Towards Holistic Charging Management for Urban Electric Taxi via a Hybrid Deployment of Battery Charging and Swap Stations

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Abstract

While previous studies focused on managing charging demand for private electric vehicles (EVs), we investigate ways of supporting the upgrade of an entire public urban electric taxi (ET) system. Concerning the coexistence of plugin charging stations (CSs) and battery swap stations (BSSs) in practice, it thus requires further efforts to design a holistic charging management especially for ETs. By jointly considering the combination of plug-in charging and battery swapping, a hybrid charging management framework is proposed in this paper. The proposed scheme is capable of guiding ETs to appropriate stations with time-varying requirements depending on how emergent the demand will be. Through the selection of battery charging/swap, the optimization goal is to reduce the trip delay of ET. Results under a Helsinki city scenario with realistic ETs and charging stations show the effectiveness of our enabling technology, in terms of minimized drivers' trip duration, as well as charging performance gains at the ET and station sides.

Key Words: Electric Vehicle, Charging System, Driver's Trip Duration, Battery Swap

1. Introduction

Electric vehicles (EVs) are gaining the popularity of general public and starting to penetrate the transportation landscape [1], driven by the advances in sustainable energy development. By integrating more renewable energy sources on the grid, such as from wind, solar and run-of-water, EV charging network can be further extended through providing renewable energy to its customers. Benefited from the rise in charging stations, the broad charging network is capable of serving more EV drivers. In order to support growing for eco-friendly travel, EVs are becoming mainstream especially in public transport.

Specifically, with government incentivizing EV use, China, now the largest developing country in the world, has introduced a plan to promote the popularity of electric taxicabs (ETs) (and goods vehicles, buses) nationwide, to reduce exhaust pollution. In southern China cities like Shenzhen, all public buses have been transitioned to electricity-powered by the end of 2017. As of Feb. 2019, 99 percent of the city's taxicabs went electric [2]. The city is expected to replace its entire fleet of taxicabs with ETs by 2020 [3]. Other countries, like the UK and US government as well as some European countries, are also actively engaged by advocating battery-powered public transportations [4].

Nevertheless, the main problem with electrification of public transportation is driving range. As one of the major players in the eco-systems, ETs face similar weakness of EVs: range anxiety and slow charging. During peak-demand hours in particular, ETs spend most of their time on-the-move, busy with picking up/dropping customers. A low range, however, would require frequent recharging, while a relatively long charging period is another hassle for drivers. The precious time for business would be affected concerning these issues. Moreover, locating convenient charging services are also among the major concerns [5].

Consequently, Electro-Mobility (E-Mobility) becomes of vital importance when considering efficient charging management. As for refueling ETs, there are presently two major ways: plugin charging (PC) and battery swapping (BS). Traditional plugin recharging is accomplished by plugging EVs into charging slots (set by PC stations placed at different city locations). In contrast, at the station providing the battery swap service [6], the automated swap platform switches the depleted battery from an EV, with a fully charged battery it maintains. Both charging modes have shown their effectiveness and have been widely deployed to provide desirable services [6]-[8]. From the perspective of economical concern, ETs are more willingly to refill batteries with plugin charging mode at off-peak period, e.g., when demand is few or energy cost is low at night time. In areas where demand-response time comes at a premium, e.g., at peak demand hours, ETs prefer to go for BS services so as not to miss the peak hours of their business. In fact, PC charging stations (CSs) and BS stations (BSSs) have been both deployed in numbers and scales in practice [9]. The evolution in charging stations of multi-modes allow ETs to have options to choose independently according to various needs. However, this inter-play pattern between the two charging operations introduces a new issue: *How to effectively enable ET charging based on a combination of PC and BS?*

Most of existing works optimistically consider a single scenario of charging mode, where all vehicles experience the same charging mode, i.e., either PC or BS. Towards a more realistic setting, the coexistence of CSs and BSSs are more practical. Within the context of a combined charging stations, relevant research works are lacking. More efforts are thus needed to put forth into the joint concern on the combination of plugin charging and battery swapping.

Considering the service provisioning, efficient inter-operations between PC and BS are thus required. Towards this end, a *hybrid charging* management framework is proposed in this paper. The basic concept is to guide ETs to appropriate stations (CS or BSS) with time-varying requirements, by accounting for trip durations as well as charging load distribution. Essentially, the trip duration considers the traveling of an ET for recharging before serving a customer, which is tightly related to the demand-response time. Therefore, it is regarded as a critical factor for decision-making on optimal station-selection. Technically, our contributions areas follows:

1) *A joint concern on plugin charging and battery swapping*: A hybrid charging management framework is proposed in this work, in order to address the issue with coexistence of the two charging modes in practice. Through the selected station, an ET would experience the shortest trip towards its destination, i.e., from current location to next customer pickup point. By additionally considering the charging demand distribution, the load could be desirably balanced over the network, which benefits the reduction on expected waiting time for recharging as well.

2) *Dynamic charging scheduling in real-time for ETs on-the-move*: ETs are consistently moving and thus, and their related knowledge changes over time and space. It is thus challenging for identification and positioning of the random varying impacts. Such issue could be effectively mitigated by enabling charging reservations, including vehicle arrival time and expected charging period, etc. Such information could also be adopted to enhance the station-selection process, wherein estimations on station status could be improved with great accuracy.

The rest of this paper is organized as follows. Section II provides a brief review on related works. System model is elucidated In Section III, and we present our proposed hybrid charging framework in Section IV. Performances of the proposed scheme is evaluated in Section V through extensive simulations and the paper is finally concluded in Section VI.

2. Related Work

Most of existing research works focus on the charging management for private EVs [6]-[8] [10]-[14], while limited works concern the charging issues with ETs [9][15]-[17].

- Private EVs Charging Management

Early works promoted to incentivize EVs not to charge at locations or during periods of high demand [10] (e.g., to avoid peak demand hours). As for charging operational aspect, several research works have proposed to optimally schedule EVs for high station utilization. Within this context, most existing researches mainly concern the issue on where to charge [7][8], and an optimal CS is selected with guidance [11][12]. Game theoretic models are extensively employed for modelling charging interactions [13]. Also, optimal pricing is achieved through maximization of individual utility functions through Nash equilibrium evaluations [14].

- Battery Swapping Service

By concept, the basic swapping approach enables the EV user to quickly replace a depleted battery with a fully-charged spare within minutes. Depleted batteries are placed and recharged for use of other EV drivers. Undesired effects of plug-in charging include longer charging time, expensive batteries and battery degradation of fast charging, etc. They can be mitigated by using the BSS [6][18]. Essentially, the immediate service in supplying power to EV can provide great benefits to power system. On the other hand, the large-scale adoption of EVs are hindered due to costly ownership. By taking out of the battery the cost can be reduced. For instance, a third party will have the ownership of the battery and the liability for replacing the discharged batteries with fresh and charged ones [19]. Clearly, separation of vehicle and battery pack might work better for all in price-conscious markets.

- ETs Charging Management Based on BSS

A single battery charging scenario (e.g., swapping mode only) is normally assumed with ET charging. Within this scenario, majority works focus on the placement and sizing of swapping stations for ETs [9][15][16], so as to reduce congestions and queueing time. With station locating/selection problem, a few works aim to select an optimal station for ETs by accounting for queueing time and driving distance [17], etc., similarly to the plugin CS selection concern however with different queueing modelling at BSS. With economical concern from ETs, authors of [20] aim at maximizing profits for individual ETs by formulating the issue as a constrained binary programming problem.

