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Life Cycle Assessment Tool for Clean Bus Technologies

Final Trolley 2.0 Conference
12.11.2020

Introduction and Motivation

Transition towards clean vehicles between 2021 and 2031

- „Clean Vehicle“: bio and synthetic fuels
- „Zero-emission heavy duty vehicle“: electric vehicles + Clean PtX
- 28-45% of procurement from 2021 to 2026
- 38-65% of procurement from 2026 to 2031
- Half of clean vehicles must be zero emission vehicles

However: Costs are highly dependent on environment, operation and technology

Goals:

- ➢ Develop a methodology that can help decision makers and operators choose the best technology for their system
- ➢ Show the impact of individual parameters on the system
- ➢ Demonstrate the importance of case-by-case analysis

Total Costs Hybrid Trolley Buses

- **Investment**
  - Vehicles
    - Initial Investment
    - Reinvestment
    - Modernisation
  - Batteries
    - Initial Investment
    - Reinvestment
  - Catenary / Charging Infrastructure
    - Initial Investment
  - Energy / Power Supply
    - Initial Investment
- **Operation**
  - Vehicles
  - Catenary / Charging Infrastructure
    - Refurbishment Masts
    - Refurbishment Catenary
  - Energy / Power Supply
    - Operation of Substation
- **Energy**
  - Vehicles
    - Traction Energy
    - HVAC

Vehicle and Battery Investment

- Total Investment Battery
  - Initial Investment Battery
    - Required Size of Battery
    - Specific cost per kWh
      - Battery Type
  - Battery Reinvest
    - Lifetime of battery
    - Required Battery size
    - Specific Cost per kWh

- Total Investment Costs Vehicles
  - Initial Investment Vehicles
    - Cost per Vehicle
      - Size of Bus
      - Type of Bus
    - Number of vehicles
      - Velocity w/o catenary
      - Velocity w/o catenary
      - Line frequency
      - Length of Line
  - Reinvestment cost
    - Lifetime of Buses
    - Number of required vehicles
    - Cost per Vehicle
  - Modernization cost
    - Modernization cost per Vehicle
    - Number of vehicles

Infrastructure Investment

- Total Investment Infrastructure
  - Total Investment catenary
    - Cost per km of catenary
    - Km of catenary
      - % of line with catenary
      - Length of Line
  - Total Investment Substations
  - Additional components
  - Planning
  - Safety

- Total Investment Substations
  - Cost per kW
  - Power per substation
    - Max Power per vehicle
      - Maximum traction power
      - Battery charging Power
      - Maximum HVAC power
    - Distance between substations
    - Distance between Vehicles
  - Number of Substations
    - Length of Line
    - Distance between substations

What Bus System to go for?

Two Scenarios:

1. Available Infrastructure:
   Conversion of Diesel lines
   Extension of trolley lines to hybrid-trolley bus lines
2. New construction
   Electrification of diesel networks

Observed Technologies: Diesel, Trolley, Hybrid-Trolley, Depot/ Opportunity Chargers

Central Questions:

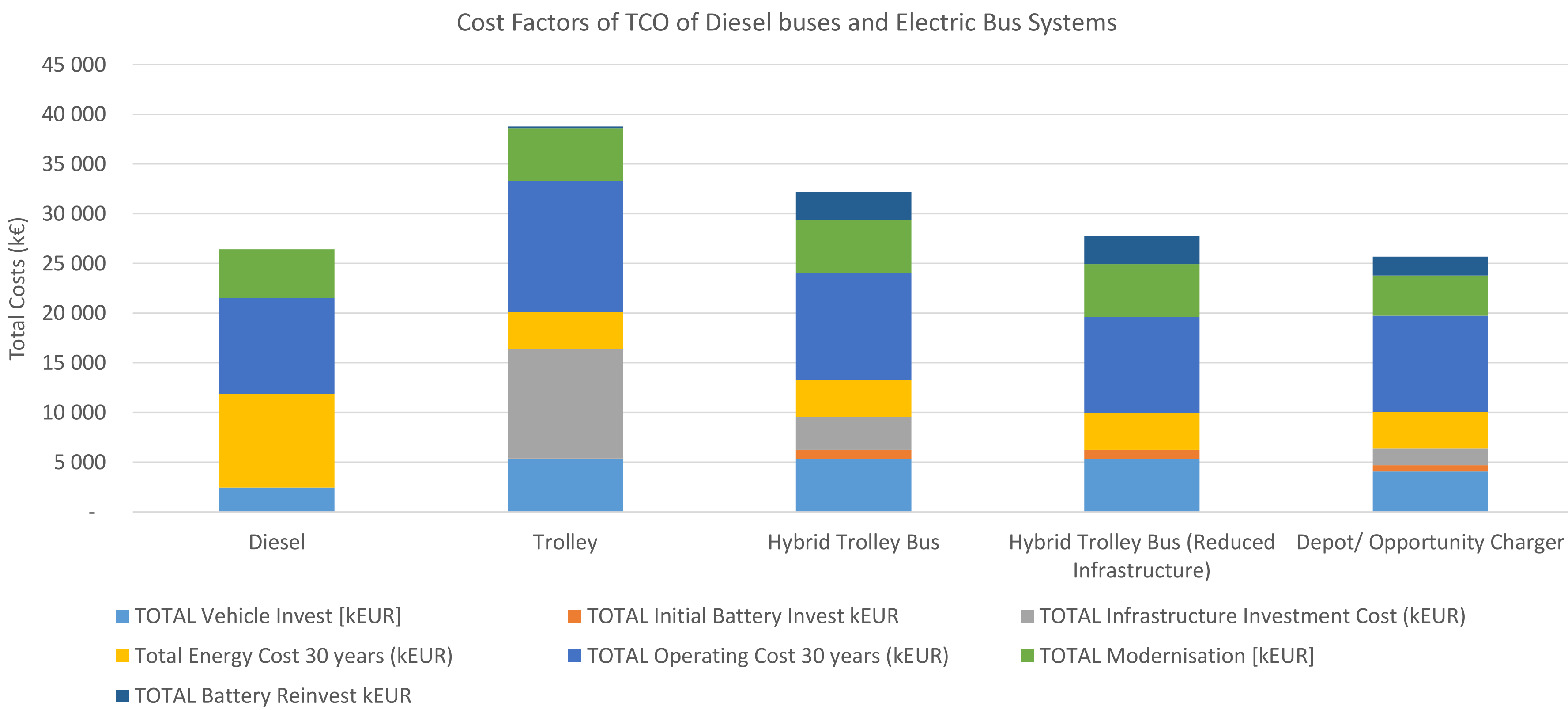
What lines are good candidates for electrification?

