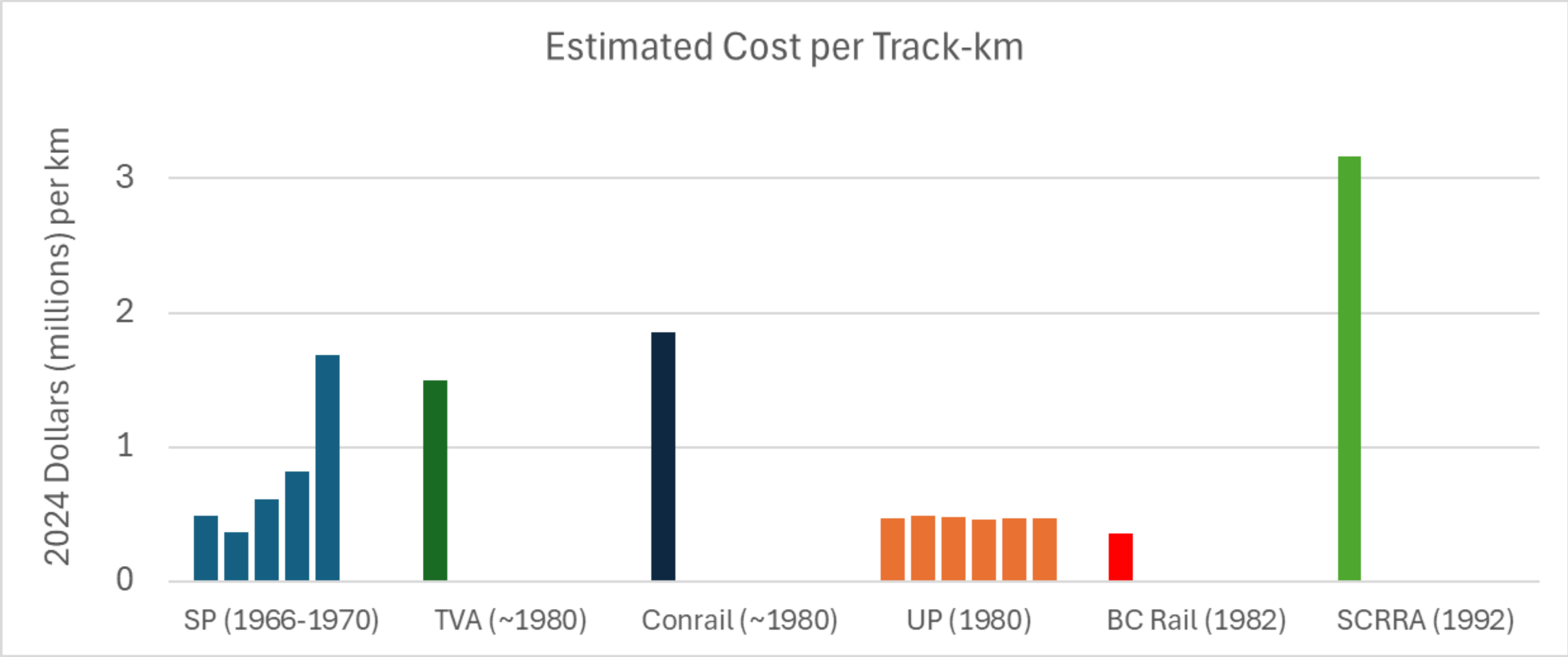
- Primary barriers are economic and institutional
- Technical barriers only related to limited North American experience
- High initial costs but simply adjusting construction costs for inflation leads to a wide range in OCS cost per mile
- Many past studies, particularly from the 1970's and 1980's do not include detailed economic valuation of public benefits
  - Studies at the time were conducted primarily from the perspective of private railroads, assuming all private financing
  - Many older studies tend to underemphasize financial risk, compared to modern company practices
- Many electrification proposals entered advanced stages of engineering design, but do not appear to have reached advanced stages of contractual negotiations

Barriers Identified in Past Studies

- Economic
  - Costs are too high
  - Benefits are too small
  - Scope of benefits is too narrow
  - Benefits are not accrued early enough during the project
  - Uncertainty and risk too high
- Technical
  - Traditional OCS dictates “All or Nothing” approach
  - Signals and clearances
- Institutional
  - Lack of experience with tri-party agreements between railroads, utilities, and/or Federal/State/Local agencies to monetize costs and benefits to each

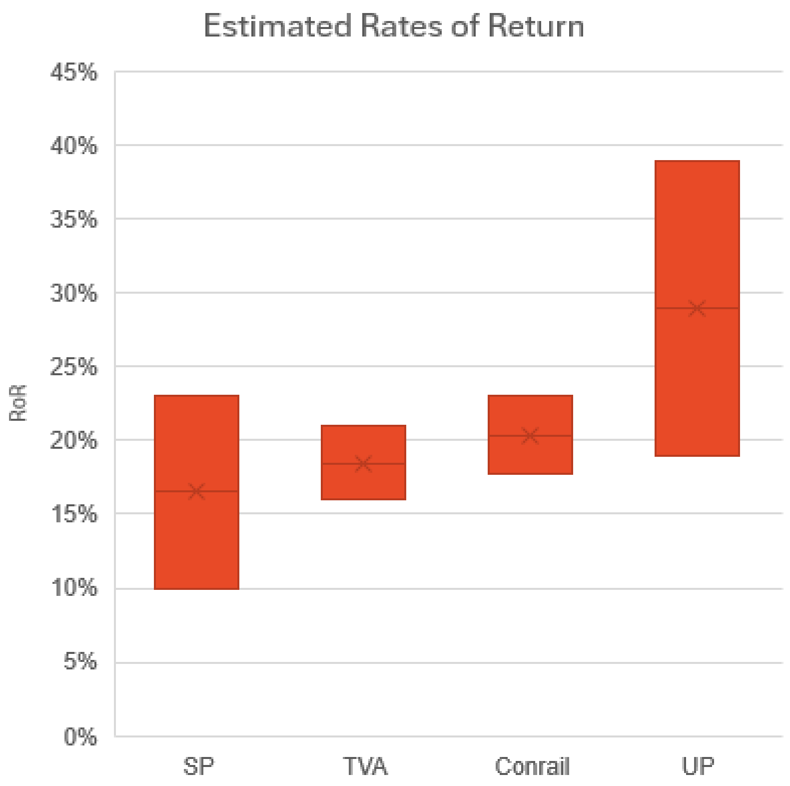
Economic Barriers – High Costs

- Electrification has high up-front capital costs
- Past studies arrived at very different unit cost estimates
  - Conversion to 2024 dollars below yields wide range of estimates
- Overall cost is uncertain, with different study-specific assumptions



Economic Barriers – Low Benefits

- Past studies had consistently high rates of return
  - Not high enough to justify the risk at the time
- Past studies only considered financial benefits
  - Primary benefit: Electricity costs vs Diesel costs
  - Secondary benefit: Locomotive Maintenance
- Social benefits can improve rate of return if railroads have incentives to monetize



Economic Barriers – Scope of Benefits

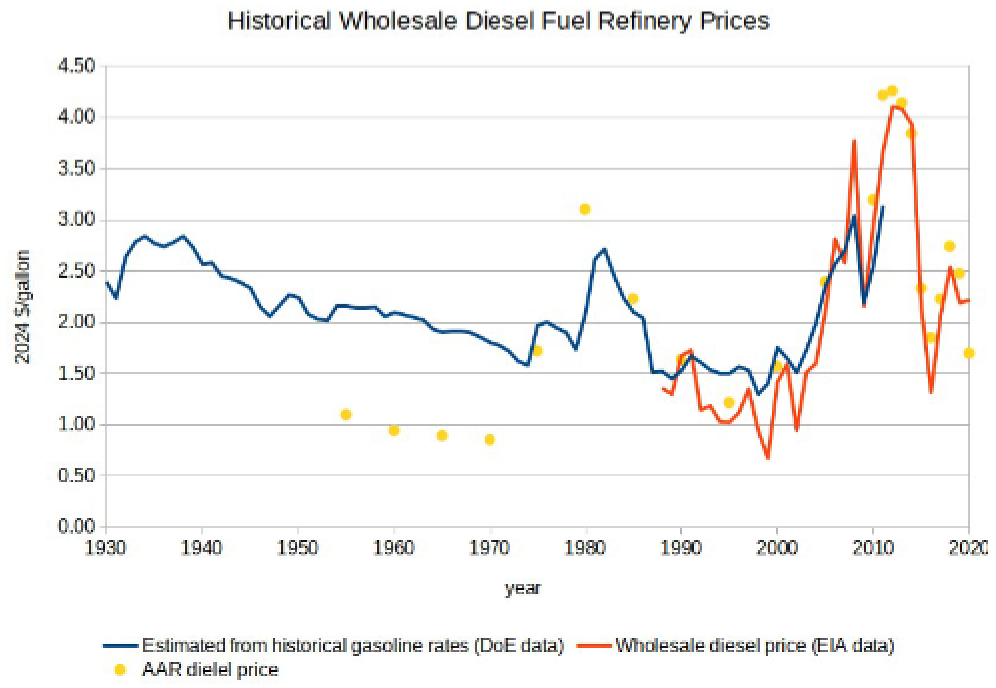
- Partnerships between railroads and utility companies can provide co-benefits
  - SP with SCE and other southwestern utilities – Catenary Associates
  - SR and L&N with TVA – Railroad Electrification Management Corporation (REMC)
- Past electrification studies did not consider alternative revenue streams stemming from the electrification
  - Right-of-way sharing agreements with utility companies
  - New transmission links create value to utilities, public and agencies
- Electrification provides value in terms of future energy flexibility
  - Railroads can avoid being captive to one fuel/energy source (depending on variety in regional sources of electrical generation)
  - Modern focus will be on decarbonization for “greater good” instead of previous focus on replacing diesel to reduce costs

Economic Barriers – Benefit Accrual

- Positive rates-of-return did not always align with railroad investment timelines
- Losses during construction would put the railroad at a negative position for the life of the project
- Longer construction without benefits to service leads to higher risk
- Where public funding was available, railroads were concerned about capital constraints

Economic Barriers – Risk & Uncertainty

- Past studies occurred during a time of historic fuel price fluctuations
- Electrification studies depended on long-term traffic forecasts that haven't panned-out
  - Coal route electrification studies particularly affected



- Added uncertainty because of lack of experience with electrification of North American heavy haul freight operations

Technical Barriers and Solutions

Traditional OCS Dictated "All or Nothing" Approach

- Intermittent partial electrification schemes
  - Allows electric trains to operate outside completely electrified territory
  - Potentially lowers or eliminates clearance costs
- Dual-mode locomotives
  - Brings benefits forward
  - Relatively small retrofit cost to make locomotives compatible with tender cars that interface with the electrification infrastructure (batteries & pantographs)

Signals, Clearances and General Construction Costs

- Cost mitigation strategies
  - Changing the voltage along the route
  - Autotransformers
  - Updated construction techniques
  - Understanding the effects of PTC and modern track circuit technology

Institutional Barriers and Solutions

Lack of experience with tri-party agreements between railroads, utilities, and agencies to monetize costs and benefits to each

- Utility companies have historically had difficulty acquiring linear right-of-way to expand distribution
  - Decarbonizing the grid exacerbates this problem
- A right-of-way sharing agreement with the railroads could provide an alternate revenue stream for electrification or reduce electricity rate uncertainty
- Public-private partnerships could be used to reduce risk for the railroads and provide incentives based on environmental benefits
- There is currently a lack of an effective implementation strategy “template” for electrification agreements

Q&A Slides

Task II Materials

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Streamlining Catenary Construction

- Efficiency Improvements
  - Higher voltages than past studies
  - Autotransformers
  - Switching voltage to improve clearance
- Pylon placement optimization
- New construction techniques
  - OCS construction trains
  - Reduced service disruptions

Locomotive Technologies

- Comparison of electric locomotives to modern diesel-electric locomotives
- Current state of battery-electric locomotives
- Dual-mode locomotives
  - Power limitations
  - Ability to accrue project benefits sooner
- Dual-mode locomotives with tenders
  - Comparison with alternatives
  - Can bypass some spatial constraints
  - Can reduce some retrofitting costs

Intermittent Electrification

- Technical aspects
  - Locomotive capabilities
  - Project mobilization uncertainty
- Analysis of potential savings
  - Clearance advantages
  - Moving electrification cash flows forward
- Network effects
  - Reduced cost for sidings
  - Reduced cost for spurs

Implementation Strategies

- Public-private partnerships for rail electrification
  - Monetizing emissions reductions
  - Risk mitigation
- Right-of-Way sharing agreements with electric utility providers
  - Suitability of railroad right-of-way for electricity distribution
  - Construction challenges
  - New revenue streams to support the project
  - Reduced ROW uncertainty for utilities and reduced energy cost uncertainty for railroads

Review of Task II

Over the course of Task I, the team identified four focus areas for technologies and strategies:

- Methods to Streamline Catenary Construction
- Look into the effect dual-mode operations have on the short-term cost-benefit analysis, and Locomotive Technologies in general
- Intermittent Electrification
- Implementation Strategies
  - Right-of-Way Sharing Agreements with electric utility companies
  - Role of public-private partnerships

Methods to Streamline Catenary Construction

- Efficiency improvements
  - Better substation spacing
  - Long-term energy savings
- Design improvements
  - Improvements in design costs
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- New construction techniques
  - OCS construction trains reduce labor costs as well as line disruption costs
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- Alternatives to OCS
  - Third rail electrification is not viable for freight applications
  - Inductive charging requires further development to achieve freight-level power transfers

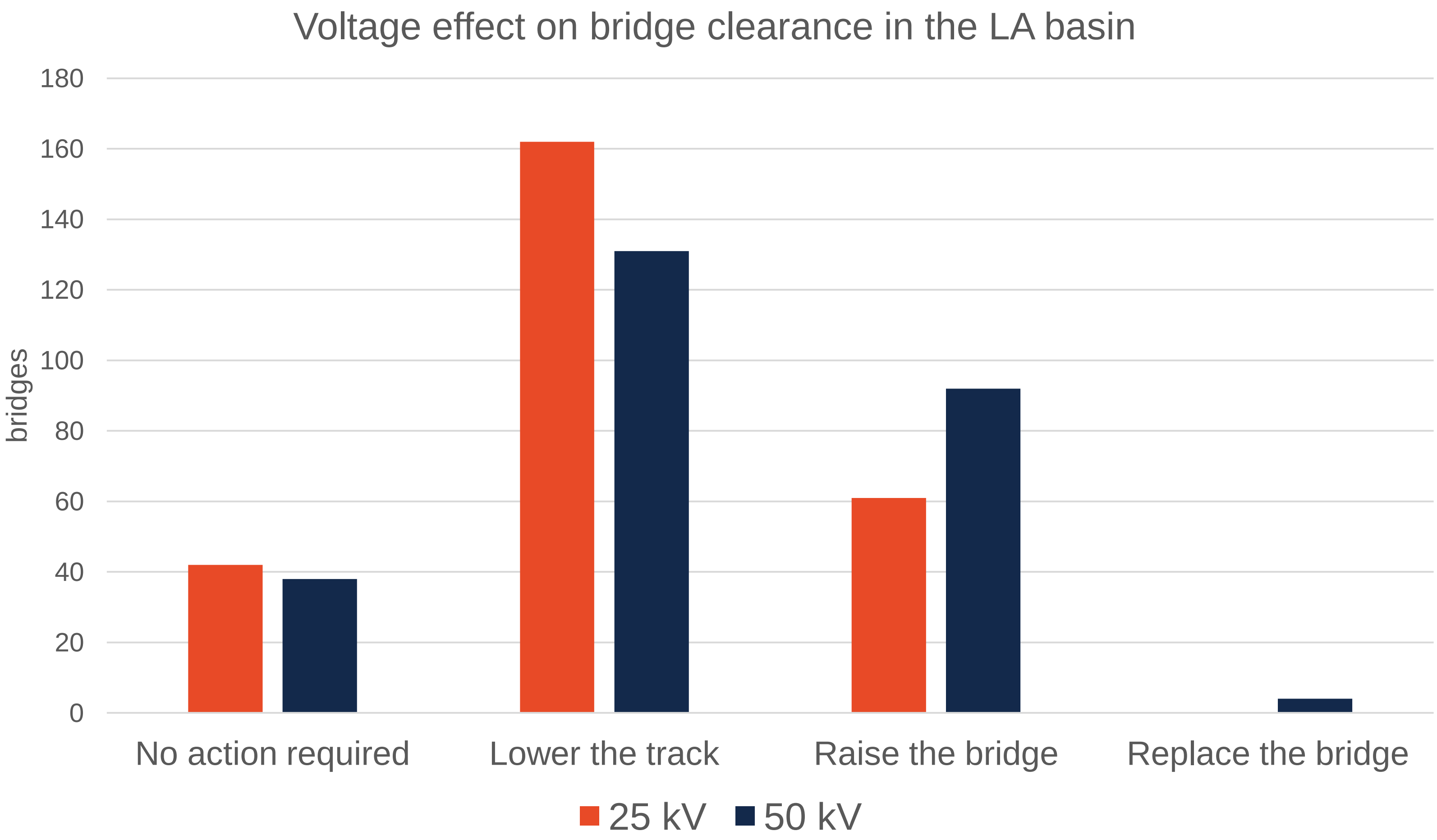
OCS Efficiency Improvements

- Higher voltage
  - Reduces resistive losses
  - High voltage configurations have better tolerance for voltage drop between substations.
  - Can lead to more expensive maintenance due to safety regulations working with 50 kV
- Lower frequency
  - Reduces inductive losses
  - Equipment for adjusting the frequency would also allow regenerative energy back into the grid.
  - ~15 Hz would allow substations to be three to four times further apart.
- Both systems use more expensive substation components, but the reduced number of substations leads to lower capital costs overall.
- Long-term energy savings further improve the economics of these techniques.

OCS Efficiency Improvements

- Autotransformers
  - Can increase substation spacing where changing the voltage or frequency is impractical
- Adjustable voltage
  - Modern locomotives can accept different OCS configurations, allowing OCS to be optimized to the territory.
  - Voltage can be adjusted to reduce clearance constraints, such as through urban areas.
- Common factor is applying improvements in the cost of solid-state electronics
- Reducing the number of substations has a compounding effect by reducing project transmission costs.

