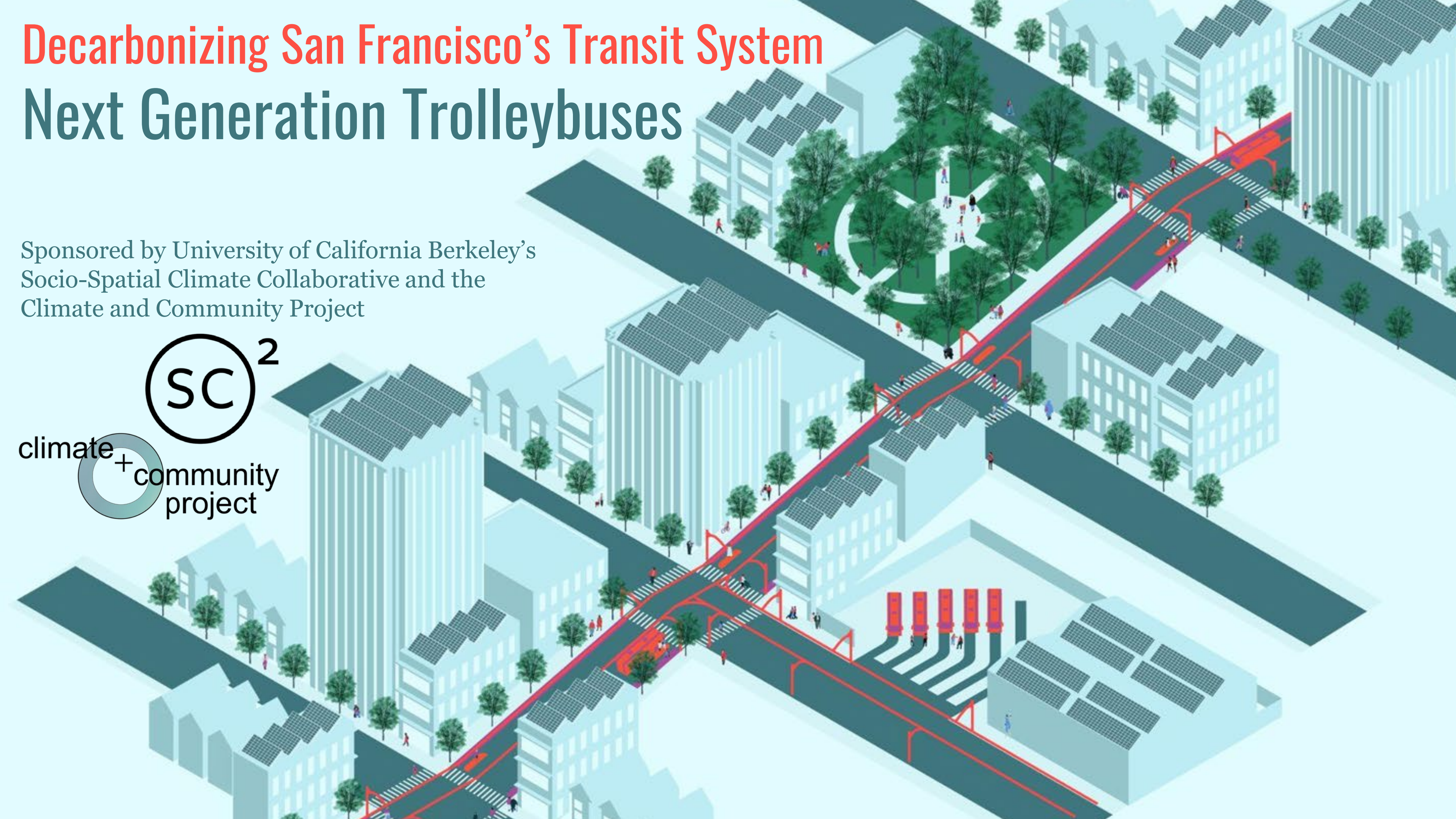
Decarbonizing San Francisco's Transit System

Next Generation Trolleybuses

Sponsored by University of California Berkeley's Socio-Spatial Climate Collaborative and the Climate and Community Project



SAN FRANCISCO MUNI ELECTRIFICATION

Alternatives Analysis

By

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JULY 2023

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Content

- Report: Team presentation
- Report: Scope and Findings
- Alternatives Analysis Methodology: single route analysis
- High opportunity electrification plan
- Battery Electric and IMC Buses procurement challenges
- Towards a Smart Grid

Report: Team presentation

Brief presentation and experience of Metro-UPB-UniNorte in similar projects

Fleet increase from 40 to 80 trains

Fleet increase from 7 to 12 trains + 2 more Metrocables

1+ Metrocable: Picacho, with 4000 phd

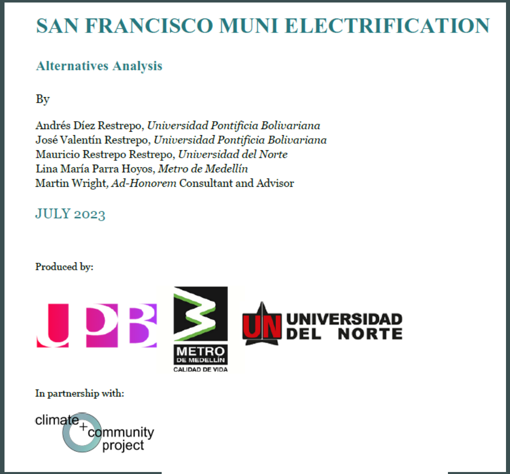
Determine the optimal electric infrastructure for the new demand

Similar to the findings for San Francisco, these projects were able to occur largely by leveraging their power supply systems from the existing medium voltage grid of the other modes.

