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Low Carbon Charging Schedule of Electric Buses: Case Study in Denmark and Japan

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***Abstract*—This study examines regional differences in time-varying carbon dioxide (CO_2) emissions from power systems in Denmark and Japan, influencing on the low-carbon charging schedules of electric buses in public transportation systems. The time-varying CO_2 emissions differ significantly due to variations in the penetration rates of variable renewable energy (VREs) sources, particularly wind power. Numerical experiments reveal that under an optimal charging schedule, total CO_2 emissions in Denmark are 81% lower in summer and 71% in winter compared to Japan when chargers are available only at their depot. Additionally, distributing chargers across all bus terminals ensures the feasibility of transportation in winter. Furthermore, distributed chargers at bus terminals have potential to reduce emissions by up to 4% further by expanding the flexibility of charging times to align with VRE utilization throughout the day. This international comparison highlights the critical importance of optimizing charging schedules in high VRE penetration systems, where CO_2 emissions exhibit significant daily fluctuations.**

***Index Terms*—electric bus, international comparison, PV, renewable energy, time-varying CO_2 emission, wind power**

I. Introduction

With the increasing electrification of public electric vehicles (EVs), such as passenger electric buses, and the substantial integration of renewable energy (RE) including variable RE (VRE) into the power grid, effective management of both resources has become crucial for low-carbon operation. The combined impact of EVs and VREs in advancing a low-carbon society has been extensively studied [1]. However, the insufficient utilization of VREs for charging significantly impairs the carbon footprint, undermining the appeal of electrification [2].

Although transparency of RE utilization improves the presence of EVs, the energy mix of VREs impacts on uncertainty of low-carbon energy supply in system level. Denmark achieves the 54% of wind power in its energy mix, along with bioenergy and photovoltaic (PV) generation occupies 81% RE [3] in 2023. Besides, as though Japanese government declared to achieve net-zero society by 2050, energy mix consists of low penetration of VREs or biomass: 9.8% of PV, 1.1% wind power and 4.1% biomass in fiscal year of 2023 [4]. In the both system with high or low penetration of VRE, smart charging management system is required to effectively utilize such variable sources while avoiding high carbon emissions.

Electric buses for public transportation are expected to effectively utilize VREs through centralized charging management by a single operator, enabling precise selection of varying low-carbon emission time periods. Several studies have explored VRE utilization by heavy-duty vehicles such as PV power utilization in Hong Kong [5] or in Taiwan [6], and wind power generation in Taiwan [7] by electric vehicles as well as garbage refuse trucks in Denmark [8], while they have ignored the level of grid emissions. Studies on grid carbon dioxide (CO_2) emissions modeling have been conducted on 30-minute electricity market level in Australia [9], quarter-hourly carbon intensity considering energy mix with life-cycle CO_2 (LC-CO_2) emission of electric buses in Germany [10], or high geographical resolution with behind-the-meter self-consumption [11]. These studies offered precise time-varying CO_2 emissions information for utilization of the low-carbon energy for electric buses. Nakano et al. [12] proposed the low-carbon charging operation by using such time-varying emission data [11] and local emissions for primarily utilizing PV generation in Utsunomiya, Japan, while they have not investigated the variety of CO_2 emissions derived from different VRE penetration rate, nor established transporting schedule model with bus terminals. Under high penetration of VREs, especially wind power, grid CO_2 emission can be significantly fluctuating, leaving optimal charging time periods unclear. Furthermore, the restricted charging period at the depot hinders the opportunity to utilize low-carbon energy from VREs.

The purpose of this paper is to examine the impact of time-varying CO_2 emissions on low-carbon charging schedules of electric buses in two regions, Denmark and Japan, with significantly different levels of VRE integration, along with the influence of distributed chargers at the bus terminals.

A. *Overview of low-carbon charging schedule*

The low-carbon charging schedule is conceptually illustrated in Figure 1. The optimal charging schedule, designed to align with time-varying CO_2 emissions, enhances low-carbon operation when the VREs generation fluctuates due to weather conditions, all while maintaining compliance with the public transportation timetable.

