A bi-level charging management approach for electric truck charging station considering power losses

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Abstract: This article presents an optimized heavy duty electric truck charging station (ETCS) design based on bi-level mixed integer linear programming. Electric truck parameters are integrated with the grid model and charging sequences are firstly formulated to optimize charging stages. As the second level of the optimization stage, line losses are aimed to be minimized for the charging station. ETCS model is obtained from actual parameters of the Istanbul Muratbey Customs zone which is one of the busiest customs zone in Europe and an ideal location for ETCS application in the future. The ETCS is equipped with roof type photovoltaic (PV) modules and the capacity of the PV generation is determined in accordance with the actual data of the customs zone buildings. The PV generated power is integrated with electric truck demand which varies in daytime based on hourly intervals along with the seasonal impact. Ultimately, an optimized ETCS model is presented including PV generated power to reduce line losses and CO₂ emission along with optimized charging sequences for ETCS with huge power consumption. The proposed model represents the reduction of line losses along with the obtained environmental and economic benefits.

Key words: i-level optimization, charging management, electrical truck, power losses, voltage profile

1. Introduction
The market share of electric vehicles (EVs) is rapidly increasing as a result of the improvements in the EV design and battery technology along with the demand caused by environmental concerns. The increasing number of EVs led to requirement of charging stations and grid infrastructure modifications to handle the power requirement that will be generated by EV charging demand. The proposed EV charging station implementations to the existing networks may lead to stability issues caused by unpredictable EV charging demand based on EV user routine [1–3]. The significant impact which is generated by EV power demand is required to be assessed and investigated before grid integration stage in order to avoid stability issues. The EV charging power impact on the grid is scaled by the battery capacity of EVs and the number of EVs located on the charging station. Two different unknown parameters are required to be investigated in terms of grid stability during modification and integration stages on existing power networks [4]. It is foreseen that the demand and grid impact will be enormous at heavy duty EV applications when it is compared with electric cars. In order to eliminate the negative impact on the grid, relevant studies are required to be conducted before the integration stage of EV charging stations. The EVs with highest battery capacity will be electric trucks for transfer of goods as commercial usage. One of the major motivations of electrical truck users and companies is to transfer of goods as fast as possible. The concern