What are the key parameters?

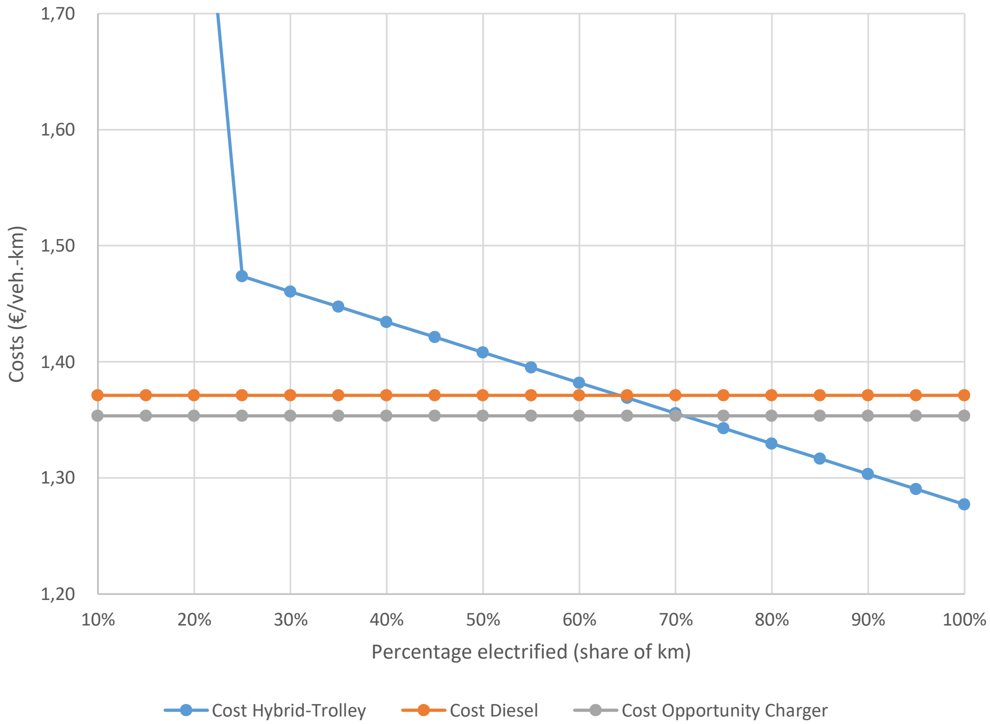
What are the effects of developing a network?

What is the best electrification option?

Total Costs over 30 Years

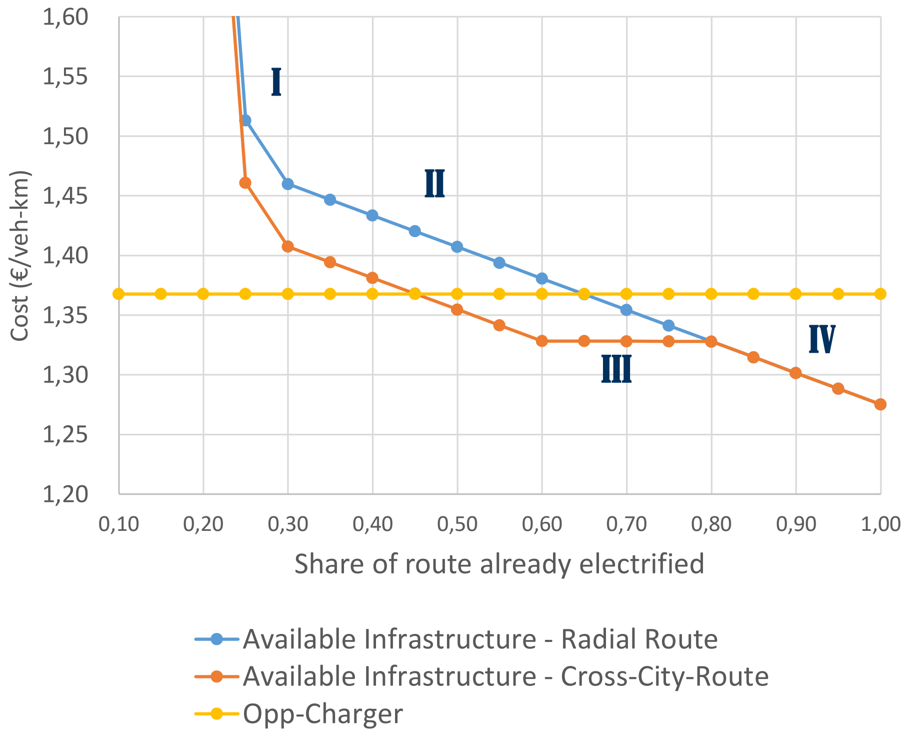


Available Infrastructure (I)



- Baseline case: 15 km line, 15 min vehicle frequency, 19 km/h, 18 m Bus
- At low electrified shares, the bus requires large batteries driving up costs
- Cost parity with diesel buses is achieved, when the diesel bus drives 60% under available infrastructure
- At 65%, the bus achieves cost parity with an opportunity charging bus
- Challenge: High investment costs of vehicles, low line frequency of buses.

Available Infrastructure (II): Route Type



I
A low share of electrified route makes the calculation adopt a large battery.

