Methods for Product Development and Mechatronics

Simulation-Based Bus Electrification Planning

The modular eflips-x framework

Lu Heide (Speaker)

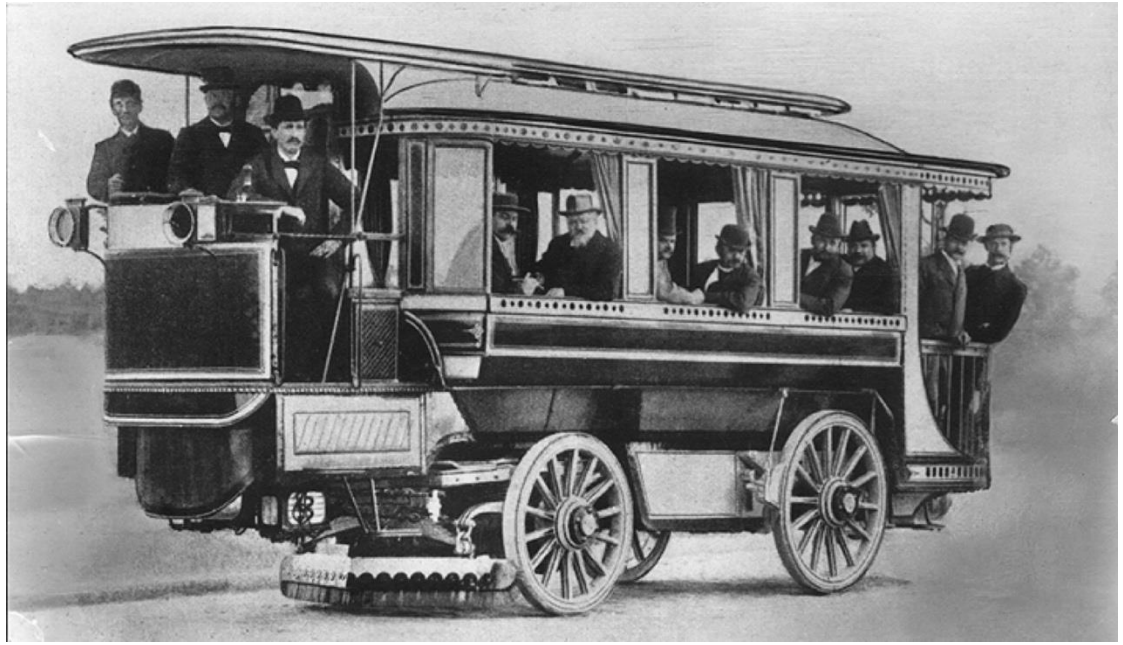
Developed by Lu Heide, Shuyao Guo, Dominic Jefferies and Dr. Enrico Lauth

www.tu.berlin/mpm/

Motivation

- E-buses exist since the 19th century
- Modern, Li-Ion based battery buses have been widely deployed for a decade
- However, a simple replacement strategy leads to significant operational inefficiencies
- Data from China: To replace one diesel bus, 1.5 to 2 e-buses are needed

- Do we need gigantic batteries?
- Or can a systematic approach create feasible electrification strategies with current technology?



Battery-Electric bus in Berlin, 1898

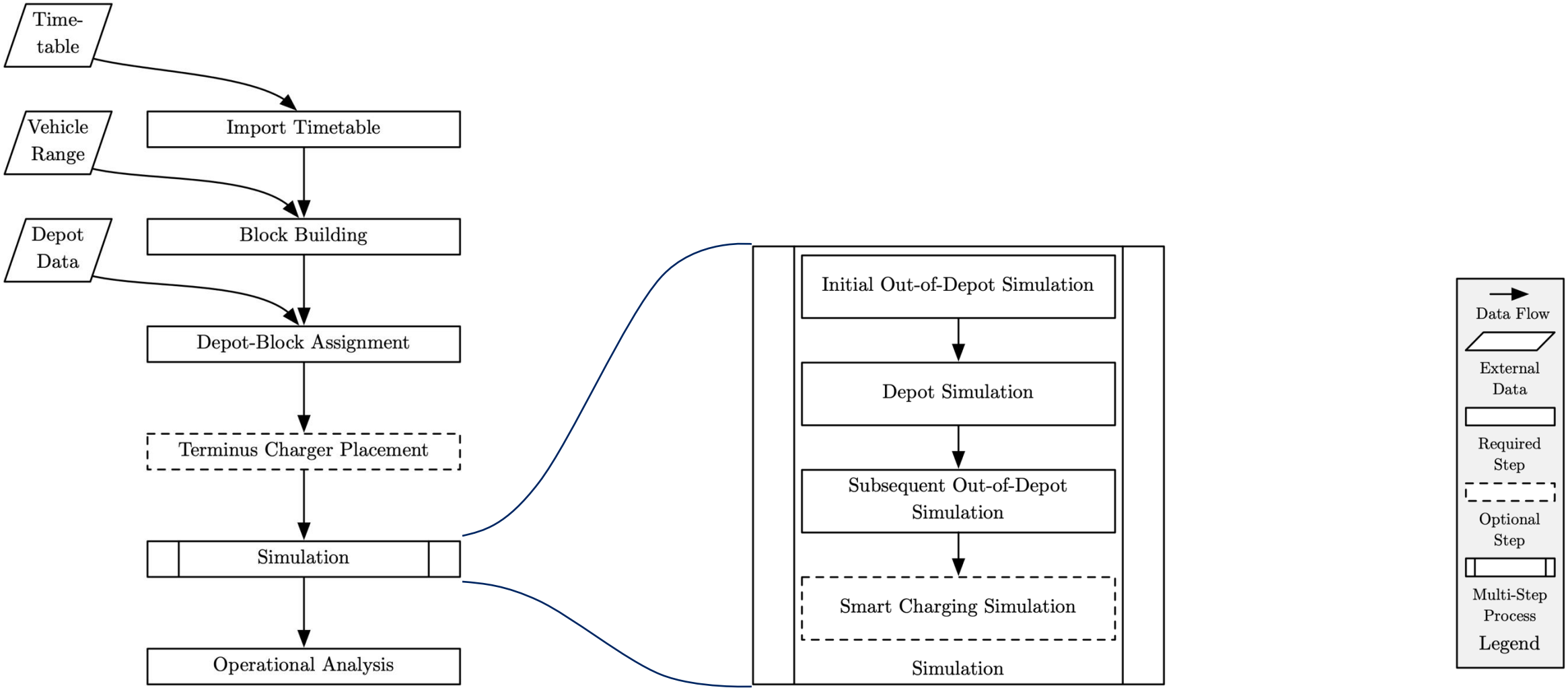
Planning an e-bus network

Overview

- Assumption: Customer-facing schedule is maintained

1. Research
   - Possible Vehicle Types, Battery Capacities and Energy Consumption
   - Grid Availability
2. Scenario Development
3. Simulation-based system planning
4. Cost & environmental analysis

