# Exploring the profitability of using electric bus fleets for transport and power grid services

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BUS

Forschungscampus Mobility 2 Grid EUREF

# Forces pulling the transition of public transport




Competitive-ness

Sustainability

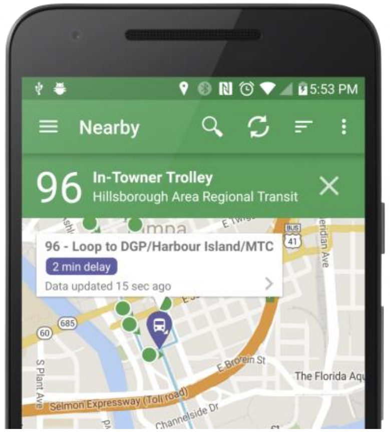
Reliability

Resilience


# Forces pulling the transition of public transport

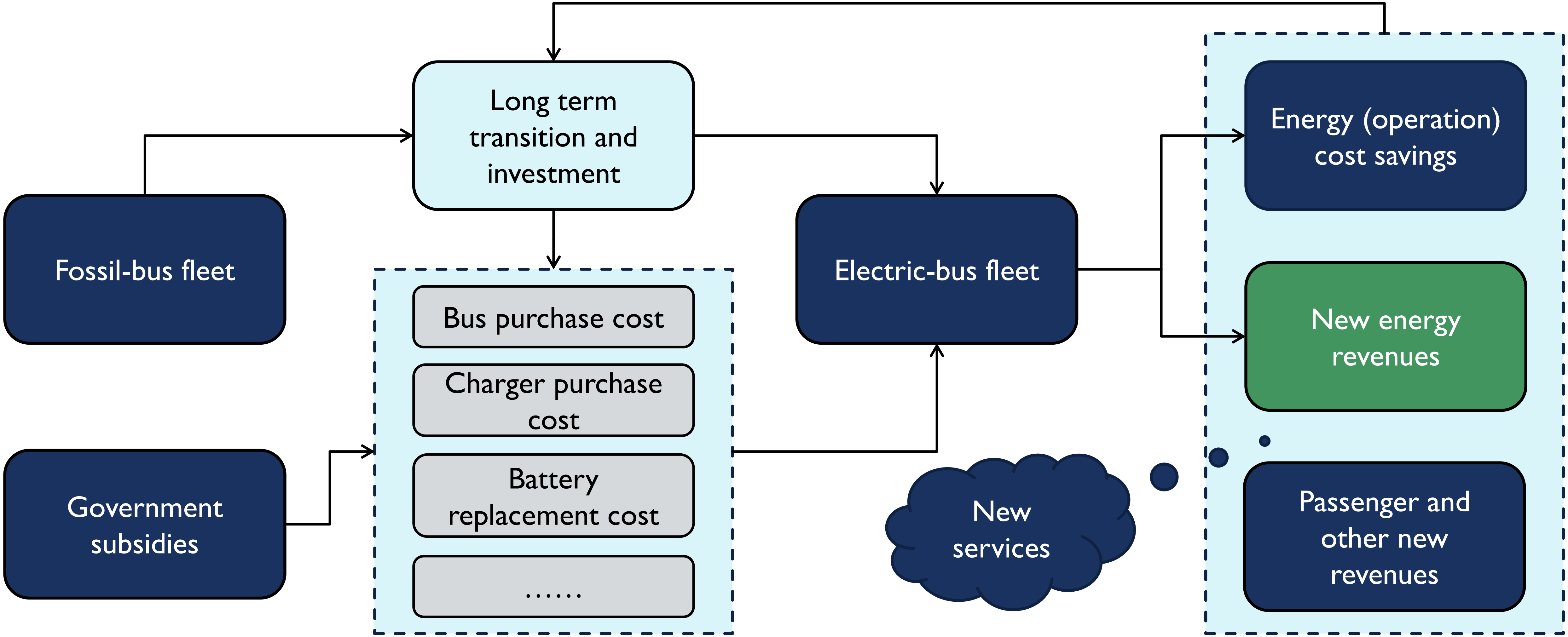



- Competitive-ness
- Sustainability
- Reliability
- Resilience




# Long-term transition of bus fleet and financial sustainability





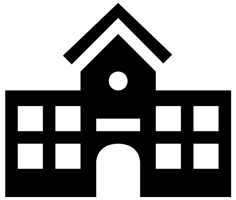
# Innovative solutions to the transition of PT: Cooperation, electrification, and new services

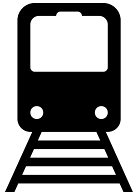


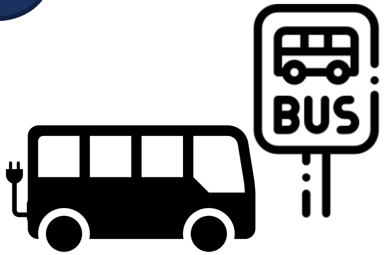
Competition
or
cooperation?

Electrification?
How to
finance it?

New
services?






# Integrating multi-modes, multi-services, and multi-systems with PT



Multi-modes

- Free taxi as delay (disruption) compensation
- Providing transit fare with a delay insurance

Multi-services

- Services (activities) aggregation as delay remedy
- Leveraging the railway station area as an activity hub and providing premium service subscription

Multi-systems

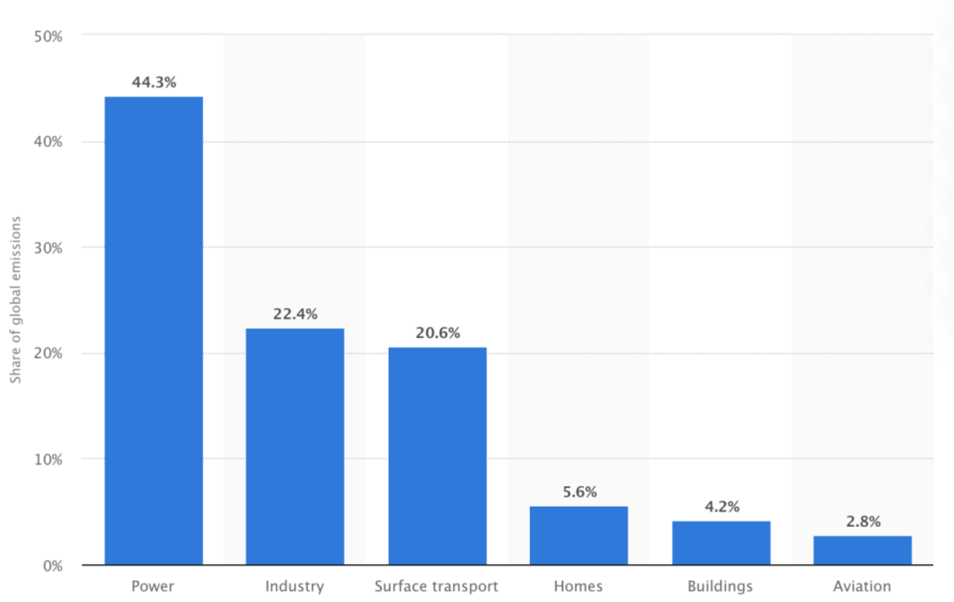
- Bus-to-Grid services
- Discharging the electricity to the power grid when the price is high or during disruptions (e.g. blackout)

- Improve travel time and network reliability
- Create new services
- Open up new source of revenues
- Shape financially and environmentally sustainable PT

