SAN FRANCISCO MUNI ELECTRIFICATION

Alternatives Analysis

By

Andrés Díez Restrepo, *Universidad Pontificia Bolivariana*
José Valentín Restrepo, *Universidad Pontificia Bolivariana*
Mauricio Restrepo Restrepo, *Universidad del Norte*
Lina María Parra Hoyos, *Metro de Medellín*
Martin Wright, *Ad-Honorem* Consultant and Advisor

JULY 2023

Produced by:

In partnership with:

CONTENTS

1. Executive Summary 9
2. Introduction 11
3. Literature Review 13
4. Glossary 14
5. Technology Overview 16

5.1. Depot-charge battery electric bus 16
5.2. Opportunity-charging battery electric bus (OCBEB) 17
5.3. In-motion charging 18

6. Methodology 20

6.1. Stage 1: Definition of operational conditions 21
6.2. Stage 2: Calculation of tractive effort and mechanical power 21
6.3. Stage 3: Electrification optimization 21
6.4. Stage 4: Analysis of the battery and its lifespan 21
6.5. Stage 5: Detailed electrical simulation 22
6.6. Stage 6: Basic electrical design 22

7. Application of the Methodology 22

7.1. Stage 1: Operating conditions 23

7.1.1. The representative route: Route 44 25

7.2. Stage 2: Tensile effort and mechanical power calculation 28
7.3. Stage 3: Electrification optimization 28
7.4. Stage 4: Analysis of the battery and its life cycle 30

7.4.1. Ratio of battery to fleet size 30
7.4.2. Vehicle characteristics 31
7.4.3. Battery technology 33
7.4.4. Estimation of the required battery capacity and size for BEB 34
7.4.5. Battery weight and passenger capacity 35
7.4.6. Fleet size to meet passenger demand 36
7.4.7. Fleet adequacy during peak periods 37
7.4.8. Size of yards for new fleet 43
7.4.9. Battery usage, life, and DoD 44
7.4.10. Influence of DOD on battery life 45
7.4.11. Daily battery behavior for BEB and IMC 46

7.5. Stage 5: Detailed electrical simulation 49

7.5.1. Trolleybuses 49
7.5.2. Battery electric buses 50
7.5.3. In-motion charging bus 50

7.6. Stage 6: Basic electrical design 51

8. Analysis of the Results for Route 44 51

8.1. Electrification optimization results 52
8.2. Results of detailed electrical simulation 54

8.2.1. Results for in-motion charging buses 54
8.2.2. Results for trolleybuses 60
8.2.3. Results for BEBs 64

8.3. Analysis of detailed simulation results 65

8.3.1. Demand characterization 65
8.3.2. Comparison of overall energy performance 66

8.4. Battery analysis 66

8.4.1. LTO battery 66
8.4.2. NMC battery 67

8.5. Stage 6: Basic electrical design 70
8.6. Discussion of the results of the basic IMC electrification design 74

8.6.1. Notes on opportunity charging 74

9. Financial Analysis of Alternatives 75

9.1. CAPEX 76
9.2. OPEX 82
9.3. Summary of financial results 96

10. Yard Electrification 96

10.1. Route 38-Geary Analysis 97
10.2. Analysis of Route 7-Haight/Noriega 100
10.3. Estimated aggregate demand for Woods Yard 102
10.4. Basic analysis of the other yards 103
10.5. Leveraging the Existing Infrastructure to Deploy the IMC Alternative 105

11. High opportunity electrification plan 106

11.1. General criteria 107
11.2. Results 108
11.3. Methods 114
11.4. Simplified model calibration for Routes 9 & 43 114

12. Risk Analysis 117

12.1. Fire risk 117
12.2. Battery maintenance 118

12.3. Battery disposal ... 119
12.4. Inadequate driver training ... 119
12.5. Bus charging time ... 120
12.6. Fleet maintenance ... 120
12.7. Battery life ... 121
12.8. Infrastructure ... 121
12.9. Location of charging stations ... 122
12.10. Catenary failure ... 122
12.11. Number of charging ports ... 123
12.12. Limitations on charging ports and stations ... 123
12.13. Impact on the energy supply network ... 124
12.14. Lack of standards and regulations in charging systems ... 125
12.15. Battery chemistry ... 125

13. Conclusion and further work ... 127
14. Acknowledgments ... 129
15. Notes ... 129

LIST OF FIGURES

Figure 1 Depot charging. Taken from (Díez y Restrepo 2021)....................17
Figure 2. Opportunity Charging. Taken from (Díez y Restrepo 2021) 18
Figure 3. Conductive In-Motion Charging. Taken from (Díez y Restrepo 2021) with permission of authors. 18
Figure 4. IMC bus electrical system. 19
Figure 5. Methodology for technology assessment. 20
Figure 6. Monthly weather ranges in San Francisco in (a) degrees Celsius and (b) Fahrenheit ..23
Figure 7. Correlation of temperature and daily average consumption of 60 ft buses. Figure taken from (VIRICITI 2020)....................25
Figure 8. Route 44 O'Shaughnessy Map taken from SFMTA (SFMTA 2022). 26
Figure 9. Route 44 O'Shaughnessy Bus Service Frequencies taken from SFMTA (SFMTA 2022). 26
Figure 10. Route and elevation profile for route 44 heading south to Hunters Point. 27
Figure 11. Route OHL intersections for Route 44.................... 27
Figure 12. Result of traction power simulation results for a 40-foot bus on Route 44.....................28
Figure 13. Detailed results for the optimization process.....................29
Figure 14. Diagram representing optimization results. 30
Figure 15. Schedules and bus frequency for routes 24 and 52. Taken from SFMTA. 38
Figure 16. Route 44 O'Shaughnessy schedule. 39
Figure 17. Power and buses throughout the day in Adjusted Dispatch scenario. 43
Figure 18. (a) BEB yard and (b) IMC yard. 44
Figure 19. (a) Life cycle vs. Depth of Discharge and (b) final discharge voltage vs. number of cycles. 45
Figure 20. Battery's depth of discharge. 46
Figure 21. Comparison between the DOD of (a) BEBs and (b) IMC buses. 47
Figure 22. Reference comparison of bus charge-discharge cycles for IMC buses on routes with (a) low degree of electrification (b) high degree of electrification.................... 47
Figure 23. State of Health for IMC buses....................48
Figure 24. State of Health for BEBs. 48
Figure 25. Reference comparison of BEB and IMC battery requirements through the project. ..49
Figure 26. Optimization of the electrification of Route 44 for 40-ft buses. 52
Figure 27. Electrification of Route 44 for 400-ft IMC buses (left) and trolleybuses (right).........53
Figure 28. Battery charge control for LTO battery according to the voltage in the overhead line. 54
Figure 29. Operational behavior of IMC-30 kWh from 4 am to 7 am. 55
Figure 30. Operational behavior of IMC-30 kWh from 4 am to 10 am. 55
Figure 31. Cumulative power demand for route 44, IMC case....................56
Figure 32. Minimum voltage in pantographs and overhead line, IMC case....................58
Figure 33. Power demand from substations and aggregated, IMC case, 4:00 am to 7:00 am.....59
Figure 34. Power demand from substations and aggregated, IMC case, 7:00 am to 10:00 am...59
Figure 35. Cumulative power demand for Route 44, IMC case 61
Figure 36. Minimum voltage in pantographs and overhead line, IMC case. 62
Figure 37. Power demand from substations and aggregated, trolleybus case, 4:00 am to 7:00 am 63
Figure 38. Power demand from substations and aggregated, trolleybus case, 7:00 am to 10:00 am....................63
Figure 39. Relative and absolute SOC of the BEB, 7:00 am to 12:00 pm....................64
Figure 40. Cumulative power demand for IMC, BEB and trolleybus.................... 65
Figure 41. Power-voltage limit for IMC battery charge Route 44. 68

Figure 42. Vehicle SOC for 40-ft IMC trolleybus, 71 kWh, Route 44. 68
Figure 43. Battery Cycle life as function of the change in the SOC (Göhlich, Fay y Park 2019)...69
Figure 44. Preliminary estimations of battery use in a 15-year period....70
Figure 45. Basic design of the electrification of Route 44. 71
Figure 46. Traction substation. 71
Figure 47. Driver current maximum value, IMC case. 73
Figure 48. Driver current maximum value, trolleybus case....73
Figure 49. SFMTA ZE plans: Reference cost for energy. 82
Figure 50. Vehicles charging through the day—BEB scenario 1. 83
Figure 51. Vehicles charging through the day—BEB Scenario 2. 84
Figure 52. Vehicles charging through the day—BEB Scenario 3. 85
Figure 53. Woods parking yard. 90
Figure 54. Land reference cost information. 91
Figure 55. Optimized electrification for Route 38 with IMC–NMC buses, 2 TPSs, and 0 intersections. 97
Figure 56. Route 38 catenary segments with IMC–NMC buses, 2 TPSs, and 0 intersections 98
Figure 57. SOC for Route 38 with IMC–NMC buses, 2 TPSs, and 0 intersections. 98
Figure 58. Optimized electrification for route 38 with IMC–LTO buses, 2 TPSs, and 0 intersections. 99
Figure 59. SOC for Route 38 electrification with IMC–LTO buses, 2 TPSs, and 0 intersections.99
Figure 60. Optimized electrification with IMC–LTO buses, 2 TPSs, and 0 intersections 100
Figure 61. Optimized electrification for Route 7 with IMC-NMC buses, 2 TPSs, and 0 intersections. 101
Figure 62. SOC for optimized electrification for Route 7 with IMC-NMC buses, 2 TPSs, and 0 intersections. 101
Figure 63. optimized electrification for Route 7 with IMC-NMC buses, 2 TPSs, and 0 intersections. 102
Figure 64. Reference projection of the Woods yard power demand. 102
Figure 65. Reference projection of the Power demand in the Potrero yard. Adapted from SFMTA Zero Emission Plan....103
Figure 66: IMC deployment in SF leveraged by existing trolleybus infrastructure. 106
Figure 67: Example of contact line infrastructure landscape in a country area (Solingen)....107
Figure 68: High opportunity electrification design....108
Figure 69: Proposed electrification for Routes 8, 9 and 19....111
Figure 70: Proposed electrification for Routes 7, 23 and 38....112
Figure 71: Proposed electrification for Routes 43 and 44. 113
Figure 72: Proposed electrification for Routes 28 and 29. 113
Figure 73: Proposed electrification for 55: no new wiring would be needed. 114
Figure 74: Route map and route profile for route 9 simulation....115
Figure 75: Simplified simulation results for route 9. 115
Figure 76: Route 43 map and route profile. 116
Figure 77: Battery State of Charge 117

LIST OF TABLES

Table 1. Overview of Similar Studies 13
Table 2. Consumption of 60-foot electric buses at different temperatures 24
Table 3. Overlaps and intersections of catenary of route 44 with other routes. 28
Table 4. OpenTrack+PowerNet simulation parameters for the IMC bus 32
Table 5. OpenTrack+PowerNet simulation parameters for the trolleybus 32
Table 6. OpenTrack+PowerNet simulation parameters for the battery electric bus 32
Table 7. Battery data for 40-foot buses 35
Table 8. BEB passenger capacity 35
Table 9. Passenger capacity for a BEB with a battery of 525 kWh 35
Table 10. Replacement ratio of different technologies with respect to 40-foot electric diesel buses (optimistic battery weight scenario) 36
Table 11. Replacement ratio of different technologies with respect to diesel buses with commercial battery values (current battery weight scenario) 36
Table 12. Number of buses required for operation at any time of day. 39
Table 13. BEB schedules on-route and charge 40
Table 14. BEB schedules on-route and charging 41
Table 15. BEB Adjusted Dispatch 42
Table 16. Power and current required for IMC 30 kWh-LTO, Route 44 57
Table 17. Energy Overview, Route 44, IMC, Network Route 44, 04:00:00 to 12:00:00 60
Table 18. Power and current required trolleybus case, Route 44 61
Table 19. Energy Overview, Route 44, Trolleybus, Network Route 44, 04:00:00 to 12:00:00 64
Table 20. Energy Overview, Route 44, Trolleybus, Network Route 44, 04:00:00 to 12:00:00 66
Table 21. Summary of battery use for all scenarios. 70
Table 22. Basic design proposal for IMC substations 72
Table 23. Basic design proposal for trolleybus substations 72
Table 24. Basic Cost Information 74
Table 25. Financial analysis item description 75
Table 26. BEB fleet scenarios 76
Table 27. Cost of the alternatives for Muni electrification. 76
Table 28. Basic data for cost evaluation 77
Table 29. Cost for infrastructure related to BEB 77
Table 30. CAPEX for BEB Scenario 1 78
Table 31. CAPEX for BEB Scenario 2 78
Table 32. CAPEX for BEB Scenario 3 78
Table 33. Cost for IMC-NMC 79
Table 34. Additional information for cost assessment for IMC-NMC 79
Table 35. CAPEX for IMC – 71 kWh NMC 80
Table 36. Cost for IMC-LTO 80
Table 37. Additional information for cost assessment for IMC-LTO 80
Table 38. CAPEX for IMC with 30 kWh LTO 81
Table 39. Cost information for trolleybus scenario 81
Table 40. Additional information for Cost assessment for trolleybus 81
Table 41. CAPEX for Trolleybus 81
Table 42. Energy prices and cost for BEB scenario 1 83
Table 43. Energy prices and cost for BEB scenario 2 84
Table 44. Number of buses comparison every hour between scenarios 1 and 2 84
Table 45. Energy prices and cost for BEB Scenario 3 85
Table 46. Energy prices and energy cost for IMC 85
Table 47. Energy prices and energy cost for trolleybus 86

Table 48. Maintenance cost for BEB Scenario 1 87
Table 49. Maintenance Cost for BEB Scenario 2 87
Table 50. Maintenance Cost for BEB Scenario 3 88
Table 51. Maintenance cost for IMC bus with NMC battery 89
Table 52. Maintenance cost for the IMC bus with the LTO battery 89
Table 53. Maintenance cost for trolleybus 90
Table 54. Cost for yard expansion—BEB Scenario 1 92
Table 55. Total CAPEX—BEB Scenario 1 92
Table 56. Cost for yard expansion—BEB Scenario 2 92
Table 57. Total CAPEX—BEB Scenario 2 92
Table 58. Cost for yard use BEB scenario 3 93
Table 59. Annual cost for land use BEB scenario 3 93
Table 60. Cost for yard use—IMC NMC 93
Table 61. Annual cost for land use—IMC NMC bus 93
Table 62. Net Present Value—BEB Scenario 1 (Fleet: 38 buses) 94
Table 63. Net Present Value BEB—Scenario 2 (Fleet: 23 buses) 94
Table 64. Net Present Value—BEB Scenario 3 (Fleet: 19 buses) 94
Table 65. Net Present Value—IMC-NMC 95
Table 66. Net Present Value—IMC-LTO 95
Table 67. Net Present Value—trolleybus 95
Table 68. 15-year financial results 96
Table 69. Route 38 service description 97
Table 70. Cost scenarios for Route 38 electrification 98
Table 71. Cost scenarios for Route 38 electrification with IMC–LTO buses, 2 TPSs, and 0 intersections 99
Table 72. Route 7 service description 100
Table 73. Cost scenarios for Route 7 with IMC-NMC buses, 2 TPSs, and 0 intersections 101
Table 74. Basic assessment for San Francisco Muni Routes 103
Table 75. Regenerative braking efficiency as a function of distance and power at 600 V 104
Table 76 Summary of electrification proposal 109
Table 77 Reference baseline for electrification 109
Table 78 IMC electrification plan compared with current situation 110
Table 79. Basic simulation data for the buses in route 9 and 43 114
Table 80. Basic operational data for the simulation of route 9 and 43 115
Table 81. Fleet parameters for the simulation of Routes 9 and 43 115
Table 82. Charging and battery parameters 116
Table 83. Summary of electrification proposal for Route 9 116
Table 84. Summary of electrification proposal for Route 43 117
Table 85. Conceptual risk assessment of alternatives 125

1. Executive Summary

In this study, we analyze and compare the main technological alternatives for the electrification of San Francisco's bus fleet. These alternatives are battery electric buses (BEBs), in-motion charging (IMC) trolleybuses (with onboard energy storage), and conventional modern trolleybuses. We find that:

- IMC trolleybuses are the most environmentally and economically sound option (thus San Francisco must maintain its trolleybus lines).
- Deploying IMC technology will allow San Francisco to leverage the existing overhead line system (including substations), thereby reducing the operational and capital costs of electrifying the bus fleet.
- Incorporating IMC trolleybuses will help optimize the energy demand curve of a fully electrified fleet, reducing peaks and, in turn, the need to increase peak capacity.
- A 33 percent increase in OHL infrastructure would allow San Francisco to more than double its fleet of zero-emission buses while adding 210 miles of electrified service.

Trolleybuses are the environmentally and economically superior option and San Francisco must maintain its trolleybus lines.

Trolleybus routes should continue as such, which will allow the city to avoid dismantling large segments of the overhead contact lines currently in use. Because new IMC trolleybuses will have batteries for autonomous operation on segments without catenary, planners can consider removing overhead wires at complicated crossings where wires from other routes or streetcar lines intersect. Nevertheless, electrical continuity should be maintained via underground conduits or isolated overhead feeders. We recommend further cost-benefit analysis to weigh the savings in maintenance costs against the required investments.

Detailed simulations indicate that trolleybuses are the most energy-efficient alternative for heavily trafficked routes, such as the ones currently operated with this kind of vehicle. Furthermore, as more buses operate simultaneously, the overhead line (OHL) system will facilitate energy exchange among the fleet and increase the overall energy efficiency of the system.

Deploying in-motion charging technology will allow San Francisco to leverage the existing overhead line system, reducing the operational and capital costs of electrifying the bus fleet.

San Francisco's best strategy for transitioning away from its diesel-hybrid bus fleet is to focus on converting routes to IMC, starting with the most heavily trafficked routes as well as those close to existing trolleybus lines. IMC technology leverages the city's current infrastructure to assume the new energy demands of an electrified fleet with relatively minor investments and low technological risk. The city's existing trolleybus network presents a tremendous opportunity for zero-emission transit using IMC technology.

Compared with BEBs, IMC trolleybuses would reduce land requirements and decrease financial costs. BEBs, for example, must be stationary while charging, thereby increasing their total vehicle needs relative to IMC and conventional trolleybuses. BEBs also require charging stations and additional parking—a substantial spatial footprint and added expense. Between these and other factors, BEBs become more expensive over a 15-year period than alternative zero-emission technologies. For example, **BEBs cost an estimated 27 percent more than IMC trolleybuses** on the representative routes analyzed in this study.

One of the most important factors in favor of IMC trolleybuses is the lower commitment to land use, as IMC technology requires a smaller fleet than BEB technologies. Another is that IMC buses, despite carrying a smaller battery, can travel farther than BEB buses. In general, an electrification plan based on IMC trolleybuses allows for reductions in battery use of between 70 percent and 90 percent—both in storage capacity and in mass—compared to the BEB alternative. This represents savings in both energy (due to the ecological footprint of battery production) and in critical raw materials such as lithium and cobalt.

Incorporating IMC trolleybuses helps to optimize the energy demand curve of a fully electrified fleet, reducing peaks as well as the need to increase peak capacity.

By virtue of its charging technology, IMC flattens the demand curve and saves the energy grid from a new demand peak in the nighttime hours (when both electric cars and BEBs would be charging). The development of newer battery chemistries with greater storage capacity will further allow the IMC system to manage the cost and/or demand of energy.

A 33 percent increase in overhead lines infrastructure would allow San Francisco to more than double its fleet of zero-emission buses while adding 210 miles of electrified service.

The deployment of IMC allows San Francisco to take advantage of existing infrastructure while strengthening currently electrified lines. Planners can utilize existing overhead contact lines on overlapping bus routes to implement IMC, thereby mitigating capital costs.

Our risk analysis finds that IMC technology has a lower overall implementation risk compared to BEB, due to factors such as the uncertainty of accelerated battery degradation, the electrical risk of high-energy-capacity batteries, and the volatility of the supply chain for raw materials such as cobalt and lithium. Overhead contact line (OCL) conductive power supply is a proven technology with low implementation risk. **In short, IMC offers the flexibility of BEB with the performance and risk management profile of trolleybus projects**.

2. Introduction

Historic Background

San Francisco has been a leader in the use of electric transit since the earliest days of modern urban public transportation. By the dawn of the twentieth century, the city's transit operators had already adopted the use of streetcars and funiculars powered by electricity. With the consolidation of disparate private systems under the control of United Railroads and the founding of the Municipal Railway (Muni) in 1912, San Francisco achieved an intricate transit network that today remains a model for the world.

Trolleybuses were particularly attractive to San Francisco planners due to the traction advantages of electric motors. The Market Street Railway installed the first trolleybus line in 1935 to replace streetcars on the 33 Line. In 1941, Muni established the R Line, a trolleybus route that expanded transit service to the Mission District. By the end of the 1940s, an additional 14 streetcar lines had been converted to trolleybus service, part of a system-wide recapitalization following the Municipal Railway's takeover of the Market Street Railway's operations.

In 1968, San Francisco was on the verge of "diesel-ifying" its rubber tire fleet and eliminating its trolley network. That same year, the San Francisco Board of Supervisors expressed its intent to remove overhead electric wires for transit from Market Street in anticipation of the opening of the Muni Metro subway. The San Francisco Public Utilities Commission (SFPUC), which ran the Muni at the time, resolved a year later "to conduct [its] efforts to improve the Municipal Railway in such manner so as to optimize the use of the City's electrical facilities and electrical transit equipment, thereby placing emphasis on electric-powered transit in San Francisco with a resulting reduction in pollution of the environment by poisoning of the air and a rising level of objectionable noise which is produced by motor coaches."

In 1975, the SFPUC formally recommended that the Board of Supervisors reconsider their 1968 resolution, stating "that there is sufficient public support, based on sound modern mass transit practices, environmental concerns, and the need for energy conservation to justify a complete review of the policy established by the Board of Supervisors in 1968 […] in the interest of the environment, fossil fuel conservation, and realistic modern mass transit practices involving the 50,000 daily passengers who use these trolley coach lines." The Board subsequently reversed course.

While the various performance issues related to diesel-powered buses in comparison to trolleybuses on steep routes helped San Francisco retain its zero-emission fleet, the dismantling wave that began in the 1950s virtually wiped trolleybus and streetcar systems from most US cities. The embrace of diesel had repercussions throughout the Western Hemisphere. Medellín, Colombia, our home city, was no exception: By 1953, it had lost more than 40 km of streetcar network alone.

In 2018, the State of California's Air Resources Board, seeking the elimination of diesel transit vehicles, adopted the Innovative Clean Transit (ICT) rule. Applying to all public transit agencies in the state that own, operate, or lease buses with a Gross Vehicle Weight greater than 14,000 lbs., ICT mandates that all bus fleets must be fully zero-emissions by 2040. Although there are varying requires for individual transit agencies depending on their size, all new transit buses must zero-emissions by 2029.

As recently as 2021, the San Francisco Municipal Transportation Agency's long-term capital plans included the replacement of Muni's extensive trolleybus network with a battery electric bus (BEB) system. This potential development raised concerns among this report's sponsors and others that the city would jettison an existing, efficient, and widely deployed zero-emission technology for a potentially inferior solution. In what follows, we consider the technologies available for the electrification of the diesel-hybrid bus fleet in San Francisco—opportunity charging, battery electric buses (BEB), trolleybuses with IMC—and analyze the results from a series of simulations to provide guidelines for the most efficient and effective transition plan. In addition, this study explores the effects of different strategies on network efficiency and environmental outcomes and evaluates the options at the route level, yard level, and citywide network level."

Route-Level Electrification

This level of analysis accounts for the topographical, operational, and vehicle-specific factors; infrastructure requirements; and energy storage and implementation costs for each of the alternatives. To that end, we conducted a 15-year lifecycle financial analysis that accounts for the time value of money, system degradation, and the useful life of critical elements, such as batteries, that are required in each alternative, as well as the fiscal implications of expanded land and fleet requirements of the alternatives.

To ensure a rational and weighted comparison, we assume that, regardless of the technology, the routes maintain the same level of service. This means that the fleets of the different alternatives must have the same maximum transport capacity—measured in passenger-hour-direction—to meet the same peak demand. Also, fleets of the different alternatives must be able to move the same number of passengers on the route, which determines the number of available buses necessary for service delivery.

Yard-Level Electrification

The results at route-level electrification are escalated to yard-level electrification by considering the aggregated effect of the main routes and their relationships to a given storage yard.

Citywide, Network-Level Electrification

Finally, the report scales the yard-level analysis up to the citywide transit network, examining the aggregate effects of the various alternative electrification scenarios and recommending the optimal path forward. As with the Route-Level analysis we assume that routes maintain the same level of service. This means that the fleets of the different alternatives must have the same maximum transport capacity, measured in passenger-hour-direction, to meet the same peak demand. Also, fleets of the different alternatives must be able to move the same number of passengers on a given day, which determines the number of necessary available buses.

We will also present a basic conceptual risk analysis supported by the results of the detailed simulations of the previous chapters.

3. Literature Review

In this section, we briefly present the results of selected studies related to the operation analysis of electric bus technologies such as battery electric buses, fuel cell electric buses (FCEB), IMC trolleybuses, and hybrid buses.

Because we do not intend to offer a thorough analysis of the large number of reports and studies evaluating the performance of electric buses, we include here only the studies that present the most common findings of the various zero-emission bus-operating agencies.

The most important observations and conclusions of each study are presented in Table 1.

Table 1. Overview of Similar Studies

Name of Study	***City***	***Technologies Analyzed***	***Observations***
Zero Emission Bus Transition Plan Metro-Transit	Minneapolis	BEB, Electric Trolley, FCEB	• Presents a comparison of different types of BEBs and trolleybuses. Unfortunately, does not consider new technological advances, such as IMC, which mitigate many of the limitations ascribed to trolleybus technology, e.g., lack of flexibility. • **Indicates that San Francisco requires trolleybuses because of the high slopes of the route.**
SEPTA Zero Emission Bus Playbook	Philadelphia	BEB, Electric Trolley, FCEB	• Analyzes the advantages/disadvantages of different electric bus technologies, studying the weight of vehicles and their effects.
Battery Electric Bus and Facilities Analysis - Milwaukee County Transit System	Milwaukee	Electric Buses	• Presents replacement relationships between buses that use fossil fuels and electric buses. It also discusses the case of electric buses that use fossil fuel heating. • Provides battery degradation rates: 2.4%/year x 7 years. • Studies energy consumption for electric buses according to its speed. • Studies the expected space needed for charging infrastructure and the possibility of in-route charging which reduces costs.
Going Electric: A Pathway to Zero Emission Buses by UITP and European Bank	Europe	BEB, IMC, Hybrid, Hybrid/Battery trolleys	• Demonstrates that trolleybuses that recharge batteries using overhead contact lines can be cost effective, especially when there is already an infrastructure in the city. • Compares different technologies in terms of operating range, battery weight, etc. • Analyzes the space required for charging infrastructure.
Hybrid Trolleybus for Berlin-Spandau by: Fraunhofer institute	Berlin	Hybrid Trolleybuses, IMC, BEB	• Studies infrastructure costs, electricity consumption, and the effect of demand peaks. It uses the same simulation tool that will be used in this study for the analysis of electrified routes: the Open Track-OpenPowerNet. • For a Berlin-Spandau line, it recommends the use of IMC trolleybuses, as it is the best in terms of cost-effectiveness.
Bus Electrification: A Comparison of Capital costs.	Multi City Study	Depot Charging (BEB), IMC, Conventional Trolleybuses	• Compares capital costs, electrical infrastructure costs, and the size of fleets required by each of the electric bus technologies.

Although all the studies reviewed for this work are not shown in this table, most are very similar to the first three cases in the table. Most of the papers, articles, and documents focus on comparisons among the most common electric bus technologies in the world; therefore, they mainly concentrate on depot charging battery electric buses and opportunity charging buses (OC).

The last three studies presented in the table do analyze IMC trolleybus technologies—and all agree on the importance of not dismissing the technology out of hand—but nevertheless fail to consider its potential. In what follows, we aim to deepen the evaluation of IMC technology to show it is a real possibility for a broad electrification of San Francisco's bus fleet.

4. Glossary

Auxiliary power system consumption

The auxiliary system in an electric bus comprises the elements that consume energy but do not contribute to traction. Some examples are:

- Fee collection system
- Lighting
- Air compressor
- Hydraulic pump
- Air conditioning
- Heating

Typically, the most electrically demanding component on buses is the heating, ventilation, and air conditioning (HVAC) system. In hot conditions, this system can account for 50 percent of the total energy consumption for auxiliaries. Because heating is more energy intensive than air conditioning, HVAC demand can reach 70 percent in colder temperatures. While San Francisco's moderate climate requires less cooling and heating, climate change–induced warming is likely to increase cooling requirements (Bartłomiejczyk y Kołacz 2020).

Battery degradation

The decrease in energy storage capacity of a battery. Battery degradation occurs due to constant charge and discharge cycles. A considerable depth of discharge, a large number of charge and discharge cycles, and the peak current demanded can accelerate the aging process.

Daily transport capacity of a route

The capacity a route has in a day, measured in passengers per day. In electrical systems terms, this variable can be understood as the "energy" that the system must supply daily.

Delta of state of charge (ΔSOC)

An indication of the change in state of charge (SOC) in a charging process. Used to characterize battery cycles.

Depth of discharge (DOD)

An indication of the percentage of battery that has been discharged compared to the total battery capacity. For example, if a battery was brought to a state of charge of 20 percent (%SOC=20%), the depth of discharge is 80 percent (%DOD=80%).

LFP battery

Lithium-ion iron phosphate battery. Its gravimetric energy density is lower than that of NMC, but it is recognized for being very safe. As it does not contain cobalt—which is subject to production restrictions and sourced from high-conflict regions—it is an attractive alternative to batteries containing that metal.

LTO battery

Lithium-ion battery whose anode is covered by a compound with a nano-structured lithium-titanate instead of carbon. Despite having a lower gravimetric energy density than NMC batteries, it has a higher gravimetric power density, so it can be charged and discharged at a higher speed.

NMC battery

Lithium-ion battery whose cathode consists of nickel, manganese, and cobalt. NMC batteries are currently preferred in electric vehicle applications due to their high gravimetric energy density.

Peak shaving technology

An innovative method of increasing battery life in electric buses and reducing stress on the grid. Peak shaving technology limits the charge/discharge power in the battery to realize a constant power demand profile.

When an IMC trolleybus is connected to the catenary, it is possible to apply peak shaving in two ways. First, when the network is experiencing overload, the traction of the vehicle can be assumed by the battery, thereby reducing demand on the network. Second, when the *battery* is subject to unusually high demand, the *grid* can assume part of the demand. The technology reduces maximum battery power, especially in periods of high demand, and improves battery life (Pham, Rosca y Wilkins 2016).

Peak transport capacity of a route

The maximum transport capacity of a route measured in passenger-hour-direction. In electrical systems terms, this variable can be understood as the “power” of the transport system.

Regenerative braking

A strategy to recover kinetic energy when an electric vehicle is braking. When the vehicle is decelerating or going downhill, the kinetic energy is converted into electrical energy and stored by the battery or returned to the catenary for use by another vehicle. In conditions where the battery cannot store more energy due to a full SOC, there are two scenarios:

- *If the bus is not connected to the catenary*: Resistors can dissipate the electrical energy from the heat breakdown.
- If *the bus is connected to the catenary*: The energy from the break is injected into the grid through the poles.

Route Demand Factor (RDF)

A factor that helps measure how long a fleet must be available to meet the passenger demand for a route. It is calculated as the ratio between the offers in buses-hour required and what the offer would be if the whole fleet could operate 24 hours a day.

Route elevation profile

An elevation profile consists of a two-dimensional, cross-sectional view of a landscape. In this case, the profile of the route presents information on the slope of the hills that will be traveled by the trolleybus. Route elevation profiles provide an understanding of the electrical power demanded by the car on critical sections of the route, such as those with very steep inclines (esri 2019).

State of charge (SOC)

The percentage of energy remaining in a battery relative to its maximum rated capacity. A complete SOC means the battery system cannot be charged further. The SOC can be absolute or relative: The absolute SOC is the available energy of the battery at a given time; the relative SOC is the ratio between available energy and battery capacity at the time of measurement was made (SFMTA 2021).

State of health (SOH)

Refers to the maximum storage capacity of the battery at any given time compared to the maximum storage capacity when it was new. This is usually expressed as a percentage. Normally, for electric vehicles and BEB, 70 percent to 80 percent SOH is considered a healthy limit.

Traction Substation (TPS)

Generally composed of a transformer-rectifier group for direct current (DC) traction systems, this substation feeds the traction network for vehicles.

5. Technology Overview

In this section, we survey the most feasible alternatives to electrify the current fleet of buses:

- Depot-charge battery electric bus (DCBEB),
- Opportunity-charging electric bus (OCBEB), and
- Electric battery–powered trolleybus with IMC.

5.1. Depot-charge battery electric bus

DCBEBs are usually charged overnight or during operational off-peak periods (Díez y Restrepo 2021). This technology requires buses with batteries with large energy storage capacity, which reduces the passenger transport capacity, as it is necessary to meet the maximum circulation weights in the buses (Oversize/Overweight Permit and Regulations). If the fleet is to be grown to meet increasing transport demand and current depots do not have the technology or space to accommodate new buses, significant modifications must be made to existing infrastructure (we discuss this scenario further later in this study). In this study, references to BEBs will correspond to this type of bus. Figure 1 shows a typical charging scheme for DCBEBs.

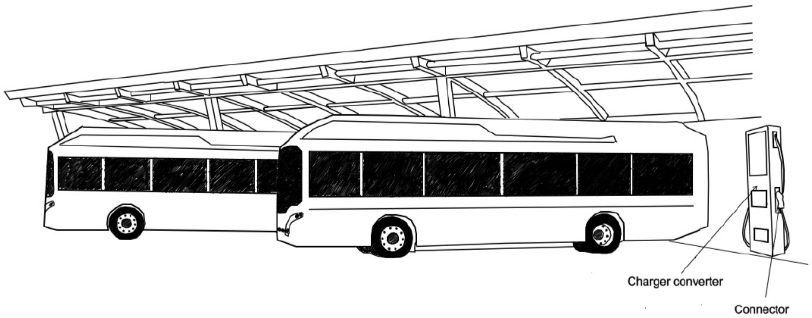


Figure 1 Depot charging. Taken from (Díez y Restrepo 2021)

5.2. Opportunity-charging battery electric bus (OCBEB)

The OCBEB aims to overcome the economic and spatial disadvantages posed by depot charging. OCBEBs are equipped with a battery with less storage capacity (i.e., lower weight) than the BEB battery, which preserves passenger capacity that would otherwise be lost.

“Opportunity charge” refers to charging that occurs during operation when the bus stops, even for brief moments—at passenger stops, for example—at high power. (Charging can also occur for longer durations at lower power in the terminals.) A common method of OC is through special pantographs located in the bus roof (Lajunen 2018) (as shown in Figure 2) or through special inverted pantographs at the charging station that connect to bars on the bus roof. There are three types of chargers used for opportunity charging: "Depot and terminal charging with powers from around 40 kW to 60 kW, 400 kW fast on-route charging, and ultra-fast on-route charging above 500 kW" (Díez y Restrepo 2021). For this study, any additional mention of OC will refer to OCBEB.

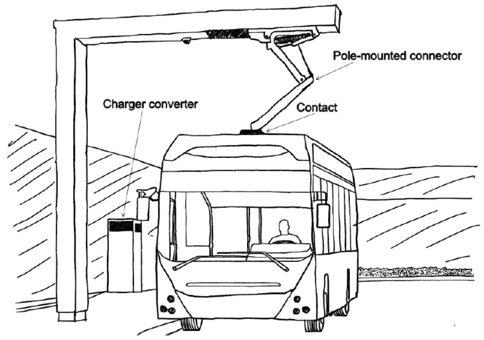


Figure 2. Opportunity Charging. Taken from (Díez y Restrepo 2021)

5.3. In-motion charging

In-motion charging is a type of opportunity charging in which a wireless feeder or external conductor is used to charge the battery of the trolleybus while traversing a given section of the route. IMC can be carried out wirelessly (wireless IMC) or conductively (conductive IMC). This study only evaluates conductive IMC (any additional mention of IMC will refer strictly to this type). Conductive IMC uses overhead wires to power buses (see Figure 3). Charging trolleys connect to the catenary in specific sections of the route and allow battery recharging both while the bus is in motion and stopped. At the end of the wired section, the collector trolleys are disconnected, and the battery supplies the bus for the remaining part of the catenary-free route. As this technology is compatible with San Francisco's existing catenary infrastructure, conductive IMC allows the utilization of existing overhead contact lines on overlapping bus routes, mitigating capital costs. presents the most important elements of an IMC overhead line infrastructure.

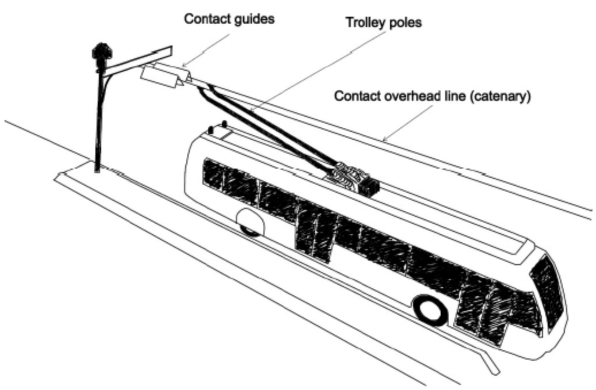


Figure 3. Conductive In-Motion Charging. Taken from (Díez y Restrepo 2021) with permission of authors.

The infrastructure required for IMC implementation consists of:

- **Medium voltage feeders**, which supply energy from the medium voltage (MV) network to traction substations and depot chargers.

- **Traction power substations (TPS),** consisting of a coupling point to an MV feeder, a power transformer, and an AC/DC converter. TPS can supply power to the overhead contact line sections and/or chargers of the depot. The cost of this infrastructure depends on its potential installed capacity.
- **Catenary section (catenary)**, which consists of the elements and equipment associated with the catenaries: poles or masts, insulators, and mechanical supports, among others. Its cost depends on the length of the catenary, the number of intersections with other catenaries, and the feed power.
- **Depot chargers:** Power converters used to charge battery electric buses with direct current (DC). The cost depends on the charging power.
- **On-board battery:** Compared to other BEB technologies, IMC battery capacity is significantly lower. The cost depends on the technology used and its storage capacity.

An IMC bus can automatically disconnect from the overhead contact line without stopping, but it must reconnect when parked at stops; it does this via guides installed in the overhead contact lines, which direct the trolleys poles toward the wires. Automatic trolley pole "catchers" can be seen on the catenary system in San Francisco, given that this type of charging is currently deployed in the city.

Figure 4 shows the additional components of the IMC bus. The collector—which can also be referred to as the pantograph or "pole"—connects to the catenary and conducts the power to a DC/DC converter. The converter transforms the voltage received from the catenary to a voltage tolerated by the battery bank. The battery and DC/DC converter connect to the DC link. This ensures that the motor receives the power it needs, and that the system prioritizes battery charging or bus traction as needed. The power required by the motor is converted to AC via the DC/AC converter, which can be configured through programming the bus controls, achieving what could in fact be considered the true smart electric bus.

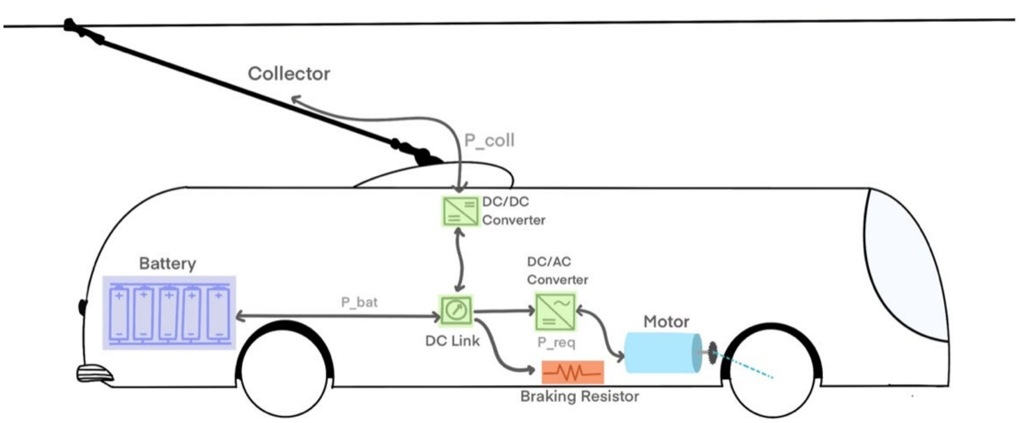


Figure 4. IMC bus electrical system.

6. Methodology

Using the Open Track and OpenPowerNet programs, we tested the three technologies described in Section 5. These are:

1. Depot-Charging Battery Electric Buses
2. Conventional trolleybuses, with the contact line along the entire route and without an energy storage system
3. In-motion charging trolleybuses

Our procedure for evaluating these three electrification alternatives consists of six stages, including detailed simulations and optimization strategies to deliver reliable and accurate information to aid in the decision-making process. The stages of the methodology are:

1. Definition of operating conditions (vehicle, route, and additional information)
2. Calculation of tractive effort and mechanical power
3. Electrification optimization
4. Analysis of battery behavior and lifespan
5. Detailed electrical simulation
6. Basic electrical design

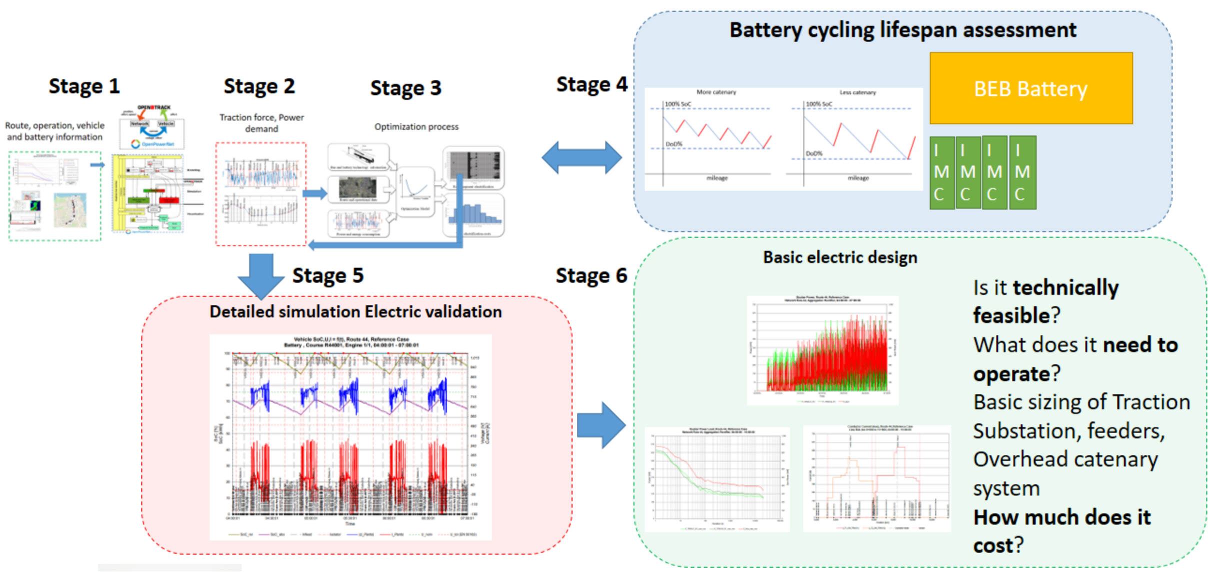


Figure 5. Methodology for technology assessment.

We apply the methodology initially to Route 44, which is currently serviced by diesel hybrid buses. This route will be used as a model for the evaluation of a general electrification case. We apply the same methodology to the other diesel-hybrid routes that are operated from the same yard (Woods) to evaluate their aggregate effect and expand the evaluation to the yard-depot level. Figure 5 presents an overview of the methodology and its stages.

It is important to note that all six stages will not be applicable to all technologies. This is because different technologies require different considerations. For example, for pure trolleybuses, researchers do not need to define the necessary overhead contact line segments, because the catenary will cover the entire route.

6.1. Stage 1: Definition of operational conditions

For all the alternatives evaluated in this study, we prepared route, vehicle, and operational information. We treated the battery-electric trolleybuses produced by New Flyer as reference vehicles. We obtained route information from Geographic Information System (GIS) data provided by the San Francisco Construction Electric Industry. (We also collected some operational information directly from SFMTA, such as itineraries (frequency of service) and the size of the fleet used for each route.) Some evaluations consider a higher frequency of dispatch to meet higher projected passenger demand.

6.2. Stage 2: Calculation of tractive effort and mechanical power

We calculated tractive effort and mechanical power using the Open Track software for all alternatives. The result is the traction effort and power profile of a bus at each point of the route. This allows us to identify the route segments that require the highest energy consumption and determine the appropriate sizing of the traction motors. Mapping the energy demand of buses is fundamental to the design of an optimal energy supply and charging system.

6.3. Stage 3: Electrification optimization

For Stage 3, we follow the algorithm presented by Díez and Restrepo (Díez y Restrepo 2021), which considers the information obtained in Stage 2 as well as the cost of energy storage systems and the market or benchmark costs of power-supply and battery-recharging systems. The algorithm was developed to find the most cost-effective solution to electrifying a given bus route. Its outputs include recommended energy supply points, the best segments for installation of overhead contact lines, and the characteristics of the energy storage system.