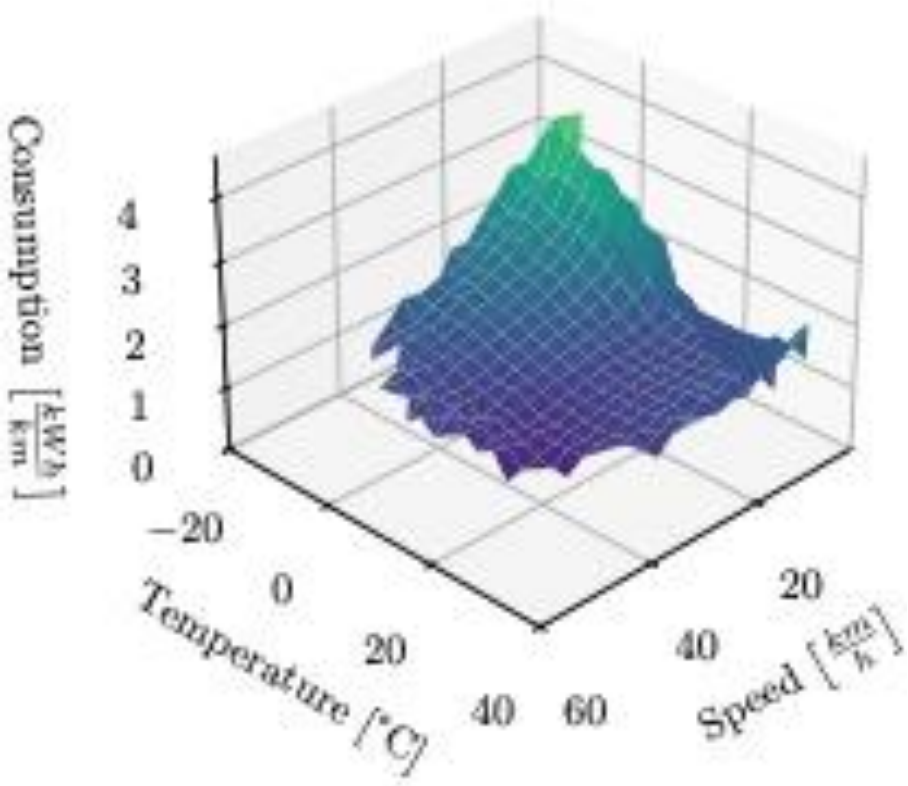
Simulation Framework



Range Estimation

- Ranges are usually presented for standardized test cycles, such as „Standardized On-Road Test“ (SORT)
- To design a reliable network, we need *worst-case* performance, not some average
- Performance mainly depends on temperature, slope and speed profile

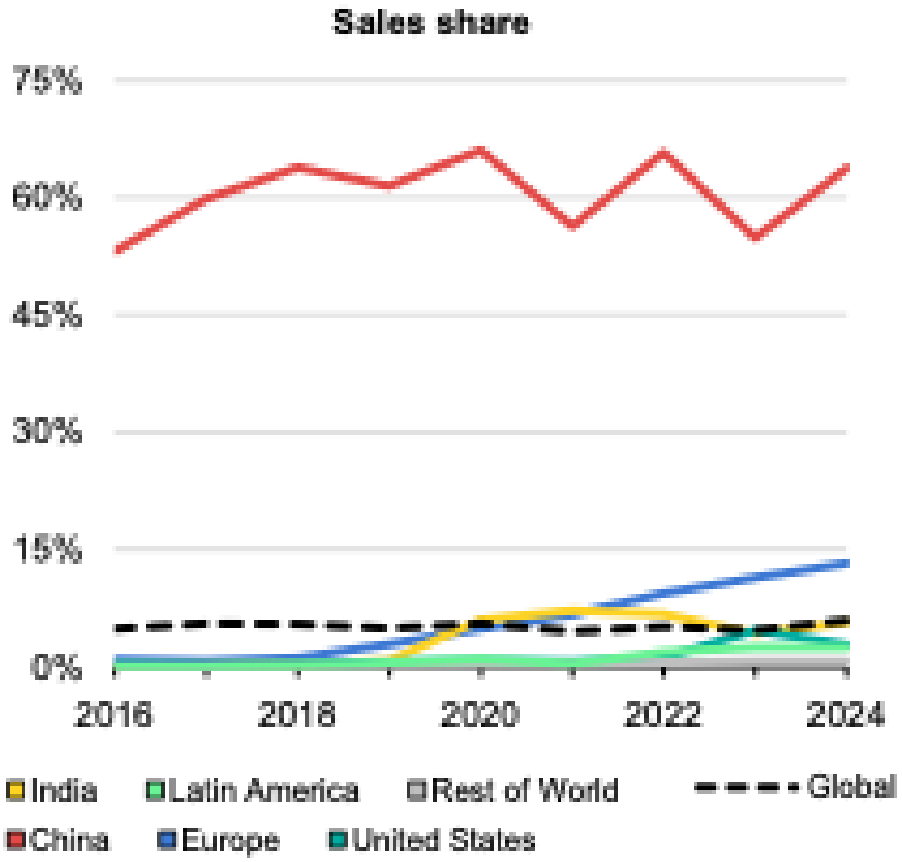
- **Suggestion for Operators: Equip vehicles with telemetry equipment to gather data for the e-bus transition**



Measurements from one year of e-Bus operation in Berlin

Vehicle Types, Battery Capacity and Range

- The electric bus market's maturity differs greatly by region, with China leading and Europe catching up
- However, maturity also varies greatly by the type of bus
  - Small (10m) & Standard (12m) buses
    wide availability
    ~100–600 kWh battery, 150 – 600 km range
  - Articulated (18m) buses
    fewer models
    ~120–800 kWh battery, 200– 600 km range
  - Double Decker buses
    limited availability
    smaller ranges due to less space for batteries
  - Double-Articulated Buses
    extremely limited availability (Volvo, Curitiba)



Electric Bus Sales Share. Source: IEA Global EV Outlook

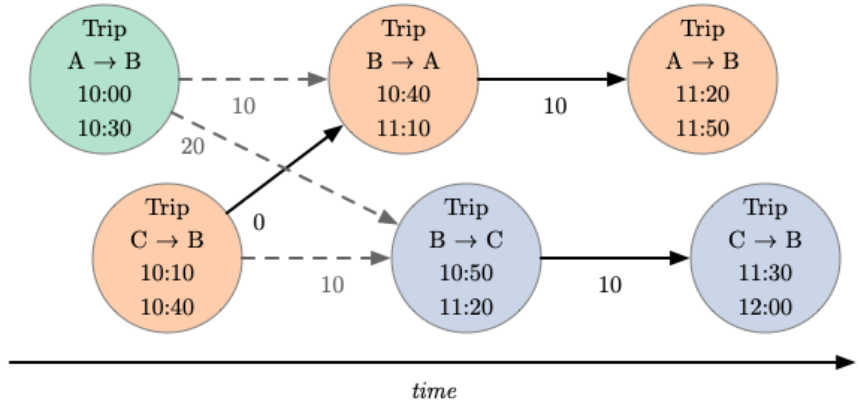
Scenario Development

- Based on available battery capacities and terminus charging, multiple electriciation scenarios should be explored.
- Using this, key trade-offs can be explored
  - Smaller batteries needing terminus charging or more vehicles
  - Maintaining existing operational schedules or optimizing planning for e-buses