# Background

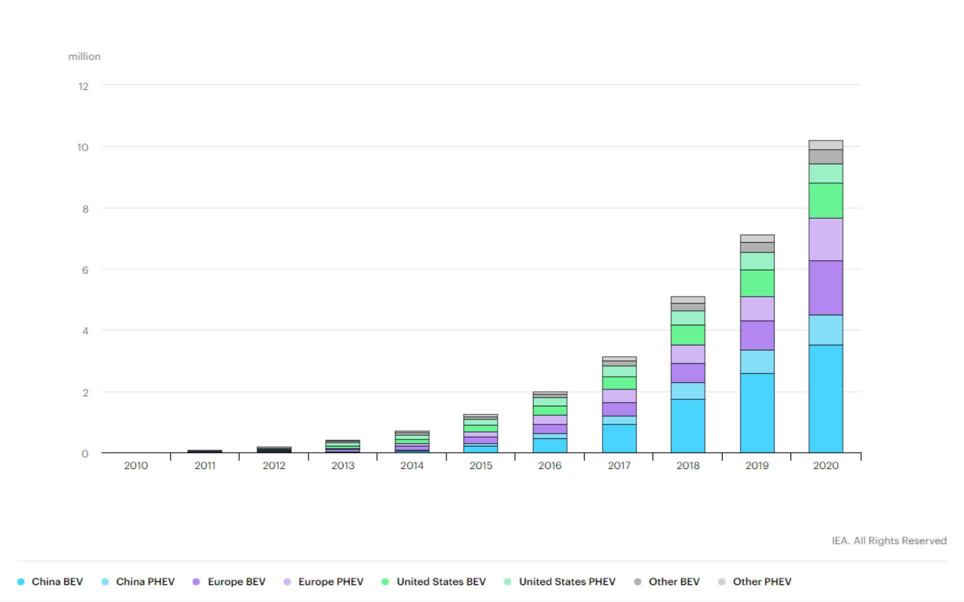


## Global CO2 emissions by economic sector




Global distribution of $CO_2$ emissions from fossil fuel and cement by sector 2020

## Increasing number of EVs




Global electric car stock by region and mode, 2010-2020

Many countries focus on developing greener transportation

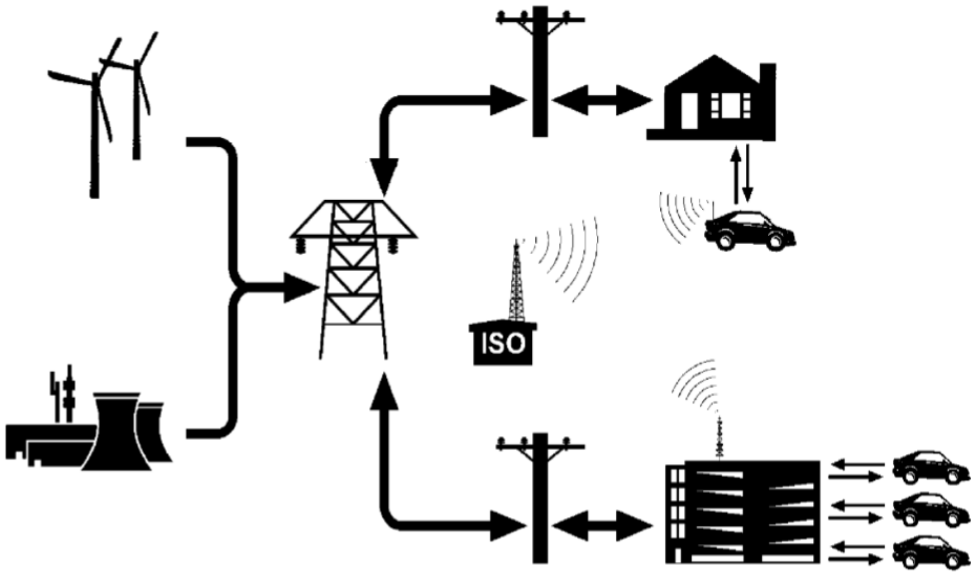
The number of EVs are increasing (especially e-buses)

# Background: Vehicle-to-grid (V2G)



**Vehicle-to-grid (V2G)**

V2G is a system in which EVs communicate with the power grid to either sell or purchase electricity. EVs function as a distributed but mobile energy storage unit which can also perform grid demand side management services.

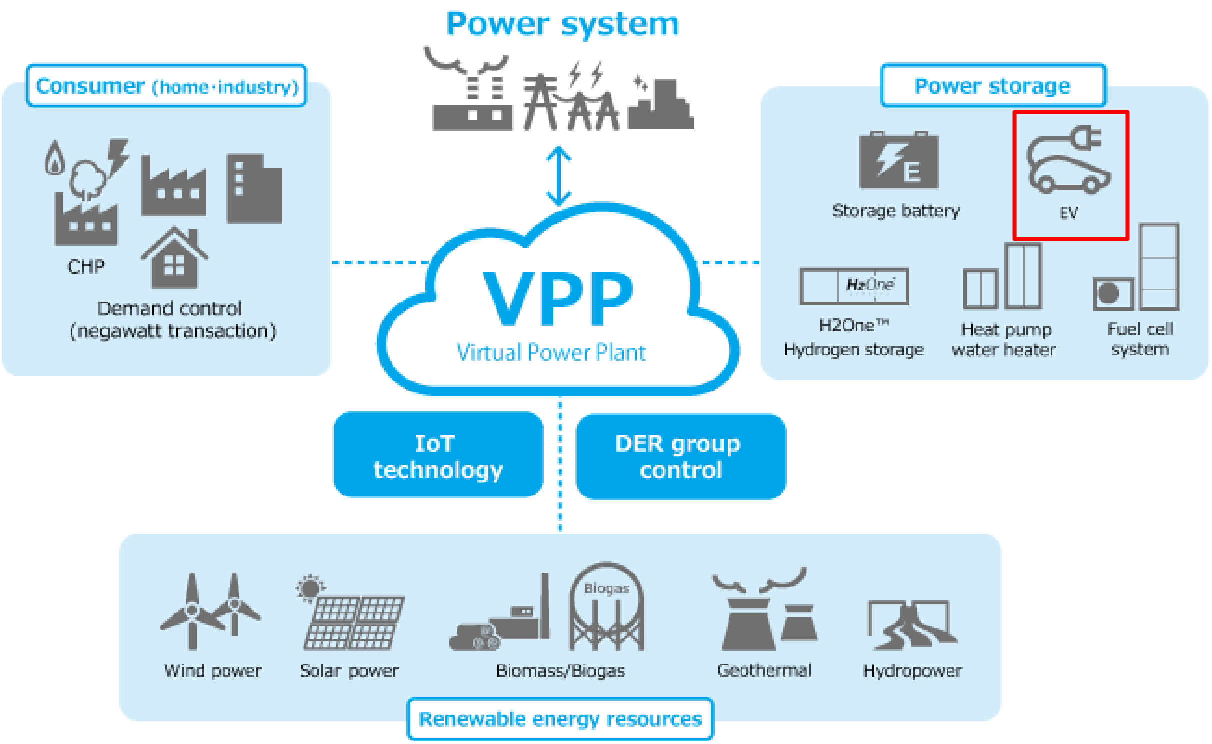


# Background: Virtual Power Plant (VPP)



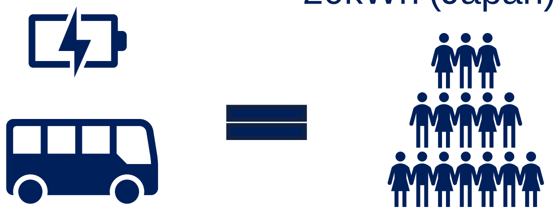
**Virtual Power Plant (VPP)**

A cloud-based distributed power plant that aggregates the capacities of heterogeneous distributed energy resources (DER) for the purposes of enhancing power generation, as well as trading or selling power on the electricity market.