Voltage & Clearance

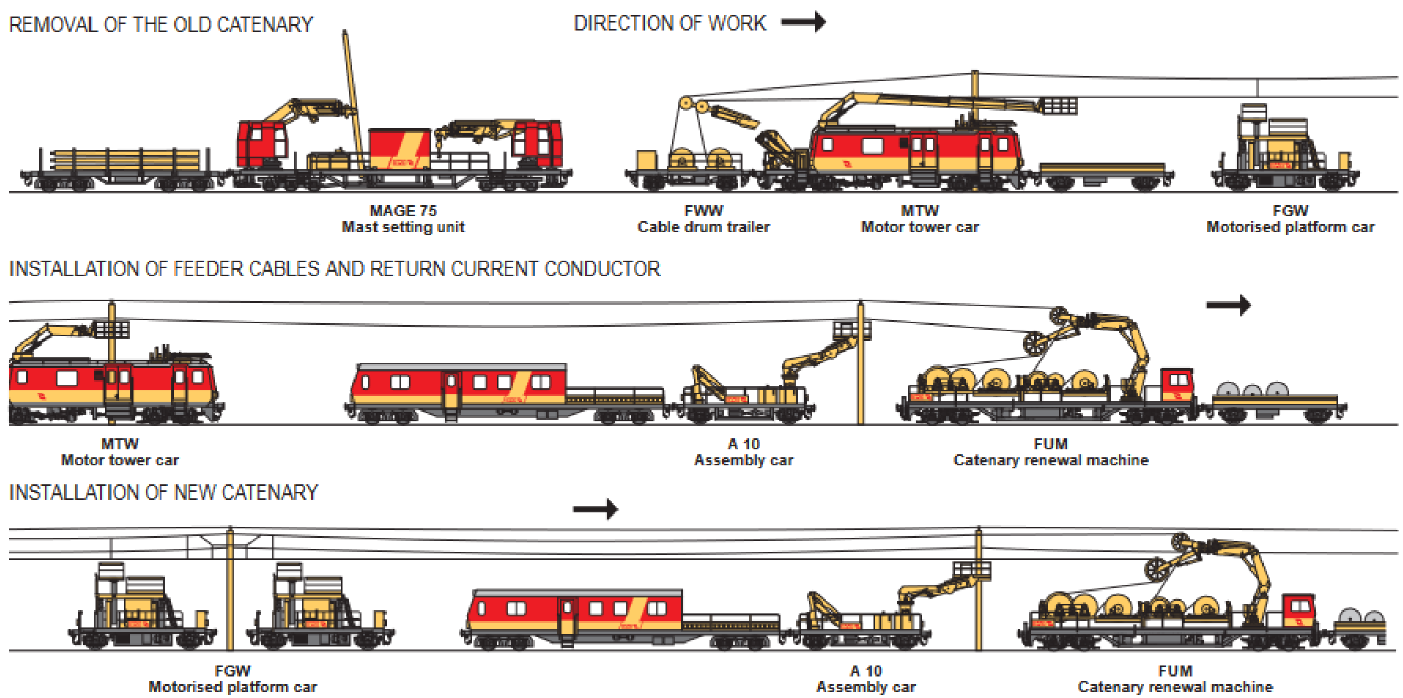


OCS design improvements

- Automated design techniques lead to fewer pylons being overdesigned.
  - Carefully matching the design of the OCS to the loading gage of the freight equipment and pantograph width can lead to longer spans with fewer pylons.
- Optimizations have been made in pylon spacing
  - It is practical today to employ different pylon designs for different curves; historical studies relied on standardized designs.
  - Particularly helpful for junctions and interlockings.
- Alternative materials can lead to savings.
  - The Desert Wester Railway used wooden poles and synthetic insulators to reduce costs to $480,000/mile in current dollars.
- Economies of scale in the North American market will come over time

OCS Construction Improvements

- OCS construction trains can achieve similar savings as track laying machines.
- Improvements in project management can reduce delay costs along busy corridors (which are most likely to be electrified).



Hestra-Verlag, Darmstadt, Germany (c. 2000)

Alternatives to OCS

- Third Rail
  - Voltage limited due to arcing risks
  - Safe voltages lead to impractical substation spacing and excessive energy losses at freight power levels.
  - Freight locomotives operating along third rail territories have required modified snow plows, reducing interoperability.
- Inductive charging systems
  - Lack of contact could lead to long-term maintenance savings.
  - Ameliorates clearance issues of OCS
  - Maximum power transfer demonstrated ~1MW in South Korea, insufficient for freight so far
  - Unclear how metal dust in freight environment will affect performance

NA Freight Technology Readiness Level

Technology	Technology Readiness Level	Explanation
Higher-voltage OCS	9	50 kV electrification has been used in the North American freight context. Examples include the Tumbler Ridge subdivision and the Black Mesa and Lake Powell Railroad.
Lower frequency AC current in OCS	8	16.67 Hz systems have been used extensively in Germany, Sweden, and other European countries. Parts of the Northeast Corridor use 25 Hz for passenger rail.
Adjustable Voltage	7	Passenger trains along the northeast corridor change voltages between 12 kV, 12.5 kV, and 25 kV. Freight rail electrifications have less experience with changing voltages, and there is little experience with switching between 25 kV and 50 kV.
Autotransformers	7	Autotransformers have been used extensively for passenger trains, but there is relatively little experience with them in the freight context.
OCS construction trains	8	OCS construction trains have been in use for a long time. They have not been used in the North American freight context, and some adaptation might be necessary for North American construction standards.
Pylon Optimization	5	Modern pylon optimization techniques have not been applied in any North American freight context. The last mainline electrification project, the Northeast Corridor between New Haven, CT and Boston, MA, was built before current models for pylon design were developed.
Third Rail	3	Third rail is extensively well understood, and there is currently no active research effort to address its known shortcomings for North American mainline freight rail operations.
Inductive Charging	2	KAIST has performed experiments that show promise for higher-power levels in inductive systems. Rail seems promising for maintaining the alignments necessary for optimal inductive charging, but no prototypes capable of the power levels required for North American freight trains have been developed. There has also been insufficient research into how to address the issues

Tech Readiness Chart for Reference

Technology Readiness Level	Definition	Description
1	Basic principles observed and reported	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development. Examples might include paper studies of a technology's basic properties.
2	Technology concept and/or application formulated	Invention begins. Once basic principles are observed, practical applications can be invented. The application is speculative and there is no proof or detailed analysis to support the assumption. Examples are still limited to paper studies.
3	Analytical and experimental critical function and/or characteristic proof of concept	Active research and development are initiated. This includes analytical studies and laboratory studies to physically validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
4	Component and/or breadboard validation in laboratory environment	Basic technological components are integrated to establish that the pieces will work together. This is relatively low fidelity compared to the eventual system. Examples include integration of ad hoc hardware in a laboratory.
5	Component and/or breadboard validation n relevant environment	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so that the technology can be tested in a simulated environment. Examples include high fidelity laboratory integration of components.
6	System/subsystem model or prototype demonstration in a relevant environment	Representative model or prototype system, which is well beyond the breadboard tested for TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in simulated operational environment.
7	System prototype demonstration in an operational environment	Prototype near or at planned operational system. Represents a major step up from TRL 6, requiring the demonstration of an actual system prototype in an operational environment, such as in a rail vehicle or on an actual track system.
8	Actual system completed and qualified through test and demonstration	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation of a component of subsystem in its intended system to determine if it meets design specifications.
9	Actual system proven through successful deployment	Actual application of the technology in its final form and under operational conditions, such as those encountered in operational test and evaluation. In almost all cases, this is the end of the last "Bug fixing" aspects of true system

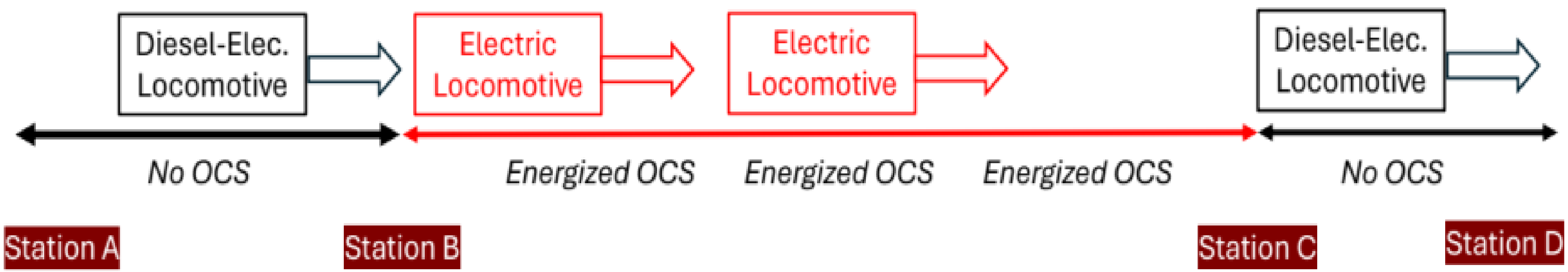
Locomotive Technologies

- Modern AC-motor diesel-electric locomotives reduce many of the performance benefits of electrification in past studies.
- A dual-mode locomotive for freight applications would assist early electrification economics.
  - Reduced upfront capital costs
  - Increase interoperability
- Dual-mode locomotives operate for passenger applications, but they required long design efforts.
- There is a lack of space for dual-mode equipment on modern freight locomotives, necessitating tenders.
  - Alternative technologies like H_2FC or BEL require tenders as well.
- Dual-mode locomotives mitigate the high costs of locomotive changes.

Dual-mode application

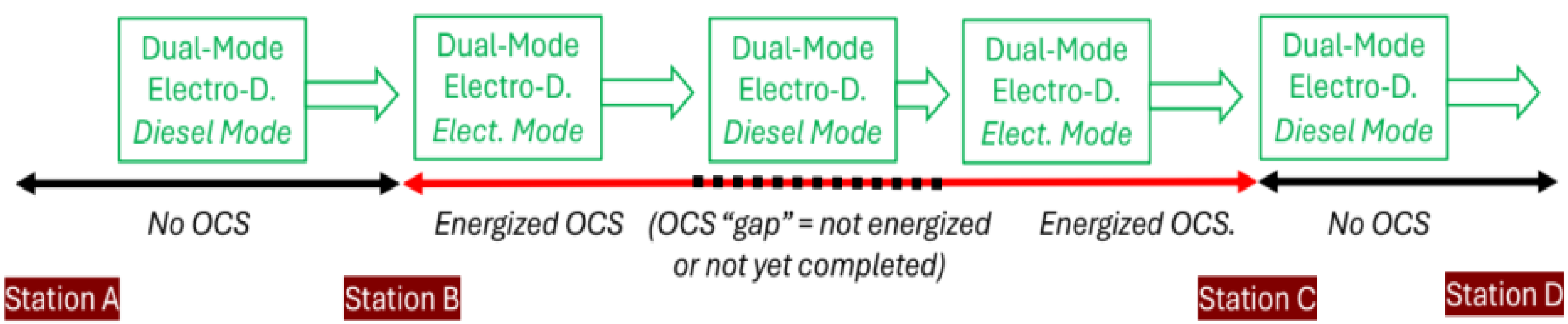
<u>Dieselized & Traditional Electrified Territories (using Diesel-Electric & Electric Locos.)</u>

- *“Power Changes” required at Stations B and C*



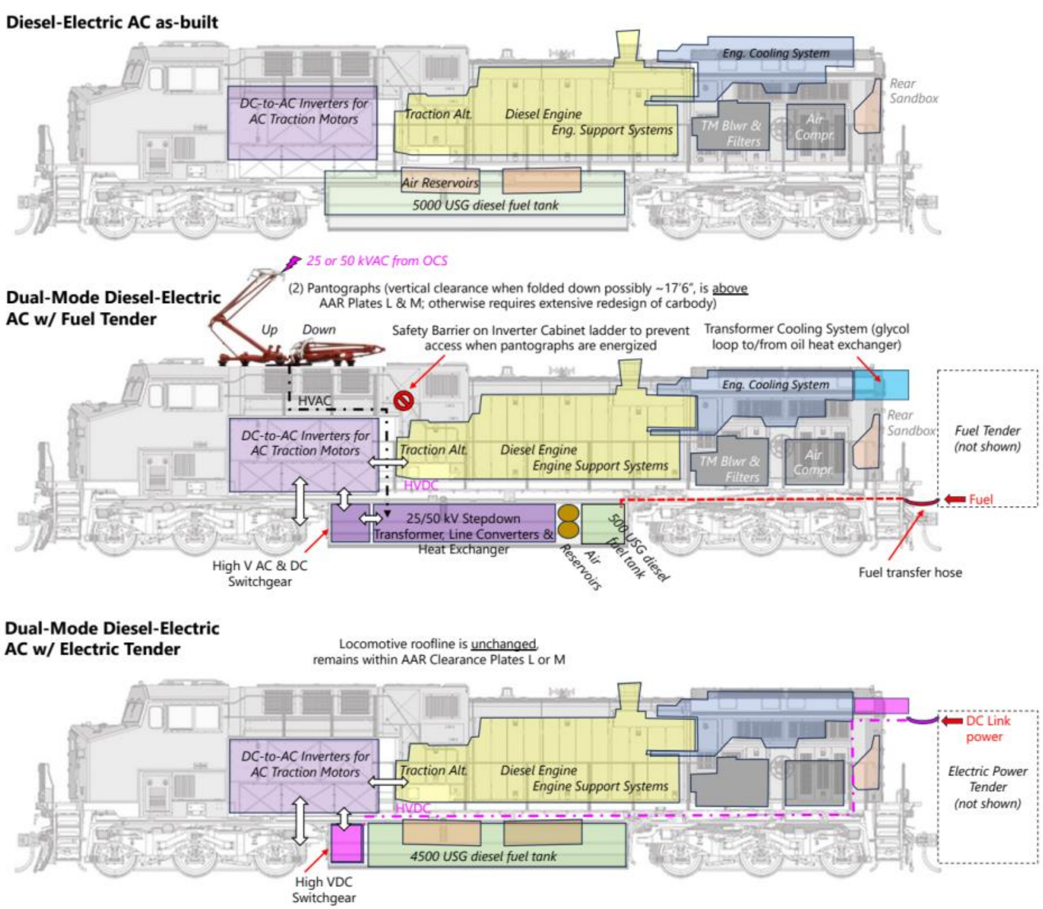
<u>Dieselized & Electrified Territories (using Dual-Mode Electro-Diesel Locos.)</u>

- *No “Power Changes” required at Stations B and C (and un-interrupted operation thru “OCS gap”*



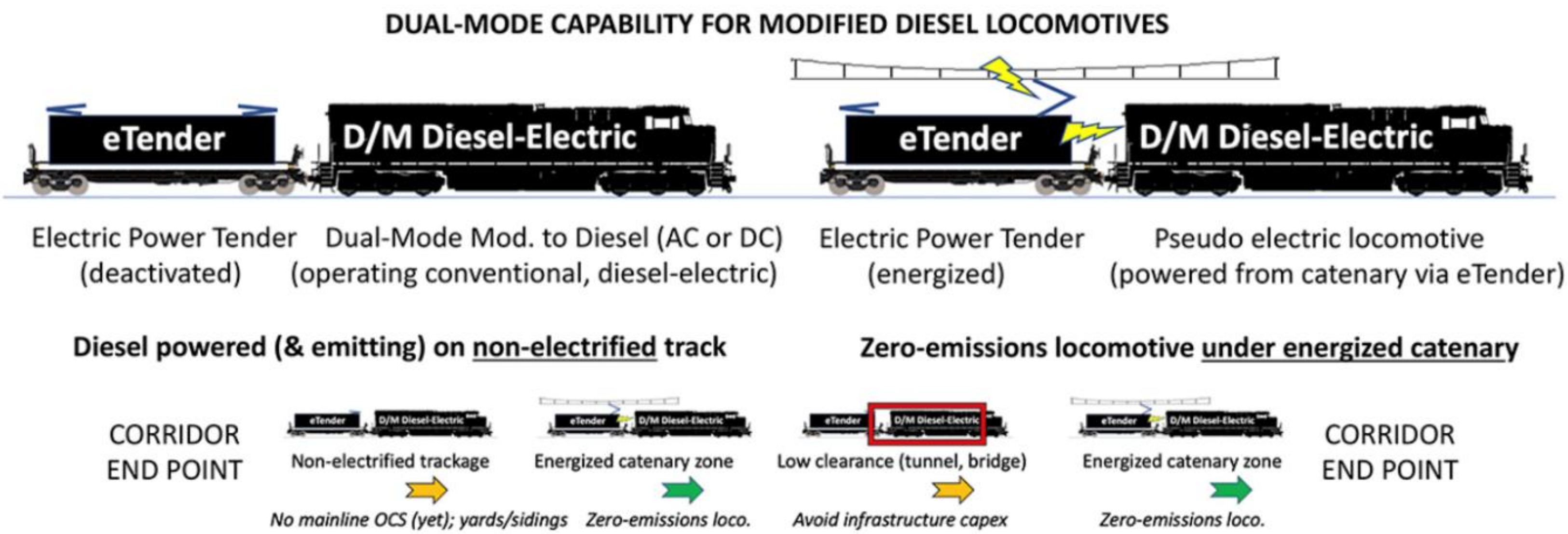
Dual-mode locomotive alternatives

- Easiest way to make space is reducing the size of the fuel tank.
- Putting electric equipment on the locomotive reduces diesel-only range by 90%.
- Putting electric equipment on a tender requires minimal changes to an existing locomotive and allows existing operations.