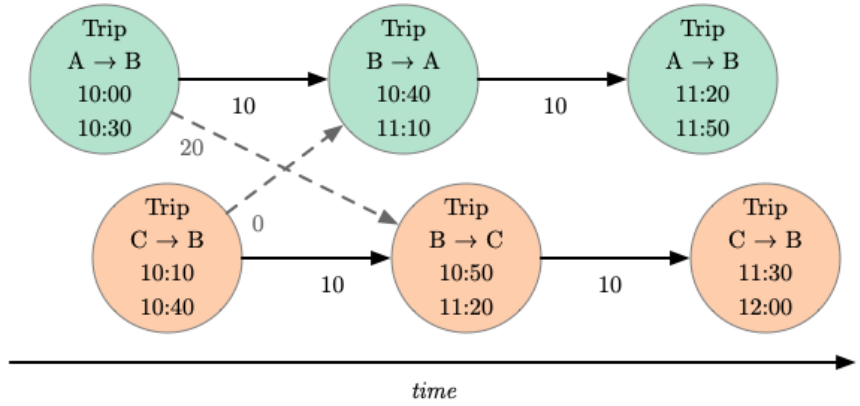
	Existing Blocks Unchanged	**Depot Charging Only**	**Small Batteries + Terminus Charging**
Battery Capacity	Large	Large	Small
Terminus Charging	Allowed	Not allowed	Allowed
Vehicle Scheduling	Existing	Optimized	Optimized

Block Building

- Block: Sequence of Journeys (sometimes also known as „Vehicle Schedule“)
- The simplest schedule has each bus going back and forth between a single line‘s termini for the whole duration of the shift
- However, interlining often significantly improves operational efficiency
  - Buses run on different lines
  - Are charged at central locations while not in service
  - Block duration is matched to battery capacity for optimum utilization.