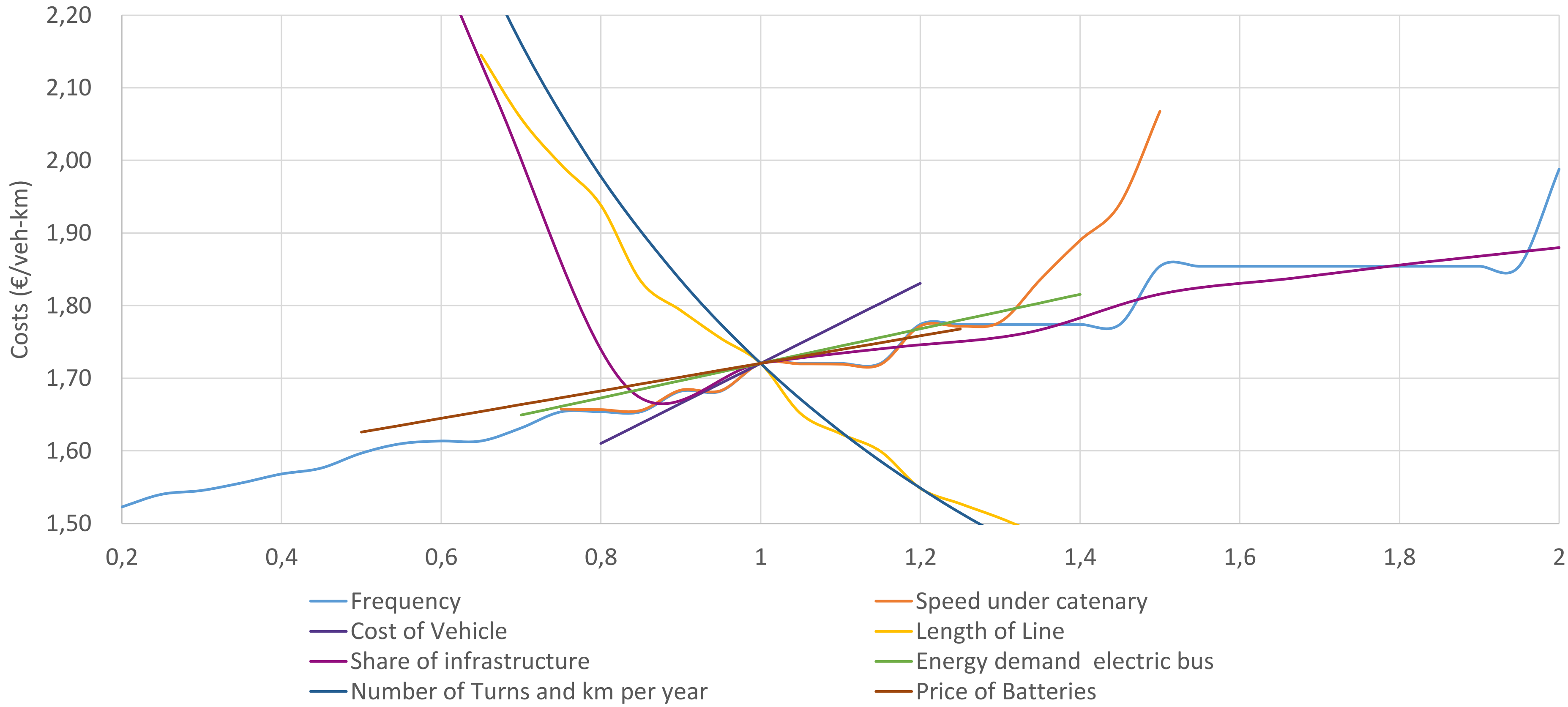
II
Increasing the share of electrified route, causes a linear decline of costs

III
Longest section now fixed and battery sized accordingly

IV
Increased share now also decreases final section

- Between 65% and 70% required to electrify the radial route below the cost of an opportunity charger
- Only 45-50% of available infrastructure required for cross-city route
- Reason: Total distance driven on battery on route is equal, but the longest section is shorter on the cross-city route

New Construction of Infrastructure: Assessing Key Parameters



„Optimizing the Situation“ for Hybrid Trolley Buses

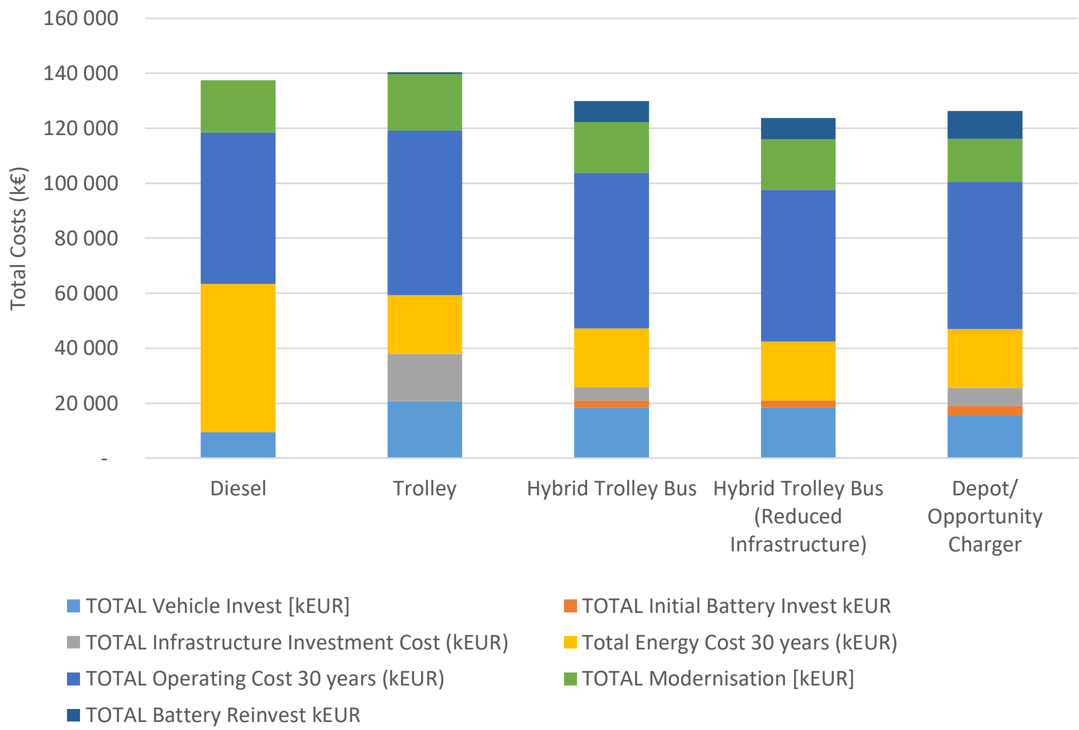
Line Parameters:

- Increase Vehicle Frequency to 5 minutes per vehicle
- Increase Line length to 20 km
- Distribute catenary free sections evenly
- Decrease speed under catenary
- Increase number of yearly km to 100.000 km (from 270 km/d to 300 km/d per vehicle)
- 30% electrified

Vehicle Parameters

- Decrease vehicle investment cost by 10%
- Increase Diesel consumption to 50 L/ 100 km (from 40 L/ 100km)
- Decrease charging time for Opportunity Chargers from 10 Min to 7 Min

Total Costs over 30 Years „Optimized Scenario“



	Baseline (€/ veh-km)	Optimised (€/ veh-km)	Cost Reduction
Diesel	1,37	1,25	-9%
Trolley	2,03	1,29	-36%
Hybrid-Trolley	1,69	1,19	-30%
Hybrid-Trolley (RI)	1,46	1,14	-22%
Opportunity Charger	1,35	1,16	-14%

Conclusions and Summary

What lines are good candidates for electrification?

- Cross-city lines below catenary infrastructure are excellent candidates for conversion
- Normally, diesel buses under catenary infrastructure should be electrified
- For lines with available infrastructure, ~250km per day, for new construction ~300 km under optimal conditions

What are the effects of developing a network?

- If no new infrastructure is necessary, hybrid trolley networks lower the cost per bus and are often the best option

What are the key parameters?

- Daily mileage, speed, line length, share of available infrastructure layout, cost of the vehicle and time at end stops

What is the best electrification option?

- Hybrid-trolley buses can be the best option, even for new trolley bus networks, when lines have a long annual mileage, they are constructed in high traffic areas and the layout benefits them
- Opportunity chargers the cheapest option in many cases but can suffer from deficits when not enough charging time is available
- Keep in mind: The graphs shown represent <u>one layout or one parameter change!</u> Parameters also influence each other.
- The focus must lie in optimizing all factors in the system, there is no "silver bullet".
- Case-by-case analysis remains important

Thank you

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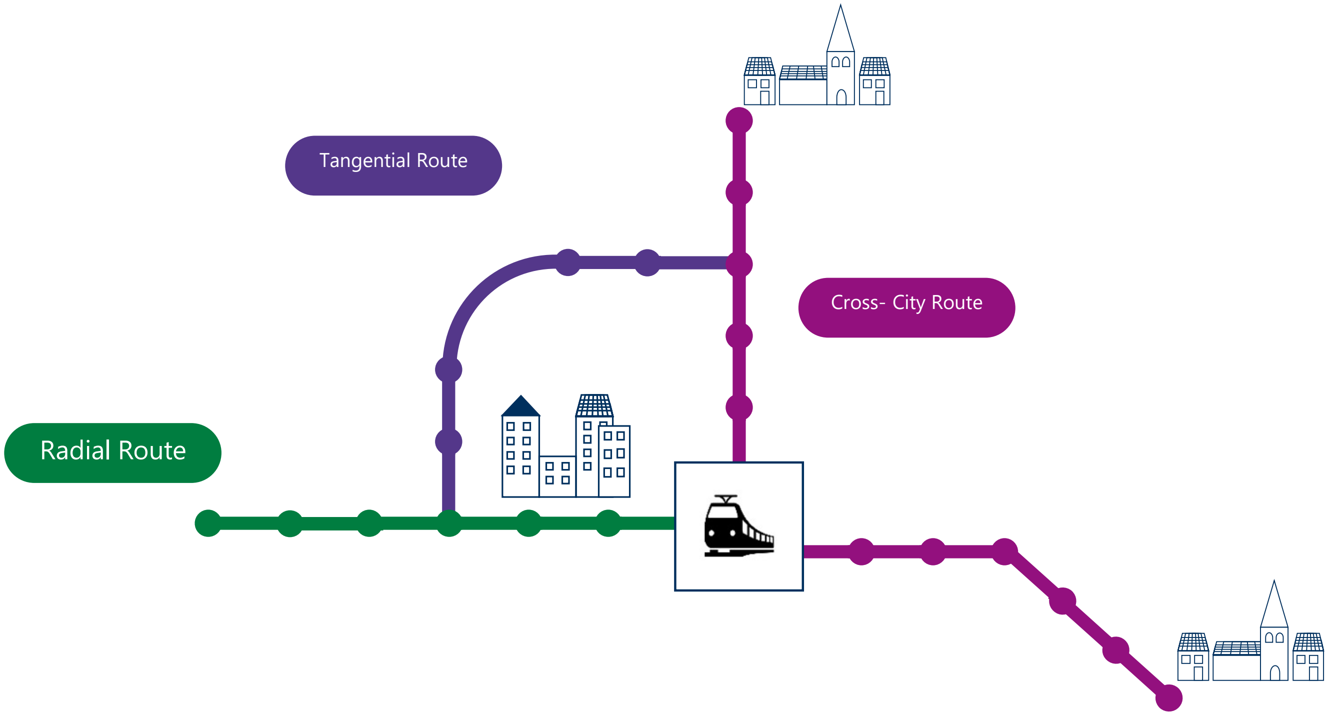
Types of routes and challenges for selecting the correct layout



Tangiential Route:

Route going around heavily populated areas

Radial Route:

One endpoint at a central hub of a city

Cross city route:

Connections of suburbs through a city

Methodology Overview

Line and Operational Data

- Line length, operational speed, number passengers, frequency, nominal network voltage