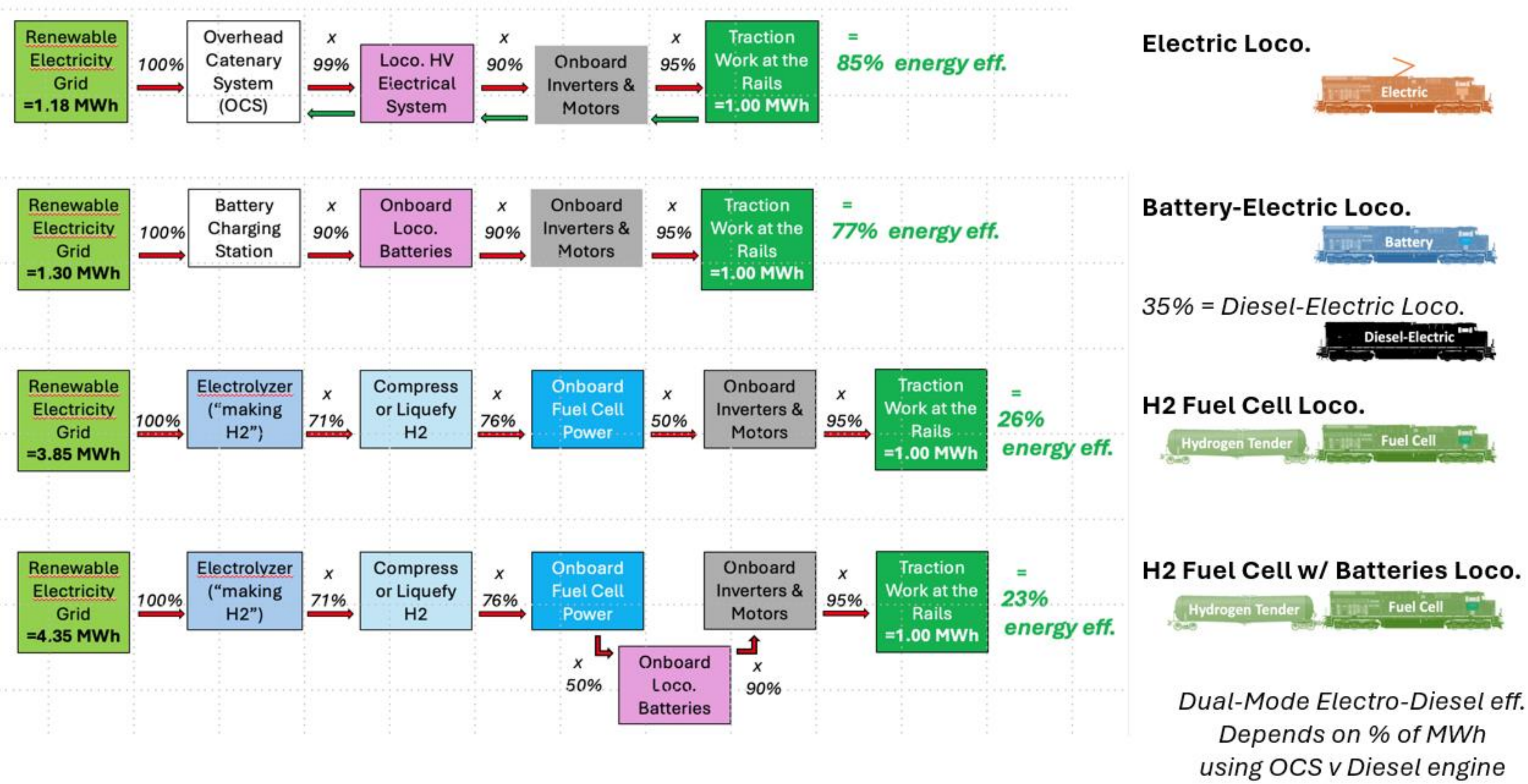


Dual-mode operation with electric tender

- Increased autonomous range and minimal modifications might make the option using an electric power tender, or eTender, preferable.
- The tender would be able to provide electric power when possible, and the locomotive would provide power through OCS gaps.
- The eTender could have some battery capacity.



Comparison of Locomotive Technologies



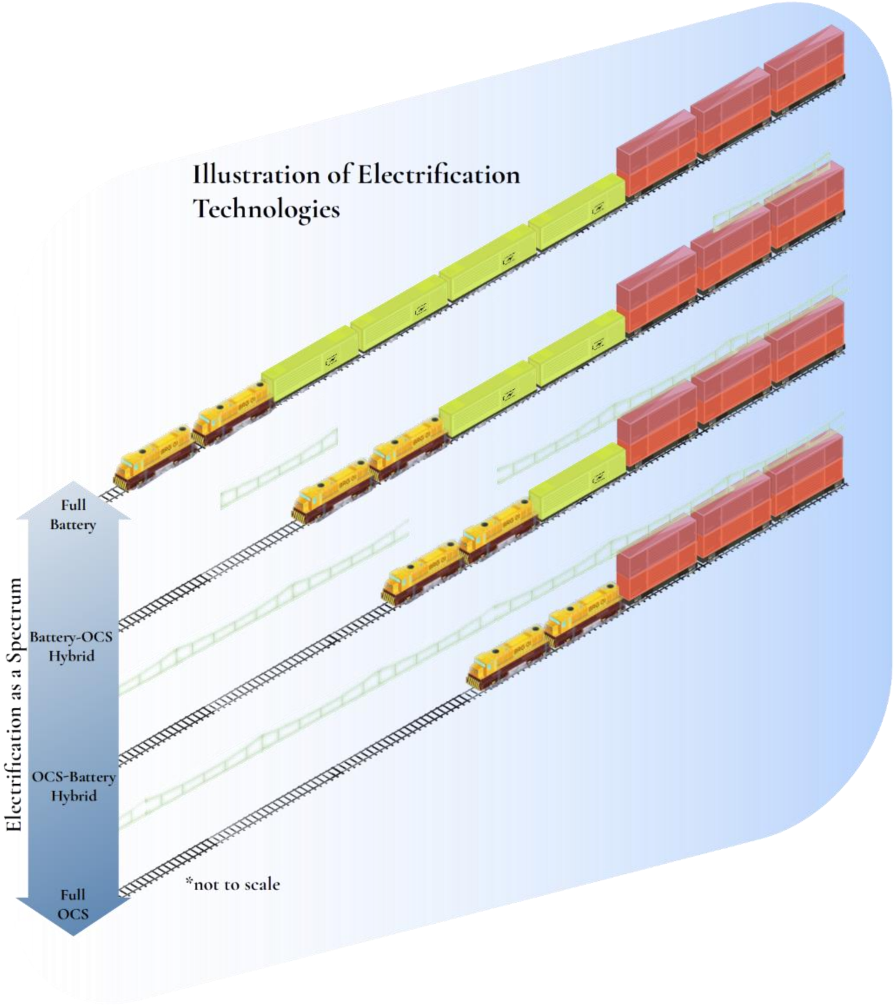
Intermittent Electrification

- Dual-mode locomotives allow for reductions in carbon intensity.
- Transitioning to battery-OCS hybrid systems allows for full decarbonization as the next step.
- Intermittent electrification further spreads capital costs.
- Battery-OCS hybrid systems allow for full decarbonization without costly bridge reconstructions or costly OCS construction along sidings and spur lines.

Electrification as a spectrum

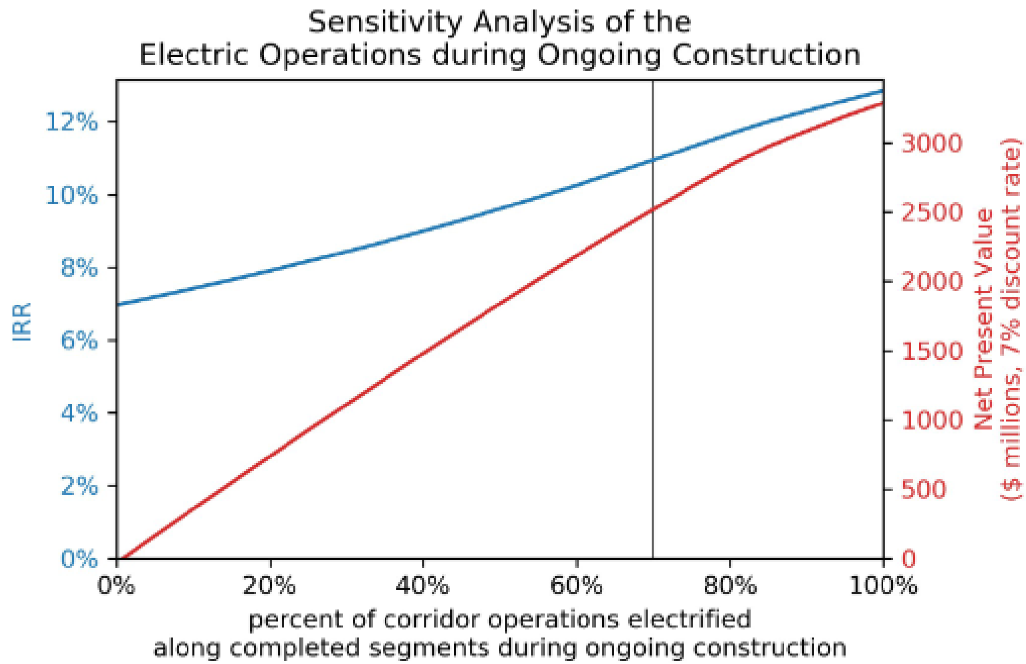
- OCS can recharge batteries en route, reducing the number of batteries required.

- Batteries can be used along the segments that would be most expensive to electrify.



Moving electrification cash flows forward

- Electrification has always suffered from high upfront capital costs.
- Conventional electrification accrues no benefits until construction along the entire line is complete.

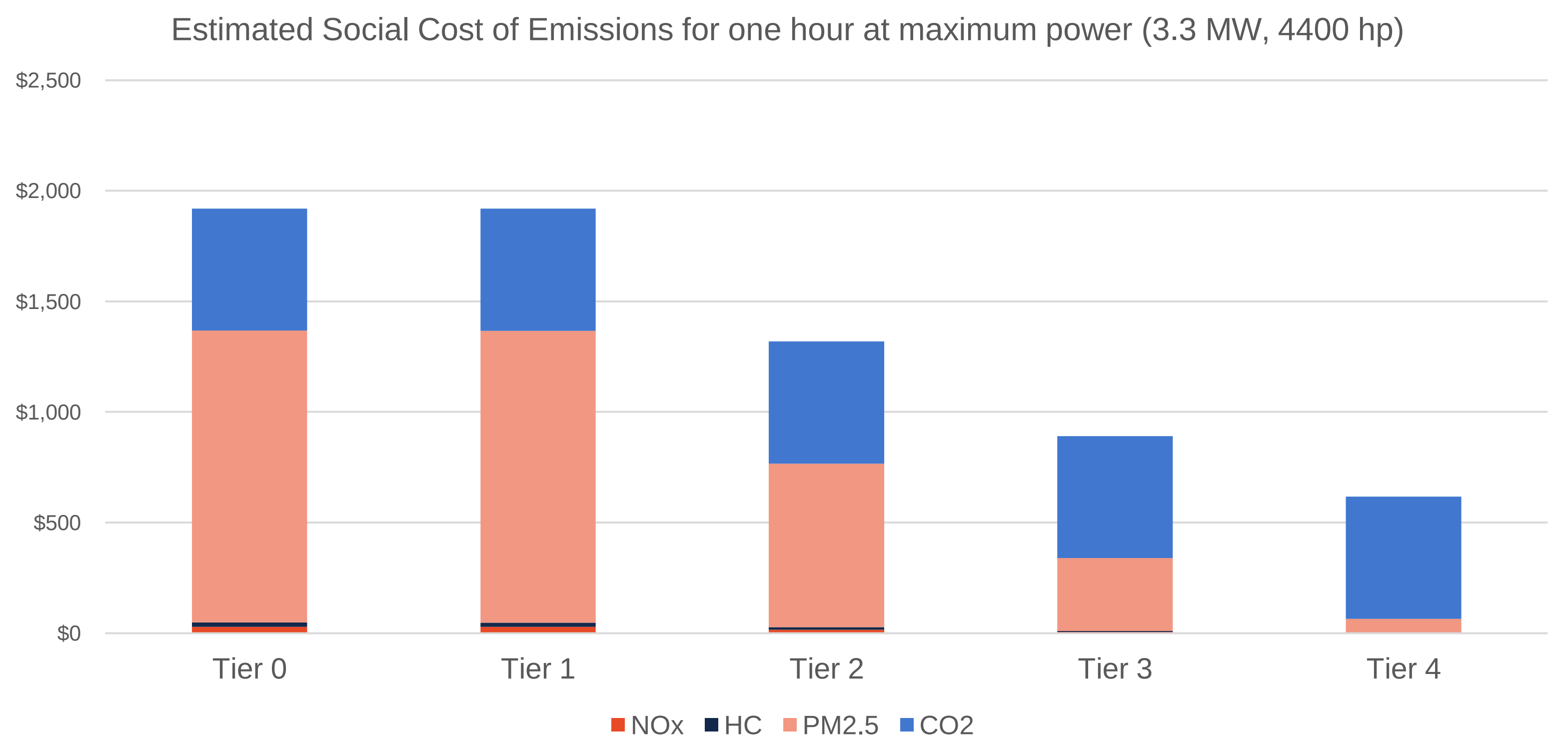


Sample output of sensitivity analysis for the electrification of the full BNSF TransCon (Walthall, 2019)

Implementation Strategies

- Freight railroads have no means to internalize environmental benefits from electrification, reducing the incentives to electrify.
- Power companies require extensive linear rights-of-way for future transmission needs. Working with railroads could create extensive co-benefits.
- Understanding these benefits and improving communications between stakeholders will be necessary.

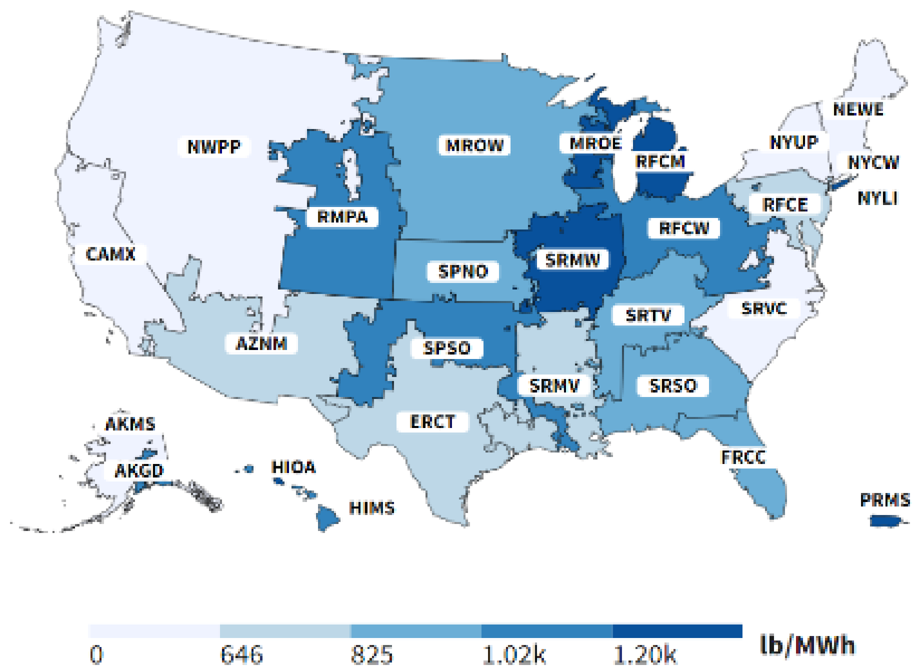
Social costs of diesel-electrics

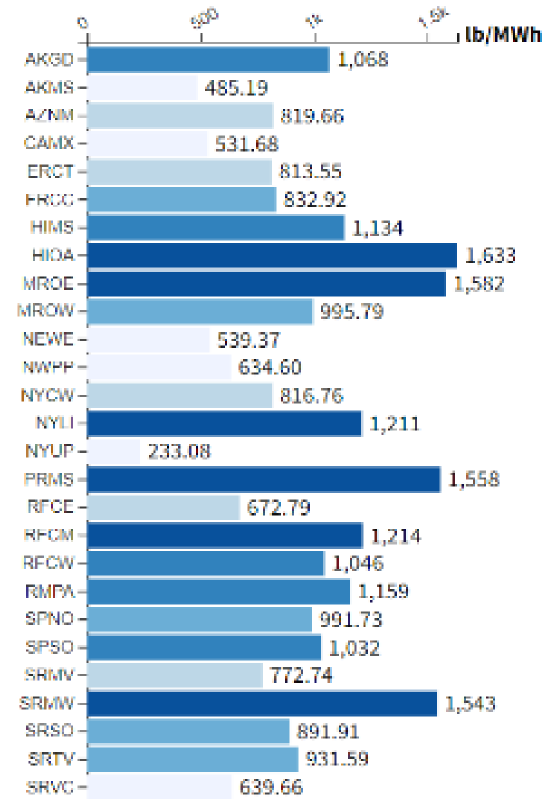


- Social costs vary substantially based on what locomotive movements are being electrified.
- Cost shifts from mainly health pollutants (primarily PM) to climate pollutants (CO_2)

Social costs of electricity

CO_2 emissions intensity across the grid (FRA's LECT)





- Electricity social costs vary based on grid composition.
- Unlike diesel, social costs of electricity can vary by time of day and by location.
- This can potentially make a prospective incentive program more complex.

Right-of-way sharing

- Benefits for railroads building OCS
  - Reduced transmission costs
  - New source of income creates cash flows during the early years of an electrification project
  - Right-of-way easement deal can be structured to reduce uncertainty in future electricity prices.
- Benefits for electric utility companies
  - Acquiring right-of-way from one entity rather than hundreds of separate property owners reduces complexity and uncertainty.
  - Railroad rights-of-way have already undergone some environmental review.
  - Assisting railroads with electrifying provides utility companies with new industrial customers.
- Potential downsides
  - Transmission line construction costs may increase due to rail traffic.
  - Derailments risk damaging transmission lines.

Right-of-way sharing negotiations

- Right-of-way is complicated to value
- Railroads and utilities have long had to work together on latitudinal easements.
- There are some examples of existing longitudinal right-of-way sharing.
- There is need for a template so both parties have a starting place for negotiations and a general understanding of each others needs.

Electrification is in a better position today

- Economic barriers identified in Past Studies in Task I:
  - Costs are too high
  - Benefits are too small
  - Scope of benefits is too narrow
  - Benefits are not accrued early enough during the project
  - Uncertainty and risk too high

- Technologies and strategies identified and explored in Task II have ways to address each of those barriers.

Q&A Slides

Task III Materials

Tasks & Work Packages

- Task I – Review past/current railway electrification studies
  - Catalog key technologies and their limitations
  - Identify the primary factors influencing costs, benefits, and risks
- Task II – Review alternative technologies and strategic implementation approaches
  - Identify innovative solutions that would improve the cost-benefit-risk assessment of electrification
- **Task III – Develop and demonstrate an updated risk-based electrification benefit-cost framework via case study**
  - **Accommodate different policy frameworks, such as Carbon taxes or Carbon reduction commitments**
  - **Consider variability & uncertainty**
  - **Analyze two representative types of rail corridors**

The CURRENT Model

- Utilizing the knowledge gained throughout the project, the research team developed the Costs, Uncertainties, and Risks of Rail Electrification with New Technologies, or CURRENT Model.
- CURRENT provides a framework to analyze many different electrification strategies along any given railway corridor.
  - Train Performance Function in Python uses a mass strap model to estimate energy consumption for different types of electrification.
  - Cost-benefit analysis model in Microsoft Excel incorporates fifteen categories of costs and benefits to provide rates of return from private and public perspectives.
  - Argo plugin provides risk assessment via Monte Carlo simulations of the cost-benefit analysis.
- CURRENT uses entirely free software. Cost-benefit analysis can utilize independent energy estimates.