- Charging with Renewable Energy

Considering the charging infrastructure planning, renewable energy sources can be installed for pollution-free and cost-effective charging, which would relieve high power demand and its impact on grid as well. Plenty of related works have been working on this area, concerning the issues with unstable renewables generated from solar and wind [25]. Within this realm, the basic concept is to maximize the usage of clean energy drawn from renewable energy sources for charging, driven by their environmentally friendly nature along with low cost. From the perspective of EV (and ET) customers, one obvious benefit is the reduced charging price, and the eco-friendly property is another compelling feature. It is worth noting that charging with renewable energy is mainly the concern in the design of charging stations, while this work takes a step further to consider the charging scheduling for moving vehicles. However, the proposed solutions in this paper can be well adopted on top of any designs integrated with renewable energy supplies.

- Our Motivation

However, few research works consider the interplay with hybrid charging when BS combined with plugin charging. An only relevant research work [21] considered such integrated scenario but mainly explored the taxi dispatching problem, rather than charging issue, therefore the detailed modeling at BSS and CS are not addressed in that work. Particularly, that work fails to investigate the optimal solution to operate CS and BSS depending on the timeliness of traveling demand. And yet, key network dynamic patterns are not taken into account, such as spatiotemporal properties associated with the fleet of taxis, which were treated as stationary loads with their research.

3. System Model

In this work, we focus on the inter-operations between plugin charging and battery swapping, and aim to propose an efficient hybrid charging management scheme for ETs *on-the-move*, so as to determine *whether to charge/swap* and *where to charge/swap* at real time.

3.1 Overview

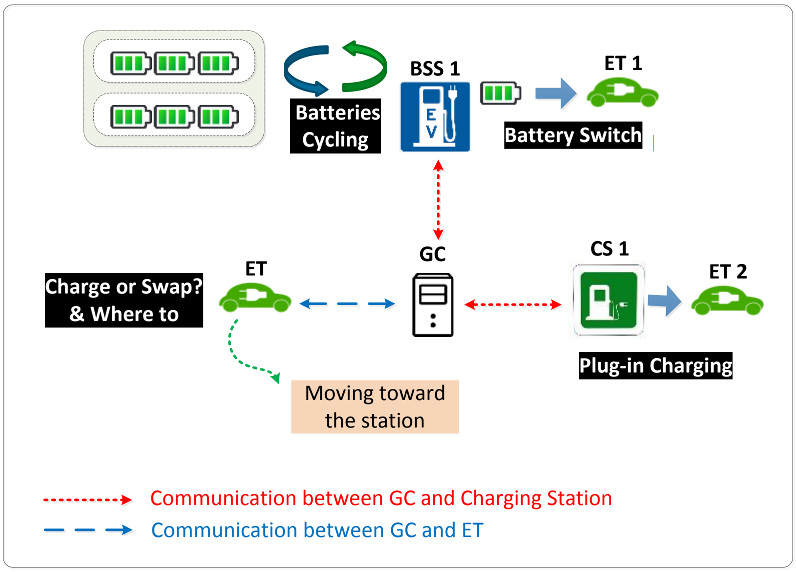


Figure 1. Big picture where GC globally aggregates charging information from BSSs and CSs and selects charging stations for ETs on-the-move.

We consider a city scenario where plugin CSs and BSSs are both geographically deployed. As depicted in Fig. 1, a global controller (GC) manages charging demands from all ETs in the network, by determining whether to charge or swap, and where to. The following network entities are involved (parameters are defined in Table I):

- **Electric Taxicab (ET)**: Each ET is with a state-of-charge (SOC) threshold. The vehicle is basically on-the-move and checks its SOC value regularly. Once its current value is below the threshold, an energy replenish request is sent to the GC to select a proper charging station (CS or BSS). Further to this, the ET confirms the recommendation by reporting a *reservation* to the GC, including context information such as vehicle identification, time to arrival and expected charging time, which could take the form of $<ev\_id,\ T_{et}^{arr},\ \delta^{cha}>$. As for a battery swap service, the expected charging time (δ^{cha}) refers to the duration to charge the depleted battery.

- **Charging Station (CS)**: CSs are scattered around the city where there are usually parking lots or shopping malls. Each CS maintains multiple charging slots to serve ETs in parallel. Its charging condition is monitored by the GC, with regard to the number of ETs parked at the station and their expected charging durations.

- **Battery Swapping Station (BSS)**: Each BSS maintains a battery inventory filled with a number of fully-charged battery spares. As ETs arrive, depleted batteries are removed and will be recharged at the BSS. If there are batteries available at the inventory, the ET will be replaced by a fully charged spare. Otherwise, ETs have to wait for drained batteries to be charged up. The condition information of each BSS is also monitored by the GC, regarding the availability of batteries for switch.

- **Global Controller (GC)**: It is a centralized entity that manages all charging demand across the network from ETs, and globally monitors the real-time charging station status, including charging sessions and number of parked ETs, etc. By aggregating such context information from the network, the GC is able to accurately estimate the available time for charging/swap[1] upon a charging request. Based on such approximation, the central network intelligence determines whether to charge at a CS or a BSS for a requestor ET, and selects the optimal station. Such station-selection decision making can be further enhanced by enabling charging reservations.

The typical procedure for the proposed hybrid charging management is described as follows (as shown in Fig. 2)

- **Step 1**: The GC globally monitors the real-time status of all BSSs and CSs over the charging network. Such condition context will be used for estimation of the Available Time for Charging (ATC) at each CS, and also the Available Time for Swap (ATS) at each BSS, which are critical context information for decision-making on optimal station-selection. These two indicates the time that a charging slot or fully charged battery becomes available for service.

- **Step 2**: Once a low SOC (i.e., compared to SOC threshold) is detected, the on-the-move ET, namely ET_r, will send a recharging request to the GC for proper station selection.

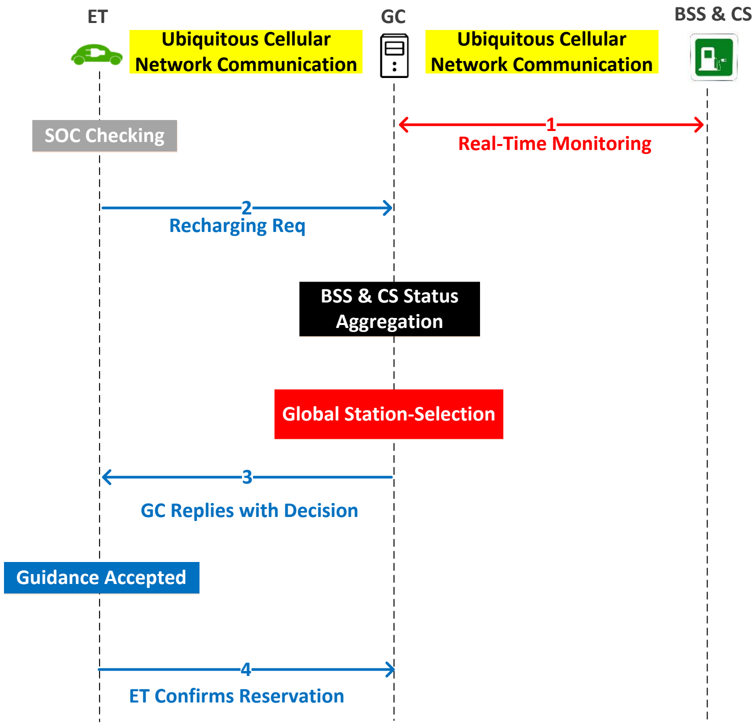


Figure 2. Time sequences for the hybrid charging framework

- **Step 3**: Upon receiving a recharging request, the GC aggregates the real-time charging status from all stations over the network, so as to estimate ATC and ATS. A proper station with BS (and PC) will be computed, respectively, which governs the final Global Station-Selection procedure. And then a most appropriate station recommendation is replied to ET_r. The

[1] For a CS, the information indicates the available time for each charging slot. With BSS, it reflects the availabilities of batteries being charged (charging finish time).

selection details will be elaborated in detail in Sec. 4.