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of delivery duration is one of the major drawbacks of electric trucks where the charging sequence may take more time if the charging stations are not available [5–7]. Loading bays of the customs zone is offered as an electric truck charging station to integrate loading duration and charging duration to increase efficiency of electric truck usage while avoiding additional charging sequence for trucks. However, electric truck charging stations (ETCS) present the issues of high charging power demand, charging station installation based on customs zone capacity, network connection modification including transformers, cables, circuit breakers and communication infrastructure [8]. The demand for electric trucks will be fueled by the disadvantages of conventional trucks along with environmental concerns. The major disadvantages of the conventional trucks are listed as inefficient fuel consumption and generation of vast amount of $CO_2$ emission [9]. However, $CO_2$ emission can be reduced thanks to integration of green energy resources such as solar and wind energy. Also, it is known that $CO_2$ emission ratio of coal power plants is around 850 kg/MWh and 950 kg/MWh [10]. The emissions are expected to increase despite the improvements in energy efficiency of the fossil fueled vehicles. The current rate of the $CO_2$ emission of the transportation industry is 9000 billion tons where it is expected to grow by 60% by 2050 [11]. The heavy duty trucks generate the half of the $CO_2$ emission of the transportation sector which is expected to increase by 56% to 70% [12]. In order to overcome the the increase on $CO_2$ emission caused by heavy duty truck applications, electric trucks are started to be presented by some manufacturers. As a clean and efficient alternative for conventional trucks, electric trucks have received increasing attention [13, 14]. The requirements for electric trucks including technical feasibility and sizing studies are being conducted [15–19]. The competitiveness of the electric trucks are investigated including speed profiles, energy consumption, route calculations and cost analysis have been investigated in [20]. In the mentioned study, scenario based analysis indicate that the major parameters are battery life, procurement cost, route planning and sizing parameters. Another alternative for conventional trucks is presented as hybrid trucks which include battery and fuel cells. Hybrid trucks are investigated including the concept of fuel efficiency based on the acceleration analysis and planning in [21]. A control algorithm comparison based on battery charging initial set point and impact on the energy management is presented in [22] where an optimal control methodology is presented in [23] to ensure fuel efficiency for hybrid trucks. The environmental impact and possible improvements are presented in [24] including externality analysis. A comparison study of electric trucks, hybrid trucks and conventional trucks is presented in [25, 26] in terms of efficiency and emissions cases based on driving cycles and fuel consumption analysis. An investigation of the comparison of truck types is presented in [27] and the superiority of electric trucks are observed with zero emission and higher energy performance. Even the electric trucks are presented as the best solution for transportation in the concept of zero emission, the charging requirements of the trucks are the main concern for integration of the electric trucks. The major drawbacks and impacts of the high demand of the electric trucks are presented in [28] where a power management strategy is investigated in [29] to reduce the effect of heavy loads on the grid. Heavy duty electric truck charging station impact on the grid is presented in [30] based on a systematic procedure to analyze the potential impact of the charging station planning. In order to increase the efficiency of such charging stations, a model is presented in [31] which includes vehicle to grid (V2G) applications where dynamic interaction between grid and charging station is presented in [32]. Bi-level optimization based energy scheduling is implemented in [33] and [34]. While predictive control integrated bi-level is examining in [35], stochastic bi-level approaches are investigated in [36, 37]. However, while energy cost minimization based approaches are investigated, physical impact of the electric vehicles on the distribution network is not taken into account. In this paper, power losses are therefore considered. The majority conducted
studies indicate the environmental impact of the electrical trucks along with the studies of energy saving and grid impact analysis. There are also studies that based on optimal sizing, distance and route analysis of electric trucks. In this study, a combinational analysis of sizing, emission reduction, optimal operation criteria of electric truck charging station is investigated. İstanbul Muratbey Customs Zone which is one of the busiest customs zone in the Europe is integrated to simulation environment as the network model including actual electrical and physical parameters of the customs zone. As a result of the customs zone investigation, it is observed that 900 trucks are present per day in the customs zone with long periods of loading and control durations. The expected growth of usage of electric trucks will lead to the customs zone to be designed as an ideal location for charging station. For that reason, the customs zone is investigated and a field study is conducted for charging station implementation for future ETCS requirements. The long period of loading and control duration at the customs zone is considered as the ideal period for charging the electric trucks in order to save the waste time. The inefficient waiting duration of the electric trucks is aimed to be used to charge the electric trucks to full charge level. In order to minimize the power demand impact on the grid, roof sections of the customs zone buildings are equipped with photovoltaic (PV) modules. The proposed PV power generation is aimed to energize the ETCS demand along with the auxiliary power consumption of the office buildings and EVs of the staff. It is aimed to integrate PV generated power, auxiliary consumption, staff EV consumption and the grid to minimize grid power losses and reduce CO$_2$ emission simultaneously. The electric truck and staff EV profile is implemented in bi-level mixed integer linear programming based Global Algebraic Modeling System (GAMS) and solved with CPLEX solver. The obtained profile of EV, electric truck, and PV generation is observed for day time variation and seasonal impact. Average values of the generation of PV modules and electric truck consumption are based on real data and combined in GAMS environment. The proposed study aims the reduction of line losses and CO$_2$ emission of a customs zone ETCS based on real consumption and PV generation data. PV modules are integrated to hourly consumption data to observe and optimize the charging of the trucks. It is known that power losses especially in distribution network level is a crucial issue. Therefore, physical conditions of the electrical grid system is also handled as well as the aforementioned literature studies. Comparison of the proposed algorithm with related literature works is shared with the Table 1. In this regard, the proposed charging algorithm considers not only typical cost minimization analysis but also power losses minimization for grid network operator in a hierarchical manner. The major contributions of the proposed study can be listed as:

- A new approach for hierarchical charging management system which takes into account both power losses for low voltage distribution grid and cost analysis for parking lot operator is developed considering seasonal impact of the PV generation and CO$_2$ emissions.
- A bi-level mixed integer linear programming based mathematical model, in which while lower level problem aims to minimize total cost of the parking lot, upper level problem aims to minimize power losses in the distribution network, is proposed.
- Impact of the large amount charging power of the heavy duty electric trucks considering as fast charge power of the normal electric vehicles is examined via İstanbul Muratbey Customs Zone which is one of the major customs zone of the Europe.