The algorithm also suggests, albeit indirectly, the feasibility of certain technologies for the electrification of routes. For example, if the algorithm finds that, for a certain route, the lowest-cost solution does not require the use of electrified segments (or that they are very few and very short), we interpret that result to mean the best option is depot charging. If the algorithm finds that the lowest-cost solution for a route includes multiple supply points with high charging power—but of a limited length—an OC scheme is probably the best option. If the algorithm suggests one or more catenary segments with significant lengths (greater than 200 m, for example), the IMC solution fits the route.

We improved on Díez and Restrepo's (Díez y Restrepo 2021) original algorithm to consider route segments where catenary installation was not feasible, for example parks or stretches of routes where the visual impact of overhead lines must be limited.

6.4. Stage 4: Analysis of the battery and its lifespan

In Stage 4, we determine the battery characteristics necessary to meet the expected operating time for IMC and BEB trolleybuses as well as consider the ecological impacts of replacing the battery. We analyze the results of this stage in Stage 3. This allows us to adjust the depth of discharge of the battery according to best practices for charge–discharge cycles.

6.5. Stage 5: Detailed electrical simulation

For catenary-based alternatives, we analyze the characteristics of the TPSs, such as its spatial distribution, configuration, and capacity-size.

TPSs feed the catenary segments identified in Stage 3. In most cases, the connection from the substation to the catenary appears at intersections or overlaps with the existing catenary infrastructure. In cases where existing substations have sufficient power capacity to support the route, the new catenary segments could be fed from those points. If this is not the case, new TPSs—with adequate power capacity—could be connected to the catenary at those same locations. Along with the additional power capacity the number of vehicles on the route could also be increased.

In this stage we identify the technical specifications of the equipment required to sustain any technological change. This also allows us to determine infrastructure costs, which will be used to compare the cost of electrification among several alternatives and scenarios.

The operational information obtained at Stage 5 includes:

- Total energy consumption of buses on route
- Losses in the catenary system and losses in the battery charge/discharge process
- Energy consumption per vehicle per mile
- Overall efficiency of the system

In all cases, we keep the maximum passenger capacity of the route constant and calculate the number of buses for each alternative via an analysis of the batteries they require. For example, for Route 44, we examine a fleet of 16 trolleybuses, 16 IMC buses, and three different BEB fleet scenarios. In the case of Route 44, 1.18 battery buses (replacement ratio 1:1.18) are required to transport the same passenger capacity of an IMC bus. We explain the replacement rate further in Section 8.

6.6. Stage 6: Basic electrical design

Stage 5 enables us to suggest a basic electrical design for the route. This design consists of the basic selection, sizing, and specification of the main equipment required to achieve the electrification of a given route. The key elements of the basic design are:

- The number of traction substations (TPS) and their recommended location and capacity;
- The segments where overhead line must be installed for efficient operation;
- The basic specifications of the buses that must be used for the operation of the corridor; and
- The energy storage capacity and its operating cycle.

7. Application of the Methodology

We focus our analysis on the electrification of routes that are currently being served by diesel-hybrid buses. The model route we selected for the application of the methodology is Route 44 due to its high capacity, challenging topography, centrality to lifeline service and regional connectivity for lower-income neighborhoods, its crossover with multiple trolley lines, and overall length.

7.1. Stage 1: Operating conditions

The operating conditions we considered for San Francisco's diesel-hybrid-bus routes include operating distance, outside temperature, energy consumption, power consumption of auxiliary services, and regenerated energy.

Operating distance

Operating distance is the distance traveled by the bus before the battery must be recharged. According to the SFMTA's zero emissions plans, an operating range of 160 miles is a good reference for battery-powered buses (SFMTA; WSP 2022). The basic design of IMC buses entails their continuous operation—that is, like a conventional trolleybus, they do not require depot charging at night.

Outside temperature

Because the energy consumption of auxiliary bus services—i.e., HVAC—depends on the outside temperature, we include in our analysis San Francisco's monthly maximum and minimum temperatures. Battery capacity must be optimized to provide continuous operation in winter when a bus's heating system is at its highest energy demand. Figure 6 shows the average minimum and maximum temperatures in the city of San Francisco in both °C and °F

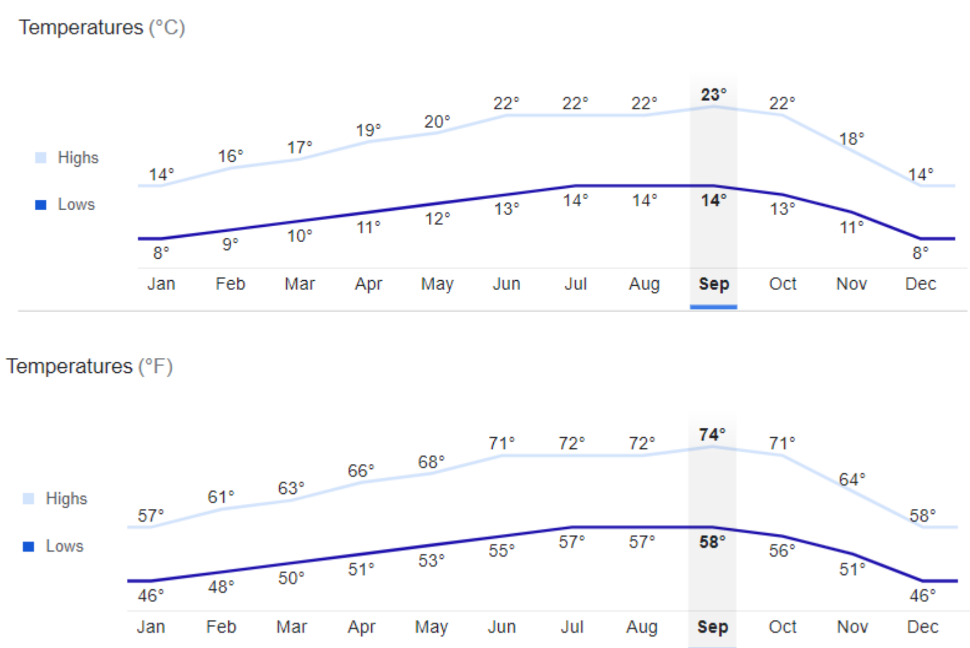


Figure 6. Monthly weather ranges in San Francisco in (a) degrees Celsius and (b) Fahrenheit

Temperatures are divided into three ranges:

- Low: 14–57°F (10–14° C)
- Normal: 58–67°F (15–19° C)
- High: 68–84°F (20–29° C)

San Francisco's climate is currently relatively mild and does not experience the extremes of cities such as Vancouver or Seattle. Nevertheless, San Francisco's average temperature has climbed 2°F since 1970 and will increase further as climate change accelerates (California Energy Commission 2019), thereby increasing the need for air conditioning.

Energy Consumption

According to the ViriCiti E-Bus Performance Report, the energy consumption of 40-foot buses is on average 0.99 kWh/km (1.59 kWh/mile). This occurs in optimal climatic conditions, i.e., in normal temperatures. When temperatures are in cold ranges, 40-foot electric buses experience up to a 14 percent increase in energy consumption, whereas in high temperatures, buses see an increase of up to 9 percent (VIRICITI 2020).

We estimate the traction energy consumption of buses on San Francisco routes using Open Track. We determine the auxiliary consumption from the information in Table 2. Finally, we use OpenPowerNet to simulate a bus's behavior, considering traction and auxiliary services.

Table 2. Consumption of 60-foot electric buses at different temperatures

Temperature	*Energy Consumption [kWh/km]*	*Energy Consumption [kWh/mi]*
Cold	1.12	1.81
Normal	0.99	1.59
High	1.08	2.73

Figure 7 shows the correlation between external temperatures and the energy consumption of electric buses. As San Francisco has temperatures in the range of 46°F to 73°F, the months of interest for this figure are from June to December. In the graph, electricity consumption remains at its minimum values when temperatures are around 68°F—the comfort temperature point for passengers.

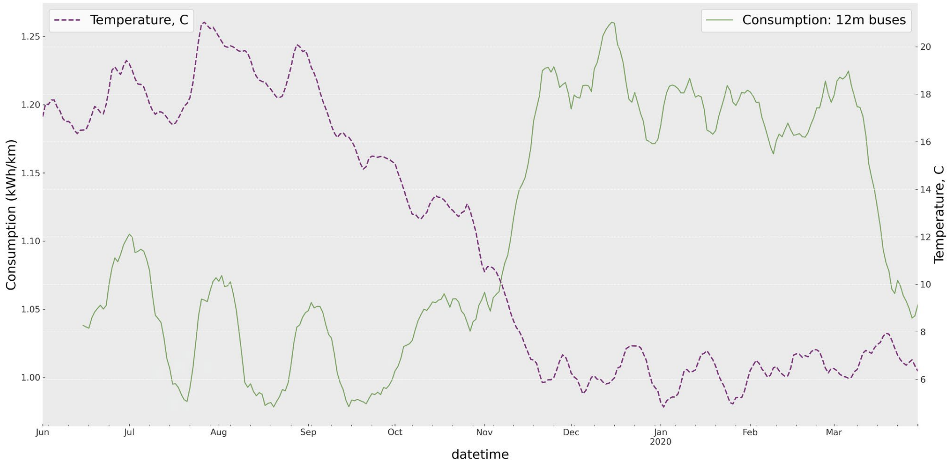


Figure 7. Correlation of temperature and daily average consumption of 60 ft buses. Figure taken from (VIRICITI 2020).

Power consumption of auxiliary services

Auxiliary services represent approximately 28.3 percent of the total energy consumed by the vehicle (ViriCiti 2020), though the exact percentage varies depending on the efficiency of the HVAC system. For this study, we calculated the consumption per auxiliary as 10 kW for a 40-foot bus, but we assumed a conservative value of 25 kW in the simulations of the detailed electrical model.

Regenerated energy

The ViriCiti report examines regenerated versus consumed energy in e-buses and concludes that the percentages of regenerated energy are in the range of 22.3 percent and 24.3 percent (ViriCiti 2020). One of the advantages of OpenPowerNet simulation is the estimation of the use of regenerated energy under the operating conditions of a route.

7.1.1. The representative route: Route 44

Route 44 O'Shaughnessy (Figure 7) is currently serviced by diesel-electric hybrid buses and is among the most challenging of routes for electrification due to its length and varied topography, operating profile as a key lifeline. The total length of the route is 17 miles, and it offers important night service, with a bus interval of 17 minutes between midnight and dawn (Figure 8). In addition, a constant interval is offered morning, midday, and afternoon, without a valley period that could serve as an additional opportunity to recharge a battery-powered bus. These characteristics and the route's crossover with. multiple trolley lines make it an ideal candidate for this alternatives analysis.

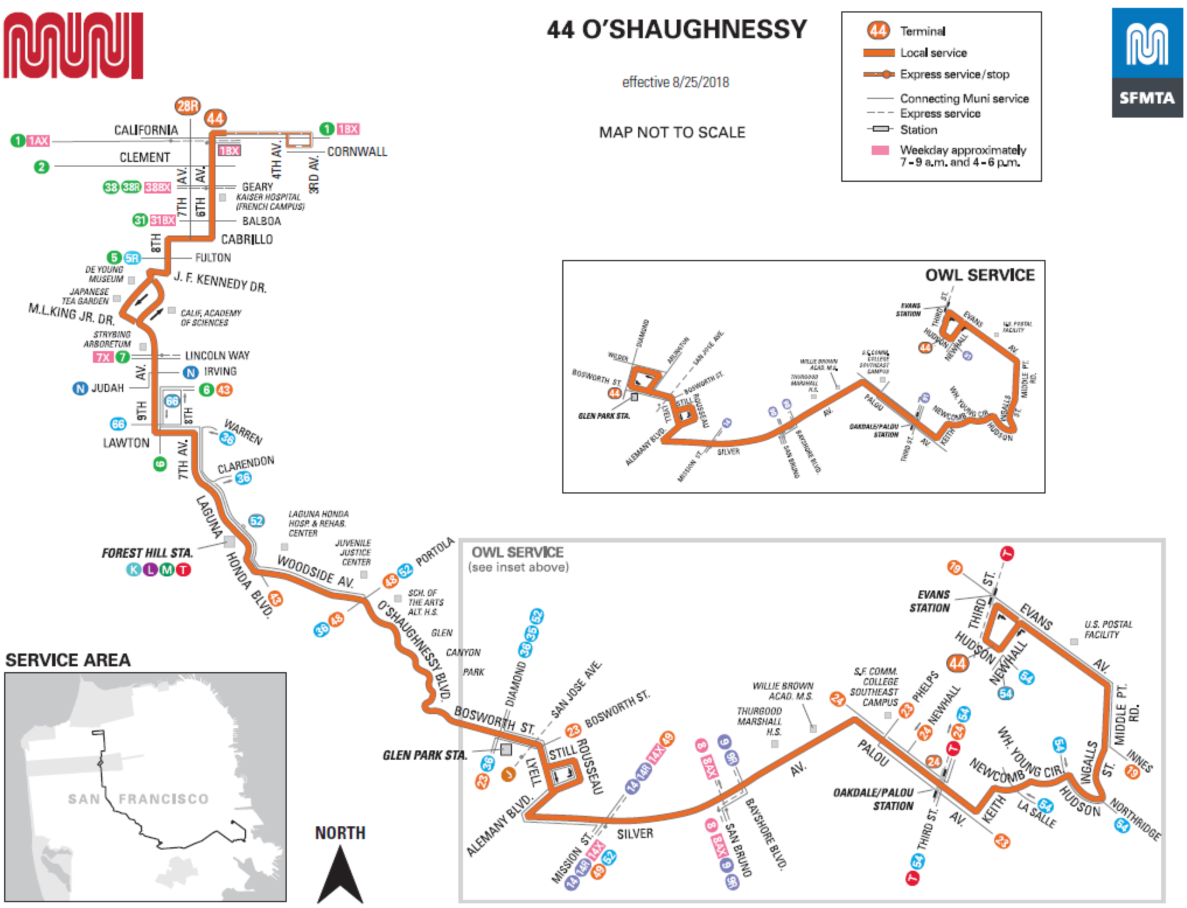


Figure 8. Route 44 O'Shaughnessy Map taken from SFMTA (SFMTA 2022).

Morning	Midday	Evening	Late Night	Owl
12	12	12	17	30

Figure 9. Route 44 O'Shaughnessy Bus Service Frequencies taken from SFMTA (SFMTA 2022).

We consider the elevation profile of the route in the optimization model, where it influences the sections that require catenary, and in the detailed operational simulations in Open Track. We analyze the route in both directions:

- North–South: to Hunters Point
- South–North: to Richmond District

Figure 10 shows the elevation profile of the route from Richmond to Hunters Point (north–south direction).

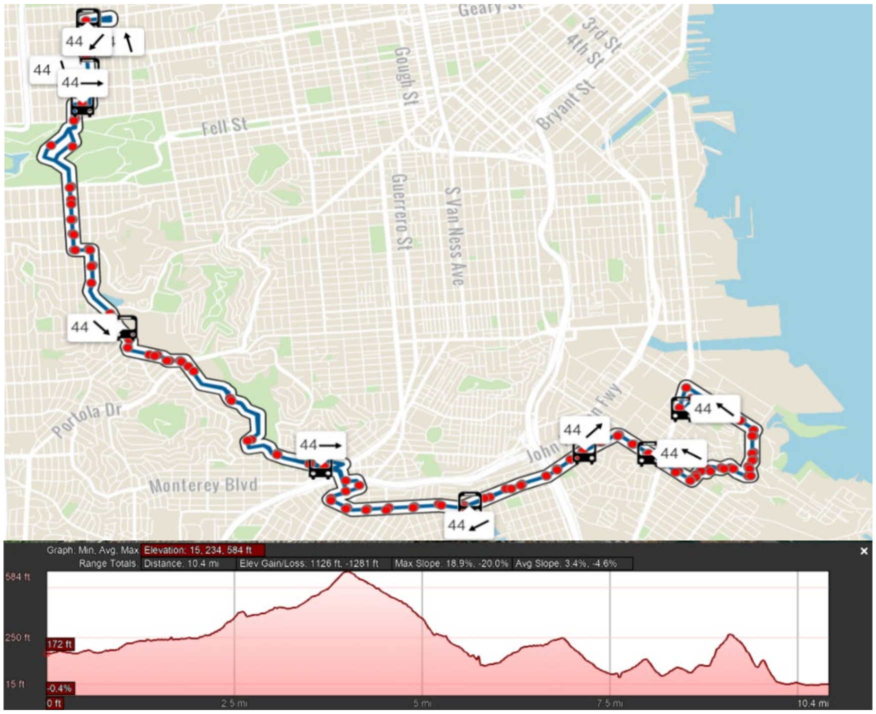


Figure 10. Route and elevation profile for route 44 heading south to Hunters Point.

The route coincides with existing contact line infrastructure that serves buses of other routes, a factor that we consider in our analysis. Figure 11 shows the intersections and common sections with overhead contact lines.

Figure 11. Route OHL intersections for Route 44.

We present the location and characteristics of the intersections with the existing overhead contact infrastructure in Table 3. The distance measurement is made from the departure at the Richmond stop (north to south).

Table 3. Overlaps and intersections of catenary of route 44 with other routes.

Type	***Route***	***Distance [km]***	***Distance [mi]***
Overlap	6 & tram	3.5 – 3.7	2.17 – 2.30
Intersection	49	9.86	6.12
Overlap	24	13.2-14.2	8.2 – 8.8

7.2. Stage 2: Tensile effort and mechanical power calculation

Using Open Track, we calculate the traction effort and mechanical power of the Route 44 bus for each point of the route and at each moment in its operation. In our model, the route is serviced by 40-foot buses, as it is currently. We assume the gross weight of the car buses is the same for all technologies—thus, in the case of BEB, passenger capacity is reduced to meet the maximum circulation weight. Figure 12 presents power results for a 40-foot bus operating on Route 44. The blue curve represents the profile of the route; the orange curve represents the mechanical power needed for traction.

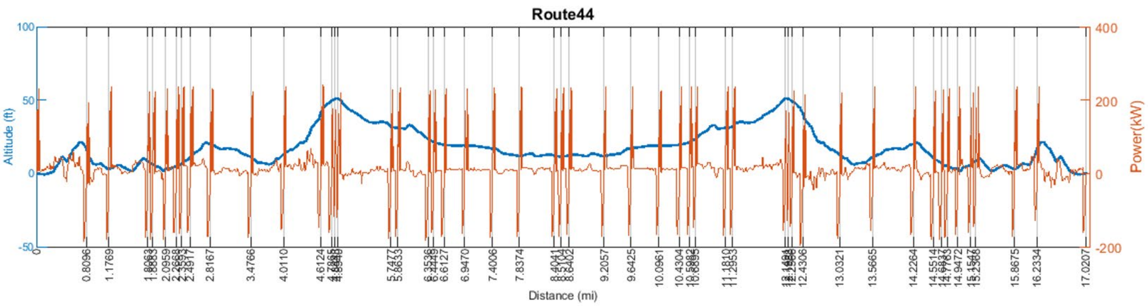


Figure 12. Result of traction power simulation results for a 40-foot bus on Route 44.

7.3. Stage 3: Electrification optimization

We use a two-stage process to determine the ideal design for a catenary system. First, we apply the Díez and Restrepo optimization model to minimize the total costs associated with the electrification of the route. The model focuses on minimizing this cost function and considers operational information such as energy consumption and bus schedules as well. As a result, the model defines which route segments should be electrified, the location of traction substations, and the battery capacity for each bus.

As shown in Figure 13, we simulate 16 different scenarios of unit costs of the different constituent elements of the system. These include:

- batteries, whose cost is a function of capacity;

- recharging infrastructure, whose cost is a function of the required power;
- overhead contact line infrastructure, whose cost is a function of segment length; and
- substations, whose cost is also a function of power.

The model calculates the optimal electrification segments, which are seen as red bars.

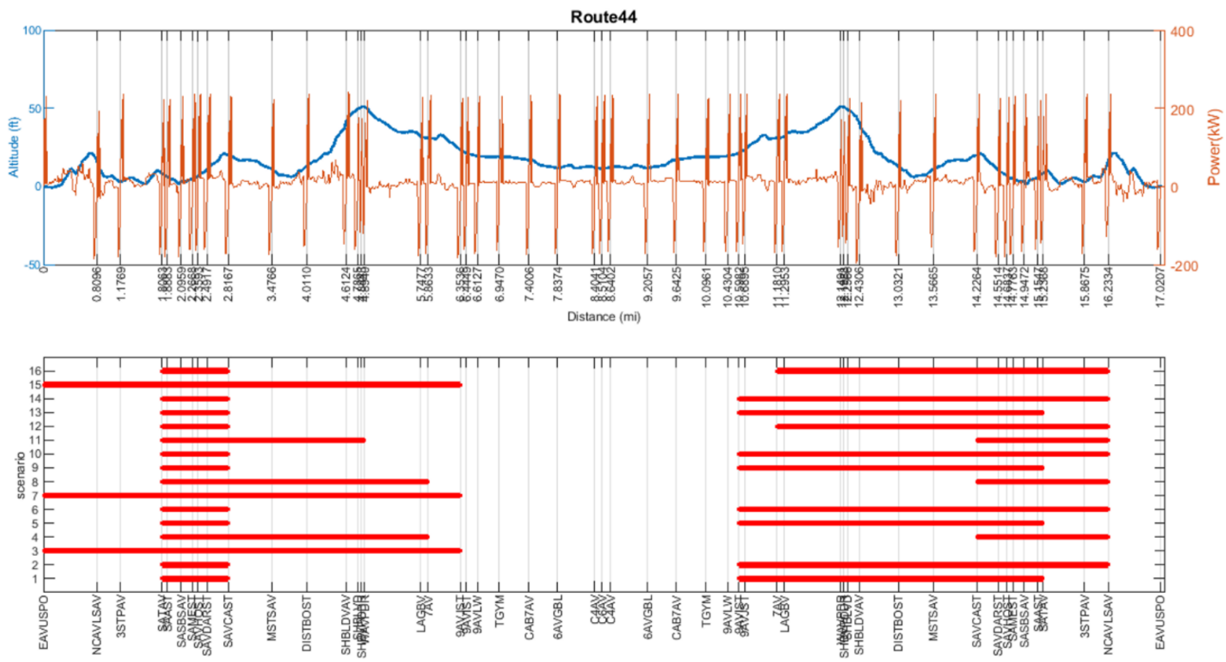


Figure 13. Detailed results for the optimization process.

The optimization process defines where sections of overhead contact line must be installed; thereby allowing each scenario to be simulated in OpenPowerNet to verify the various alignments' technical feasibility. OpenPowerNet simulations provide key information necessary for system planning, including the energy demand in the traction substations; the current by the power conductors and the overhead contact line; the voltage profiles in contact line and pantograph; and, for vehicles with storage system, the state of charge of the battery.

According to the optimization model, the catenary infrastructure that best suits Route 44 entails a minimum length 6.3 miles of new OHL infrastructure (37 percent of the total distance of the route). Figure 14 shows how the new OHL should be implemented. The OHL is divided into two sections: red for the north–south direction; green for the south–north direction. Additionally, we have designed the model to avoid construction of an overhead contact line in the segment that passes inside Golden Gate Park to minimize permitting conflicts. We expect that one-mile stretch of catenary of Route 24 can be used for the operation of Route 44 buses.

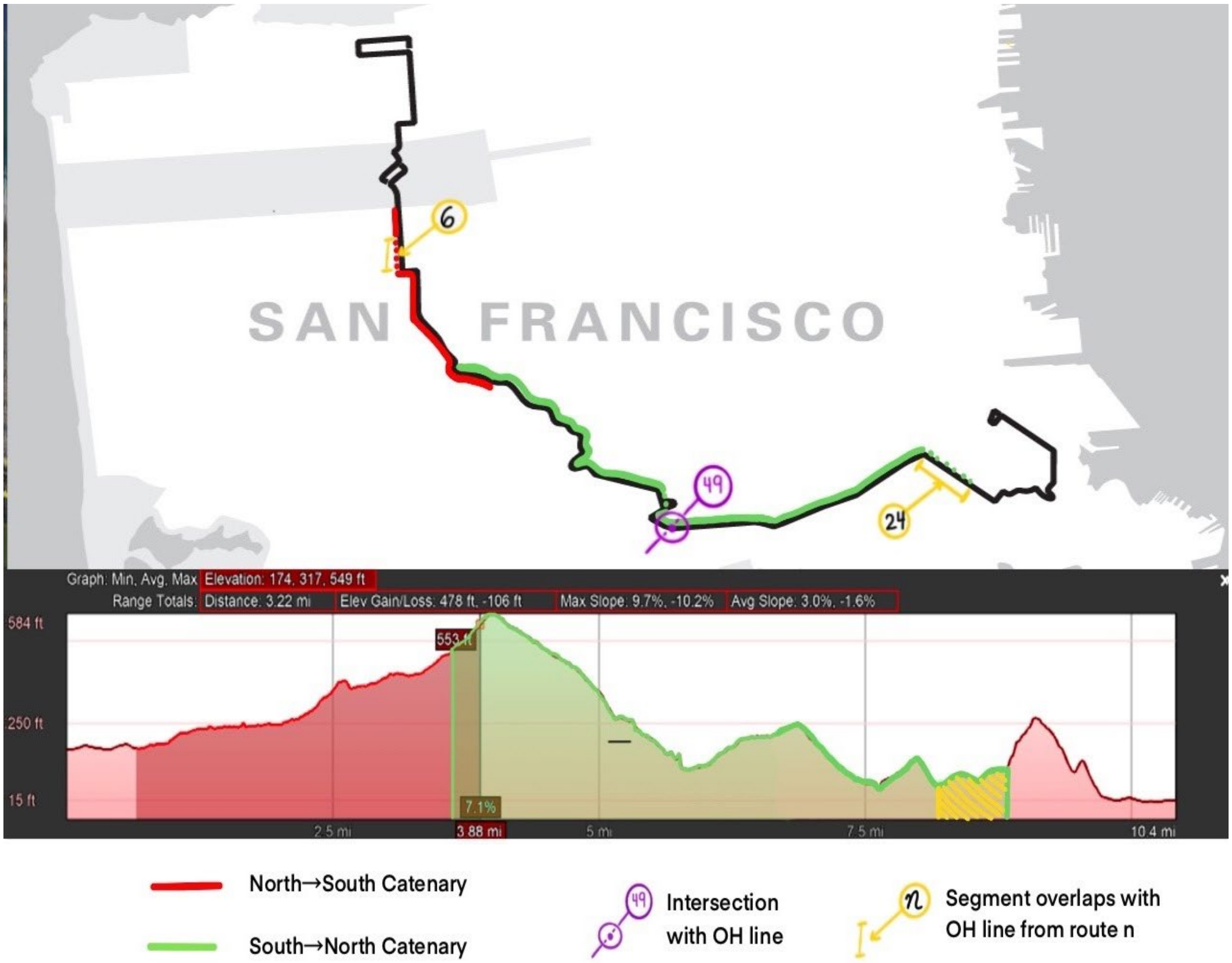


Figure 14. Diagram representing optimization results.

The catenary is strategically located to assist buses on steep slopes and thus reduce the maximum current required of the battery. Partial overlap in the two round-trip segments will facilitate the exchange of regenerative energy between buses operating in both directions.

The red and green dotted lines represent segments that do not require catenary installation, as there is existing OHL infrastructure.

7.4. Stage 4: Analysis of the battery and its life cycle

7.4.1. Ratio of battery to fleet size

Fleet size affects the cost of ownership of any transportation project. Bus prices vary in terms of technology and manufacturers. Other additional costs include:

- The cost of maintaining the bus and the infrastructure used for charging;
- The cost of parking yards by area and location; and
- The cost of energy to power the fleet.

In our model, we calculate fleet size according to each technology. The size of a given fleet is affected by:

Passenger occupancy. Each route has a number of passengers that must be transported at any given time. The demand for the service allows us to calculate a minimum fleet size as well as the necessary bus frequencies for each part of the day.

Downtime. Maintenance times and operational limitations, such as the need for charging in the depot, must be considered when determining fleet size.

Battery specifications. We include the storage capacity of each vehicle's battery, the weight and space required, and the distance range for each battery in our model.

7.4.2. Vehicle characteristics

In many cases, although the technology used to power the vehicle may be different, aspects of the vehicle itself remain consistent. For example, a manufacturer can use the same chassis when producing buses with different battery technologies. Manufacturers may also use the same electrical subsystems for items such as lights, doors, communication, and signage. Seats, grip handles or straps, floor surfaces, and other elements can also remain uniform. The only differential we consider is the type of technology used to deliver power.

The key difference among the types of electric buses is the battery. In pure trolleybuses, the battery is either very small or nonexistent. In IMC buses, the battery is larger than the backup battery of a conventional trolleybus and has a capacity like the battery of an electric sedan car (from 30 KWh to 120 kWh). OC buses use a battery similar to those found in IMC buses, though the batteries tend to be larger due to the absence of a contact line.

Among the alternatives considered herein, BEBs are equipped with the largest batteries, reaching storage capacities greater than 300 kWh in the case of 40-foot buses. Table 4 presents the characteristics of the simulated IMC bus for route 44. In our analysis, we consider two battery possibilities for the IMC bus: an NMC chemistry battery with a capacity of 71 kWh (like the one offered in the New Flyer catalogs) and a 30 kWh LTO battery. Table 5presents the characteristics of the trolleybus; Table 6, the characteristics of the BEB.

Table 4. OpenTrack+PowerNet simulation parameters for the IMC bus

Parameter	*Setting*
Motor control	DC/AC converter
Voltage	600 V
Total auxiliary consumption	25 kW
Max speed	60 kph
Max acceleration	1.3 m/s²
Empty weight	12400 kg
Adhesion weight	10000 kg
Gross weight	20000 kg
Number passengers	85
Length of vehicle	40 ft
Front surface area	80.7 ft²
Energy recovery	Yes
Battery capacity	71 kWh for NMC – 30 kWh for LTO
Battery weight	430 kg
Battery chemistry	NMC- LTO
Max C rate discharge	3 for NMC, 8 for LTO
Max C rate charge	2 for NMC, 3 for LTO

Table 5. OpenTrack+PowerNet simulation parameters for the trolleybus

Parameter	*Setting*
Motor control	DC/AC converter
Voltage	600 V
Total auxiliary consumption	25 kW
Max speed	60 kph
Max acceleration	1.3 m/s²
Empty weight	12000 kg
Adhesion weight	10000 kg
Gross weight	20000 kg
Number passengers	85
Length of vehicle	40 ft
Front surface area	80.7 ft²
Energy recovery	Yes
Battery capacity	N/A
Battery weigh	N/A
Battery chemistry	N/A
Max C rate discharge	N/A
Max C rate charge	N/A

Table 6. OpenTrack+PowerNet simulation parameters for the battery electric bus

Parameter	*Setting*
Motor control	DC/AC converter
Voltage	600 V
Total auxiliary consumption	25 kW
Max speed	60 kph
Max acceleration	1.3 m/s²
Empty weight	15000 kg
Adhesion weight	12000 kg
Gross weight	20250 kg
Number passengers	72
Length of vehicle	40 ft
Front surface area	80.7 ft²
Energy recovery	Yes
Battery capacity	350 kWh
Battery weigh	1350 kg
Battery chemistry	NMC -LTO
Max C rate discharge	3
Max C rate charge	2

Another difference among the alternatives is the power supply system. In trolleybuses, electricity is supplied through the overhead contact line and bus collection trolleys while OC buses rely on their internal battery. While IMC buses share the same type of power system as trolleybuses OC buses generally use a high-capacity pantograph that can withstand the demands of fast and ultra-fast charging.

The last difference we consider is the supply of energy, whether via charging or direct through the catenary. For trolleybuses, the catenary is available in the parking yard and on the route, but the bus could also be charged with opportunity chargers of limited power (up to 250 kW) while parked at some stops. Different IMC buses serving different routes may share the same catenary on overlapping or common sections, an innovative approach could be to charge the IMC buses using the same connectors or dispensers used to charge BEBs in the depots.

OC buses have low-power charging stations in the parking lot and high-power charging stations at some stops along the route. Although BEBs only need infrastructure in the yard, they often require several high-power charging stations near each bus. Although the use of higher output fast-chargers would minimize the number of total chargers it will degrade battery life.

7.4.3. Battery technology

Batteries are among the indispensable components of an electric vehicle and can be differentiated by size, weight, energy storage capacity, and chemistry. Size refers to the physical space needed to hold the battery and is proportional to the energy storage capacity. Weight too is proportional to the energy storage capacity.

The volumetric density of a battery (kWh/cu-ft) is the ratio of energy storage capacity to occupied volume is. A battery with a higher volumetric density holds more energy using the same volume of space as one with a lower density. The ratio of stored energy to weight is the gravimetric energy density (kWh/lb.). Gravimetric energy densities are more determinant than volumetric densities for buses however both volumetric and gravimetric energy density are critical factors when analyzing bus batteries, because an excessive large or heavy battery can limit the bus's transport capacity.

Three terms (defined above in Section 5) are used to measure battery performance: state of charge (SOC), state of health (SOH), and depth of discharge (DOD). Battery chemistry is what determines the operating ranges for SOC, SOH, and DOD; it also determines the weight and size of the battery and the amount of power it can produce. The usual chemistries are LFP, NMC, LTO, and NCA. It is important to note that:

- Depot charging buses tend to use batteries with higher gravimetric density of energy than power (NMC-LFP)
- OC vehicles tend to use LTO batteries because they have the highest capacities in terms of charge and discharge rates (higher gravimetric power density)
- IMC buses can use any chemistry depending on the preferred charging strategy. For example, if planners want to minimize the use of the catenary, batteries with high energy densities are the best choice. If the objective is to minimize the use of batteries, batteries with high power densities are preferable.

When the critical factor is weight, NMCs are preferred; when it is safety, LFPs are the better choice.

In our analysis, we model BEBs with NMC batteries and assume an optimistic gravimetric energy density of 280 W / Kg (127 W / lb.) (Weijiang Xue 2017). (Optimistic because this level of performance has yet to be achieved at the commercial level.)

We model two distinct IMC trolleybuses: one equipped with 71 kWh NMC battery, the other with a 30 kWh LTO battery. For each case, the charging and discharging power of the batteries must be configured differently due different charging specifications of the various battery chemistries. The NMC battery is limited to a charging power of 70 kW (C=1) and discharging power of 210 kW (C=3); the LTO battery is limited to a charging power of 90 kW (C=3) and a discharging power of 240 kW (C=8).

7.4.4. Estimation of the required battery capacity and size for BEB

Proper sizing of energy storage capacity is critical for meeting the route's range requirements. In this section we estimate the energy storage capacity required to meet the range requirements of the BEB alternative.

40-foot battery electric bus

To find the battery required for a 40-foot BEB, we analyzed the datasheet of an existing BEB: the New Flyer Xcelsior CHARGE NG bus. The datasheet indicates that this bus has a range of 174 ml using a 350 kWh battery. Because the required range is 160 ml, the bus's capacity meets the requirements of the route. The average energy consumption of a BEB is 1.59 kWh/mi. The average consumption of the same vehicle equipped with HVAC is 1.85 kWh/ml. If the required distance is 160 ml, the battery size for this vehicle is:

$$E_{prelim_{NO\ HVAC}} 160\ mi\ \times 1.59 \frac{kWh}{mi} = 255\ kWh$$

$$E_{prelim_{HVAC}} = 160\ mi\ \times 1.85 \frac{kWh}{mi} = 296\ kWh$$

We do not consider the DOD in the estimated values. Usually, a battery must be discharged until the SOC value reaches 20 percent (max DOD of 80%). The calculated battery sizes must then be increased to meet this limit. So, the required value for the battery is:

$$Batt = 255\ kWh \frac{1}{(1 - 20\%)} = 319\ kWh$$

$$Batt = 296\ kWh \frac{1}{(1 - 20\%)} = 370\ kWh$$

The latest value is in line with the New Flyer BEB specification sheet. The weight of the battery at 370 kWh is 1,322 kg (2,900 lb.), and the weight of the 319 kWh is 1,139 kg (2,900 lb.).

Table 7 shows the battery values used and their characteristics.

Table 7. Battery data for 40-foot buses

Bus	***Battery size***	***Battery weight***
BEB (non-HVAC)	319 kWh	1,139 kg (2,500 lb.).
BEB (HVAC)	370 kWh	1,322 kg (2,900 lb.)

7.4.5. Battery weight and passenger capacity

Buses are limited by the maximum weight allowed by the chassis and each axle. On battery-powered buses, battery size and passenger capacity are inversely proportional: The more the battery size increases, the less capacity there is for passengers. Therefore, the maximum number of passengers must be reduced to keep the bus's weight within the necessary limits.

Each technology has unique weight versus passenger relationships. Treated strictly, the size of the battery in the IMC bus assumed in this study would require a capacity reduction of three passengers (assuming ~80 kg per person) compared to the trolleybus however because slight weight exceedance can be mitigated though the use of composite materials and other mass savings we assume no passenger reduction for IMC, as can be seen in the New Flyer Xcelsior Trolley-Electric datasheet.

40-foot battery electric bus

According to the New Flyer datasheet for the 40-foot BEB, the number of passengers is conditioned on a 160 kWh battery. For the non-HVAC BEB bus, the battery capacity must be increased by an additional 159 kWh (for a total 319 kWh) to meet the same requirements. This equates to an addition of 568 kg or 1,250 lb. If the same passenger weight is considered (80 kg, or 180 pounds, per passenger), the number of passengers is reduced by 7. If the same calculation is made for the BEB bus *with* HVAC, the increase in battery capacity is 210 kWh. The weight of this battery increases the total weight by 750 kg, or 1,650 lb. This equates to a reduction of 10 passengers. Table 8 presents the results.

Table 8. BEB passenger capacity

Bus	*Battery size*	*Number of passengers*
BEB (non-HVAC)	319 kWh	77
BEB (HVAC)	370 kWh	74

The manufacturer also envisages a 40-foot BEB configuration that can hold a 525 kWh battery. With this battery, the vehicle would have a range of 280 miles with the HVAC on and about 330 miles with the HVAC off. However, the extra weight further limits passenger capacity. Using the same calculations, we find that a BEB with this battery capacity will have a passenger reduction of 16. The results are shown in Table 9.

Table 9. Passenger capacity for a BEB with a battery of 525 kWh

Bus	*Battery size*	*Max. distance (mi)*	*Number of passengers*
BEB (non-HVAC)	525 kWh	330	68
BEB (HVAC)	525 kWh	280	68

7.4.6. Fleet size to meet passenger demand

The number of vehicles used must meet the passenger demand for the route. Bus route operators must ensure that these vehicles are reliable, efficient, and attractive to their customers. If a fleet of a certain number of buses is to be replaced by another type of vehicle, the number of passengers it can accommodate must remain the same.

In the case of IMC, these buses have almost the same number of passengers as trolleybuses. Thus, the replacement ratio is 1:1. (This is true for both the NMC battery (71 kWh) and the LTO battery (30 kWh), as the additional weight does not compromise the passenger transport capacity of the buses.)

In the case of BEB buses, the weight of the batteries entails reductions in the passenger capacity of the buses and, ipso facto, increases in the size of the fleet to meet passenger demand. We perform these calculations below when we consider the freight and logistics requirements of the route.

Similar calculations could be executed for an average passenger of 70 Kg (150 lb.). The results for different scenarios are presented in Table 10. For this calculation, a gravimetric energy density of 280 kWh/kg is assumed, which is slated to become commercially available in the coming years. In Table 11, we present replacement ratios with respect to the diesel-hybrid buses currently on the road.

Table 10. Replacement ratio of different technologies with respect to 40-foot electric diesel buses (optimistic battery weight scenario)

Bus	*Battery Capacity*	*Passengers (80 Kg - 180 lb.)*	*Ratio*	*Passengers (70 Kg - 155 lb.)*	*Ratio*
IMC NMC	71 kWh	84	1:1	84	1:1
IMC LTO	30 kWh	84	1:1	84	1:1
BEB (non-HVAC)	319 kWh	77	1:1.08	74	1:1.10
BEB (HVAC)	370 kWh	74	1:1.12	70	1:1.13
BEB	525 kWh	68	1:1.23	65	1:1.3

Table 11. Replacement ratio of different technologies with respect to diesel buses with commercial battery values (current battery weight scenario)

Bus	*Battery Capacity*	*Passengers (80 Kg - 180 lb.)*	*Ratio*	*Passengers (70 Kg - 155 lb.)*	*Ratio*
IMC NMC	71 kWh	84	1:1	84	1:1
IMC LTO	30 kWh	84	1:1	84	1:1
BEB (non-HVAC)	319 kWh	75	1:1.11	73	1:1.13
BEB (HVAC)	370 kWh	72	1:1.14	70	1:1.17
BEB	525 kWh	63	1:1.34	60	1:1.4

Note about the LTO battery chemistry

Battery charge and discharge cycles are expressed by the letter C. A rate of C (1C) means that the charging and/or discharging current of a battery is equal to its total capacity. For example, a 20Ah battery can be fully charged or discharged within an hour using a 20A current. The same battery with a current of 2C can be charged or discharged in half an hour using a current of 40A.

The LTO battery has a charge and discharge current that is several times greater than the NMC battery. The normal C parameter for an NMC battery is usually around 0.5 C for charging and 1 C for discharge (however high values of C could be reached during limited time). The LTO battery is usually around 10C for charging and 10C for discharge. As a useful simplification, C can be estimated as the ratio of the battery power in kW to its energy in kWh.

This feature comes at a price. LTO batteries are the most expensive commercially available technology. In addition, they have the worst gravimetric density and volumetric density compared to other commercial cells; the poor volumetric density is compensated to the extent that the battery to be used requires less energy capacity thereby allowing for smaller batteries.

7.4.7. Fleet adequacy during peak periods

In the previous section, we introduced a bus replacement factor that accounts for the total transport capacity of the fleet, but it is also necessary to account for the passenger demand that must be satisfied throughout the day. In this case, it is the *availability* of buses, rather than their total number, that is the critical issue.

BEBs require long downtimes for battery recharges, a logistical challenge for transport agencies needing to guarantee that, with the minimum fleet, they can meet the maximum transport offer. Conventional trolleybuses, meanwhile, could operate 24 hours a day (although in practice they are taken out of service for cleaning and maintenance). The same holds true for properly equipped IMC buses. Although they can also be outfitted for depot charging, for this study we have assumed they can operate indefinitely like conventional trolleybuses.

Finally, any estimation of fleet size must account for other variables: additional fleet necessary to meet peak demand or backup buses to replace out-of-service vehicles or vehicles involved in incidents on route. We estimate this number also according to the required number of passengers on each route.

In this section we introduce two schemes for charging the fleet to satisfy the daily patronage, a simple manual scheme and an adjusted dispatch scheme. Along with the scheme consistent in the fleet required solely to meet the hourly peak passenger demand (minimum fleet for peak hour), these schemes will be taken as the three BEB scenarios to compare with the trolleybus and IMC alternatives. It is important to note that the minimum fleet scheme to meet peak hour demand would not be sufficient to meet daily patronage if the route has intensive use, and most of the buses are required to operate through the day, given little time margin for charging the batteries.

Bus and fleet scheduling

Bus schedules are determined by the SFMTA. Some routes operate on a daytime schedule (from 5:00 am to 11:00 pm); other routes operate on a 24-hour schedule. In both cases, the number of buses depends on the time of day. An example can be seen in Figure 14.

24 Divisadero
24-hour service daily
Share this: Facebook Twitter Email
SFMTA.com/24

Masks Recommended
Until Further Notice

Service Frequencies

Schedule	Morning	Midday	Evening	Late Night	Owl
Weekday	10	10	10	13	30
Saturday	12	12	12	13	30
Sunday	12	12	12	13	30

52 Excelsior
Weekdays 6am - 10pm; Weekends 8am - 10pm
Share this: Facebook Twitter Email
SFMTA.com/52

Masks Recommended
Until Further Notice

Service Frequencies

Schedule	Morning	Midday	Evening	Late Night	Owl
Weekday	20	20	20	24	–
Saturday	30	30	30	30	–
Sunday	30	30	30	30	–

Figure 15. Schedules and bus frequency for routes 24 and 52. Taken from SFMTA.

A 24-hour route, unsurprisingly, requires a larger fleet (depending on the stops and maintenance schedule of each bus). In the case of diesel-hybrid buses, stops will be for fuel, cleaning, and driver change. In the case of trolleybuses, stops will be mainly for cleaning and driver shifts. **However, for BEBs, stops will be for cleaning, driver shifts, and battery charging**. The last requires much more time than the other two. For a BEB with a 370 kWh battery, recharging could last at least 3 hours using a 120 kW charger.

The number of BEB buses purchased for a fleet must not only meet passenger demand and schedules but also cover the charge of buses to ensure continuous operation. Any estimate of the fleet must also consider the operating time of buses. This value requires knowledge of the size of the battery used (ef-batt) and the average speed and power consumption per mile (eff). The equation is as follows:

$$time = \frac{\dfrac{ef - batt\ (kWh)}{eff\ \left(\frac{kWh}{mi}\right)}}{speed\ \left(\frac{mi}{h}\right)}$$

We calculate the size of the battery from the desired operating range and the accepted DoD. For example, a 370 kWh battery with an 80 percent DoD has an effective battery use of 296 kWh. When we place these values into the equation, the result is:

$$time = \frac{\dfrac{296\ (kWh)}{1.85\ \left(\frac{kWh}{mi}\right)}}{15\ \left(\frac{mi}{h}\right)} = 10.66\ hours$$

The next step is to schedule the bus to meet SFMTA requirements. The route schedule for Route 44 is shown in Figure 15.