3 buses are needed



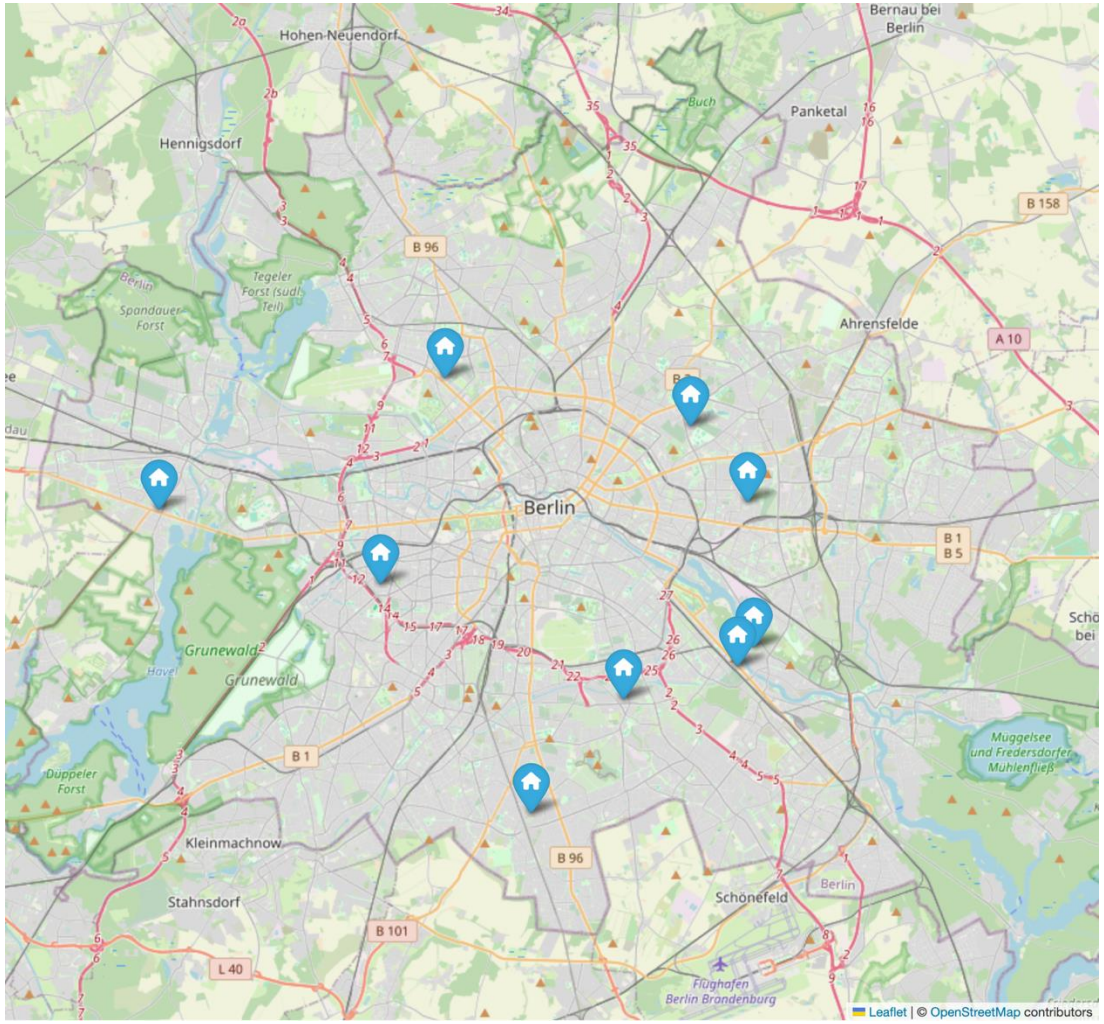
Here, only 2 buses are needed

Depot Assignment

Definitions

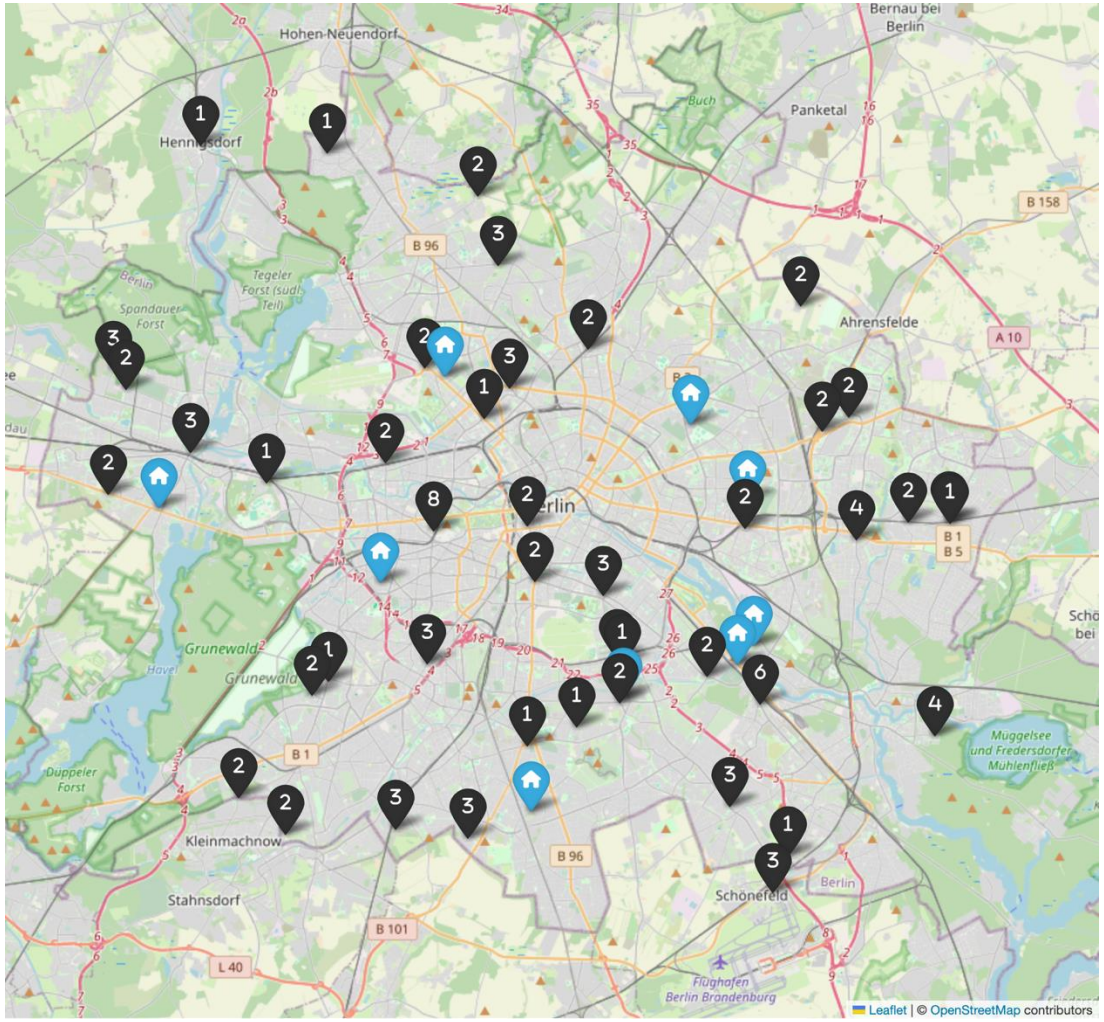
- **Depot:** Off-Route place where long charging breaks take place
- **Electrified Terminus:** In between trips, the bus takes a short charging place at the end of a route

- Electrification often requires changes to the placement of depots in the city
- Which blocks are served from which depot?
- Optimization
  - Respects depot capacity limits
  - Respects vehicle type or operator restrictions
  - Minimizes total deadhead duration



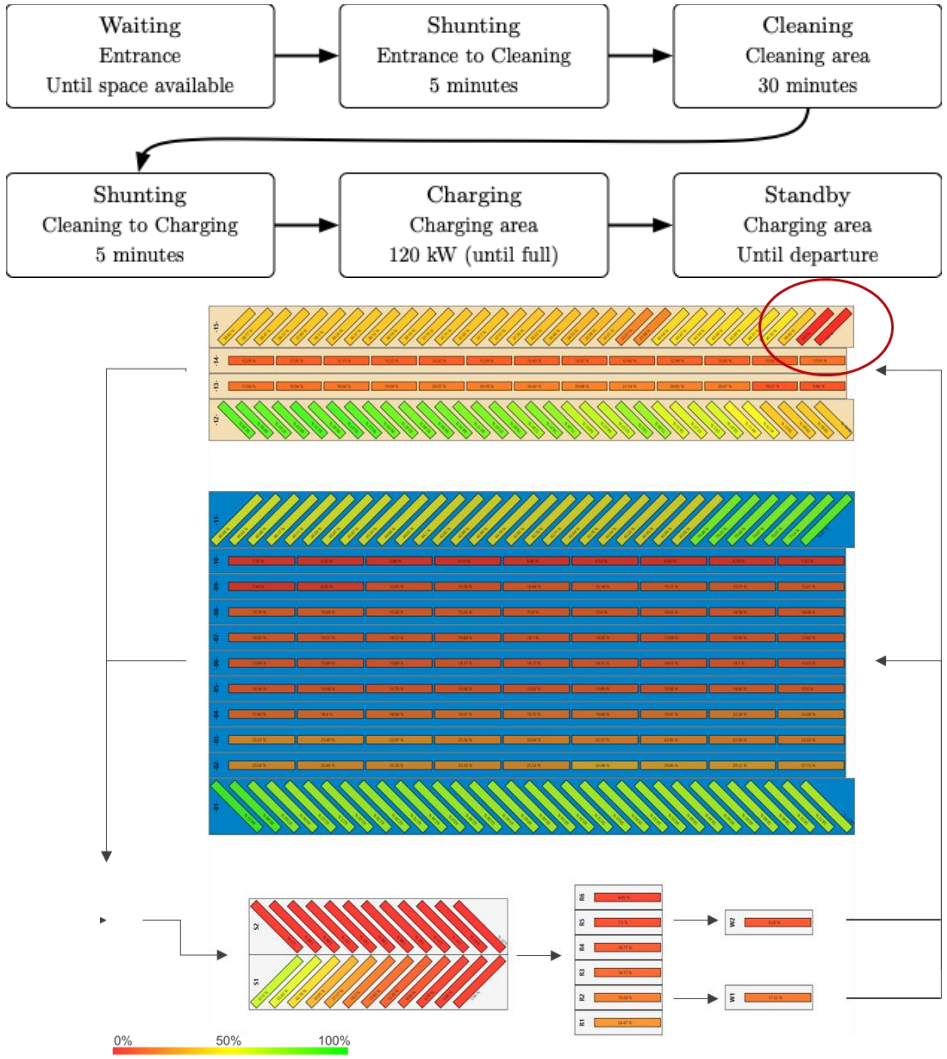
Terminus Charger Placement

- Some blocks may not be possible without a charging stop outside the depot
- Where to place the chargers?
- Iterative approach
  1. Are there any blocks with critical battery state?
  2. Place the charger where the vehicles with critical battery state have the longest standing time
  3. Continue placing charger until no vehicle has an empty battery
- How many chargers at each terminus?
  - We use a realistic (but not optimal) approach where vehicles charge whenever they can, but wait if all chargers are occupied and there is time



Depot Simulation

- Process-based discrete event simulation of depot behavior
- Configurable processes and areas
- Smart heuristics for parking and dispatch
- Block coupling
  - What the vehicle does outside the depot is fixed
  - Inside the depot, the vehicle charges, then goes on ist next trip
  - Therefore, what the vehicle does throughout the week – and the total vehicle count – are only known after depot simulation.