Vehicle Data

- Capacity, specific energy demand, traction and HVAC power demand

Infrastructure Data

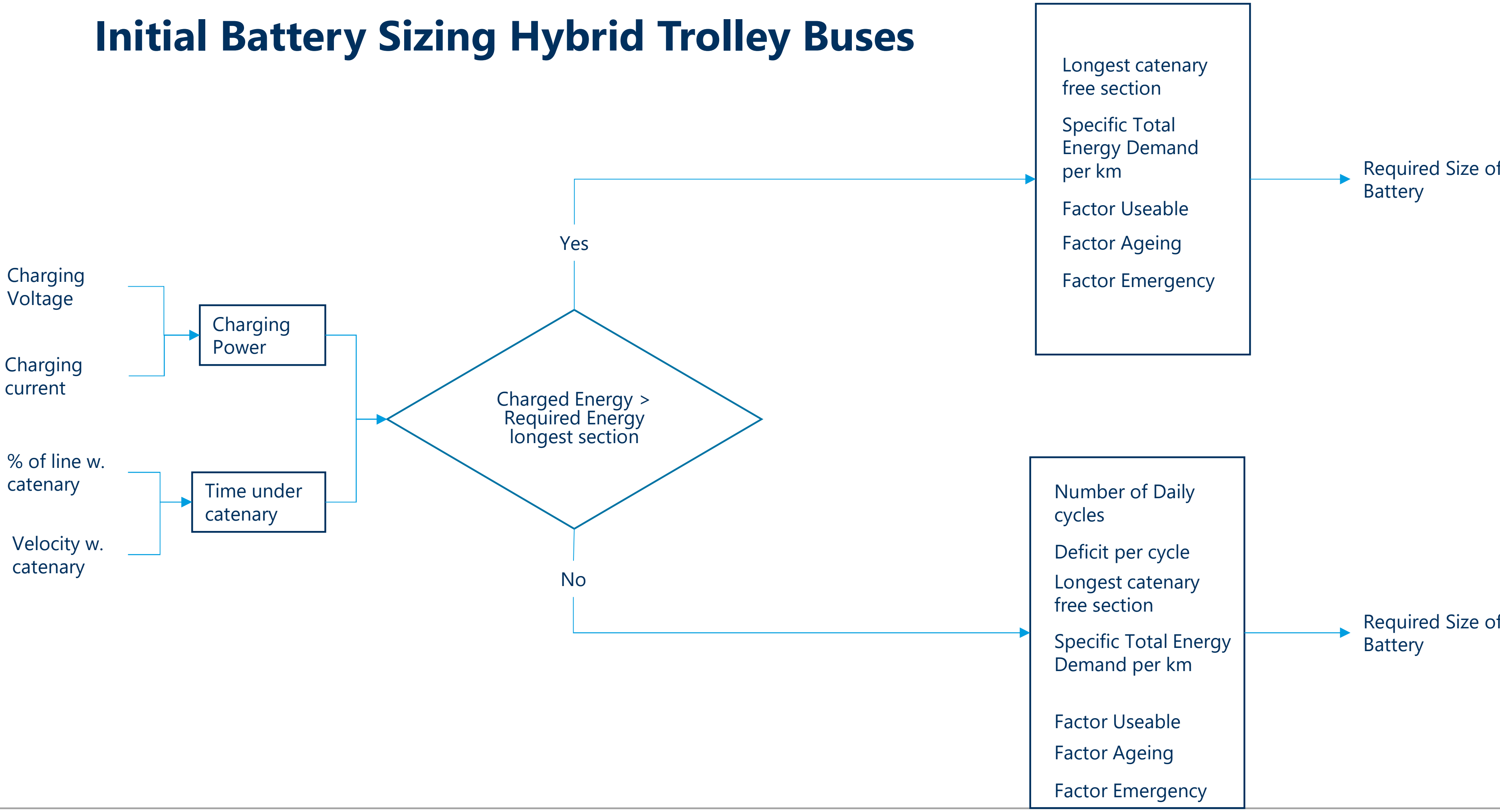
- Components such as transformers and rectifiers sized according to vehicle traffic under the line

Battery Data

- Battery types, charging behavior and costs

Input Data from measurements, simulations and literature

Initial Battery Sizing Hybrid Trolley Buses



Vehicle Energy and Operation Calculation Overview

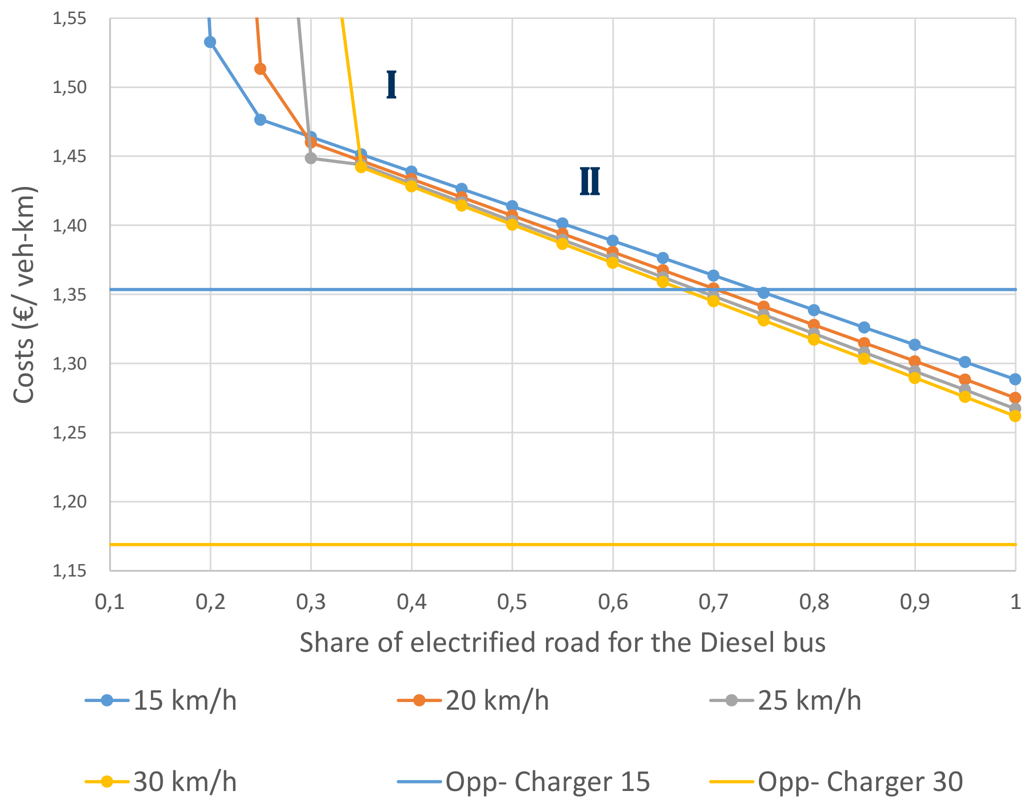
- **Total Traction Energy Demand**
  - Required Traction Energy Demand per km
  - km per year
    - Number of cycles per day
    - Operating days
    - Length of Line