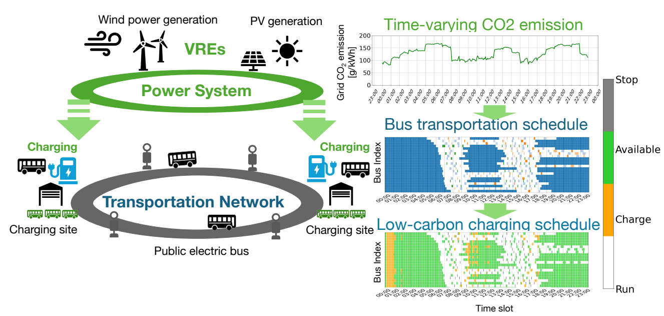


Fig. 1: Conceptual diagram of low-carbon operation for electric buses by utilizing energy derived from VREs.

B. *Time-varying CO_2 emission and bus transportation model*

Grid CO_2 emissions are solely disclosed by transmission system operators as annual average value in Japan [13], while five-minute CO_2 emissions data are updated in every 15 minutes in Denmark [14]. Time-varying CO_2 emission has been modeled by one-hour output of each generation types in service area of Tokyo Electric Power Company Holdings weighted by LC-CO_2 emissions described in Table I. Figure 2 illustrates typical monthly time-varying CO_2 emission in summer and winter season in Japan and Denmark. In general, the emissions in Japan are higher than in Denmark due to a lower VRE installation rate. In the case of Japan, PV generation in daytime contributes to improving grid emissions while they are consistently high during night-time because of low penetration of other types of RE sources such as wind power. On the contrary, the emissions in Denmark are significantly variable throughout the day. Notably, CO_2 emission during night is low due to the wind power generation. In the viewpoint of seasonal difference, CO_2 emissions in summer are relatively lower than in winter at both regions. The difference in daylight hours between summer and winter significantly affects daytime CO_2 emission factors, with this impact being particularly pronounced in Denmark: a high-latitude region. In addition, the range of emissions during each day in night time becomes wider in summer season in Denmark, which might derive from the heavy energy demand for light or heat.

The public electric bus transportation schedule is modeled by using data provided by the Danish public transport authority Movia, which works towards achieving a fossil-free bus fleet by 2030. As of 2023, its fleet includes 404 operational electric buses, with approximately 380 active on a typical week/day. The average usable [15] battery capacity across the fleet is 430 kWh, with individual capacities ranging from 288 to 525 kWh. We selected 22 Yutong E15 buses currently operating on a specific route, line 150S between Kokkedal and Nørreport terminal in Copenhagen, with the charging depot. We assume that each bus runs throughout the day without switching back-up buses. Figure 3 visualizes the transportation schedule of each bus as well as energy consumption summarized into five minutes timetable. Seasonal variation in electricity consumption rates was accounted for, with a 20% increase in winter compared to summer [16].

Charging infrastructure for Danish electric buses is centralized at operator garages, with a standard charging power of 150 kW across the fleet. Opportunity charging is allowed only for vehicles equipped with the smallest battery capacities. In contrast, Japan's electric buses are primarily deployed in urban centers such as Tokyo and Yokohama. Japan's urban-focused operations generally involve shorter route distances, reducing the need for backup buses and enabling efficient use of compact battery systems.