Economic & Environmental Analysis

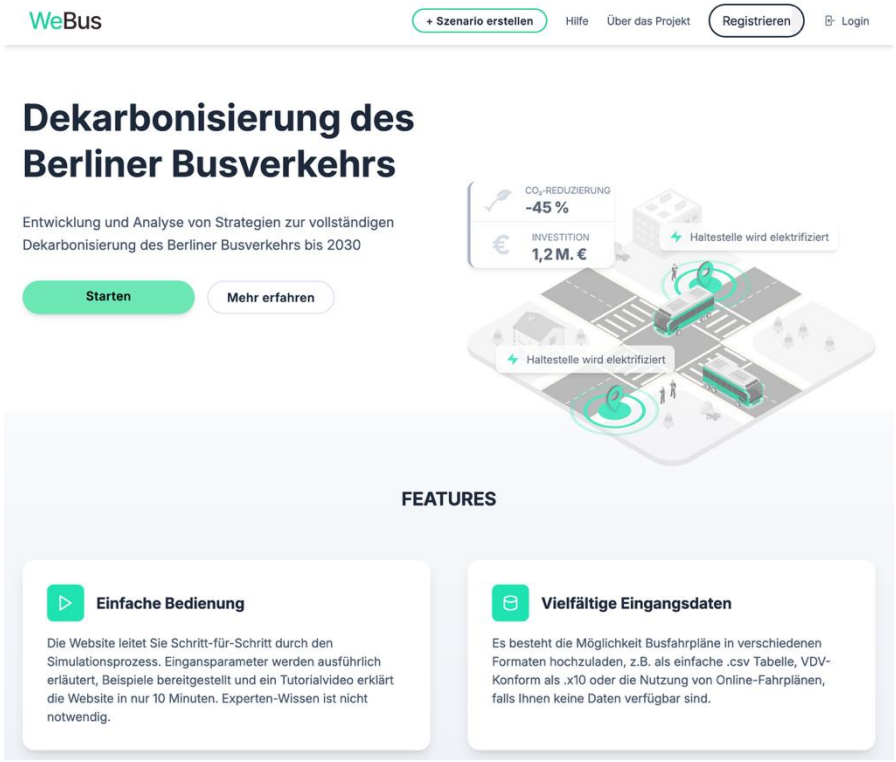
- After the simulation is complete, we know
  - How many vehicles are needed
  - The depot layout
  - The locations and numbers of electrified termini
  - The energy consumption

- With this information, we can
  - Calculate the total cost
  - Calculate the environmental impact *(coming soon...)*

Open Source Availability

- All code is available as Free Software under the AGPLv3 license
- However, it is not easy to run for everybody
  - Schedule Import from GTFS is missing
  - Documentation is not great

- Two-pronged strategy for increasing accessibility
  - *eflips-x* command line tool
  - *WeBus* simplified graphical interface

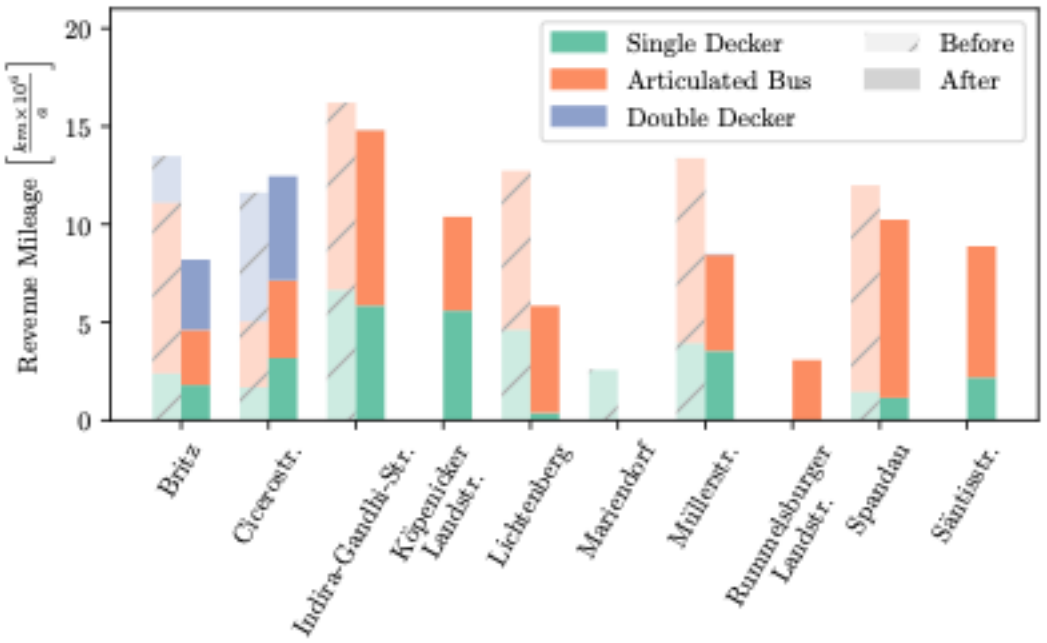


Reiner Lemoine Institute‘s upcoming *WeBus* platform

BVG Case Study

Scope

- The Berlin bus operator BVG is the largest operator in Germany
- Totally ~1.500 buses split over 7 depots
  - 1179 operational buses considered
  - Caution: Only ~90% of total buses are operational at any give moment
  - With electrification, one depot will be closed and three new ones added
- Customer-facing schedule should be maintained



Scenario Development

- Based on discussions with BVG, three vehicle types and scenarios were chosen
- These reflect the outer edges of the possible electrification envelope, compromise solutions in between some of these scenarios are also possible

	Existing Blocks Unchanged	Depot Charging Only	Small Batteries + Terminus Charging
Battery Capacity	Large	Large	Small
Terminus Charging	Allowed	Not allowed	Allowed
Vehicle Scheduling	Existing	Optimized	Optimized

	Single Decker	Double Decker	Articulated Bus
			
Reference Model	Ebusco 3.0 12	Alexander Dennis Enviro500EV	Solaris Urbino 18 electric (2023)
Battery Capacity	500/250 kWh	472/320 kWh	640/320 kWh