Structure of Benefit-Cost Tool

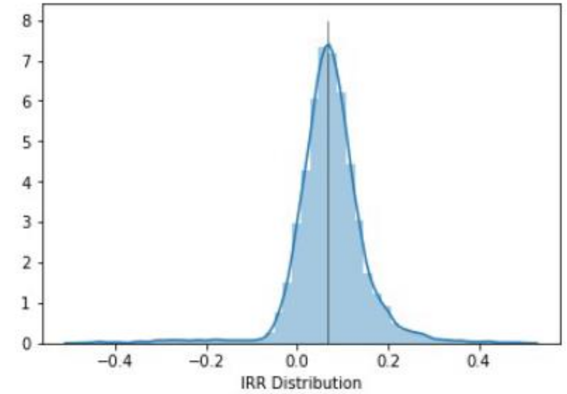
- Results (Overview)
- Capital Costs
- Maintenance Costs
- Energy Costs
- Emissions
- ROW Sharing
- Parameters
- Route Data Input
- Traffic Data Input
- Calculations

Detailed Output

User Input

Monte Carlo Risk/Uncertainty Analysis

- Implemented in Excel using ARGO
  - Free Monte Carlo simulation plug-in
  - Developed by Booz Allen Hamilton
  - Repeats economics calculations 1,000+ times using input distributions to create distribution of output metrics
  - User can select between normal, triangular and uniform input distributions for each parameter



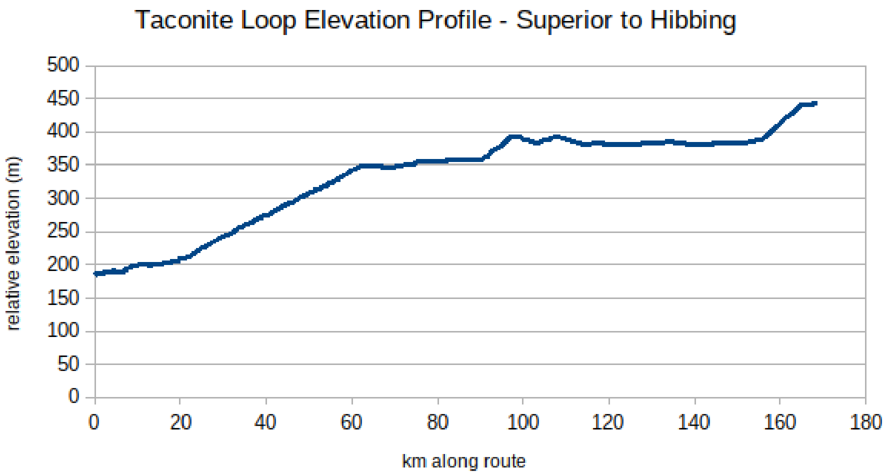
- Partial example of simulation input:

Variable		Unit	Default Value	Distribution	Normal Distributions: Confidence Level	Mean	Standard Deviation	normal distribution
Catenary		$1000/km						
	Single Track	$1000/km	403	Normal	95%	403	125	474
	Double Track	$1000/km	737	Normal	95%	737	228	722
	Along Bridge Deck	$/m	1 474	Normal	95%	1 474	188	1 800
Substations		ea ($1000)	7 094	Normal	95%	7 094	2 758	6 100
Substation Spacing		km/substation	50	Normal	95%	50	5	52
Transmission		$1000/km	49	Normal	95%	49	19	69
Public Works*		Lump						
	Track Lowering	ea	50 000	Normal	95%	62 500	19 133	13 593
	Bridge Raising	ea	3 000 000	Normal	95%	3 250 000	892 874	2 557 836
	Tunnel Reconstruction	linear m	300 000	Normal	95%	250 000	51 021	264 568
	Bridge Reconstruction	linear m	100 000	Normal	95%	125 000	38 266	73 124
Signaling and Communications		$1000/km	947	Normal	95%	947	424	1 047
OCS Construction per year		km	250	Normal	95%	250	26	246
Days of Mobilization for a new segment		days	7	Normal	95%	9	3	10
OCS maintenance		$ per km	7 652	Normal	95%	7 652	1 301	7 734
Substation maintenance		ea	73 662	Normal	95%	73 662	12 528	70 973

Illustrative Case Study #1

- Minnesota taconite mine-to-port line
  - ~105 miles from Superior, WI (Allouez) to Hibbing, MN on BNSF
  - Short route with grades favorable for battery operations

- Traffic Parameters
  - 5 round trip trains per day
  - Loads downhill, empties uphill
  - 180 cars per train, 97 tons each
  - 3 locomotives per train
  - Total fleet size of 15 locomotives



- Electrification Scenarios
  - Full OCS and electric locomotives
  - OCS with short gaps and electric locomotives with last-mile battery
  - Minimal OCS charging sections and battery locomotives
  - No OCS; battery locomotives plus tenders

Taconite Route: Full OCS

- Full OCS with electric locomotives

- Infrastructure
  - 169 km OCS
  - 5 substations
  - 6 bridges raised
  - 5 track sections lowered
  - 1.2 km OCS on bridges

- Motive Power
  - 15 electric locomotives converted from AC traction diesel-electrics

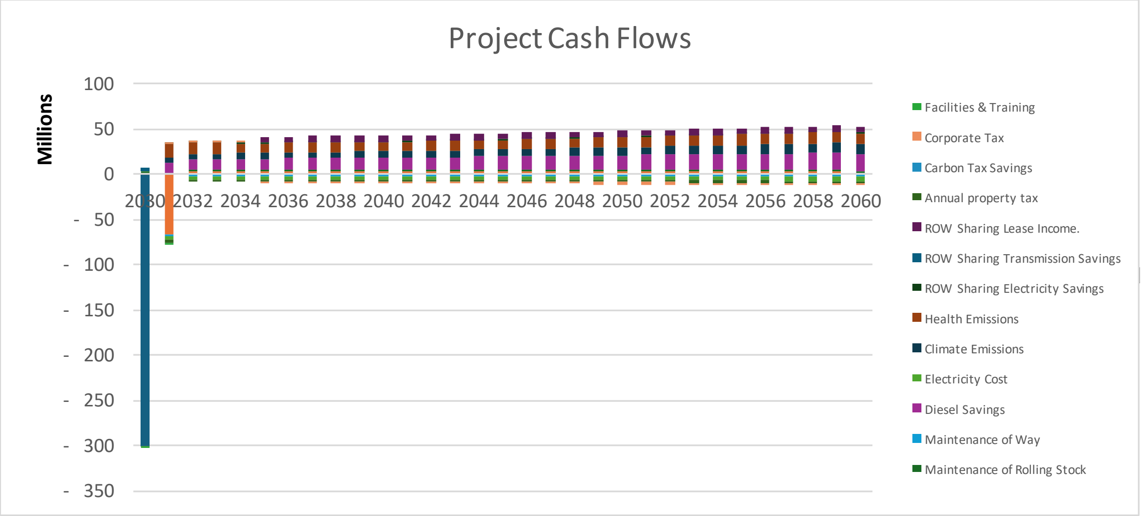
- Utility ROW sharing along entire route
- 20-year study period

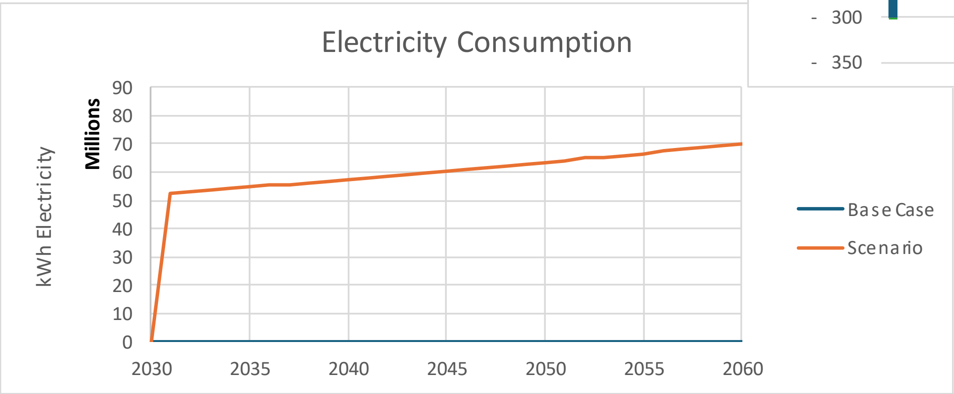
Taconite Route: Full OCS

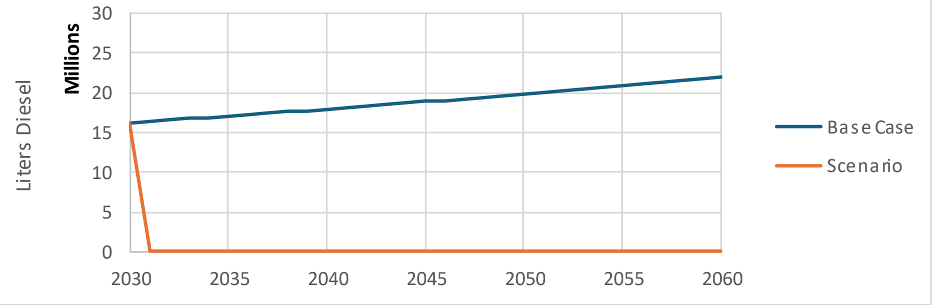
Discount Rate	15%		100%	Climate Emissions Value
Start Year	2030		100%	Health Emissions Value
End Year	2050	(2079 max)		

Private	Purely Private RR Investment			With ROW Sharing			Public Incentive + ROW Sharing		
	3%	7%	15%	3%	7%	15%	3%	7%	15%
Net Present Value ($ millions)	-230	-268	-304	-143	-210	-274	124	-20.7	-162
Internal Rate of Return		-5.7%			-1.6%			6.3%	
B/C Ratio	0.4	0.3	0.2	0.6	0.4	0.2	1.3	0.9	0.6

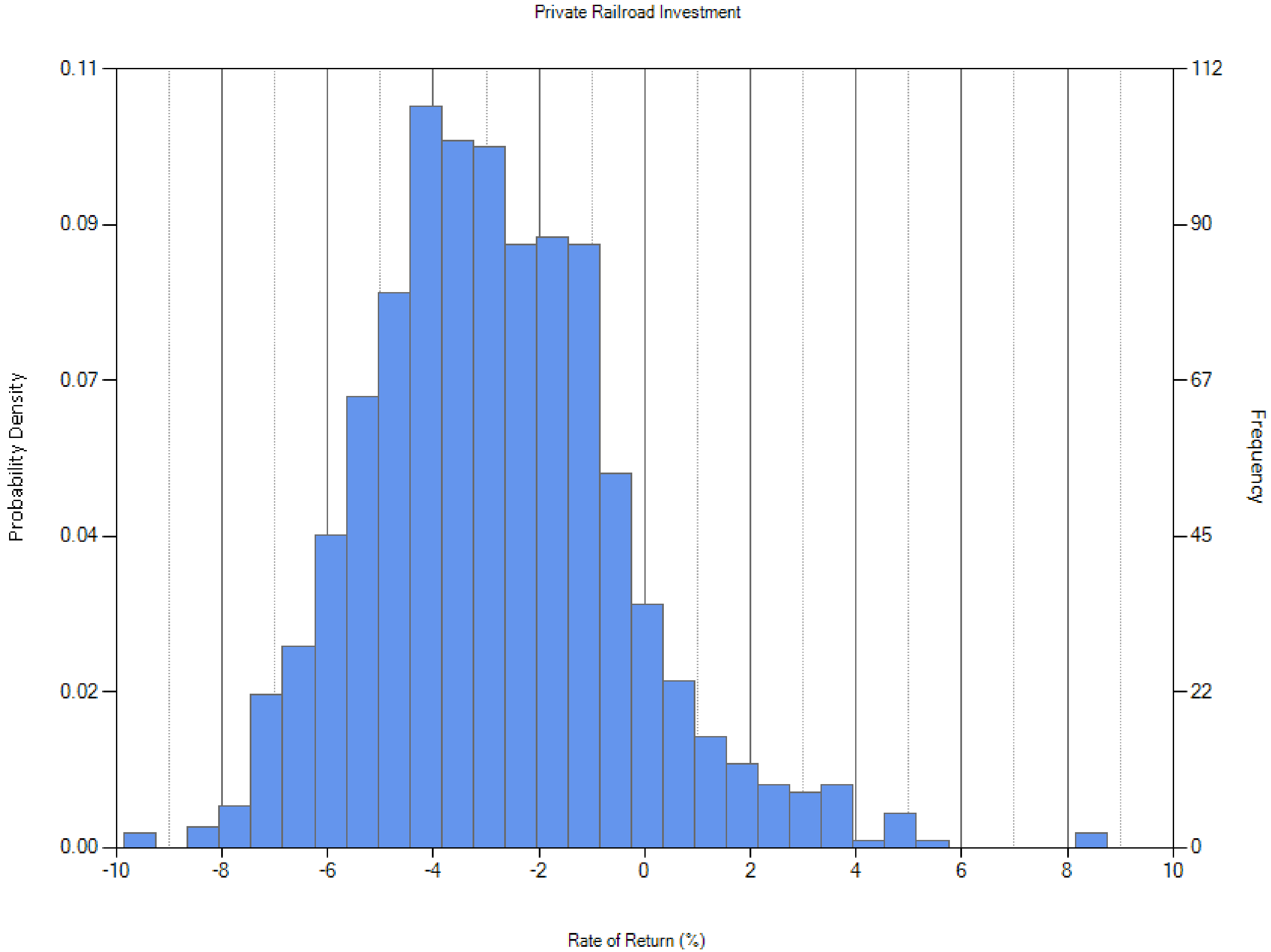
Public	With Environmental Benefits		
	3%	7%	15%
Net Present Value ($ millions)	86.7	-45.1	-174
Internal Rate of Return		5.4%	
B/C Ratio	1.3	0.9	0.5