- **Total HVAC Energy Demand**
  - HVAC Energy Demand
    - Operating time per cycle
      - Time without catenary catenary
        - Velocity w/o catenary
        - % of line with catenary
      - Time under catenary
        - Velocity with catenary
        - % of line with catenary
    - Average HVAC Power Demand
    - Number of cycles per day
    - Operating days

- **Operating Cost Infrastructure**
  - Operating Cost Masts
    - Length of Line
    - Number of Masts
    - % of line with catenary
  - Operating Cost Overhead Wire
    - Length of Line
    - Number of wires
    - % of line with catenary
  - Operating Cost Substations
    - Number of Substations

- **Operating Cost Vehicles**
  - km per year
    - Length of Line
    - Operating days
    - Number of cycles per day
  - Average Operating Cost per km

Available Infrastructure (II): Radial Route Combine with III

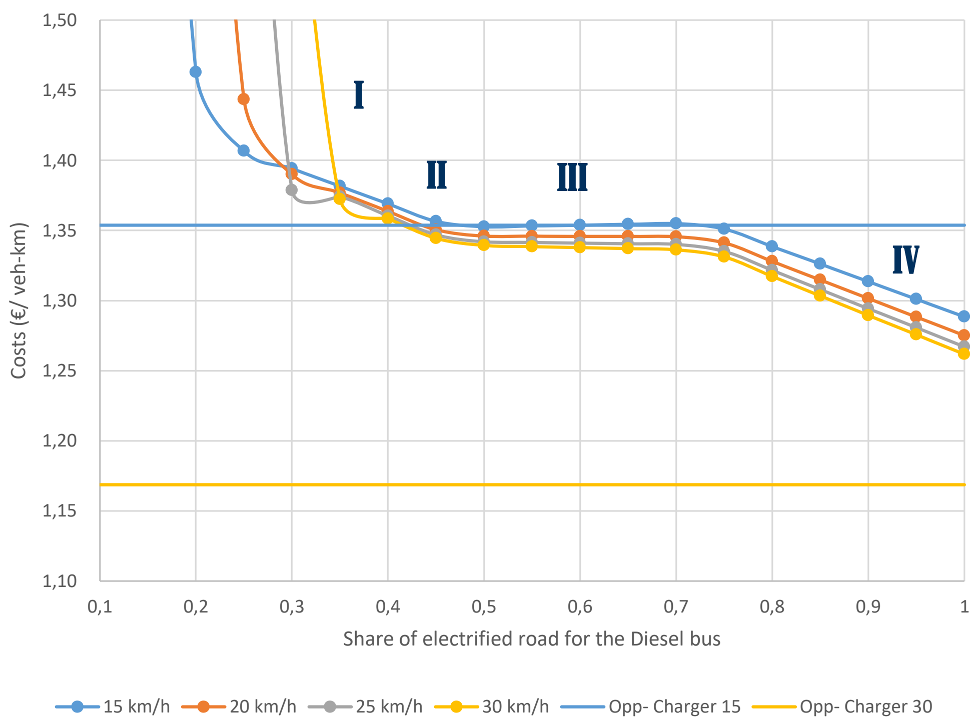


I
A low share of road makes the calculation adopt for a large battery

II
Increasing the share of electrified route for the diesel bus, causes a linear degression of costs.

- Between 70% and 75% are necessary to electrify this line below the cost of an opportunity charger

Available Infrastructure (III): Cross-City Route



I
Very little electrified line available, large battery required to continue operation