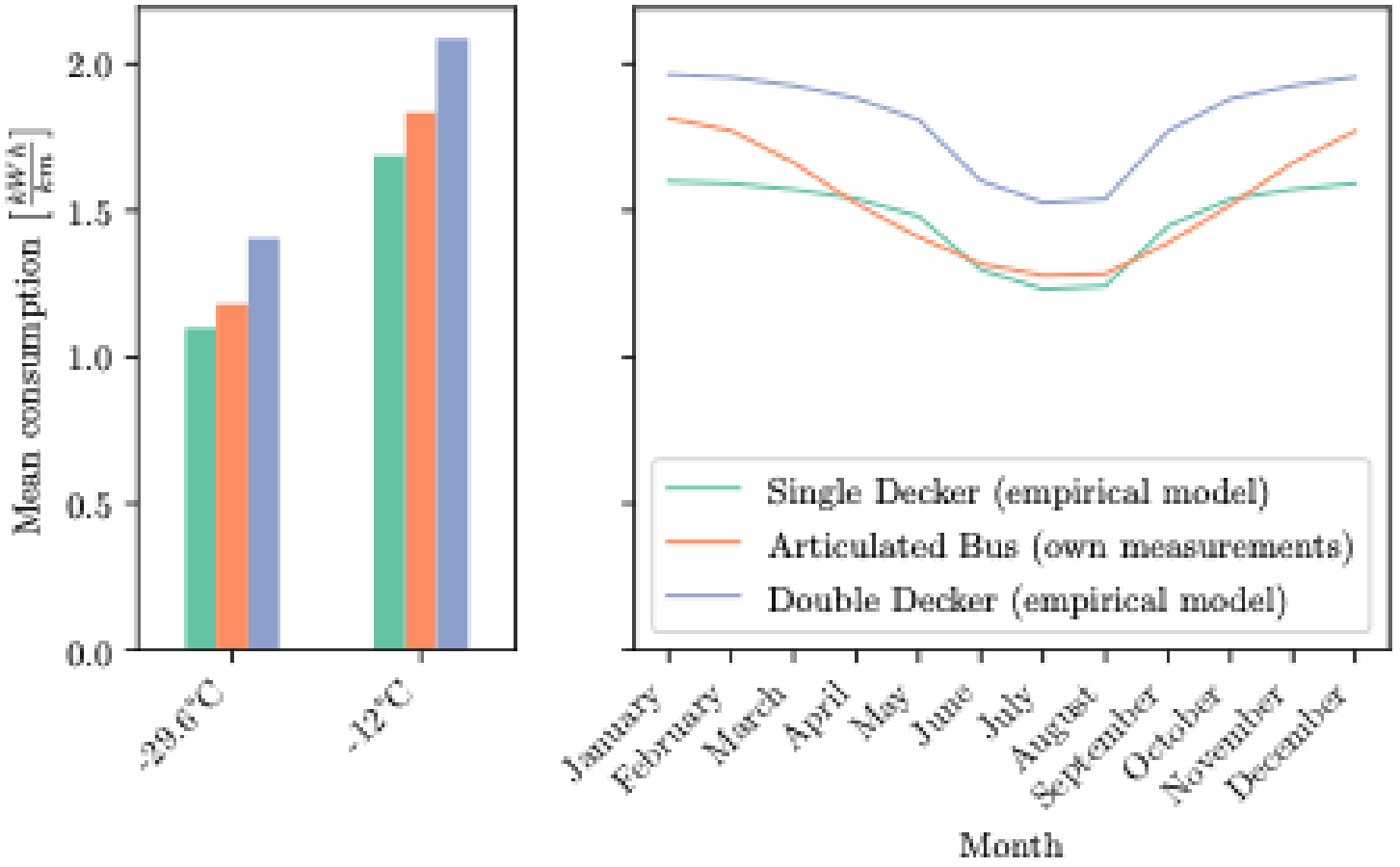
Vehicle Scheduling

- One scenario with the original schedule, two with new schedules
  - Depot Charging Only: Limit schedule duration to not exceed battery capacity
  - Small Batteries + Terminus Charging: Allow arbitrarily long schedules
- Results show similar efficiency to original blocks
- Block count is where longer blocks are allowed, higher if distance is limited

	Schedule Efficiency	Number of Blocks
Existing Blocks Unchanged	73.4%	8498
Depot Charging Only	74.2%	8794
Small Batteries + Terminus Charging	71.2%	8203