The remainder of the study is organized as follows:

The proposed charging management structure and mathematical model are detailed in Section II. Test results and comments are presented in Section III. Finally, conclusions are evaluated in Section IV.
Table 1. Comparison of the proposed algorithm with related literature works

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<th>Electric Vehicle</th>
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<th>Bi-level</th>
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<th>Grid Power Losses</th>
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2. Methodology

2.1. Overview of the structure

The proposed ETCS model consists of electrical trucks, PV generation units, office buildings, and parking lot for staff EVs. The operation strategies of ETCS elements and the interface with grid are defined by Aggregator. Aggregator carries out the charging schedules of all the electric vehicles considering arrival and departure time intervals, initial energy level of the batteries, and grid price signals in the hierarchical energy management system. Here, priority is given to PV system in order to satisfy the requirements of reducing stress on the grid and decreasing CO$_2$ emission. After the self-generation of PV, the deficit demand, consists of auxiliary consumption and charging power, of the ETCS is provided from the grid. Signals of charging powers along with the optimal scheduling are sent to the Distribution System Operator (DSO) by means of cloud computing. Whereas, DSO reschedules the charging signals received from the aggregator considering grid constraint that includes power losses. When it is reached to the equilibrium point for both DSO and the aggregator, final charging signals are announced back from DSO to the aggregator. Finally, the aggregator sends the ultimate signals to the charging points in the ETCS in an attempt to charge electric trucks and cars optimally. The schematic diagram of the proposed charging station model is presented in Figure 1.

The customs zone is physically examined in terms of applicability of proposed charging station design and integration of roof type PV system. Real application of the proposed model in Istanbul Muratbey Customs Zone is planned as indicated in Figure 2.a. Both PV system installation area and location of the charging station are quite suitable for the application of the proposed model as reflected to the figure. There is also availability of installation of PV modules to the roof of customs zone management office. Thus, 35000 $m^2$ area can obtain in total for the integration of PV. Sample charging stations planned to be placed are indicated in Figure 2.b. The PV generated power can be directly routed to charging stations thanks to the appropriate structure of the customs zone. Due to the short distance between generation and consumption units, the power losses can be minimized. Furthermore, it can be seen in the figure that installation of wind turbine is convenient at close distance. Penetration of renewables to ETCS can be realized with integration of PV and wind power generation units which presents the advantages of reduced power losses, reduced CO$_2$ emissions, and availability of selling...
power to the grid.

Figure 1. Proposed charging station model

Figure 2. (a) Proposed model of Istanbul Muratbey Customs Zone, (b) Planned charging stations
2.2. Mathematical formulation

2.2.1. Lower level problem

Objective function

The objective of the lower level problem is minimizing the total cost of ETCS that includes auxiliary consumptions of office buildings, staff EVs and charging power of electric vehicles and trucks. In (1), the net cost is the cost of power bought from the grid. In the objective function, model variable is the demand power bought \( P_{i,t}^{\text{grid,buy,load}} \) on the connected node. \( \lambda_{i,t}^{\text{grid,buy}} \) is the buying price signal of grid and \( (\Delta T) \) is the time interval and is accepted as 5 min.

\[
\min \sum_i \sum_t \lambda_{i,t}^{\text{grid,buy}} \cdot P_{i,t}^{\text{grid,buy,load}} \cdot \Delta T \\
\tag{1}
\]

Demand power

\[
0 \leq P_{i,t}^{\text{grid,buy,load}}, \forall i, t : \gamma_{i,t}^1
\tag{2}
\]

\[
P_{i,t}^{\text{grid,buy,load}} \leq P_{i,t}^{\text{net,demand}} + P_{i,t}^{\text{EV,PL,tot}}, \forall i, t : \gamma_{i,t}^2
\tag{3}
\]

\[
P_{i,t}^{\text{net,demand}} = \begin{cases} 
P_{i,t}^{\text{Load,aux}} - P_{i,t}^{\text{PV,avl}} & ; \text{if} \ (P_{i,t}^{\text{Load,aux}} - P_{i,t}^{\text{PV,avl}} > 0) \\
0 & ; \text{if} \ (P_{i,t}^{\text{Load,aux}} - P_{i,t}^{\text{PV,avl}} \leq 0)
\end{cases}
\tag{4}
\]