- **Step 4**: The ET then confirms the selected station by reporting its reservation to the GC, including context information concerning <ev_id, T_{et}^{arr}, δ^{cha}>.

Table I List of Notations

Symbol	Description
N_B	Number of switchable batteries
N_C	Number of batteries being charged at a CS
N_D	Number of depleted batteries removed from incoming ETs
N_W^{cs}	Number of ETs parked at a CS
N_W^{bss}	Number of ETs parked at a BSS
N_R^{bss}	Number of ETs that have made reservations at a BSS station
N_R^{cs}	Number of ETs that have made reservations at a CS station
ρ_{sw}	Time duration to swap a battery
θ	Number of charging slots at a BSS
μ	Number of charging slots at a CS
σ	Constant parameter indicating the tolerance range
ATS	Available time for swap
ATC	Available time for charging
T_{et}^{arr}	ET arrival time
T_{et}^{tra}	Duration to travel to the selected charging station from the ET's current location
$T_{cs,d}^{min}$	Time to travel from the CS to trip destination
$T_{bss,d}^{min}$	Time to travel from the BSS to trip destination
$T_{et}^{cs,d}$	Trip duration of an ET through charging at a CS
$T_{et}^{bss,d}$	Trip duration of an ET through charging at a BSS
T_{et}^{arr}	ET's arrival time at the charging station
l_{cs}	Location of a CS
l_{bss}	Location of a BSS
EWTC	Expected waiting time for charging at CS
EWTS	Expected waiting time for swap at BSS
δ^{cha}	Expected (battery) charging duration for the ET
D_{et}^{trip}	Customer trip tolerance for a reserved ET
$d_{et\rightarrow cus}$	Direct distance from ET location to customer spot
$\delta_{et\rightarrow cus}$	Travel duration for an ET from its current location to customer spot without intermediate charging
v_{et}	Moving speed of ET

3.2 Assumption

In practice, there are limited charging slots installed at a CS. As a result, arriving ETs often have to queue up waiting while all slots are occupied. Considering the potential issue of overcrowding, CSs would be benefited more if deployed at places with enough parking space. Therefore, CSs are assumed to be installed at suburban areas around the city [16], where space is usually not a concern. In comparison, ETs does not suffer from too much waiting at a BSS, mainly owing to the short swapping time (e.g., at minutes level) [6], thus requiring less parking space. As such, BSSs are normally assumed to be scattered within city areas where land resources are precious in urban centers.

Considering the cost for deployment, it is more practical to assume more CSs than BSSs installed in the network, since BSSs are often more costly and complicated to set up with involvement of complex robotic devices [22].

ET services usually require prior booking by customers. This way, an ET will directly travel from current customer drop-off spot to next reserved pickup location, where the trip duration is treated as key attribute for service satisfactions.

The ET battery is assumed to be swappable and thus, an ET can choose between a BSS and CS whenever recharging is required. Once arrived at the charging station, ETs will be served by following the order of First In First Out (FIFO), which has been widely adopted within the branch of EV charging management. Note that the route for recharging will be initiated only when there are none customers on-board. Otherwise, the ET firstly continues to drive to the customer's destination before heading to the selected station[2].

4. System Design for Hybrid Charging Framework

Next, we present our configuration logics toward hybrid charging management concerning the details of highly dynamic ET recharging demand, relating to spatiotemporal properties due to mobility nature of ETs. Fig. 3 depicts such operational framework with three main functions involved: the *BSS battery cycle*, the plugin *CS charging process* and the *global planning process*.

4.1 BSS Battery Cycle

Each BSS manages the cycling of ET batteries, with batteries cycled from depleted state to fully-charged state, corresponding to the **swap phase** and the **charging phase**, respectively.

[2] In practice, ETs drivers normally plan their charging carefully prior to picking up the next customer due to customer service concern. Therefore, they generally have sufficient energy to drive customers toward their destinations [21].

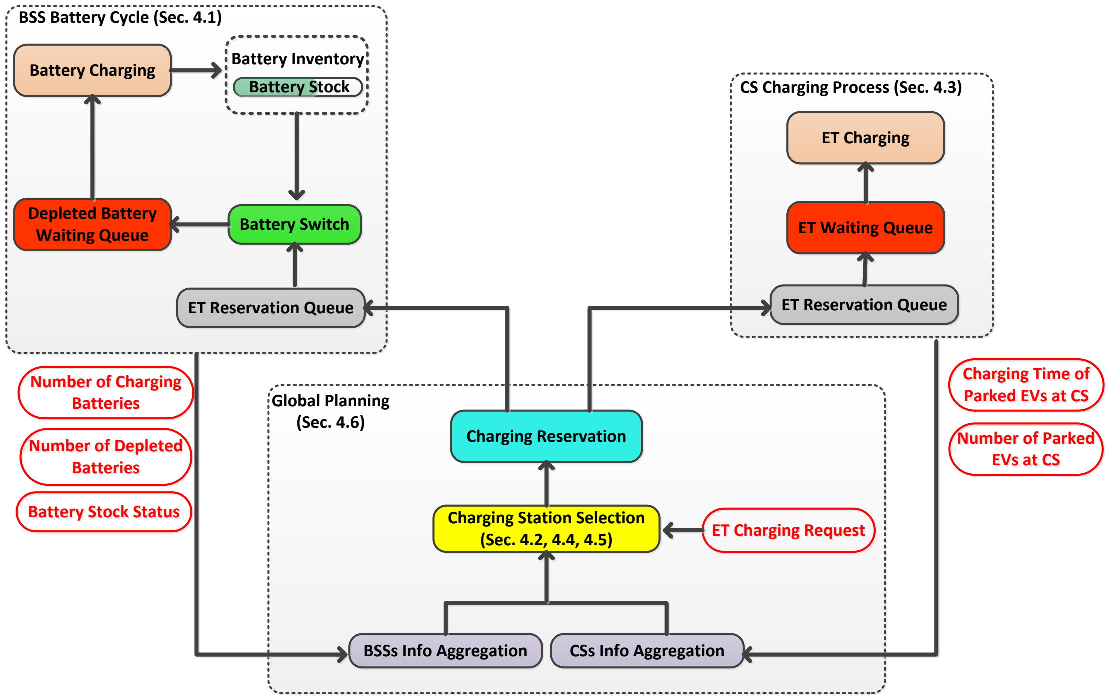


Figure 3. Operational framework of the proposed hybrid charging management

Specifically, upon the arrival of an ET at a BSS, the battery swap process depends on the following conditions:

- If there are battery spares readily available at the selected BSS, given by ($N_B > 0$), the ET will be switched right away. Here after the swap duration of ρ_{sw}, battery stock number N_B is reduced by one, while the drained battery is included into the depleted battery queue (N_D) waiting for recharging.