Service Frequencies

Schedule	Morning	Midday	Evening	Late Night	Owl
Weekday	12	12	12	17	30
Saturday	12	12	12	17	30
Sunday	12	12	12	17	30

Figure 16. Route 44 O'Shaughnessy schedule.

Below we explore two approaches to solving the problem of meeting passenger demand during the day while simultaneously accounting for the recharging time of the buses. In the first approach, we assume that buses can only be charged once a day and that, as a consequence, a significant fleet increase will be necessary to guarantee the daily offer. On the other hand, this scheme significantly reduces the peak demand of the network, to such an extent that the buses can be charged throughout the day and the batteries of the buses function as an energy storage system, thereby flattening the demand curve. We call this approach the Simple Manual Dispatch scheme.

The second approach is based on the fact that, through logistics optimization systems, it is possible to keep the buses operational as long as possible (which, in turn, results in the use of as few buses as possible). We refer to this approach as the Adjusted Dispatch scheme.

Simple Manual Dispatch scheme

To start, we proposed an eight-minute service frequency for morning, noon, and evening. To meet this frequency, the simulation showed that 16 active buses would be needed. Table 12 shows the number of buses required at any time of day (assuming that a bus will only be charged once a day).

Table 12. Number of buses required for operation at any time of day.

Num-buses	5	5	5	5	5	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	10	10	10
hour	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23

The complete data is shown in Table 13. Each operating fleet is shown in a different color. Each vehicle must run for 10 hours. We excluded time spent exiting and entering the parking lot from the simulation. Each bus has enough time to recharge as well as be cleaned and maintained.

Given that an additional BEB is needed for every 7 diesel-hybrid buses, 4 additional BEB buses are needed to meet the number of passengers currently using the route. We also include a spare bus for maintenance and emergency needs. The result is that 38 40-foot BEBs are required to replace an IMC fleet, trolleybus fleet, or diesel-hybrid fleet. (As we note above, diesel-hybrid, IMC, and conventional trolleybuses all have a 1:1 replacement ratio and a 24-hour operating capacity.)

Table 13. BEB schedules on-route and charge

Num-buses	5	5	5	5	5	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	16	10	10	10
Time (h)	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
BUS1																								
BUS2																								
BUS3																								
BUS4																								
BUS5																								
BUS6																								
BUS7																								
BUS8																								
BUS9																								
BUS10																								
BUS11																								
BUS12																								
BUS13																								
BUS14																								
BUS15																								
BUS16																								
EXTRA																								
EXTRA																								
SPARE																								
BUS17																								
BUS18																								
BUS19																								
BUS20																								
BUS21																								
BUS22																								
BUS23																								
BUS24																								
BUS25																								
BUS26																								
BUS27																								
BUS28																								
BUS29																								
BUS30																								
BUS31																								
BUS32																								
EXTRA																								
EXTRA																								
SPARE																								

There is a logical problem evident in the schedule reproduced in Table 13. Given that there are only eight principal chargers and two spare chargers, it is necessary to carefully synchronize the charging time of each bus. If the schedule is not met for any reason, there could be BEB dispatch problems the next day. Each bus has a ten-hour operation and a fourteen-hour maintenance routine (charging, cleaning, tires, and minor work). Identifying which BEBs are charged and which are not will induce difficulties in the yard operation plan.

Adjusted Dispatch scheme

The point of departure for this type of dispatch is the optimal use of the available fleet to meet daily demand. It includes partial charges of the buses during the day (but not fast charges) to avoid affecting battery life.

For this scheme, we calculate the availability of the bus first via factors such as the relationship between the operating time and the recharge time. In the case of routes operated with 40-foot buses, we assume two recharges—a main one lasting 4 hours and a partial-secondary one of 3 hours—for a total of 7 hours of charging, which would allow the bus to operate 17 hours. We include bus preparation times in the recharging times. The battery is recharged at a charging rate of C/4 to protect the life of the battery, so the charging power per bus is 100 kW.

The availability of battery buses (without fast charging) is:

$$BEB_A = \frac{17\ h}{24\ h} = 0.71$$

If we assume that trolleybuses and IMC buses have an availability of 0.95, the ratio between fleet availabilities would allow us to have an idea of the minimum replacement factor for the attention of the same daily demand (non-peak). Given these parameters, the replacement factor for daily demand attention ("RFDD") is:

$$RFDD = \frac{IMC_A}{BEB_A} = 1.34$$

Therefore, the fleet replacement factor of a trolleybus or bus IMC by BEB is 1:1.34.

Route demand factor

To account for the behavior of a route in terms of demand throughout the day, we include a route demand factor in our analysis. The route demand factor can be considered a representation of the relationship between the required transport offer in bus-hours and the offer that would exist if the maximum fleet required operated 24 hours.

Table 14. BEB schedules on-route and charging

Period	*Hours*	*Buses*	*Bus hours*
Owl	5	8	40
Morning	7	19	133
Midday	2	19	38
Evening	7	19	133
Late Night	3	14	42
Total	**24**	**79**	**386**

For Route 24, for example, the Route Demand Factor ("RDF") is:

$$RDF = \frac{386\ b-h}{19\ b\ \times 24\ h} = 0.85$$

This factor measures how long the maximum fleet of buses must be available; thus, it tends to be very high for high-use routes such as Route 44. Trolleybuses and IMC buses, thanks to their high availability, are suitable for the operation of this type of routes, while BEBs would have difficulties in meeting the same demand at the same fleet size.

The route demand factor, combined with the bus availability factor, allows us to estimate the relationship between the fleet required to cover the daily demand and the maximum operating fleet: the Additional Fleet Factor ("AFF"). For Route 44, served by battery buses:

$$FFA_{24} = \frac{RDF_{24}}{BEB_A} = \frac{0.85}{0.71} = 1.2$$

This means that in order to guarantee that BEBs can be available to meet the offer of the route, the bus operation must have 20 percent more buses (making the minimum fleet size, without reserve buses, 22 buses). However, when accounting for real-life constraints—such as bus recharging speed, charger availability, running times, etc.—the required fleet size will have to be even larger.

Using an iterative, computer-aided method, we design a tight dispatch based on the following constraints:

- A bus operates a maximum of 17 hours a day, with a long-term recharge and a partial recharge.
- The minimum charging period per bus is 2 hours, and no fast charges are made.
- No bus can operate more than 10 continuous hours, which can be checked in the last column.
- The number of total buses operating each hour satisfies the requirements of transport offer, which can be verified in the last row.
- When a bus appears green, it is operational; when it appears in red, it is being charged.
- There are no reserve buses.

Table 15. BEB Adjusted Dispatch

Bus/hour	Owl					Morning							Midday		Evening							Late Night			Total operational hours
	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	
1	0	0	0	0	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	0	17
2	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	17
3	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	17
4	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	16
5	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	17
6	0	0	0	0	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	1	1	17
7	0	0	0	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	0	0	0	16
8	0	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	1	1	1	0	0	0	17
9	0	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	1	1	1	0	0	0	17
10	0	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	1	1	1	0	0	0	17
11	0	1	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	1	1	1	0	0	0	17
12	0	0	0	0	0	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	17
13	0	0	0	0	1	1	1	0	0	1	1	1	1	1	1	1	1	0	0	1	1	1	1	0	15
14	0	0	0	0	0	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	1	1	1	16
15	0	0	0	0	0	1	1	1	1	1	1	0	0	0	1	1	1	1	1	1	1	1	1	1	16
16	1	0	0	0	1	1	1	1	1	1	1	0	0	1	1	1	1	0	0	1	1	1	1	1	17
17	1	1	1	1	0	0	0	0	1	1	1	1	1	1	1	1	1	1	0	0	0	0	1	1	16
18	1	1	1	1	0	0	0	0	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	1	15
19	1	1	1	1	0	0	0	0	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	1	15
20	1	0	0	0	0	0	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	17
21	1	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	0	0	16
22	1	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	0	0	15
23	1	1	1	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	0	0	0	1	1	15
Total Operational buses	8	8	8	8	9	17	19	18	17	18	18	19	18	18	19	18	18	19	18	19	19	14	14	14	
Bus Charging	0																								
Bus running	1																								

Although there are multiple solutions, the one presented in Table 15 allows for the satisfaction of 97 percent of the 386 bus-hours required daily by the example route using 96 percent of the hours that the buses would have available. Note, however, that any delay of a bus, unavailability of chargers, or increase in travel times would lead to the transport offer, at least in the case of battery buses, being compromised. In this scenario, the ratio of chargers to buses is 2:3.

From the previous analysis, from the number of chargers operating simultaneously, we can derive the demand curve.

As can be seen in Table 15, the timeframe of highest demand is between zero hours and 5 hours, reaching 1.6 MW. Figure 17 shows the offer of buses operating on the route (black) and the power demand of chargers throughout the day.

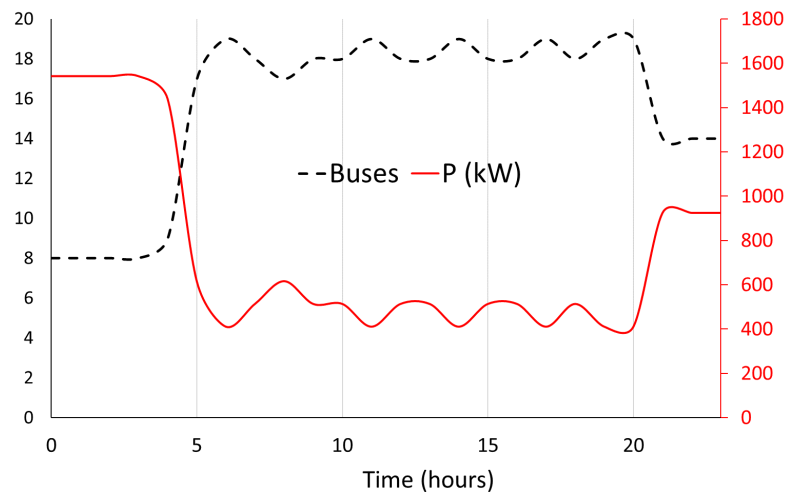


Figure 17. Power and buses throughout the day in Adjusted Dispatch scenario.

7.4.8. Size of yards for new fleet

Buses are usually maintained and checked in parking lots. These lots have the infrastructure required for each vehicle. In the case of trolleybuses, the lots are equipped with parking spots, service areas, and access to the catenary.

According to previous estimates for the Simple Manual Dispatch scheme, 38 BEBs must be parked and kept in the same yard. **That is 100 percent more buses than if the same scheme were serviced by IMC or trolleybuses.**

To calculate the total area of the BEB fleet yard, we consider the size of the vehicles, the charging apparatus, and other variables. Forty-foot BEBs require an area of 3.5m x 12m = 42m² (12 ft x 40 ft = 480 ft). The 1.5 MW substation for charging occupies an area of 9 m x 9 m = 81 m² (900 square feet). Charge and circulation areas are 4m x 3.5m = 14m² (14ft x 12ft = 168ft). For 38 BEBs and 10 chargers, the required area is:

$$Area = 38 \times 480 sq.ft + 900 sq.ft + 10 \times 168 sq.ft$$
$$Area = 20{,}830 sq.ft$$

The area for IMC trolleybuses is composed of a substation and parking spaces. The estimated number of IMC buses is 19. The total area for IMC buses is:

$$Area = 19 \times 480 sq.ft + 900 sq.ft$$
$$Area = 10{,}020\ sq.ft$$

Chargers can be added to the BEB yard to ease logistical issues related to charging. For example, if the number of chargers is increased to 19 from 10, the area of the BEB parking yard has to grow 1,512 square feet. Figure 18 presents a comparison between a possible BEB parking yard

(a) and an IMC parking yard (b). Note that these diagrams do not include circulation spaces for buses. We calculate the yard area for the other BEB scenarios using this method.

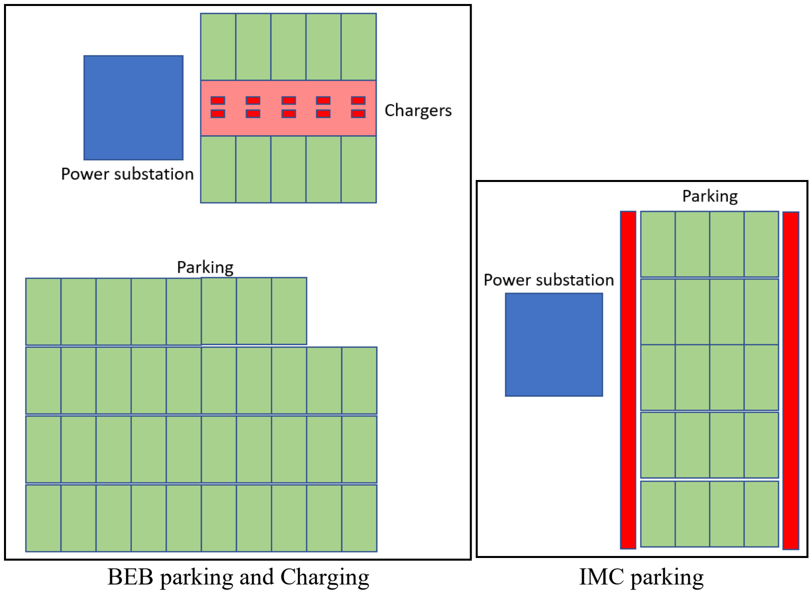


Figure 18. (a) BEB yard and (b) IMC yard.

7.4.9. Battery usage, life, and DoD

Estimating the battery life, determinable from the State of Health (SOH) parameter, is a complex task. Multiple variables can improve or worsen cell life. However, the main factor affecting battery life is the number of charge and discharge cycles—that is, the number of times a battery is charged and discharged before becoming unusable. In battery-electric vehicles, this percentage is between 70 percent and 80 percent.

A second important factor affecting battery life is the C charge rate. If the battery is charged with a charger whose charge rate is faster than the recommended C value of the battery—for example, by a fast charger —it reduces the life expectancy of the battery.

The last factor that affects the life of a battery is the battery's chemistry. An NMC battery can reach up to 3,000 charge-discharge cycles; an LFP battery can tolerate more than 5000 cycles. Other technologies, such as NCA, only support 1,500 cycles.

Battery utilization—that is, depth of discharge (DOD)—can increase or decrease the number of charge and discharge cycles in a battery. Typically, the number of cycles is calculated for a battery using a state of charge (SOC) between 20 percent and 80 percent. The relationship between SOC and DOD is:

$$DOD = 100\% - SOC$$

If the DOD increases beyond 80 percent, the battery life decreases faster: the maximum number of cycles is significantly inversely related to the DOD. A battery with a low DOD can achieve a higher number of cycles than a similar battery with a larger DOD. The McEvoy Photovoltaic Manual states that: "The cycle life of batteries is the number of charge and discharge cycles that a battery can complete before losing performance. The cycle life of Li-ion batteries is affected significantly by the depth of discharge (DOD%). The depth of discharge is the amount of a battery's storage capacity that is utilized. For example, a battery that is discharged only by 20 percent of its full energy capacity has a much greater cycle life than a battery that is discharged more deeply by 80 percent of its capacity so that only 20 percent of its full energy charge remains" (Kalogirou 2018).

Figure 19 (a) and (b) show this relationship. Note that the cycle life scale is logarithmic.

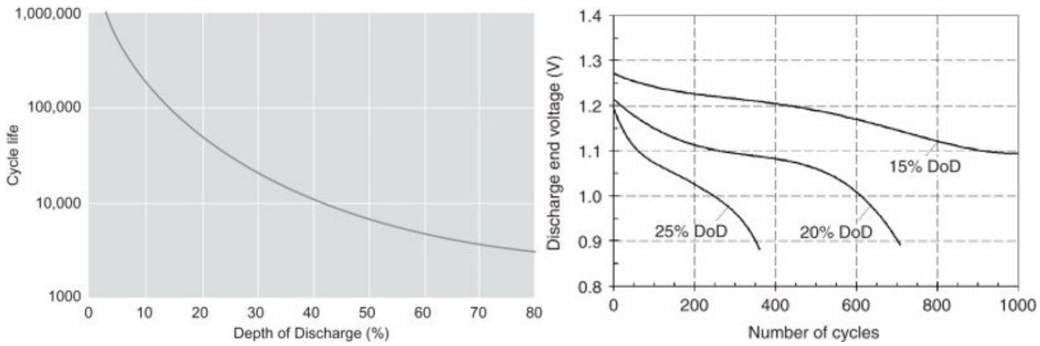


Figure 19. (a) Life cycle vs. Depth of Discharge and (b) final discharge voltage vs. number of cycles.

7.4.10. Influence of DOD on battery life

BEBs usually discharge the battery near to its minimum capacity, as they are meant to run without recharging for several kilometers or a full workday. Typically, planners estimate that meeting the operational distance of a given route will require 80 percent DOD when the battery is new. This means that the energy retained by the battery will be reduced faster than normal while cycling. After several cycles, the SOH will decline and the battery will maintain less charge. As the SOH worsens, consuming the same amount of energy will result in a slightly higher DOD. This means that the DOD will be a little over 80 percent.

As the battery degrades more, the next cycle will worsen the SOH and the DOD will be greater. This cycle continues to the point where the battery is completely degraded and cannot be used to power the vehicle. The following graph (see Figure 20) illustrates this phenomenon. The blue curve represents battery utilization and the orange represents SOH.

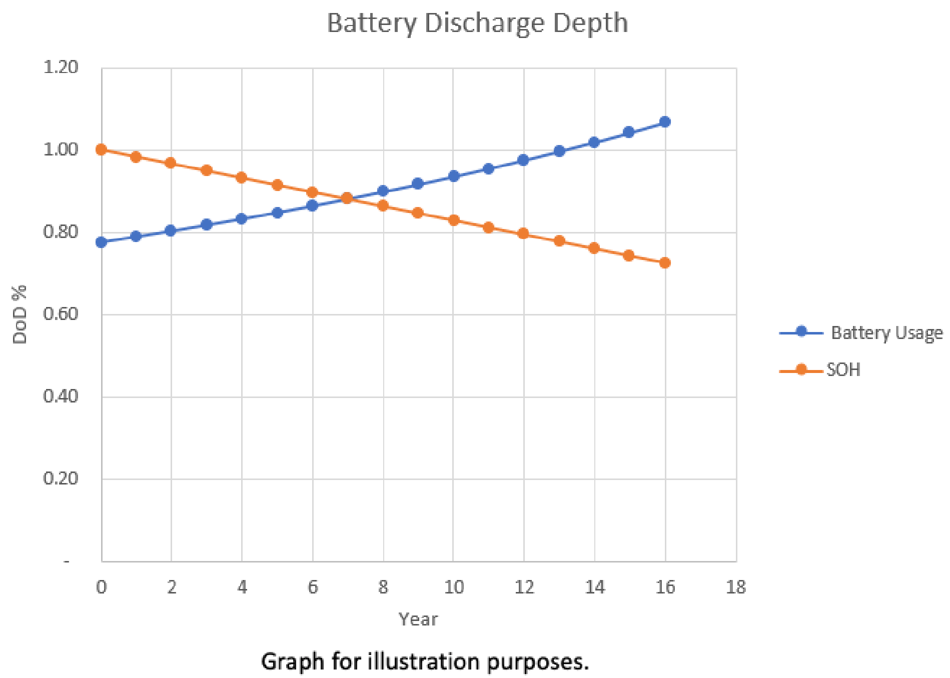


Figure 20. Battery's depth of discharge.

As the battery ages, BEBs lose storage energy capacity and, therefore, miles before charge. To compensate for the effect of increased downtimes, operators are pressured to purchase additional buses. The use of solutions such as battery swapping would result in a significant increase in the need for batteries and the associated materials.

7.4.11. Daily battery behavior for BEB and IMC

Both BEBs and IMC buses have very different discharge cycles. BEBs are fully recharged at night or during off-peak hours via processes through which the SOH changes significantly in just a few hours. They then operate until they discharge the battery almost completely, maintaining a residual charge that can vary between 20 percent and 10 percent. IMC buses, however, charge the battery while connected to the catenary and discharge it when operating on non-electrified sections. To ensure that the IMC bus battery can have a reasonable life cycle, it is necessary to avoid deep discharges by controlling the DOD. Figure 21 illustrates these behaviors.

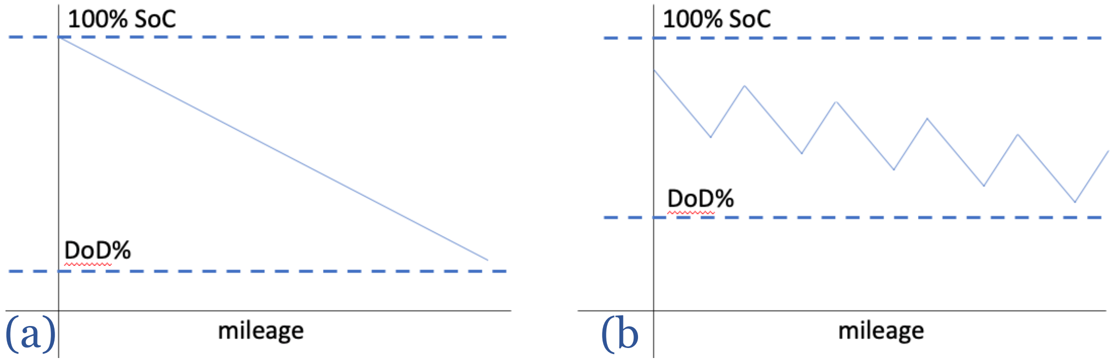


Figure 21. Comparison between the DOD of (a) BEBs and (b) IMC buses.

In most cases, BEBs operate on a battery charge and discharge cycle during the day. IMC buses, on the other hand, operate during the day with multiple charge-discharge cycles determined by the spacing and arrangement of the segments with overhead contact line. The distance between non-electrified segments determines the DOD of the battery. Regarding IMC buses, two possible scenarios are:

- *IMC buses on a route with a low degree of electrification (<40 percent)*: Buses must operate more miles without the possibility of recharging. This means a higher percentage of DOD, and thus high gravimetric energy density batteries such as NMC or LFP are appropriate.
- *IMC buses on a route with a high degree of electrification (>50 percent)*: These routes could have more charge and discharge cycles—if the segments are not continuous—but the depth of the discharge is controlled, which favors extending the useful life of the battery whatever the chemistry. Figure 22 illustrates these two possibilities; catenary segments are marked in red.

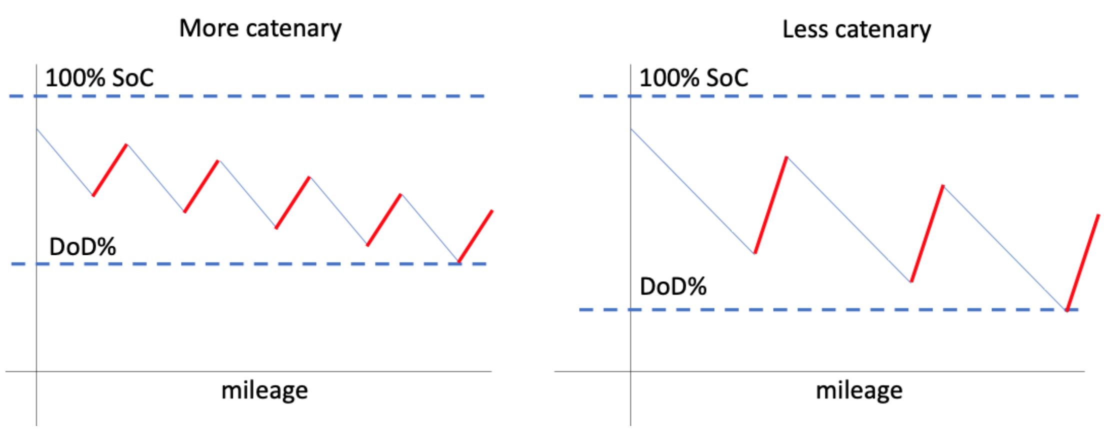


Figure 22. Reference comparison of bus charge-discharge cycles for IMC buses on routes with (a) low degree of electrification (b) high degree of electrification.

A well-designed IMC bus system ensures that the charge cycling does not produce a higher consumption of batteries (due to degradation) than in the case of depot charging (BEB).

Using the experimental behaviors of batteries before different charge cycles, we perform simulations to estimate the behavior of the SOH from a cycling pattern of a battery. Figure 23 and Figure 24 present the results for two NMC batteries: 350 kWh for BEB and 71kWh for IMC. The IMC bus route has ten charging sections during a day of operation. The BEB is recharged once a day. The mileage in the simulation is the same for both vehicles. We also simulate energy consumption for both vehicles.

In the best-case scenario, we find that the 350 kWh battery of the BEB must be replaced while 4 battery changes are required for the IMC bus. However, because the cost of a battery is proportional to its power capacity, the four IMC batteries are only 56 percent of the cost of the BEB battery and will have the same lifespan. **In terms of storage capacity required for the system, the IMC scheme represents a saving of 46 percent in batteries** (Figure 25)**.** While the IMC battery needs to be replaced more often than the BEB battery, the IMC battery is 7 times smaller than the BEB battery (71 kWh vs 500 kWh) (for 60-ft buses) or 71 kWh vs 350 kWh (for 40 ft buses) and costs significantly less.

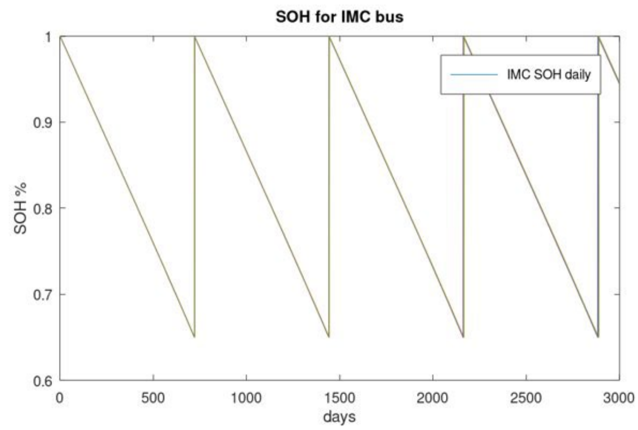


Figure 23. State of Health for IMC buses.

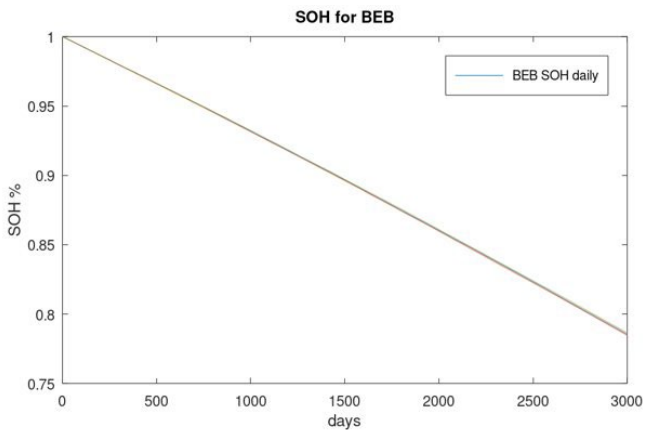


Figure 24. State of Health for BEBs.

Regarding manufacturing, it should be noted that the cost of a small battery pack is around USD $30 per kWh. Larger packs may have an additional cost associated with the higher volume, but it is usually the case that they in fact have a *lower* cost due to the volume of manufacturing. In the worst-case scenario, the cost of six IMC battery packs is equivalent to the cost of one BEB battery pack. In a normal scenario, the cost is linear, and an IMC battery pack costs a 1/7th of a full BEB battery pack. (Bhutada 2022) The US Department of Energy estimates that electric vehicle battery pack costs in 2021 were 87% lower than in 2008 (Edelstein s.f.).

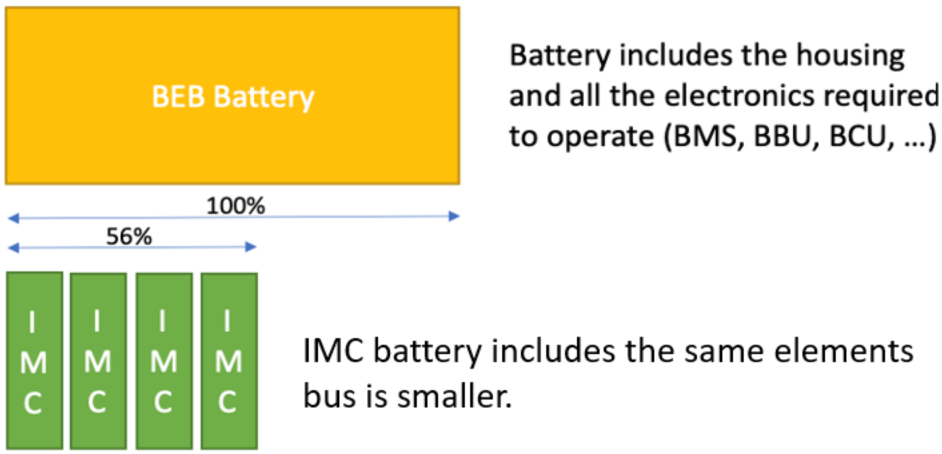


Figure 25. Reference comparison of BEB and IMC battery requirements through the project.

7.5. Stage 5: Detailed electrical simulation

7.5.1. Trolleybuses

The general criteria for our simulation of trolleybuses are:

1. **The overhead contact line must cover 100 percent of the route**. This information provides an estimate of infrastructure costs for a pure trolleybus technology. The software used for this simulation is Open Track.
2. **Traction substations—TPSs—must be located according to the current infrastructure of San Francisco**. for example, we give priority to the points where the route is intercepted by other lines that operate trolleybus systems. The results of this simulation define the convenience of the location of the TPSs, its configuration, and power capacity. The software used for this simulation is OpenPowerNet.
3. **TPSs will be added until the simulation shows the model is feasible**.
4. **The overhead contact line infrastructure must be a simple configuration line, with a positive and a negative thread and without additional reinforcement or accompaniment conductor** (which would require civil work to install). The conductors of the overhead contact line shall have a cross section of 150 mm2 and a composition CuAg0.1.

7.5.2. Battery electric buses

BEB simulation with OpenPowerNet allows us to establish the most likely range of operation and the state of charge of the battery at each point along the route. As the vehicles do not need to connect to the electricity grid to operate, there will be no results associated with the electrical infrastructure.

7.5.3. In-motion charging bus

We use OpenPowerNet, using as input data the results of the operational simulation in Open Track and a pre-design of the electrification system, to simulate the operation of the IMC trolleybus. Simulations like these can lead to redesigns regarding battery capacity, electrification level, or number of TPSs required. One of the fundamental results of this simulation is the charge-discharge cycle of the battery, including the elements that define its duration, such as depth of discharge and number of operating cycles.

In these simulations, we considered detailed aspects of the route, such as its topographic profile, the location of passenger stops on routes and stations, and existing catenary infrastructure. In addition, we analyzed operating conditions posed by the vehicle: in this case, a 40-foot New Flyer IMC trolleybus. In one scenario, the bus was equipped with a 71 kWh battery with NMC chemistry; in the other, with a 30 kWh battery with LTO chemistry. We also considered the speed profile of vehicles when traveling along the route.

For the special case of IMC buses, we configured the energy management strategy using parameters that are already standard in the industry:

1. The battery charging model: This configuration is meant to limit the battery charging power. When the catenary voltage is higher—more than 120 percent of the rated catenary voltage—the battery is allowed to charge at full power to help control overvoltage in the grid. However, if the main voltage falls below 70 percent of the rated voltage, the battery charge is cut off to the benefit of the grid.
2. When the bus is connected to the catenary, the battery charge and discharge model is adjusted so that the trolleybus prioritizes catenary power until the current reaches a maximum limit on the pantograph. After that, the battery controller determines that the battery must contribute current to the motor to compensate for the energy deficit.

This configuration flattens the demand curve in both ways: When the network is overloaded, the battery discharges power; when the battery is depleted and requires protection from over-discharge, the network contributes by injecting power. In addition, the battery-charging process is used to compensate the catenary voltage, which allows the same electrical infrastructure to support a greater number of buses.

The OpenPowerNet software allows for the calibration of the parameters for the model. We provide a detailed account of the parameters and settings in the annex. The simulations serve as an initial estimate of the technical requirements of future trolleybuses with IMC and can determine a preliminary budget for the acquisition of the buses. The proper configuration of these parameters is critical, as it defines whether the trolleybus will meet the operational requirements.

7.6. Stage 6: Basic electrical design

In the general application of Stage 6, planners will modify a basic, abstracted design then incorporate the various specifications of the buses and electrical infrastructure through the use of computer aided tools like OpenTrack or Power-System Computer Aided Design to develop a preliminary implementation scenario.

Our basic electrical designs include:

For the conventional trolleybus:

- Number, specification, and location of traction substations
- Overhead line parameters
- Vehicle specification

For the in-motion charging bus:

- Number, specification, and location of traction substations
- Specifications of the overhead contact line and the segments where it is installed
- Vehicle specification
- Specification of the energy storage system on board the trolleybus
- Power management settings or rules

For the battery-electric bus:

- Estimation of installed capacity for energy supply
- Specification of the energy storage system on board the bus
- Estimation of chargers required under each recharging scheme

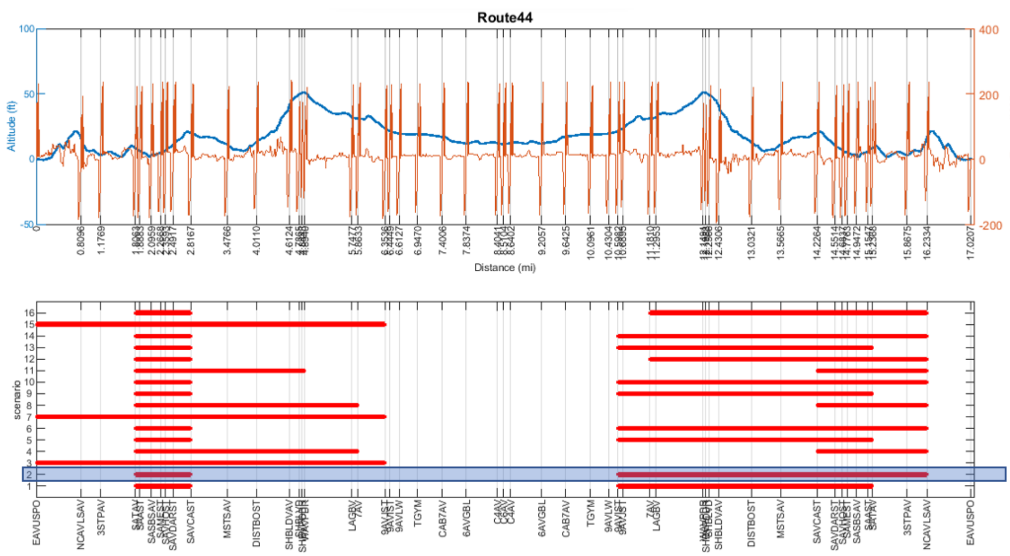
8. Analysis of the Results for Route 44

Currently, the frequency of buses for Route 44 is 12 minutes on weekdays and at rush hour. We propose a maximum number of 16 trolleybuses to offer a minimum increased frequency of 8 minutes. Increasing the supply of public transport is the trend in modern cities; by anticipating a future scenario we ensure that the infrastructure that is installed will remain sufficient. Also, a higher bus frequency makes the system more likely to take advantage of regenerative braking when it is connected to the network.

We assume the number of IMC buses on the route to be the same due to 1:1 replacement ratio discussed above, whereas 19 BEBs would be required to meet the same peak demand.

8.1. Electrification optimization results

In the electrification optimization model for Route 44, as noted above, we follow the restriction that the overhead contact line should not be installed along Golden Gate Park. Since the optimal result will depend on the unit costs of the battery, the overhead contact line, the substations, the state of charge of the chargers, and other elements of the system, 16 scenarios are run combining these costs and different charging possibilities, varying the initial and final state of charge of the operation, and an eventual night charging of the IMC buses. Recurrent electrification segments are found (recommended in all scenarios), and finally scenario 2 is chosen (marked in the blue box), which does not require depot charging of the buses, and which assumes costs that can be read in the table at the bottom of the Figure 26 . This scenario corresponds to the costs that have been defined as the benchmarks in this project. The scenarios with lower electrification correspond to scenarios where we assume a higher cost of overhead-contact-line installation.



Scenario	Objective Function	Battery Capacity (kWh)	Number of buses	Number of trips	Catenary distance (mi)	Number of Substations	Charging Power (kW)	Depot charging power (kW)	Initial SoC	Final SoC	Catenary Cost (USD/mi)	Substation Cost	Battery Cost (USD/kWh)	Depot Charger Cost (USD/KW)	Night charging duration
1	$12,870,355.25	71	16	10	5.648948	2	25	80.19111	0.6	0.3	$1,500,000.00	$2,000,000.00	$ 300.00	$ 700.00	4
2	$14,309,240.56	71	16	10	6.645627	2	25	0	0.6	0.6	$1,500,000.00	$2,000,000.00	$ 300.00	$ 700.00	4
3	$11,957,773.98	71	16	10	6.353583	1	25	123.7144	0.8	0.3	$1,500,000.00	$2,000,000.00	$ 300.00	$ 700.00	4
4	$13,474,460.40	71	16	10	6.064024	2	25	53.75	0.8	0.6	$1,500,000.00	$2,000,000.00	$ 300.00	$ 700.00	4
5	$14,870,355.25	71	16	10	5.648948	2	25	80.19111	0.6	0.3	$1,500,000.00	$3,000,000.00	$ 300.00	$ 700.00	4
6	$16,309,240.56	71	16	10	6.645627	2	25	0	0.6	0.6	$1,500,000.00	$3,000,000.00	$ 300.00	$ 700.00	4
7	$12,957,773.98	71	16	10	6.353583	1	25	123.7144	0.8	0.3	$1,500,000.00	$3,000,000.00	$ 300.00	$ 700.00	4
8	$15,474,460.40	71	16	10	6.064024	2	25	53.75	0.8	0.6	$1,500,000.00	$3,000,000.00	$ 300.00	$ 700.00	4
9	$15,694,829.07	71	16	10	5.648948	2	25	80.19111	0.6	0.3	$2,000,000.00	$2,000,000.00	$ 300.00	$ 700.00	4
10	$17,632,054.07	71	16	10	6.645627	2	25	0	0.6	0.6	$2,000,000.00	$2,000,000.00	$ 300.00	$ 700.00	4
11	$14,629,249.42	71	16	10	5.094685	2	25	141.5433	0.8	0.3	$2,000,000.00	$2,000,000.00	$ 300.00	$ 700.00	4
12	$16,506,000.38	71	16	10	6.064024	2	25	56.62667	0.8	0.6	$2,000,000.00	$2,000,000.00	$ 300.00	$ 700.00	4
13	$17,694,829.07	71	16	10	5.648948	2	25	80.19111	0.6	0.3	$2,000,000.00	$3,000,000.00	$ 300.00	$ 700.00	4
14	$19,632,054.07	71	16	10	6.645627	2	25	0	0.6	0.6	$2,000,000.00	$3,000,000.00	$ 300.00	$ 700.00	4
15	$16,134,565.26	71	16	10	6.353583	1	25	123.7144	0.8	0.3	$2,000,000.00	$3,000,000.00	$ 300.00	$ 700.00	4
16	$18,506,000.38	71	16	10	6.064024	2	25	56.62667	0.8	0.6	$2,000,000.00	$3,000,000.00	$ 300.00	$ 700.00	4

Figure 26. Optimization of the electrification of Route 44 for 40-ft buses.

From the segments suggested by the optimization model, we proceed to propose a basic electrification, locating TPSs at the points where the route is intersected by other trolleybus lines (because at those points there could be remaining capacity to supply energy to the new line). If there is no remaining capacity, or insufficient capacity, the installation at that point of a new TPS would serve to supply the two lines, improving their cost-effectiveness ratio.

Using OpenPowerNet, we simulate the operation of each of the IMC and trolleybus fleets independently, under the same conditions, for a period of 8 hours, adding a bus every 8 minutes, until the complete fleet of 16 vehicles is obtained. Depending on the results of the first simulation, we make modifications until we obtain a simulation that is considered technically feasible. To be technical feasible, a solution must fulfill the following requirements:

- Buses can complete the route without limitations on traction.
- The voltages in the pantograph and in the overhead contact line are within the regulatory ranges given by the standard EN 50163:2004, *Railway applications - Supply voltages of traction systems*, at all times and in all places.
- The current capacity of the overhead contact line is not exceeded.
- Battery cycling ensures a long service life

In the case of IMC buses with the LTO battery, we increase catenary coverage by an additional mile to limit the depth of discharge to 40 percent, so that the state of charge is never below 60 percent (at least during the first years of the battery). In total, it would be necessary to install 7.25 miles of catenary in addition to the small section that is shared with Route 24. Figure 27 shows the electrification arrangement.

In the case of the conventional trolleybus, the OpenPowerNet simulation found that a new traction substation would be necessary, which we propose be located a few meters before Golden Gate Park. This additional substation is required not because of a power deficit but rather because, with only three substations and the distances between them, it is not certain that the voltages will remain within the regulatory limits.

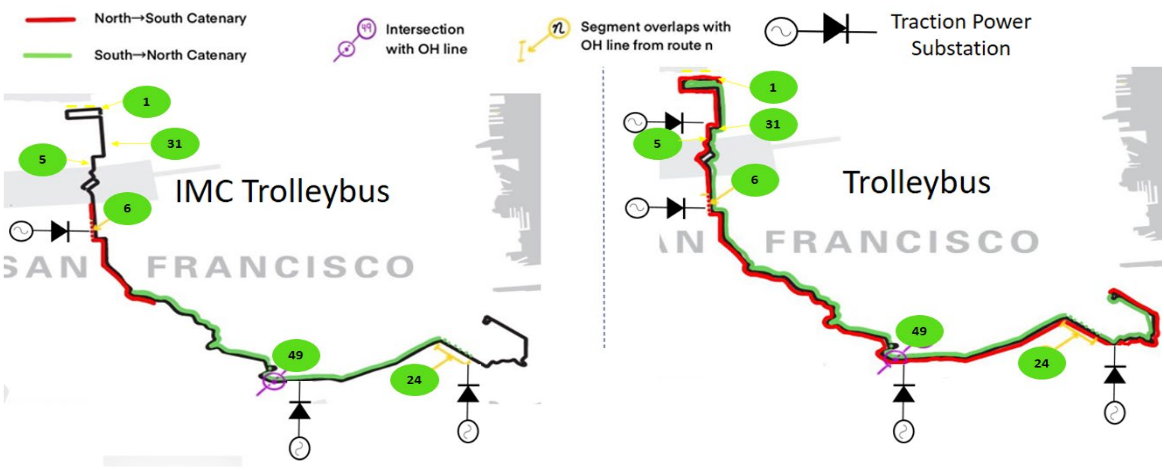


Figure 27. Electrification of Route 44 for 400-ft IMC buses (left) and trolleybuses (right).

In the area north of Golden Gate Park, Route 44 intersects with three major trolleybus lines: the 5 (Fulton), 1 (California), and 31 (Balboa). Part of the route on the north end is under the Route 1 catenary, which could be used for additional battery charges beyond those considered in our simulation. The use of these segments would reduce the depth of discharge of the battery, further extending its useful life. We exclude consideration of these possible charges for the purposes of the electrical simulation, so the electrification scenario we present can be considered conservative from a technical and economic point of view.

We did not consider catenary installation in the zone north of Golden Gate Park to avoid new catenary intersections with the California, Fulton, and Balboa routes; it is also relatively flat terrain.

8.2. Results of detailed electrical simulation

We present the results of the detailed simulations of the three alternatives below. There are basically three types of results: simulation from the point of view of the vehicle, for IMC and BEB buses, simulations from the point of view of the network, for trolleybus and IMC bus, and energy balance of the system as a whole.

8.2.1. Results for in-motion charging buses

For the reference case—a 40-foot bus with an LTO battery—we proposed the charge control curve shown in Figure 28 with good results based on the voltage of the overhead contact line at the time of recharging.

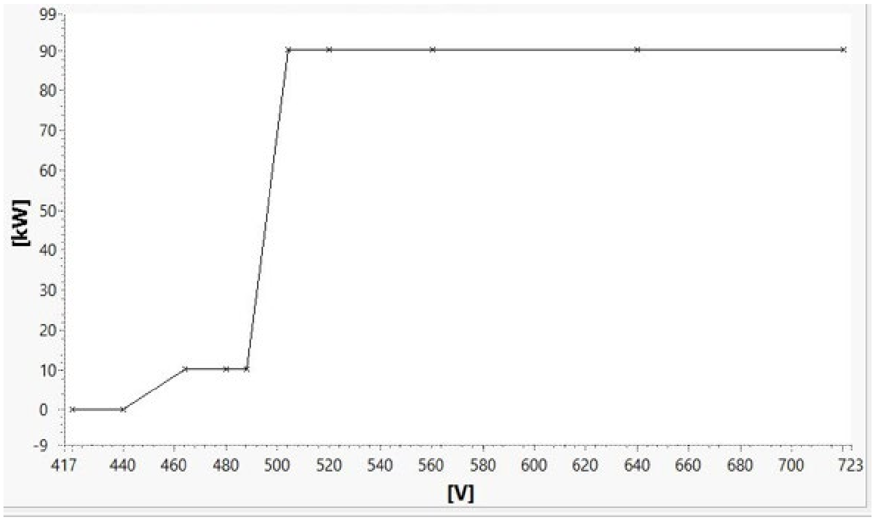


Figure 28. Battery charge control for LTO battery according to the voltage in the overhead line.