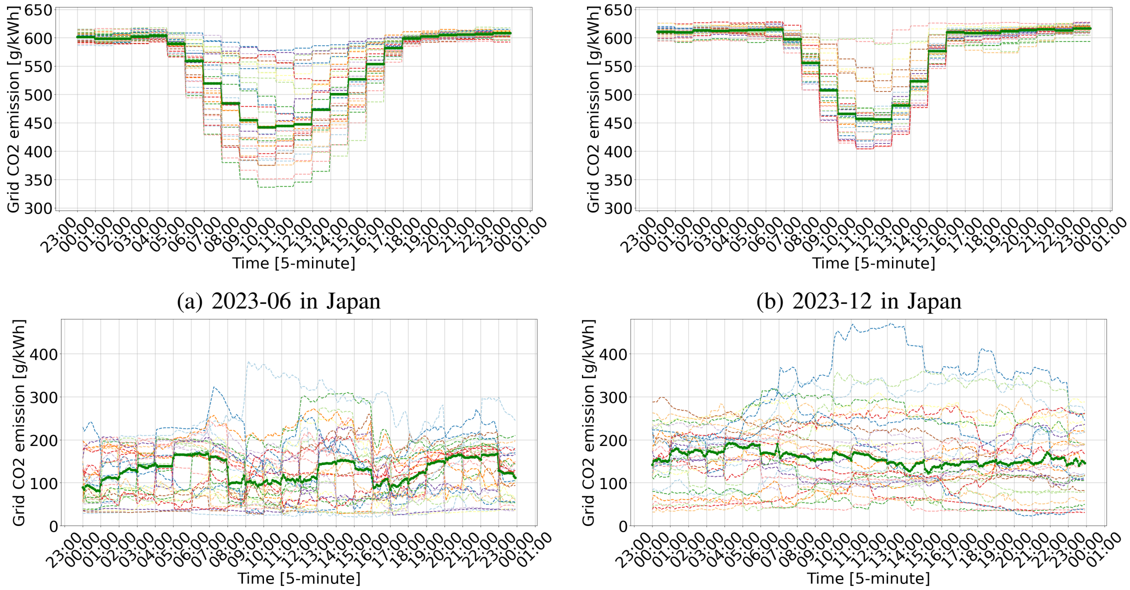
TABLE I: LC-CO_2 emissions in Japan

Generators	Life-cycle emissions [g-CO_2/kWh]
Thermal	686
Pumped storage	474
Interconnection	463
Solar PV	55.0
Wind	26.0
Biomass	23.0
Nuclear	19.0
Geothermal	13.0
Hydro	11.0

LC-CO_2 emissions described by Sugano et al. [11] for the Japanese case, considering construction materials for typical generators and representative carbon intensity of interconnections reported by CRIEPI [17].

II. Low-carbon charging schedule

The purpose of low-carbon charging schedule is to minimize the total CO_2 emission being recharged into all buses during operation. Let $\mathcal{N} = \{1, \ldots, N\}$ be the set of bus vehicle,



(a) 2023-06 in Japan

(b) 2023-12 in Japan

(c) 2023-06 in Denmark

(d) 2023-12 in Denmark

Fig. 2: Comparison on time-varying CO_2 emission in Japan and Denmark. Horizontal axis describes five-minute time slot, while vertical axis indicates the CO_2 emission [g-CO_2/kWh]. Bold green lines show the median value in every five-minute slot for representing the dynamics of monthly CO_2 emission. Dashed lines represent the actual value of each day of the month.

$\mathcal{M} = \{1, \ldots, M\}$ be the set of charging site and $\mathcal{T} = \{1, \ldots, T\}$ be the set of time slots. The optimization model minimizes the total amount of CO_2 emission by optimizing the output of the charge flag, $c_{n,m,t} \in \{0, 1\}$, for vehicle $n \in \mathcal{N}$, charging site $m \in \mathcal{M}$, and time slot $t \in \mathcal{T}$. A value of $c_{n,m,t} = 1$ indicates that the vehicle is charging at the site during the time slot. The objective function and the decision variables are as follows:

$$\underset{c_{n,m,t}, q_{n,t}}{\operatorname{argmin}} \sum_{t \in \mathcal{T}} w_t \sum_{m \in \mathcal{M}} \sum_{n \in \mathcal{N}} c_{n,m,t} \cdot g, \tag{1}$$

where the decision variables are as follows:

- $c_{n,m,t}$: Charge flag for vehicle n at the charging site m during the time interval t.
- $q_{n,t}$: State-of-Charge (SoC) of vehicle n at time slot t.