- Often, there have not been any switchable batteries available yet ($N_B = 0$). As a result, ET has to wait until a battery becomes available. The number of ETs waiting at a BSS is defined as N_W^{bss}.

With charging phase, each BSS is equipped with θ charging slots, and depleted batteries removed from vehicles will be recharged in parallel, depending on the condition ($N_C < \theta$). The charging order follows the Shortest Time Charge First (STCF), whereby battery with the shortest charging time will be associated with the highest priority. The STCF is proved to achieve the best performance gains according to [6]. Once the recharging finishes, the battery is then added into the battery stock N_B. Meanwhile, a depleted battery will be scheduled from the line of batteries (N_D) into recharging process.

4.2 Recommended BSS-Selection Process

Among all BSSs, a best choice will be found by the GC (as described in Alg. 1), whereby the ET would experience the shortest *trip duration*, including:

- Time to travel to a BSS (T_{et}^{tra})

- Stay time at a BSS, including waiting duration and swapping period (ρ_{sw})

- Time to travel from a BSS to trip destination ($T_{bss,d}^{min}$) (usually next customer pickup point)

We thus denote $T_{et}^{bss,d}$ as the trip duration for requesting ET_r, which can be formulated as

$$T_{et_{(r)}}^{bss,d} = T_{et_{(r)}}^{tra} + EWTS + \rho_{sw} + T_{bss,d}^{min} \qquad (1)$$

While other metrics are easy to obtain, the expected waiting time for swap (EWTS) needs to be estimated, which can be approximated as (from line 16 to 19 in Alg. 1)

$$EWTS = \begin{cases} 0, & N_B > 0 \\ ATS_1 - T_{et_{(r)}}^{arr}, & N_B = 0 \end{cases} \qquad (2)$$

where the term ATS_1 refers to the earliest time for the availability of a battery, and the approximation of ATS involves the following steps, similarly to our previous work [6]:

Step 1: Upon a charging demand from ET, the GC would query each BSS for their respective charging status, including context such as $<N_C, N_D, N_B>$, as depicted in line 2 of Alg. 1.

Step 2: By aggregating such information from all BSSs in the network, a list of ATS can be computed for each BSS, as illustrated from line 5 to 7.

Step 3: Based on Step 1 and 2, the estimation on ATS only considers local states at a BSS. By additionally accounting for reservations from ETs (i.e., N_R^{bss}), the prediction of ATS can be further refined and updated for a future moment (from line 8 to 10).

Therefore, the recommended BSS, denoted as l_{bss}^{min}, can be obtained if the following condition holds (line 23)

$$\arg\min\left(T_{et_{(r)}}^{bss,d}\right) \qquad (3)$$

Algorithm 1: Recommended BSS-Selection

1: **for** each BSS station in the network **do**
2: obtain $<N_C, N_D, N_B>$
3: calculate $T_{et_{(r)}}^{tra}$
4: calculate $T_{bss,d}^{min}$
5: **for** each battery under (and waiting for) charging **do**
6: add charge finish time to list ATS
7: **end for**
8: **for** each charging reservation earlier than $T_{et_{(r)}}^{arr}$ **do**
9: refine list ATS
10: **end for**

for each value from list ATS **do**

N_B is increased by one if battery charged up earlier than $T_{et_{(r)}}^{arr}$

end for

sort list ATS with ascending order

obtain ATS_1 from list ATS

if $(N_B > 0)$ **then**

EWTS = 0

else

EWTS $= ATS_1 - T_{et_{(r)}}^{arr}$

end if

$T_{et_{(r)}}^{bss,d} = T_{et_{(r)}}^{tra} + EWTS + \rho_{sw} + T_{bss,d}^{min}$

end for

$l_{bss}^{min} \leftarrow \arg\min\left(T_{et_{(r)}}^{bss,d}\right)$

return l_{bss}^{min}

4.3 CS charging process

As presented previously, a CS manages a couple of charging slots, the number of which is given by μ. Since chargers at a station are normally limited, the charging procedure depends on the conditions as below:

- Once an ET arrives, it would be plugged into a charger when there are idle charging slots.
- In cases that all slots have been occupied upon the arrival, the ET has to wait before a charging slot becomes available.

Here the availability of a charging slot (or the ATC) can be estimated by accounting for local charging states $<N_C, N_W^{cs}>$ as well as charging reservations (N_R^{cs}), which will be detailed in the following section.

4.4 Recommended CS-Selection Process

Considering the shortest trip duration, an optimal CS can also be found. In order to achieve this, the estimation on ATC is necessary, the process of which is presented in Alg. 2. Specifically,

Step 1: Upon a charging demand from ET_r, the GC would query each CS for their respective charging status, including context such as $<N_C, N_W>$, as depicted in line 2 of Alg. 2.

Step 2: By aggregating such information from all BSSs in the network, a list of ATC can be obtained for each CS. And the prediction of ATC can be refined and updated for a future moment, by additionally concerning charging reservations (N_R^{cs}), as illustrated from line 8 to line 10.

According to the estimation on ATC, the expected waiting time for charging (EWTC) (exclude charging period) can thus be approximated as the following for requesting ET_r (from line 13 to line 16 in Alg. 2), depending on the availability of charging slot (μ):

$$EWTC = \begin{cases} 0, & N_C < \mu \\ ATC_1 - T_{et_{(r)}}^{arr}, & N_C \geq \mu \end{cases} \quad (4)$$

where the term ATC_1 corresponds to the earliest time for the availability of a charging slot.

Therefore, the recommended CS, denoted as l_{cs}^{min}, can be obtained if the trip duration (denoted as $T_{et_{(r)}}^{cs,d}$) can be minimized (line 20)

$$\arg\min\left(T_{et_{(r)}}^{cs,d}\right) \quad (5)$$

$$\text{where } T_{et_{(r)}}^{cs,d} = T_{et_{(r)}}^{tra} + EWTC + \delta^{cha} + T_{cs,d}^{min} \quad (6)$$

Algorithm 2: Recommended CS-Selection

1: **for** each CS station in the network **do**
2: obtain <N_C, N_W>
3: calculate $T_{et_{(r)}}^{tra}$
4: calculate $T_{cs,d}^{min}$
5: **for** each ET under (and waiting for) charging **do**
6: add charge finish time to list ATC
7: **end for**
8: **for** each charging reservation earlier than $T_{et_{(r)}}^{arr}$ **do**
9: refine list ATC
10: **end for**
11: sort list ATC wit ascending order
12: obtain ATC_1 from list ATC
13: **if** ($ATC_1 \leq T_{et_{(r)}}^{arr}$) **then**
14: EWTC = 0
15: **else**
16: $EWTC = ATC_1 - T_{et_{(r)}}^{arr}$
17: **end if**
18: $T_{et_{(r)}}^{cs,d} = T_{et_{(r)}}^{tra} + EWTC + \delta^{cha} + T_{cs,d}^{min}$
19: **end for**

$l_{cs}^{min} \leftarrow \arg\min\left(T_{et_{(r)}}^{cs,d}\right)$

return l_{cs}^{min}

Note we have discussed the above recommended station-selection with PC and BS modes, respectively, wherein related computations have also been well-studied in our previous works [6][8]. However, the challenge here is the decision-making between l_{bss}^{min} and l_{cs}^{min}, both of which have pros and cons regarding charging performances. Such issue is our focus in this work, which will be detailed in the following section.