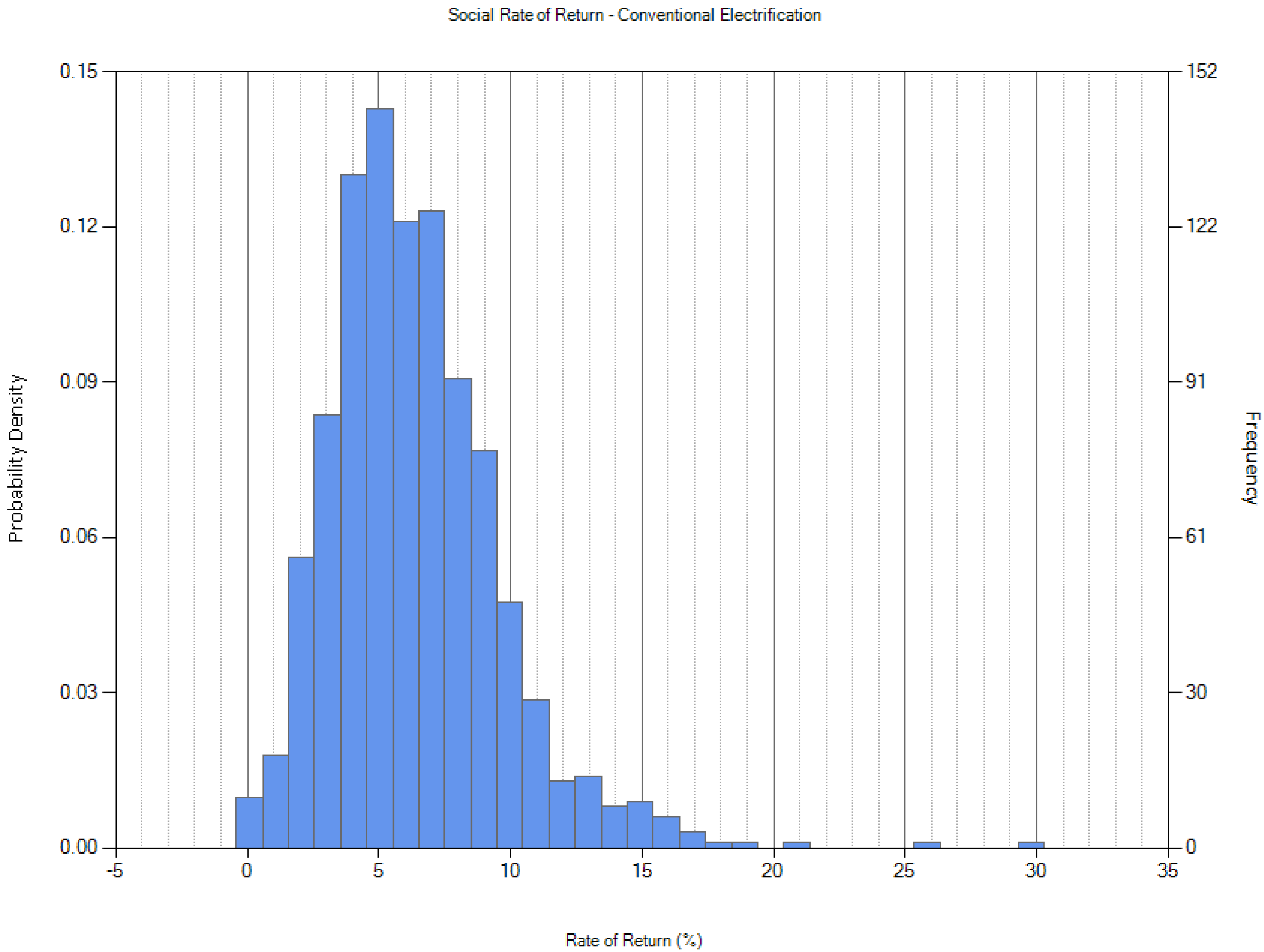




Taconite Route: Full OCS

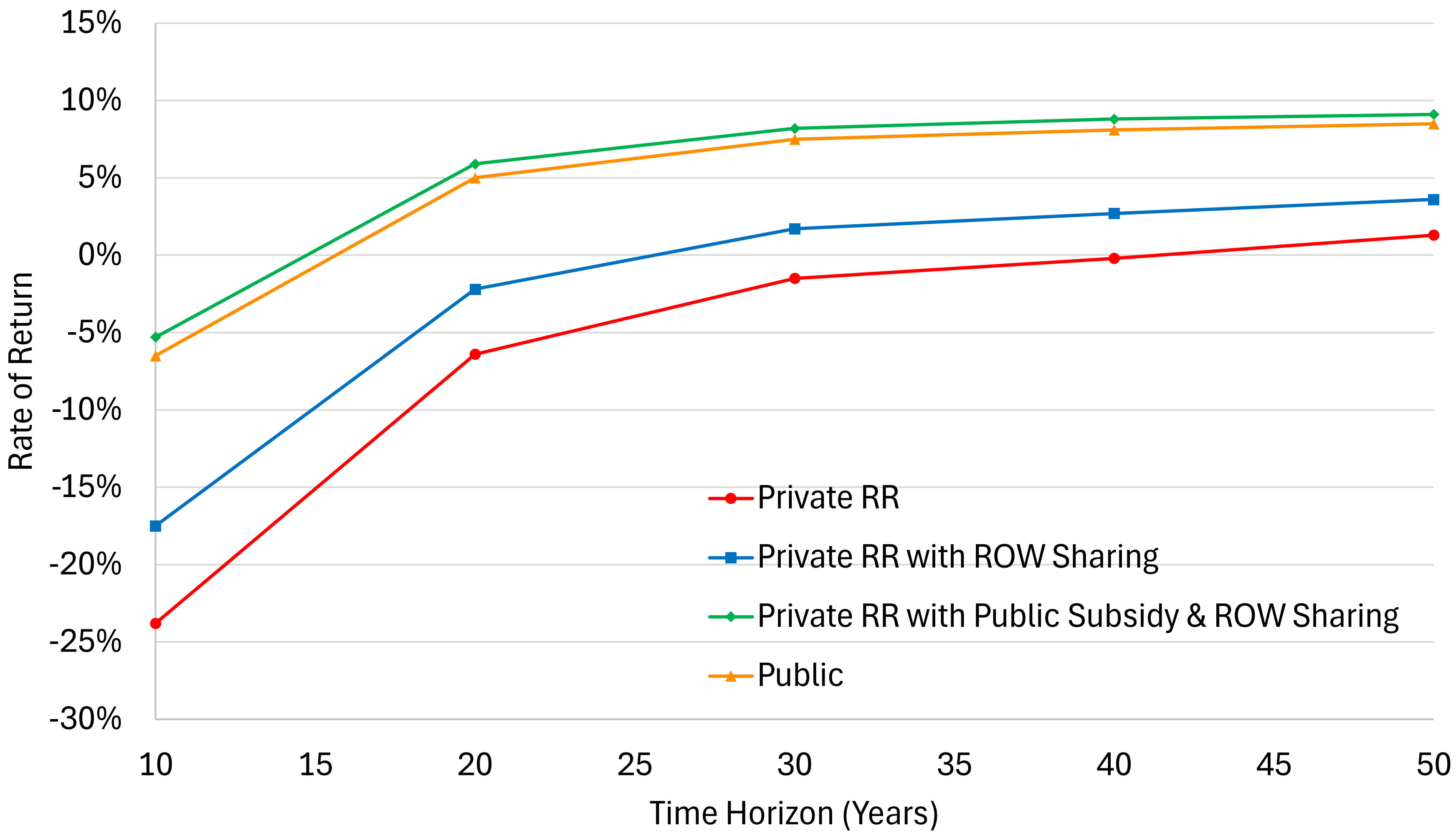


Taconite Route: Full OCS



Taconite Route: Full OCS

- Impact of different analysis periods (time horizon length)



Taconite Route: OCS with Short Gaps

- OCS with short gaps and electric locomotives with last-mile battery

- Infrastructure
  - **102** km OCS
  - 5 substations
  - **0** bridges raised
  - **0** track sections lowered
  - **0** km OCS on bridges

- Motive Power
  - 15 electric locomotives converted from AC traction diesel-electrics
    - **With last-mile battery**

- Utility ROW sharing along entire route
- 20-year study period

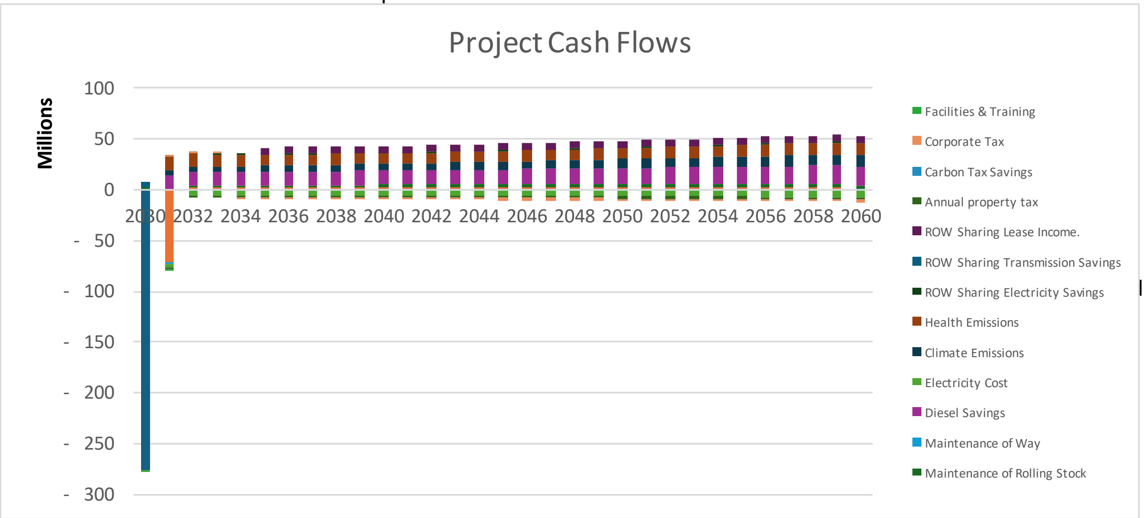
Taconite Route: OCS with Short Gaps

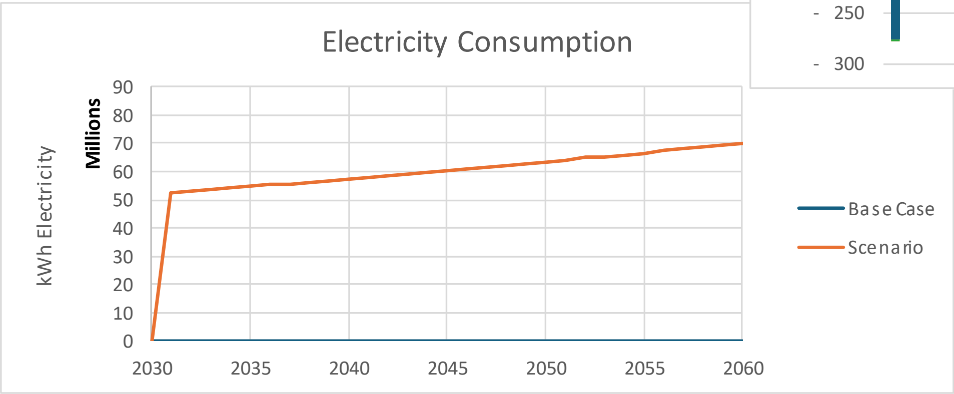
Discount Rate	15%	
Start Year	2030	
End Year	2050	(2079 max)

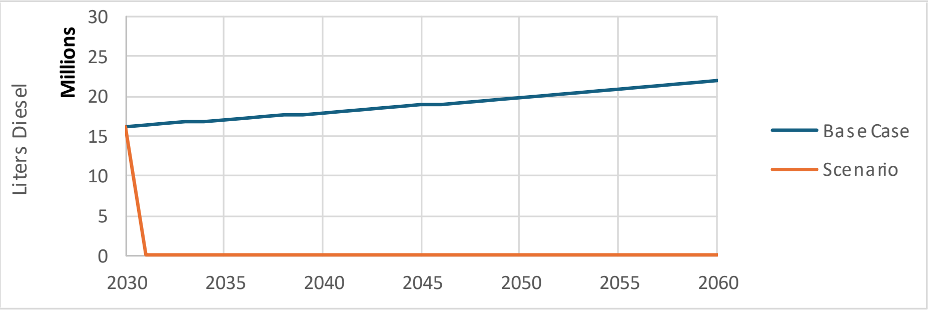
100%	Climate Emissions Value
100%	Health Emissions Value

Private	Purely Private RR Investment			With ROW Sharing			Public Incentive + ROW Sharing		
	3%	7%	15%	3%	7%	15%	3%	7%	15%
Net Present Value ($ millions)	-208	-247	-283	-122	-189	-253	146	0.847	-141
Internal Rate of Return		-5.2%			-1.1%			7.0%	
B/C Ratio	0.4	0.3	0.2	0.7	0.5	0.3	1.4	1.0	0.6

Public	With Environmental Benefits		
	3%	7%	15%
Net Present Value ($ millions)	108	-23.8	-153
Internal Rate of Return		6.1%	
B/C Ratio	1.3	0.9	0.5







Taconite Route: Minimal OCS and BEL

- Minimal OCS charging sections and battery locomotives

- Infrastructure
  - **11** km OCS (multiple sections along route)
  - 5 substations (conservative)
  - **1 battery charging facility – 11 chargers, rated at 1 MW each**

- Motive Power
  - **15 BELs (8 MWh)** converted from AC diesel-electrics
    - **With en route charging capability**
  - **5 battery tenders (10 MWh)**

- Utility ROW sharing along entire route
- 20-year study period

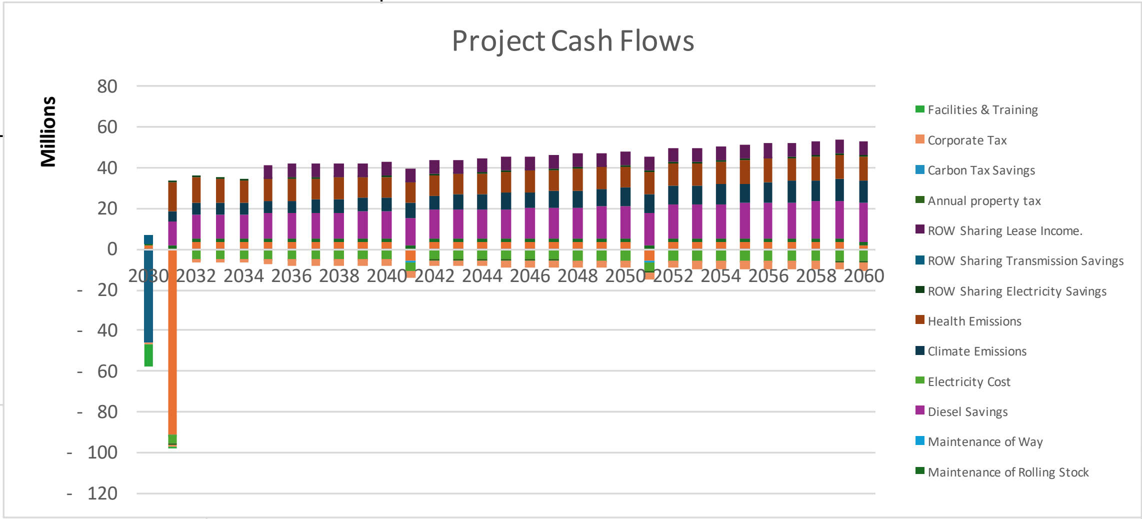
Taconite Route: Minimal OCS and BEL

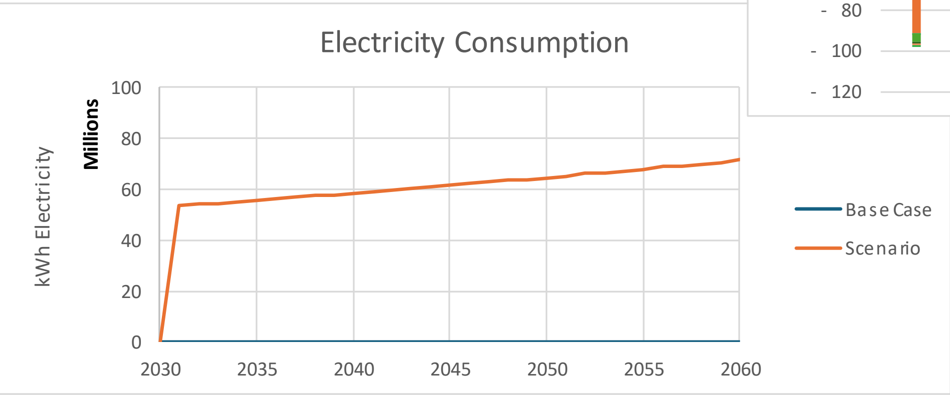
Discount Rate	15%	
Start Year	2030	
End Year	2050	(2079 max)

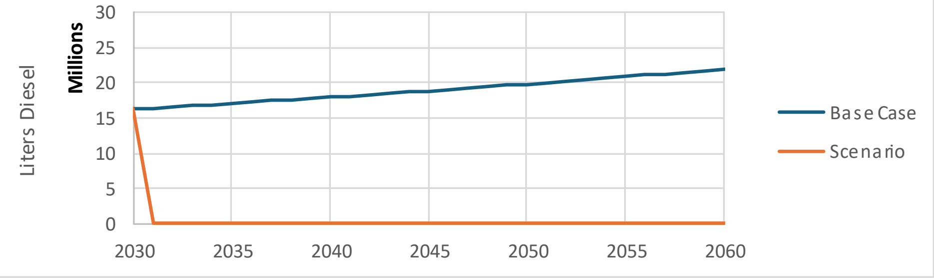
100%	Climate Emissions Value
100%	Health Emissions Value

Private	Purely Private RR Investment			With ROW Sharing			Public Incentive + ROW Sharing		
	3%	7%	15%	3%	7%	15%	3%	7%	15%
Net Present Value ($ millions)	5.89	-35.2	-73.5	92.6	22.7	-43.3	356	210	67.2
Internal Rate of Return		3.5%			9.0%			24.3%	
B/C Ratio	1.1	0.7	0.4	1.8	1.2	0.6	4.2	2.8	1.6

Public	With Environmental Benefits		
	3%	7%	15%
Net Present Value ($ millions)	314	182	53.1
Internal Rate of Return		22.5%	
B/C Ratio	3.8	2.5	1.4







Taconite Route: BEL with No OCS

- No OCS; only battery locomotives plus tenders

- Infrastructure
  - **0** km OCS
  - **1 battery charging facility – 11 chargers, rated at 1 MW each**
  - **1 battery charging facility – 33 chargers, rated at 1 MW each**

- Motive Power
  - 15 BELs (8 MWh) converted from AC diesel-electrics
  - **20 battery tenders (10 MWh)**

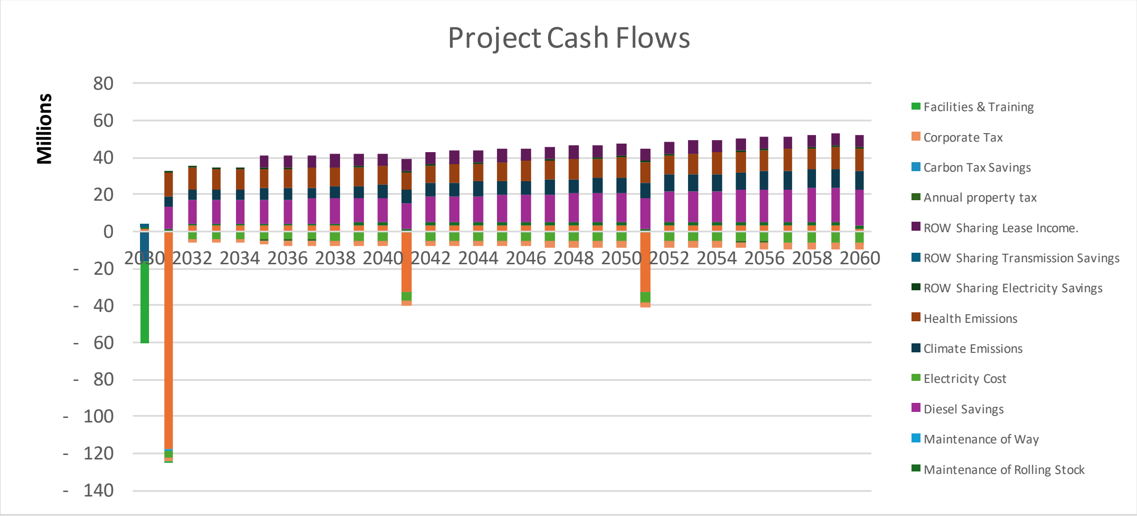
- Utility ROW sharing along entire route
- 20-year study period

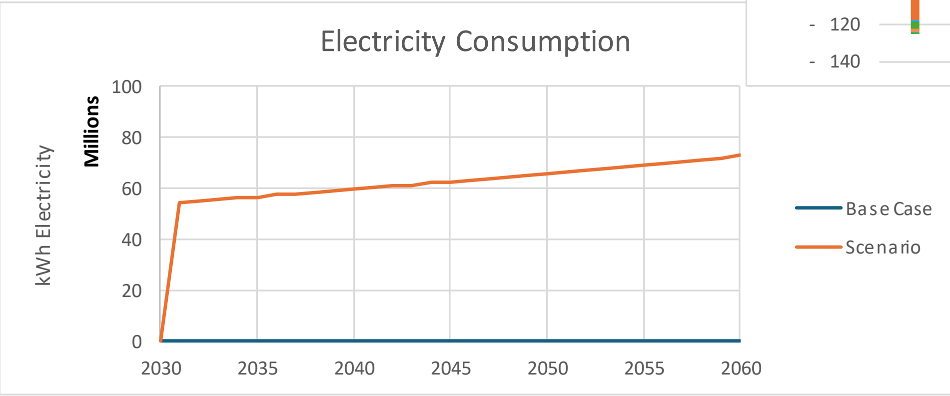
Taconite Route: BEL with No OCS

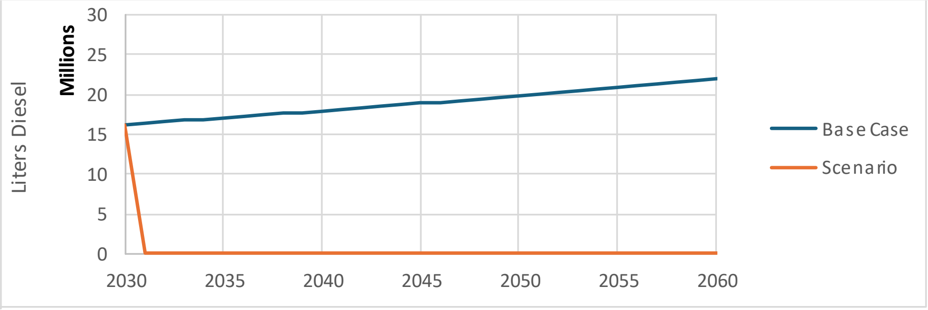
Discount Rate	15%		100%	Climate Emissions Value
Start Year	2030		100%	Health Emissions Value
End Year	2050	(2079 max)		