In the case of the LTO battery, the charge has been limited to a maximum rate of 3C (90 kW) and a maximum discharge of 8C (240 kW). However, as can be seen in the charge control curve, the battery recharge can only be done when the catenary voltage is above 500 V; otherwise, the charging power is limited to 10 kW, and charging is cut when the voltage of the overhead line drops to 440 V. This allows the IMC bus to function as an indirect compensator of the voltage in the overhead contact line, because the battery is charged with greater power in situations of high voltage while charging is inhibited when the voltage in the overhead contact line is low.

Bus-level results

Figure 29 presents the battery SOC behavior for the first trolleybus dispatched on route 44, from 4 am to 7 am. Figure 30 shows how operating conditions are maintained during an 8-hour operation. As shown in the figures, the battery is never discharged below a SOC of 60 percent.

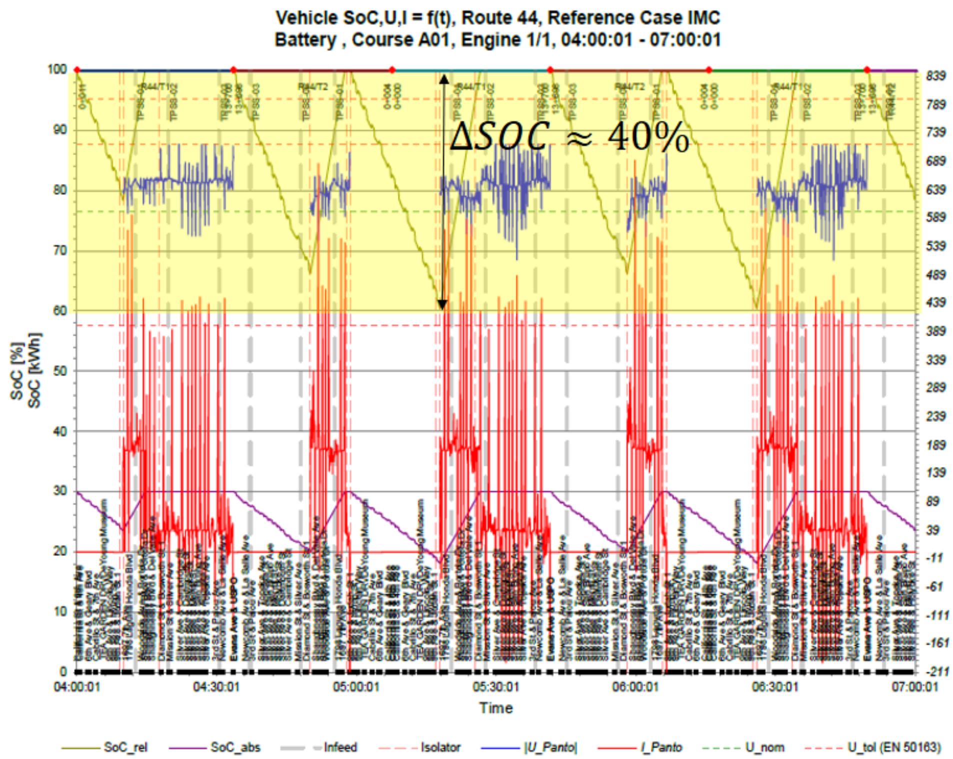


Figure 29. Operational behavior of IMC-30 kWh from 4 am to 7 am.

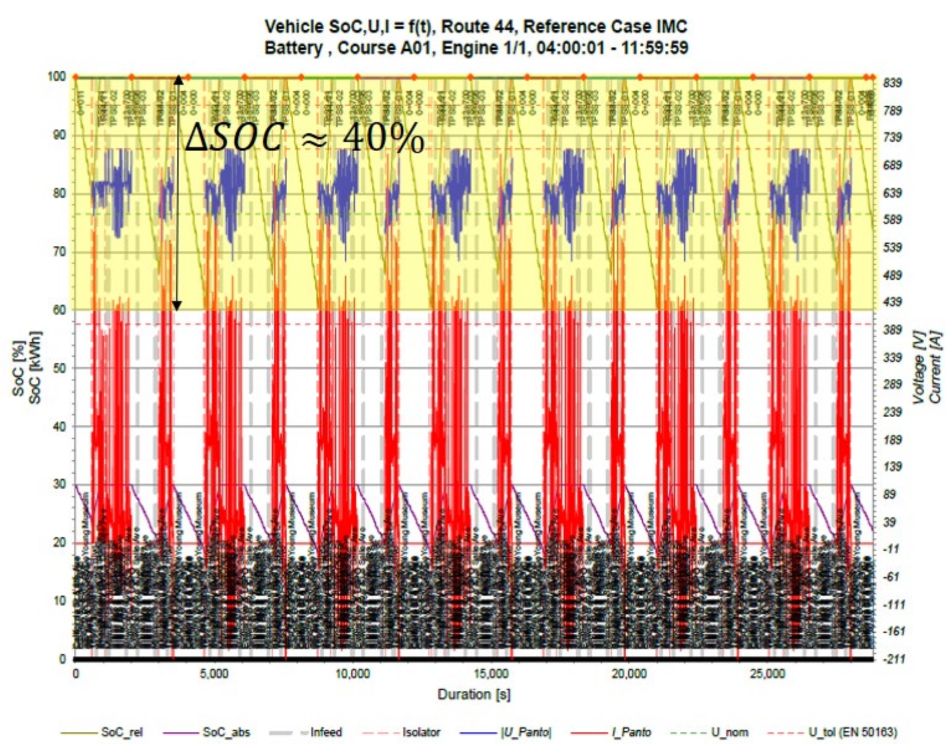


Figure 30. Operational behavior of IMC-30 kWh from 4 am to 10 am.

In these graphs, the curves are:

- SOC_rel: Relative state of charge of the battery
- SOC_abs: Absolute state of charge of the battery
- Infeed: Overhead line feeder
- Isolator: Electrical insulation point
- U_panto: Voltage in the trolleybus pantographs
- I_panto: Current in the trolleybus pantographs
- U_nom ---: Nominal voltage of the system
- U_tol ---: Voltage tolerance according to EN 50163

Network-level results

Demand in traction substations, IMC case

Figure 31 presents the demand duration curve (ordered from highest to lowest) required from the three traction substations, in the three shades of green, and the aggregated demand of the system, in red, which must be read on the axis on the right.

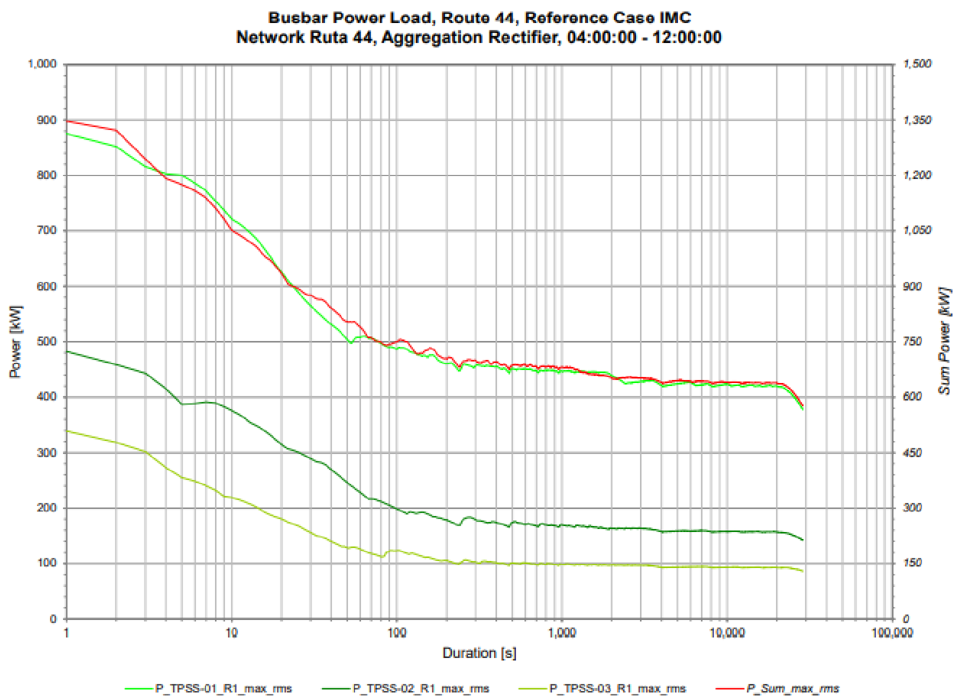


Figure 31. Cumulative power demand for route 44, IMC case

The curves presented are:

- P_TPSS-01_R1_max_rms: Cumulative Power Demand in Substation 1, Rectifier 1, Left Scale
- P_TPSS-02_R1_max_rms: Cumulative Power Demand in Substation 2, Rectifier 1, Left Scale
- P_TPSS-02_R3_max_rms: Cumulative Power Demand in Substation 3, Rectifier 1, Left Scale
- P_Sum_max_rms: Total Cumulative Power Demand, Right Scale

Table 16 shows the energy demand of the three supply points (intersections with lines 6, 49 and 24). In the event that there is no capacity available on those circuits, a new traction substation located nearby would help reinforce the two trolleybus lines.

The maximum values (max) correspond to the maximums recorded in the period lasting 1 second. The rms15 values correspond to the maximum effective values lasting 15 minutes, and the rms values correspond to the effective values of the variables for the 8-hour period. E is the energy consumed in the period.

Table 16. Power and current required for IMC 30 kWh-LTO, Route 44

Substation	*Device*	*Type*	*Signal*	$\|I\|_{,max}$	I_{rms}	I_{rms15}	$\|Q\|_{,max}$	P_{rms}	P_{rms15}	*E*
				A	**A**	**A**	**kW**	**kW**	**kW**	**kWh**
TPSS-01	A1	Rectifier	total	1,344	577	683	875	378	447	2,715
TPSS-02	A1	Rectifier	total	736	216	256	482	142	168	914
TPSS-03	A1	Rectifier	total	516	131	149	339	86	98	485

Voltage profile in the catenary, IMC case

One of the conditions required to ensure the operation of the IMC system is minimum voltages within the limits given by the EN 50163 standard. For a nominal voltage of 600 V, voltages must not rise above 20 percent (780 V) or drop below 420 V. Figure 32 shows that these requirements are met by the proposed system. Only the extreme values at each point during the 8 hours of the simulation are shown in the figure.

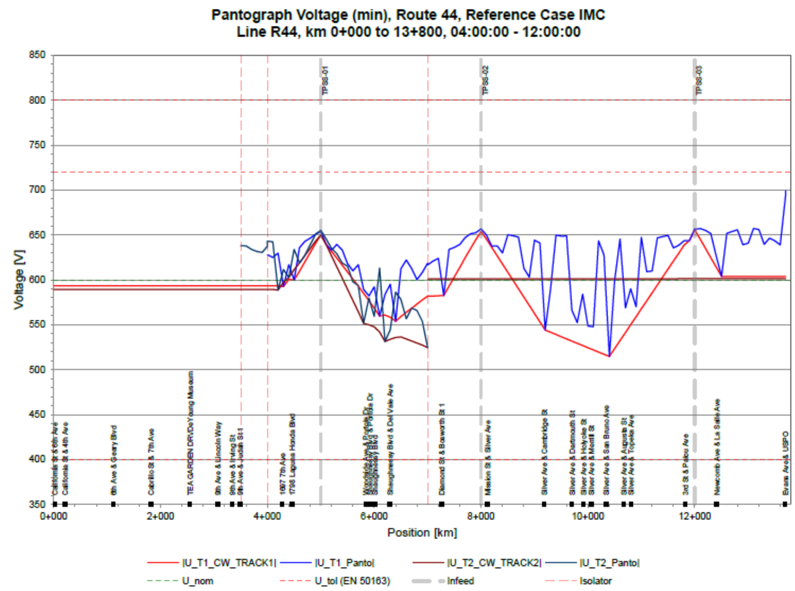


Figure 32. Minimum voltage in pantographs and overhead line, IMC case.

The description of each of the curves is:

- Infeed: Overhead line feeder
- U_T1_CW_TRACK1: Voltage in the contact wire in Track 1
- Isolator: Electrical insulation point
- U_T1_panto: Voltage in the trolleybus pantographs in Track 1
- U_tol ---: Voltage tolerance according to EN 50163

TPS demand curves, IMC case

Figure 33 and Figure 34 present the demand behavior from each of the TPSs as a function of time, the first in the period between 4:00 am and 7:00 am, the second in the period between 7:00 am and 10:00 am. We have excluded a graph of the behavior between 10:00 am and 12:00 pm, which is within the time of the simulation, because the operation of the system has already stabilized and because the entire fleet is already operational, as can be seen in Figure 34.

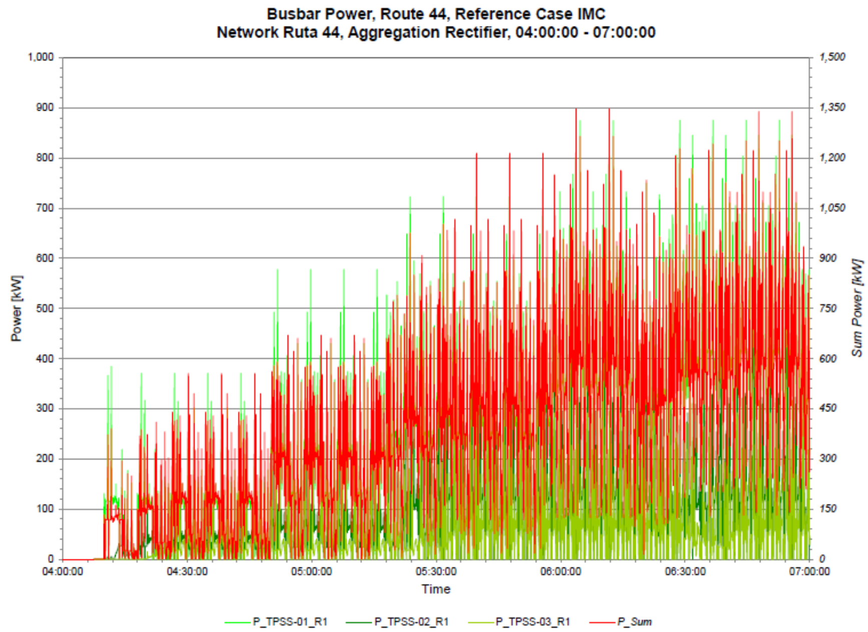


Figure 33. Power demand from substations and aggregated, IMC case, 4:00 am to 7:00 am

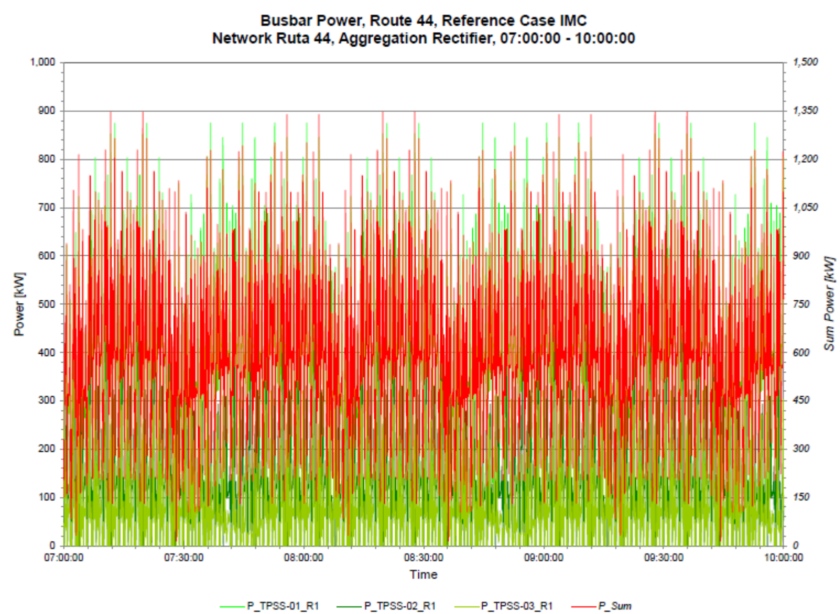


Figure 34. Power demand from substations and aggregated, IMC case, 7:00 am to 10:00 am.

The simulation reports the energy balance of the complete fleet operation for the 8-hour operating period. The results are presented in Table 17. We note that the software can quantify the effect of regenerative energy management, losses in the overhead contact wire, energy storage systems, feeders, and connectors.

Table 17. Energy Overview, Route 44, IMC, Network Route 44, 04:00:00 to 12:00:00

Total energy at traction power supplies	**4,114 kWh**
Energy from traction power supplies to catenary system	4,114 kWh
Energy from catenary system to traction power supplies	0 kWh
Total energy at vehicle pantographs	**3,878 kWh**
Energy from catenary system to vehicle pantographs	4,101 kWh
Energy from vehicle pantographs to catenary system	223 kWh
Total energy at vehicle energy storages	**449 kWh**
Energy from vehicles to energy storages	2,775 kWh
Energy from energy storages to vehicles	2,327 kWh
SOC balance of vehicle energy storages	-62 kWh
Total losses in catenary system	**236 kWh**
Losses in substation feeder cables	4 kWh
Losses in contact wires	161 kWh
Losses in rails (negative wire)	70 kWh
Losses in earth wires	0 kWh
Losses in connectors	1 kWh

Given the information on the energy consumption from the power supplies and considering the initial energy stored in the batteries of the buses, we find an average consumption per bus of 2.49 KWh/mi.

8.2.2. Results for trolleybuses

We conduct a network and fleet analysis for trolleybuses, but there are no results regarding each vehicle (because there is no battery whose status we can check). However, the model can produce average results per vehicle, if necessary.

Network results

Demand in traction substations, trolleybus case

Figure 35 presents the demand duration curve (from highest to lowest) of the four traction substations (the three green lines and one blue) as well as the aggregate demand of the system (in red), which must be read on the axis on the right. As the illustration indicates, the peak demand of the system is greater than in the case of IMC buses: **Trolleybuses, due to their lacking batteries, cannot contribute to the reduction of the peak demand of the system.**

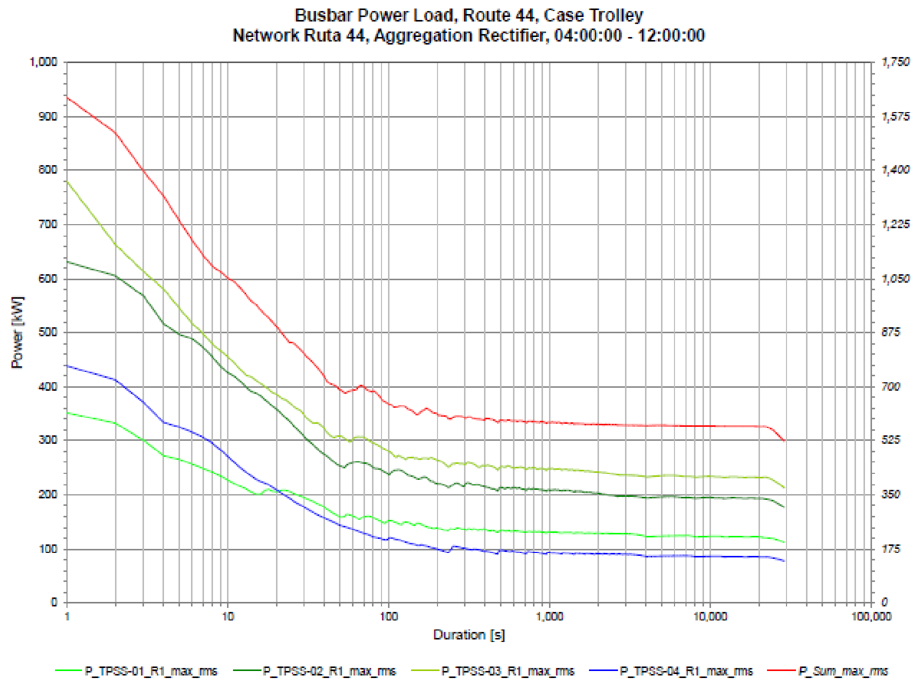


Figure 35. Cumulative power demand for Route 44, IMC case

The curves presented are:

- P_TPSS-01_R1_max_rms: Cumulative Power Demand in Substation 1, Rectifier 1, Left Scale
- P_TPSS-02_R1_max_rms: Cumulative Power Demand in Substation 2, Rectifier 1, Left Scale
- P_TPSS-03_R1_max_rms: Cumulative Power Demand in Substation 3, Rectifier 1, Left Scale
- P_TPSS-04_R1_max_rms: Cumulative Power Demand in Substation 4, Rectifier 1, Left Scale
- P_Sum_max_rms: Total Cumulative Power Demand, Right Scale

Table 18 shows the energy demand of the three supply points (the new TPS before Golden Gate Park and the intersections with lines 6, 49, and 24). If there is no capacity available on those circuits, planners could locate a new traction substation nearby to reinforce the two trolleybus lines. The maximum values (max) correspond to the maximums recorded in the period lasting one second. The rms15 values correspond to the maximum effective values lasting 15 minutes, and the rms values correspond to the effective values of the variables for the 8-hour period.

Table 18. Power and current required trolleybus case, Route 44

Substation	*Device*	*Type*	$\|I\|_{max}$	I_{rms}	I_{rms15}	$\|P\|_{max}$	P_{rms}	P_{rms15}	*E*
			A	**A**	**A**	**kW**	**kW**	**kW**	**kWh**
TPSS-01	A1	Rectifier	540	172	199	352	112	131	688
TPSS-02	A1	Rectifier	979	271	321	631	177	209	1,145
TPSS-03	A1	Rectifier	1,217	327	382	780	213	249	1,365
TPSS-04	A1	Rectifier	675	119	140	439	78	92	454

Voltage profile in the catenary, trolleybus case

As in the case of IMC buses, the minimum voltages of trolleybuses must be within the limits given by the EN 50163 standard. For a nominal voltage of 600 V, the voltage must not rise above 20 percent (780 V) nor dip below 420 V. Figure 36 shows that the proposed system meets these requirements. This figure only presents the extreme values at each point during the 8-hours of the simulation.

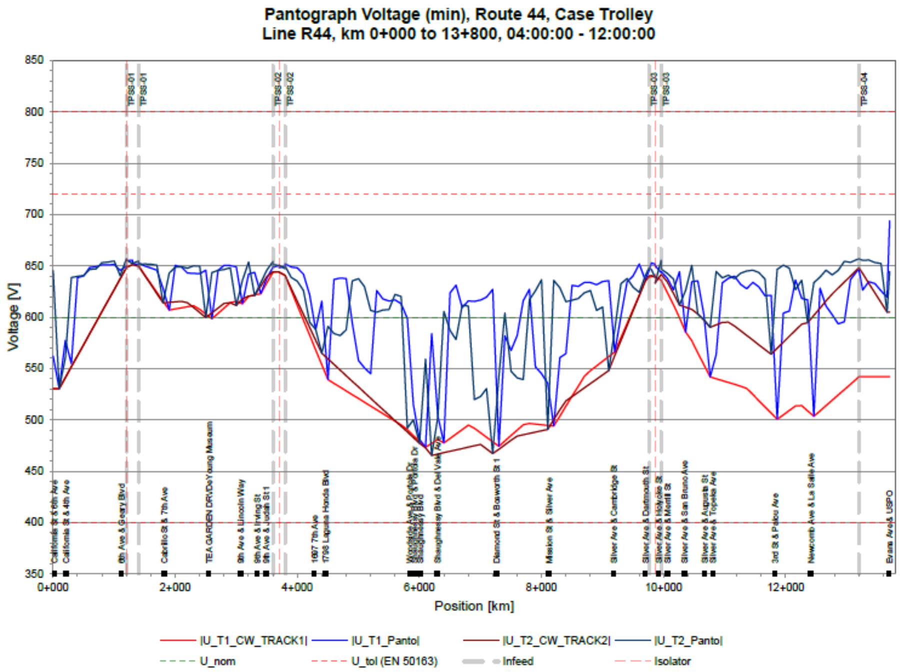


Figure 36. Minimum voltage in pantographs and overhead line, IMC case.

The description of each of the curves is:

- Infeed: Overhead line feeder
- U_T1_CW_TRACK1: Voltage in the contact wire in track one
- Isolator: Electrical insulation point.
- U_T1_panto: Voltage in the trolleybus pantographs in track one
- U_tol ---: Voltage tolerance according to EN 50163

TPS demand curves, trolleybus case

Figure 37 illustrates the behavior of demand from each of the traction substations (TPS) as a function of time, the first in the period between 4:00 am and 7:00 am, the second in the period between 7:00 am and 10:00 am. We have omitted a graph of the behavior between 10:00 am and 12:00 pm—though it is in within the time of the simulation—because the operation of the system has already stabilized and the entire fleet is already operational (see Figure 38).

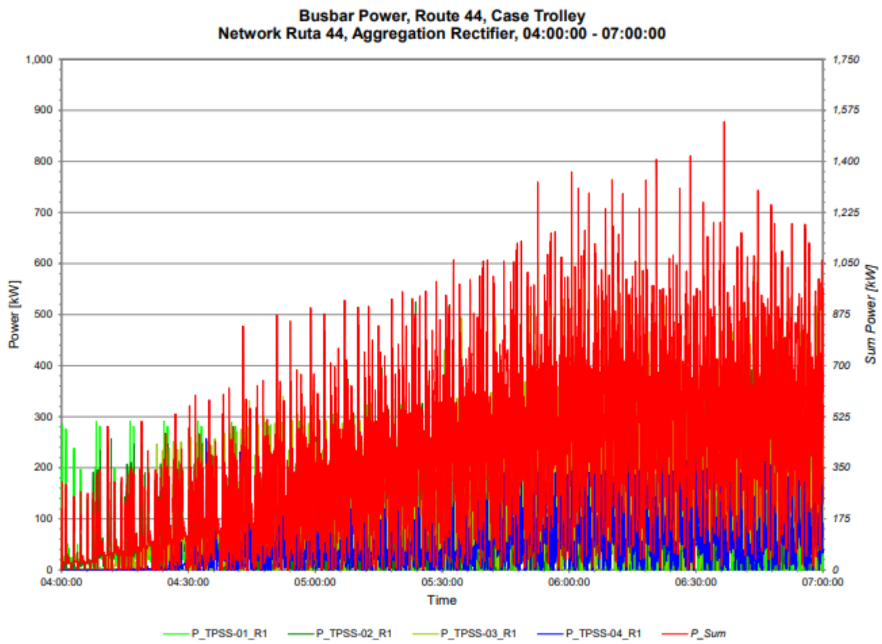


Figure 37. Power demand from substations and aggregated, trolleybus case, 4:00 am to 7:00 am

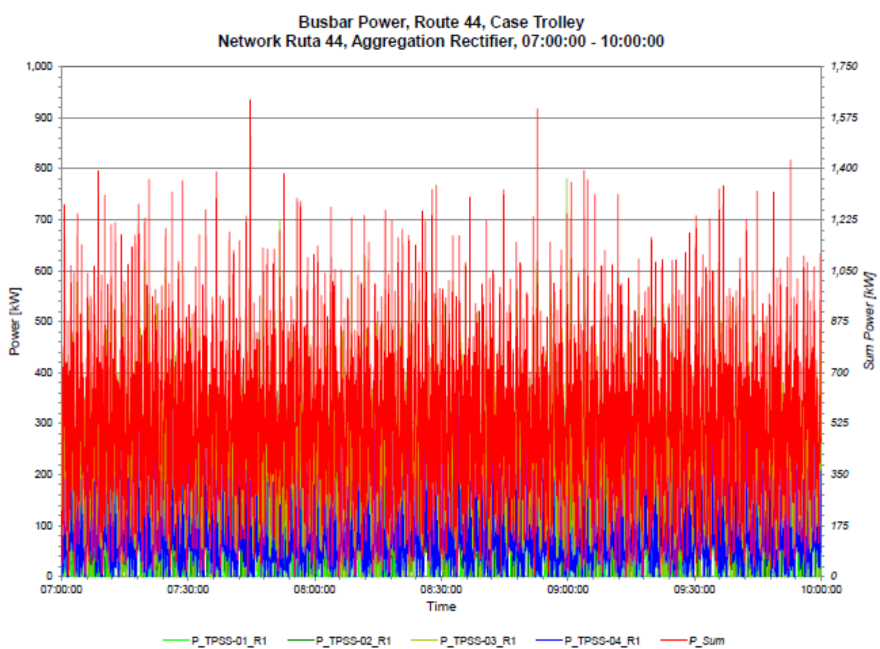


Figure 38. Power demand from substations and aggregated, trolleybus case, 7:00 am to 10:00 am.

The simulation reports the energy balance of the complete fleet operation for the 8-hour operating period. Those results are presented in Table 19. It is important to highlight that the simulation can quantify the effects of regenerative energy management, losses in the overhead contact wire, energy storage systems, feeders, and connectors.

Table 19. Energy Overview, Route 44, Trolleybus, Network Route 44, 04:00:00 to 12:00:00

Total energy at traction power supplies	**3,651 kWh**
Energy from traction power supplies to catenary system	3,651 kWh
Energy from catenary system to traction power supplies	0 kWh
Total energy at vehicle pantographs	**3,396 kWh**
Energy from catenary system to vehicle pantographs	4,296 kWh
Energy from vehicle pantographs to catenary system	901 kWh
Total losses in catenary system	**256 kWh**
Losses in substation feeder cables	3 kWh
Losses in contact wires	178 kWh
Losses in rails	75 kWh
Losses in earth wires	0 kWh
Losses in connectors	0 kWh

Based on the energy consumption of the power supplies, we obtain an average consumption per trolleybus of 2.17 KWh/mi.

8.2.3. Results for BEBs

Results from the point of view of the bus

For the depot-charging BEB, we did not study the variables associated with the network (except for the implications of the charge demand).

Figure 39 presents the battery behavior of the 40-foot bus on Route 44, assuming an initial battery power of 350 kW. The green curve presents the %SOC; the purple, the absolute SOC in kWh. The ratio of bus energy consumption to distance traveled determines performance in kWh/km or kWh/mi. In many BEBs, there are recording systems that present this value. However, it is important to note that the consumption of a BEB system must include the energy required in the charging process, which comprises the losses of the converters in the chargers and the electrochemical losses of the batteries.

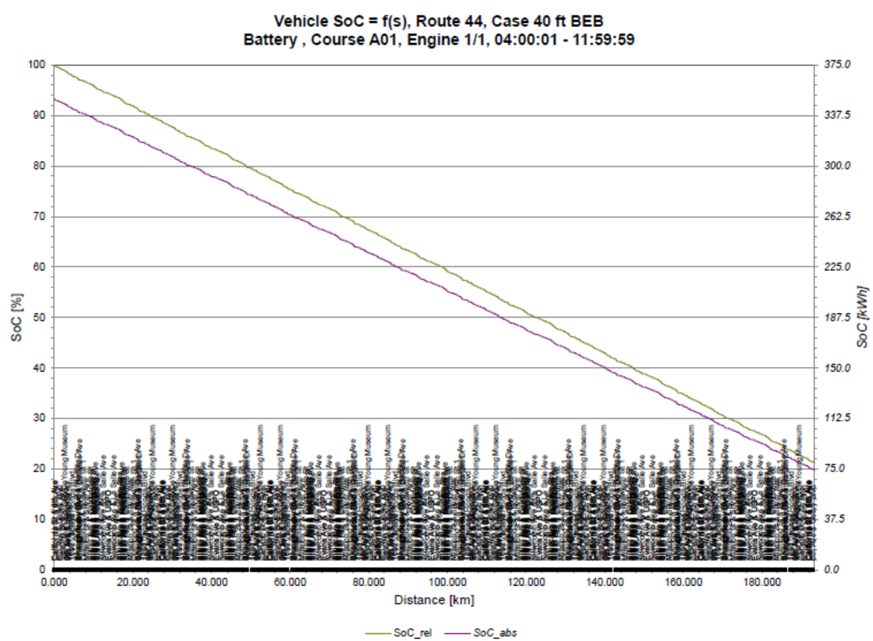


Figure 39. Relative and absolute SOC of the BEB, 7:00 am to 12:00 pm.

We find that after 8 hours of operation on Route 44, the BEB bus battery will have a %SOC of 22 percent and will have traveled a distance of 193 km (120 miles). The bus will have consumed 276 kWh, yielding a consumption from the average battery of 2.3 kWh/mi (counting the energy of the recharging process, the value becomes 2.55 kWh/mi). Although this consumption value can be considered conservative—as we assume a high consumption of auxiliary services (25 kW)—we also assume that the bus is operating with very few additional stops to the stations, which causes the average speed to increase (15 mi/h). To realize this speed increase, planners could give preference to the bus through a dedicated lane and/or intelligent traffic-light systems that give priority to the bus at intersections.

8.3. Analysis of detailed simulation results

8.3.1. Demand characterization

In our comparison of the demands of the three bus alternatives, we take the intermediate scenario case of the depot-charging BEB as a reference (which scenario corresponds to the Adjusted Dispatch scheme). Figure 40 superimposes the results of the demand duration curves, from which we conclude:

- The IMC bus has an instantaneous (one second) peak demand 18 percent lower than the trolleybus alternative and 12 percent lower than the BEB alternative, **making it the alternative with the lowest instantaneous peak demand.**
- For one-minute demand, **the trolleybus requires the least amount of power (20 percent less than IMC)**. However, the IMC bus's one-minute demand is half of the BEB alternative.
- In the BEB alternative, the demand remains very high for a period of four continuous hours, which implies important demands on the equipment associated with the power supply, such as transformers and feeders.

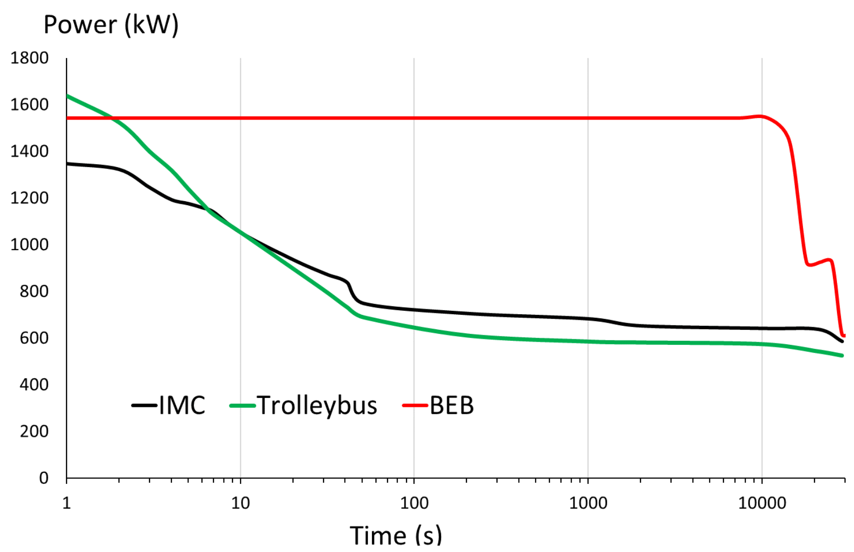


Figure 40. Cumulative power demand for IMC, BEB and trolleybus.

8.3.2. Comparison of overall energy performance

Finally, to compare all the alternatives, we analyze the energy consumption needed per bus and between the fleets to meet the maximum passenger demand at peak hour. Table 20 presents the results for each of the alternatives.

We summarize the results as follows:

- The alternative with the lowest net energy consumption—approximately 15 percent lower than that of the IMC bus and BEB—is the trolleybus. This is due to the trolleybus's higher efficiency in regenerative braking processes that do not necessarily involve battery charging-discharging, and because energy transport losses in a modern grid tend to be lower than those currently offered by electrochemical storage processes. This situation can change unfavorably, if the number of buses is reduced, and favorably, if the number of buses increases. The more buses that are operating, the more likely they are to be able to exchange energy through regenerative braking.
- The IMC alternative is marginally more efficient (approximately 2 percent) than the depot-charging option for reasons very similar to those outlined above in the trolleybus case. Limited overhead contact line coverage and the use of batteries to compensate voltage is detrimental to the efficiency of the IMC bus, but the deficit is not enough to result in an efficiency lower than the BEB.
- When we consider the fleet required to meet the peak passenger demand, the dead weight of the BEB battery places it in a very unfavorable position compared to the other alternatives. To serve the same number of passengers during a peak hour, the trolleybus alternative consumes 28 percent less energy than the depot-charging BEB alternative while the IMC alternative consumes almost 18 percent less.

Table 20. Energy Overview, Route 44, Trolleybus, Network Route 44, 04:00:00 to 12:00:00

40-ft bus; Route 44; 8.25 miles (7.25 New) electrification; 25 kW of auxiliary consumption

	Trolleybus 600 V	**IMC 600 V**	**BEB**
Fleet size for peak periods	16	16	19
Energy from traction substations (kWh)	3651 (Fleet)	4114 (Fleet)	0
Simulation time (h)	8	8	8
Energy from batteries (depot charging) (kWh)	0	62 (Fleet)	276 (one bus)
Operational energy consumption (kWh)	3651 (Fleet)	4176 (Fleet)	306.7 (one bus)
Loses in catenary (kWh)	256	236	0.0
Depot-charging battery loses (kWh)	0	7	30.7 (one bus)
Total energy consumption (including depot charging) (kWh)	3651	4183	306.7 (one bus)
Average energy consumption per bus per km (kWh/km)	**1.349**	**1.545**	**1.586**
Average energy consumption per bus per km (kWh/mi)	**2.17**	**2.49**	**2.55**
Fleet energy consumption per km in peak period (kWh/km)	**21.58**	**24.72**	**30.13**
Fleet energy consumption per km in peak period (kWh/mi)	**34.73**	**39.79**	**48.49**

8.4. Battery analysis

8.4.1. LTO battery

Based on the simulation results and our analysis of the battery cycle, we find that the IMC operation has the following characteristics:

- The depth of discharge (DOD) of the battery must be controlled to achieve a long service life. In this case, the design is intended to maintain a change in state of charge (ΔSOC) of up to 40 percent, ensuring a DOD of less than 60 percent as the battery is charged to 100 percent.
- The battery must supply the full power of the bus, even if the segments with steep slopes are electrified with catenary, because the power required for starting at bus stops tends to reach the maximum power of the bus. This becomes a limit to reduce the capacity of LFP and NMC batteries. For example, to avoid discharge rates above 3C for a maximum power of 210 kW, a 70 kWh battery would be the lower limit.
- As lithium-titanate (LTO) batteries have higher charge and discharge rates (7C to 10C), the IMC trolleybus could be equipped with lower-capacity LTO batteries without compromising traction power output.
- Even though the LTO battery has a lower gravimetric energy density (GED) than NMC and LFP batteries, its relatively higher weight is compensated for because each bus requires a lower power capacity. For example, if a 71 kWh NMC battery (average 170 Wh/kg) is replaced by a 30 kWh LTO battery (average 80 Wh/kg), the battery weight and passenger capacity of the bus will remain constant (GED ratio 2.42 vs capacity ratio 2.36).
- The life cycle of the LTO battery (15,000 to 20,000 cycles), compared to LFP and NMC (3,000 to 5,000 cycles), is another key factor favoring its use in IMC applications.

Considering that an 8-hour operation involves 14 battery charge/discharge cycles, and assuming an average daily run of 16 hours, the daily cycles of the LTO battery would be 28. For an average of 300 days/year of operation, the annual cycles of a battery would be around 8,400. Given an operational depth of discharge of 40 percent, the life cycle of the LTO battery would extend to more than 50,000 cycles (Figure 30). If, conservatively, we assume a life cycle of 30,000 charge and discharge cycles, only four LTOs would be required for 15-year operation.

8.4.2.NMC battery

The use of a battery with the highest energy capacity—NMC or LFP—means that, for the same level of electrification used for a low-energy capacity (but high-power, i.e., LTO) battery, the depth of discharge is reduced further.

For the NMC battery, we set the maximum limit discharge rate to 3C (213 kW), and the charge rate to 1C (70 kW) (see Figure 41). We present a better approximation of the problem of charge limitation than that adopted with regard to the LTO battery, by dint of a more sensitive adjustment of the charge limits. Note that the charge controller is set to ensure that the rate of 1C (70 kW) it is only allowed for catenary voltages greater than 750 V accentuate the voltage compensation effect by making the network more receptive to regenerative energy reception. Once the voltage is reduced—so as not to compete with other trolleybuses that are beginning to take advantage of regenerative energy directly—the recharging power is further limited. Under normal operating conditions, with the voltage between 600 V and 500 V, the charge is 30 kW (C/2). Below 420 V, the battery recharge is turned off (see Figure 40).

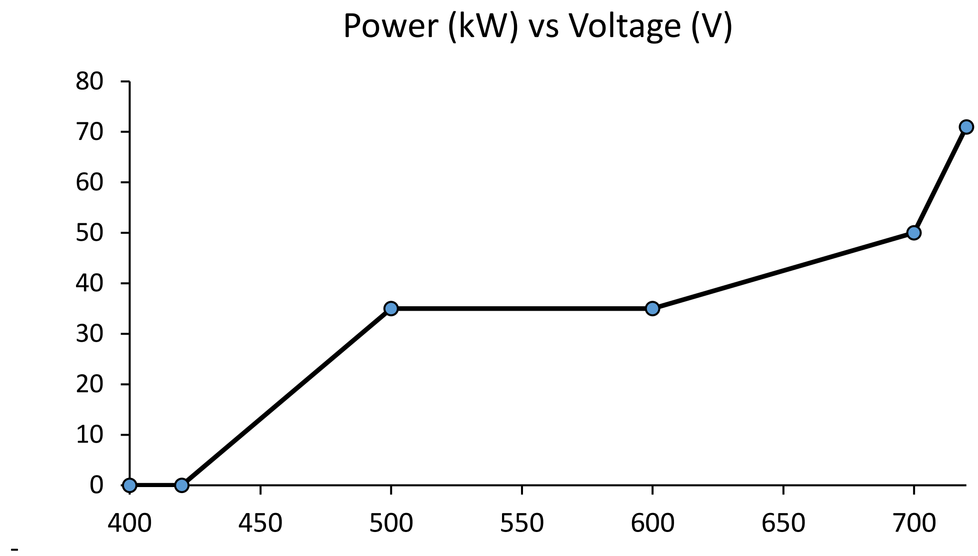


Figure 41. Power-voltage limit for IMC battery charge Route 44.

Route 44's proposed level of electrification allows the DOD under normal operating conditions to be only 15 percent. The %ΔSOC in each cycle is also 15 percent when recharging the catenary. A battery with a lower power capacity has greater restrictions on charge and discharge rates.

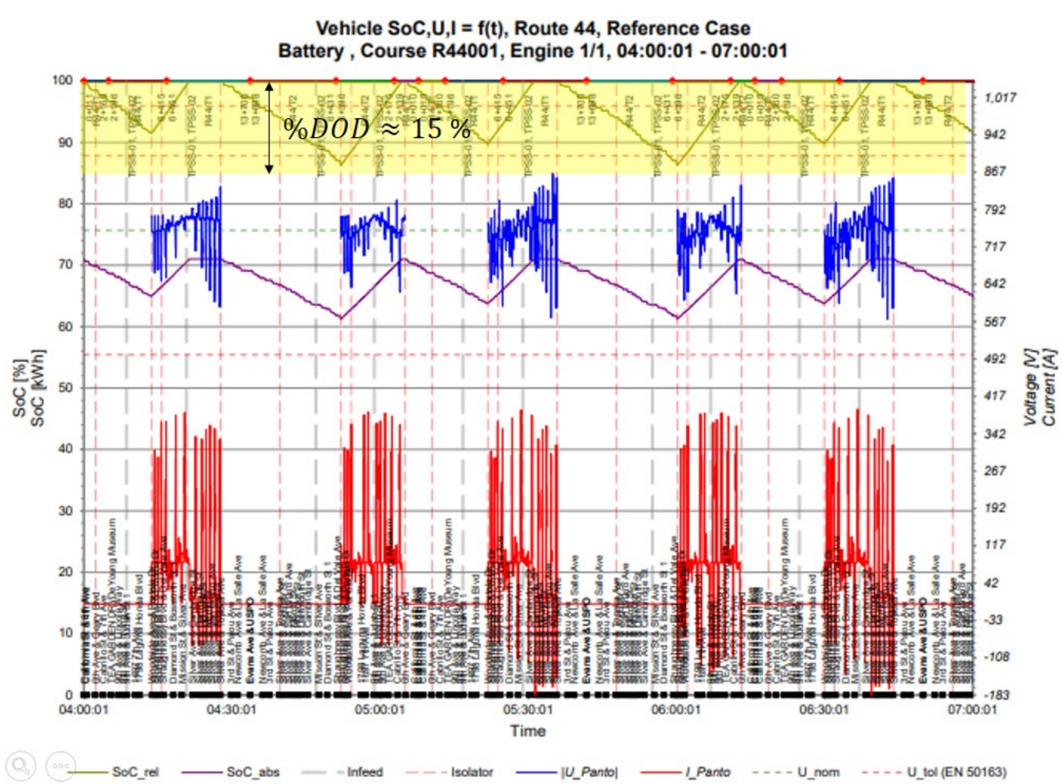
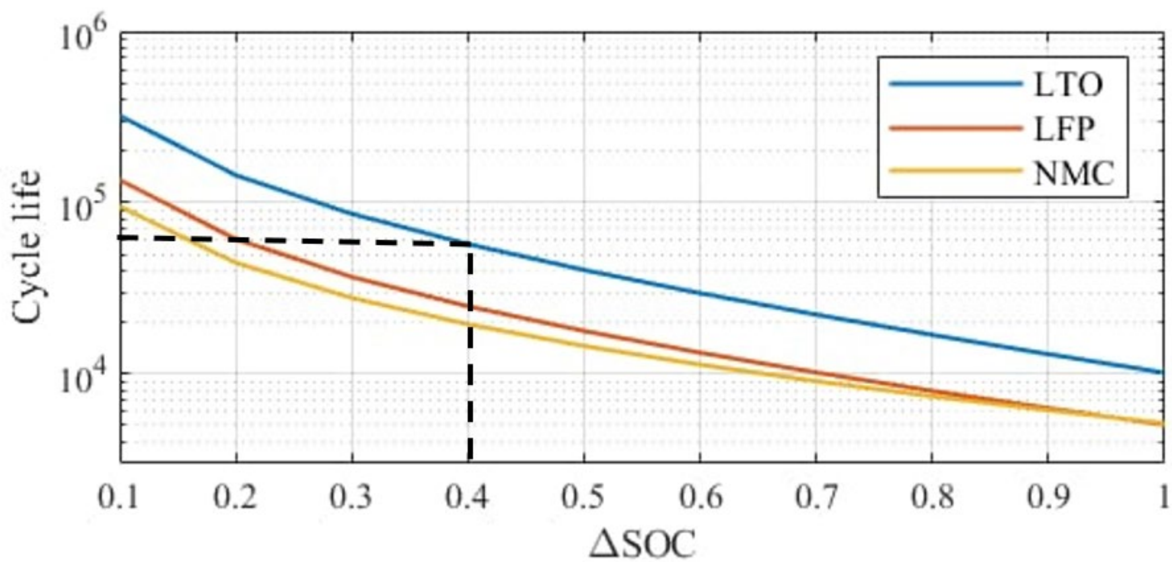


Figure 42. Vehicle SOC for 40-ft IMC trolleybus, 71 kWh, Route 44.