4.5 Final Station-Selection Logics

As discussed previously, recharging process could happen only during the trip between a drop-off place and next pickup location, while none customers onboard. As a result, customers would have to wait extra time period if the booked EV needs recharging. Clearly, the trip duration is closely in relation to service qualities, since a short trip leads to a short wait for the customer. In order to describe such customer's service experience, we introduce the *trip tolerance* in this work, which can be defined as below

$$D_{et}^{trip} := \delta_{et\rightarrow cus} \cdot \sigma \qquad (1)$$

where $\delta_{et\rightarrow cus}$ refers to the travel duration for the ET from its current location to next customer spot without intermediate charging, which can be computed as $d_{et\rightarrow cus}/v_{et}$. σ is a constant parameter indicating the tolerance range, assumed to follow a uniform distribution over the interval $[1, a]$, $a > 1$. Clearly, a large value of a implies that the customer can cope with long wait and vice versa.

Given the recommended CS (l_{cs}^{min}) and BSS stations (l_{bss}^{min}) based on previous analysis of Alg. 1 and 2, the shortest trip duration for the ET (e.g., ET_r) through intermediate recharging (at l_{cs}^{min} or l_{bss}^{min}) can be estimated, given by El_{cs}^{min} and El_{bss}^{min}, respectively. The trip includes the travel from ET's current place to the station, the charging period, plus from that site to next customer's location.

Hence, the station-selection logic is to find an appropriate one (denoted as l^{opt}) between l_{cs}^{min} and l_{bss}^{min} that not only experience the shortest trip duration, but also with concern on service quality, in terms of tolerance threshold D_{et}^{trip}. The process is detailed in Alg. 3. Namely,

- If the condition ($El_{bss}^{min} \leq D_{et}^{trip} \parallel El_{cs}^{min} \leq D_{et}^{trip}$) holds, the optimal station (l^{opt}) will be selected as given by $\min\{El_{bss}^{min}, El_{cs}^{min}\}$, as illustrated from line 3 to line 5 of Alg. 3.

In this case, assured service quality can be achieved, since the selected station (l_{cs}^{min} or l_{bss}^{min}) is surely within trip tolerance threshold.

- Otherwise, both recommended stations (l_{cs}^{min} and l_{bss}^{min}) are beyond the trip tolerance, due to ($El_{bss}^{min} > D_{et}^{trip}$ && $El_{cs}^{min} > D_{et}^{trip}$). As such, the station with the minimum amount of parked ETs will then be selected, given by $\min\{N_W^{bss}, N_W^{cs}\}$ (line 7).

Under such circumstances, even optimal stations cannot guarantee desired service quality for customers. If following $\min\{El_{bss}^{min}, El_{cs}^{min}\}$, however, there is a potential that BSSs may become hotspots owing to short charging period, resulting in overcrowding due to limited parking space. In such circumstances, the key attribute for station-selection decision-making becomes the charging load. Therefore, the number of parked ETs at l_{bss}^{min} and l_{cs}^{min} is considered, given by N_W^{bss} and N_W^{cs}, respectively. The rational is that the customer may cancel the service when trip tolerance is beyond the threshold value. Still, the ET has to go for a recharge whatsoever, and charging load comes at a premium in this case. As such, a desirable charging-demand load balancing (i.e., with roughly equal distribution of parked ETs across all stations) could be achieved hereof, as will be analyzed in Sec. 5.5.

Algorithm 3: Station-Selection Logics

1: compute l_{bss}^{min} and l_{cs}^{min} via Alg. 1 and 2

2: compute D_{et}^{trip}

3: calculate El_{bss}^{min} and El_{cs}^{min} according to Eq. (1) and (6), respectively

3: **if** ($El_{bss}^{min} \le D_{et}^{trip}$ || $El_{cs}^{min} \le D_{et}^{trip}$) **then**

4: $\quad l^{opt} \leftarrow \min\{El_{bss}^{min}, El_{cs}^{min}\}$

5: $\quad$ **return** l^{opt}

6: **else**

7: $\quad l^{opt} \leftarrow \min\{N_W^{bss}, N_W^{cs}\}$

8: $\quad$ **return** l^{opt}

9: **end if**

4.6 Global Planning Process

The global planning process is enabled at the GC side, in order to efficiently manage ET charging demand over the network, as depicted in Alg. 4. Particularly, it determines the optimal charging station-selection for an ET. Specifically, upon receiving an ET_r charging demand, the following main functions are involved:

- Context information aggregation from all BSSs and CSs, regarding $<N_C, N_D, N_B>$ with each BSS and $<N_C, N_W>$ with each CS, respectively (line 2)

- Estimation on ATS and ATC for each BSS and each CS, respectively (line 3)

- Recommended station-selection procedure, with BS mode (l_{bss}^{min}) and plugin-charging mode (l_{cs}^{min}), respectively (line 3)

- Determine the optimal station by enable the station-selection logics (line 4)

Algorithm 4: Global Planning

1: upon receiving an ET recharging request
2: aggregate info from all BSSs and CSs
3: execute Alg. 1 and Alg. 2
4: execute Alg. 3
5: reply selected station (l^{opt}) info back to ET_r

5. Simulation

We have built up a hybrid ET charging system in Opportunistic Network Environment (ONE) [23]. As shown in Fig. 4, the scenario is with 4500×3400 m^2 area based on the downtown area of Helsinki city in Finland abstracted from Google map (Fig. 5).

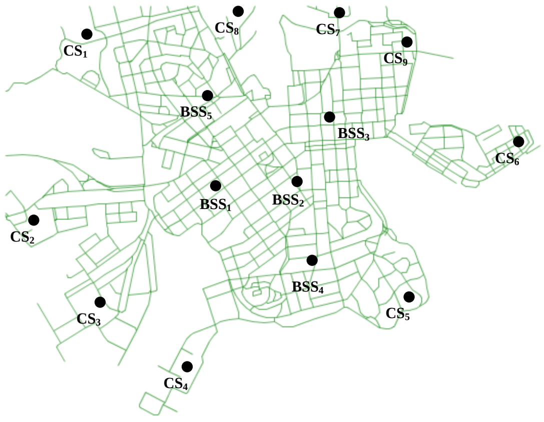


Figure 4. Simulation scenario of Helsinki City

Figure 5. Google map of Helsinki City

There are 300 ETs on-the-move initialized in the network, with variable speed ranging from [30~50] *km/h*. The destination (or customer pick-up point) of each ET route is randomly selected from the map, and a new spot is chosen once the current destination is reached. An ET will require a recharging service once the SOC reaches the threshold. All routes are formed based on the shortest path feature considering the actual Helsinki road topology. The setting of ETs follows the charging specification {Maximum Electricity Capacity, Max Traveling Distance, SOC threshold}.