The CO_2 emissions for bus charging consists of the charging demand, g, for designated flag, $c_{n,m,t}$, weighted by time-varying CO_2 emission index, w_t.

For feasible transport operations of a public electric bus, this problem is subject to two types of constraints:

1) **SoC constraints:** ensuring that each bus maintains an adequate SoC for operation.
2) **Charge availability constraints:** considering the number of chargers available at each site.

The SoC constraints guarantee the feasibility of transportation schedule by tracking sequential SoC of each bus:

$$\underline{q} \leq q_{n,t} \leq \overline{q} \qquad (n \in \mathcal{N}, t \in \mathcal{T}), \tag{2}$$

$$q_{n,t=1} - \eta \cdot g \leq q_{n,t=T} \leq q_{n,t=1} + \eta \cdot g \qquad (n \in \mathcal{N}), \tag{3}$$

$$b \cdot q_{n,t} = b \cdot q_{n,t-1} - l_{n,t} + \sum_{m \in \mathcal{M}} c_{n,m,t-1} \cdot \eta \cdot g \qquad (n \in \mathcal{N}, t \in \mathcal{T} \setminus \{1\}), \tag{4}$$

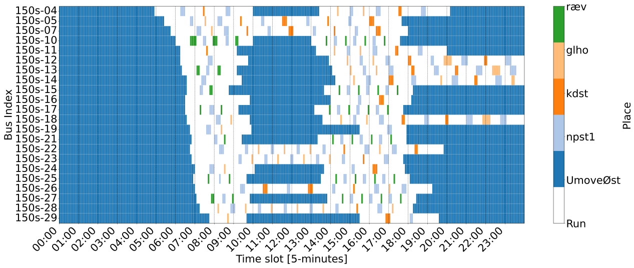
where $\underline{q}$ and $\overline{q}$ are the upper and lower bounds of the SoC of the onboard battery pack capacity, b. The energy consumption required for transporting customer as well as returning the depot is described by $l_{n,t}$, which takes the seasonal electricity consumption into account. The coefficient g denotes the constant value of energy delivered from the charger during the time slot, and η represents the overall charging efficiency. Equation (2) represents the upper and lower bound constraints on the SoC, which are maintained between a reasonable range primarily ensuring the feasible operation and secondarily sustaining the state of health (SoH) of the battery pack. Equation (3) provides the SoC value relationship between the initial and final time slot. The initial and final SoC is optimized for low carbon operation in the target day. The SoC of each bus in the final time interval must be within a range to be adjusted to the initial value of the next day with an additional charge or discharge of five minutes. Equation (4) represents the time-series of the SoC.

The charging availability constraints identify the number of buses being recharged as well as the charging timing at any time slot as follows:

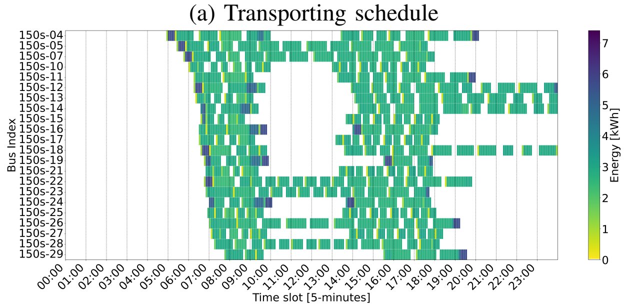
$$\sum_{n \in \mathcal{N}} c_{n,m,t} \leq k_m \qquad (m \in \mathcal{M}, t \in \mathcal{T}), \tag{5}$$

$$c_{n,m,t} \leq s_{n,m,t} \qquad (n \in \mathcal{N}, m \in \mathcal{M}, t \in \mathcal{T}), \tag{6}$$