Report: Scope and Findings

Analyze and compare the main technological alternatives for the electrification of San Francisco's bus fleet. Battery electric buses (**BEBs**), in-motion charging (**IMC**) trolleybuses, and conventional **modern trolleybuses.**

- **IMC trolleybuses** are the **most environmentally and economically option** (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.



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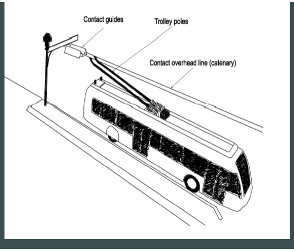
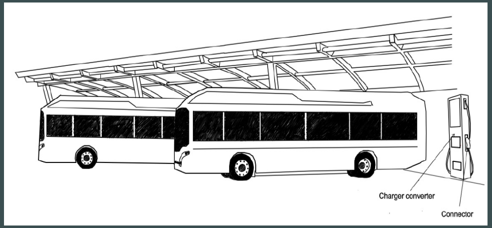
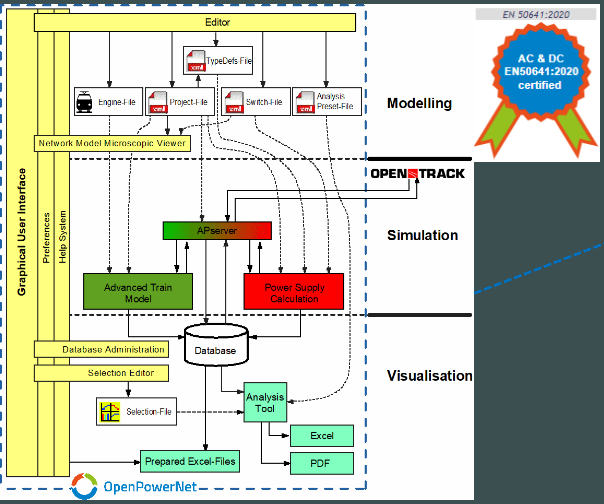


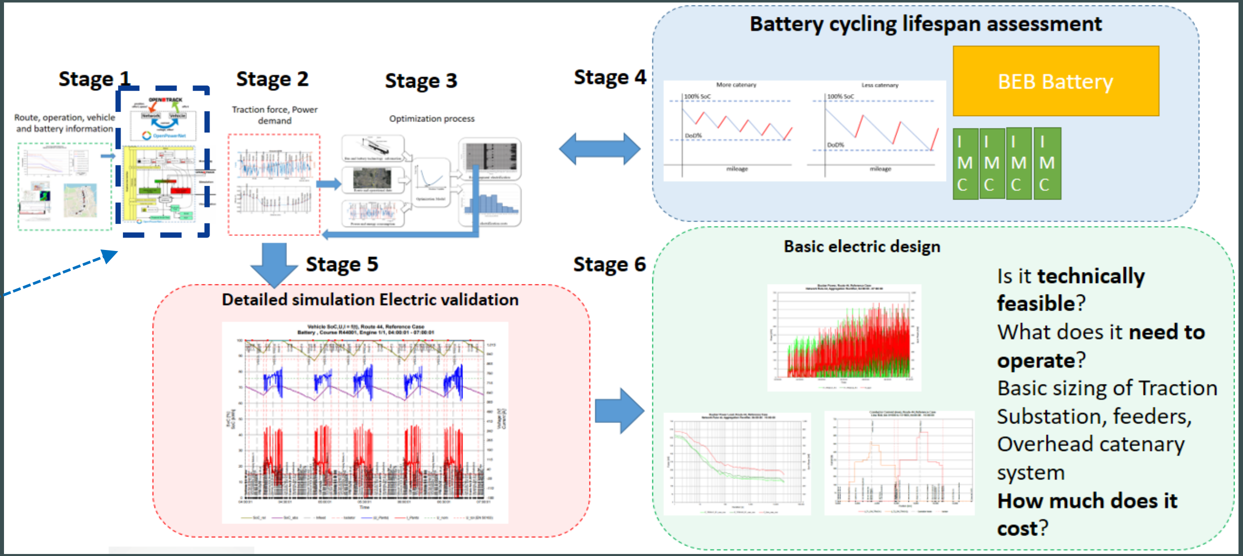


Alternatives Analysis Methodology: single route analysis

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: equipment especification TPS, Conductors





Alternatives Analysis Methodology

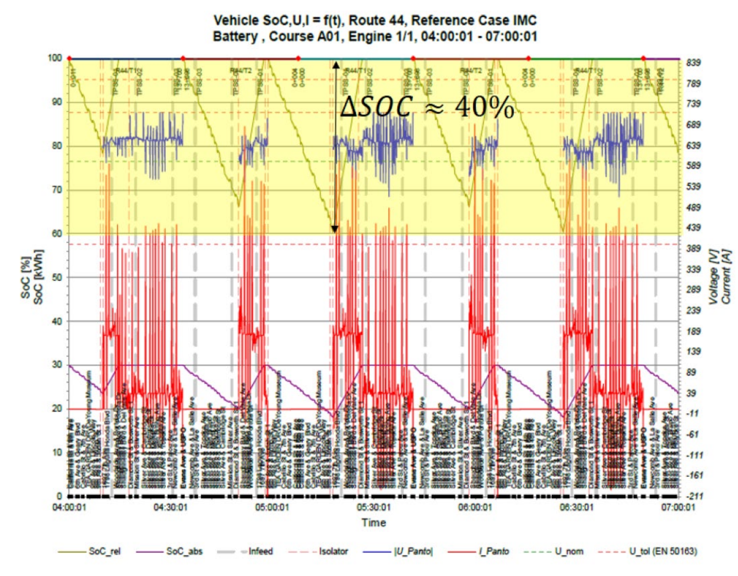


Figure 29. Operational behavior of IMC-30 kWh from 4 am to 7 am.