In these graphs, the curves are:

- SOC_rel: Relative state of charge of the battery
- SOC_abs: Absolute state of charge of the battery
- Infeed: Overhead line feeder
- Isolator: Electrical insulation point.
- U_panto: Voltage in the trolleybus pantographs
- I_panto: Current in the trolleybus pantographs
- U_nom ---: Nominal voltage of the system
  U_tol ---: Voltage tolerance according to EN 50163

Figure 43 summarizes preliminary estimations of battery usage for both the 71 kWh NMC battery (DOD 18 percent) and 30 kWh LTO battery (DOD 40 percent) over the course of a 15-year operating period.



-

Figure 43. Battery Cycle life as function of the change in the SOC (Göhlich, Fay y Park 2019).

Compared to the BEB schemes where only one charge is done in a daily basis, IMC would provide battery savings as shown in Figure 44.

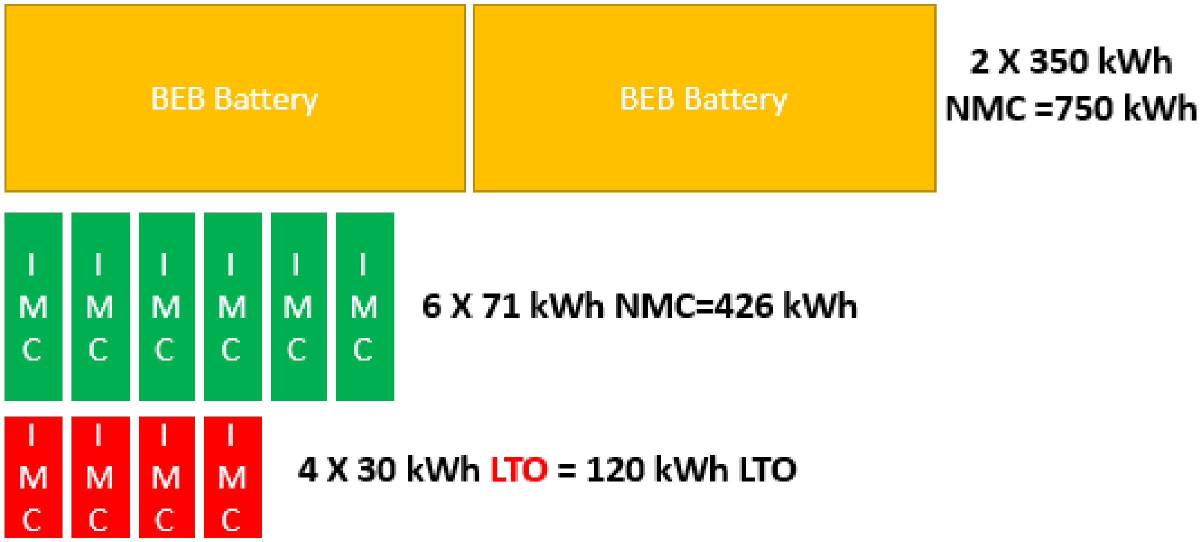


Figure 44. Preliminary estimations of battery use in a 15-year period.

Considering that we have proposed three different schemes (simple manual dispatch, adjusted dispatch, and minimum fleet for peak hour) for the operation of the battery electric bus, there will be five scenarios to compare the electrification alternatives. We must note that each charging scheme requires different charge cycles. For example, in Scenario 2 (adjusted dispatch), the bus is partially charged a second time in the day, which increases the number of cycles and consequently the number of batteries required. Table 21 presents battery use values for each of the scenarios we consider.

Table 21. Summary of battery use for all scenarios.

Scenario	***Battery capacity per bus (kWh)***	***Number of batteries for 15 year per bus***	***Battery capacity for 15 year per bus (kWh)***	***Battery capacity for the fleet -15 years (kWh)***	***Battery use as % of maximum capacity***
BEB Scenario 1: simplified dispatch minimum chargers	350	2	700	25200	100%
BEB Scenario 2: adjusted dispatch	350	3	1050	24150	96%
BEB Scenario 3: minimum fleet for peak hour	350	2	700	13300	53%
IMC Scenario LTO	30	4	120	1920	8%
IMC Scenario NMC	71	6	426	6816	27%

In general, **an electrification plan based on IMC buses allows reductions in battery use between 90 percent and 70 percent, both in storage capacity and in mass, compared to BEB alternative**. These reductions represent savings in energy—due to the ecological footprint of battery production—as well as in in critical raw materials such as lithium and, especially, cobalt.

8.5. Stage 6: Basic electrical design

The iterative work of simulating each of the electrification alternatives results is what can be considered a basic electrification design. Figure 45 presents the basic electrification schemes for both IMC and trolleybus alternatives. These diagrams indicate the possible location of traction substations (TPS) for each of the cases as well as their minimum voltage profile.

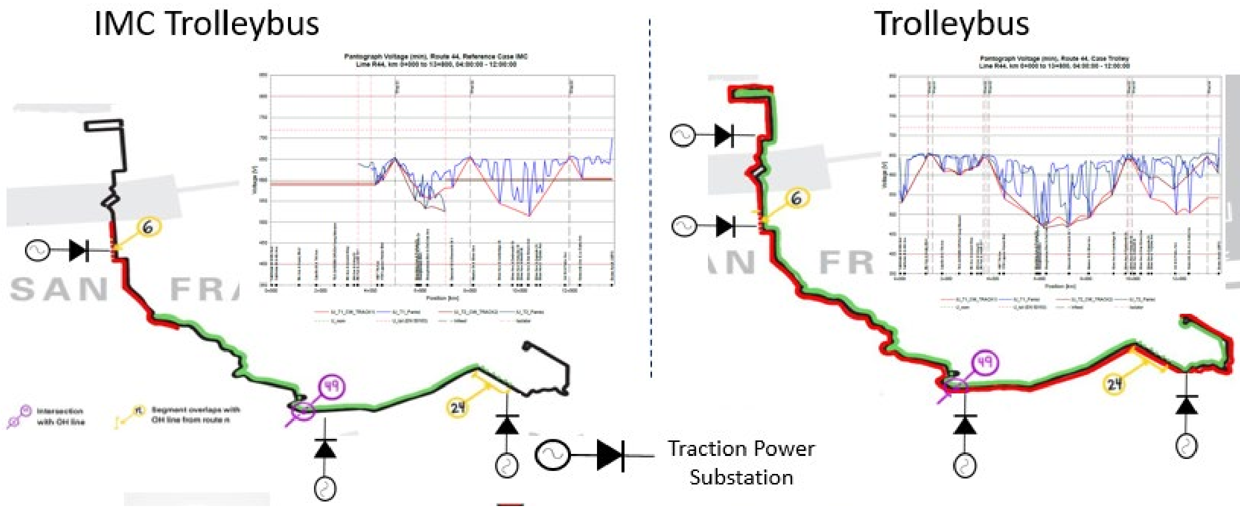


Figure 45. Basic design of the electrification of Route 44.

Traction Substations

Figure 46 shows a reference configuration of the TPS we considered to feed the DC overhead line segments. For Route 44, the two catenary segments we identified have an overlap. Therefore, the DC system is strengthened by the parallel connection of the feeders.

Whether a new transformer with its rectifiers can be installed depends on the capacity of the existing infrastructure and the space available. If the capacity is sufficient to satisfy demand on Route 44, additional TPSs may not be needed immediately. However, as more diesel-hybrid bus routes are replaced with electric buses, electricity demand will increase, requiring additional power upgrades or traction substations.

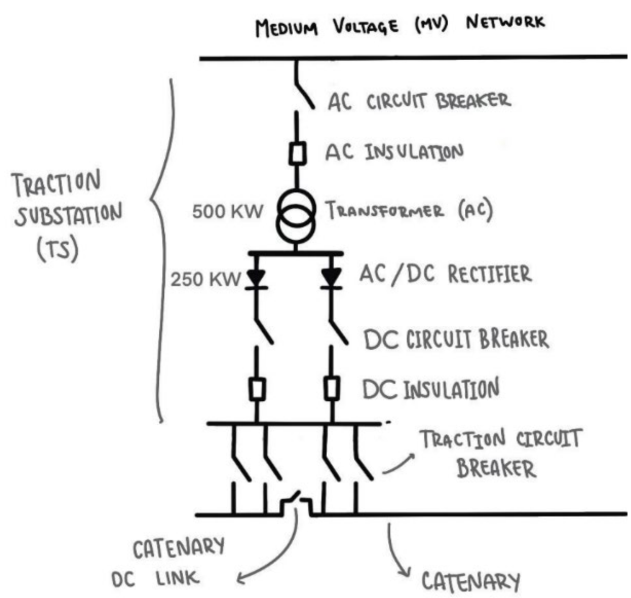


Figure 46. Traction substation.

Traction substation converters shall be designed to comply with the Class VI specification in accordance with EN 50328:2003, Railway applications - Fixed installations - Electronic power converters for substations. Traction transformers are also specified for the Class VI specification, according to EN 50329:2003, Railway applications - Fixed installations - Traction transformers. In general, Class VI determines that transformer-rectifier groups can withstand a demand of 300 percent for 1 minute, 150 percent for two hours, and 100 percent continuously.

Table 22 presents a basic proposal for sizing and locating traction substations for the IMC case.

Table 22. Basic design proposal for IMC substations

Traction Power Substation	*Nominal capacity*	*Specification*	*Reference location*
TPSS-01	550 kVA	Class VI: EN 50328:2003 Class VI: EN 50329:2003	1798 Laguna Honda Blvd
TPSS-02	350 kVA	Class VI: EN 50328:2003 Class VI: EN 50329:2003	Mission St & Silver Ave
TPSS-03	200 kVA	Class VI: EN 50328:2003 Class VI: EN 50329:2003	3rd St & Palou Ave

Table 23 presents a design proposal for traction substations in the case of trolleybuses.

Table 23. Basic design proposal for trolleybus substations

Traction Power Substation	*Nominal capacity*	*Specification*	*Reference location*
TPSS-01	250 kVA	Class VI: EN 50328:2003 Class VI: EN 50329:2003	6th Ave & Geary Blvd
TPSS-02	250 kVA	Class VI: EN 50328:2003 Class VI: EN 50329:2003	9th Ave & Judah St 1
TPSS-03	250 kVA	Class VI: EN 50328:2003 Class VI: EN 50329:2003	Silver Ave & Dartmouth St
TPSS-04	250 kVA	Class VI: EN 50328:2003 Class VI: EN 50329:2003	Evans Ave & USPO

Basic overhead contact line design

One of the fundamental elements for the economic competitiveness of an IMC system is the simplification of the overhead contact line. By minimizing the maintenance of critical elements such as switches and chargers, operators can realize cost reductions in both implementation and operation.

One of our most important design premises is that the assembly of the overhead contact wire can be done without the installation of auxiliary feeders, which are generally situated underground and ostensibly raise the cost of civil works.

The basic design we consider comprises:

- Cross section of contact wire and proposed material: 150 mm^2 CTA (CuAg0.1)
- DC resistance (at 70ºC): 176 mΩ/km (including 20 percent contact wire wear)
- Current capacity: 687 A (according to IEEE Std 738 and considering 30ºC ambient temperature)

We simulated this basic design in OpenTrack+OpenPowerNet to determine its operational feasibility, in particular the maximum current present on the contact wire. Figure 47 shows the maximum current result for the IMC bus case and Figure 48 for the trolleybus case.

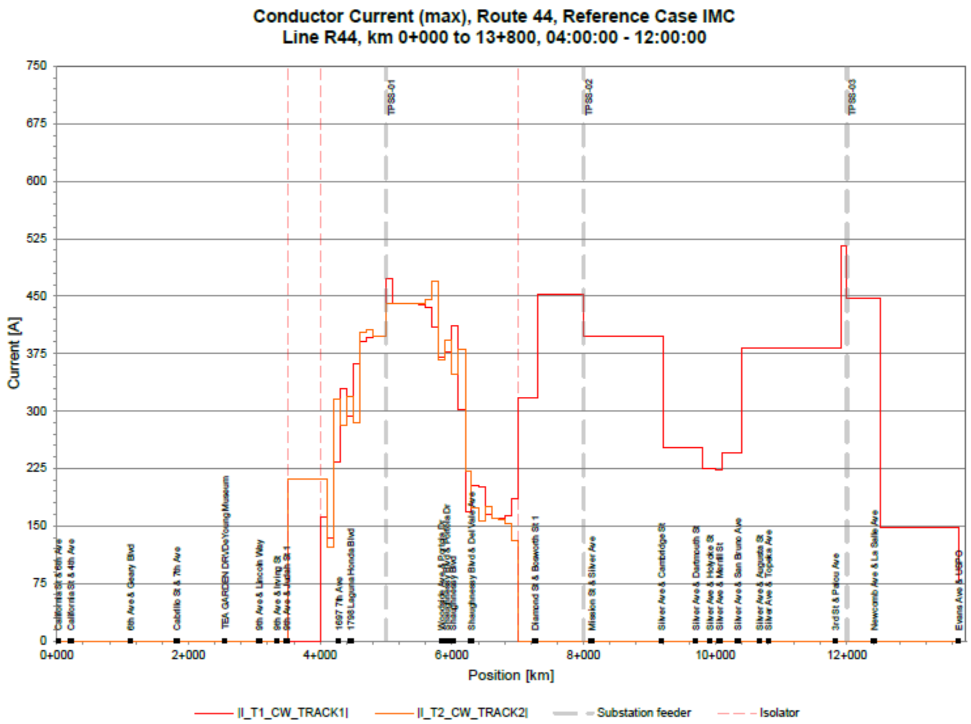


Figure 47. Driver current maximum value, IMC case.

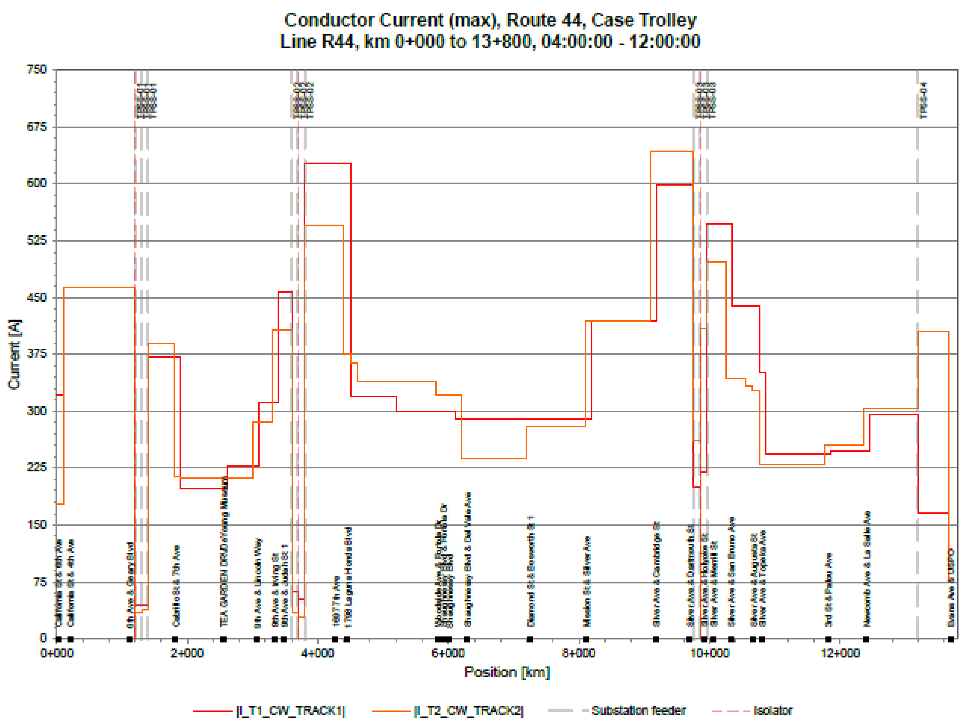


Figure 48. Driver current maximum value, trolleybus case.

The explanation of each of the curves is:

I_T1_CW_Track1: Maximum current registered in Track 1

I_T2_CW_Track2: Maximum current registered in Track 2

In sum, the basic design—with a simple catenary and without the need for accompanying feeders—is technically feasible for both IMC buses and conventional trolleybuses. We would be able to model a better distribution of demand between traction substations in a detailed design, which would also include electrical integration with the other trolleybus lines.

Costs for implementing basic designs

Although the cost of implementing the different types of systems depends significantly on the site conditions, Table 24 presents some of the costs that we will treat as a reference for our subsequent analysis. These have as their source the market costs of equipment that the Medellín Metro has recently installed, weighted with the costs reported in the literature review of Section 1.

Table 24. Basic Cost Information

Electrification main investment	***Cost***	***Comment***
Catenary (MUSD/mi)	1.5	This value does not include the cost of traction substations. It is limited to new poles, overhead lines, and accessories.
IMC simplified catenary (MUSD/mi)	1.2	As IMC will simplify the overhead lines, intersections and special accessories will not be required.
Substation cost (MUSD/MVA)	3	Includes MV feeders, cabinets, protection equipment, circuit breakers, and control equipment.
Charger cost (MUSD/MW)	0.9	The cost of the depot chargers, dispensers, and connectors along with management, control, and communication equipment (small scale/individual conversion).
Rectifier cost (MUSD/MW)	0.3	The cost of traction substation rectifiers (large-scale conversion) and the associated equipment.
Storage cost (MUSD/MWh)	0.2	The cost of the batteries required for the fleet.
Trolleybus (MUSD)	1.1	A premium over the cost of a BEB is assumed because of the trolley poles and the DC/DC double isolated converter. Conversely, we assume cheaper, longer-lasting induction motors than those used by BEBs, which are based on rare-earth magnets. The cost of the battery is not included here.
BEB (Without battery)	1	The cost of the battery is not included

8.6. Discussion of the results of the basic IMC electrification design

Given our findings, we can confidently recommend that the city of San Francisco electrify the reference route—Route 44—using IMC technology due to its obvious technical advantages over the alternatives.

8.6.1. Notes on opportunity charging

Our optimization procedure does not show that Route 44 is prone to OC. This is because optimization favors longer segments with relatively lower charge power rather than multiple, short, isolated segments that perform high-power charging.

For reference, we compare the IMC bus simulation results with the OC line operating in Geneva, Switzerland (line 23 connecting the airport with the suburbs of Geneva). The basic specifications of the electrical infrastructure on the Geneva line are:

- 13 Flash-charging stations: 20s, 600 kW, 600 VDC
- 3 Terminal feeding stations: 4-5 min, 400 kW, 600 VDC
- 4 Depot feeding stations: 30 min, 45 kW, 500 VDC

And we consider the following operational parameters in the comparison:

- Fleet: 12 electric-articulated buses
- Bus length: 18.75 m
- Passenger capacity: 133
- Route length: 12 km (total round-trip 24.5 km)

Given these specs, the power of just *two* ultra-fast 600 kW chargers would be enough to electrify Route 44 in its entirety. However, having a 1000 kW substation—which is the case with IMC—replaces the need to install multiple ultra-fast chargers.

While IMC ensures both charging and reducing the maximum current of the battery when connected, OC only guarantees that the battery is charged to stay on track. Therefore, when faced with steep slopes, the maximum current of the OC battery will degrade the SOH of the battery faster than IMC.

9. Financial Analysis of Alternatives

We now turn to an analysis of the economics of the three electrification alternatives. In what follows, we perform analyses of the implementation costs of each alternative as well as a 15-year financial evaluation. Salaries, personnel costs, and special costs arising from the on-site installation of equipment are not included. Our aim in this section is to provide general elements that can guide decision-making.

Table 25 presents the description of the items used in the financial analysis. CAPEX comprises overhead line infrastructure (poles, overhead wire, accessories, etc.), vehicles, batteries, chargers, and traction substations. OPEX is composed of the cost of the energy to power the fleet, the land use required, the cost of battery replacement, and the maintenance cost.

Table 25. Financial analysis item description

Category	***ITEM***
CAPEX	OHL Infrastructure
	Buses
	Batteries
	Chargers
	Traction Substations
OPEX	Energy
	Land use
	Battery replacement
	Maintenance

9.1. CAPEX

Each technology requires investments for its implementation. Some of those investments—roads, spaces, furnishings and auxiliary parts for the vehicles—are common to all the alternatives, whereas others are specific to the particular technology. For example, in trolleybuses, the catenary along the entire route is a differentiator from the other technologies. For BEBs, charging stations sited exclusively in the vehicle parking lot are the differentiating factor.

Summary of costs

Table 26 summarizes the costs of the different vehicle options. We explain these costs in detail below.

We consider three scenarios with regard to the fleet size of the BEBs: **Simplified Dispatch**, where 38 vehicles are needed; **Adjusted Dispatch,** where 23 vehicles are needed; and **Minimum Fleet for Rush Hour**, where only 19 vehicles are needed. (In the Fleet Minimum scenario, the fleet is large enough—at a replacement ratio of 1.18 BEBs per diesel or trolleybus in this case— to meet passenger requirements only at rush hour. However, this scenario does not allow operation for a full day, unless ultra-fast charges are made to the detriment of battery life.)

Table 26. BEB fleet scenarios

Scenario	***Fleet***	***Comments***
Scenario 1: Simplified Dispatch— minimum chargers	38	The buses act like an energy storage system to reduce the number of chargers and smooth energy demand.
Scenario 2: Adjusted Dispatch	23	The bus dispatch has to be carefully controlled. The bus has to be fully charged once a day and requires a second partial charge of about ΔSOC≈50%.
Scenario 3: Minimum Fleet for Rush Hour	19	Service to satisfy daily offer unless ultra-fast charging is implemented.

Table 27 presents the cost results for the six electrification alternatives we consider: the three depot-charging BEB scenarios, the two IMC alternatives, and the conventional trolleybus alternative, not including the real-estate value.

Table 27. Cost of the alternatives for Muni electrification.

	BEB			IMC		
ROUTE 44	Scenario 1	Scenario 2	Scenario 3	NMC	LTO	**Trolleybus**
Values in MMUSD						
Buses	$38.00	$23.00	$19.00	$16.00	$16.00	$16.00
Batteries	$2.81	$1.70	$1,406	$0.23	$0.29	$0.08
Subtotal	**$40.81**	**$24.70**	**$20,406**	**$16.23**	**$16.29**	**$17.68**
Substations	$4.20	$5.40	$7.20	$3.06	$5.40	$3.60
Chargers for BEB / catenary for IMC and Trolleybus	$1.08	$1.53	$1.89	$9.84	$9.84	$22.22
Subtotal	**$5.28**	**$6.93**	**$9.09**	**$12.90**	**$12.90**	**$25.82**
Total	***$46.09***	***$31.63***	***$29.49***	***$29.13***	***$29.19***	***$43.50***

Detail of the BEB CAPEX

BEBs have several elements that differentiate them from the other alternatives. First and foremost is the size of the battery; because the bus is expected to run a full day without recharging, the battery must be of significant size. The second element is the charging methodology. BEBs are charged in the yard, so enough space must be allotted for the necessary electrical equipment. (With regard to bus maintenance, there is a difference in the cost of tires, but we omit that variable because it can depend, in addition to weight, on other second. Table 28 presents the basic information for the BEB fleet cost analysis:

Table 28. Basic data for cost evaluation

Variable	*Value*	*Unit*
time	15	years
size	40	Ft
battery size	370	kWh
daily energy use DOD	80%	percent

The number of chargers reflects what is required to charge the entire fleet and have at least one backup available. The energy use reflects the level of battery discharge on each trip and considering the minimum of 160 miles.

Table 29 features other infrastructure costs.

Table 29. Cost for infrastructure related to BEB

Variable	*Value*	*Unit*
Bus Cost BEB (wo battery)	1	MMUSD
Battery Cost	0.2	MMUSD / MWh
Charger Power	0.1	MW
Power Requirement for 10 chargers (Scenario 1)	1.2	MW
Power Requirement for 15 chargers (Scenario 2)	1.7	MW
Power Requirement for 19 chargers (Scenario 3)	2.1	MW
Power Efficiency of substation	90%	percent
Active Power Substation (Scenario 1)	1.4	MVA
Active Power Substation (Scenario 2)	1.8	MVA
Active Power Substation (Scenario 3)	2.4	MVA
Maintenance cost of substations as percentage of price	0.50%	percent
Power substation cost / MVA	3	MMUSD / MVA
Charger cost	0.9	MMUSD/MW

We have priced the battery at 200 USD/kWh. Prices for an NMC lithium battery are on the order of 130 USD/kWh, but this number does not include the battery container, electronics, and protection systems. (According to several studies, the 130 USD/kWh cost will likely increase in the coming months due to the increase in the price of raw materials.)

We price a substation at three million dollars per MVA, which number does not include cost of purchase of land or similar. We assessed the cost of a CD changer at $900,000.00, which value includes the equipment and rectifiers needed per unit.

CAPEX BEB Scenario 1

The CAPEX values for Scenario 1 are shown in Table 30. We only estimate fleet and electrical equipment.

Table 30. CAPEX for BEB Scenario 1

ROUTE 44	CAPEX
all values in MMUSD	
Buses	38
Batteries	2.812
Subtotal	**40.81**
Substations	4.2
Chargers	1.08
Subtotal	**5.28**
Total	**46.09**

CAPEX BEB Scenario 2

The CAPEX values for Scenario 2 are shown in Table 31. We only estimate fleet and electrical equipment.

Table 31. CAPEX for BEB Scenario 2

ROUTE 44	CAPEX
all values in MMUSD	
Buses	23
Batteries	1.70
Subtotal	**24.70**
Substations	5.4
Chargers	1.53
Subtotal	**6.93**
Total	**31.63**

CAPEX BEB Scenario 3

The CAPEX values for Scenario 3 are shown in Table 32. We only estimate fleet and electrical equipment.

Table 32. CAPEX for BEB Scenario 3

ROUTE 44	CAPEX
all values in MMUSD	
Buses	19
Batteries	1.406
Subtotal	**20.41**
Substations	7.2
Chargers	1.89
Subtotal	**9.09**
Total	**29.50**

CAPEX IMC with NMC battery

Like BEBs, IMC buses have specific characteristics. The first is the size of the battery. Relative to the BEB battery, the IMC battery can be one fifth the size.

The second differentiating element is the length of catenary that feeds the bus. The percentage of catenary length compared to route length is usually less than 50 percent.

Table 33 outlines the costs for the IMC bus with an NMC battery.

Table 33. Cost for IMC-NMC

Variable	Value	Unit
time	15	years
Bus size	40	ft
IMC battery size	71	kWh
Fleet size	16	buses
energy use DOD (depth of discharge)	15%	percent

The fleet size is equal to the current fleet size due to the 1:1 replacement ratio. NMC buses contain a 71 kWh battery that allows them to roll on a full charge up to 20 miles. But having different charges on the track will only discharge a maximum of 15 percent.

Table 34 presents other important variables in the cost assessment.

Table 34. Additional information for cost assessment for IMC-NMC

Variable	Value	Unit
Bus IMC cost	1	MMUSD
Battery cost	0.2	MMUSD / MWh
Substation average power	0.34	MVA
Number of substations in route	3	
Power efficiency of substation	90%	percent
Maintenance cost of substations as percentage of price	0.50%	MMUSD
Power substation cost / MVA	3	MMUSD
Number of battery charges per day per bus	36	cycles
Charges per year	13140	cycles
Catenary price	1.2	MMUSD/mi.
Catenary intersections price	0.3	MMUSD/mi.
Route length	17.02	mi
Catenary length	8.2	mi
Catenary length percentage	48%	
Number of Intersection	0	

It is important to note that the wiring length in the table refers to wiring in a single direction only, not to a double catenary in two directions.

We assume the same substation costs as in the BEB assessment. However, the substations are smaller compared to the BEB. The maximum number of substations is three.

IMC buses can travel this route a number of times in a day. An IMC bus can complete the route in one hour. Given that they can operate constantly without the need for a full recharge stop, they could service the route 18 hours or 24 hours depending on the schedule. If the bus operates 18 hours, then it would perform 36 battery recharges in the catenary sections. If it operates 24 hours, it would perform 48 battery recharges in the catenary sections. For this exercise, we assume 36 battery recharges because it is the most frequent cycle for each bus.

We estimated the amount of catenary needed to meet the demand for IMC buses at 48 percent of the route. This is to ensure optimal battery utilization—guaranteeing a discharge of only 15 percent. In addition, we reduce the number of intersections with other catenary sections to zero because we model only plain catenary sections, which are more economical to maintain.

Table 35 presents the capital values required for the implementation of IMC buses with NMC batteries.

Table 35. CAPEX for IMC – 71 kWh NMC

ROUTE 44	CAPEX
All values in MMUSD	
Buses	$ 16.00
Batteries	$ 0.23
Subtotal	**$ 16.23**
Catenary	$ 9.84
Substations	$ 3.06
Subtotal	**$ 12.90**
Total	**$ 29.13**

CAPEX IMC with LTO battery

There are two principal distinctions between the IMC bus with the LTO battery and IMC bus with the NMC battery. First, the LTO battery can take many more charge and discharge cycles than an NMC battery. Second, the LTO battery is heavier, and its capacity is only 30kWh. Table 36 presents the cost of the principal parameters.

Table 36. Cost for IMC-LTO

Variable	Value	Unit
Time	15	years
Bus Size	40	ft
Battery size	30	kWh
Fleet size	16	buses
Energy use from battery. DOD	40%	percent

Another difference between IMC-LTO and IMC-NMC is the depth of discharge. Being the smallest battery, the LTO's discharge will be deeper in the shorter sections of catenary. This impacts service life.

Table 37 presents the remaining variables in the model.

Table 37. Additional information for cost assessment for IMC-LTO

Variable	Value	Unit
Bus IMC cost	1	MMUSD
Battery cost LTO	0.6	MMUSD / MWh
Substation average power	0.34	MVA
Number of substations in route	3	
Power efficiency of substation	90%	percent
Maintenance cost of substations as percentage of price	0.50%	MMUSD
Power substation cost / MVA	3	MMUSD
Number of battery charges per day per bus	36	cycles
Charges per year	13140	cycles
Catenary price	1.2	MMUSD/mi.
Catenary intersections price	0.3	MMUSD/mi.
Route length	17.02	mi
Catenary length	8.2	mi
Catenary length percentage	48%	
Number of Intersection	0	

The LTO battery is more expensive than the NMC battery: The latest prices place it at a ratio of 1:3. Thus, we price the LTO battery at approximately $600 per kWh. The efficiency of the substation is lower than that of the BEB bus due to the distance between the sources and rectifiers with the vehicle; six percent of energy is lost in transmission. The rest of the values are similar to the IMC bus with NMC battery.[i]

Table 38 presents the results of the initial capital calculation.

Table 38. CAPEX for IMC with 30 kWh LTO

ROUTE 44	***CAPEX***
all values in MMUSD	
Buses	$ 16.00
Batteries	$ 0.29
Subtotal	**$ 16.29**
Catenary	$ 9.84
Substations	$ 5.40
Subtotal	**$ 12.90**
Total	**$29.19**

CAPEX trolleybus

The characteristic of trolleybuses is that they require a catenary line throughout the route to operate. Although they have a battery, it is only used for emergencies. Therefore, the battery is small. Table 39 shows the variables.

Table 39. Cost information for trolleybus scenario

Variable	***Value***	***Unit***
time	15	years
Bus size	40	Ft
battery size	25	Kwh
Fleet size	16	buses

Trolleybuses have a replacement ratio of 1:1 so there is no need to increase the fleet. The other parameters are in Table 40.

Table 40. Additional information for Cost assessment for trolleybus

Variable	***Value***	***Unit***
Trolleybus Cost (wo battery)	1.1	MMUSD
Battery Cost	0.2	MMUSD / MWh
Substation power	0.3	MWA
number of substations	4	unit
Power Substation Cost / MVA	3	MMUSD / MVA
Power Efficiency in substation	90.00%	
Power substation Maintenance cost percent	0.50%	percent
Catenary price	1.2	MMUSD/mi.
Catenary intersection additional cost	0.3	MMUSD/unit
Route length	17.02	mi
Catenary length	17.02	mi
Number of Intersections	6	unit

The entire route has catenary. Therefore, all 17.02 miles are covered with catenary. The number of intersections with other catenary routes observed was six. This adds extra value to each segment equivalent to $300,000. The number of substations is four to deliver power to the entire catenary.

With the above, the results of the CAPEX calculation are (Table 41):

Table 41. CAPEX for Trolleybus

ROUTE 44	***CAPEX***
all values in MMUSD	
Buses	16
Batteries	0.08
Subtotal	**17.68**
Catenary	22.224
Substations	3.6
Subtotal	**25.824**

ROUTE 44	CAPEX
Subtotal	43.504

9.2. OPEX

Energy

Energy is the main input of the different alternatives. With regard to energy consumption, we consider two variables: the amount of energy used per day, expressed in a dollar value; and the cost of such energy per passenger per mile.

For the former, we simply calculate how many MWh of energy are used each day. For the latter, we use the vehicle's annual mileage, total energy, and the assumed maximum passenger capacity of the route. These variables yield the minimum possible value, an indicator of a vehicle's total efficiency. The formula is as follows:

$$E_{PMi} = \frac{E_T}{N_P D_T}$$

Where E_T is the energy, N_p total number of passengers per mile, and D_T the total number of miles.

Our energy calculation accounts for the number of recharges made. The number of refills in BEB Scenario 1 is only 1, since each bus has a substitute to comply with the stipulated frequency. Scenarios Two and Three, however, include more than 1 recharge a day, implying that the bus will use more energy. For IMC buses, we consider the number of recharges per day and the depth of each recharge in addition to the amount of energy needed to travel the requisite kilometers in catenary. We presume the price of the energy in two different cases. The first case uses the commercial value of energy as of October 2022. The second uses the price of energy negotiated with SFMTA by PG&E[ii] (Figure 49).

Time Category	Time Frame	Cost Per kWh
Wholesale	--	$0.079
Super Off-Peak	9:00 AM – 4:00 PM	$0.098
Peak Energy	4:00 PM – 9:00 PM	$0.33
Off-Peak	9:00 PM – 9:00 AM	$0.12

Source: PG&E

Figure 49. SFMTA ZE plans: Reference cost for energy.

Although San Francisco's public hydropower system provides public agencies, including SFMTA, 100 percent renewable energy at exceptionally low prices, the entire California grid faces a variety of capacity constraints that limit how much energy can be transmitted into the city, meaning that we must estimate the daily energy consumption of each fleet.

Energy cost—BEB Scenario 1

In this scenario, charging occurs throughout day and night. A maximum of 8 vehicles are charged simultaneously, and there are vehicles charging at all hours. Each vehicle charges 4 hours. During those 4 hours, each vehicle consumes 83kWh. Depending on the possible programming, the operability of the chargers can be seen in Figure 50.

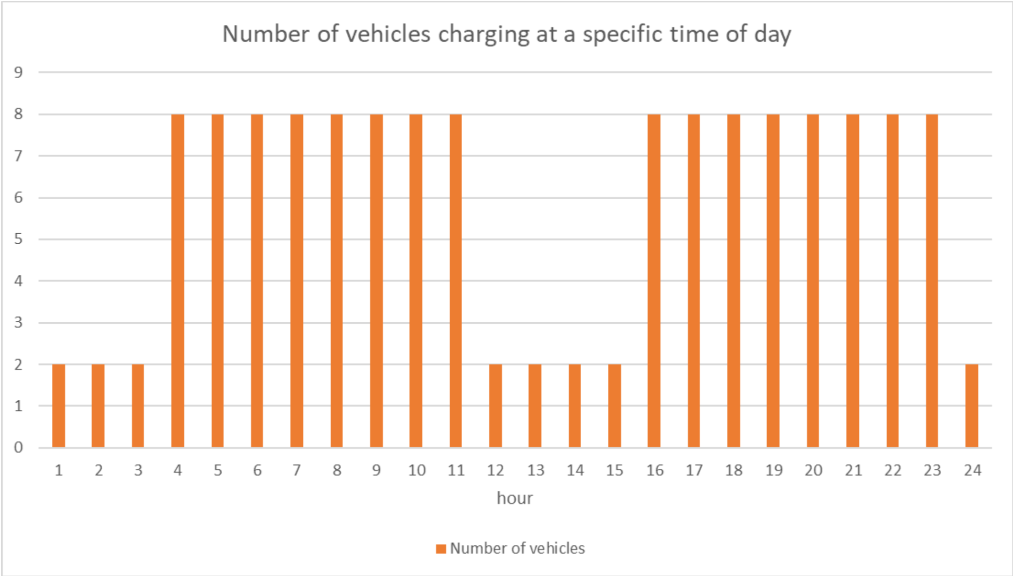


Figure 50. Vehicles charging through the day—BEB scenario 1.

By multiplying the different energy costs by the consumption of each vehicle and by the number of vehicles charging, we establish the total cost of energy per day. We record the results in Table 42.

Table 42. Energy prices and cost for BEB scenario 1

		Day	**Year**
Energy price	Energy (kWh)	11,952.00	4,362,480.00
	Energy priced hourly (USD)	$ 2,078.32	$ 758,586.80
	Energy priced wholesale (USD)	$ 956.16	$ 348,998.40

Energy cost—BEB Scenario 2

In this scenario, we change the programming of the buses to conduct several charges in a day. We summarize the use of the chargers in Figure 51.

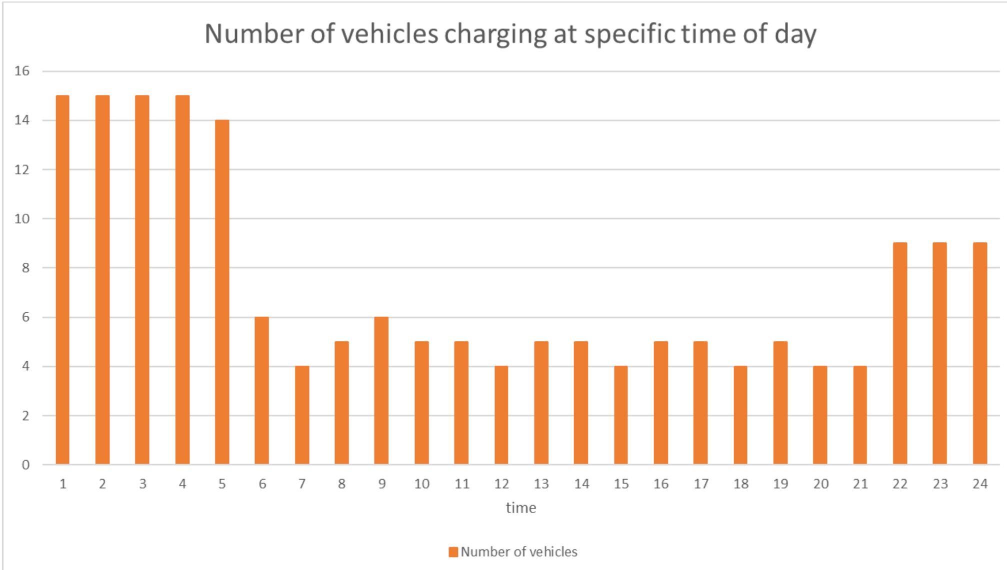


Figure 51. Vehicles charging through the day—BEB Scenario 2.

Table 43 shows the daily and annual energy costs.

Table 43. Energy prices and cost for BEB scenario 2

		Day	***Year***
	Energy (kWh)	12,980.00	4,737,700.00
Energy price	Energy priced hourly (USD)	$ 1,848.00	$ 674,520.00
	Energy priced wholesale (USD)	$ 1,038.40	$379,016.00

In this scenario, the buses required are the minimum. This means they undergo two charges a day: a full charge of 4 hours and a partial charge of 2 hours. Some buses operate for 16 hours; others for 17 hours. Charging times are in the 7-to-8-hour range. The number of chargers in this scenario is the highest of the two. More energy is used because more buses are operating in this scenario than the first scenario, as shown in Table 44.

Table 44. Number of buses comparison every hour between scenarios 1 and 2

Time of day	*0*	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*	*20*	*21*	*22*	*23*
Scenario 2	8	8	8	8	9	17	19	18	17	18	18	19	18	18	19	18	18	19	18	19	19	14	14	14
Scenario 1	5	8	8	8	8	16	18	18	18	18	18	18	18	18	18	18	18	18	18	18	18	10	10	10
Difference	3	0	0	0	1	1	1	0	-1	0	0	1	0	0	1	0	0	1	0	1	1	4	4	4
Total extra buses	22																							

Energy cost—BEB Scenario 3

In this scenario, the buses required are the minimum. This means they undergo two charges a day: a full charge of 4 hours and a partial charge of 2 hours (Figure 52). There are hours where zero buses are operating, which makes this scenario unfeasible. We present it here simply for reference purposes. The annual energy costs are shown in Table 45.

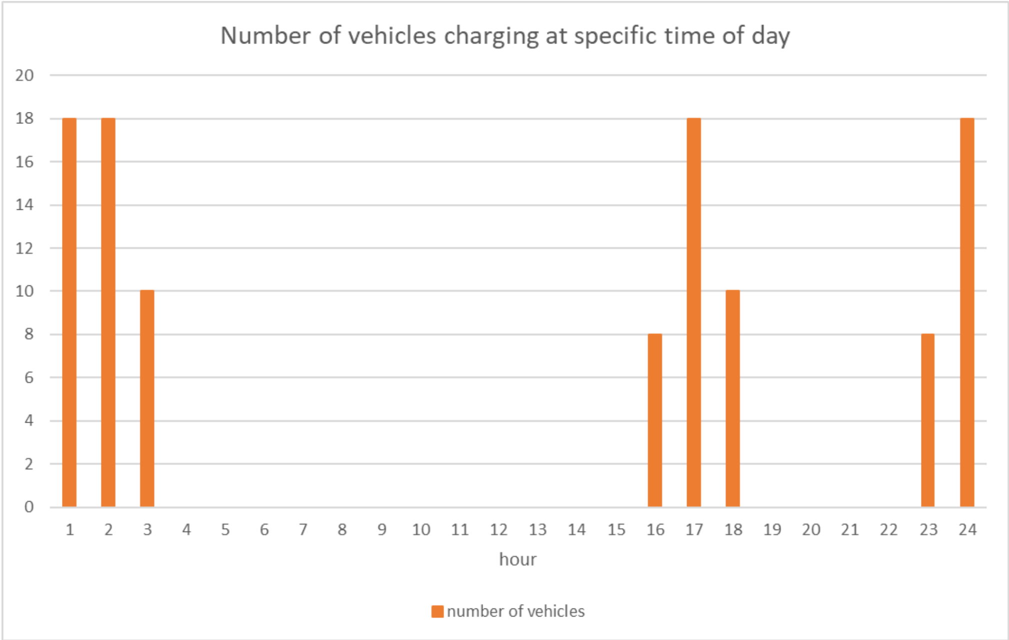


Figure 52. Vehicles charging through the day—BEB Scenario 3.

Table 45. Energy prices and cost for BEB Scenario 3

		Day	***Year***
	Energy (kWh)	8,964.00	3,271,860.00
Energy price	Energy priced hourly (USD)	$ 1,550.44	$ 565,910.60
	Energy priced wholesale (USD)	$ 717.12	$ 261,748.80

Cost of energy—IMC buses

The energy consumed by IMC buses is the same regardless of the battery chemistry. Therefore, we consider the charges and discharges done made to maintain the operation of the system without differentiating between LTO and NMC.