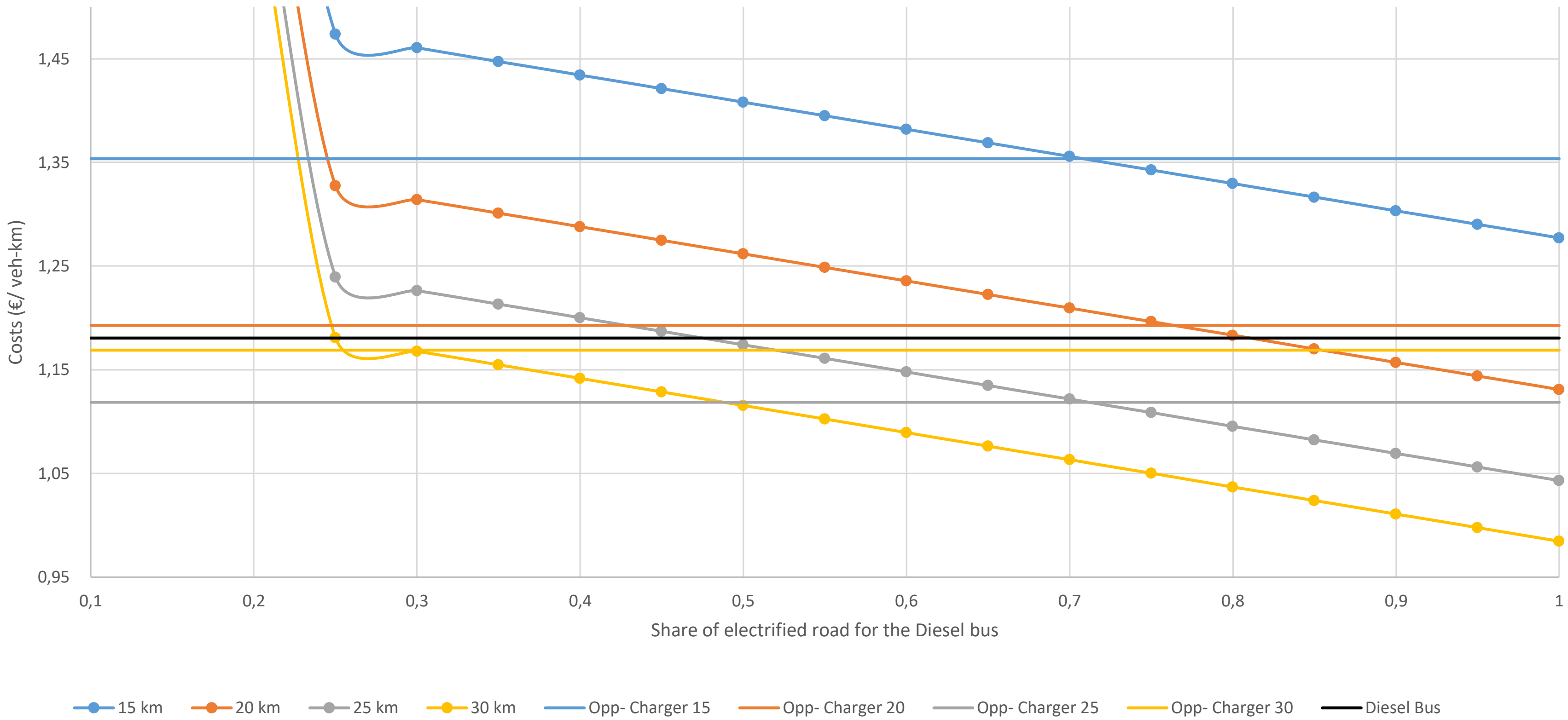
II
Decrease in cost as longest section decreases with increasing share of electrified road

III
Longest section now fixed and battery sized according to it

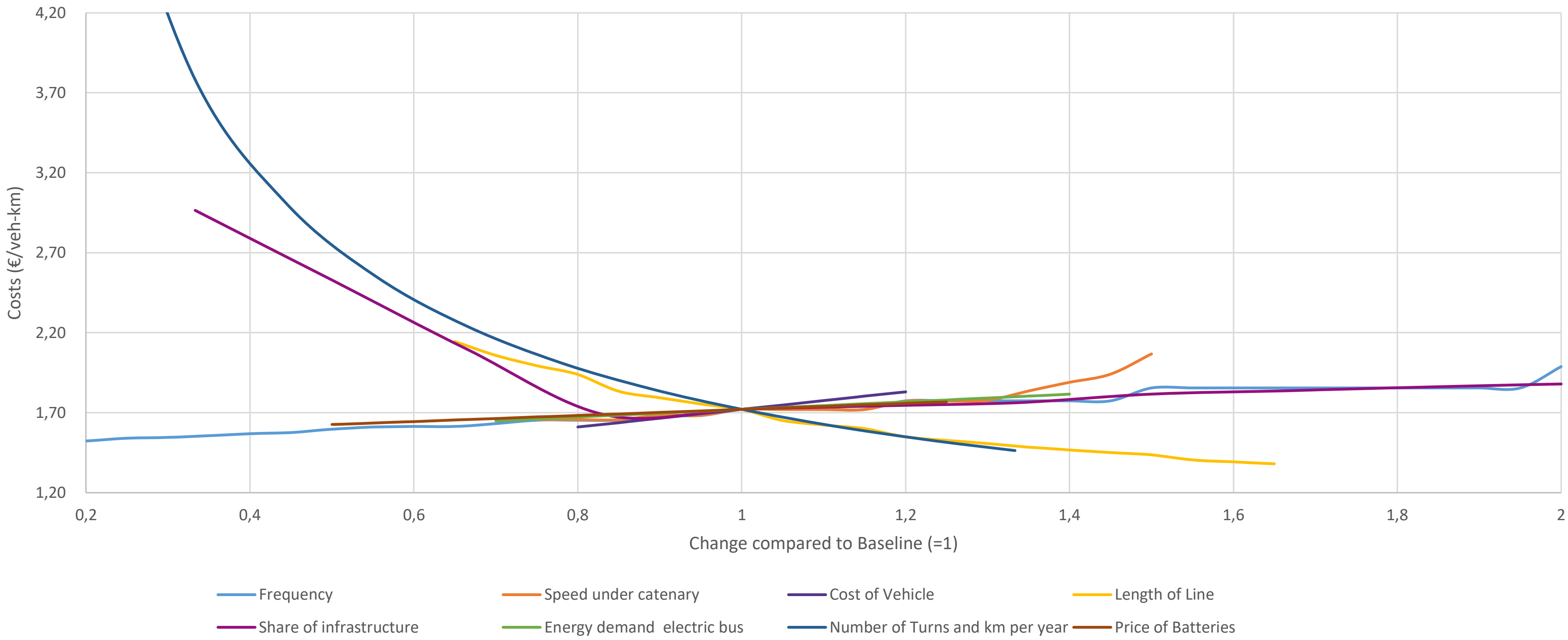
IV
Increased share now also decreases final section

- Only 45-50% electrified road necessary!
- Reason: required energy demand for one route is reduced