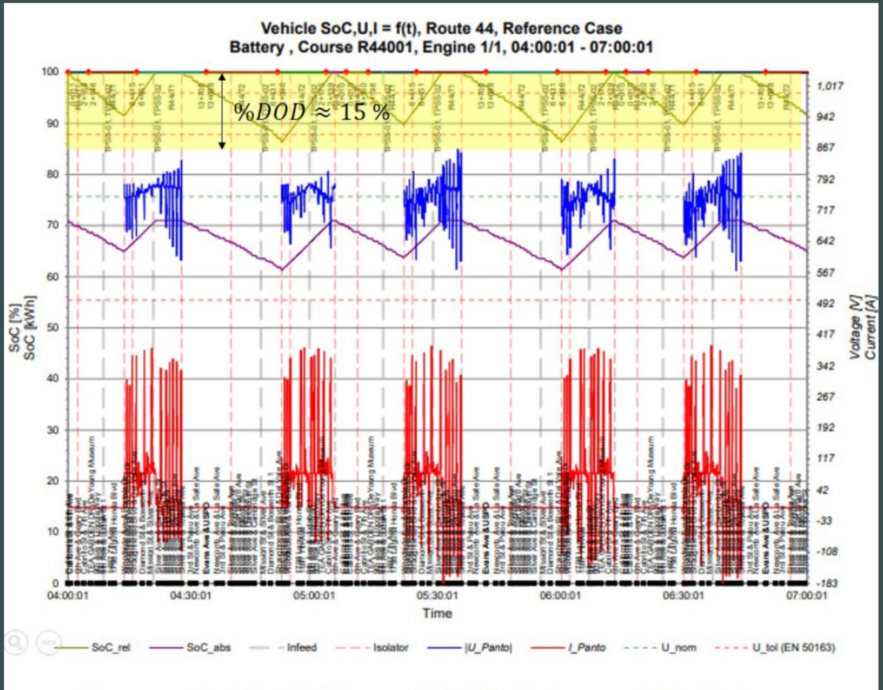
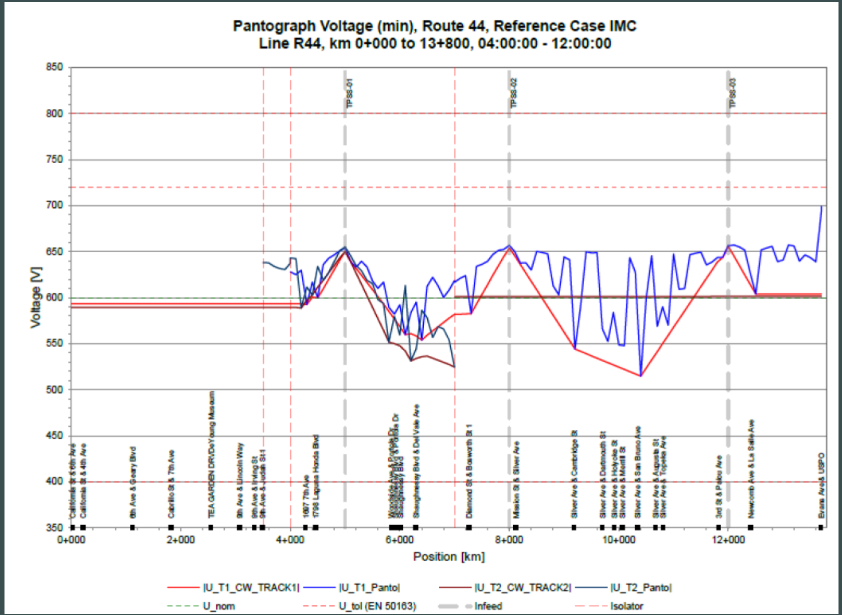


Figure 42. Vehicle SOC for 40-ft IMC trolleybus, 71 kWh, Route 44.

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

OpenTrack open PowerNet allows a simulation of the operation of the fleet emulating the real operation, calculating the electrical and mechanical variables. The electrification proposals made in the report are technically feasible.

Alternatives Analysis Methodology



The description of each of the curves is:

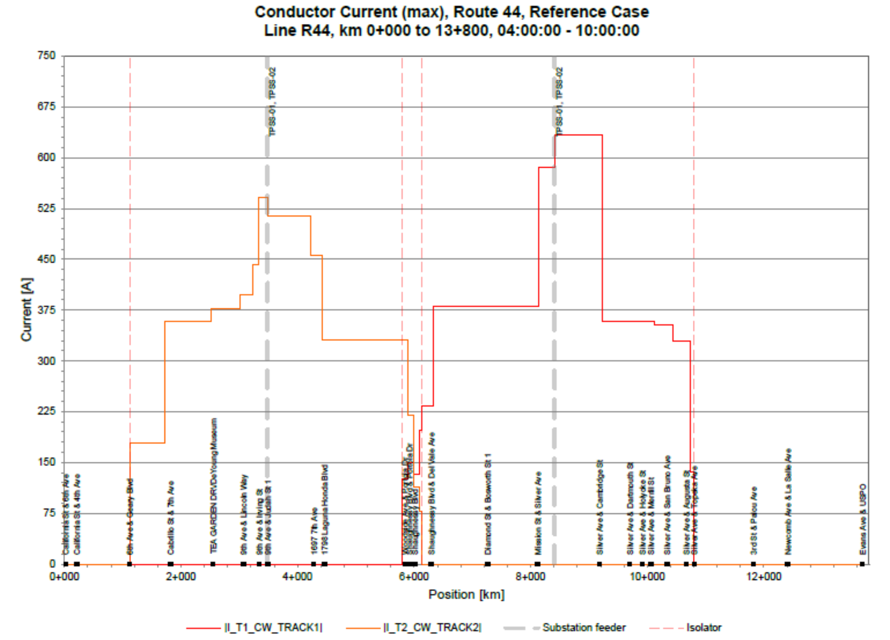
- Infeed: Overhead line feeder
- U_T1_CW_TRACK1: Voltage in the contact wire in Track 1
- Isolator: Electrical insulation point
- U_T1_panto: Voltage in the trolleybus pantographs in Track 1
- U_tol ---: Voltage tolerance according to EN 50163