A total of 9 CSs and 5 BSSs are deployed. Each CS is equipped with $\mu = 30$ charging slots, by a charging power 10 kW. For each BSS, the suggested battery swap time is set as $\rho_{sw} = 5$ minutes, and the number of switchable batteries (fully charged) are given as $N_B = 30$ from beginning. Also, Up to $\theta = 30$ of depleted batteries (removed from ETs) are able to be charged in parallel at each BSS. The simulation time represents a duration of 12 hours.

The following schemes are implemented for comparisons:

- **MinTrip&R-Hybrid**: The proposed hybrid charging scheme with minimum trip duration, without reservation reporting.

- **MinTrip-Hybrid**: The proposed hybrid charging scheme with minimum trip duration, coupled with reservation reporting.

- **Queuing-Hybrid**: The station-selection based on local minimum queuing time as proposed in [24].

The performance metrics below are evaluated:

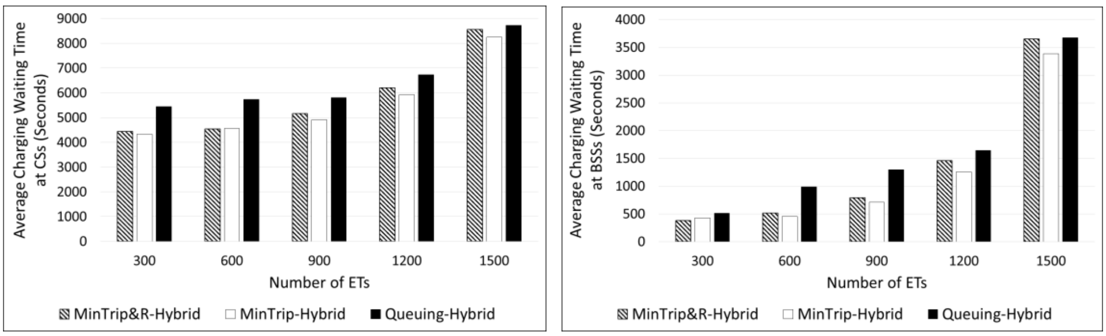
- *Average Charging Waiting Time*: The average time duration for an ET to spend at the selected station, including the waiting time for charging and the charging duration. With BS, the metric refers to the waiting time plus battery swap period.

- *Totally Charged ETs (or totally switched batteries (TSB))*: The total number of fully-charged ETs at CSs. For BSSs, the TSB metric refers to the total number of ETs that have been replaced with fully-charged batteries in the network. In our experiments, the value refers the summation of the two.

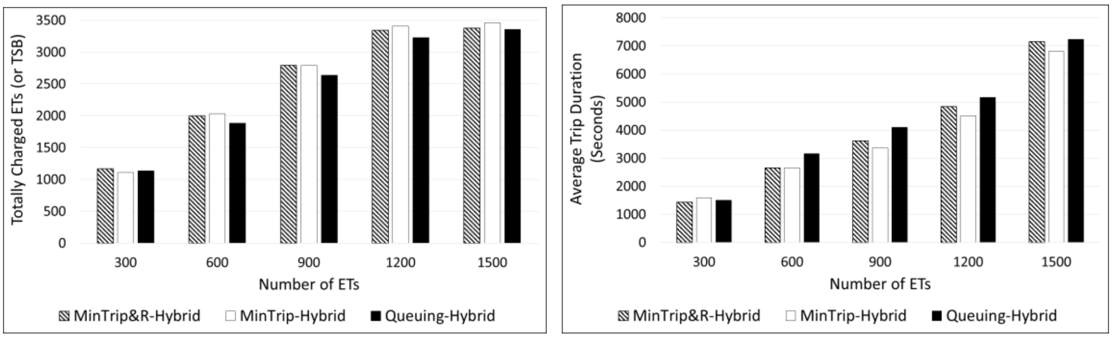
- *Average Trip Duration*: The average time that an ET experiences for its trip, through recharging service at an intermediate charging station.

5.1 Impact of ET Density

As observed from Fig. 6(a) and (b), the average charging waiting time increases with more ETs deployed in the network. This is mainly due to congestions happened at charging stations, where ETs have to wait long time before getting charged. Comparing Fig. 6 (b) to (a), BS reduces much less time than plugin charging, benefited from short charging duration. Among all schemes, the Queuing-Hybrid scheme experiences longer waiting time. However, with increased ET density, MinTrip&R-Hybrid is less effective. The rational is that all stations would become saturated over increment on ET density, and benefits from charging reservations are hard to achieve with heavily congested stations.



(a) Average Charging Waiting Time at CSs (b) Average Charging Waiting Time at BSSs



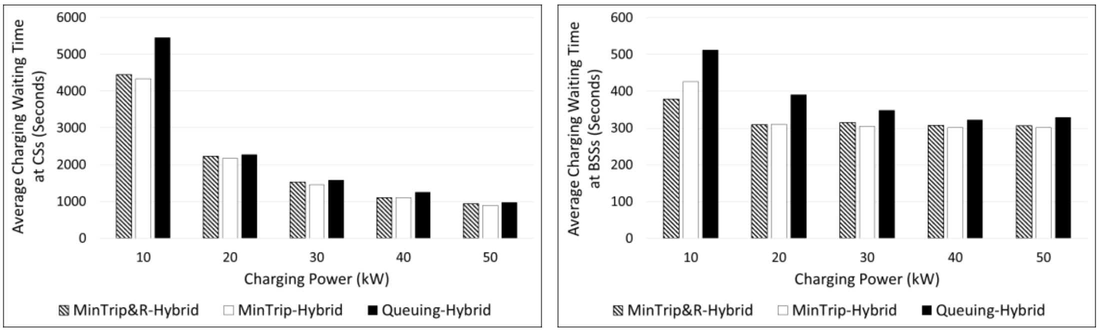
(c) Totally Charged ETs (or TSB) (d) Average Trip Duration

Figure 6. Impact of ET density

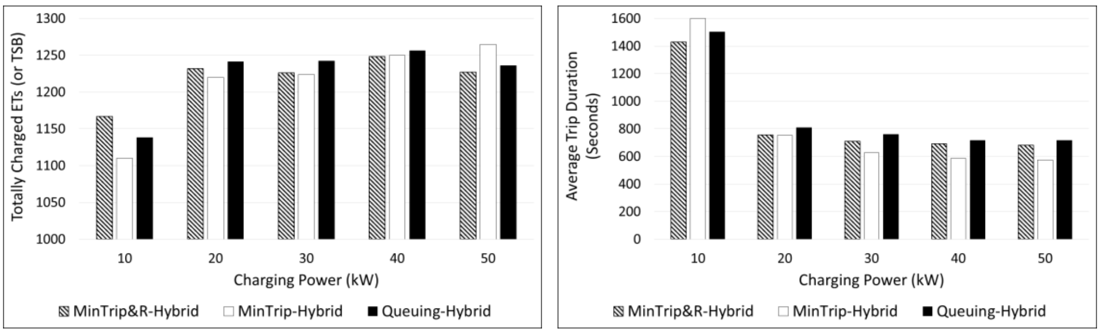
The advance of MinTrip&R-Hybrid can be displayed in terms of totally charged ETs (Fig. 6(c)). More ETs can be charged or swapped with fully charged batteries under such scheme. Here, MinTrip-Hybrid is comparable to MinTrip&R-Hybrid, especially when ETs become dense. Also, reduced trip duration can be achieved by both MinTrip schemes when ETs number not large (e.g., less than 1200 as shown in Fig. 6(d)), and Queuing-Hybrid performs worse. Still, benefits of reservations are not obvious with a heavily congested charging network.