Battery capacity per bus:
50-500 kWh

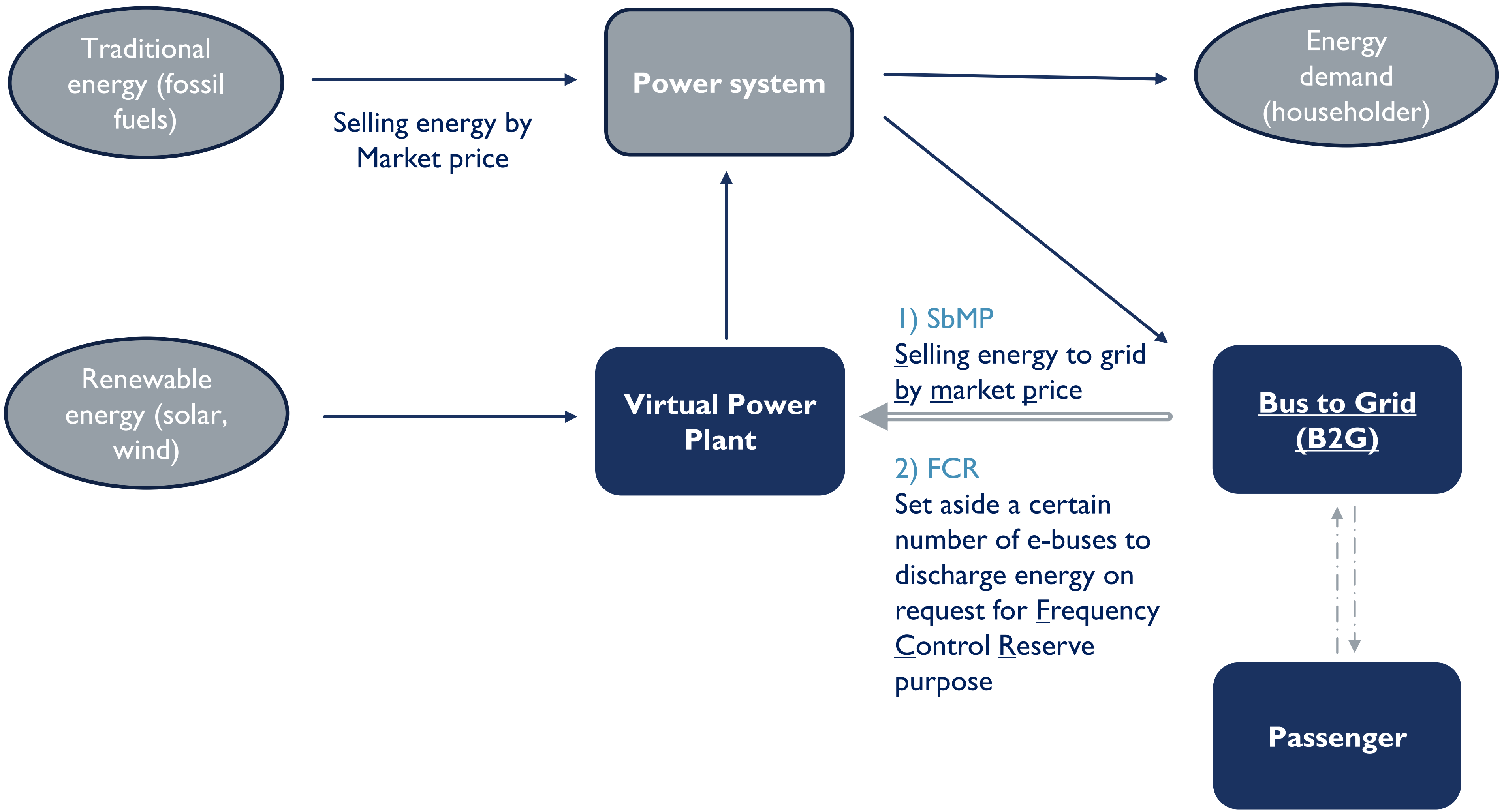
Energy consumption per person per day:
10kWh (World)
20kWh (Japan)



- E-buses are considered as potential power storage in this research
- Advantages compared with private vehicles
  - Larger battery capacity
  - More callable electricity

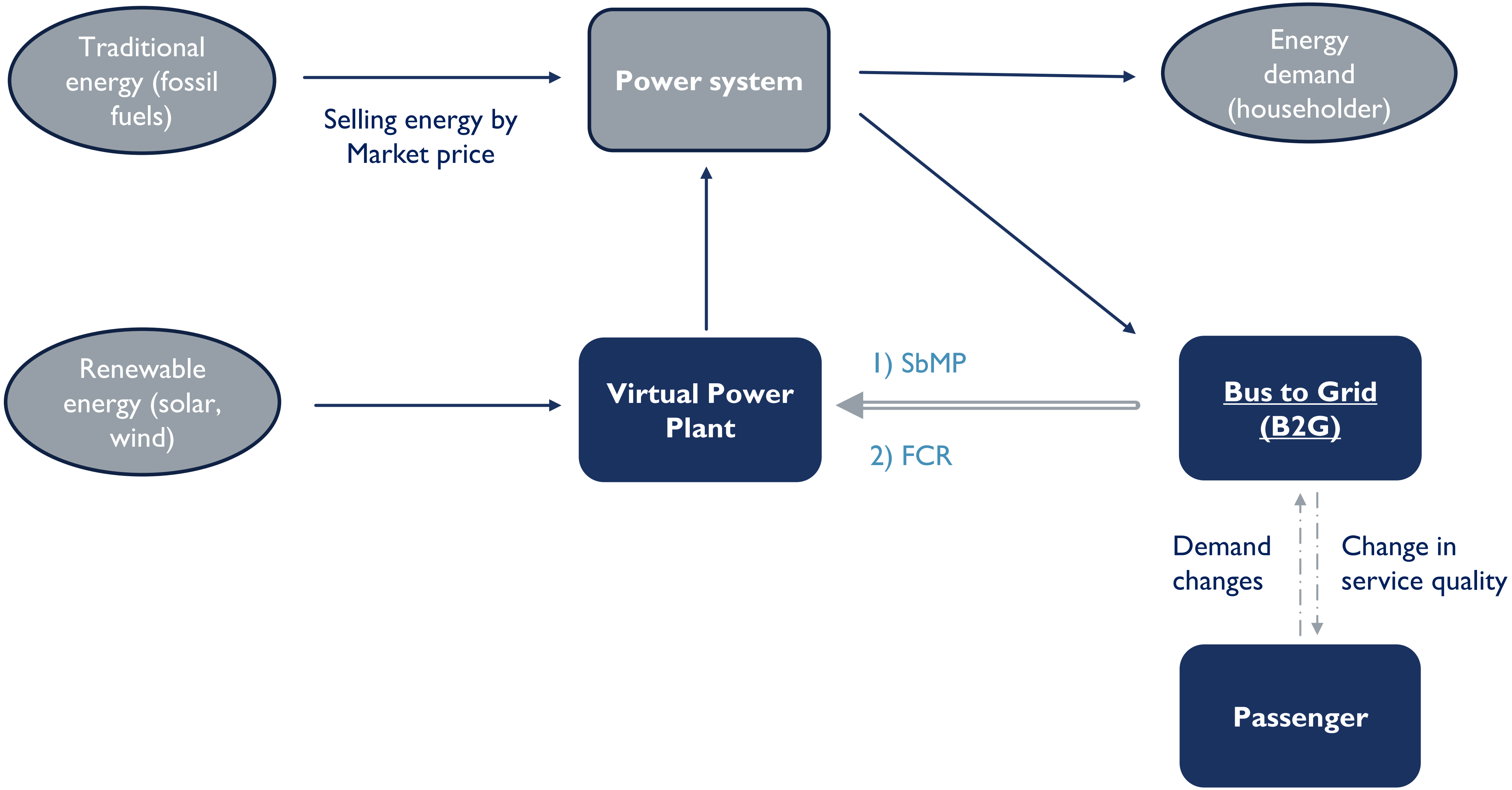
# The Bus-to-Grid (B2G) concept and contracts





# The Bus-to-Grid (B2G) concept and contracts





# Objectives and contribution



## Research objective

- Understanding the feasibility of the concept by modelling the interactions among energy providers, bus operator and passengers.
- Showing the service quality impacts and optimal condition for bus operator.

  Finding out optimal bus fleet, timetable and energy exchange plans.

## Contribution

- Promoting the electrification of bus transit.
  - The profitability of bus operator is enhanced by new incomes from grid
  - Greener bus transport may attract more users
- Reducing the fluctuation of renewable energy supply and therefore stabilizing the energy market price.

Fan Fei, Wenzhe Sun, Riccardo Iacobucci, & Jan-Dirk Schmöcker. (2023). Exploring the profitability of using electric bus fleets for transport and power grid services. *Transportation Research Part C: Emerging Technologies*, *149*, 104060.