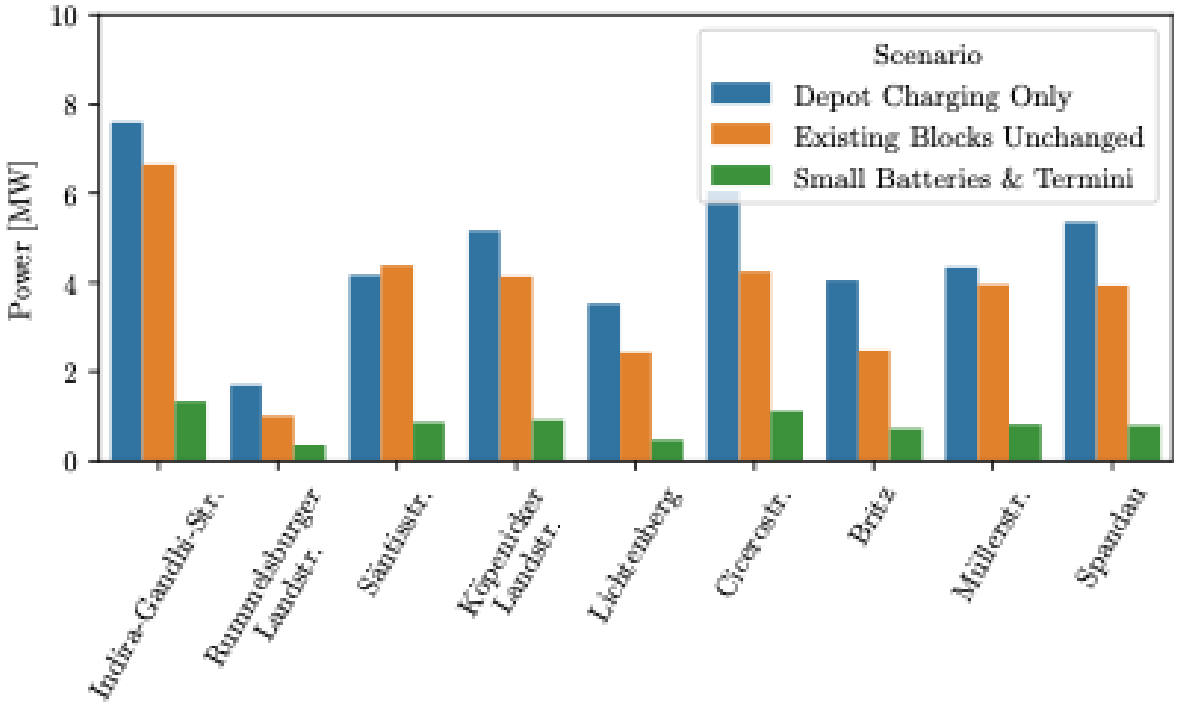
Results

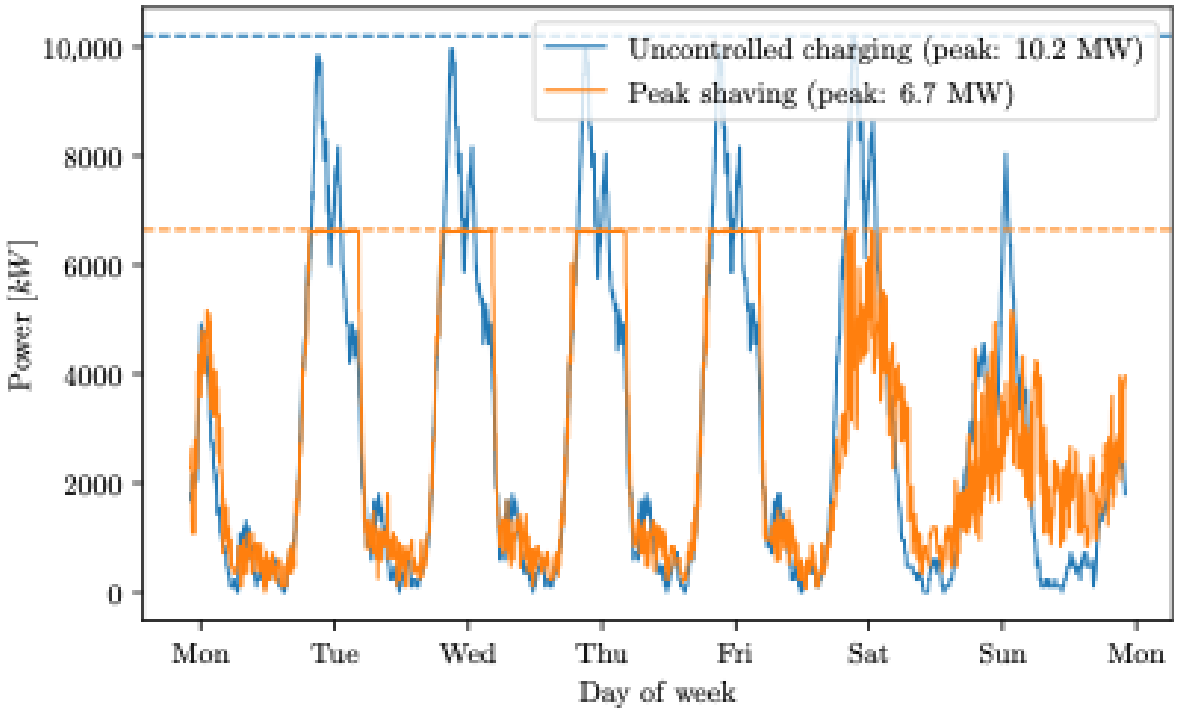
Energy Consumption



Results

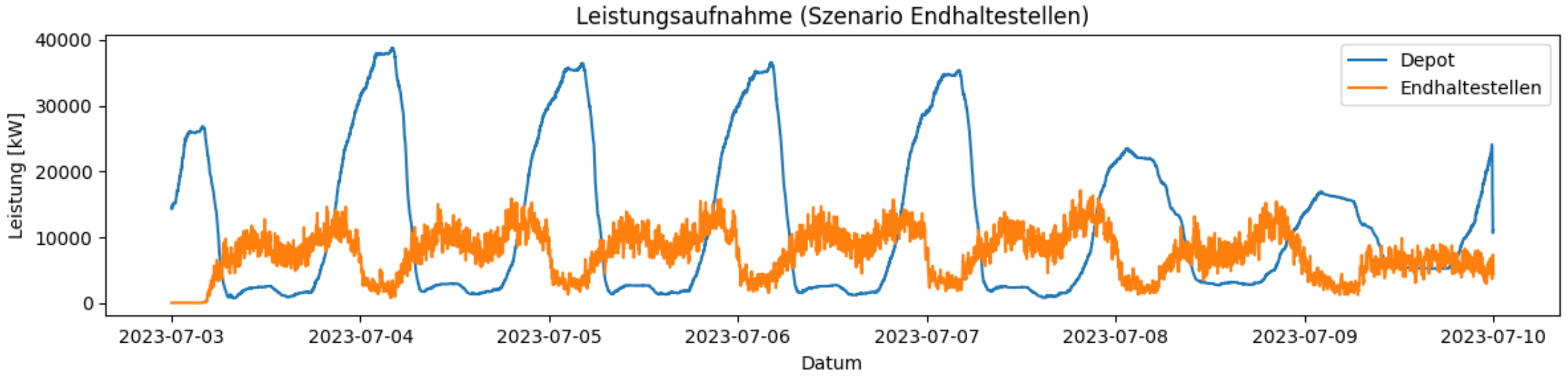
Depot Power





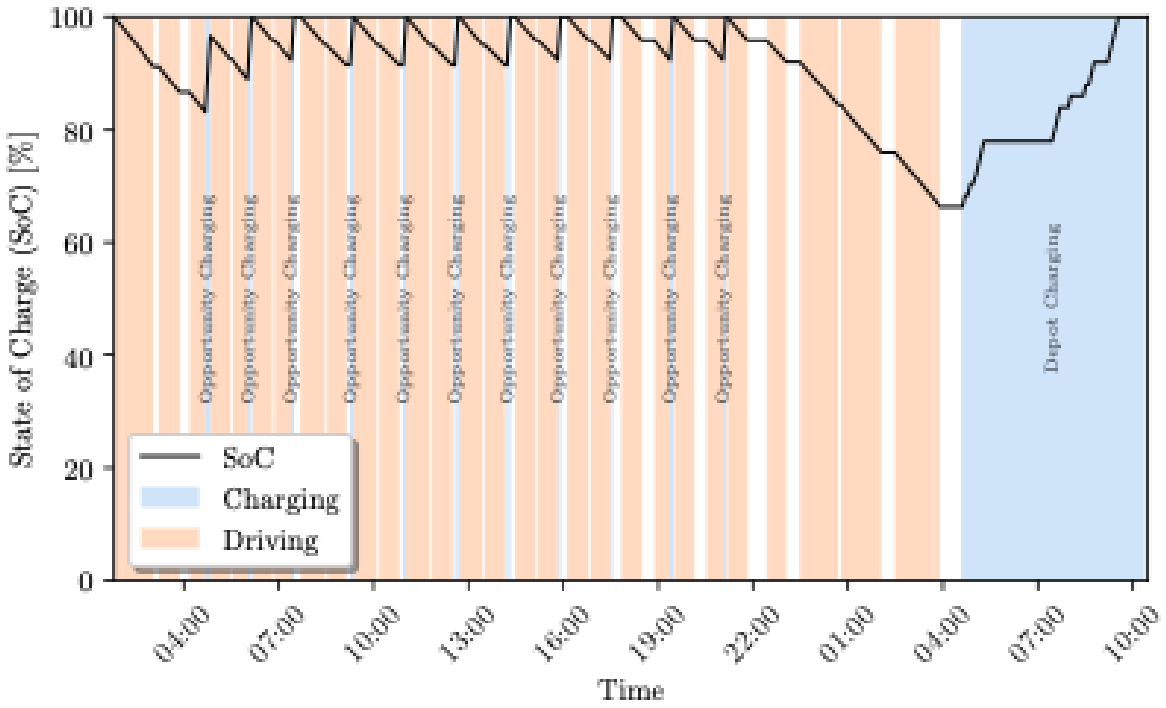
Impact of Depot vs. Terminus Charging

- Choice of Terminus or Depot Charging changes when the energy is consumed
- This can be used to optimize for power grid or renewable electricity generation
  - Minimize power grid demand by pushing charging to times with low residential usage?
  - Minimize CO2 emissions by charging when solar energy is available?
- Also, there is a tradeoff between peak grid power and charging flexibility