- 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

Alternatives Analysis Methodology

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



Catenary

Cross section contact wire: 150 mm2 CTA (CuAg0.1)

DC-resistance (at 70°C): 176 mΩ/km (including 20% wear of contact wire)

Current carrying capacity: 687 A and considering 30°C ambient temperature)

No underground/additional feeders required

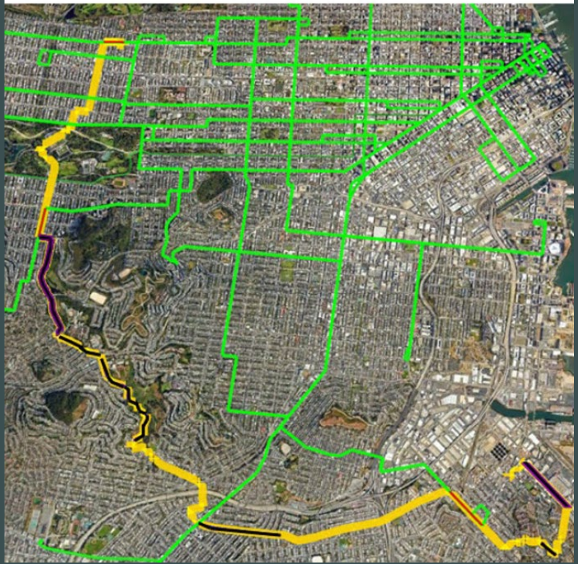
The explanation of each of the curves is:

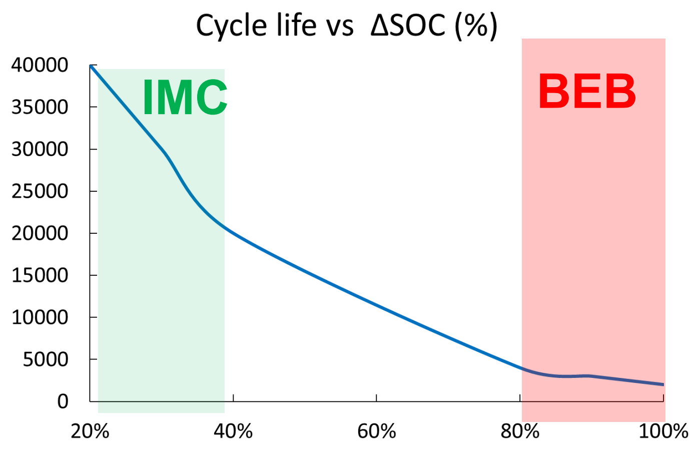
I_T1_CW_Track1: Maximum current registered in Track 1

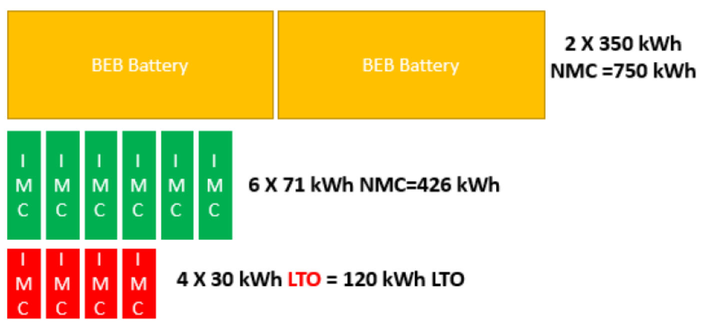
I_T2_CW_Track2: Maximum current registered in Track 2

Alternatives Analysis Methodology

Route 44







2 X 350 kWh NMC =750 kWh

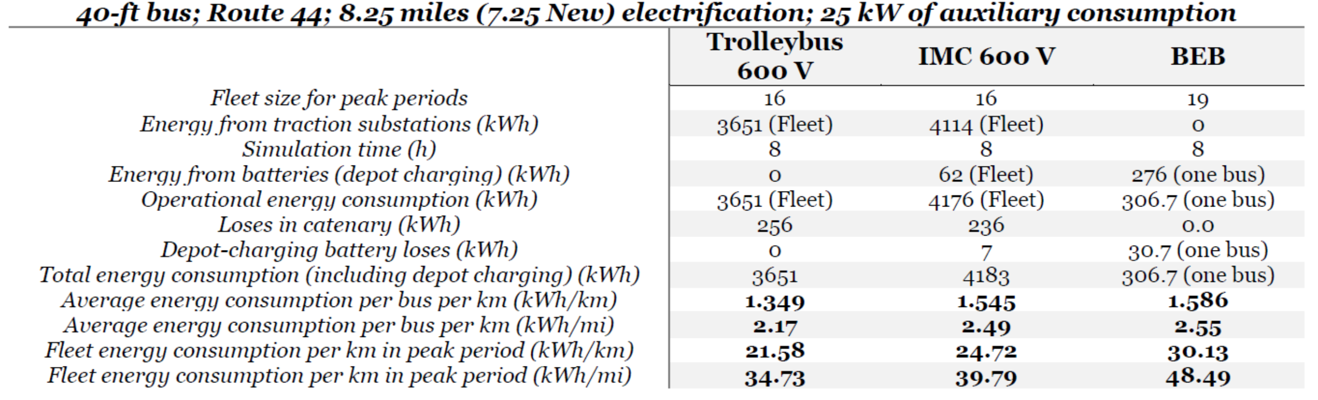
6 X 71 kWh NMC=426 kWh

4 X 30 kWh LTO = 120 kWh LTO

IMC operation cares the battery through state-of-charge control. If the ΔSOC is limited to 20 %, the number of life cycles is increased by 200 %. IMC opens the door for non-cobalt batteries such as LFP and LTO

Outcomes: Single route results

IMC trolleybuses are the most environmentally and economically option



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**

Higher energy efficiency is related to lower direct energy transmission losses (compared to battery charge-discharge processes), better regenerative energy management, and reduced dead weight transport.