# Models: An optimization approach from an aggregate energy perspective (SbMP contract)



**Objective function: Total profit of public transport operator**

$$\underset{f(t),E^-(t),E^+(t),R(t),\forall t\{1,2,\ldots,H\}}{\text{Max}} P = \sum_t \left(P_p(t) + P_g(t) - C_e(t)\right) - C_m$$

**Decision variables: Bus frequency, charging energy, discharging energy, and bus fleet allocation**

Subject to:

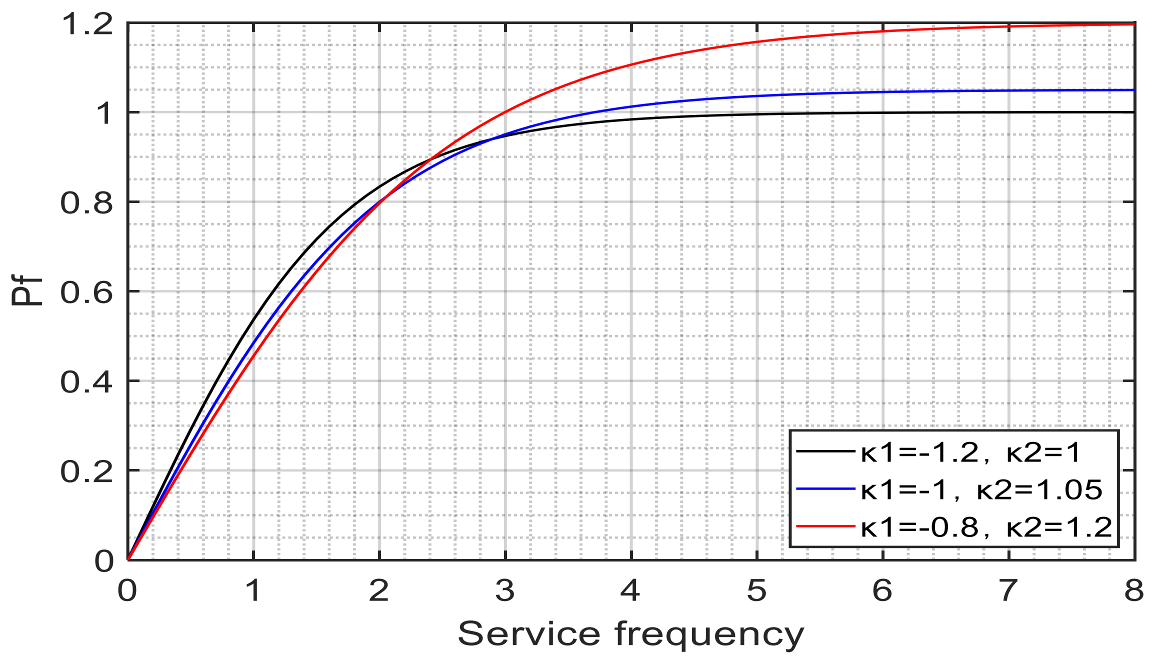
| | |
|---|---|
| **Running buses constraint** | $U(t) \le N, \forall t \in \{1,2,\ldots,H\}$ |
| **Buses connected to the grid** | $R(t) \le N - U(t), \forall t\{1,2,\ldots,H\}$ |
| **Number of chargers constraint** | $R(t) \le S, \forall t\{1,2,\ldots,H\}$ |
| **Aggregate energy of bus line at the end of *t*** | $E_{min} \le E(t) \le E_{max}, \forall t\{1,2,\ldots,H\}$ |
| **Ensure the energy for running back** | $E_c(t)Tf(t) \le E_{min}, \forall t\{1,2,\ldots,H\}$ |
| **The amount of charging and discharging will be limited by the number of buses connected to the grid and battery capacity** | $\frac{E^-(t)}{\gamma^-} + \frac{E^+(t)}{\gamma^+} \le R(t), \forall t\{1,2,\ldots,H\}$ <br> $E^+(t) - E^-(t) \le R(t)B, \forall t\{1,2,\ldots,H\}$ |
| **Non-negative constraints** | $f(t), E^-(t), E^+(t), R(t) \ge 0, \forall t\{1,2,\ldots,H\}$ |

| | |
|---|---|
| **Revenue from passengers** | $P_p(t) = \rho Y(t) P(f)$ |
| **Revenue from the grid** | $P_g(t) = c_e(t) E^-(t)$ |
| **Energy costs** | $C_e(t) = c_e(t) E^+(t)$ |
| **Maintenance costs** | $C_m = N c_m$ |
| **Passenger demand loss due to reduced frequency** | $P(f) = \frac{2\kappa_2}{1 + e^{-\kappa_1 f}} - \kappa_2$ |

# Passenger demand elasticity to service frequency



$$P(f) = \frac{2\kappa_2}{1 + e^{-\kappa_1 f}} - \kappa_2$$




- An increase in service frequency will attract new passengers but with an upper bound to limit the total potential demand.
- Since the service is already in operation, it is likely that some kind of demand equilibrium has been reached with the current $f = 3$.

# Models: An optimization approach from an aggregate energy perspective (FCR contract)



**Objective function: Total profit of public transport operator**

$$\max_{K, f(t), E^+(t), R(t), \forall t\{1,2,\ldots,H\}} P = P_g - C_m + \sum_t \left(P_p(t) - C_e(t)\right)$$

**Decision variables: Buses for FCR contract, bus frequency, charging energy, discharging energy, and bus fleet allocation**

Subject to:

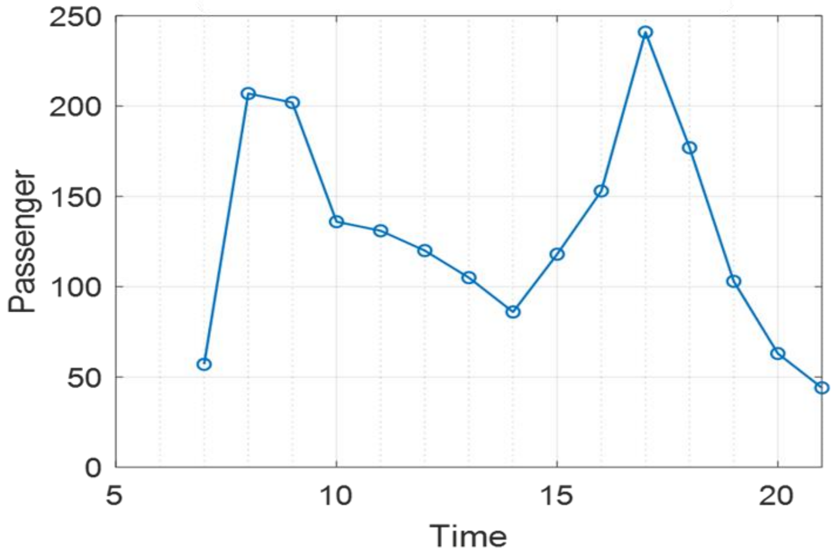
| | |
|---|---|
| **Running buses constraint** | $U(t) \le N, \forall t \in \{1,2,\ldots,H\}$ |
| **Buses connected to the grid** | $R(t) \le N - U(t), \forall t\{1,2,\ldots,H\}$ |
| **Number of chargers constraint** | $R(t) \le S, \forall t\{1,2,\ldots,H\}$ |
| **Aggregate energy of bus line at the end of t** | $E_{min} \le E(t) \le E_{max}, \forall t\{1,2,\ldots,H\}$ |
| **Ensure the energy for running back** | $E_c(t)Tf(t) \le E_{min}, \forall t\{1,2,\ldots,H\}$ |
| **Buses for FCR no more than those connected the grid** | $K \le R(t), \forall t\{1,2,\ldots,H\}$ |
| **Charging amount constraints** | $E^+(t) \le \gamma^+ R(t), \forall t\{1,2,\ldots,H\}$<br>$E^+(t) \le R(t)B, \forall t\{1,2,\ldots,H\}$ |
| **Non-negative constraints** | $K, f(t), E^+(t), R(t) \ge 0, \forall t\{1,2,\ldots,H\}$ |

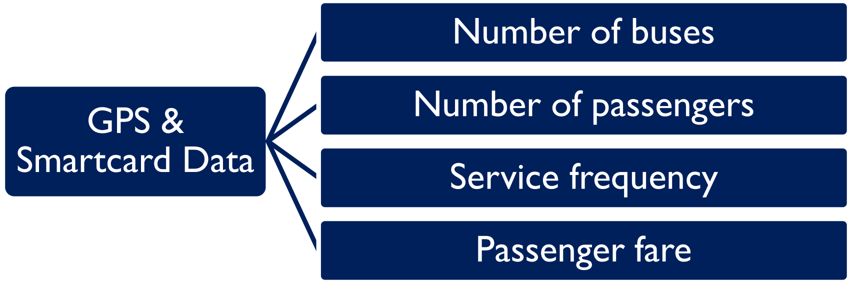
| | |
|---|---|
| **Revenue from passengers** | $P_p(t) = \rho Y(t) P(f)$ |
| **Revenue from the grid** | $P_g = \varepsilon K \gamma^-$ |
| **Energy costs** | $C_e(t) = c_e(t) E^+(t)$ |
| **Maintenance costs** | $C_m = N c_m$ |
| **Passenger demand loss due to reduced frequency** | $P(f) = \dfrac{2\kappa_2}{1 + e^{-\kappa_1 f}} - \kappa_2$ |