5.2 Impact of Charging Power

With enhancement on charging power, all schemes experiences short charging waiting time, as shown in Fig. 7(a) and (b). As noticed, advantages of reservation are less effective when charging power is higher than 50 kW, wherein a simpler MinTrip-Hybrid is able to guarantee desirable service experiences for ETs, however.



(a) Average Charging Waiting Time at CSs (b) Average Charging Waiting Time at BSSs



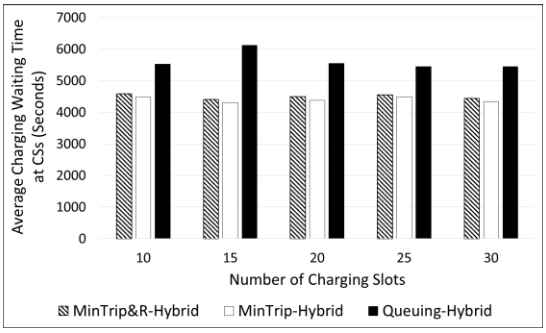
(c) Totally Charged ETs (or TSB) (d) Average Trip Duration

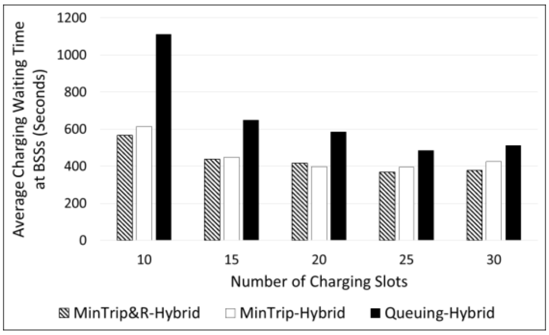
Figure 7. Impact of charging power

As shown in Fig. 7(c), the number of totally charged ETs (or TSB) can be increased with higher charging power. As observed, all hybrid schemes can achieve better performances with increased power. Not surprisingly, MinTrip&R-Hybrid achieves the highest performances, especially when power is not high. With increased charging power, the trip duration is reduced as observed from Fig. 7(d). As for low charging power (e.g., lower than 20), the MinTrip&R-Hybrid outperforms other schemes. However, such reservation-based scheme seems to be not necessarily optimal in higher power circumstances. Actually, both CSs and BSSs would suffer from overcrowding when charging power is low, due to slow charging and increased waiting time for ETs. With reservation-enabled, charging hotspots in such cases could be effectively avoided through accurate predictions. When charging power is high, ETs (or batteries) will experience short charging period, thus eliminating congestions at CSs or BSSs naturally. This implies that under a low charging power, a joint charging management might work better for all. Benefited from such hybrid charging, the power system could achieve great efficiency especially at peak power load.

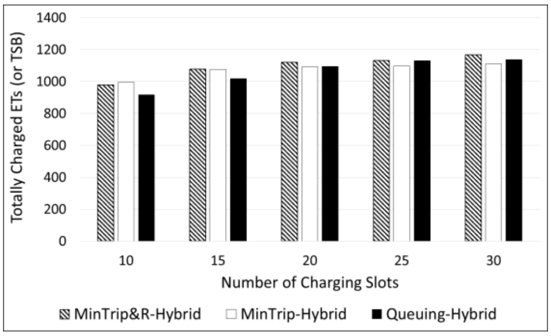
5.3 Impact of Charging Slots

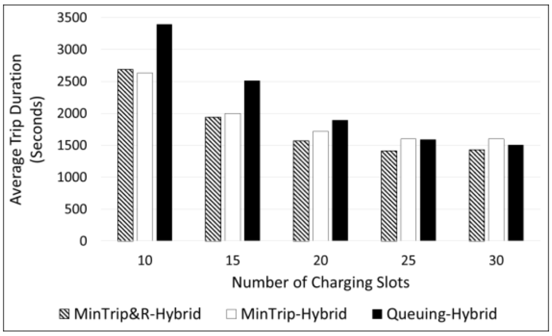
With more charging slots deployed at CSs, as shown in Fig. 8(a), the average charging waiting time seems to stay relatively stable with all schemes. As compared, reduced waiting time can be achieved at BSSs in Fig. 8(b) with increased charging slots. This indicates that experiences with plugin charging would not be effectively improved with enhancement on charging slots. As observed, MinTrip schemes outperforms Queuing-Hybrid at both CSs and BSSs, owing to advantageous concerns beyond local charging states.





(a) Average Charging Waiting Time at CSs (b) Average Charging Waiting Time at BSSs





(c) Totally Charged ETs (or TSB)

(d) Average Trip Duration

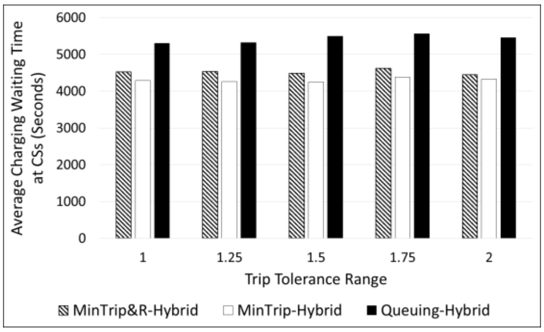
Figure 8. Impact of charging slots

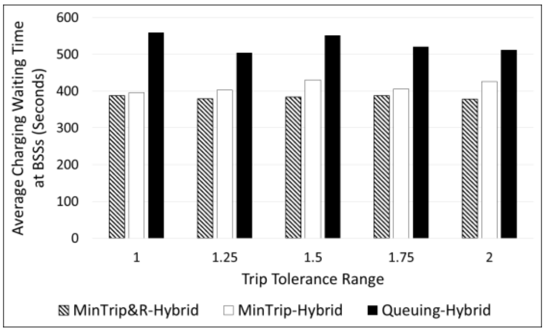
In Fig. 8(c), the total amount of charged ETs (or TSB) is slightly increased with more charging slots installed. Fig. 8(d) shows that all schemes experience reduced trip duration with increased charging slots. As observed from Fig. 8(c) and (d), MinTrip&R-Hybrid achieves highest performance gains, while Queuing-Hybrid experiences worse performances. However, such differences tend to be mitigated with more charging slots deployed (e.g., more than 30).

5.4 Impact of Tolerance Range

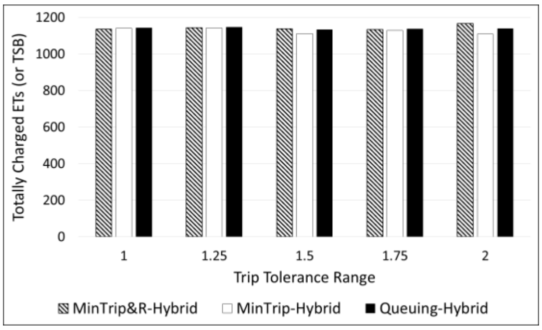
As for the influence of tolerance range denoted by σ according to Eq. (1), concerned performances are shown in Fig. 9. Intuitively, relatively stable performances are achieved by all schemes with varied tolerance ranges. This implies that the tolerance range from customer side has little impact on the charging planning of ETs. According to the proposed hybrid station-selection scheme, range values will be considered only when decision-making on selection between recommended CS and BSS, where each station represents the optimal choice under specific charging mode. Essentially, ETs are assumed to be fully charged before heading to customers. As such, performances would be less influenced unless ET's charging period is limited by the tolerant deadline.