Outcomes: Single route results

IMC trolleybuses option requires less vehicles than BEB

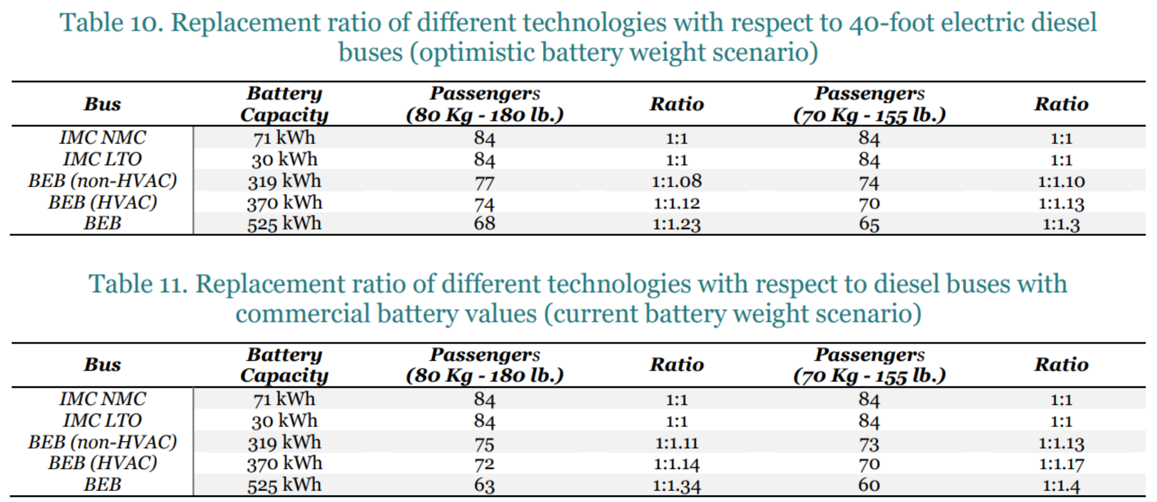


Table 10. Replacement ratio of different technologies with respect to 40-foot electric diesel buses (optimistic battery weight scenario)

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

Higher deadweight is one of the causes of a larger BEB fleet, bus availability is the other. Controlling bus weight is important: tire wear (generates particulate matter) and pavement wear.

Outcomes: Single route results

BEB: a larger fleet and thus more space is required

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%.

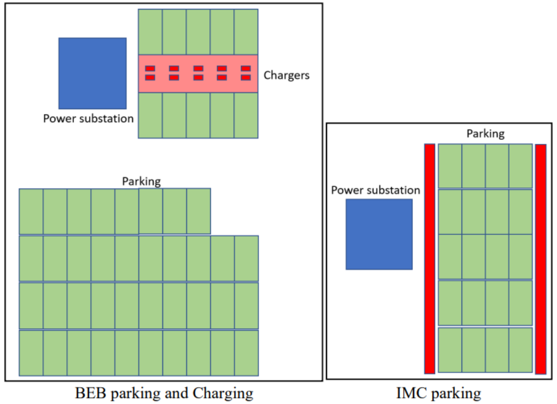
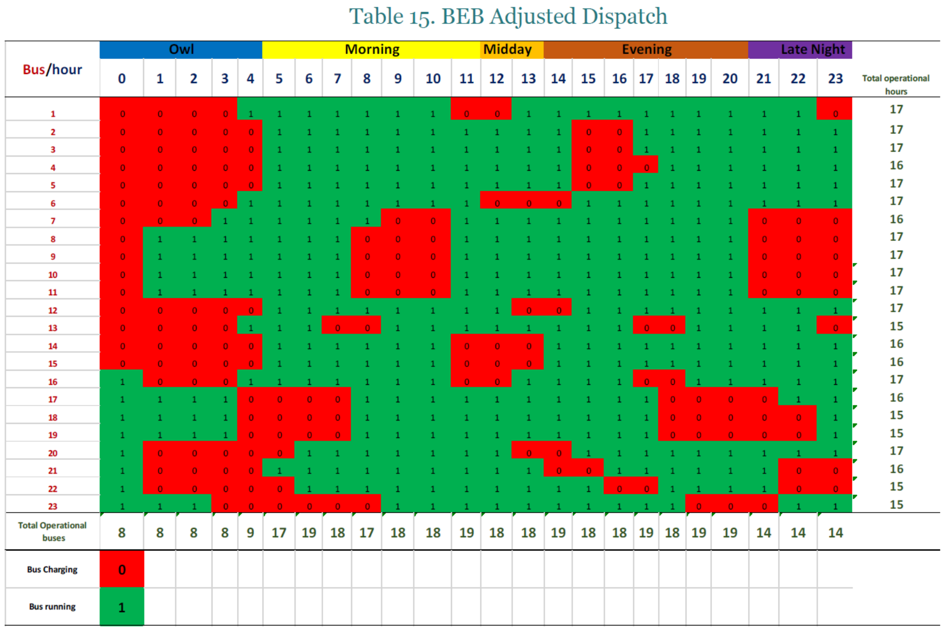


Figure 18. (a) BEB yard and (b) IMC yard.