# Input data

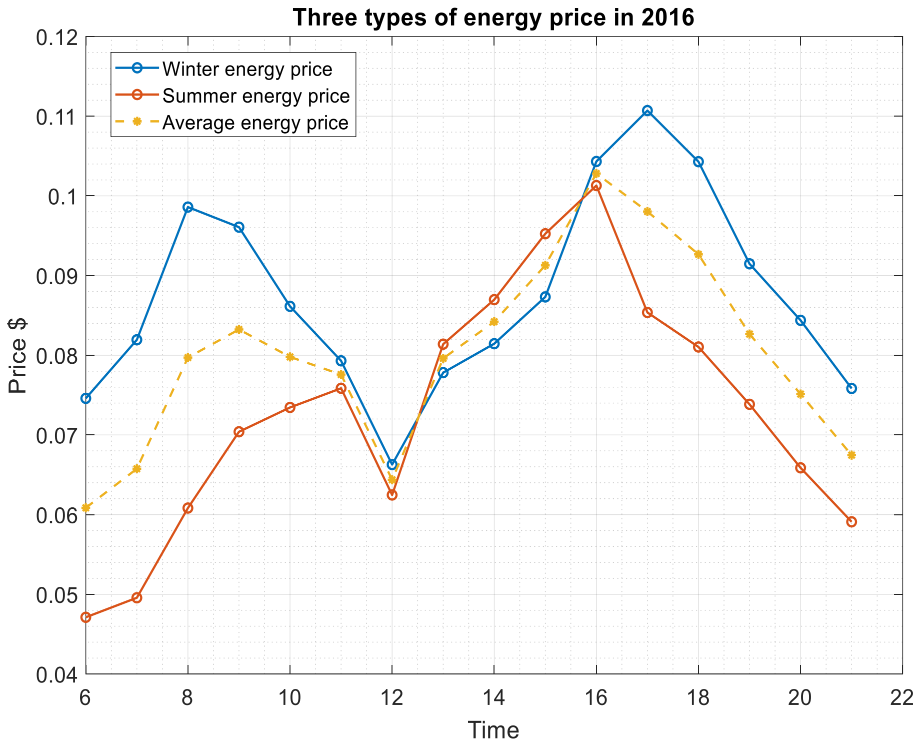


## Bus lines selected in this research




## Energy market price




Source: Japan Electric Power eXchange (JEPX)
http://www.jepx.org/index.html

# Input data

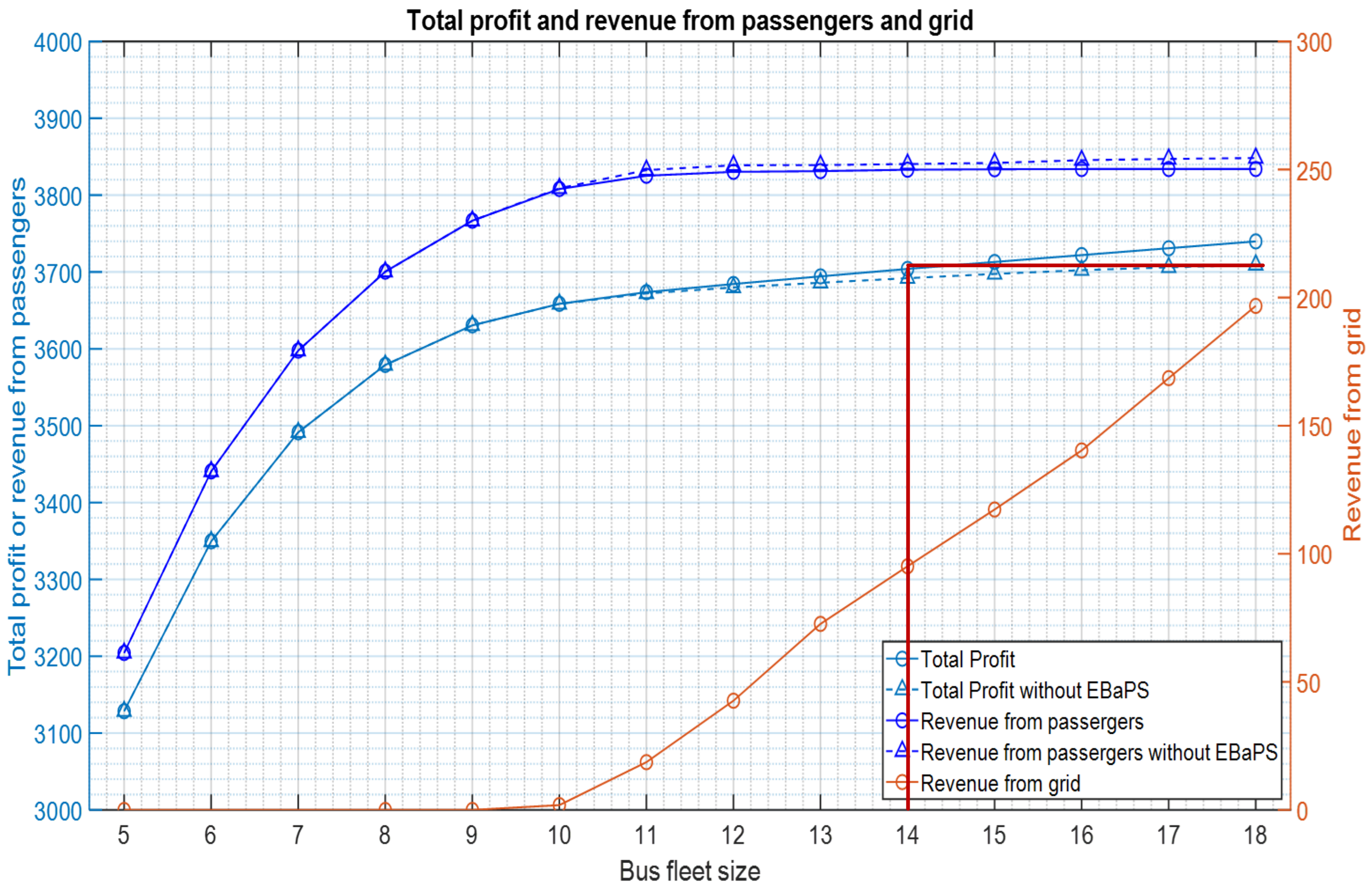


| Bus operation related input | | Energy-related input | |
|---|---|---|---|
| **Variables** | **Value** | **Variables** | **Value** |
| $\rho$ | 2 $/pas | $E_{ba}$ | 200 kWh |
| $H$ | 6 | $\gamma_{dis}$ | 40 kW/bus |
| $N$ | 18 | $\gamma_{char}$ | 60 kW/bus |
| $T$ | 1.15 | $\eta$ | 1.35 kW/km |
| | | $\varepsilon$ | 0.2 $/Kw per bus |
| $P(f)$ | $\kappa_1 = -1.2, \kappa_2 = 1$ | $SOC_{min}$ | 30% |
| | | $SOC_{max}$ | 100% |
| $\tau$ | 1 | $SOC_0$ | 100% |
| $S$ | 20 | | |
| $c_m$ | 6 $/bus per day | | |