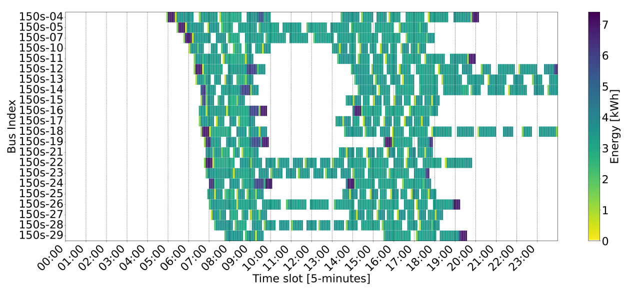
where $k_m > 0$ denotes the number of chargers at charging site m, and $s_{n,m,t} \in \{0, 1\}$ represents whether bus n is at charging



(a) Transporting schedule



(b) Energy consumption in summer



(c) Energy consumption in winter

Fig. 3: Bus transportation model in Denmark. We selected buses at the line 150S operated by Umove during workday and defined Umove Øst as the depot for their buses.

site m during time slot t. $s_{n,m,t} = 1$ indicates the bus is stopping at the charging site. Equation (5) describes the maximum number of buses able to be recharged simultaneously at each charging site. Equation (6) uses the preset condition of being stopped, $s_{n,m,t}$, to omit the running time slot for charging.

III. Numerical simulation

The purpose of this numerical simulation is to evaluate the impact of time-varying CO_2 emissions on the optimal charging schedule in two regions with different introduction of VREs, along with the influence of widespread chargers at the bus terminals on their route.

A. Set up

The monthly median value of time-varying CO_2 emission data for every five minutes in Jun. and Dec. 2023 are used to investigate the differences between Japan and Denmark. The bus transportation model is described in Fig. 3 and the specification of chargers are summarized in Table II. We assume a single depot equipped with one charger per bus, totaling 22 chargers, each with 150 kW power. In addition, we examine the case when one 150 kW charger is equipped at each bus terminal for evaluating the effect of distributed charger on the route, which is available only if the bus stops for more than five minutes. We further assume that the buses charge at constant power rate by the charger.

TABLE II: Simulation settings

Specifics	**Values**	**Units**
# bus	$N = 22$	-
Battery pack capacity	$b = 563$	kWh
Upper / lower bounds of SoC	$\underline{q}/\overline{q} = 5.00/95.0$	%
Electricity consumption: Jun. / Dec.	$1.02/1.23$	kWh/km
# charger at depot m	$k_m = 22$	-
# charger at each bus terminal m	$k_m = 1$	-
Charging power output	$g = 150$	kW
Total charging efficiency	$\eta = 98$	%

B. Results and discussions

Figure 4 describes the total amount of CO_2 emissions charged into buses during daily operation. CO_2 emissions were lower in both regions in Jun. compared to Dec. due to the longer duration of daylight and PV generation. However, the total amount of CO_2 emissions was significantly lower in Denmark due to high penetration of wind and PV generations. In the scenario where chargers are available only at the depot, the total emission in the case of Denmark decreased 81% in Jun. and 71% in Dec. relative to that of Japan. The lower installation rate of low-carbon generators in Japan resulted in higher emissions. In the scenario of widespread chargers in every bus terminal, the total emissions decreased 4.0% in Jun. compared to the scenario where the chargers are available only at the depot in Japan as well as 1.7% in Jun. in Denmark. The chargers at each bus terminal expanded the opportunities for bus operators to recharge buses during time slots with lower emissions as well as stability of operation. Furthermore, in the winter season, the model without distributed chargers did not yield feasible results for additional two buses operated in the same line, due to a higher energy consumption in a colder climate. Hence, distributed chargers along the route are necessary to safely fulfill the driving requirements of all buses.

Figure 5 demonstrates the series of operation result for each case in Jun. In the case of Japan in Fig. 5a, the charging time slots were concentrated during the daytime for utilizing PV oriented energy, while buses are recharged in high-carbon emission slots during early morning and evening to achieve their transportation needs; thus, the carbon emission increased. Figure 5b indicated that the charging slots spread across the whole day, considering variable CO_2 emissions. The low-carbon slots appeared not only in daytime but also in night time, which derived from wind power. The optimal charging schedule determined successfully the low-emission slots. This result indicates that time-varying emissions with high penetration of wind power, as well as PV, influences significantly the charging schedule. However, due to the transportation in rush hour, the buses were unable to utilize low-carbon energy around 8 A.M. as well as 4 P.M. in the two cases.