Constraints (2) and (3) impose the limits of demanded power from the grid on the connected node. Equation (4) states the remaining power \( P_{i,t}^{\text{net,demand}} \) after usage of PV generation \( P_{i,t}^{\text{PV,avl}} \) for inflexible auxiliary consumptions \( P_{i,t}^{\text{Load,aux}} \). Therefore, maximum power that can be bought from the grid is the sum of net power and total charging power \( P_{i,t}^{\text{EV,PL,tot}} \) of vehicles. \( \gamma_{i,t}^1 \) and \( \gamma_{i,t}^2 \) are the Lagrange multipliers of the demand power on the connected node.

Electric trucks and vehicles

\[
0 \leq P_{i,m,t}^{\text{EV, ch}}, \forall i, m, t \in [T^a, T^d] : \gamma_{i,m,t}^3
\tag{5}
\]

\[
P_{i,m,t}^{\text{EV, ch}} \leq CR_{m}, \forall i, m, t \in [T^a, T^d] : \gamma_{i,m,t}^4
\tag{6}
\]

\[
SoE_{i,m,t}^{\text{EV}} \leq SoE_{m}^{\text{EV, max}}, \forall i, m, t \in [T^a, T^d] : \gamma_{i,m,t}^5
\tag{7}
\]

\[
SoE_{i,m,t}^{\text{EV}} = SoE_{i,m,t-1}^{\text{EV}} + P_{i,m,t}^{\text{EV, ch}} \cdot CE_{m}^{\text{EV}} \cdot \Delta T, \forall i, m, t \in (T^a, T^d) : \lambda_{i,m,t}^1
\tag{8}
\]

\[
SoE_{i,m,t}^{\text{EV}} = SoE_{m}^{\text{EV, ini}}, \forall i, m, t = T^a
\tag{9}
\]

\[
SoE_{i,m,t}^{\text{EV}} = SoE_{m}^{\text{EV, max}}, \forall i, m, t = T^d
\tag{10}
\]
Equation (11) states that SoE\(_{i,m,t}^{EV}\) is equal to \(P_{i,m,t}^{EV,ch}\) at all times, except during the arrival and departure intervals.

Constraints (5) and (6) state the minimum and maximum \((CR_m^{EV})\) boundaries of the charging power \(P_{i,m,t}^{EV,ch}\) of vehicles. In (7), the energy level of battery is limited by maximum charging capacity \((SoE_{m,\text{max}}^{EV})\).

Equation (8) defines general energy equilibrium of the batteries of electric vehicles. SoE \((SoE_{i,m,t}^{EV})\) level at time \(t\) is equal to sum of the previous value \((SoE_{i,m,t-1}^{EV})\) and the charging power at the related time interval \(\Delta T\). \(\lambda_{i,m,t}^3\), \(\lambda_{i,m,t}^4\), and \(\lambda_{i,m,t}^1\) are the Lagrange multipliers of the constraints of electric vehicles. Equation (9) and (10) state the initial and maximum SoE level, respectively. In (11), SoE level and charging power should be equal to zero apart from arrival \((T^a)\) and departure \((T^d)\) time intervals.

**Power balance**

Equation (12) states general power balance of ETCS. The sum of demand power from the grid and available power of the PV must be equal to the sum of load group that includes auxiliary consumption and total charging power of EVs, and power sold back to the grid on each time \(t\) on the node \(i\). \(\lambda_{i,t}^2\) is the Lagrange multiplier of general balance.

\[
P_{\text{grid,load}}^{\text{buy,load},i,t} + P_{\text{PV,avl}}^{\text{PV,avl},i,t} = P_{\text{Load,aux}}^{\text{Load,aux},i,t} + P_{\text{EV,ch,tot}}^{\text{EV,ch,tot},i,t} + P_{\text{grid,sell,load}}^{\text{grid,sell,load},i,t}, \forall i, t : \lambda_{i,t}^2
\]

**2.2.2. Upper level problem**

**Objective function**

Equation (13) defines that the objective of the upper level problem is to minimize total power losses \((P_{b,t}^{\text{loss,tot}})\).