*The notation of these variables is given in Appendix

# Results: Profit given different fleet sizes, SbMP contract

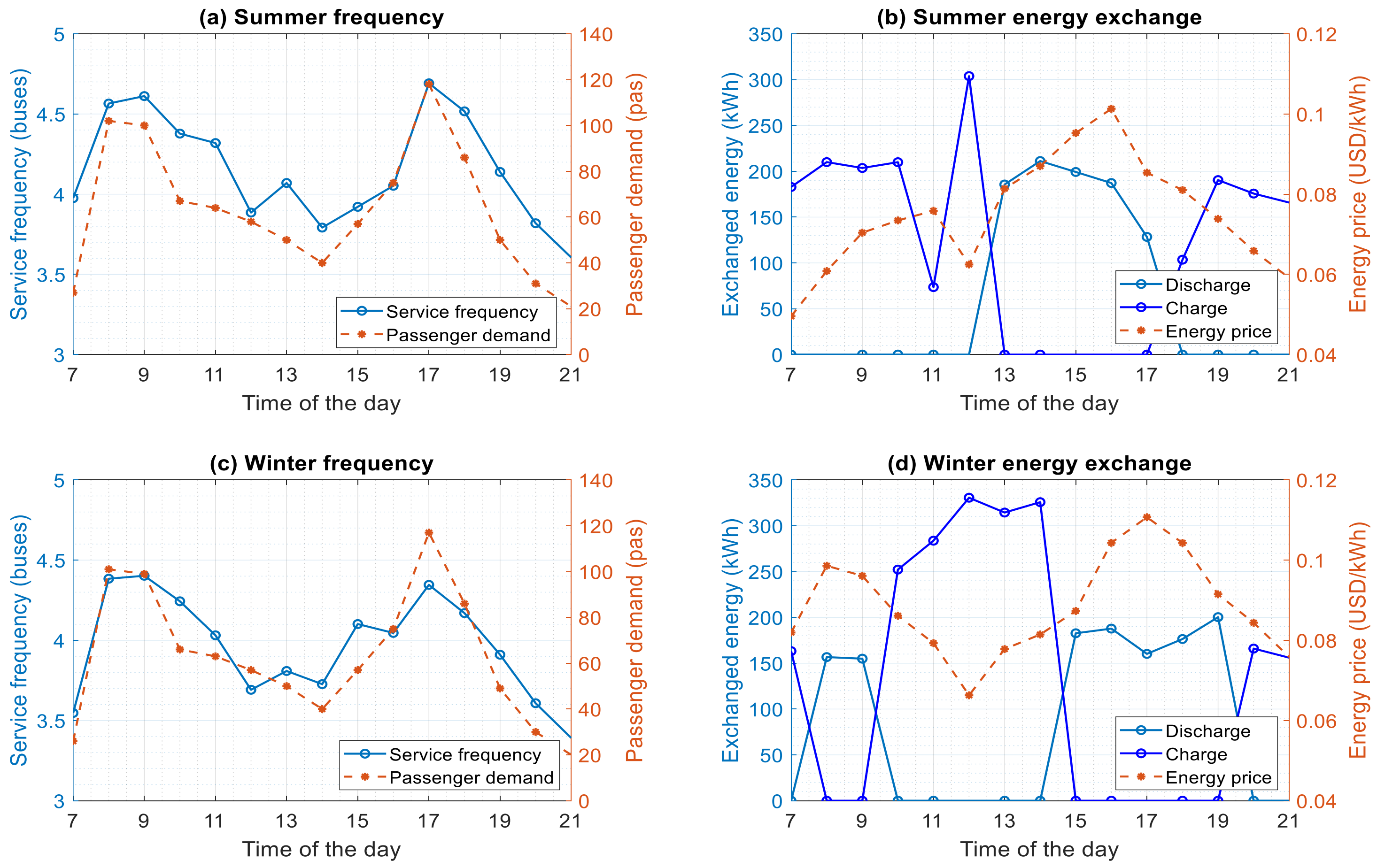





- Higher profit with B2G than without if the size of the bus fleet is larger than 10.
- Currently, the line operates with 18 buses. The total profit could increase from USD3702 to USD3749 per day.
- A new electrified fleet of 14 buses can maintain the previous level of profit obtained from 18 buses

# Results: Timetables in the Winter and Summer, SbMP contract

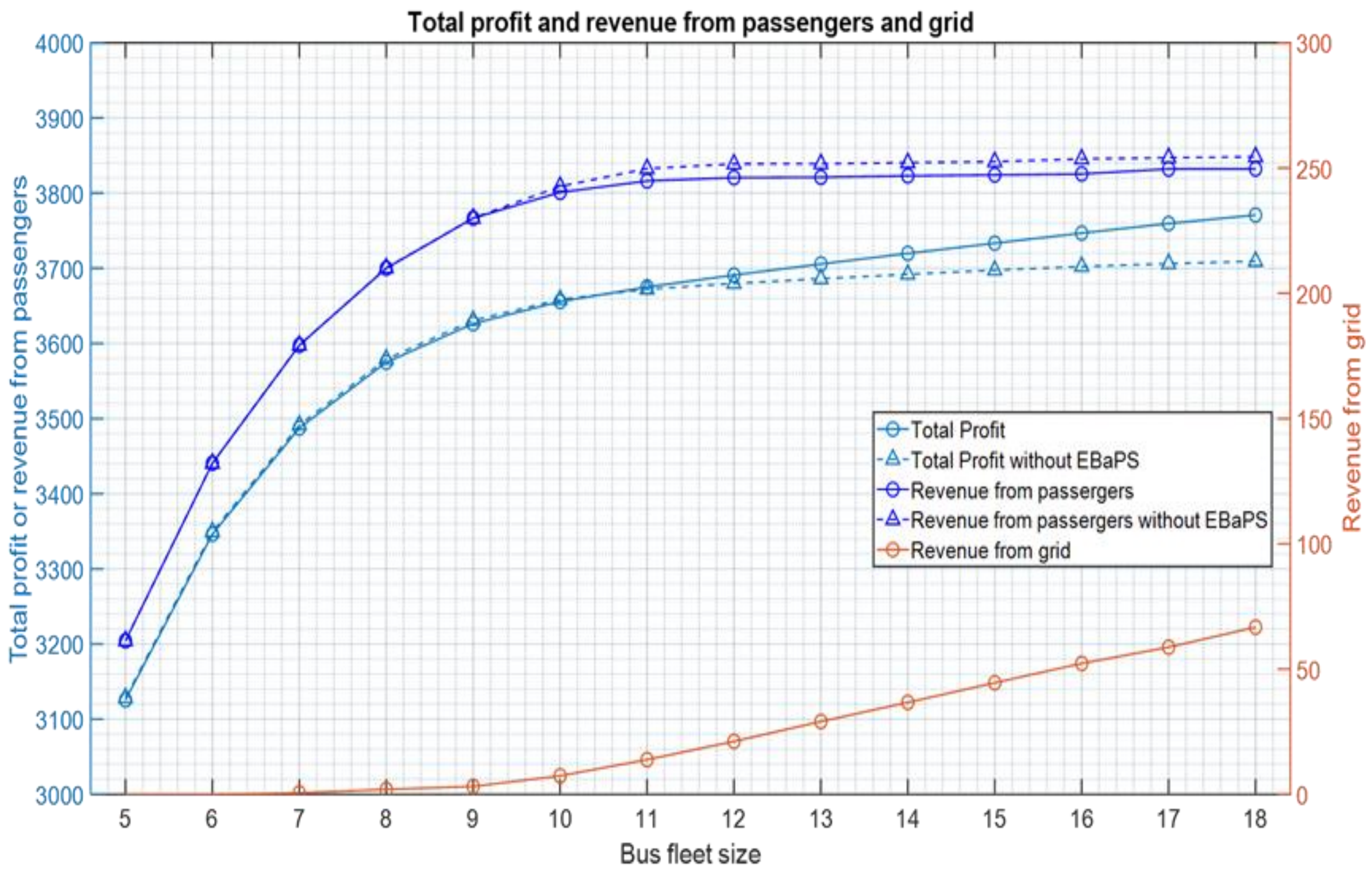





- Bus timetable does not change significantly given the significant changes in energy price.
- Seasonal service adjustment to meet the fluctuation of energy price is manageable.
- In winter, there are two discharging peaks according to the two price peaks. They offer the operator more trade-off opportunities.