On the other hand, Fig. 5c shows that the buses are able to use low-carbon energy derived from PV generation by utilizing chargers at bus terminals during day-time. Similarly, Fig. 5d represents that the chargers at bus terminals are used in such periods. This result suggests that the chargers in the bus terminals contribute to expanding the opportunity to utilize low-carbon energy. The charging demand was concentrated in specific time for solely achieving low-carbon emission and resulted in extreme demand. This is because the maximum charging demand was not taken into account to validate the influence of time-varying CO_2 and charger availability. In fact, the number of simultaneous charging buses can be affected by the available grid capacity and affordable price for grid connection. A smaller number of chargers at the depot will place greater importance on the availability of distributed chargers at bus terminals, while achieving a balance between the distribution of local electricity demand and accessibility to low-carbon charging periods.

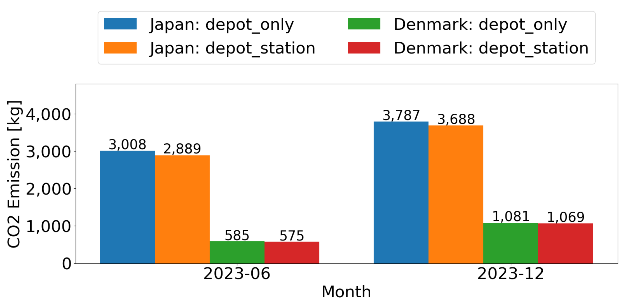


Fig. 4: Comparison of total amount of CO_2 emission. The color shows each case: blue and orange bar suggests the case of Japan while green and red bar indicates the case of Denmark, with each charging availability conditions.

IV. Conclusion

This paper investigated regional differences in time-varying CO_2 emissions of power systems between Japan and Denmark as well as the impact of the distribution of chargers, influencing on low-carbon charging schedule of electric buses for public transportation systems. The characteristics of time-varying emissions between the two countries differ significantly due to the penetration rate of VREs, particularly wind power. The numerical simulations demonstrated that the total CO_2 emissions under the optimal charging schedule in Denmark are 81% lower in summer and 71% compared to Japan in the scenario where chargers are available only at depots. In addition, in case the chargers are distributed into every bus terminal, optimization schedule guarantees the feasibility of operation in winter. Furthermore, the emission decreased in this case because flexibility of charging time expands to follow VREs throughout the day. This international comparison highlights that optimizing charging schedules becomes increasingly critical in systems with large VRE penetration, where CO_2 emissions fluctuate significantly during the day.