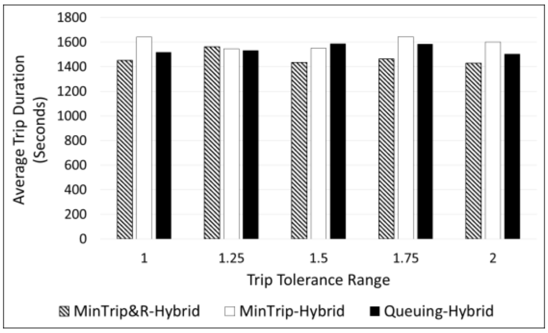
Noticeably, MinTrip&R-Hybrid outperforms other schemes with all concerned metrics, while Queuing-Hybrid performs the worst. Similarly as above analysis, the benefits of reservations are not that advantageous at CSs side, which is an interesting observation. This indicates that in a complex scenario of multi-charging modes coexisting, a simpler MinTrip scheme is able to serve ETs with desirable QoE without reservation-enabled.





(a) Average Charging Waiting Time at CSs (b) Average Charging Waiting Time at BSSs



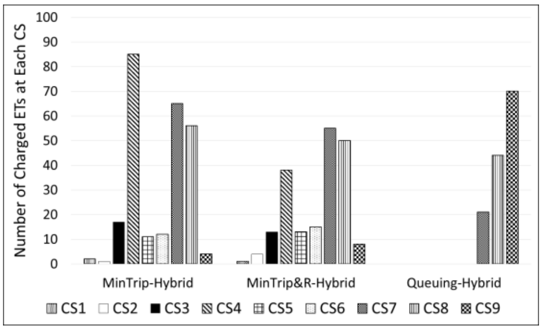


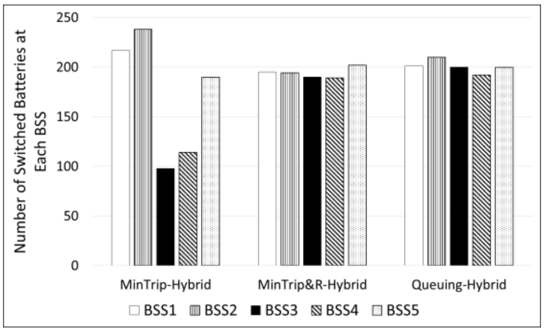
(c) Totally Charged ETs (or TSB) (d) Average Trip Duration

Figure 9. Impact of tolerance range

5.5 Distribution of Charged ETs (and TSB) at Each Station

Fig. 10(a) shows the distribution of charged ETs at each CS. As observed, all schemes behave in a skewed distribution, while the Queuing-Hybrid serves even zero ETs at certain CSs (e.g., CS1 to CS6). In comparison with BSSs (Fig. 10(b)), a perfect load balancing can be achieved under MinTrip&R-Hybrid and Queuing-Hybrid schemes. As noticed, the MinTrip-Hybrid performs a slight skewed distribution as shown in the figure.





(a) Distribution of charged ETs at each CS (b) Distribution of TSB at each BSS

Figure 10. Distribution of number of charged ETs (or TSB) at each station

From the above observations, we can see that with a hybrid charging network, desirable charging experiences can be benefited more from BS services, as compared to plugin charging. Therefore, this will encourage the deployment of BSSs that would benefit all players in the charging network, especially when install cost is not a big concern. Besides, ETs would be benefited more if their busy routines would not be frequently occupied by long period of charging. On the other hand, since adequately deployed BSS is able to alleviate the hotspot of charging service, the impact of reservation in this case becomes insignificant.

5.6 Impact of Renewable Energy

ETs and renewable energy can strengthen one another. For instance, if daytime charging syncs with peak solar output, while nighttime charging can align well with wind output, customers can go large amount of their charging electricity from renewable energy sources. In practice, ET charging can be paired and co-locating with renewable energy generation, such as on-site solar energy systems [26]. In this part of our experiment, we assume that 50% of charging energy comes from renewables, which can be generated from on-site solar photovoltaic (PV) systems, or from other renewable generations. In this case, the charging energy consumption of ETs can be displayed in Fig. 11 under the proposed MinTrip&R-Hybrid scheme, with variation of the number of ETs. Similar patterns apply as well with other schemes installed.

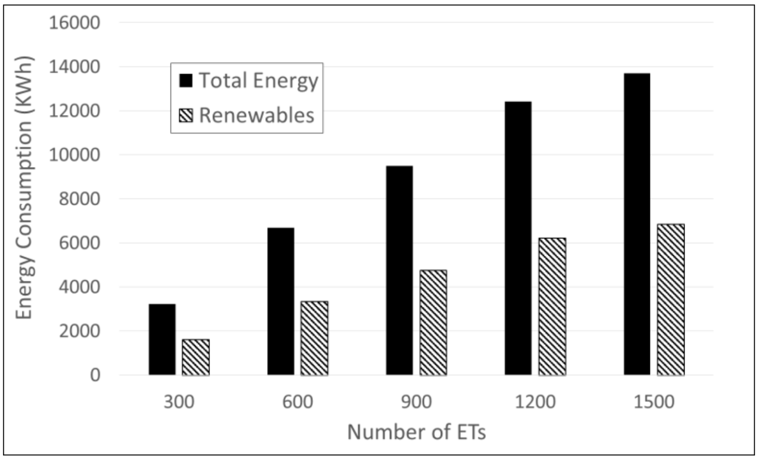


Figure 11. Charging energy consumption involving renewables under MinTrip&R-Hybrid scheme

As observed, the increment in ET loads would incur higher energy consumption. Particularly, if plethora of renewable energy can be generated and accounts for a great amount of charging, both customers and charging providers can be benefited. On the one hand, customers is able to receive lower rate for charging from renewables. On the other hand, utility providers can reduce the stress over grid since variable energy sources can be leveraged, such as solar and wind. It is worth noting that EV/ET charging can be an important source of flexible electricity demand to enable renewable-powered transportation. However, more effective designs are required to align ET charging (and pricing model) with the generation of clean energy sources, which would be our future work.

6. Conclusion

Most research works are mainly based on charging management for private EVs, we take a different step to focus on charging issues with moving ETs in this paper. Considering the practical scenario of BS and plugin charging coexisting, a hybrid charging management framework is proposed in this work. With the proposed solution, an optimal choice between recommended CS and BSS is selected for ETs with time-varying requirements. Through intermediate charging with the selected station, ETs are able to experience the shortest trip towards customers. The charging experiences are further enhanced with reservations. A comprehensive simulation experiments under a Helsinki city scenario are conducted with realistic ETs and charging stations settings, which show the effectiveness of our proposed scheme, in terms of minimized drivers' trip duration and charging waiting time, as well as great charging performance gains at station side.

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