# Results: Profit given different fleet sizes, FCR contract






- Compared to SbMP, the revenue from grid and the revenue from passengers are lower though, the gap between the total profits with and without EBaPS is enlarged.
- The operation (charging) cost is reduced due to the reduced number of buses available for transportation service.
- The potential negative impacts on passengers can be further considered

# Conclusions



**Findings**

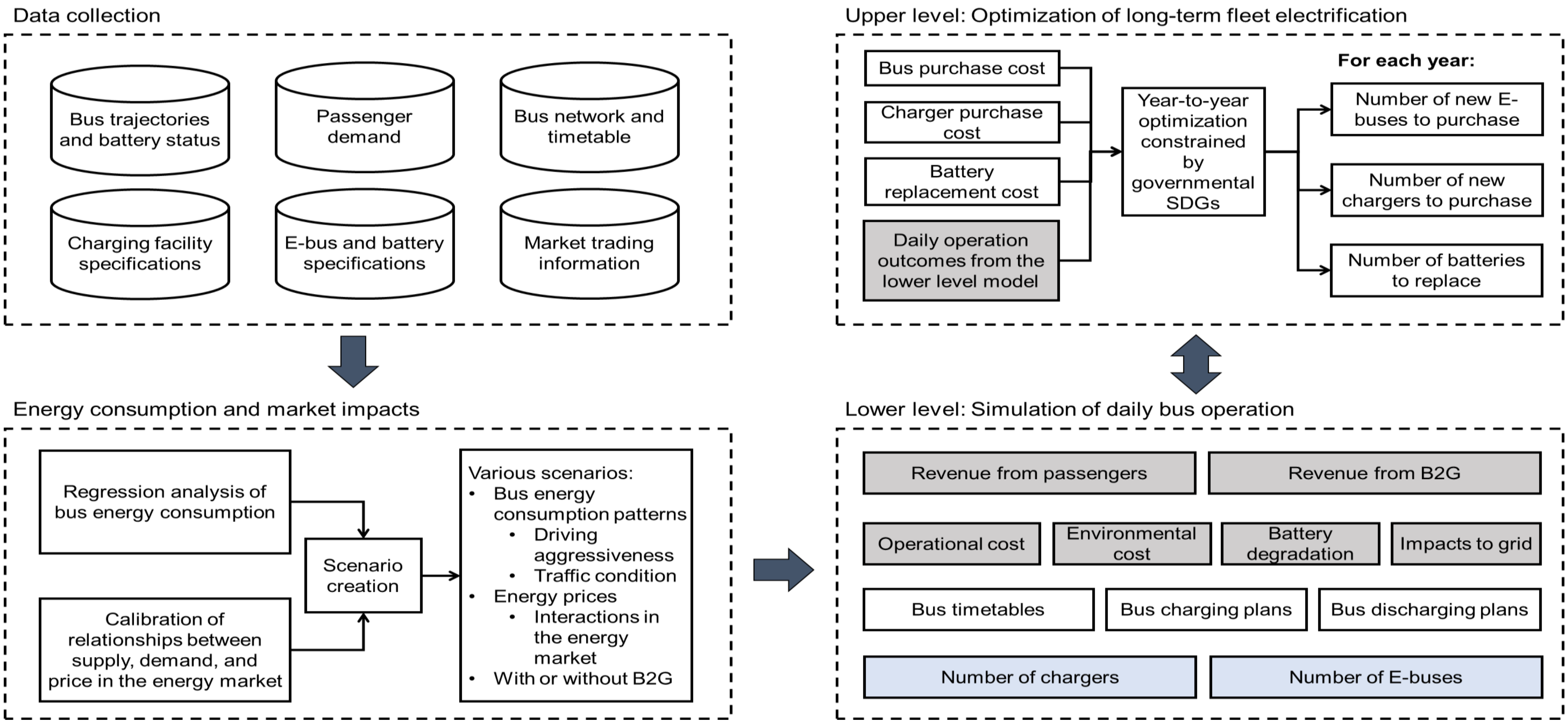
- We show the feasibility and profitability of E-buses as power storage providing grid service to VPP by two types of contract, from the perspective of a bus operator.
- The difference in bus timetables obtained from significantly varying winter/summer energy price were found acceptable.
- The optimal timetable, bus fleet size, charging and discharging plans can be rapidly found.

**Further work**

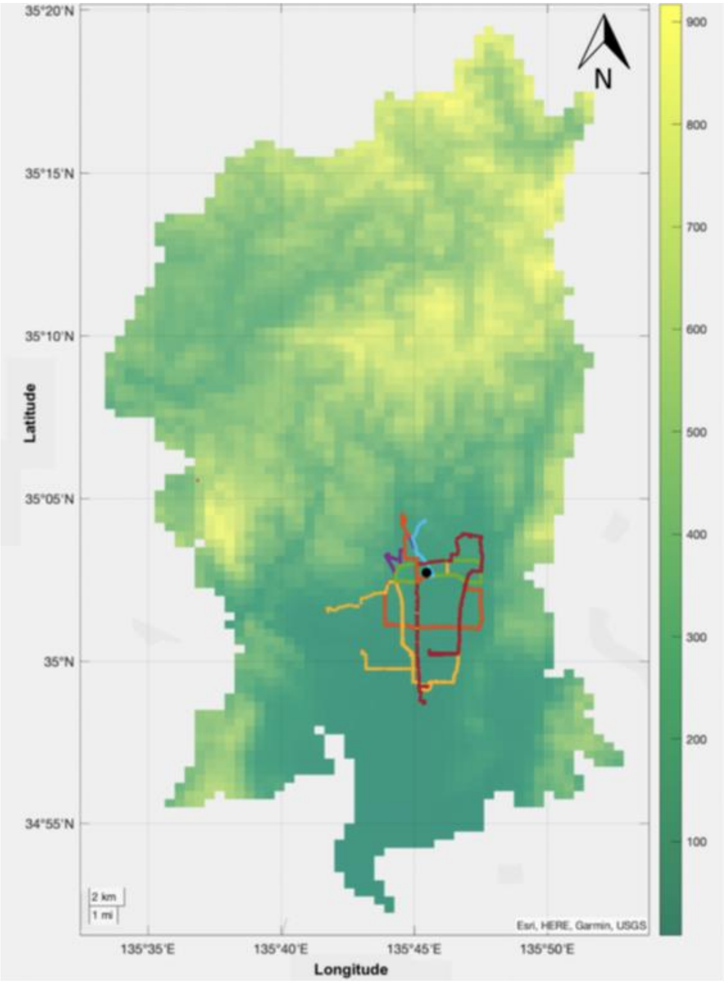
- Illustrating the feasibility of the concept in more complex situations
  A large-scale bus transit network, the competitions among multiple bus fleets operated by different operators.
  Timetable-based bus operation and scheduling constraints
- If the operator is the government, the profit will be discussed from more aspects.
  From the perspective of "social welfare", government subsidies to encourage electrification, and so on.
- The cost of E-buses, the cost of discharging, and other parameter settings could also be considered in the future.