To determine the energy consumption per hour of IMC buses, we use the simulation data—that is, 4,114 kWh for 16 IMC buses from 4:00 am to 12:00 pm. The consumption per hour of energy is thus 25.7125 kWh.

With this value established, we program the schedule proposed for this route. The number of buses is 16, except overnight: There are 8 buses at night and four buses servicing the midnight schedule. We then multiply the number of buses per hour by the energy consumed by each bus per hour as well as by the corresponding price of energy.

We present our results in Table 46.

Table 46. Energy prices and energy cost for IMC

		Day	***Year***
	Energy (kWh)	8,022	2,928,140
Energy price	Energy priced hourly (USD)	$ 1,337.05	$ 488,023.25
	Energy priced wholesale (USD)	$ 641.78	$ 234,251.16

Cost of Energy—trolleybus

The process for determining the energy cost of the trolleybus alternative is similar to that of the IMC bus: It is based on the energy consumption of the buses in the simulation—that is, 3,651 kWh. This means that, on average, each vehicle consumed 22.81 kWh. We use these values to calculate the total cost of energy (Table 47).

Table 47. Energy prices and energy cost for trolleybus

		Day	**Year**
	Energy (kWh)	7,119	2,598,599
Energy price	Energy priced hourly (USD)	$1,186.58	$ 433,099.88
	Energy priced wholesale (USD)	$ 569.56	$ 207,887.94

Maintenance

To establish maintenance values, we consider an array of elements while omitting features common to each fleet, such as chassis, body, and auxiliary services. (Although these features may differ slightly according to the vehicle manufacturer, we consider them similar enough not to warrant their inclusion in the calculation.) Although tire costs are, in fact, much higher in BEBs, we hold tire costs constant across alternatives in our calculation.

BEB maintenance

BEB buses feature two pieces of equipment that require specific maintenance: chargers and batteries. Preventive charger maintenance is common and is accompanied by corrective maintenance on internal contactors and the connection cable to the vehicle. The connection cable usually must be replaced every 5,000 charges, and cables for power chargers are particularly expensive due to the cooling systems included in the cable.

The cost of maintenance of a given element—whether the vehicle or a piece of equipment—is usually around 0.5 percent of the value of the element. In year 10—or at 500,000 miles—the bus requires a complete maintenance that usually corresponds to 30 percent of the vehicle's value. Batteries, however, must be changed when they reach 80 percent SOH. This depends on the periodicity of the charges and the depth as indicated in the above sections.

BEB Scenario 1

Vehicles are charged once a day, and each vehicle moves 160 miles in a day. The battery with 2,500 cycles would last 7 years and must be changed in year 8. These circumstances produce the costs shown in Table 48 (only the first 10 years are shown).

Table 48. Maintenance cost for BEB Scenario 1

Maintenance (MMUSD)										
Year	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
Bus										
Other maintenance	$0.19	$0.19	$0.19	$0.19	$0.19	$0.19	$0.19	$0.19	$0.19	$0.19
Higher maintenance (30%)										$12.24
Battery replacement								$2.81		
Subtotal	**$0.19**	**$0.19**	**$0.19**	**$0.19**	**$0.19**	**$0.19**	**$0.19**	**$3.00**	**$0.19**	**$12.43**
Substation and chargers Maintenance										
Charger maintenance	$0.01	$0.01	$0.01	$0.01	$0.01	$0.01	$0.01	$0.01	$0.01	$0.01
Substation	$0.02	$0.02	$0.02	$0.02	$0.02	$0.02	$0.02	$0.02	$0.02	$0.02
Subtotal	**$0.03**	**$0.03**	**$0.03**	**$0.03**	**$0.03**	**$0.03**	**$0.03**	**$0.03**	**$0.03**	**$0.03**

BEB Scenario 2

Vehicles are charged twice a day, and each vehicle moves about 270 miles in a day. As the battery is charged twice, the maximum number of cycles is reached faster. Batteries must be changed 3 times in 15 years: at year 4, year 8, and year 12. Deep maintenance is also done sooner because the mileage limit—500,000—is reached more quickly (five years). If the bus continues to operate after that time, another maintenance must be performed in year 10, or the vehicle must be replaced with a new one. Table 49 presents maintenances costs for Scenario 2.

Table 49. Maintenance Cost for BEB Scenario 2

Maintenance										
Year	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
Bus										
Other maintenance	$0.12	$0.12	$0.12	$0.12	$0.12	$0.12	$0.12	$0.12	$0.12	$0.12
Higher maintenance (30%)					$7.41					$7.41
Battery replacement				$1.70				$1.70		
Subtotal	**$0.12**	**$0.12**	**$0.12**	**$1.83**	**$7.53**	**$0.12**	**$0.12**	**$1.83**	**$0.12**	**$7.53**
Substation and chargers maintenance										
Charger maintenance	$0.01	$0.01	$0.01	$0.01	$0.01	$0.01	$0.01	$0.01	$0.01	$0.01
Substation	$0.03	$0.03	$0.03	$0.03	$0.03	$0.03	$0.03	$0.03	$0.03	$0.03
Subtotal	**$0.03**	**$0.03**	**$0.03**	**$0.03**	**$0.03**	**$0.03**	**$0.03**	**$0.03**	**$0.03**	**$0.03**

BEB Scenario 3

Vehicles are charged twice a day, and each vehicle moves about 240 miles in a day. As the battery is charged twice, the maximum number of cycles is reached faster. Batteries must be changed 3 times in 15 years: at year 4, year 8, and year 12. Deep maintenance in Scenario 3 is performed at 6 years—sooner than in Scenario 1 but slower than in Scenario Two. If the bus continues to operate after that time, further maintenance must be performed in year 12, or the vehicle must be replaced with a new one. Table 50 presents the maintenance costs for Scenario 3.

Table 50. Maintenance Cost for BEB Scenario 3

Maintenance										
Year	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
Bus										
Other maintenance	$0.10	$0.10	$0.10	$0.10	$0.10	$0.10	$0.10	$0.10	$0.10	$0.10
Higher maintenance (30%)						$6.12				
Battery replacement				$1.41				$1.41		
Subtotal	**$0.10**	**$0.10**	**$0.10**	**$1.50**	**$0.10**	**$6.22**	**$0.10**	**$1.51**	**$0.10**	**$0.10**
Substation and chargers maintenance										
Charger maintenance	$0.01	$0.01	$0.01	$0.01	$0.01	$0.01	$0.01	$0.01	$0.01	$0.01
Substation	$0.04	$0.04	$0.04	$0.04	$0.04	$0.04	$0.04	$0.04	$0.04	$0.04
Subtotal	**$0.05**	**$0.05**	**$0.05**	**$0.05**	**$0.05**	**$0.05**	**$0.05**	**$0.05**	**$0.05**	**$0.05**

IMC Maintenance

IMC buses feature two key pieces of equipment that require specific maintenance: Batteries and catenaries. Batteries must be replaced periodically due to the number of charge and discharge cycles. For the IMC bus with an NMC battery, the number of cycles necessitates a battery change every 2.5 years. For the IMC bus with an LTO battery, the replacement time is 3.5 years.

The catenary, being an open infrastructure, must be constantly maintained to ensure its viability and public safety. As we note above, the catenary for IMC buses is simple and costs less to maintain because it does not have intersections with other catenaries.

Given that IMC buses can operate 24 hours a day, maintenance is more periodic. For rotation's sake, we assume IMC buses to operate an average of 18 hours without stopping. This equates to a distance of 288 miles a day. At that rate, the bus reaches 500,000 miles in 4.5 years.

The IMC catenary is different from the trolleybus catenary. The IMC catenary is designed to avoid the installation of wires in closed curves, crossings with other catenary sections, and areas of complex or limited space. In addition, the IMC catenary is much shorter. It is possible to achieve reductions of 40 percent to 75 percent in the length of the catenary sections. For our model, we assume the catenary reduction is 52 percent.

To estimate the value of catenary maintenance we use several reports on trolleybuses. These reports specify that the value per kilometer per bus is USD 0.5. For the IMC case, we assume a 40 percent savings because of the catenary's simplicity. So, in our model, catenary maintenance costs USD 0.3—a conservative estimate, in our view, given that complex accessories account for between 80 percent to 90 percent of the total cost of overhead line maintenance.

The reports we consulted report the cost of trolleybus maintenance to be USD 0.5. The maintenance of the IMC bus is a little more expensive since it incorporates elements of both the BEB bus and the trolleybus. Therefore, we use 0.7 percent of the bus value as an annual maintenance value.[iii]

IMC with NMC

We present the maintenance costs of the IMC bus with the NMC battery in Table 51. The battery must be changed six times over the first 15 years, but we only show the first 10 years here.

Table 51. Maintenance cost for IMC bus with NMC battery

Maintenance										
Year	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
Bus										
Other maintenance	$0.11	$0.11	$0.11	$0. 11	$0. 11	$0. 11	$0. 11	$0. 11	$0. 11	$0. 11
Higher maintenance (30%)				$4.80					$4.80	
Battery replacement		$0.23			$0.23		$0.23			$0.23
Subtotal	**$0.11**	**$0.34**	**$0.11**	**$4.91**	**$0.34**	**$0.11**	**$0.34**	**$0.11**	**$4.91**	**$0.34**
Substation and catenary Maintenance										
Catenary maintenance (materials only)	$0.26	$0.26	$0.26	$0.26	$0.26	$0.26	$0.26	$0.26	$0.26	$0.26
Substation	$0.02	$0.02	$0.02	$0.02	$0.02	$0.02	$0.02	$0.02	$0.02	$0.02
Subtotal	**$0.28**	**$0.28**	**$0.28**	**$0.28**	**$0.28**	**$0.28**	**$0.28**	**$0.28**	**$0.28**	**$0.28**

IMC with LTO

We present the maintenance costs of the IMC bus with the LTO battery in Table 52. The difference in costs between the two cases lies in the type of battery and the time between major overhauls to replace batteries. Battery-replacement schedules vary among alternatives as their degradation depends on the cycling and operational conditions.

Table 52. Maintenance cost for the IMC bus with the LTO battery

Maintenance										
Year	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*
Bus Maintenance										
Other maintenance	$0.11	$0.11	$0.11	$0.11	$0.11	$0.11	$0.11	$0.11	$0.11	$0.11
Mayor maintenance (30%)				$4.89					$4.89	
Battery replacement				$0.29			$0.29			$0.29
Subtotal	**$0.11**	**$0.11**	**$0.11**	**$5.29**	**$0.11**	**$0.11**	**$0.40**	**$0.11**	**$5.00**	**$0.40**
Substation and Catenary Maintenance										
Catenary maintenance (materials only)	$0.26	$0.26	$0.26	$0.26	$0.26	$0.26	$0.26	$0.26	$0.26	$0.26
Substation	$0.02	$0.02	$0.02	$0.02	$0.02	$0.02	$0.02	$0.02	$0.02	$0.02
Subtotal	**$0.28**	**$0.28**	**$0.28**	**$0.28**	**$0.28**	**$0.28**	**$0.28**	**$0.28**	**$0.28**	**$0.28**

Trolleybus maintenance

With trolleybuses, the principal maintenance costs derive from the trolley and catenary. Modern traction motors are very low maintenance. The induction motor is robust, simple, and energy efficient and has been the industry standard for trolleybuses since the last two decades. The need to achieve the highest energy efficiency on heavy, limited range BEBs has led to the adoption of Permanent Magnet Motors (PMM). While smaller and lower weight, these motors' benefits are marginal in relation to their higher cost and difficulty in maintenance. Unlike PMMs, induction motors don't require rare-earth materials, making it less necessary to rely on long international supply chains and current manufacturing constraints.

The catenaries on trolleybus routes are complete. This means that 100 percent of the route must be considered when evaluating maintenance. Likewise, the cost per mile of maintenance should be considered complete, without discount for intersections and sharp curves that require a lot of maintenance.

We present estimated costs for the trolleybus alternative over a period of 8 years in Table 53.

Table 53. Maintenance cost for trolleybus

Maintenance								
Year	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*
Bus Maintenance								
Other maintenance	$0.12	$0.12	$0.12	$0.12	$0.12	$0.12	$0.12	$0.12
Mayor maintenance (30%)				$5.30				
Battery replacement						$0.08		
Subtotal	**$0.12**	**$0.12**	**$0.12**	**$5.43**	**$0.12**	**$0.20**	**$0.12**	**$0.12**
Substation and Catenary Maintenance								
Catenary maintenance (materials only)	$0.89	$0.89	$0.89	$0.89	$0.89	$0.89	$0.89	$0.89
Substation	$0.02	$0.02	$0.02	$0.02	$0.02	$0.02	$0.02	$0.02
Subtotal	**$0.92**	**$0.92**	**$0.92**	**$0.92**	**$0.92**	**$0.92**	**$0.92**	**$0.92**

Parking Yard

Space is scarce in San Francisco. The Woods garage/bus yard is located east of the city in an area completely developed by industries and warehouses. There is a Muni METRO and Isla Creek Muni workshop in the same area (see Figure 53).

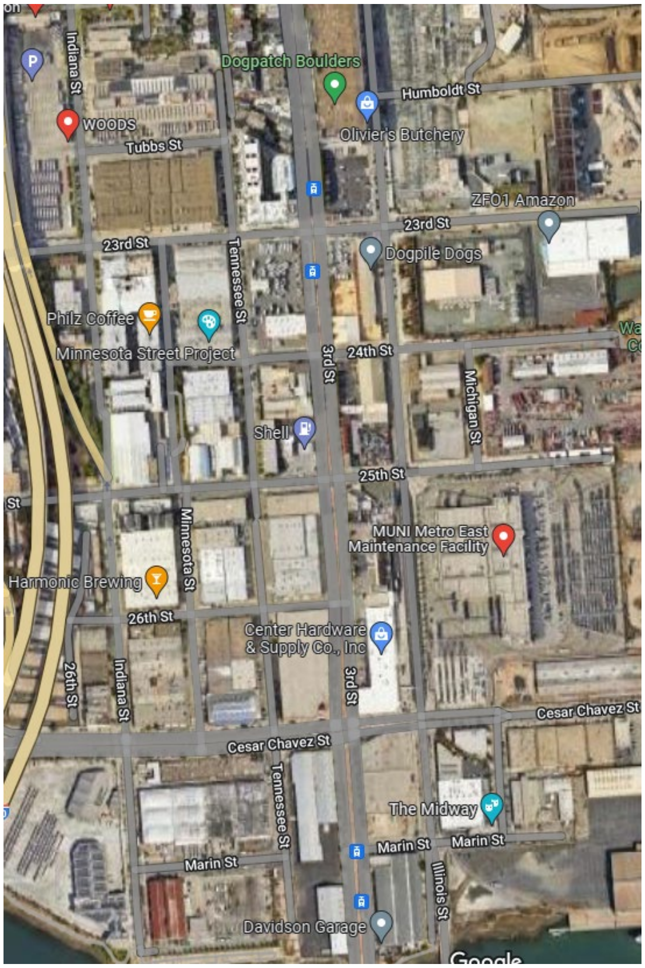


Figure 53. Woods parking yard.

We acquired property value information from https://www.sfassessor.org/property-information/homeowners/property-search-tool. The site shows that there are different buildings belonging to MUNI SFMTA in the area. Prices around these buildings range from USD 10 per square foot to prices of USD 500 per square foot (see Figure 54). We observe an average price of USD 375.

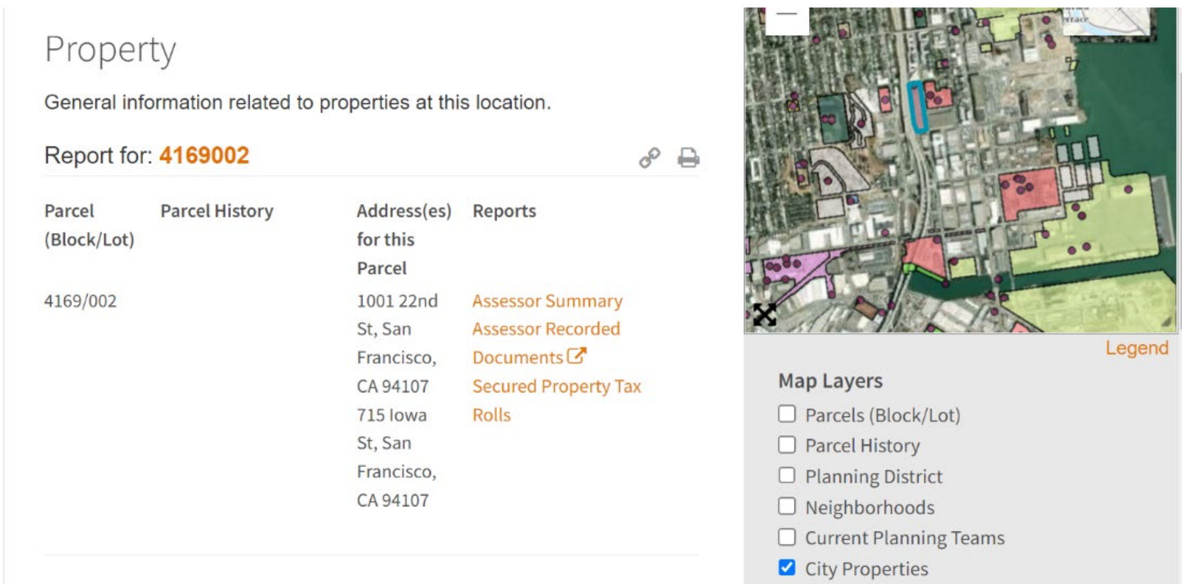


Figure 54. Land reference cost information.

Knowing the spatial requirements for storing and charging the fleet is of the utmost importance. If the available space is sufficient to accommodate the new fleet, then the transition is that much easier. But if the available space requires vertical construction to accommodate the fleet, or if planners need to purchase nearby properties, the costs could multiply.

As we note above, trolleybuses and IMC buses have a 1:1 replacement ratio with diesel-hybrid or gas buses. Thus, only catenary adjustments within and from the parking site to the different routes are required. These adjustments should neither require much additional space nor affect capacity.

In the case of BEBs, however, space requirements could range from 18 percent to 50 percent more than what is currently available. For Route 44, in the three BEB scenarios, we see fleet increases of 100 percent, 30 percent, and 18 percent respectively. A 100 percent increase in the area required would necessitate the purchase of additional space or the construction of a multilevel parking lot. A 30 percent increase could be accommodated with partial construction to fit charging sites and some additional parking. An 18 percent increase could be accommodated with the design of a new charging-site space. We reiterate, however, that the lowest fleet increase (BEB Scenario 3) is infeasible in terms of meeting daily passenger demand (it is only feasible for peak capacity).

BEB Scenario 1

The Woods garage/bus yard has an area of 171,000 sq-ft. Doubling that area would cost USD 64.13 million simply to purchase the additional property. There would then be the costs of demolitions, adaptations, and new constructions. For example, we estimate that the adaptations of the charging spaces would require an additional 21,800 square feet. We detail the costs of Scenario 1 in Table 54.

Table 54. Cost for yard expansion—BEB Scenario 1

YARD	Value	Unit
Current yard size	171,000.00	sq-ft
Price (sq-ft)	$375	USD
Expansion (sq-ft)	21,800.00	sq-ft
Expansion price (MMUSD)	$8,212,500	USD
Catenary	0	mi
Catenary price (MMUSD)	$0	MMUSD

The CAPEX required for this scenario including the parking yard expansion is shown in Table 55.

Table 55. Total CAPEX—BEB Scenario 1

Item	Value
CAPEX (MMUSD in Infrastructure, buses...)	$46.092
Real-estate expansion (MMUSD)	$8.212
Subtotal (MMUSD)	**$54.30**

BEB Scenario 2

In this scenario, less additional space is required; however, the retrofits are more labor-intensive given the need for more chargers. This does not affect our calculation, though, since we are not including public works in our estimations. Prospective costs for Scenario 2 are detailed in Table 56 and Table 57.

Table 56. Cost for yard expansion—BEB Scenario 2

YARD	Value	Unit
Current yard size	171,000.00	sq-ft
Price (sq-ft)	$375	USD
Expansion (sq-ft)	14.700.00	sq-ft
Expansion price (MMUSD)	$5,475.000	USD
Catenary	0	my
Catenary price (MMUSD)	$0	MMUSD

Table 57. Total CAPEX—BEB Scenario 2

Item	
CAPEX (MMUSD in Infrastructure, buses...)	$31.63
Real-estate expansion (MMUSD)	$5.475
Subtotal (MMUSD)	**$37.11**

BEB Scenario 3

There is no difference in fleet in Scenario 3. Nevertheless, there is a similar need for chargers as in the other scenarios. The costs are detailed in Table 58 and Table 59.

Table 58. Cost for yard use BEB scenario 3

YARD	Value	Unit
Current yard size	171,000.00	sq-ft
Price (sq-ft)	$375	USD
Expansion (sq-ft)	-	sq-ft
Expansion price (MMUSD)	$0	USD
Catenary	0	mi
Catenary price (MMUSD)	$0	MMUSD

Table 59. Annual cost for land use BEB scenario 3

Annual	
CAPEX (MMUSD in Infrastructure, buses…)	$29.496
Real-estate expansion (MMUSD)	$0
Subtotal (MMUSD)	**$29.496**

IMC buses and trolleybuses

As with BEB Scenario 3, there is no need to add fleet with the IMC bus and trolleybus alternatives. The only additional requirement is the catenary in the bus yard and the possible additional catenary to reach the routes (the latter is unnecessary for IMC buses). We present the costs in Table 60 and Table 61 for IMC buses.

Table 60. Cost for yard use—IMC NMC

YARD	Value	Unit
Current yard size	171,000.00	sq-ft
Price (sq-ft)	$375	USD
Expansion (sq-ft)	-	sq-ft
Expansion price (MMUSD)	$0	USD
Catenary	2	mi
Catenary price (MMUSD)	$3.00	MMUSD

Table 61. Annual cost for land use—IMC NMC bus

Annual	
CAPEX (MMUSD in Infrastructure, buses…)	$29.13
Real-estate expansion (Catenary) (MMUSD)	$3.00
Subtotal (MMUSD)	$32.13

Net present value

For the calculation of net present value, we sum the corrected values at an annual equivalent rate. Since the values reflect constant prices, we must first normalize each year to the future value corresponding to the inflation rate budgeted in all periods. Then, with those values in hand, we calculate the net present using a market rate of return.

The discount rate is determined by the California Department of Finance. The rate of return will be risk-free for a 20-year bond at an interest rate of 3.82 percent.[iv]

We present the results for all alternatives in Table 62 (BEB Scenario1), Table 63 (BEB Scenario 2), Table 64 (BEB Scenario 3), Table 65 (IMC-NMC), Table 66 (IMC-LTO), Table 67 (trolleybus):

Table 62. Net Present Value—BEB Scenario 1 (Fleet: 38 buses)

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
CAPEX	$54.30															
OPEX (Constant Value)		$0.57	$0.57	$0.57	$0.57	$0.57	$0.57	$3.38	$0.57	$0.57	$12.81	$0.57	$0.57	$0.57	$3.38	$0.57
CPI		5.21%	3.28%	2.94%	3.09%	3.09%	3.09%	3.09%	3.09%	3.09%	3.09%	3.09%	3.09%	3.09%	3.09%	3.09%
Indexing		1.05	1.09	1.12	1.15	1.19	1.23	1.26	1.30	1.34	1.38	1.43	1.47	1.52	1.56	1.61
OPEX Future Value		$0.59	$0.61	$0.63	$0.65	$0.67	$0.69	$4.27	$0.74	$0.76	$17.72	$0.81	$0.83	$0.86	$5.28	$0.91
RoR	3.82%															
NPV	$79.46															

Table 63. Net Present Value BEB—Scenario 2 (Fleet: 23 buses)

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
CAPEX	$37.11															
OPEX (Constant Value)		$0.54	$0.54	$0.54	$2.24	$7.95	$0.54	$0.54	$2.24	$0.54	$7.95	$0.54	$2.24	$0.54	$0.54	$7.95
CPI		5.21%	3.28%	2.94%	3.09%	3.09%	3.09%	3.09%	3.09%	3.09%	3.09%	3.09%	3.09%	3.09%	3.09%	3.09%
Indexing		1.05	1.09	1.12	1.15	1.19	1.23	1.26	1.30	1.34	1.38	1.43	1.47	1.52	1.56	1.61
OPEX Future Value		$0.57	$0.58	$0.60	$2.58	$9.45	$0.66	$0.68	$2.92	$0.72	$11.00	$0.77	$3.29	$0.81	$0.84	$12.80
RoR	3.82%															
NPV	$70.97															

Table 64. Net Present Value—BEB Scenario 3 (Fleet: 19 buses)

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
CAPEX	$29.50															
OPEX (Constant Value)		$0.43	$0.43	$0.43	$1.83	$0.43	$6.55	$0.43	$1.83	$0.43	$0.43	$0.43	$7.95	$0.43	$0.43	$0.43
CPI		5.21%	3.28%	2.94%	3.09%	3.09%	3.09%	3.09%	3.09%	3.09%	3.09%	3.09%	3.09%	3.09%	3.09%	3.09%
Indexing		1.05	1.09	1.12	1.15	1.19	1.23	1.26	1.30	1.34	1.38	1.43	1.47	1.52	1.56	1.61
OPEX Future Value		$0.45	$0.46	$0.48	$2.11	$0.51	$8.02	$0.54	$2.39	$0.57	$0.59	$0.61	$11.70	$0.65	$0.67	$0.69
RoR	3.82%															
NPV	$51.47															

Table 65. Net Present Value—IMC-NMC

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
CAPEX	$32.13															
OPEX (Constant Value)		$0.64	$0.87	$0.64	$5.44	$0.87	$0.64	$0.87	$0.64	$5.44	$0.87	$0.64	$0.87	$5.44	$0.64	$0.87
CPI		5.21%	3.28%	2.94%	3.09%	3.09%	3.09%	3.09%	3.09%	3.09%	3.09%	3.09%	3.09%	3.09%	3.09%	3.09%
Indexing		1.05	1.09	1.12	1.15	1.19	1.23	1.26	1.30	1.34	1.38	1.43	1.47	1.52	1.56	1.61
OPEX Future Value		$0.67	$0.94	$0.71	$6.27	$1.03	$0.78	$1.09	$0.83	$7.30	$1.20	$0.91	$1.27	$8.24	$1.00	$1.40
RoR	3.82%															
NPV	$56.52															

Table 66. Net Present Value—IMC-LTO

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
CAPEX	$32.19															
OPEX (Constant Value)		$0.64	$0.64	$0.64	$5.81	$0.64	$0.64	$0.93	$0.64	$5.53	$0.93	$0.64	$0.64	$5.81	$0.64	$0.64
CPI		5.21%	3.28%	2.94%	3.09%	3.09%	3.09%	3.09%	3.09%	3.09%	3.09%	3.09%	3.09%	3.09%	3.09%	3.09%
Indexing		1.05	1.09	1.12	1.15	1.19	1.23	1.26	1.30	1.34	1.38	1.43	1.47	1.52	1.56	1.61
OPEX Future Value		$0.67	$0.69	$0.72	$6.70	$0.76	$0.78	$1.17	$0.83	$7.42	$1.28	$0.91	$0.94	$8.81	$1.00	$1.03
RoR	3.82%															
NPV	$56.63															

Table 67. Net Present Value—trolleybus

Year	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
CAPEX	$46.50															
OPEX (Constant Value)		$1.26	$1.26	$1.26	$6.57	$1.26	$1.34	$1.26	$1.26	$6.57	$1.26	$1.26	$1.34	$6.57	$1.26	$1.26
CPI		5.21%	3.28%	2.94%	3.09%	3.09%	3.09%	3.09%	3.09%	3.09%	3.09%	3.09%	3.09%	3.09%	3.09%	3.09%
Indexing		1.05	1.09	1.12	1.15	1.19	1.23	1.26	1.30	1.34	1.38	1.43	1.47	1.52	1.56	1.61
OPEX Future Value		$1.33	$1.37	$1.41	$7.57	$1.50	$1.65	$1.60	$1.65	$8.82	$1.75	$1.80	$1.98	$9.96	$1.98	$2.04
RoR	3.82%															
NPV	$80.26															

9.3. Summary of financial results

Table 68 presents a summary of the financials of the differential elements of the technologies, both for capital costs and operational costs, over a 15-year project period. We have included BEB Scenario 3 for reference purposes.

At the present time, **the most technically feasible and economical option for the electrification of Route 44 is the IMC bus with the 71 kWh NMC battery**. (The IMC bus with the LTO battery is a very close second.) Although the IMC-NMC alternative requires higher battery consumption over the 15-year project window, the current cost of the LTO battery—approximately three times the price per kWh of the NMC battery—undermines any financial advantage.

Table 68. 15-year financial results

Item	*BEB SC1*	*BEB SC2*	*BEB SC3 (Not VIABLE)*	*IMC NMC*	*IMC LTO*	*trolleybus*
CAPEX (MMUSD)	**54.30**	**37.11**	**29.50**	**32.13**	**32.19**	**46.50**
FLEET	38	23	19	16	16	16
CATENARY EXPANSION	0	*0*	*0*	*9.84*	*9.84*	*22.22*
Battery packs	2.81	1.70	1.41	0.23	0.29	0.08
CHARGERS	1.08	1.53	1.89	*0*	*0*	*0*
SUBSTATIONS	4.2	5.4	7.2	3.06	3.06	3.6
OPEX NPV (MMUSD)	**25.16**	**33.86**	**21.73**	**24.39**	**24.44**	**33.75**
Additional YARD REAL Estate (sq-ft)	21,900	13,200	0	0	0	0
NPV	**79.46**	**70.97**	**51.23**	**56.52**	**56.63**	**80.26**

The best BEB alternative (peak demand care and daily supply fulfillment) is Scenario 2 (Adjusted Dispatch). **But it is approximately 25 percent more expensive than IMC-LTO, the more expensive IMC option.**

One of the most important factors in favor of IMC technology is the reduced land use. As noted above, IMC technology requires a smaller fleet and less vehicle storage and charging space than BEB technologies.

10. Yard Electrification

Now that we have determined the best electrification strategy for a typical route, we turn to the yard level. First, we assess two other routes that use the Woods yard. Then, using a basic analysis—which considers indicators such as Route Demand Factor (RDF) and bus density—we postulate which technological alternative best suits each route.

In general, **we find that if the main routes of a yard use IMC buses, a desirable demand curve is more easily attained.**

For one, IMC flattens the power demand curve. Whereas BEBs charge overnight, thereby causing a new peak demand during the night hours as buses and electric cars charge, IMC buses charge continuously over the course of operation.

Second, in the case of NMC or LFP batteries—both of which have greater storage capacity than LTO, on the order of 71 kWh per bus)—with IMC, planners can implement strategies to manage the cost and/or demand of energy. For example, planners might pre-charge the battery in the depots at off-peak hours when prices are best, or even accumulate energy via solar panels during the prime daylight hours—but also off-peak hours—of 11:00 am to 3:00 pm.

10.1. Route 38-Geary Analysis

Route 38-Geary is another high-use diesel-hybrid route that offers the potential for IMC-based electrification. Like Route 44, Route 38 operates 24 hours, intersects trolleybus lines, and has a short overlap of catenary.

As practical matter, two routes operate in the 38-Geary corridor: standard service and a rapid line (38 R) with limited stops (see Table 69).

Table 69. Route 38 service description

	Service frequency (min)					
Service	Morning	Midday	Evening	Late Night	Owl	Peak fleet (buses)
38	8	8	10	15	30	14
38 R	8	8	8	10	--	14

For Route 38, we modeled an improvement in the electrification optimization algorithm to (1) avoid the installation of overhead contact line at crossings with other trolleybus lines and (2) reduce the purchase and installation of the accessories required for this type of intersections, which represent significant installation and operation costs. In any case, through short underground feeders, the feeding systems of the different routes can be connected in parallel to contribute to stability in the grid.

Electrification of Route 38-Geary via IMC–NMC with two TPSs and no intersections

Figure 55 shows the 8 electrification scenarios of Route 38 given the following parameters: an IMC bus equipped with a 71 kWh NMC battery, 2 power points (TPSs), and 0 intersections with other trolleybus tracks. Table 70 explains the costs for each scenario, and Figure 56 shows the overhead line segments in the map.

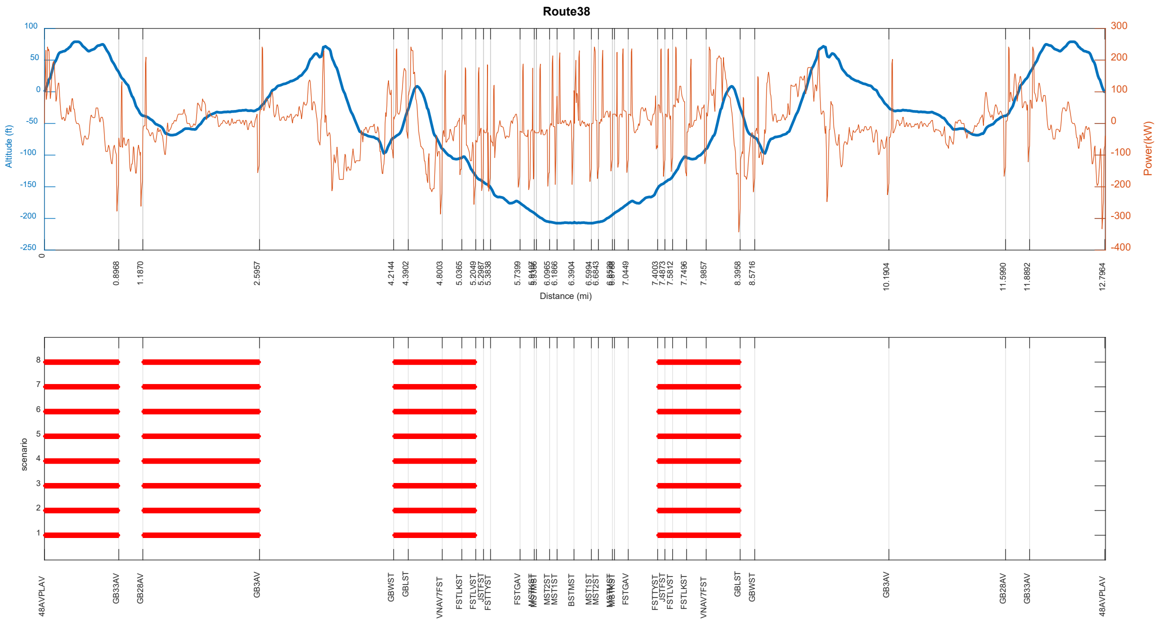


Figure 55. Optimized electrification for Route 38 with IMC–NMC buses, 2 TPSs, and 0 intersections.

Table 70. Cost scenarios for Route 38 electrification

Scenario	Objective Function	Battery Capacity (kWh)	Number of buses	Number of trips	Catenary distance (mi)	Number of Substations	Charging Power (kW)	Depot charging power (kW)	Initial SoC	Final SoC	Catenary Cost (USD/mi)	Substation Cost	Battery Cost (USD/kWh)	Depot Charger Cost (USD/KW)	Night charging duration
1	$ 14,756,563.80	71	15	12	4.289512	4	50	0	0.6	0.6	$ 1,500,000.00	$ 2,000,000.00	$ 300.00	$ 700.00	4
2	$ 14,756,563.80	71	15	12	4.289512	4	50	0	0.8	0.8	$ 1,500,000.00	$ 2,000,000.00	$ 300.00	$ 700.00	4
3	$ 18,756,563.80	71	15	12	4.289512	4	50	0	0.6	0.6	$ 1,500,000.00	$ 3,000,000.00	$ 300.00	$ 700.00	4
4	$ 18,756,563.80	71	15	12	4.289512	4	50	0	0.8	0.8	$ 1,500,000.00	$ 3,000,000.00	$ 300.00	$ 700.00	4
5	$ 16,902,251.73	71	15	12	4.289512	4	50	0	0.6	0.6	$ 2,000,000.00	$ 2,000,000.00	$ 300.00	$ 700.00	4
6	$ 16,902,251.73	71	15	12	4.289512	4	50	0	0.8	0.8	$ 2,000,000.00	$ 2,000,000.00	$ 300.00	$ 700.00	4
7	$ 20,902,251.73	71	15	12	4.289512	4	50	0	0.6	0.6	$ 2,000,000.00	$ 3,000,000.00	$ 300.00	$ 700.00	4
8	$ 20,902,251.73	71	15	12	4.289512	4	50	0	0.8	0.8	$ 2,000,000.00	$ 3,000,000.00	$ 300.00	$ 700.00	4

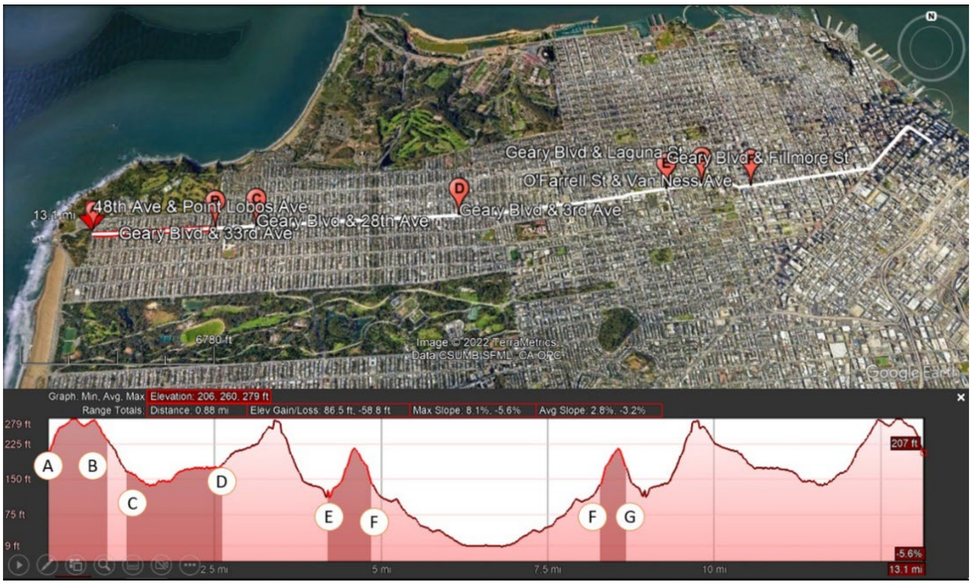


Figure 56. Route 38 catenary segments with IMC–NMC buses, 2 TPSs, and 0 intersections

We derived the various scenarios by combining the cost of the electrical infrastructure between MUSD 1.5 per km and MUS 2 per km, TPS costs between MUSD 2 per kWh and MUSD 3 per kWh, and an initial–final SOC between 0.6 and 0.8.

Figure 57 shows the behavior of the battery's state of charge, which remains within the 20 percent range required to ensure a long service life. In addition, we have sought a maximum charge of 90 percent and a highest DOD of 30 percent. Although this was not a constraint on the model, failure to comply would have meant an additional iteration.

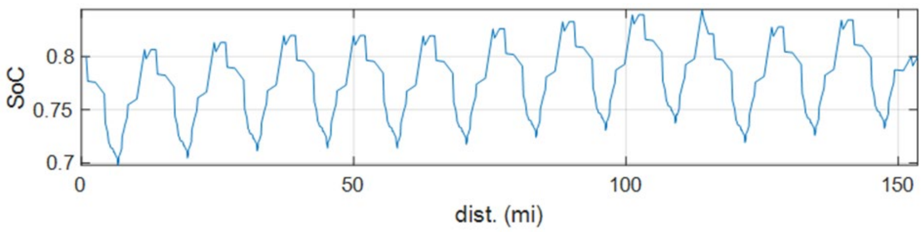


Figure 57. SOC for Route 38 with IMC–NMC buses, 2 TPSs, and 0 intersections.

Electrification of Route 38-Geary via IMC-LTO, 2 TPS, and no intersections

Similarly, Figure 58, Figure 59 and Figure 60 present the previous electrification case, but now with LTO battery. Table 71 presents the Cost scenarios assumed.

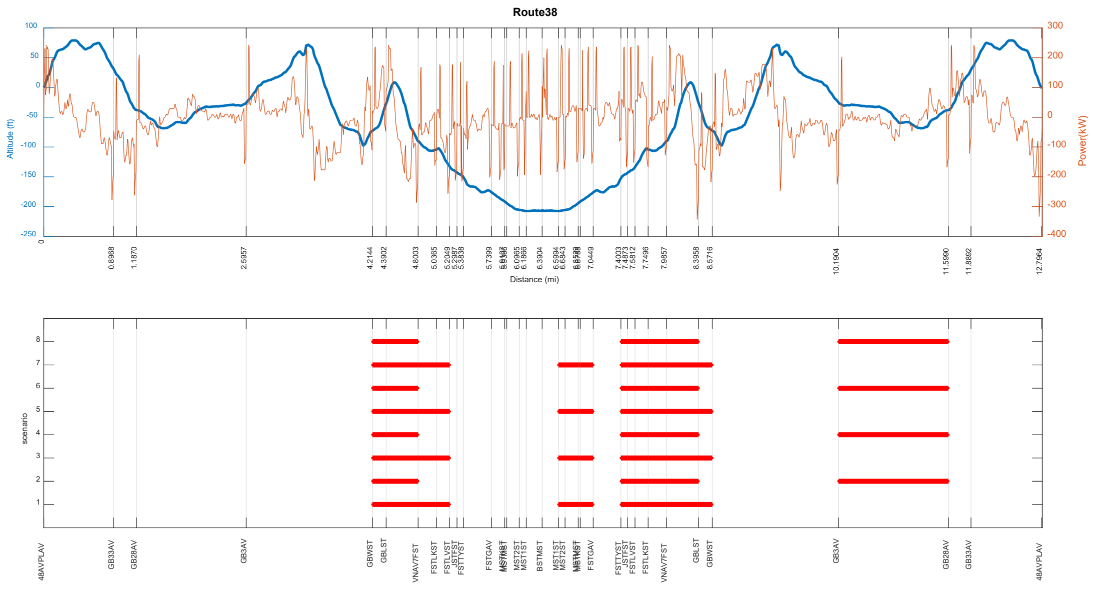


Figure 58. Optimized electrification for route 38 with IMC–LTO buses, 2 TPSs, and 0 intersections.

Table 71. Cost scenarios for Route 38 electrification with IMC–LTO buses, 2 TPSs, and 0 intersections

Scenario	Objective Function	Battery Capacity (kWh)	Number of buses	Number of trips	Catenary distance (mi)	Number of Substations	Charging Power (kW)	Depot charging power (kW)	Initial SoC	Final SoC	Catenary Cost (USD/mi)	Substation Cost	Battery Cost (USD/kWh)	Depot Charger Cost (USD/KW)	Night charging duration
1	$ 10,045,910.28	30	15	12	2.606652	3	90	0	0.6	0.6	$ 1,500,000.00	$ 2,000,000.00	$ 300.00	$ 700.00	4
2	$ 10,620,057.27	30	15	12	2.988174	3	90	0	0.8	0.8	$ 1,500,000.00	$ 2,000,000.00	$ 300.00	$ 700.00	4
3	$ 13,045,910.28	30	15	12	2.606652	3	90	0	0.6	0.6	$ 1,500,000.00	$ 3,000,000.00	$ 300.00	$ 700.00	4
4	$ 13,620,057.27	30	15	12	2.988174	3	90	0	0.8	0.8	$ 1,500,000.00	$ 3,000,000.00	$ 300.00	$ 700.00	4
5	$ 11,349,547.04	30	15	12	2.606652	3	90	0	0.6	0.6	$ 2,000,000.00	$ 2,000,000.00	$ 300.00	$ 700.00	4
6	$ 12,115,076.35	30	15	12	2.988174	3	90	0	0.8	0.8	$ 2,000,000.00	$ 2,000,000.00	$ 300.00	$ 700.00	4
7	$ 14,349,547.04	30	15	12	2.606652	3	90	0	0.6	0.6	$ 2,000,000.00	$ 3,000,000.00	$ 300.00	$ 700.00	4
8	$ 15,115,076.35	30	15	12	2.988174	3	90	0	0.8	0.8	$ 2,000,000.00	$ 3,000,000.00	$ 300.00	$ 700.00	4

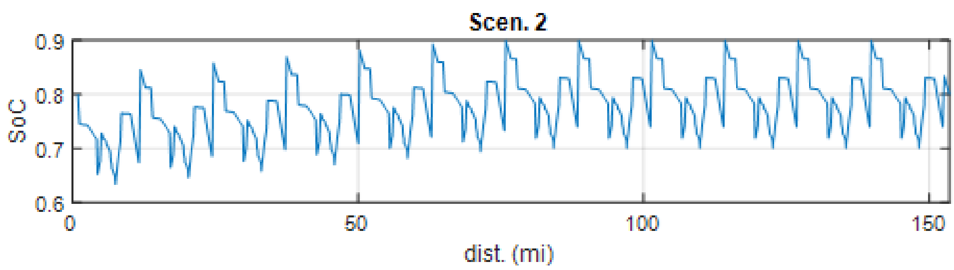


Figure 59. SOC for Route 38 electrification with IMC–LTO buses, 2 TPSs, and 0 intersections

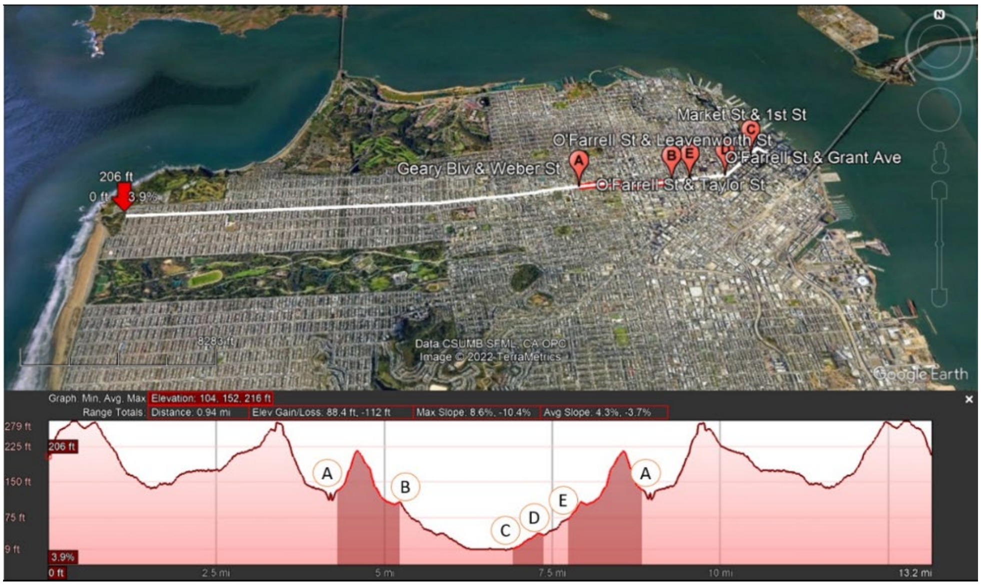


Figure 60. Optimized electrification with IMC–LTO buses, 2 TPSs, and 0 intersections

10.2. Analysis of Route 7-Haight/Noriega

Route 7-Haight/Noriega offers the opportunity for rapid electrification through IMC buses because there is already a large section of catenary serving the overlapping trolleybus route. Table 72 describes the operation of route 7.