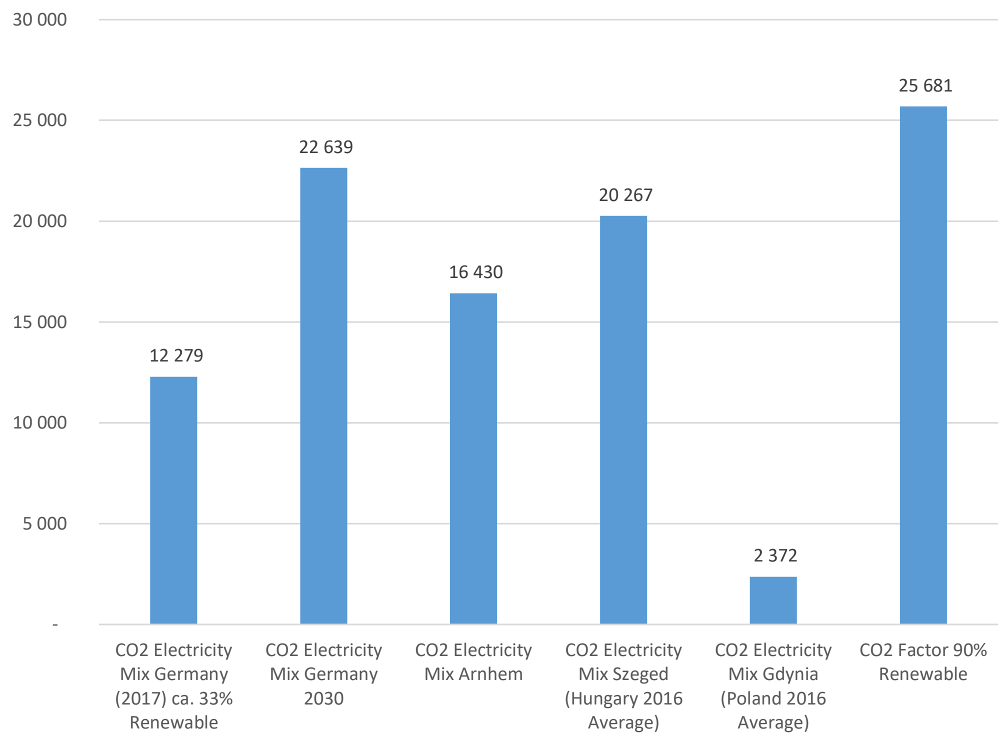
Available Infrastructure (IV): Demonstration of Importance of Case-by –case analysis as a function of line length



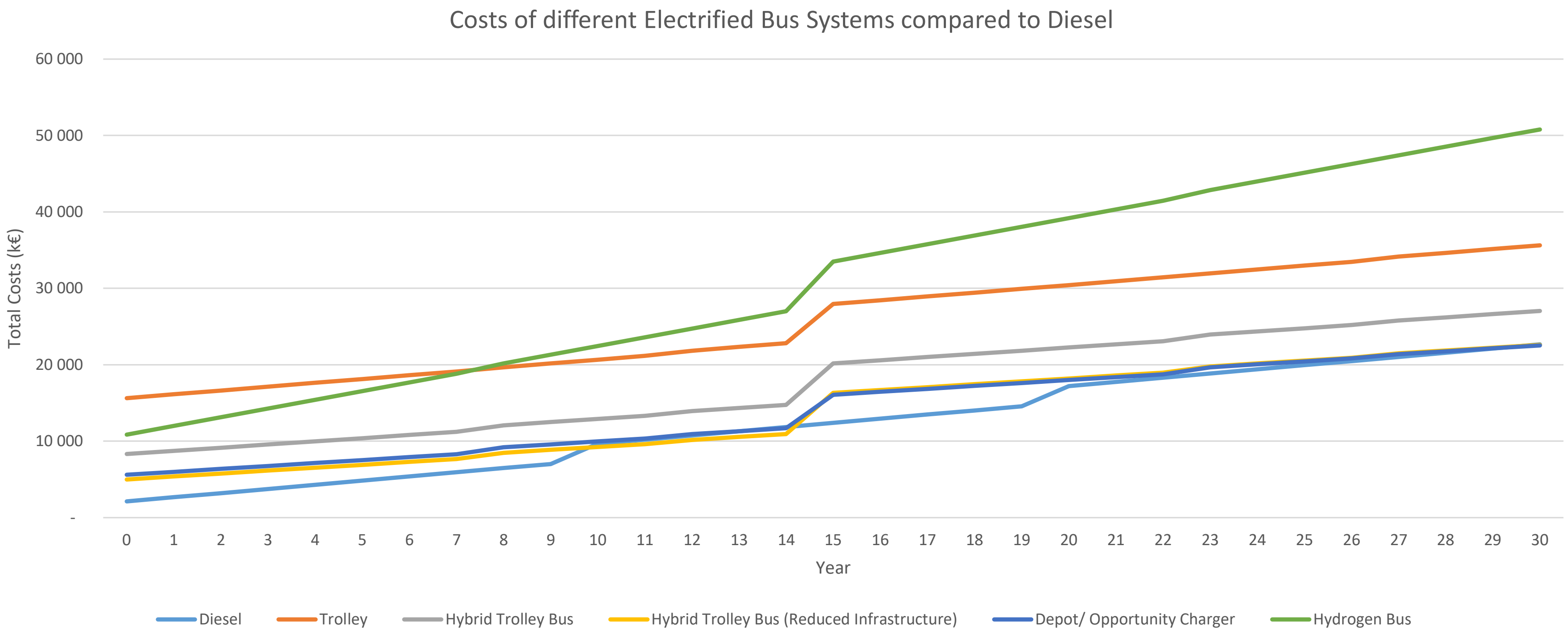
New Construction of Infrastructure (I): Assessing Key Parameters



Reduction of CO_2-Emissions



- Constructed CO_2 mixes based on individual CO_2 emissions of different energy carriers
- CO_2-Emission reduction potential with all energy mixes
- Long lifetime and daily km outweight CO_2 backpack of battery, buses and infrastructure


Costs of different Electrified Bus Systems compared to Diesel
60 000
50 000
40 000
30 000
20 000
10 000
-
Total Costs (k€)
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
Year
Diesel
Trolley
Hybrid Trolley Bus
Hybrid Trolley Bus (Reduced Infrastructure)
Depot/ Opportunity Charger
Hydrogen Bus