Table 15. BEB Adjusted Dispatch



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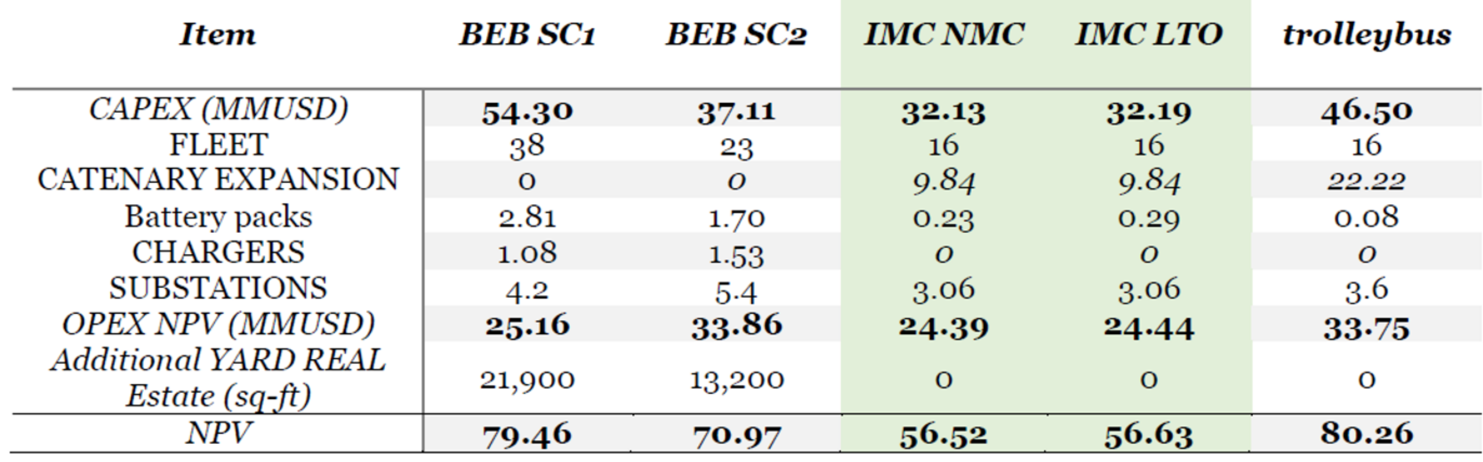
17	1	1	1	1	0	0	0	0	1	1	1	1	1	1	1	1	1	1	0	0	0	0	1	1	16
18	1	1	1	1	0	0	0	0	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	1	15
19	1	1	1	1	0	0	0	0	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	1	15
20	1	0	0	0	0	0	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	1	1	1	17
21	1	0	0	0	0	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	1	1	0	0	16
22	1	0	0	0	0	0	1	1	1	1	1	1	1	1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

Outcomes: Single route results

Financials of the differential elements of the technologies, both for capital costs and operational costs, over a 15-year project period

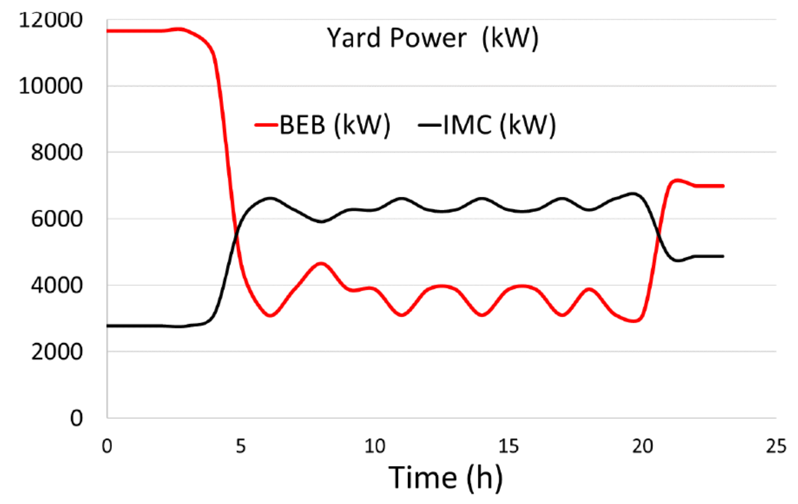


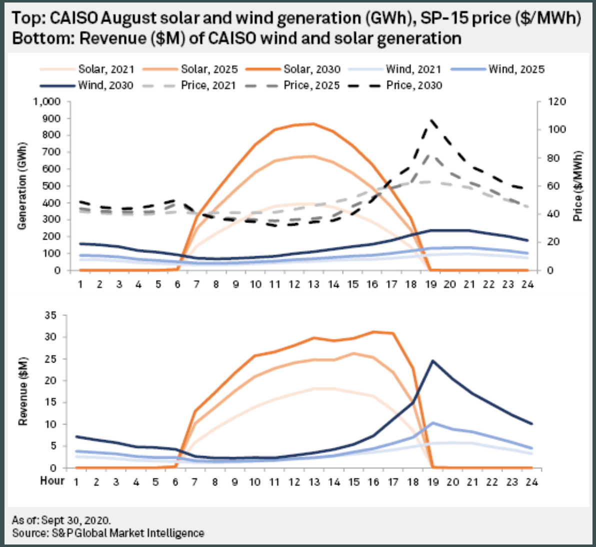
Item	*BEB SC1*	*BEB SC2*	*IMC NMC*	*IMC LTO*	*trolleybus*
CAPEX (MMUSD)	**54.30**	**37.11**	**32.13**	**32.19**	**46.50**
FLEET	38	23	16	16	16
CATENARY EXPANSION	0	*0*	*9.84*	*9.84*	*22.22*
Battery packs	2.81	1.70	0.23	0.29	0.08
CHARGERS	1.08	1.53	*0*	*0*	*0*
SUBSTATIONS	4.2	5.4	3.06	3.06	3.6
OPEX NPV (MMUSD)	**25.16**	**33.86**	**24.39**	**24.44**	**33.75**
Additional YARD REAL Estate (sq-ft)	21,900	13,200	0	0	0
NPV	**79.46**	**70.97**	**56.52**	**56.63**	**80.26**

At the end of 15 years, substations and catenary will be in good condition for another 15 years of operation. IMC buses can perfectly operate for up to 20 years. BEB: a larger fleet and thus more space is required

Outcomes: Single route results

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.