Private	Purely Private RR Investment			With ROW Sharing			Public Incentive + ROW Sharing		
	3%	7%	15%	3%	7%	15%	3%	7%	15%
Net Present Value ($ millions)	-39.3	-73.8	-104	44.9	-18.5	-76.8	305	166	32.3
Internal Rate of Return		0.3%			5.6%			18.8%	
B/C Ratio	0.8	0.5	0.3	1.3	0.9	0.5	2.9	2.1	1.2

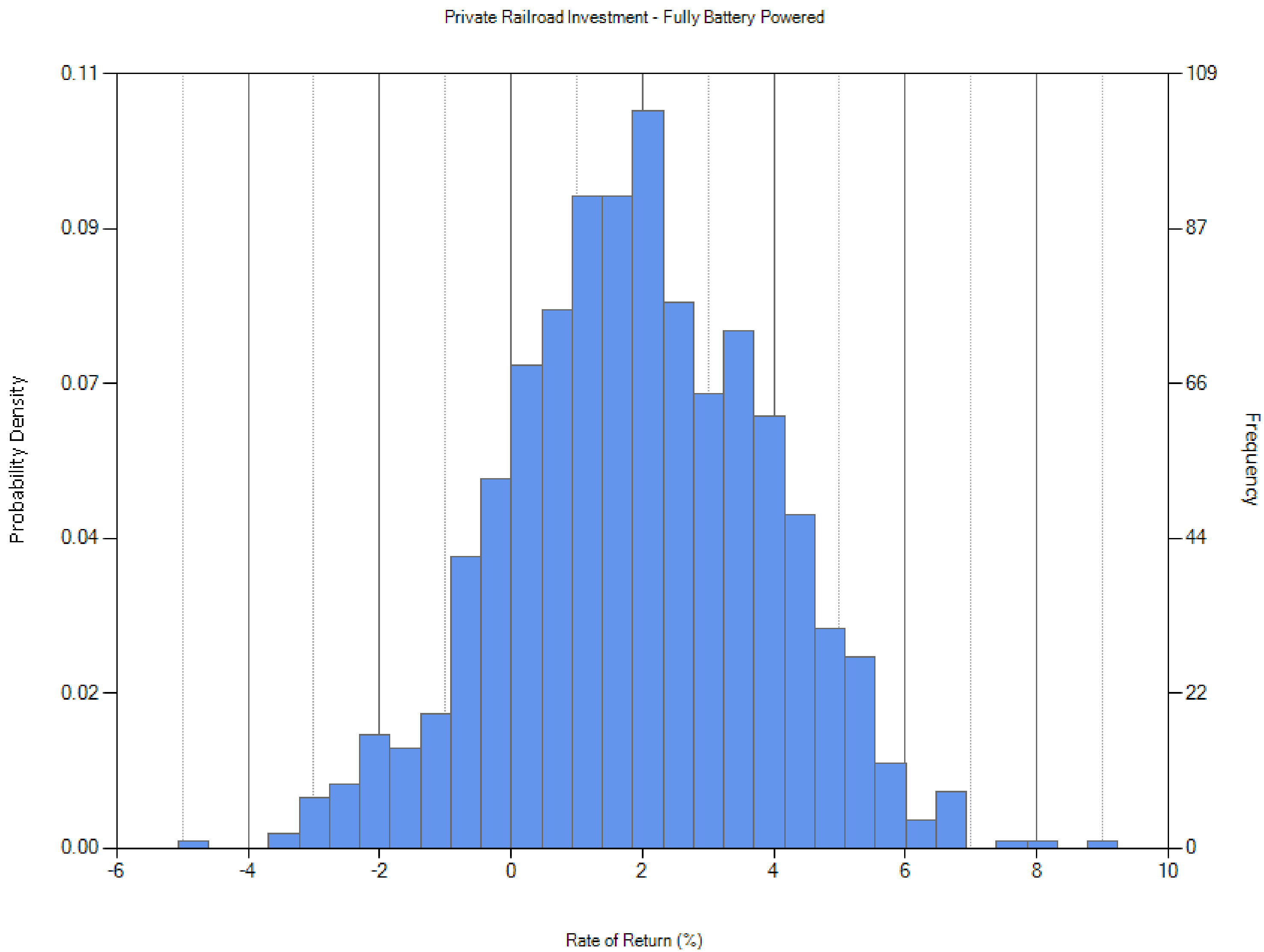
Public	With Environmental Benefits		
	3%	7%	15%
Net Present Value ($ millions)	261	138	19.3
Internal Rate of Return		17.4%	
B/C Ratio	2.7	1.9	1.1



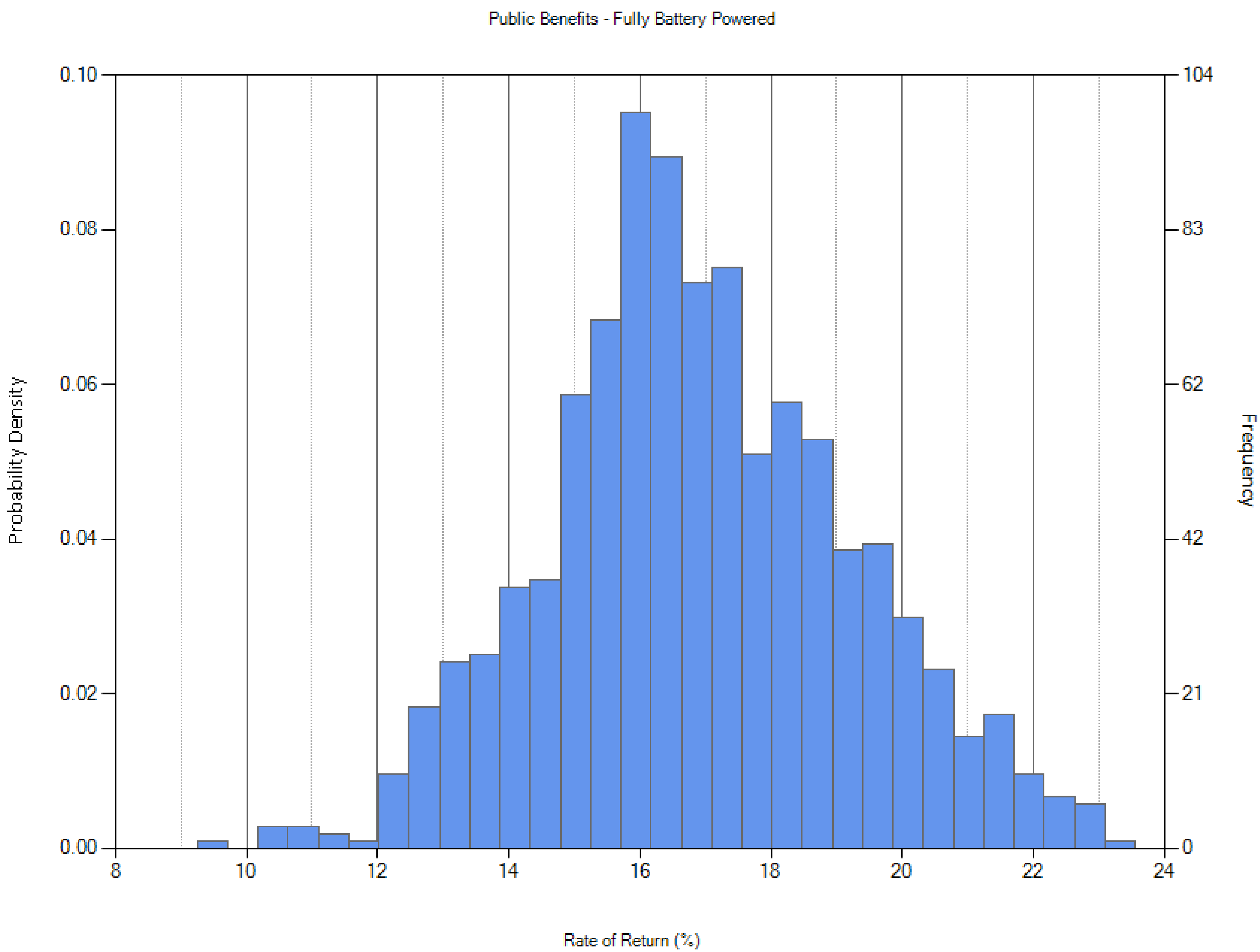




Taconite Route: BEL with No OCS



Taconite Route: BEL with No OCS

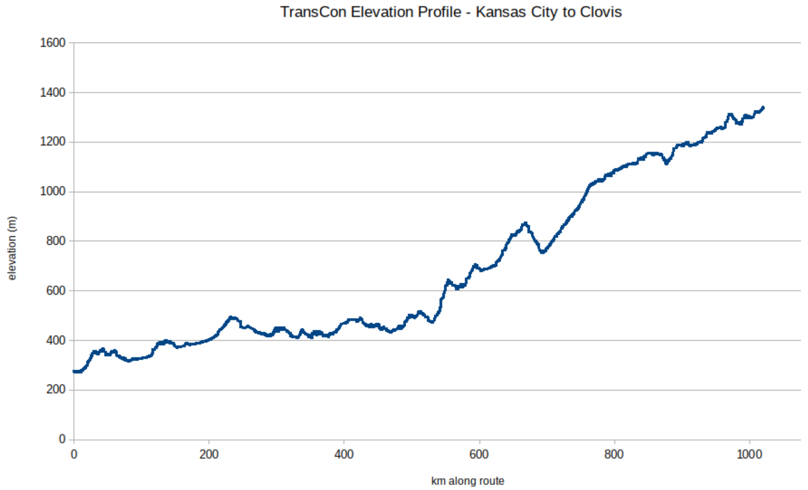


Taconite Route: Summary

- Minimal OCS and BEL offers the best rate of return and B/C ratios across all implementation scenarios
- Short route with low traffic does not favor full OCS
  - OCS with gaps at structures offers slight improvement
- Full BEL with no OCS carriers burden of:
  - Terminal charging infrastructure
  - Larger battery tender fleet
  - Multiple battery replacement cycles
- Current levels of cost uncertainty for many modern electrification options create substantial risk of low return
- Decarbonization through electrification likely to require full value capture of climate and health benefits

Mainline Corridor Case Study

- Double-track mainline corridor with dense traffic
  - ~1020 km (635 miles) from Kansas City, KS (Argentine) to Clovis, NM on BNSF
  - Long route requires multiple years of OCS implementation
  -



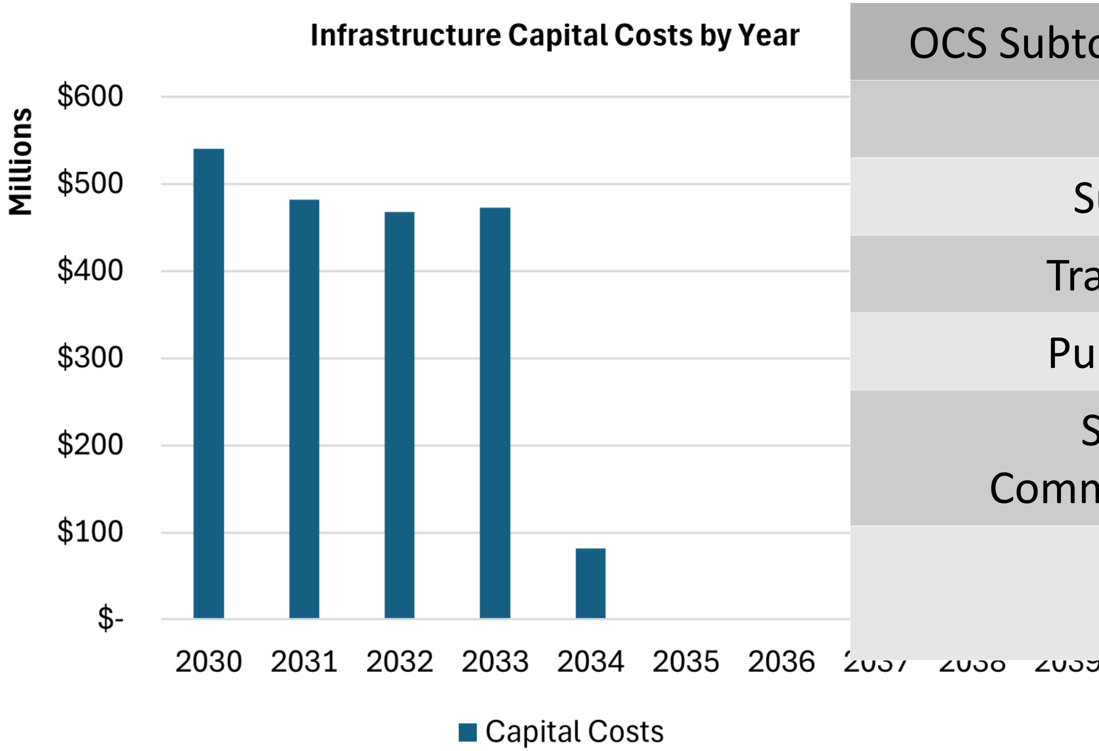
- Traffic Parameters
  - 60 trains per day
    - Intermodal: 150 platforms
    - Bulk: 125 cars, 286k GRL
    - Manifest: 77 loads, 38 empty (286 GRL)
    - 3 or 4 locomotives per train

Mainline Corridor: OCS costs

- Analyzed four electrification scenarios:
  - Full conventional electrification
  - OCS with short gaps at public works and last-mile batteries
  - Intermittent electrification via battery tenders and OCS recharging segments
  - Progressive electrification via dual-mode locomotives
- Short gaps scenario is assumed to avoid all public works costs
- Intermittent electrification scenario included broad analysis of different combinations of OCS power and OCS coverage
- Progressive electrification scenario starts electric operations as the infrastructure is built in the initial years of the project

Mainline Corridor: OCS costs

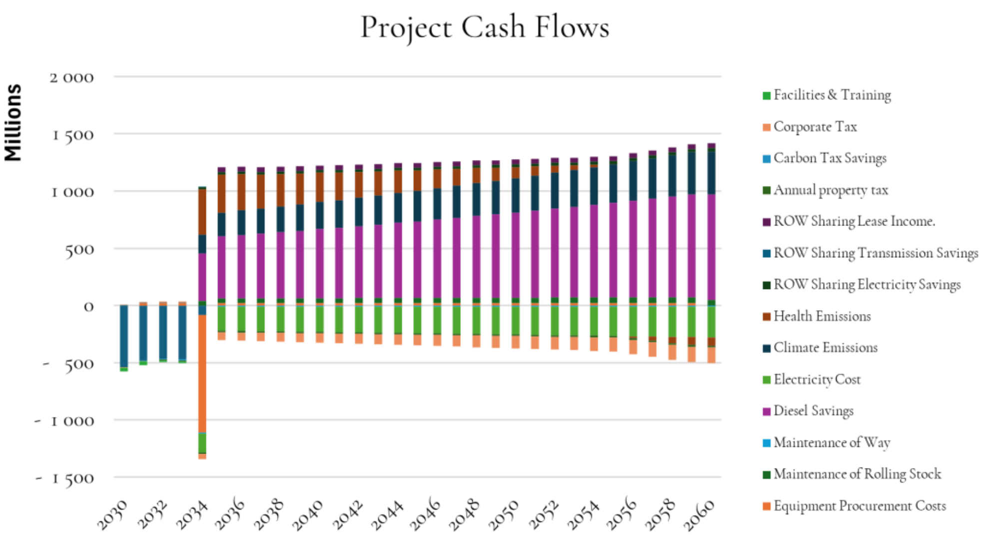
- Signaling & Communication is the largest expense, highlighting the need for more research in this area.
- Public Works cost shows the potential savings for intermittent electrification



OCS Subtotals ($ millions):	
Catenary	754
Substations	149
Transmission	25
Public Works	149
Signaling & Communication	969
Total	**$2,046**

Mainline Corridor: Conventional Electrification

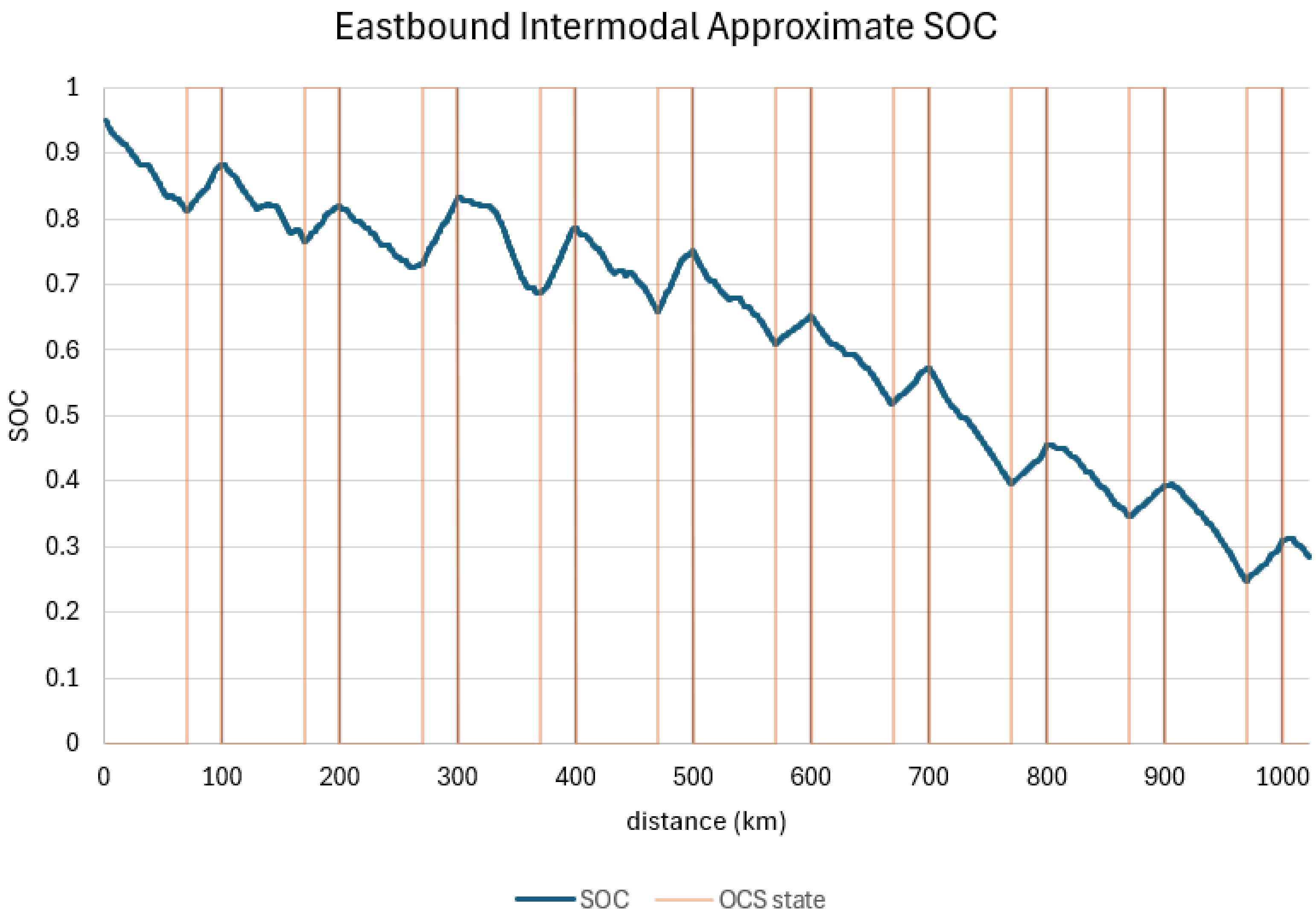
- Conventional electrification produces positive returns.
- Public support might be necessary to bring-about private investment.