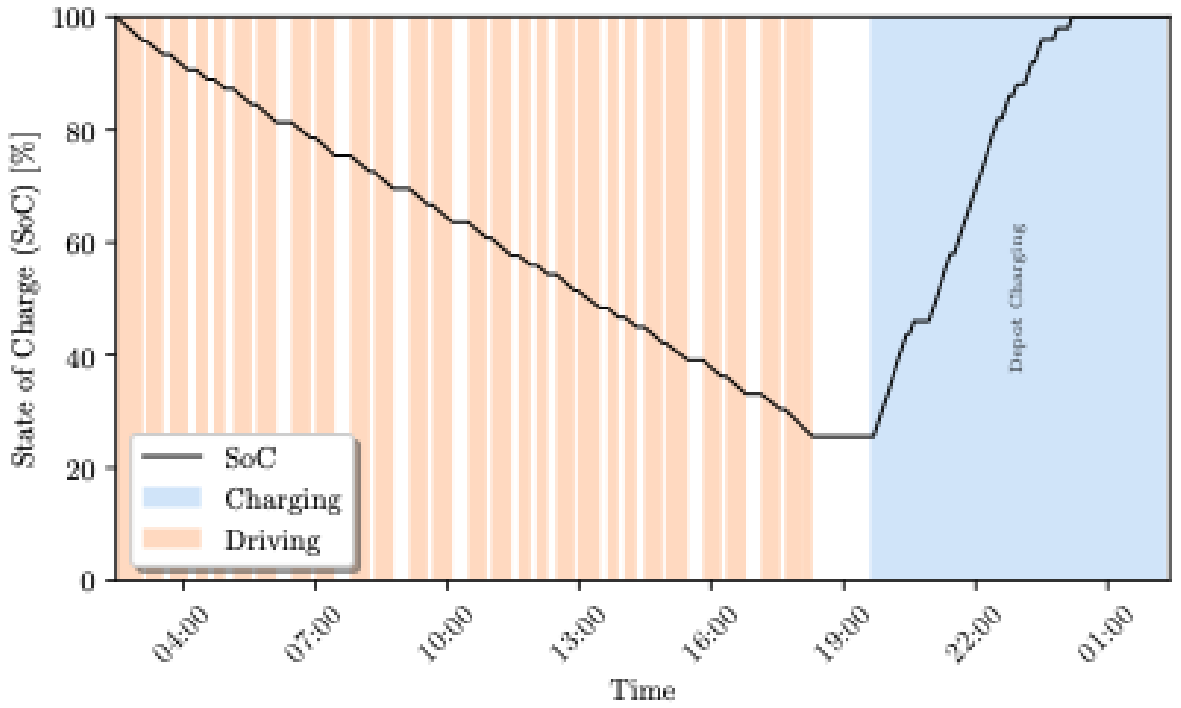


Results

Example – What does one vehicle do?



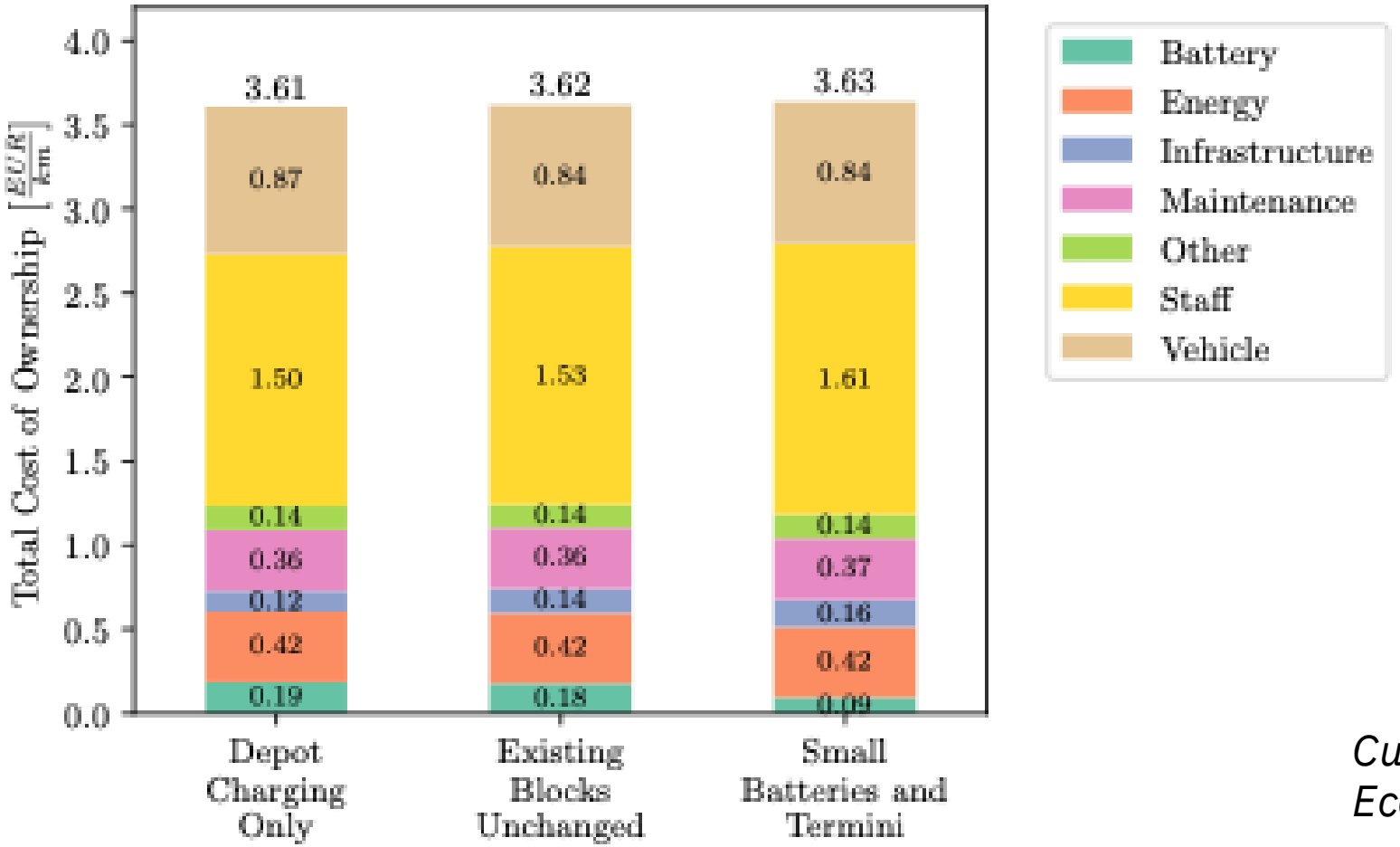
With Terminus Charging



Depot Charging Only

Results

Cost Analysis



Currently in Progress: Ecological Assessment

Key Learnings

- „1-for-1“ replacement is not the best plan du to the needed battery size
  - If done smartly, it can be done with less than 10% more vehicles
- Accurate estimation of energy consumption and definition of „worst case“ temperature where system should still operate normally
  - This has the most direct impact on how many buses and chargers are needed
- System design has significant impact on temporal and spatial distribution of energy demand
  - Electric buses are „storage systems“ from a grid perspective
- Range-aware block building, interlining and optimized depot assignment raise efficiency

How to apply this to Brazil?

Scenario Development

- Which stakeholders exist and how are they connected?
- How does a „charging operator“ fit into the existing stakeholder mapping?
- (How?) does the current framework constrain interlining and depot assignment?

- Develop possible future scenarios
  - What vehicles, depots and terminus charging configuration is realistic?
  - What organizational changes could be made?

Simulation

- Data collection
  - Energy consumption of existing e-buses
  - High-Resolution Speed Profiles
  - Schedules/Headways
  - Depot Locations
- Technical Specifications for the different scenarios
- Simulation & Evaluation