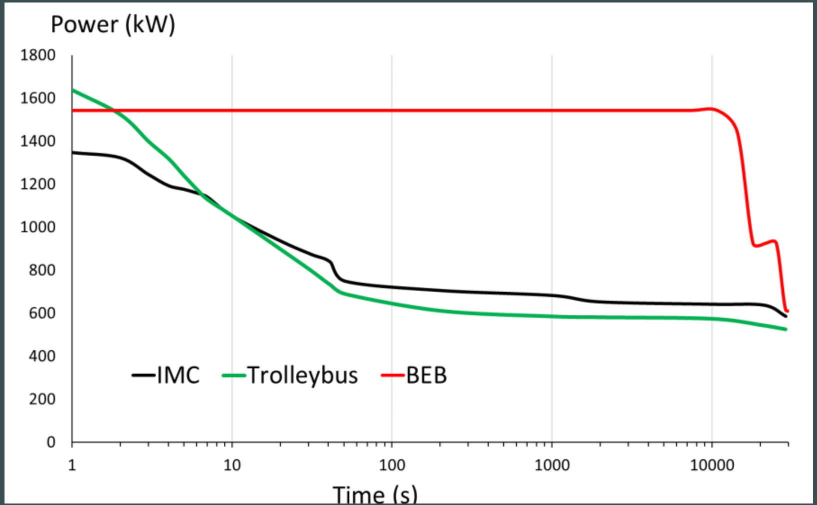

Top: CAISO August solar and wind generation (GWh), SP-15 price ($/MWh)
Bottom: Revenue ($M) of CAISO wind and solar generation

As of: Sept 30, 2020.
Source: S&P Global Market Intelligence

BEBs: very high demand in a limited and concentrated period of time, very low demand the rest of the day. Risk of excess consumption of reactive energy an low demand such as ferro-resonance. IMC: perfect fit to solar power and very good for wind

Outcomes: Single route results

Cumulative power demand for IMC, BEB and trolleybus.



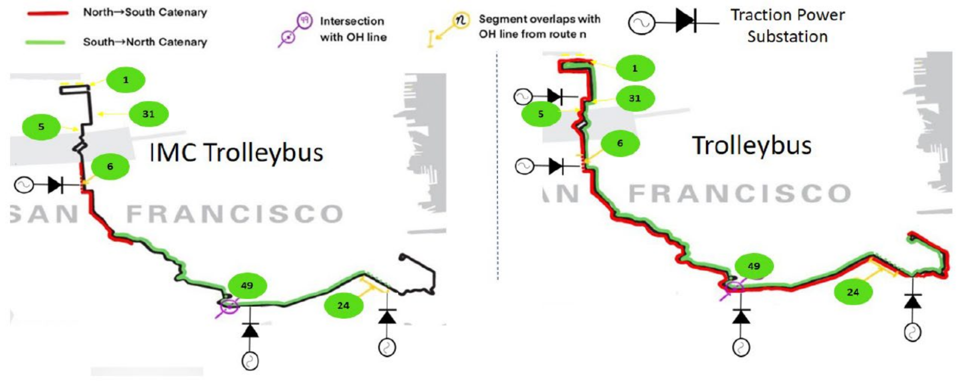


Figure 27. Electrification of Route 44 for 400-ft IMC buses (left) and trolleybuses (right).

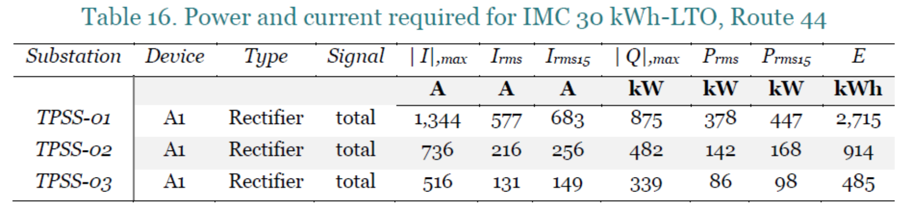


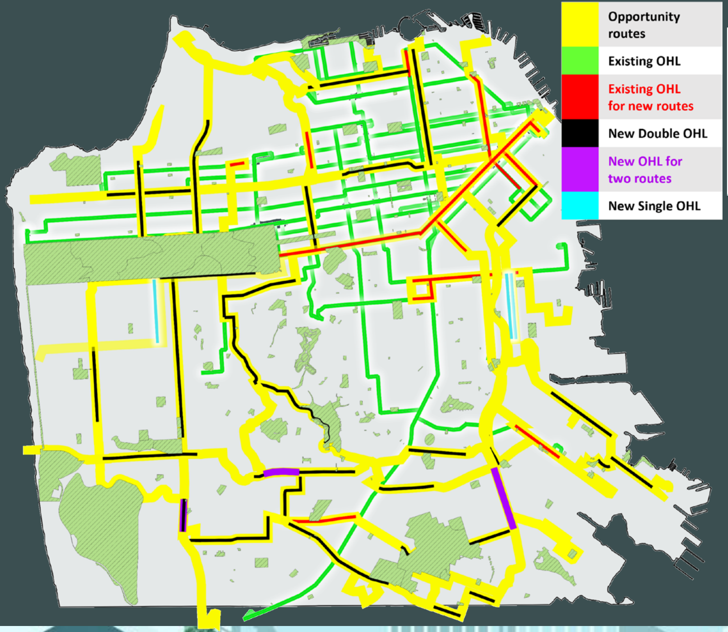
Table 16. Power and current required for IMC 30 kWh-LTO, Route 44

Substation	*Device*	*Type*	*Signal*	$\lvert I\rvert_{,max}$	I_{rms}	I_{rms15}	$\lvert Q\rvert_{,max}$	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

BEBs: very high demand in a limited and concentrated period of time, very low demand the rest of the day. Risk of excess consumption of reactive energy an low demand such as ferro-resonance. IMC: perfect fit to solar power and very good for wind

High opportunity electrification plan

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.