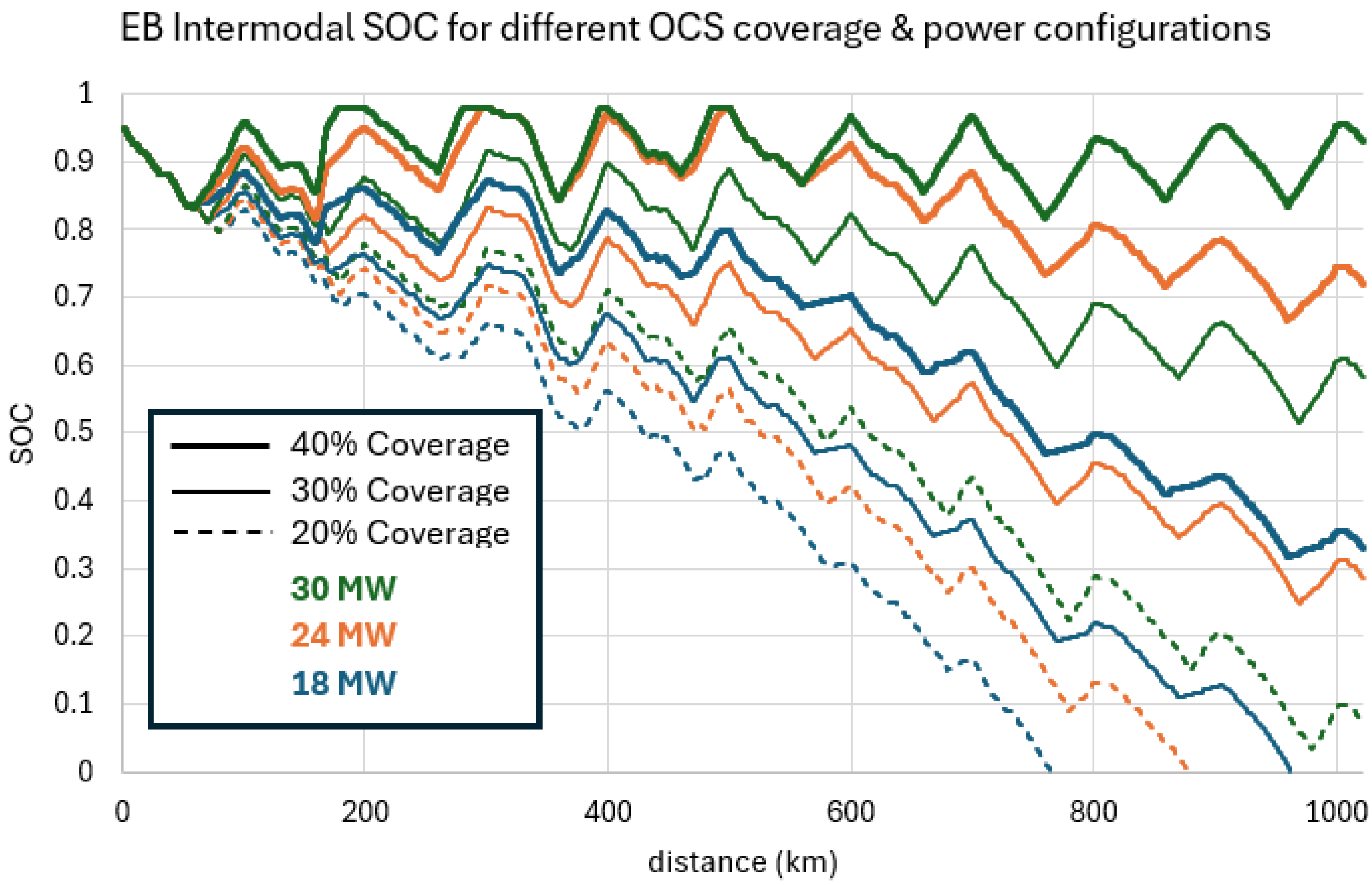
Perspective	Net Present Value ($ millions)			Internal Rate of Return	Benefit-Cost Ratio		
Discount Rate:	3%	7%	18%		3%	7%	18%
Purely Private RR Investment	1320	48	-1170	7.2%	1.4	1.0	0.5
Private Investment with ROW Sharing	2060	538	-975	9.3%	1.7	1.2	0.6
Private investment with ROW sharing and public support	7870	4440	643	22.9%	3.7	2.7	1.3
Public Perspective	8280	4700	728	23.5%	4.0	2.8	1.3

Mainline Corridor: Intermittent Electrification

- Initial test of 24 MW OCS at 30% coverage:



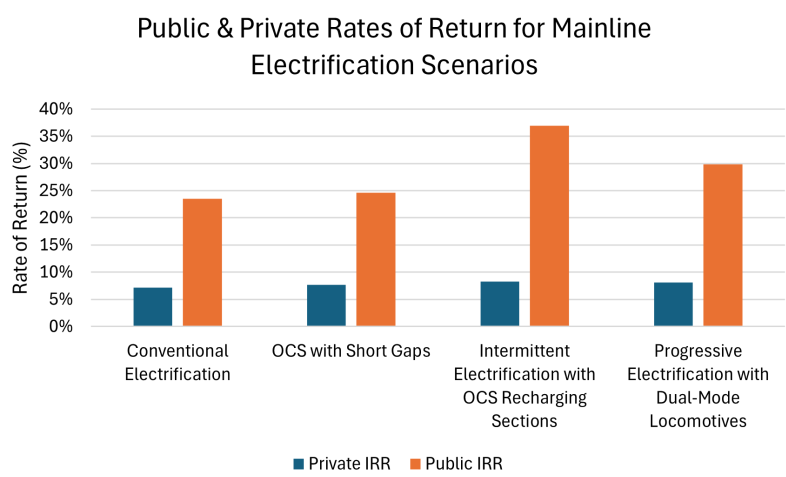
Mainline Corridor: Intermittent Electrification



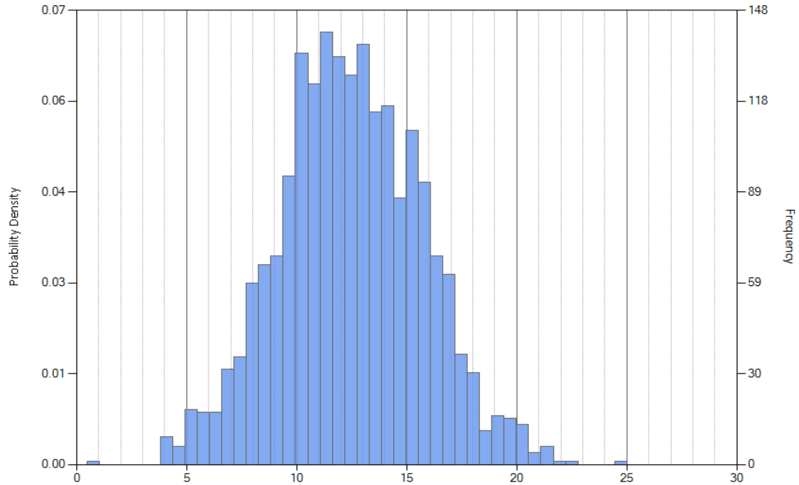
Mainline Corridor: Scenario Comparison

- Each of the technologies tested improved the project's economic performance
- Some internalization of public benefits might be necessary to bring about large enough returns for investment

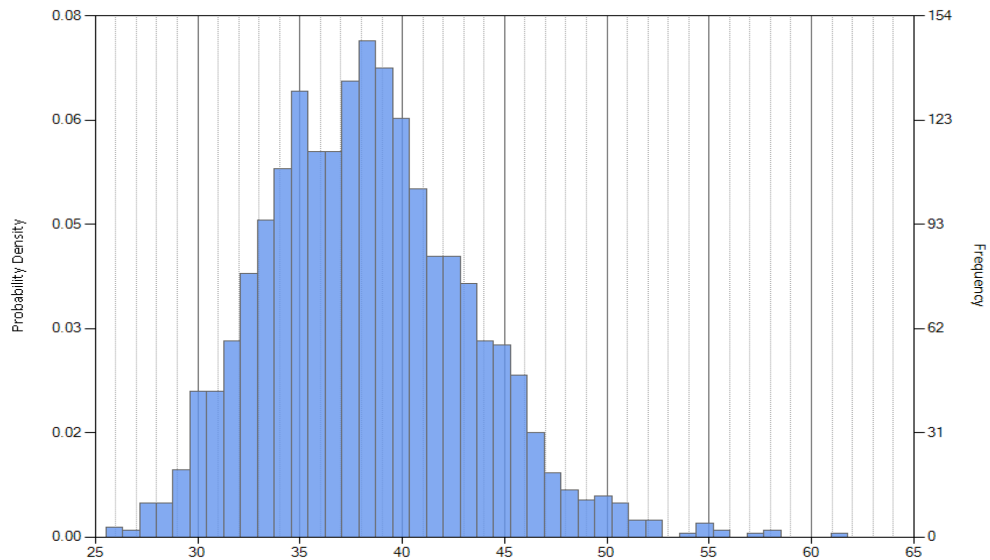
Scenario	Private Internal Rate of Return	Public Internal Rate of Return
Conventional Electrification	7.2%	23.5%
OCS with Short Gaps	7.7%	24.6%
Intermittent Electrification with OCS Recharging Sections	8.3%	36.9%
Progressive Electrification with Dual-Mode Locomotives	8.1%	29.8%



Risk and Uncertainty – Intermittent Electrification case



Private Rate of Return

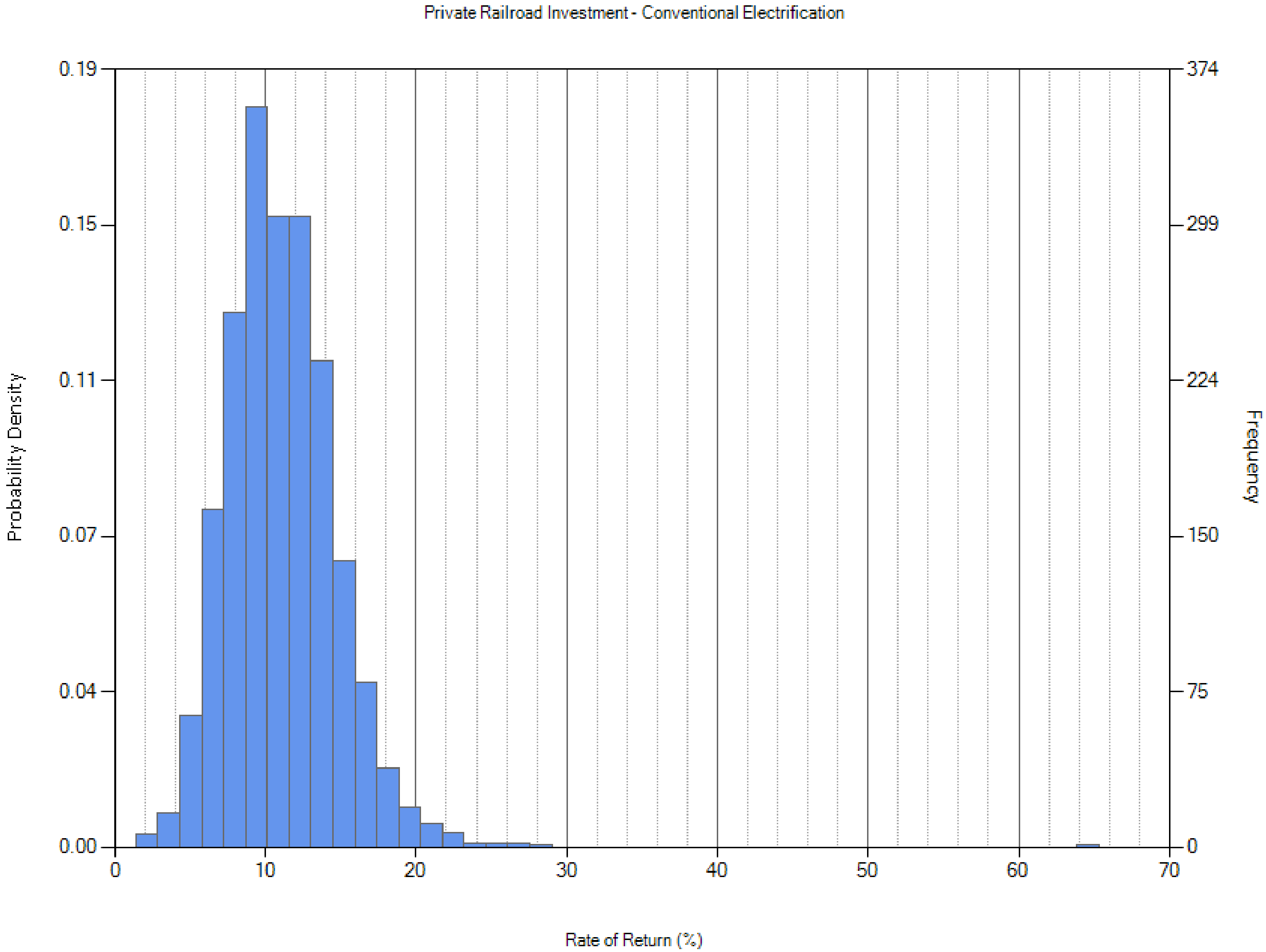


Public Rate of Return

Scenario 2a – Mainline Conv. Elec.

Perspective	Net Present Value ($ millions)			Internal Rate of Return	Benefit-Cost Ratio		
Discount Rate:	3%	7%	18 %		3%	7%	18%
Purely Private RR Investment	1320	48	-1170	7.2%	1.4	1.0	0.5
Private Investment with ROW Sharing	2060	538	-975	9.3%	1.7	1.2	0.6
Private investment with ROW sharing and public support	7870	4440	643	22.9%	3.7	2.7	1.3
Public Perspective	8280	4700	728	23.5%	4.0	2.8	1.3

Scenario 2a – Mainline Conv. Elec.