Table 72. Route 7 service description

	Service frequency (min)					
Service	Morning	Midday	Evening	Late Night	Owl	Peak fleet (buses)
7	12	12	12	15	--	13

Considering the existing catenary, we modify the optimization model to privilege the installation of the overhead contact line in those sections. As can be seen in Figure 61, the need for additional electrification to achieve technical feasibility is minimal.

To the extent that other trolleybuses already use part of the existing catenary, it is necessary to install connection points at the most important stops so that the buses can overtake one another. Trolleybuses should be equipped with the appropriate automatic shutdown capability to facilitate operation and avoid having to install double catenary with overtaking accessories.

To smooth demand on the existing overhead contact line and at the same time facilitate flexible operational logistics with trolleybuses that also operate in the corridor, it is advisable to avoid the higher power charges corresponding to the LTO battery; thus, this scenario only considers NMC battery use. However, definitively ruling out the LTO alternative would require a more detailed case study.

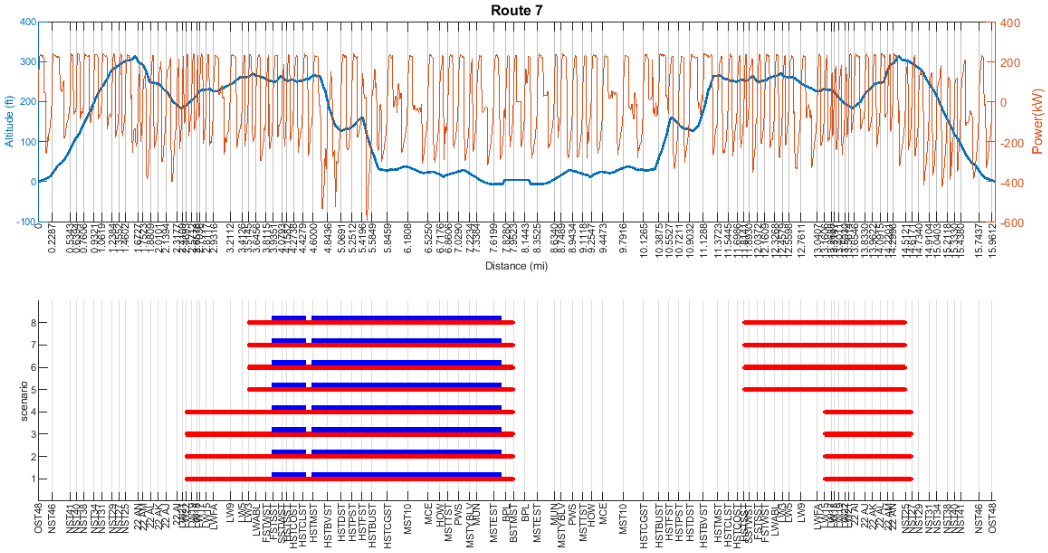


Figure 61. Optimized electrification for Route 7 with IMC-NMC buses, 2 TPSs, and 0 intersections.

Table 73 presents the cost scenarios considered for the electrification of Route 7.

Table 73. Cost scenarios for Route 7 with IMC-NMC buses, 2 TPSs, and 0 intersections

Scenario	Objective Function	Battery Capacity (kWh)	Number of buses	Number of trips	Catenary distance (mi)	Number of Substations	Charging Power (kW)	Depot charging power (kW)	Initial SoC	Final SoC	Catenary Cost (USD/mi)	Substation Cost	Battery Cost (USD/kWh)	Depot Charger Cost (USD/KW)	Night charging duration
0	$ 14,652,281.56	71	15	10	6.888521	2	50	0	0.6	0.6	$ 1,500,000.00	$ 2,000,000.00	$ 300.00	$ 700.00	4
1	$ 16,652,281.56	71	15	10	6.888521	2	50	0	0.6	0.6	$ 1,500,000.00	$ 3,000,000.00	$ 300.00	$ 700.00	4
2	$ 18,096,542.07	71	15	10	6.888521	2	50	0	0.6	0.6	$ 2,000,000.00	$ 2,000,000.00	$ 300.00	$ 700.00	4
3	$ 20,096,542.07	71	15	10	6.888521	2	50	0	0.6	0.6	$ 2,000,000.00	$ 3,000,000.00	$ 300.00	$ 700.00	4
4	$ 14,844,285.25	71	15	10	7.016524	2	50	0	0.8	0.8	$ 1,500,000.00	$ 2,000,000.00	$ 300.00	$ 700.00	4
5	$ 16,844,285.25	71	15	10	7.016524	2	50	0	0.8	0.8	$ 1,500,000.00	$ 3,000,000.00	$ 300.00	$ 700.00	4
6	$ 18,352,547.01	71	15	10	7.016524	2	50	0	0.8	0.8	$ 2,000,000.00	$ 2,000,000.00	$ 300.00	$ 700.00	4
7	$ 20,352,547.01	71	15	10	7.016524	2	50	0	0.8	0.8	$ 2,000,000.00	$ 3,000,000.00	$ 300.00	$ 700.00	4

Figure 61 presents the SOC states for each of the scenarios derived from the optimization exercise. We use the result of Scenario 5 as a reference to identify the route segments ideal for electrification.

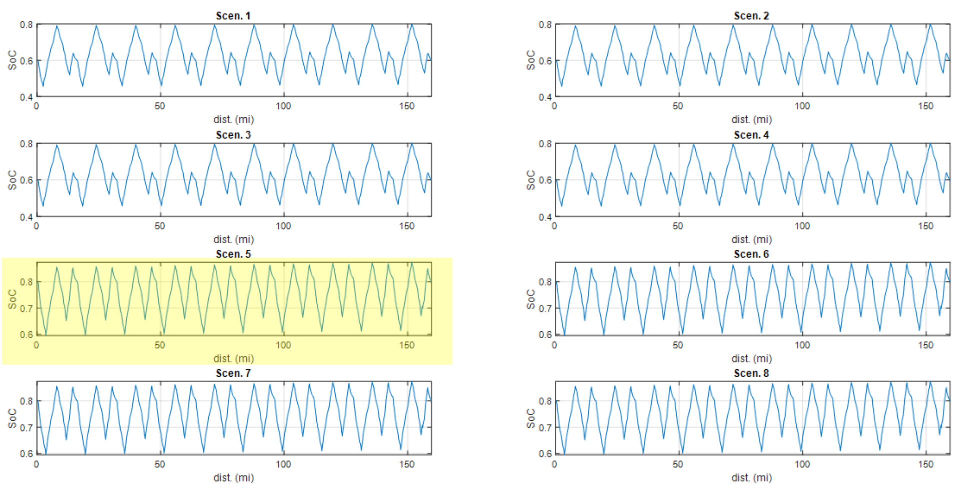


Figure 62. SOC for optimized electrification for Route 7 with IMC-NMC buses, 2 TPSs, and 0 intersections.

Finally, Figure 63 presents the electrification map for the IMC bus with NMC battery alternative.

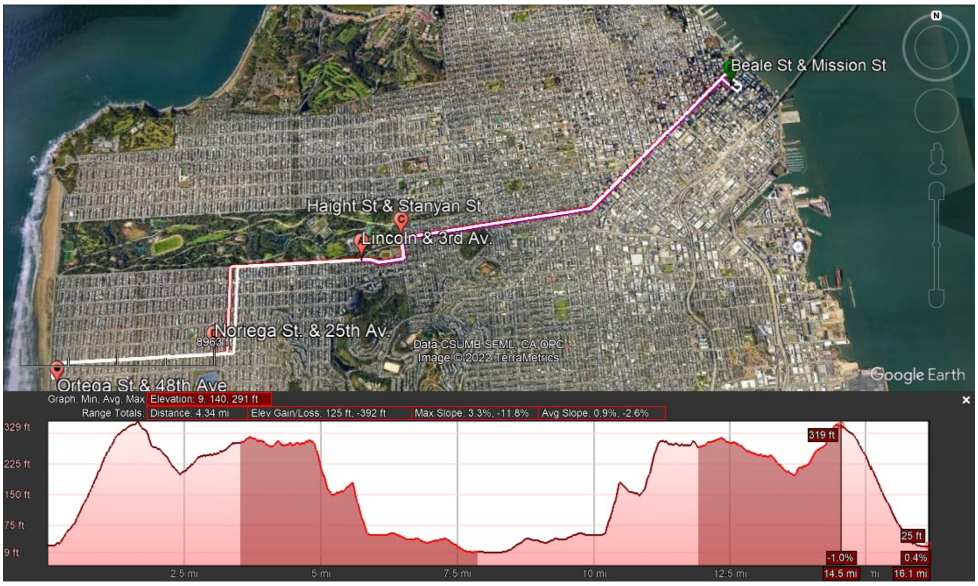


Figure 63. optimized electrification for Route 7 with IMC-NMC buses, 2 TPSs, and 0 intersections.

10.3. Estimated aggregate demand for Woods Yard

Based on the main routes served from the Woods yard, it is possible to project, albeit in simplified fashion, the energy demand on the yard's power supply circuits. For comparison, we model two alternatives—BEB Scenario 2 (Adjusted Dispatch) and the IMC bus—but the result is similar for both cases. We present the estimated demand for Woods Yard, consisting of 144 40-foot buses, in Figure 64.

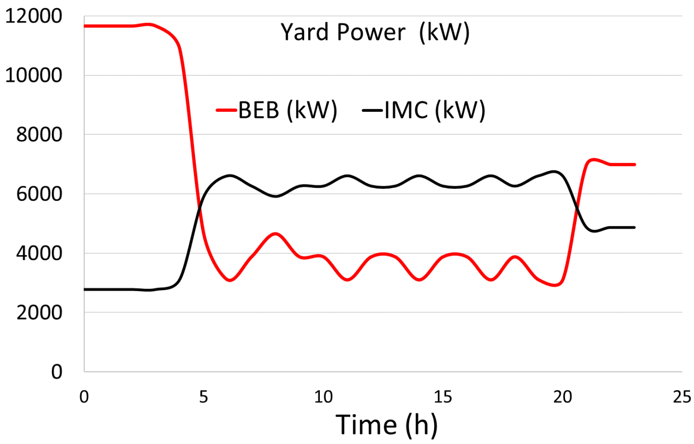


Figure 64. Reference projection of the Woods yard power demand.

As these results indicate, **the IMC alternative is superior with regard to the proper use of the power infrastructure**. The required energy for a fleet of BEBs with depot charging would tend to exceed 12 MVA, while IMC buses would require less than 7 MVA. Likewise, considering the large amount of solar energy that California will incorporate in the coming years, the daily IMC demand curve would allow a better use of this resource, given that IMC buses would be recharging their batteries in the hours of greatest availability of the solar resource.

However, some lower-intensity routes or those served by smaller buses could be operated via a depot-charge scheme. These segments of the fleet could take advantage of already extant infrastructure to supply energy to the trolleybuses in the yards—even achieving a flatter demand curve.

In the document “Zero Emission Facility and Fleet Transition Plan Task 2: Facility Power Needs and Technology Assessment,” the authors present various projected demand curves for the San Francisco yards; those projections largely mirror ours. Figure 65, adapted from the authors’ projection for the Potrero yard, evidences the pitfalls of an electrification based exclusively on depot-charging BEBs: very high demand in a limited and concentrated period of time, very low demand the rest of the day. This demand picture can put the system at risk of excess consumption of reactive energy as well as some typical phenomena of low demand, such as ferro-resonance.

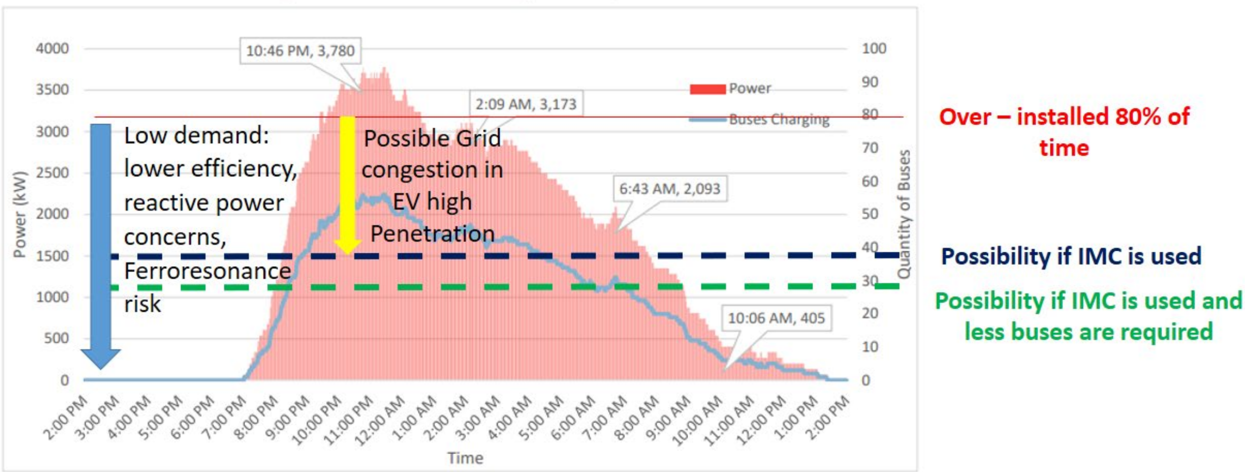


Figure 65. Reference projection of the Power demand in the Potrero yard. Adapted from SFMTA Zero Emission Plan.

10.4. Basic analysis of the other yards

To give a simplified overview—but one supported by the results of the electrification of the archetype route (44) and the analysis of other routes—of the other yards, we use the Route Demand Factor (RDF) and the maximum density of buses (bus/mi). **When the RDF of a route is greater than 0.7—which is the availability factor of the BEB—and the density of buses per mile is greater than 1, depot-charging buses are not the most advisable option.** For routes with low daily demand and low peak intensity, depot-charge buses can be considered as a complementary measure to the electrification of more intensive routes.

Table 74. Basic assessment for San Francisco Muni Routes

Yard	Route Number	RDF	Max Bus density (bus/mi)	Better Fit
Woods	38	0.742	4.194	IMC
	9	0.758	2.588	Trolleybus
	8	0.705	2.599	IMC
	44	0.831	1.778	IMC
	7	0.763	1.733	IMC
	29	0.696	1.750	IMC
	27	0.771	1.176	IMC
	23	0.632	0.963	BEB

Yard	Route Number	RDF	Max Bus density (bus/mi)	Better Fit
	54	0.745	0.889	BEB
	25	0.865	0.833	IMC
Presidio	21	0.792	1.250	Trolleybus
	24	0.827	1.970	Trolleybus
	31	0.792	1.071	Trolleybus
	45	0.724	1.951	Trolleybus
Kirkland	19	0.792	1.429	IMC
	30	0.858	2.727	Trolleybus
	49	0.786	3.239	Trolleybus
Potrero	5	0.777	3.188	Trolleybus
	6	0.792	0.952	Trolleybus
	14	0.760	3.425	Trolleybus

We hasten to emphasize that routes currently operated by trolleybuses should continue to be operated with trolleybuses and that no major dismantlement of overhead contact line should be undertaken, except in critical sections or sections where maintenance costs are to be reduced. At these points, the dismantlement should be limited the point itself and electrical continuity should be facilitated by means of underground or aerial feeders. As we have shown, **the conventional trolleybus alternative has the lowest energy consumption from the system point of view.**

To justify the use of bus density per unit distance, we calculate the efficiency of the regeneration process as a function of the distance between a bus regenerating and another bus receiving energy and the braking power. Since the efficiency of the charge-discharge cycle of a battery is currently 81 percent (90 percent charge, 90 percent discharge), a good criterion for choosing whether the energy is stored or transmitted directly is a comparison of the efficiency of both processes, as can be seen in Table 75. However, storage in batteries is justified vis-à-vis energy efficiency only for routes where exchanges are made over long distances and with high power.

Table 75. Regenerative braking efficiency as a function of distance and power at 600 V

	Regenerative Power (kW) -600 V							
Distance between buses (miles)	25	50	75	100	125	150	175	200
0	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%	100.0%
0.1	99.7%	99.4%	99.0%	98.7%	98.4%	98.1%	97.7%	97.4%
0.2	99.4%	98.7%	98.1%	97.4%	96.8%	96.1%	95.5%	94.8%
0.3	99.0%	98.1%	97.1%	96.1%	95.1%	94.2%	93.2%	92.2%
0.4	98.7%	97.4%	96.1%	94.8%	93.5%	92.2%	90.9%	89.6%
0.5	98.4%	96.8%	95.1%	93.5%	91.9%	90.3%	88.6%	87.0%
0.6	98.1%	96.1%	94.2%	92.2%	90.3%	88.3%	86.4%	84.4%
0.7	97.7%	95.5%	93.2%	90.9%	88.6%	86.4%	84.1%	81.8%
0.8	97.4%	94.8%	92.2%	89.6%	87.0%	84.4%	81.8%	79.2%
0.9	97.1%	94.2%	91.2%	88.3%	85.4%	82.5%	79.6%	76.6%
1	96.8%	93.5%	90.3%	87.0%	83.8%	80.5%	77.3%	74.0%
1.1	96.4%	92.9%	89.3%	85.7%	82.2%	78.6%	75.0%	71.4%
1.2	96.1%	92.2%	88.3%	84.4%	80.5%	76.6%	72.7%	68.9%
1.3	95.8%	91.6%	87.3%	83.1%	78.9%	74.7%	70.5%	66.3%
1.4	95.5%	90.9%	86.4%	81.8%	77.3%	72.7%	68.2%	63.7%
1.5	95.1%	90.3%	85.4%	80.5%	75.7%	70.8%	65.9%	61.1%
1.6	94.8%	89.6%	84.4%	79.2%	74.0%	68.9%	63.7%	58.5%
1.7	94.5%	89.0%	83.5%	77.9%	72.4%	66.9%	61.4%	55.9%
1.8	94.2%	88.3%	82.5%	76.6%	70.8%	65.0%	59.1%	53.3%
1.9	93.8%	87.7%	81.5%	75.3%	69.2%	63.0%	56.8%	50.7%
2	93.5%	87.0%	80.5%	74.0%	67.6%	61.1%	54.6%	48.1%

Trolleybus- IMC

BEB

10.5. Leveraging the Existing Infrastructure to Deploy the IMC Alternative

The process of expanding the electrification of Muni's bus system is explained in Figure 66. We identify for electrification the diesel-hybrid bus routes (marked in red) with the highest operational intensity and closest proximity to trolleybus lines.

The points of proximity or intersection with trolleybus lines (green) become the feeder points for the new IMC lines. If there is no power capacity available at the connection points, a traction power substation provides power.

Thanks to the use of IMC (i.e., onboard energy storage) and the synergy with existing infrastructure, the required substations would be compact and easily located. The substation would be very similar to a fast charger for opportunity-charging systems. We select the segments where an overhead contact line should be installed using an optimization method that considers the energy consumption of the buses along the route; we then validate the method using detailed electrical simulations. The system can be reinforced with a few underground DC feeders.

It is important to note that all these modifications can be made at a much lower cost and with higher efficiency than the deployment of depot- or opportunity-charging systems for battery buses. For reference, we present a hypothetical electrification of routes 44, 38, and 7—all currently operated with diesel-hybrid buses—in Figure 66.

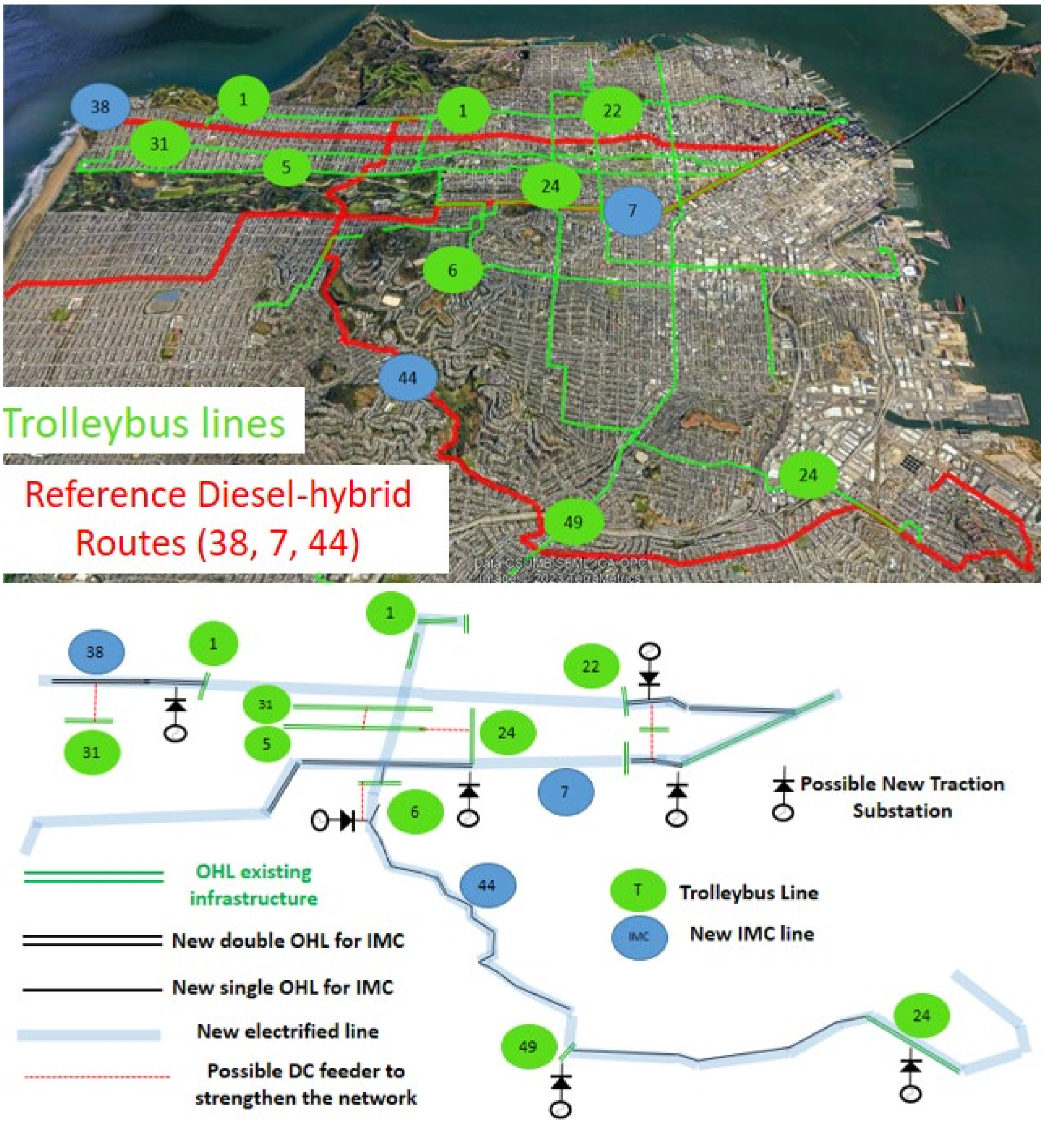


Figure 66: IMC deployment in SF leveraged by existing trolleybus infrastructure.

It is quite possible that buses can begin operating on the routes to be electrified without the need to install new traction substations. Our simulations show that, due to new IMC buses' ability to compensate voltage and regulate battery charging, peak demand requirements are relatively low and controllable.

The resultant, more meshed DC grid, with its distributed storage systems (on-board batteries), voltage controllers, and energy-management strategies would be a replicable example of a Smart Grid for urban bus systems worldwide. The new network will have more resilience, lower losses, and higher reliability than today's trolley grid.

11. High opportunity electrification plan

In this section we analyze the effects of a broad electrification plan for eleven high-opportunity diesel hybrid routes. In contrast to a single-route electrification plan, the approach of multiple-route electrification involves additional criteria, such as convenience of electrification of segments common to two or more routes, optimization of new and existing major infrastructure. The target routes for electrification are: 7, 8, 9, 19, 23, 28, 29, 38, 43, 44 and 55. The routes have been selected based on daily boardings, the ease of electrification, existing electrified route overlap, and infrastructure proximity.

This addendum is structured as follows:

1. General criteria for electrification and for the selection of the sections where the overhead contact line is proposed to be installed.
2. Results of the overall electrification plan and individual route electrification maps
3. Methodology
4. Simplified model calibration for Routes 9 & 43

11.1. General criteria

As with the route and yard level electrification analyses, the results are based on conservative design assumptions for the most robustly engineered system to meet San Francisco's needs. The electrification sections have been selected based on the following criteria:

A) Proximity to currently electrified lines to avoid the installation of traction power substations, and in case they are necessary, that the new substations serve to electrically strengthen nearby lines.
B) The installation of the overhead contact line in narrow curves has been avoided, preferring straight sections, where they are also clear of trees.
C) High slope sections are prioritized for electrification, including parks except for Golden Gate Park. At these points it is considered that the installation can be done without major detriment to the landscape. For this purpose, some references of how the installation of the contact line would look like in this type of routes are given below, in Figure 67.

Figure 67: Example of contact line infrastructure landscape in a country area (Solingen)

These criteria are based on the following underlying assumptions:

A) The design ensures no overnight charging. The introduction of overnight charging can reduce the electrification level by 20% to 30% of the results of this analysis.
B) the change in the state of charge should not be greater than 20% to extend the useful life of the batteries. Greater variability in the SOC can reduce the overall electrification level at the expense of more frequent battery swaps.
C) The design eliminates operational restrictions. For example, if a bus cannot connect in a segment shared with another route because other buses are using it and there is no opportunity to connect at its prescribed point it will do so on its next lap.
D) The IMC trolleybus fleet would be able to maintain the operation without restrictions. In case of outage of a TPS or the absence of voltage in a catenary segment (*n-1* criteria). With BEBs *n-1* criteria must be fulfilled installing additional redundant medium voltage feeders, using a high-power diesel generator, or using an Energy Storage System, thereby increasing the cost and difficulty of deployment.

11.2. Results

System Electrification Design

The overall electrification plan for 11 routes of San Francisco Muni, currently operating with diesel-hybrid buses is presented in Figure 68. The route of the diesel-hybrid lines is shown in light yellow, while the route of the current trolleybus lines is shown in green. The red lines indicate the existing overhead contact line sections that will be used for the electrification of the new routes, since hybrid buses are already operating under these catenaries. The proposed single catenary sections are marked with light blue, and the new double catenary sections are marked with black. When one of the dual catenary segments proposed to be installed serves two routes, it is colored purple and highlighted with increased thickness.

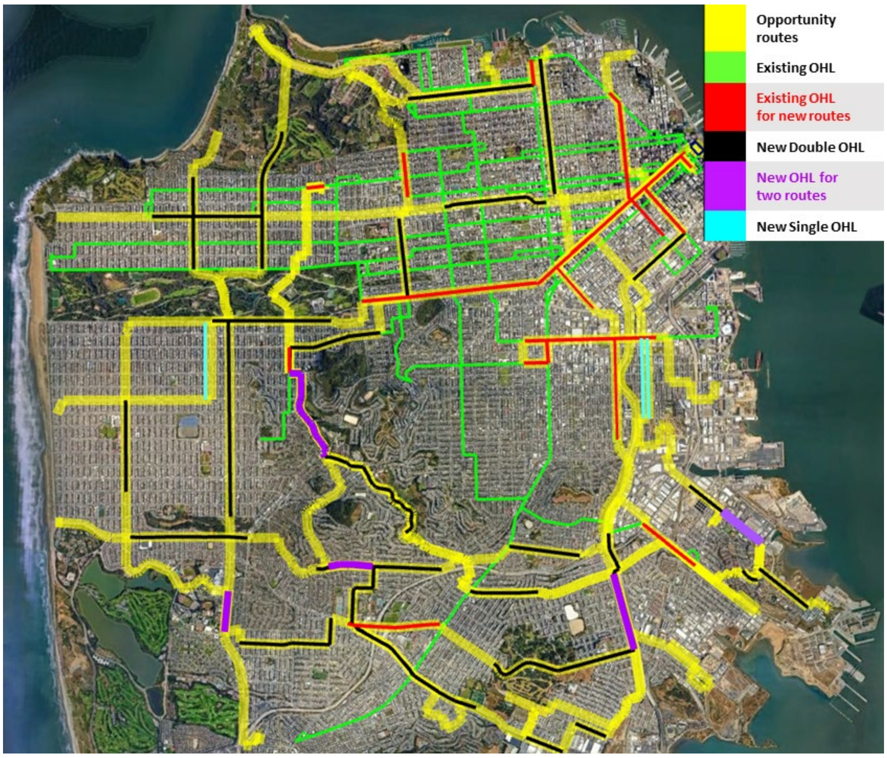


Figure 68: High opportunity electrification design

The summary of the electrification proposal, indicating the diesel hybrid routes with the greatest opportunity for electrification with IMC and new catenary construction is shown in Table 76. The results report the length of overhead line used from existing routes and the length of new catenary that is required to install for each route. The electrification ratio is the proportion of a route requiring new OHL.

Table 76 Summary of electrification proposal

Route	Buses	Daily Boardings	Length (mi)	Existing OHL (mi)	Proposed new catenary (mi)	Electrification ratio %
38 - 38 R	35	37,500	13.25	1.5	4.18	32%
8	27	17,200	22.6	3.3	6.22	28%
29	21	14,700	28.1	1.82	10.08	36%
28	12	12,300	23.5	0.52	9.24	39%
44	16	10,900	21	1.44	7.16	34%
7	13	10,000	16	7.26	3.09	19%
9 -9R	31	17,300	18.25	6.88	3.9	21%
43	12	8,200	25	4.88	7.18	29%
19	10	5,900	16.87	0.54	7.2	43%
23	5	2,000	18.5	1.62	6.34	34%
55	3	1,800	6.8	3.2	0	0%
Total	**185**	**137,800**	**210**	**32.96**	**58.27**	**28%**

To define a baseline for the current electrified services, we show the number of buses operating on 16 electrified routes in Table 77. The length of the overhead contact lines of these routes has also been taken as the current electrification baseline. All buses observed operating on these routes (on the SFMTA website) are assumed to be trolleybuses, i.e., zero emission buses.

Table 77 Reference baseline for electrification

Route	OHL approx. length (mi)	Zero emission Buses
1	12.48	18
2	10.87	3
3	7.5	Suspended
5	13.87	3
6	12.63	6
14	15.5	14
21	9.9	3
22	11	18
24	14.1	10
30	11,4	14
31	14.4	6
33	12.8	8
41	7	Suspended
45	8.7	8
49	14.1	20
Total	**176.2**	**131**

Now we will compare how much electric infrastructure is required to be installed compared to the baseline infrastructure, and how many new zero emission buses the city would achieve through the overall electrification plan. Table 78 presents both the increase in overhead contact line infrastructure and the increase in the number of zero emission buses, thanks to the global electrification plan, using the IMC alternative. As can be seen in the table, **a 33% increase in OHL infrastructure would allow San Francisco to more than double its fleet of zero-emission buses while adding more than 200 miles of electrified service.**

Table 78 IMC electrification plan compared with current situation

	OHL approx length (mi)	ZEBs (approx)	OHL %	Zero Emission Buses %
Current baseline	176	131	**100%**	**100%**
IMC Electrification plan	234	316	**133%**	**241%**

Note also that we included express routes 9R and 38R. While even express routes on trolley enabled lines are currently served by diesel hybrid buses IMC trolleybuses are ideal for this service. Some alternatives for interoperating express IMC trolleybuses with non-express IMC buses include:

- Dispatching teams of A and B buses where the A buses operate express in one direction without connecting to catenary and return in the other direction connected switching to non-express operation.
- Rotating the express and non-express buses in different periods, morning, noon, afternoon, etc.
- Charge the batteries of the express fleet that is not needed during off-peak hours using the depot catenary.

Usually the buses that have to make the most starts and stops tend to consume more energy, but at the same time, as their average speed is lower, they have more time to recharge the catenary. In the conservative design proposed, when a bus operates a complete lap making connections at all points, it increases its SOC between 5% and 10%, therefore, express buses can recover their battery charge when switching to non-express service.

Route-level electrification maps

Figure 69 presents the electrification maps proposed for Routes 8, 9 and 19. The diesel-hybrid route is shown in light yellow, while the route of the current trolleybus lines is shown in green. The red lines indicate the existing overhead contact line sections that will be used for the electrification of the new routes, since hybrid buses are already operating under these catenaries. The proposed single catenary sections are marked with light blue, and the new double catenary sections are marked with dark blue. When one of the dual catenary segments proposed to be installed serves two routes, it is colored purple and highlighted with increased thickness.

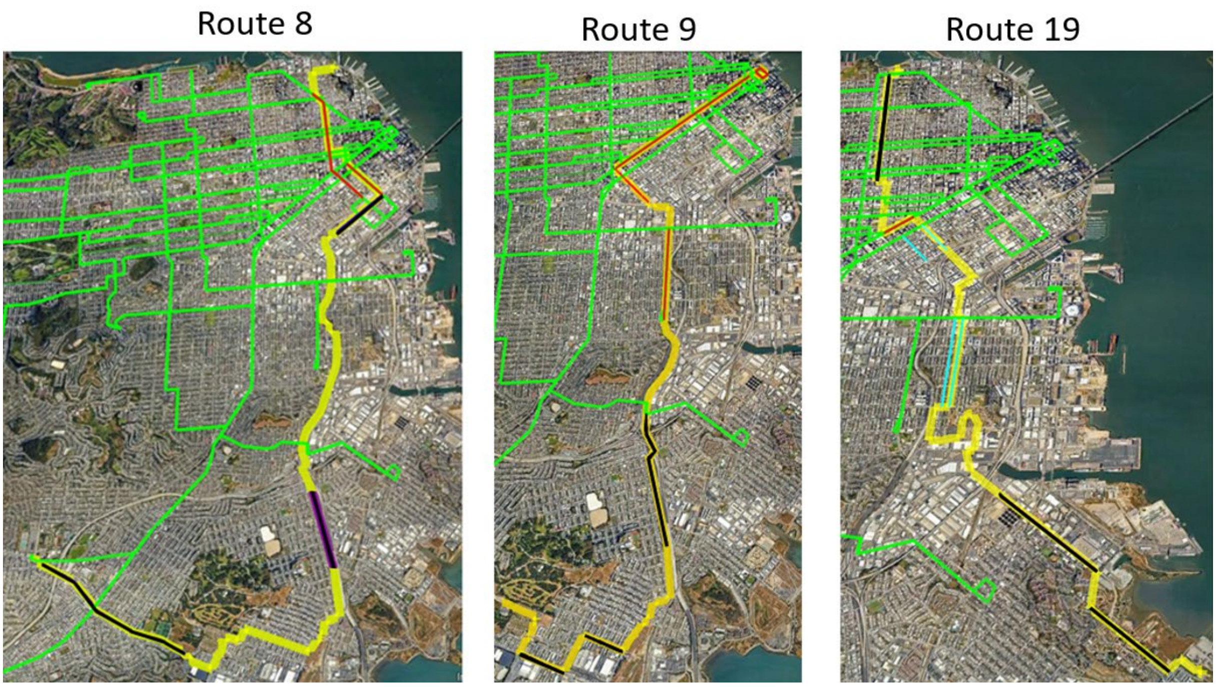


Figure 69: Proposed electrification for Routes 8, 9 and 19.

Figure 70 presents the proposed electrification maps for routes 7, 23 and 38.

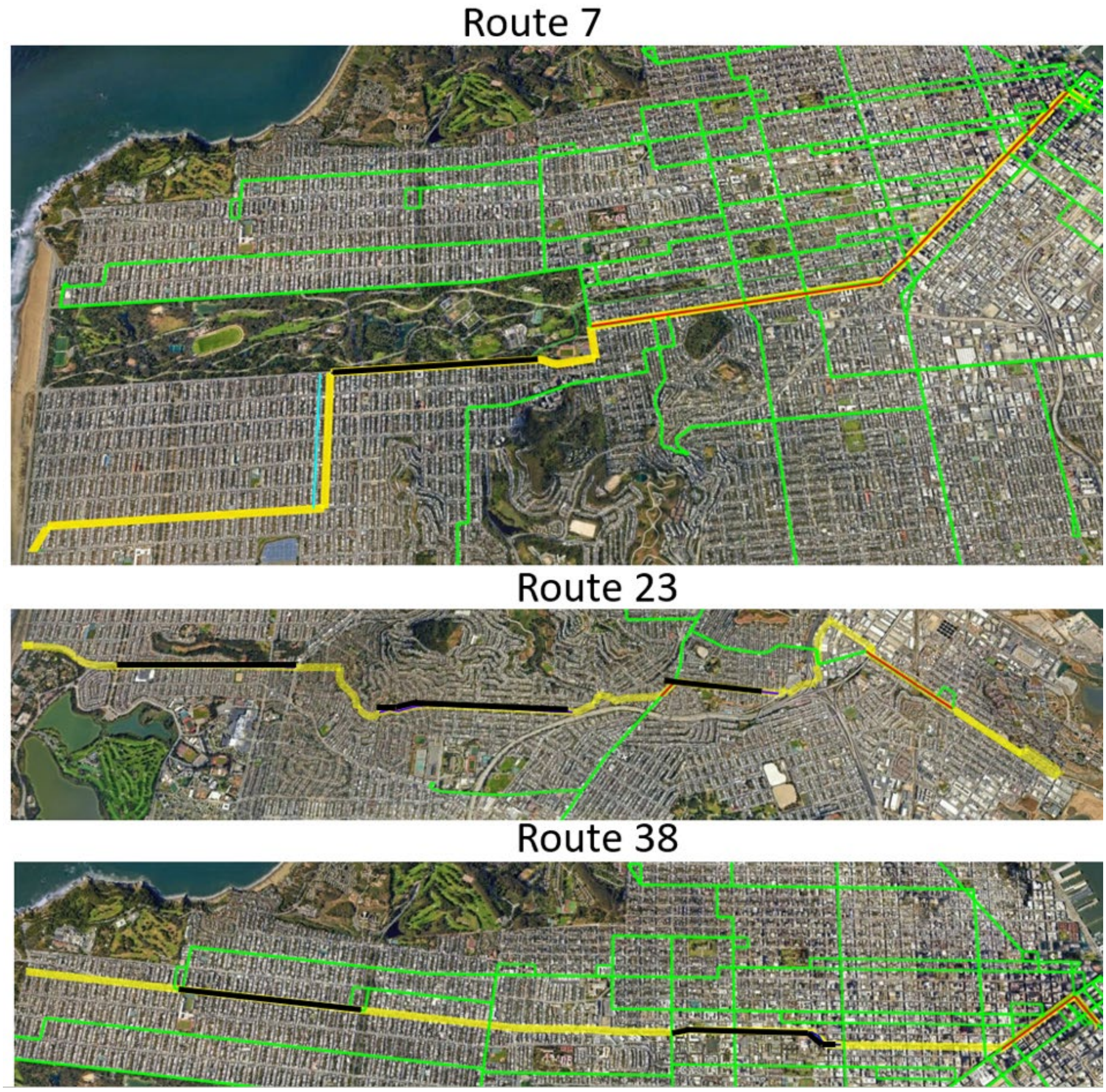


Figure 70: Proposed electrification for Routes 7, 23 and 38.

Figure 71 presents the electrification maps for routes 43 and 44. It must be note that here the electrification of Route 44 slightly differs of that presented in the main body of the report. The changes done are to maximize the integration with route 44, as the share an important segment.

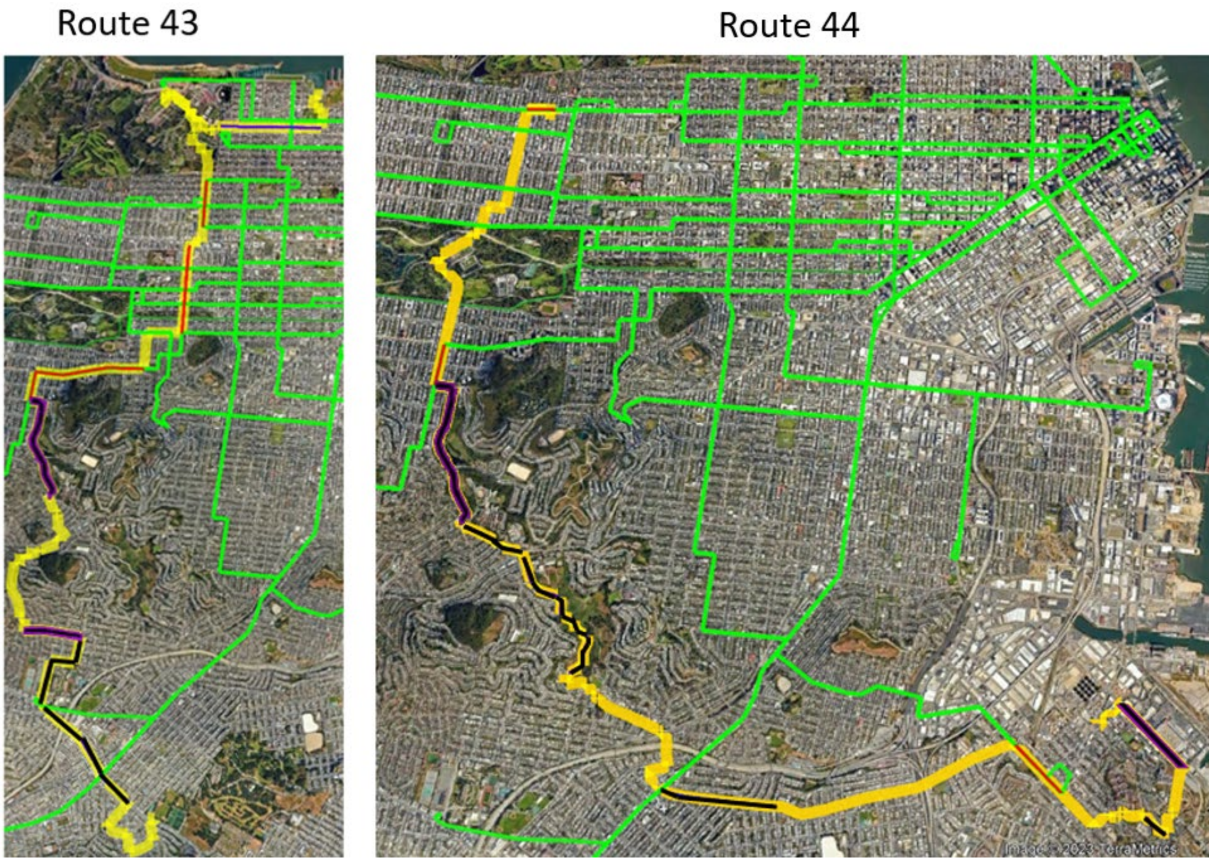


Figure 71: Proposed electrification for Routes 43 and 44.

Figure 72 presents the electrification maps proposed for routes 28 and 29.