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

When taking a global approach, the **margins in favor of IMC technology over BEB increase synergistically**: the more routes and buses are incorporated, the lower the average energy consumption, the lower the average cost of vehicle ownership and the lower the infrastructure required per bus. This result is relevant for all cities that advocate a massification of the zero emission bus mode.

High opportunity electrification plan

Under bus density and Route Demand Factor (RDF) criteria, some lines seem to fit better as trolleybus, however, after financial analysis, the use of IMC is recommended. Routes that will maintain low-intensity operation are suitable for BEB electrification.

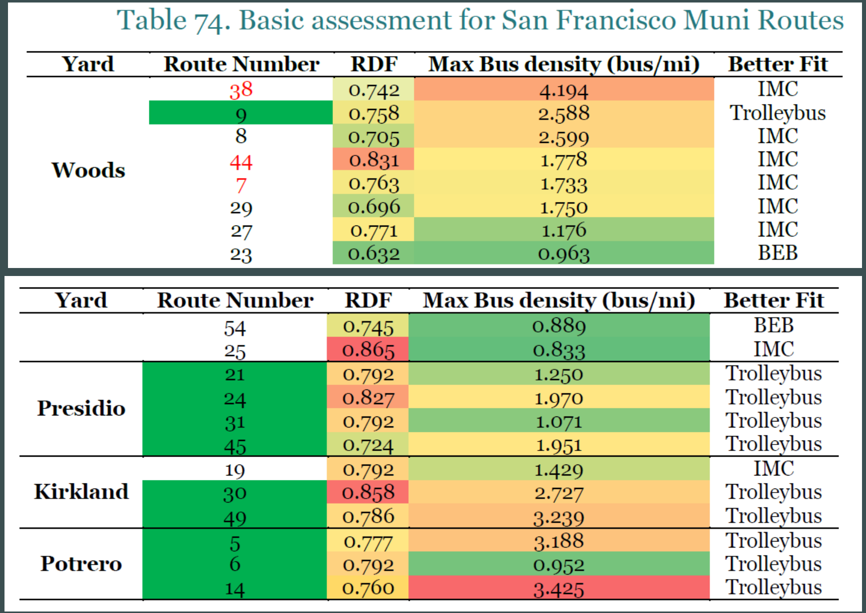


Table 74. Basic assessment for San Francisco Muni Routes

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

High opportunity electrification plan

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.

High opportunity electrification plan

Design 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.

Battery Electric and IMC Buses procurement challenges

- The recent bankruptcy **of Proterra, pending closure of Novabus in 2025, and reliability of BYD raise significant questions about adequacy of North American manufacturing capacity**. That said, the entrance of Solaris into the North American marketplace is adding an additional manufacturer for both trolleybuses and BEBs. **SFMTA's efforts to assemble a trolleybus procurement consortium are admirable and we look forward to assisting with that initiative**.
- Additionally, Kiepe Electric is committed to the North American market and is likely to become more proactive under new independent ownership. Kiepe has been quite willing to take the lead where necessary as illustrated with the **supply of trolleybuses to Dayton using bus bodies manufactured by the Bay Area's own Gillig**. Furthermore, because **the replacement of diesel-hybrid and battery drives with IMC requires only modest retooling**, it can be accomplished by traditional bus manufacturers in the case of a substantial order. SFMTA's work to assemble a trolleybus procurement consortium is admirable and We also note that while our study focused on **San Francisco, urban transit systems across the US will face the same logistic and technical issues regarding BEB operations and may find the IMC alternative to be superior in their cases as well.**

Towards a Smart Grid

Electric grid features	Depot Charging	Oportunity Charge	In Motion Charging
Demand curve	Could yield to **grid night congestions** in EV high penetration scenario	Better than Depot Charging but high **fluctuant demand** from MV grid	Ideal
Power Quality	Night high demand could yield to **problems** with **voltaje regulation** and **reactive power compensation**	**High flicker levels** in MV grid. Charge over 400 kW would require **in-site storage**. High currents=**EMC** issues	Ideal
Compatibility with California Renewable generation	Solar power is not available in night	Better than Depot Charging	Ideal
Integration of distribute generation	**Difficult** for Solar **photovoltaic**	Difficult because the **high fluctuacting demand**	Ideal

Towards a Smart Grid

Services to the grid	Depot Charging	Oportunity Charge	In Motion Charging
Energy Storage	**Restricted** to the period of night charge	**Restricted** to the period of night charge. High power discharge from flash chargers is not recommended	The energy of the batteries is available during night and operation
Grid Voltage compensation	**Restricted** to the period of night charge	**Restricted** to the period of night charge	DC and AC grid compensation posible during night charging and during operation
Reactive Power and harmonic Compensation	Restricted to the period of night charge	Restricted to the period of night charge	With partially-reversible substations Reactive Power compensation is posible to the grid
Regenerative energy management	Only posible regenerative braking in the bus	Only posible regenerative braking in the bus	Regenerative braking in the bus, regenerative braking to DC, Regenerative braking to AC