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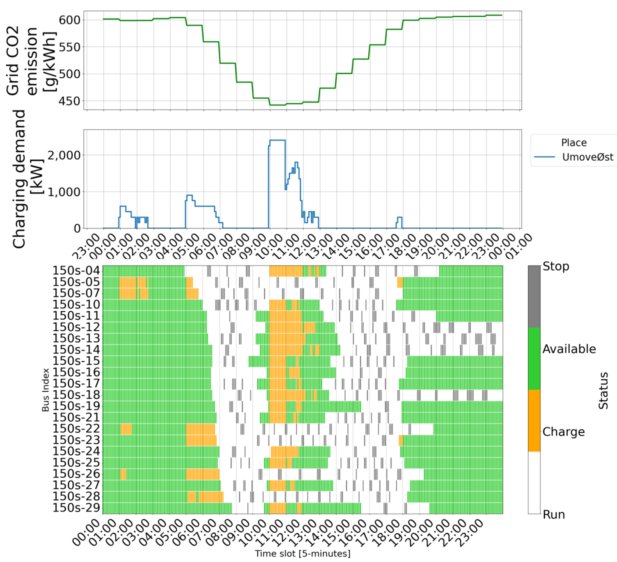
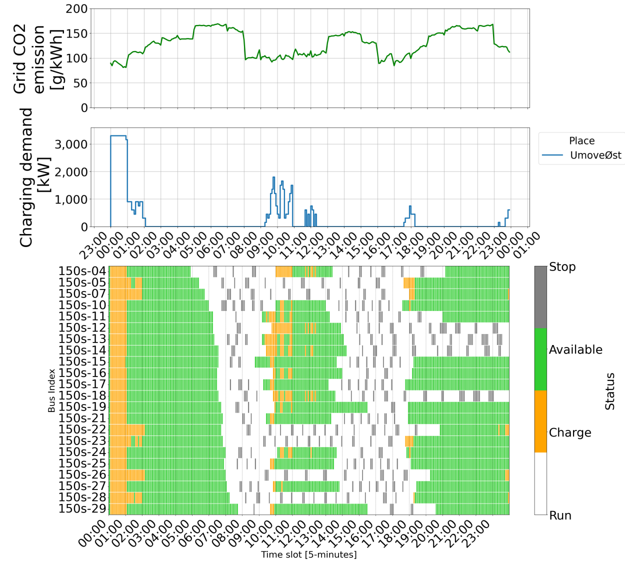
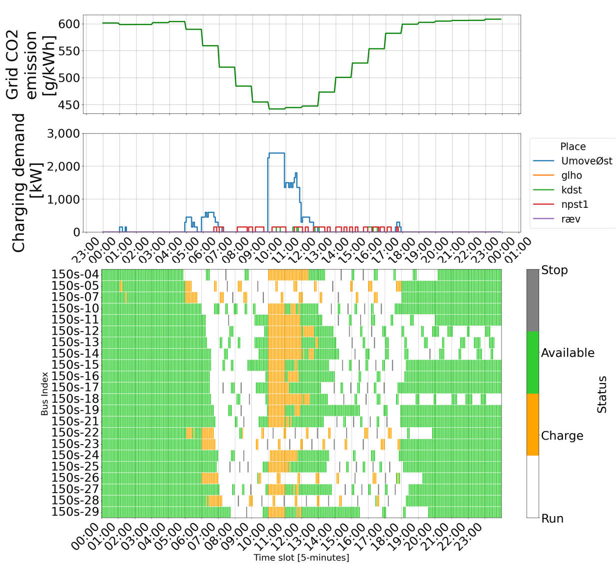


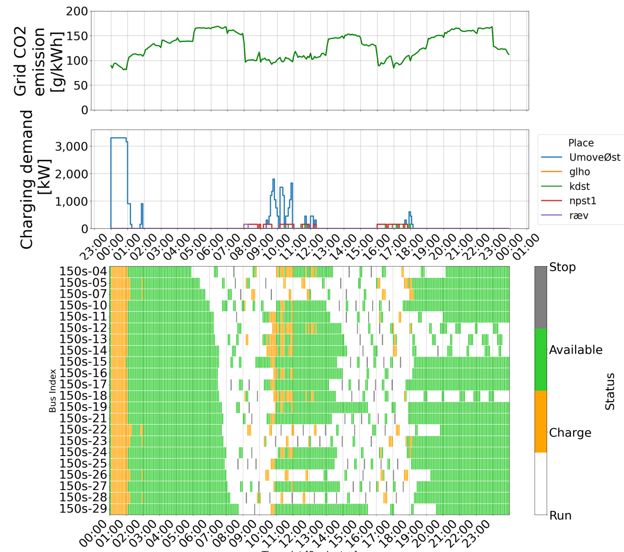
(a) Charger available only at depot with CO_2 in Japan



(b) Charger available only at depot with CO_2 in Denmark



(c) Charger available at depot and terminals with CO_2 in Japan



(d) Charger available at depot and terminals with CO_2 in Denmark

Fig. 5: Comparison of operation under different emissions and charger availability. The upper subfigure shows the representative time-varying emissions in Jun. while the middle summarizes the charging demand at each sites. The determined timetable is described in the bottom; yellow cells indicate the charging slots, green cells represent the available slots and gray cells denote the bus stopping without availability of charger.

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