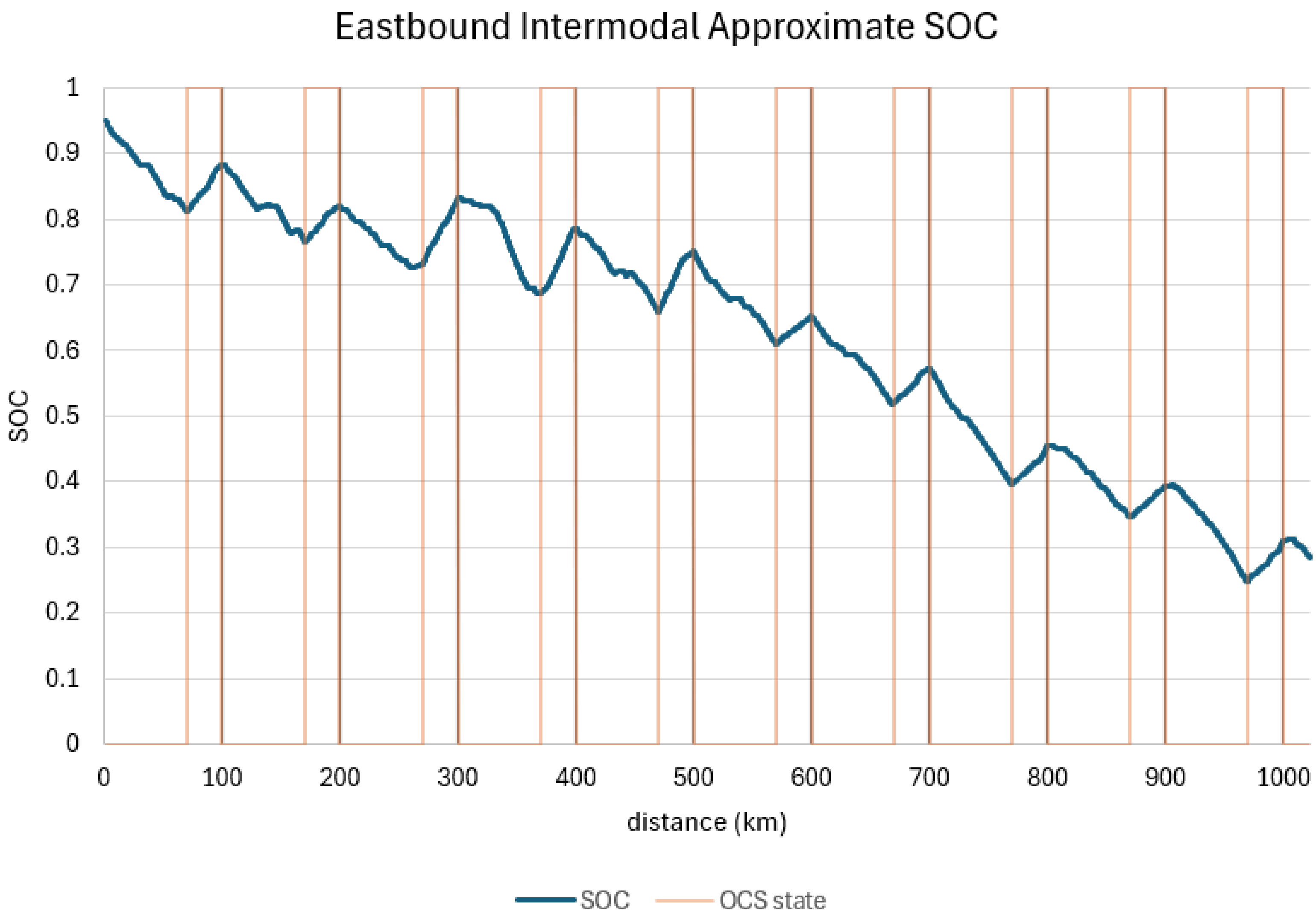


Scenario 2b – Mainline Short OCS Gaps

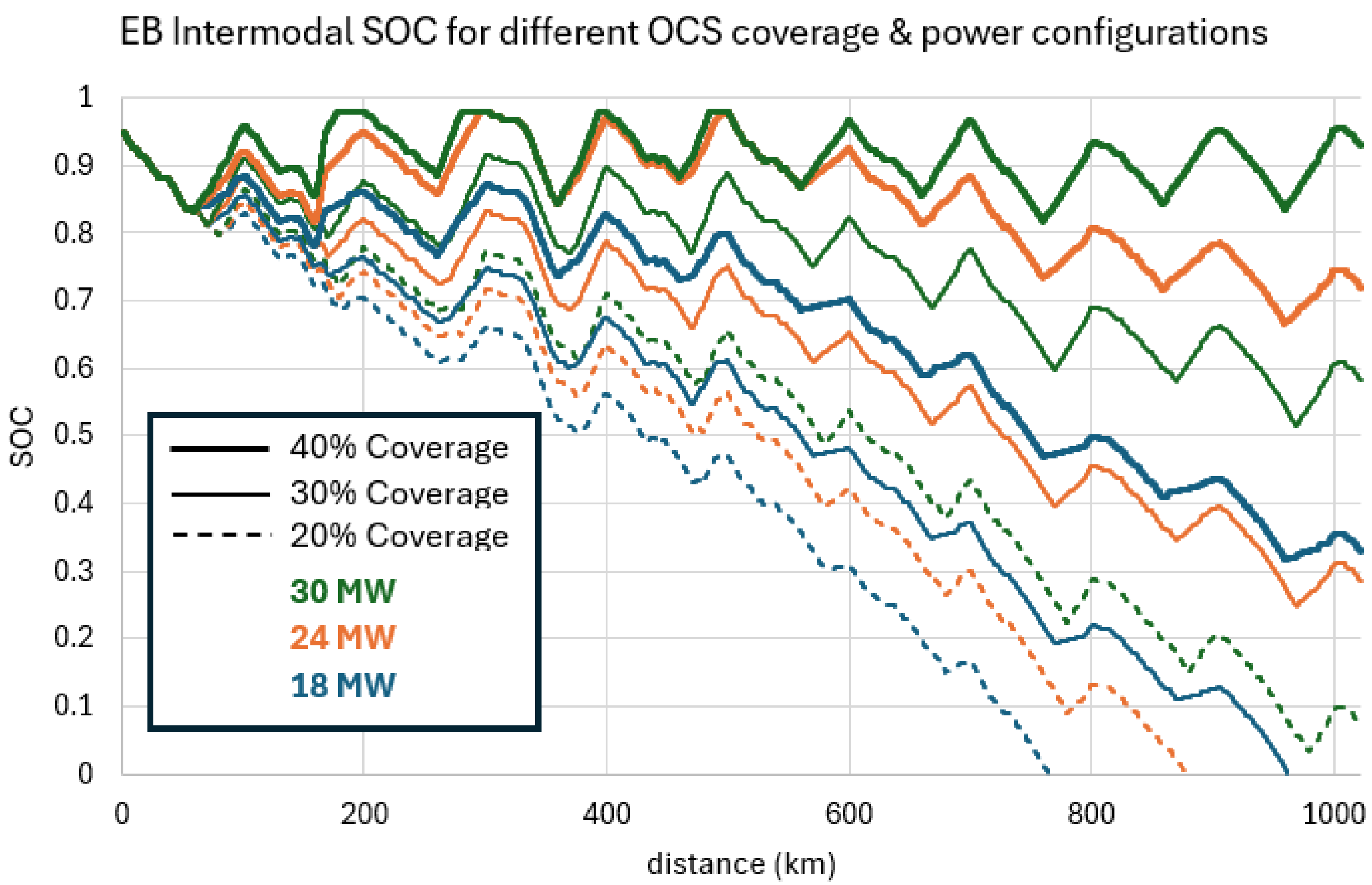
Perspective	Net Present Value ($ millions)			Internal Rate of Return	Benefit-Cost Ratio		
Discount Rate:	3%	7%	18 %		3%	7%	18%
Purely Private RR Investment	1410	147	-1070	7.7%	1.5	1.1	0.5
Private Investment with ROW Sharing	2160	637	-871	9.8%	1.8	1.2	0.6
Private investment with ROW sharing and public support	7960	4540	747	24.1%	3.8	2.8	1.4
Public Perspective	8370	4800	830	24.6%	4.1	2.9	1.4

Mainline Corridor: Intermittent Electrification

- Initial test of 24 MW OCS at 30% coverage:



Mainline Corridor: Intermittent Electrification



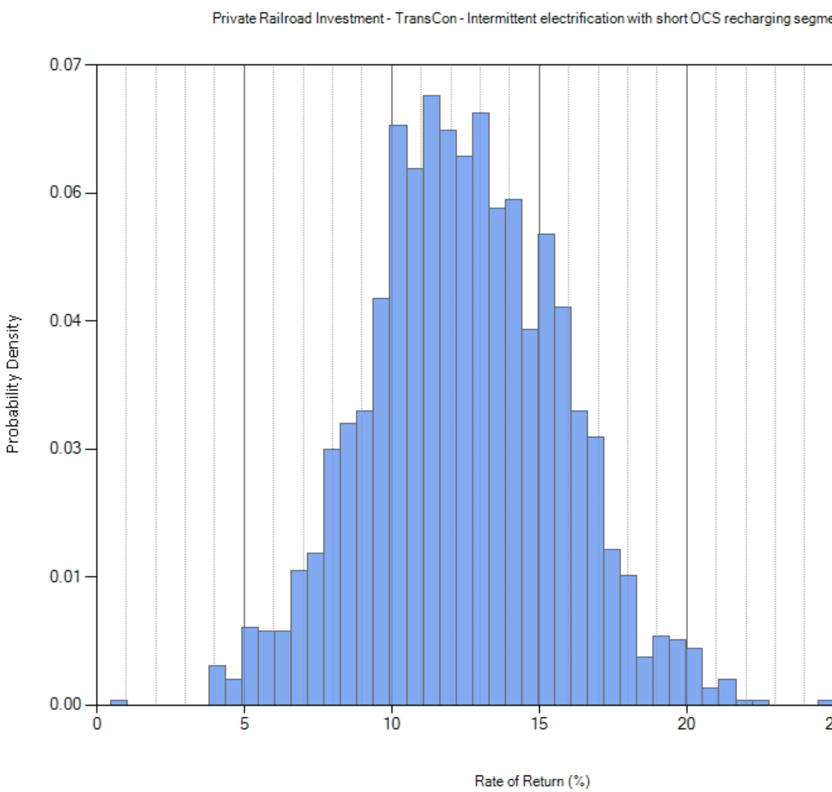
Scenario 2c – Mainline Intermittent

Perspective	Net Present Value ($ millions)			Internal Rate of Return	Benefit-Cost Ratio		
Discount Rate:	3%	7%	18 %		3%	7%	18%
Purely Private RR Investment	1530	279	-1060	8.3%	1.5	1.1	0.6
Private Investment with ROW Sharing	2310	806	-835	10.6%	1.8	1.3	0.7
Private investment with ROW sharing and public support	9530	6020	1850	35.7%	4.2	3.2	1.8
Public Perspective	9890	6270	1980	36.9%	4.4	3.3	1.8

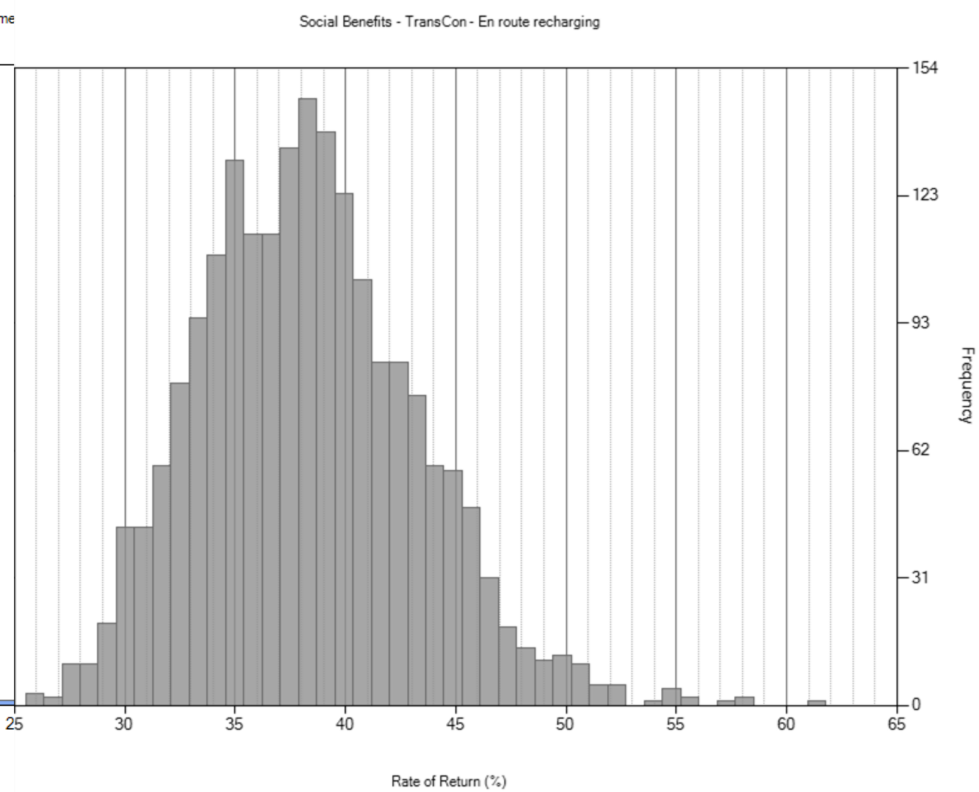
All values in $ millions:	
Catenary	85
Substations	142
Transmission	12
Public Works	0
Signaling & Communication	291
Total	**530**

Scenario 2c – Mainline Intermittent

Private RoR



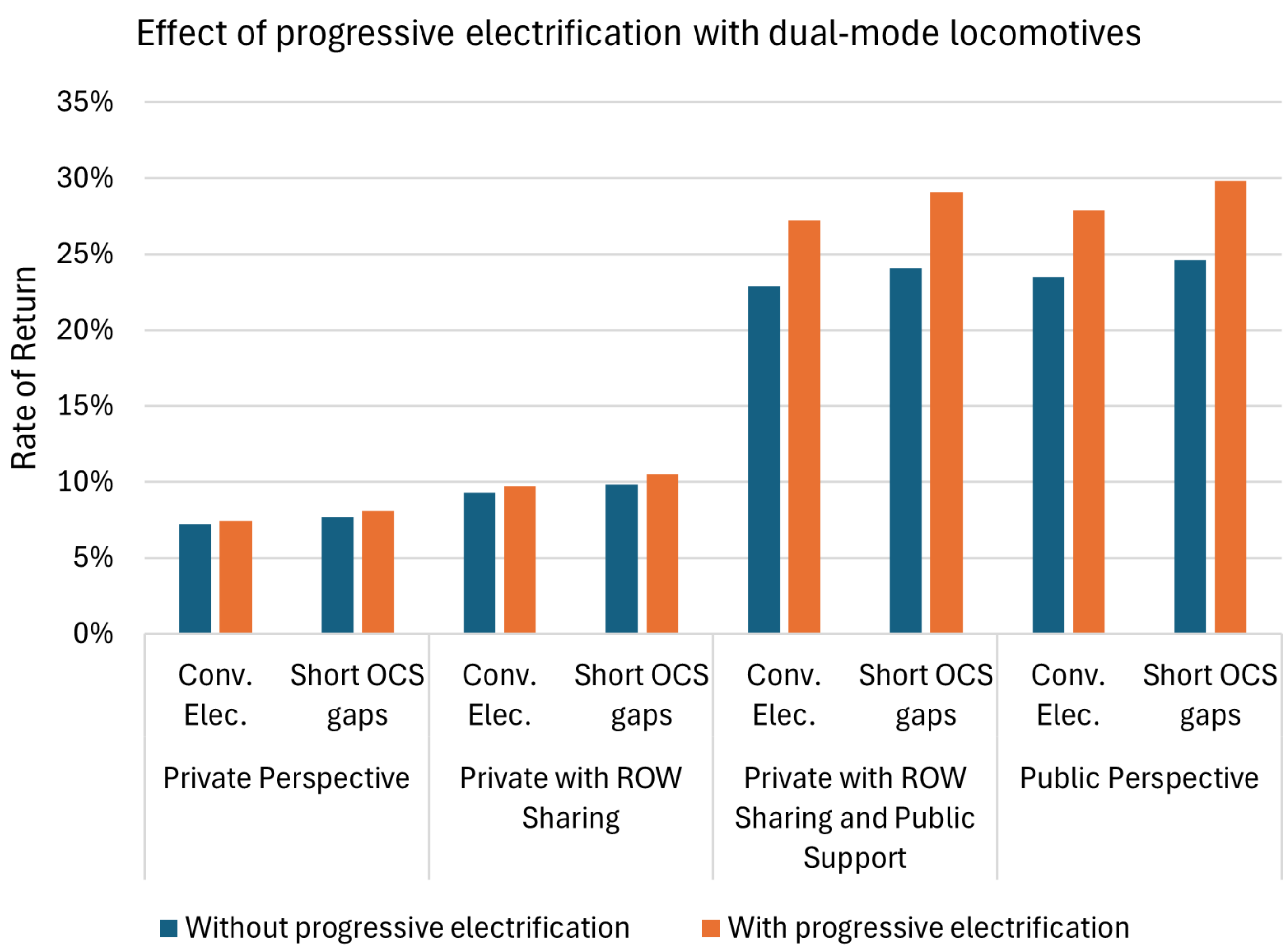
Public RoR



Scenario 2d – Mainline Progressive Elec.

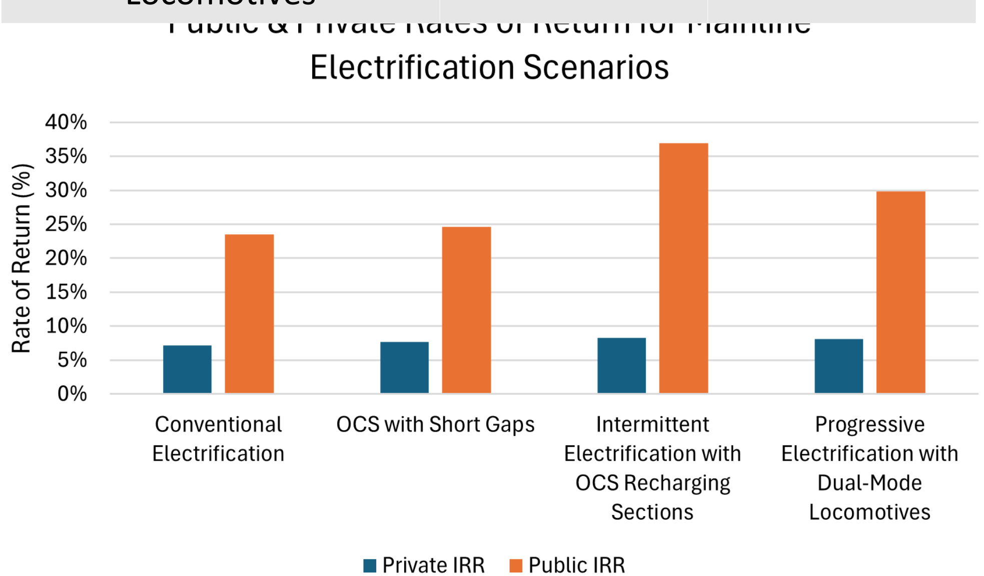
	Perspective	Net Present Value ($ millions)			Internal Rate of Return	Benefit-Cost Ratio		
	Discount Rate:	3%	7%	18%		3%	7%	18%
Progressive electrification towards full OCS	Purely Private RR Investment	1280	81	-1100	7.4%	1.4	1.0	0.5
	Private Investment with ROW Sharing	2050	589	-888	9.7%	1.7	1.2	0.6
	Private investment with ROW sharing and public support	8280	4890	1060	27.2%	3.8	2.8	1.5
	Public Perspective	8690	5150	1150	27.9%	4.1	3.0	1.5
Progressive electrification towards OCS with short gaps	Purely Private RR Investment	1410	213	-962	8.1%	1.5	1.1	0.5
	Private Investment with ROW Sharing	2180	720	-755	10.5%	1.8	1.3	0.6
	Private investment with ROW sharing and public support	8410	5020	1190	29.1%	4.0	3.0	1.6
	Public Perspective	8810	5280	1280	29.8%	4.3	3.2	1.6

Comparison with/without Progressive Electrification



Mainline Public vs Private Rate of Return

Scenario	Private Internal Rate of Return	Public Internal Rate of Return
Conventional Electrification	7.2%	23.5%
OCS with Short Gaps	7.7%	24.6%
Intermittent Electrification with OCS Recharging Sections	8.3%	36.9%
Progressive Electrification with Dual-Mode Locomotives	8.1%	29.8%



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Federal Railroad Administration