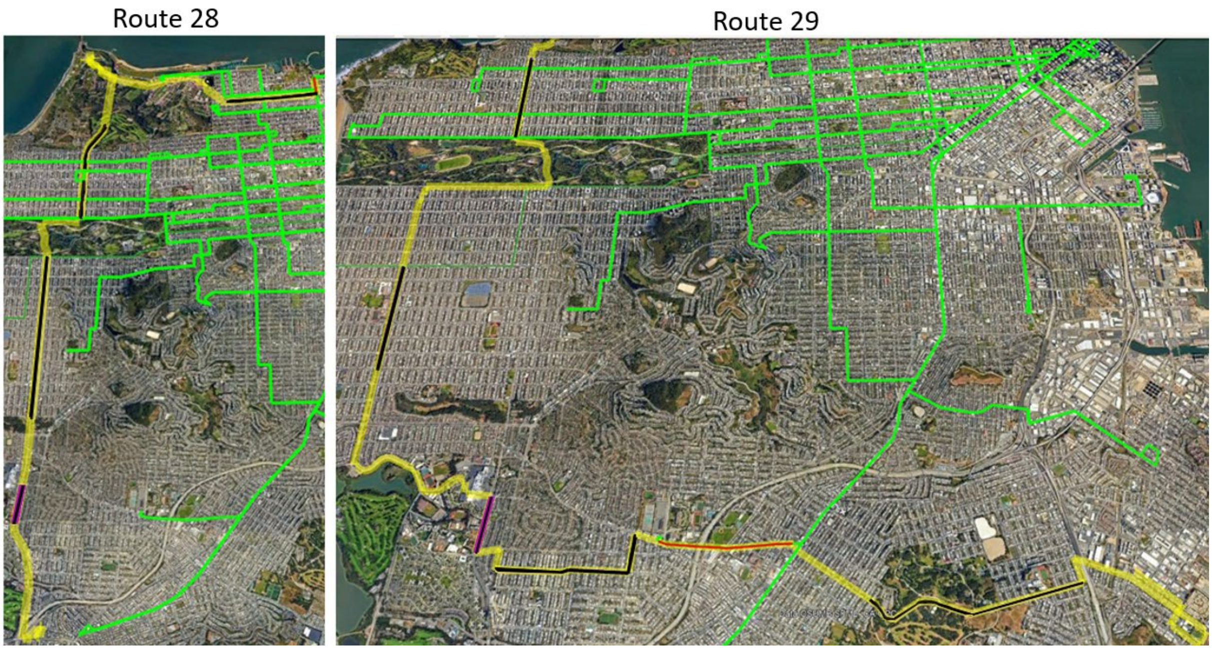


Figure 72: Proposed electrification for Routes 28 and 29.

Finally, Figure 73 presents the electrification map of route 55, where IMC trolleybuses could start operating without new wiring.

Figure 73: Proposed electrification for 55: no new wiring would be needed.

11.3. Methods

For this portion of the analysis, we simulated bus operation using proprietary software developed for simplified corridor analysis, previously validated against OpenTrack results. Routes 9 and 43 are used as reference lines, the detailed results of which are presented in the following section. For the other routes, the lessons learned in the detailed simulations have been used to offer an approximation to the electrification of these routes, which can be considered at a conceptual design level with the goal of maintaining electrification levels required for the simulated routes while prioritizing the criteria described above.

11.4. Simplified model calibration for Routes 9 & 43

Route 9 detailed electrification

Table 79 shows the Basic simulation data used for the simplified simulations to verify the operational feasibility in routes 9 and 43 and Table 80 includes the basic operational data for the simulation. It is important to note that we are using worse case scenarios of energy consumption, such a very high auxiliary load consumption.

Table 79. Basic simulation data for the buses in route 9 and 43

fr: rolling friction coefficient	0.02
m [kg]: total vehicle mass	20000
g [m/s2]: gravity acceleration	9.81
rho [kg/m3]: air density	1.29
Alpha: air resistance coefficient	0.66
A [m2]: front area of the vehicle	7.5
Paux [kW]: Auxiliary load consumption	25
nout [%]: Consumption efficiency	85
Nin [%]: Regeneration efficiency	80

Table 80. Basic operational data for the simulation of route 9 and 43

Acceleration [m/s2]	1
Braking [m/s2]	1.2
Maximum speed [km/h]	35
ITS [s]: Idle time at each stop	45

Table 81 presents the fleet parameters. As shown, we are simulating a single bus, and then the regeneration bus to bus is not considered.

Table 81. Fleet parameters for the simulation of Routes 9 and 43

NBP: Total number of buses	1
ITS [s]: Idle time at each stop	45
Laps simulated	1

Figure 74 presents the Route 9 map and profile as shown in our software.

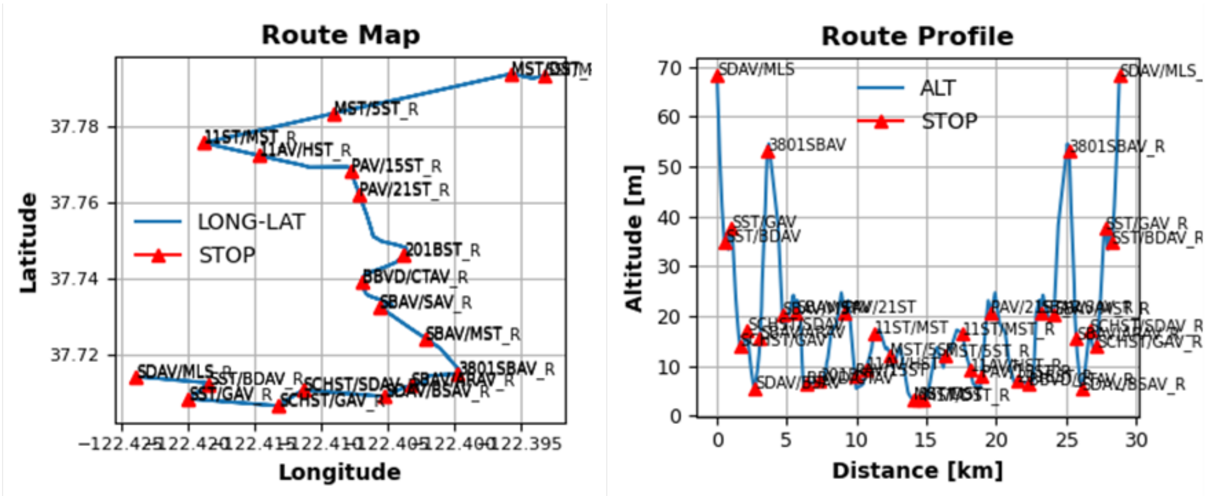


Figure 74: Route map and route profile for route 9 simulation.

Figure 75 shows the results of energy consumption, power demand, battery state of charge and power charge in each section during simulation period. The results show how with the level of electrification proposed, the change of the state of the charge of the battery is maintained in a 20 % frame (50 %-70 %).

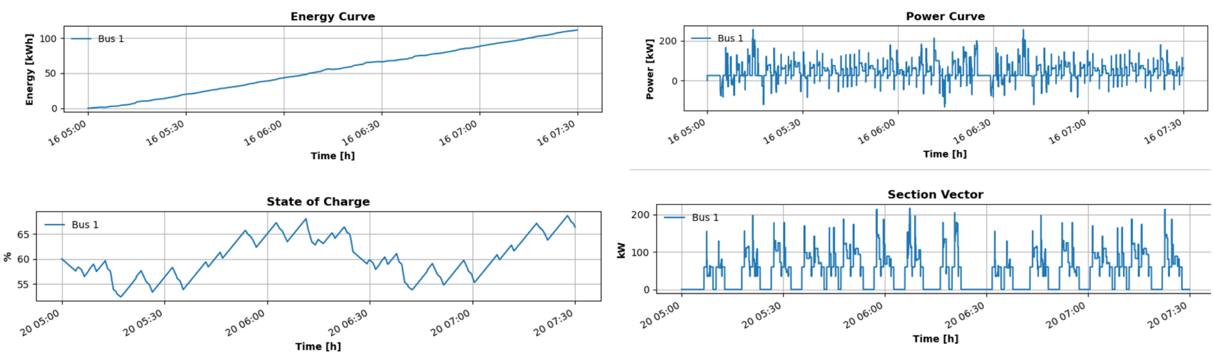


Figure 75: Simplified simulation results for route 9.

Table 82 presents the battery and charging parameters used for the simulation.

Table 82. Charging and battery parameters

BC [kWh]: Battery capacity per bus	70
SoCi [%]: Initial state of charge	60
CP [kW]: Charger power	35
nc [%]: Charging efficiency	90
IT [s]: Connection time to charging	8
DT [s]: Disconnection time	4

Table 83 describes the OHL segments used for the electrification of route 9.

Table 83. Summary of electrification proposal for Route 9

Type of catenary	*Stops that define the segment*	*Designation in the simulation*
Double	Santos St & Geneva Av – Schwerin St & Geneva Av	•SST/GAV-SCHST/GAV •SCHST/GAV_R- SST/GAV_R
Double	Schwerin St & Sunydale Av- Sunydale Av & Bay Shore Blvd	•SCHST/SDAV-SDAV/BSAV •SDAV/BSAV_R- SCHST/SDAV_R
Double	San Bruno Ave & Mansell St to Bayshore Blvd & Cortland Ave Blvd	•SBAV/MST-SBAV/SAV-BBVD/CTAV •BBVD/CTAV_R-SAV/SAV_R-SBAV/MST_R
Double	Potrero Ave & 25^{th} St to Potrero Ave & 15^{th} St	•PAV/25ST – PAV/21^{ST} – PAV/15ST •PAV/15ST_R-PAV/21^{ST}_R-PAV/25ST_R
Double	11^{th} st & Market St to Market St & Beale St	•11ST/MST-MST/5ST-MST/BSL •MST/BST_R- MST/SST_R-11ST/MST_R
Double	Market St & Drum st to Spear st & Market St	•MST/DST – SST/MST •SST/MST – MST/DST_R

Route 43 detailed electrification

Figure 76 presents the Route 43 map and profile as shown in our software.

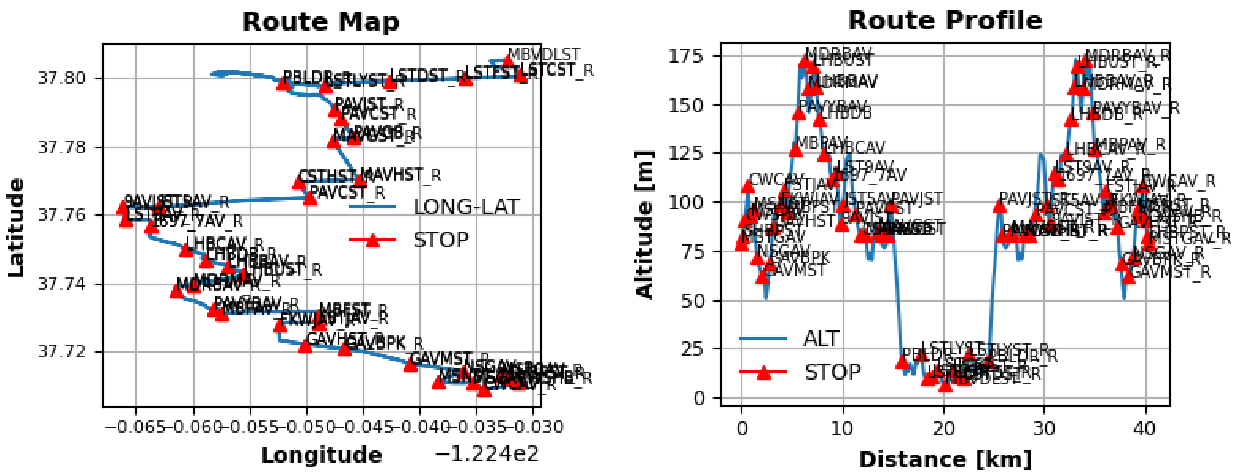


Figure 76: Route 43 map and route profile.

Table 84 presents the electrification segments proposed for route 43.

Table 84. Summary of electrification proposal for Route 43

Type of catenary	*Stops that define the segment*	*Designation in the simulation*
Double	Naples street & Geneva Av – Geneva Avenue & Howard St	NSGAV-GAVMST-GAVBPK-GAVHST GAVHST_R- GAVBPK_R- GAVMST_R-NSGAV_R
Doble	Laguna Honda BLV & Dewey BLVD - 9th Ave & Judah St	LHBDB-LHBCAV-1697_7AV-LST9AV-9AVJST
Double	9th Ave & Judah St – Parnassus AV & Cole st	9AVJST-JST5AV-PAVCST PAVCST_R- JST5AV_R-9AVJST_R
Double	Cole St & Haight St – Masonic Av & Haight St	CSTHST – MAVHST MAVHST_R-CSTHST_R
Double	Masonic Av & Haight St – Masonic AV & Geary Blvd	MAVHST-MAVGST MSVGST_R-MAVHST_R
Double	Presidio AV & Geary BLVD – Presidio AV & Jackson St	PAVGB-PAVCST-PAVJST PAVJST_R-PAVCST_R-PAVGB_R
Double	Lombard St & Lyon St – Laguna St & Chestnut St	LSTLYST-LSTDST-LSTFST-LSTCST LSTCST_R-LSTFST_R-LSTDST_R-LSTLYST_R

The feasibility of this electrification is proved by the simulation. In this case for easy view, we only provide the result of the state of charge of the battery in Figure 77.

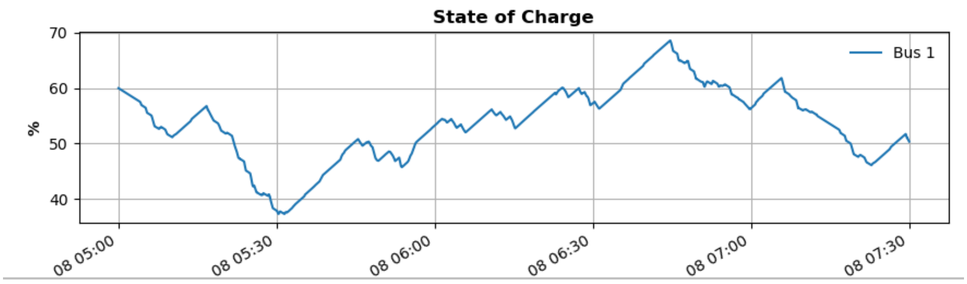


Figure 77: Battery State of Charge

12. Risk Analysis

In what follows, we detail, at a conceptual level, the possible risks for the electrification alternatives analyzed in this study.

12.1. Fire risk

There is a chance that the battery of a battery-powered electric bus will catch fire due to a collision, a faulty cell, or problems with charging systems and electronics in general. This risk depends largely on the chemistry of the battery. Some battery chemistries are more likely to catch fire. For example, NMC batteries have an unstable cathode that, in the presence of heat, can react with lithium and catch fire. On the contrary, LFP batteries are more stable than others because of a cathode material that is more stable at high temperatures.

In the event of a collision, the risk of fire arises from the perforation of the cell. The lithium inside a battery is insulated. In case of perforation, the lithium oxidizes and generates heat that feeds back the combustion process.

There is also the risk of short circuit. For example, a faulty cell can short circuit, overheating the battery and causing the combustion of the materials. Flawed cells are difficult to detect as they can function like a healthy battery. They are also difficult to repair as they are assembled in small groups. To change a faulty cell requires replacing an entire battery pack. Another type of cell failure is mechanical failure, though it is fairly uncommon. A mechanical failure is caused by the flaws in the welds or moorings that hold the cells and/or their electrical contacts.

Charging and electronics systems in general must manage the battery as carefully as possible. These elements must exercise precise control of the temperature, charging current, and voltage of the cells. A failure in the measurement of a sensor or in the wiring that connects chargers to the general system can cause abnormal behaviors and lead to catastrophic failure. These are specifically evident in charging processes or high-power discharges.

Throughout the history of battery-powered buses, there are reports of accidents with batteries. This year, two buses caught fire in Paris,[v] and another caught fire in Philadelphia[vi]. Although statistically these events are not common, the need for specialized fire-suppression systems, as well as the time required by firefighters, make the associated cost high.

The key factor mitigating fire risk is the containers that house the batteries. The batteries must be situated in containers that withstand all types of impacts to avoid damage and, in case of combustion, contain the fire. These containers usually add weight to the vehicle, and the smaller, lighter, and safer containers usually come at a higher cost.

Risk assessment

- **BEB**: High risk due to the number of batteries and chemical (NMC) used. 370 kWh.
- **IMC**: Medium/low risk due to the number of batteries and chemistry used NMC/LTO. 71kWh.
- **Trolleybus**. Low risk due to the number of batteries and chemistry used. <30kWh.

12.2. Battery maintenance

Rechargeable batteries in electric vehicles must be properly maintained to ensure their operation. This maintenance consists of:

- Verification of the operation of each cell according to the records of the electronic systems;
- Insulation assurance of electrical circuits; and
- Verification of the operation of the different sensors.

When a fault is detected, the relevant parties must take the necessary corrective action. For example, in the case of the cell, technicians would have to replace the failed unit or group. In the case of insulation, it would be the repair or substitution of cables or contacts with abnormal values. In the case of sensors, it would be their replacement with sensors that have a nominal operation.

The maintenance operation itself can be done continuously using the appropriate telemetry. Computers can access the systems remotely and send the information to technicians. The technicians can then decide on one-off actions to maintain the ideal state of the battery or suggest actions for repairs.

Corrective operations involve dismantling the battery. The disassembly operation can be complicated depending on the weight of the battery. Likewise, the diagnostics and repairs must be conducted by the adequate personnel with the requisite tools and space to work. Corrective actions must be performed by specialized personnel designated by the vehicle or battery manufacturer.

Risk assessment

- **BEB**: High risk due to battery size.
- **IMC**: Medium risk due to battery size and frequency of charging and discharging.
- **Trolleybus**: Low or no risk due to battery size and use as a backup system in specific cases.

12.3. Battery disposal

The batteries must be disposed of according to the conditions indicated by the manufacturer. In most cases, bus batteries can be used in other equipment as second-life batteries—for example, as backup to electrical systems. In other cases, they can be recycled to extract the rare materials. However, it is complicated to perform the latter since the relevant processes are not economical at the moment.

The disposal of the battery cannot be conducted in landfills or spaces not suitable for storage. Battery materials can contaminate soil and water if leaks occur. Improper disposal can lead to fires or polluted combustion in the air or nearby areas.

Risk assessment

- **BEB**: High risk: Rare materials in a large battery with high polluting power.
- **IMC**: High risk: Foreign materials in a battery.
- **Trolleybus**: Medium risk: Foreign materials in a smaller battery.

12.4. Inadequate driver training

The correct operation of an electric vehicle depends largely on the driver. Drivers should operate the vehicle in such a way to prolong its operational capacity. Acceleration, braking, and cruising speeds must be optimal according to the drive technology used. For example, for battery-powered vehicles, the demand on the equipment is high during acceleration. Excesses in acceleration reduce the life expectancy of the battery. IMCs and trolleybuses are not as sensitive to excessive acceleration as they depend on the catenary to obtain the necessary power rather than the battery.

Also, drivers should be aware of the speeds and alignments of vehicles on the road. Catenary buses must be properly aligned on the track to operate properly and connect and disconnect from the catenary. This is not the case for battery-powered vehicles, which can travel in any lane.

Risk assessment

- **BEB**: Medium risk: Drivers must be trained in battery operation. Internal systems can keep bus operation within safe limits.
- **IMC**: Medium risk: The driver must be trained to operate with the catenary in sections. Aligned driving is necessary.

- **Trolleybus**: High risk: The driver must be trained to maintain track- and catenary-aligned driving.

12.5. Bus charging time

The charging time depends on two main elements: the chemistry of the battery and the power of the charger. The chemistry of the battery determines the rate of charging. The power of the charger limits the duration of charging.

BEBs with LFP chemistries have long charging times because the charge is made at 0.3C. In addition, for a bus with a 370-kWh battery, the power to charge must be 120kW. This would yield a charging time of between 3 and 4 hours. BEBs with NMC chemistry can tolerate charges performed at 1C. Therefore, a 350-kW charger should charge the battery within an hour. However, this charge reduces the life expectancy of the battery.

IMC buses with NMC or LTO batteries perform charges of shorter duration and at lower current speeds because their battery is discharged in a small percentage. In addition, as they are in motion in that process, it is not necessary to suspend service. Therefore, in addition to respecting the battery-charge regime, IMC buses operate without interruption.

Risk assessment

- **BEB**. High risk: The BEB must be stopped for several hours to charge, suspending its operation.
- **IMC**. Low risk: The IMC vehicle does not have to suspend its charging due to its mode of operation.
- **Trolleybus**. N/A.

12.6. Fleet maintenance

Fleet maintenance is a coordinated task. Every time a bus enters the garage/yard, it must undergo different maintenance activities. These activities typically include cleaning, charging, inspections, and evaluation of levels and pressures of liquids in different components. All these tasks require special attention.

BEBs have to charge. As this process takes 1 to 4 hours for each bus, there is less time left for general maintenance. In addition, because there are buses simultaneously charging and undergoing maintenance, staff and space must be secured to accommodate these activities. Scaling operations can limit the difficulties, but they require increasing the size of the garage/yard and redefining work plans.

IMC buses can be maintained immediately on arrival at the garage/yard. Fleet maintenance can be spread over time without a corresponding increase in the staff and/or space required. Thus moving each bus in the garage/yard and scheduling its maintenance should be easier.

Trolleybuses require the same maintenance as IMC buses.

Risk assessment

- **BEB**: Medium risk: Less maintenance time due to charging time. Maintenance and batch charges require more personnel, space, and coordination.
  - BEB with space constraints: High risk: Due to the increased requirements of unavailable space, there will be logistical bottlenecks.

- **IMC**: Minimal risk: No new activities are required compared to trolleybuses except for batteries.
- **Trolleybus**: Minimal risk: There are no new maintenance activities.

12.7. Battery life

The battery is an electrochemical system with a limited life expectancy. Every day the battery loses a little of its initial storage capacity. The rate of this loss is affected by the following factors: depth of battery discharge, charging and discharging currents, battery temperature, and number of battery charge-discharge cycles. Optimal operation can ensure the highest possible life expectancy.

BEB batteries normally operate at their limits. The battery is fully charged and discharged every day. Therefore, the battery typically only reaches its minimum expected lifespan. For a standard battery, the minimum lifespan is around 2,500 charge-discharge cycles or eight years. However, shorter lifespans have been seen on some fleets.[vii]

IMC buses have the same difficulties as a battery-powered bus. But thanks to the catenary, the state of charge of the battery does not fall below 60 percent. This allows the battery to last longer. However, as the battery is charged and discharged many times in a day, life expectancy barely reaches three years. In the end, more battery changes are needed.

Risk assessment

- **BEB**: High risk: The use of the battery decreases its useful life.
- **IMC**: Medium risk: Charge and discharge cycles affect battery life.
- **Trolleybus**: N/A.

12.8. Infrastructure

Charging stations

Charging stations for electric buses and IMC buses depend on the location of the electrical infrastructure. Bus charging stations are different from conventional electric-vehicle stations because they require more power. IMC buses use these charging stations (traction substations) to charge the battery while moving on the track by means of a catenary. BEBs are charged at a charging station located in the yards while they are parked.

The substations and chargers of BEBs are more powerful than those of IMC buses (greater than 1,000 kVA). Thus, they are only located in the garage/yard. Their power level requires that they have redundancy in power sources, electrical backups, and significant security in operation. If a charger fails, it is not a problem in operation. If the substation fails, the entire operation of the buses can be affected. However, the probability of the substation's failing is very low, and if it has backup systems, it is even lower.

Substation power for IMC buses is usually lower than 1,000 kVA. There are multiple substations along the route, and, because of their small size, they are easier to install. In the case of IMC-NMC, the failure of one substation is not critical for the operation; IMC-NMC buses can still operate without one substation. In the case of IMC buses with LTO battery, the failure of one substation can affect the entire operation. This is also the case with trolleybuses. These vehicles are also affected by a substation contingency because of the small size of their batteries and their high dependence on the catenary; however, the substations are very reliable.

Risk assessment

- **BEB**: Medium risk: The failure of the charge substation, although unlikely, makes it impossible to operate the system.
- **IMC**:
  - NMC: Low risk: The failure of one of the substations is superable.
  - LTO: Medium risk: Substation failure can affect the entire operation, though it is unlikely.
- **Trolleybus**: Medium risk: Substation failure can affect the entire operation, though it is unlikely.

12.9. Location of charging stations

The charging station for a BEB must be connected to a station with sufficient power. This infrastructure is complex, and high power is required. Therefore, the location of the charger for a BEB is usually the garage/yard. If the bus battery has a low SOC and is far from the charging station, there is the risk of not reaching the charging station.

On the other hand, the distance to the route from the garage/yard may limit the operation of the bus. A route that passes through the garage/yard has no risk. But routes that operate a distance from the garage/yard require operators to budget the level of battery discharge to make it from the yard to the route and back again. That means less uptime and higher costs.

IMC buses need less power to charge. A fast charger compatible for conventional vehicles can suffice for these buses. Another charging point may be a catenary route to which the bus can connect. The autonomy of the bus is sufficient for it to operate without catenary and reach the garage/yard or charge in a public facility or another catenary segment.

Risk assessment

- **BEB**: Medium risk: The bus must operate within yard range. In addition, operating time is lost when the route moves away from the garage/yard.
- **IMC**: Lower risk: Many non-catenary charge options along the route.
- **Trolleybus**: N/A.

12.10. Catenary failure

The catenary line and the contact wire, being two exposed conductors, can fail for various reasons. Collisions of vehicles with infrastructure, accidents, or natural events such as high winds or atmospheric discharges are enough to break the cables and stop the system. However, in case of failure, the affected section can be isolated and repaired while other sections operate without problem. This means that, in practice, a section of catenary can be removed while the other sections remain operational.

IMC-NMC buses have the ability to operate without catenary for long stretches; therefore, the loss of a catenary section is not critical. For buses with LTO batteries, there is a risk that depends on the length of the missing section and the distance to the next energized section. The risk with IMC-LTO buses is greater.

Trolleybuses have a battery that allows them to travel small distances. In this case, the risk depends on the length of the missing section, which depends exclusively on the design of the sections between points of the track. We estimate the risk to be similar to that of the IMC bus with LTO battery.

Risk assessment.

- **BEB**: N/A.
- **IMC**:
    - NMC: Minimal risk: The battery allows the bus to operate long distances without catenary.
    - LTO: Medium risk: The battery allows the bus to operate a section without catenary.
- **Trolleybus**: High risk: It can operate for short stretches without catenary.

12.11. Number of charging ports

The number of charging ports available in a garage/yard depends on the available space and cost. Depending on the technology, a charging port needs at least the space of a vehicle and the space for a charger. This space can only be occupied by buses charging; buses subject to other activities—maintenance, parking, etc.—must be located elsewhere.

BEBs should be parked near charging stations to reduce cable resistance and operate with high-power-high-current energy exchanges. Cables and chargers must be close together to allow power transfer. Thus, a space must be separated for the charging equipment near the parking points. This area is fixed in the garage/yard and cannot be moved to other sites.

IMC buses and trolleybuses use the catenary for charging. The catenary can be in the parking spaces of these buses without interfering with other activities. Likewise, it is not necessary to separate additional space near parking sites because rectifiers and substations may be far away. Cables do not normally interfere with the distribution of objects on the ground or with the spaces separating vehicles. Thus, the space required for parking and charging infrastructure is the same.

Risk assessment

- **BEB**: High risk: If many chargers are needed, space must be available.
- **IMC**: Low risk: IMC buses use the same infrastructure as trolleybuses in garages/yards.
- **Trolleybus**: N/A.

12.12. Limitations on charging ports and stations

Different types of charging ports exist for electric vehicles. The most common are cables with connectors. There are many standards for the cables, but they all consist of a connector linked to a charging station with a thick cable. They are easy to maintain and operate; however, its operation is manual and requires a person.

The other types of connectors consist of elements on the vehicle. Two such connectors are pantographs and trolleys. Pantographs are mechanical systems that raise the connectors vertically to the charge contact and allow a high flow of current. They are complex structures that cannot be operated by people; rather, electromechanical systems are required to operate the pantograph.

Trolleys, on the other hand, can be operated by people or by lightweight electromagnetic systems. They consist of two lightweight bars that connect the vehicle to conductors with very light cables and allow current to pass.

Battery-powered buses are usually connected with pantograph or cables as they allow high power transport. IMC or trolleybus buses connect to trolleys as they require lower current.

Risk assessment

- **BEB**:
  - With pantograph: High risk: Complex structures that require space and maintenance. Connection failures are common because the vehicle's tolerated error at the parking site is low.
  - With plug and cable: Low risk: Common form of vehicle charging. Known use. However, it requires more space.
- **IMC**: Low risk: The same system is used for charging and for operation.
- **Trolleybus**: Low risk: The same system is used for charging and for operation.

12.13. Impact on the energy supply network

The adequate provision of energy depends on a delicate balance between generators and consumers. Power generation must be perfectly planned to ensure that there is enough energy for populations' daily use. This process is even more complex if we consider that the power demanded varies throughout the day. During the night, power demand is usually lowest; during the morning and evening the power demand is usually greatest.[viii]

Different phenomena can affect the stability of the power grid. A drop in supply—very common in solar generation—can reduce the available power. The network protections must then disconnect multiple consumers to maintain stability. A sudden rise in energy demand causes a similar phenomenon, and likewise consumers must be disconnected to compensate.[ix]

Renewable-energy grids see the most instability. To compensate for this, energy storage systems are used as a backup. When the generation system has a sudden drop in power, the backup system activates to compensate. Among the common backup systems are batteries, capacitors, inertial wheels, and reversible water reserve systems. The most common system is the battery because it has the fastest response.[x]

BEBs have a significant impact on energy demand. When a fleet charges, the impact on the power grid is in MW. For example, a BEB charges at a power of around 120kW. Ten buses demand 1.2 MW of power in one place. This level of demand will necessitate a backup system in case of there are other sudden changes in demand.

IMC buses and trolleybuses demand energy at a lower rate because charges and discharges occur during operation throughout the day. The stress on the grid is less than that generated by BEBs. For example, an IMC bus with a 71 kWh battery requires a charging power of 25 kW. Ten buses in this fleet demand a total of 250 kW. This demand is not concentrated at one point but distributed along the route and time and thus is much easier for the network to deliver.

Risk assessment

- **BEB**: High risk: Charging high-power batteries in a short period of time places excessive demand on the power grid. Different backup system strategies must be incorporated at a higher cost.
- **IMC**: Minimal risk: Energy demand is distributed throughout the day.
- **Trolleybus**: Minimal risk: Energy demand is distributed throughout the day.

12.14. Lack of standards and regulations in charging systems

Standards facilitate processes by ensuring that any device is used only according to certain certifications and without modifications, adaptations, or add-ons. For vehicle charging, many standards have emerged to enable different technologies. But worldwide there are many versions of connectors and voltage levels that make it difficult to incorporate universal standards. For example, the electric vehicle charging connector has at least four globally accepted standards.

- **BEB**: Low risk: Standards in the US require specific electrical regulations. Electric vehicle vendors must comply with existing infrastructure.
- **IMC**: N/A.
- **Trolleybus**: N/A.

12.15. Battery chemistry

Energy storage is one of the key variables in sustainable energy systems, and so the evolution of battery chemistry is a central element in finding the ideal energy storage system. Today's batteries are the result of years of evolution, but they are still far from reaching the desired goal. More energy must be stored using better and more sustainable materials.

Today's vehicles use the technologies available today. There are no guarantees that a new and better battery will work for an old vehicle. In a space of 15 years, new developments can appear in the transportation industry and change everything. For personal vehicles, this is not a problem since a person has a vehicle for a limited period. But for public transport, the choice of technology involves a commitment to operation for many years.

It also bears mentioning that batteries today contain many toxins. New rules restricting the use of such materials may change the fate of currently operational vehicles. This would force the batteries of such vehicles to be changed to comply with the law. This procedure can be very expensive.

Risk assessment

- **BEB**: High risk: The batteries are big. Deployment can be expensive and complex.
- **IMC**: High risk: The batteries are small and cheaper than those of a BEB, but adjustments must be made for the change of technology.
- **Trolleybus**: N/A.

Table 85 presents the summary of risks and their assessment for each alternative.

Table 85. Conceptual risk assessment of alternatives

		Impact		
	Probability	***BEB***	***IMC***	***Trolley***
Operational				
Battery fire	Very low	High Risk. Battery size >100kWh. Chemistry NMC.	Medium Risk. Battery size<100kWh. Chemistry LTO, NMC	Low Risk. Battery size<30kWh. Chemistry LFP, NMC
Battery maintenance.	Low	Considerable risk. Heavy and highly energetic battery. Large space needed. Specialized tools.	Medium risk. Large space needed. Specialized tools.	Low or non-existent risk due to the smaller battery capacity and use as secondary systems.
Battery disposal	High	Considerable risk. Raw and non-abundant rare earth materials in a big battery with high contaminating potential.	Considerable risk. Raw and non-abundant	Medium risk. Raw and non-abundant materials in a small battery.

	Probability	Impact: BEB	Impact: IMC	Impact: Trolley
			materials.	
Inadequate training of drivers	Medium	Medium risk. The vehicle should be driven according to the battery capacity. Internal systems can maintain the bus operation between safe limits.	Medium risk. The vehicle should be aligned with the catenary to connect or disconnect as needed.	High risk. The vehicle cannot operate if the driver is not aligned with the catenary.
Time to charge an EV	High	Medium risk. Off-service times can be long enough that a bus needs a replacement. Bus must be charged at the parking yard.	Minimal risk. Vehicles charge while moving with passengers.	DNA
Maintenance duties of vehicles (fleet)	High	Medium risk. Shorter maintenance times due to charging time. Fleet charging and maintenance require more personnel and coordination. Safety issues if maintenance staff are not properly trained to work with batteries. *BEB with limited parking yard space*. Elevated risk. As there is no available space to maintain the buses with more personnel, complications and logistic bottlenecks should be encountered.	Minimal risk. No new maintenance activities compared to a trolleybus except for the batteries.	Minimal risk. No new maintenance activities.
Battery life	Extremely high	Elevated risk. Battery use is heavy which affects the lifespan.	Medium risk. Battery cycles affect lifespan.	DNA
Infrastructure				
Charging substation failure	Extremely low	Minimal risk. Failure of the substation can affect the BEB operation.	NMC: Low risk if using battery. LTO: Medium risk. Failure in substation, albeit extremely low, can affect the operation.	Medium risk. Failure in the substation can affect the operation albeit extremely low.
Charging station location	Medium	Medium risk. Bus needs to operate in range of the parking yard. Operating time is reduced if the route is at a considerable distance from the parking yard.	Minimal risk. Many options to charge besides the catenary in his route.	DNA
Catenary failure	Medium	DNA	NMC: Minimal risk. Battery lets the bus operate for long distances without catenary. LTO: The risk is measured according to the distance between catenary sections.	Medium risk. The risk is measured by the length of the electric sections of the catenary.
Number of charging ports	Low	Elevated risk. If several chargers are needed, the required space should be available.	Low Risk. IMC buses charge using the same infrastructure of trolleybuses in the parking yard	DNA
Limitations on the charging ports and stations.	Medium	*With pantograph*: Elevated risk. Complex structures that require space and maintenance. Failure to connect pantographs to chargers is common as the	Minimal risk. The same system is used for charging and operation.	Minimal risk. The same system is used for charging and operation.

	Probability	Impact BEB	Impact IMC	Impact Trolley
		allowed error in the vehicle's position in the parking spot is low. *With plug*: Minimal risk. A common way to charge electric vehicles is the wire plug. Straightforward operation. Requires more space.		
Grid instability	Medium	Elevated Risk. Charging high-powered batteries in short times will stress the energy distribution network. Different energy compensation strategies should be implemented with higher costs.	Minimal risk. The energy demand is mostly distributed through the day.	Minimal risk. The energy demand is mostly distributed through the day.
Lack of standards and regulations on charging infrastructure.	Extremely low	Low Risk. Standards in the US require specific electrical systems. Sellers of BEB must be compliant with the available infrastructure.	DNA	DNA
Technology				
Battery chemistry	Low	Elevated risk. As batteries are big, the change could be expensive and complex.	Elevated Risk. These batteries are smaller and cheaper than BEB batteries, but adaptations must be made for modern technologies	DNA

13. Conclusion and further work

To electrify its diesel-hybrid routes quickly, efficiently, and cost-effectively, San Francisco must leverage its current trolleybus and overhead catenary systems to make them the core of their electrification effort—a process in which the utilization of IMC trolleybus technology is critical. A 33 percent increase in OHL infrastructure will allow San Francisco to more than double its fleet of zero-emission buses.

To reach this conclusion, we compared the most prominent electrification alternatives vis-à-vis some of the most representative routes in the city. Using computational tools such as OpenTrack and OpenPowerNet and optimization algorithms, we modeled each alternative. We also conducted a 15-year financial evaluation and risk assessment for each alternative.

We emphasize again that **routes currently operated with trolleybuses should continue to be operated with trolleybuses and that no major demolition of overhead contact line should be made**. The only points where lines should be modified are in particular segments or sections where maintenance costs can be reduced and system performance remain consistent. At these points, any dismantling should be limited to complex route intersection locations, where planners can maintain electrical continuity by means of underground or aerial feeders as needed. As demonstrated above, the trolleybus alternative is the one with the lowest energy consumption from a transit-system-wide point of view.

Based on our study of Route 44 O'Shaughnessy—a representative, high-use diesel-hybrid route—and simulation of the alternatives, **we found that the most cost-effective**

electrification method for the route is the IMC trolleybus alternative. This technology presents the easiest logistics in terms of charging, the lowest operating and investment costs, and the greatest possibilities to benefit from regenerative braking. Likewise, IMC favors greater passenger capacity in buses since its battery is lighter than in BEB technologies.

The optimization process we conducted confirmed the optimal charging method for the bus fleet. **The optimization solution our analyses suggested is long catenary segments.** The results did not suggest specific sites for fast chargers—which are key for opportunity charge schemes—therefore the optimization results indicated that IMC was the optimal electrification strategy. (When the optimization results indicate many distributed and short segments of overhead lines with high power charge, opportunity charge schemes become viable; however, this was not the case of the routes analyzed.)

Although our optimization process had already suggested a zero-emission technology for the incoming fleet, we conducted further studies to better evaluate the replacement of the technology. The battery study was crucial in assessing the feasibility of battery electric buses. Under normal operating conditions, this technology required battery changes every seven years. However, because San Francisco's route profiles have steep slopes, the battery life cycle can deteriorate enough to require battery changes every 5 years, or fewer.

A key factor in favor of IMC is its 1:1 replacement ratio. **That is, if planners chose the BEB alternative—with its 1:1.18 replacement ratio—a larger fleet would be required to maintain present operation.** In addition, due to the time required to charge the batteries, the bus fleet would show an additional increase between 30 percent and 100 percent of the size of the original fleet, depending on demand conditions. Although this percentage may vary due to the requirements of the route, it nevertheless constitutes an excessive investment cost. **A larger fleet also requires a larger bus depot, which increases both investment and operating costs.**

In addition to aiding bus-system electrification, strengthening DC systems in cities is a great advantage in terms of resilience. In the event of natural disasters, underground AC conductors can be damaged. Therefore, overhead lines can serve as a safe power source for hospitals or critical users, and the DC system could be used to receive exceeds of distributed photovoltaic energy from nearby users and households. For example, the UCSF Medical Center might find some alternative power in the catenary of Parnassus Street.

Further work

Given our findings, there are numerous further lines of inquiry researchers could pursue. Researchers could, for example,

- Study the system's capacity to accommodate new trolleybuses on the proposed IMC routes and establish the actual traction substation needs and their most appropriate location, taking into account space constraints at the locations and San Francisco's medium-voltage grid;
- Conduct a more detailed financial assessment that considers local implementation costs and the results of the detailed electrical studies mentioned above;
- Perform detailed electrical modeling of the entire DC network to study the power supply to the trolleybus-IMC network;
- Study the integration of distributed solar power as part of future partial power supply sources for the Muni bus network;
- Determine the savings in critical materials, such as cobalt, as well as the ecological benefits that accompany the IMC trolleybus alternative;

- Accurately estimate the greenhouse-gas-emission reductions resulting from replacing Muni's hybrid diesel fleet with a zero-emission IMC fleet; or
- Evaluate the possibility of offering fast-charging services to cabs and other small public transport vehicles, based on the new DC network for the power supply of the new IMC routes.

14. Acknowledgments

The authors would like to thank Daniel Alberto Arroyave Molina for assistance with the simulations in OpenTrack and OpenPowerNet; Carolina Villamizar Agudelo, for assistance with the simulation, diagrams, and drafting the of report; Andrés Cadavid Álvarez, for assistance with OpenTrack and insight in terms of mechanical engineering; and Camilo Vargas Valdivieso, for assistance with the geographical data presented in the report.

15. Notes

Bartłomiejczyk, Mikołaj, and Robert Kołacz. 2020. "The reduction of auxiliaries power demand: The challenge for electromobility in public transportation." *Journal of Cleaner Production* 252 (119776). doi:https://doi.org/10.1016/j.jclepro.2019.119776.

Bhutada, Govind. 2022. *Breaking Down the Cost of an EV Battery Cell*. Visual Capitalist. February. Accessed November, 2022. https://www.visualcapitalist.com/breaking-down-the-cost-of-an-ev-battery-cell/.

California Energy Commission. 2019. *CALIFORNIA'S FOURTH CLIMATE CHANGE ASSESSMENT: San Francisco Bay Area Region Report*. Sacramento, CA: California Energy Commission. https://www.energy.ca.gov/sites/default/files/2019-11/Reg_Report-SUM-CCCA4-2018-005_SanFranciscoBayArea_ADA.pdf.

Díez, Andrés Emiro, and Mauricio Restrepo. 2021. "A Planning Method for Partially Grid-Connected Bus Rapid Transit Systems Operating with In-Motion Charging Batteries." *Energies* 14 (2550).

2021. *DOE Estimates That Electric Vehicle Battery Pack Costs in 2021 Are 87% Lower Than in 2008*. Office of ENERGY EFFICIENCY & RENEWABLE ENERGY. October. https://www.energy.gov/eere/vehicles/articles/fotw-1206-oct-4-2021-doe-estimates-electric-vehicle-battery-pack-costs-2021.

Edelstein, Stephen. n.d. *Report: EV battery costs hit another low in 2021, but they might rise in 2022*. GREEN CAR REPORTS. https://www.greencarreports.com/news/1134307_report-ev-battery-costs-might-rise-in-2022#:~:text=Lithium%2Dion%20battery%20pack%20prices,cell%20basis%2C%20the%20report%20said.

esri. 2019. "Elevation profiles." https://www.esri.com/content/dam/esrisites/en-us/media/pdf/teach-with-gis/elevation-profiles.pdf.

Göhlich, D, T. A. Fay, and S Park. 2019. "Conceptual design of urban e-bus systems with special focus on battery technology." *International Conference on Engineering Design* 1 (1): 2823-2832.

Kalogirou, Soteris. 2018. *McEvoy's Handbook of Photovoltaics (Third Edition)*.

Kunith, A. W. 2018. "Elektrifizierung des urbanen öffentlichen Busverkehrs." Berlin.: Technische Universität Berlin.

Lajunen, Antti. 2018. "Lifecycle costs and charging requirements of electric buses with different charging methods." *Journal of Cleaner Production* 172: 56-67. https://www.sciencedirect.com/science/article/pii/S0959652617323594.

NOAA. n.d. *San Francisco, CA, USA Weather Averages*.

Pham, T.H, B Rosca, and s Wilkins. 2016. "Battery Peak Power Shaving Strategy to Prolong Battery Life for Electric Buses." *Science Direct* (Science Direct) 077-083. https://www.sciencedirect.com/science/article/abs/pii/S2405896316313337.

SFMTA. 2022. *44 O'Shaughnessy*. https://www.sfmta.com/routes/44-oshaughnessy.

—. 2021. "Agreement between the City and County of San Francisco and Nova Bus, A Division of Prevost Car (US) Inc. (Through the Commonwealth of Virginia." April. https://www.sfmta.com/sites/default/files/reports-and-documents/2021/04/4-20-21_item_15_contract_-_novabus.pdf.

SFMTA; WSP. 2022. "ZERO EMISSION FACILITY AND FLEET TRANSITION PLAN - TROLLEY BUS AND BATTERY-ELECTRIC BUS EVALUATION REPORT." San Francisco.

UN. 2015. "Transforming our world: the 2030 Agenda for Sustainable Development."

ViriCiti. 2020. "INSIGHTS INTO THE ENERGY USAGE DISTRIBUTION OF ELECTRIC BUSES." https://info.chargepoint.com/rs/079-WYC-990/images/Viriciti-Energy-Distribution-Report-Nov-2020.pdf.

VIRICITI. 2020. "Viriciti Report: E-Bus Performance." Amsterdam. https://viriciti.com/wp-content/uploads/2020/07/ViriCiti-E-Bus-Performance-Report-July2020.pdf.

Weijiang Xue, Lixiao Miao, Long Qie, Chao Wang, Sa Li, Jiulin Wang, Ju Li,. 2017. "Gravimetric and volumetric energy densities of lithium-sulfur batteries." *Science Direct* 6 (1): 92-99. doi:https://doi.org/10.1016/j.coelec.2017.10.007.

---

[i] https://www.mdpi.com/2076-3417/12/6/2961

[ii] https://www.sfmta.com/sites/default/files/reports-and-documents/2021/06/sfmta_zeb_task_2_facility_needs_final_report_2.pdf

[iii] https://www.adb.org/sites/default/files/linked-documents/54123-001-ld-03.pdf

[iv] https://dof.ca.gov/forecasting/Economics/

[v] https://bnonews.com/index.php/2022/04/bus-on-fire-in-central-paris/

[vi] https://www.inquirer.com/transportation/septa-proterra-electric-bus-battery-fire-philadelphia-20221111.html

[vii] https://www.nrel.gov/docs/fy21osti/80022.pdf

[viii] https://www.gov.ca.gov/wp-content/uploads/2021/07/Electricity-System-of-the-Future-7.30.21.pdf

[ix] https://www.bloomberg.com/news/articles/2022-05-05/california-s-all-renewable-moment-shows-the-future-of-the-power-grid

[x] https://abcnews.go.com/US/california-blackouts-power-grid/story?id=89460998