# A long-term bus fleet electrification framework considering B2G

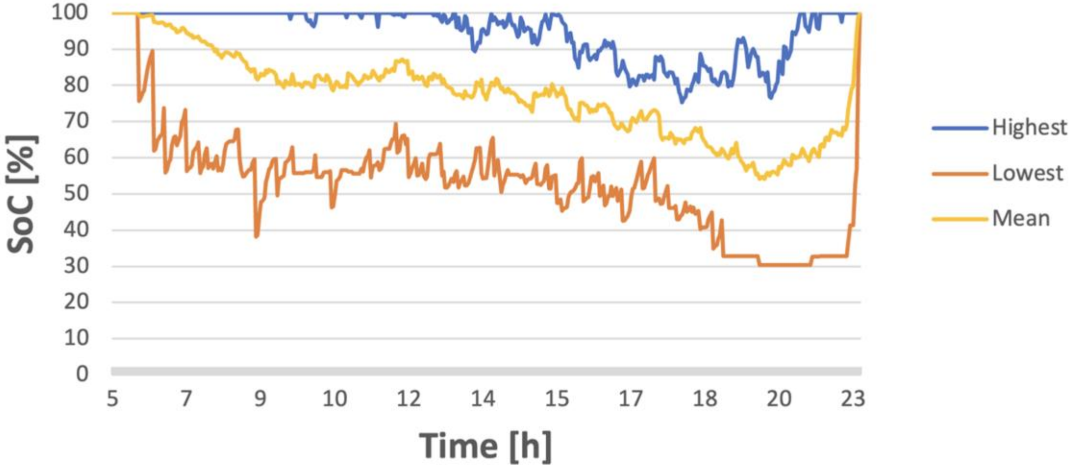




# Ongoing research and collaboration: Energy consumption modelling

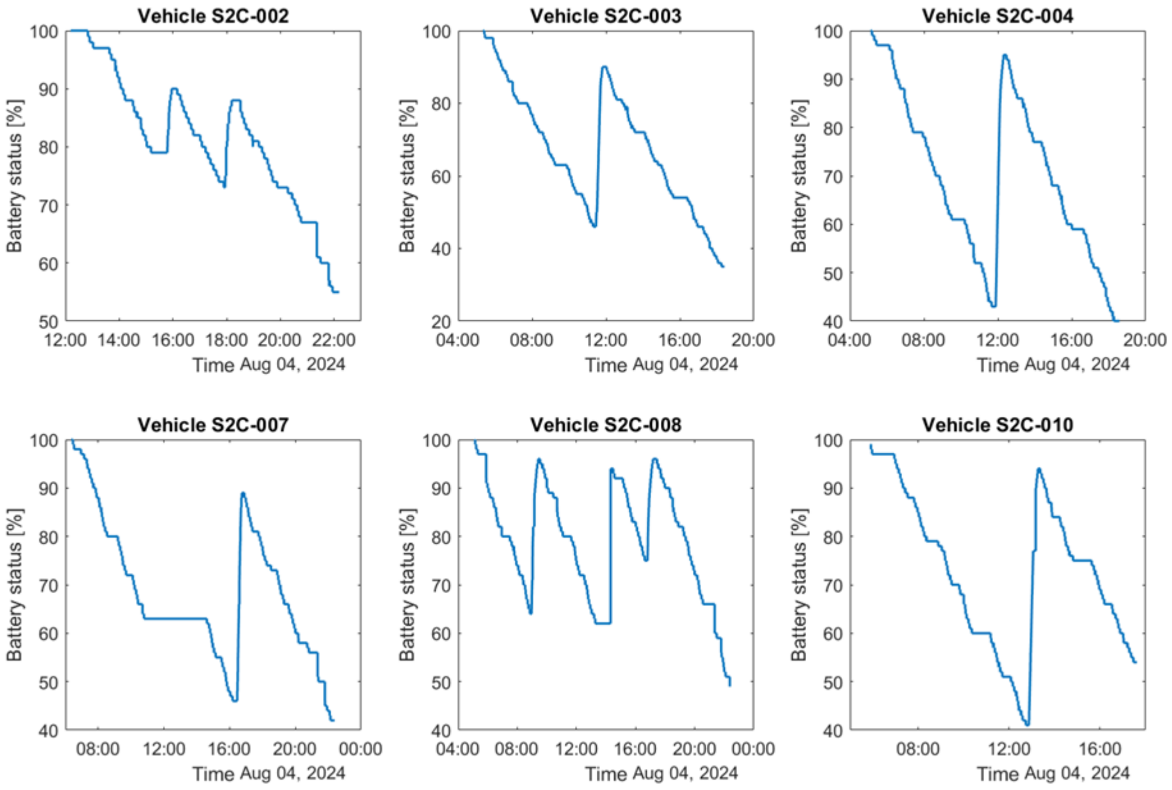


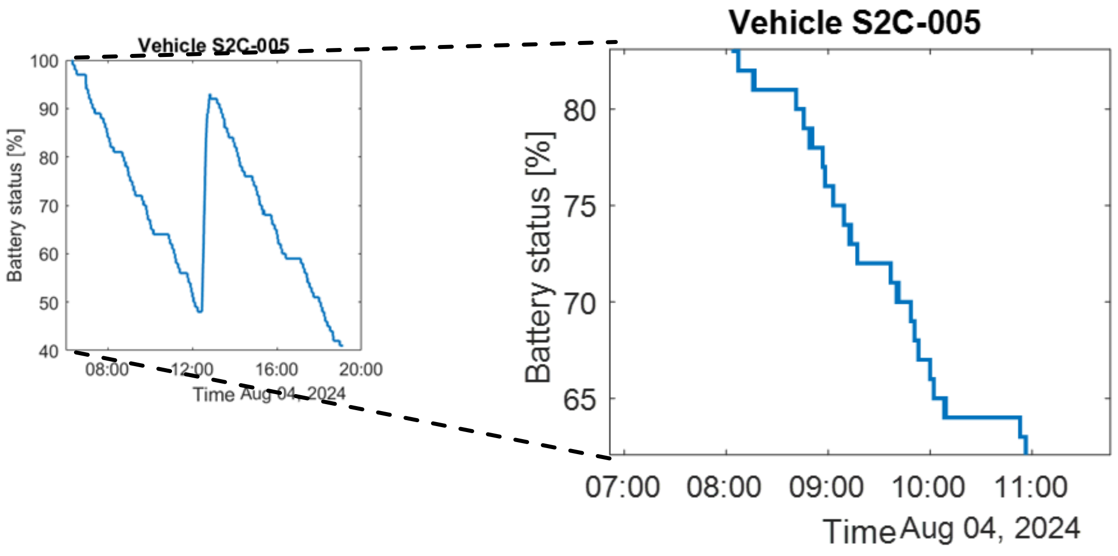

- Trip-based bus energy consumption considering speed, acceleration, road gradient, …
    - Variables are from bus GPS data, and parameters are from literature
- Manage the E-bus fleet of a bus terminal having 22 lines, using current arrival and departure times as constraints and energy consumption as input
- Consider the charging and dispatching problem as a bin packing or a knapsack problem, each trip with its energy consumption as an item




Taken from Kim Bottinelli (2023) Profitability of using electric bus fleets: A case study of Kyoto. Master's thesis, ETH Zurich. (Supervised by: Wenzhe Sun, Jan-Dirk Schmöcker, and Francesco Corman)

# Data collection progress: E-bus GPS and battery status data




| 2 | 3 | 4 | 10 | 11 | 12 | 13 | 14 |
|---|---|---|---|---|---|---|---|
| Vehicle_ID | VIN_ID | Time | Total_voltage | Total_current | Battery_status | Lon | Lat |
| 'S2C-001' | 'LSFD13209... | 04-Aug-2024 08:06:16 | 555.5000 | 11.7000 | 99 | 121.5178 | 30.8412 |
| 'S2C-001' | 'LSFD13209... | 04-Aug-2024 08:06:26 | 555.7000 | 9.2000 | 99 | 121.5175 | 30.8417 |
| 'S2C-001' | 'LSFD13209... | 04-Aug-2024 08:06:26 | 555.7000 | 9.2000 | 99 | 121.4936 | 30.9071 |
| 'S2C-001' | 'LSFD13209... | 04-Aug-2024 08:06:36 | 555.5000 | 9.1000 | 99 | 121.5175 | 30.8417 |
| 'S2C-001' | 'LSFD13209... | 04-Aug-2024 08:06:36 | 555.5000 | 9.1000 | 99 | 121.5077 | 30.8328 |
| 'S2C-001' | 'LSFD13209... | 04-Aug-2024 08:06:46 | 555.9000 | 6.7000 | 99 | 121.5081 | 30.8323 |
| 'S2C-001' | 'LSFD13209... | 04-Aug-2024 08:06:46 | 555.9000 | 6.7000 | 99 | 121.5173 | 30.8419 |
| 'S2C-001' | 'LSFD13209... | 04-Aug-2024 08:06:56 | 555.7000 | 9.2000 | 99 | 121.5087 | 30.8316 |
| 'S2C-001' | 'LSFD13209... | 04-Aug-2024 08:06:56 | 555.7000 | 9.2000 | 99 | 121.5169 | 30.8426 |
| 'S2C-001' | 'LSFD13209... | 04-Aug-2024 08:07:06 | 0 | 0 | 99 | 121.5093 | 30.8307 |

Sustainable, reliable, comfortable, and enjoyable multi-modal mobility holding PUBLIC TRANSPORT at the center

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# Appendix: Notation



| Variables | Expression | Unit |
|---|---|---|
| $\tau$ | The period in the unit of hour | h |
| $N$ | Bus fleet size | bus |
| $H$ | Bus line operation hours in one day | h |
| $T$ | Travel time between terminals | h |
| $S$ | The number of charging points at terminals | point |
| $\gamma_{dis}$ | Energy discharging rate | kW/bus |
| $\gamma_{char}$ | Energy charging rate | kW/bus |
| $\eta$ | Energy consumption per bus | kW/bus |
| $c_e(t)$ | Energy market price in time period t | $/kWh |
| $c_m$ | Maintenance cost for a bus per day | $/day |
| $\varepsilon$ | Discharge price to the grid (FCR contract) | $/bus per day |
| $\rho$ | The fee paid per passenger | $ |
| $E_{ba}$ | Battery capacity per bus | kWh |
| $SOC_{min}$ | Minimum state of system energy | % |
| $SOC_{max}$ | Maximum state of system energy | % |
| $SOC_0$ | The initial state of charge of system energy | % |
| $Y(t)$ | Passenger demand in time period t | pas |
| $P(f)$ | Demand multiplier considering service frequency | % |