In (14), total power losses are the sum of bought power losses \((P_{b,t}^{\text{loss,buy}})\) and sold power losses \((P_{b,t}^{\text{loss,sell}})\).

\[
\min \sum_b \sum_t P_{b,t}^{\text{loss,tot}}
\]

\[
P_{b,t}^{\text{loss,tot}} = (P_{b,t}^{\text{loss,buy}} + P_{b,t}^{\text{loss,sell}}) \cdot \Delta T
\]

**Power balances and decomposition method**

Equation (15) states general power balance of DSO. The power losses on transmission lines \((P_{b,t}^{\text{line}})\) are included in formulation in line with upper level objective function requirements which were not reflected in lower level objective function. Thus, total power losses are considered by DSO at the upper level problem. Equation (16) states total charging power of ETCS \((P_{i,t}^{\text{EV,ch,tot}})\). In (17), total power bought from the grid \((P_{i,t}^{\text{grid,buy,tot}})\) is the sum of demand power on the node where ETCS is connected. Similarly, in (18), total power sold to the grid \((P_{i,t}^{\text{grid,sell,tot}})\) is excess power on the node where ETCS is connected. The total power losses at connection nodes are also included in (17,18). Constraints (19) and (20) define that power cannot be bought and sold at
the same time interval $t$. Here, $N$ is a sufficiently large number.

$$P_{i,t}^{\text{grid, buy, load}} + P_{i,t}^{\text{PV, avl}} + \sum_{b \in B : i \in \Omega_i^b} P_{b,t}^{\text{line}} - \sum_{b \in B : i \in \Omega_i^b} P_{b,t}^{\text{line}} = P_{i,t}^{\text{Load, aux}} + P_{i,t}^{\text{EV, ch, tot}} + P_{i,t}^{\text{grid, sell, load}}, \forall i, t$$ (15)

$$P_{i,t}^{\text{EV, ch, tot}} = \sum_m P_{i,m,t}^{\text{EV, ch}}, \forall i, t$$ (16)

$$P_{i,t}^{\text{grid, buy, tot}} = P_{i,t}^{\text{grid, buy, load}} + \sum_b P_{b,t}^{\text{loss, buy}}, \forall i \in \Omega_i^\text{Grid}, t$$ (17)

$$P_{i,t}^{\text{grid, sell, tot}} = P_{i,t}^{\text{grid, sell, load}} - \sum_b P_{b,t}^{\text{loss, sell}}, \forall i \in \Omega_i^\text{Grid}, t$$ (18)

$$P_{i,t}^{\text{grid, buy, tot}} \leq N \cdot u_{i,t}^\text{grid}, \forall i \in \Omega_i^\text{Grid}, t$$ (19)

$$P_{i,t}^{\text{grid, sell, tot}} \leq N \cdot (1 - u_{i,t}^\text{grid}), \forall i \in \Omega_i^\text{Grid}, t$$ (20)

**Line constraints**

Constraints (21) impose limits $(-P_{b}^{\text{max}}, P_{b}^{\text{max}})$ of the maximum power flow capacity of the lines which is valid for all the lines in the test system.

$$-P_{b}^{\text{max}} \leq P_{b,t}^{\text{line}} \leq P_{b}^{\text{max}}, \forall b, t$$ (21)

**Linear power losses model**

Special Order Sets of Type 2 (SOS2) method is used to linearize the power losses model. In (22), linear model of total power losses which includes second order function is indicated. Wherein, $|P_{b,t}^{\text{line, abs}}|$ is the absolute value and $(P_{b,t}^{\text{line}})^2$ is the square of power flow of lines. $c$ and $d$ are the coefficients for linear approach. While equation (23) defines the constraint of the SOS2, linear approaches of the transmitted power are represented in (24) and (25).

$$P_{b,t}^{\text{loss, tot}} = d \cdot |P_{b,t}^{\text{line, abs}}| + c \cdot (P_{b,t}^{\text{line}})^2, \forall b, t$$ (22)

$$\sum_p z_{b,p,t} = 1, \forall b, t$$ (23)

$$P_{b,t}^{\text{line}} = \sum_p X_p \cdot z_{b,p,t}, \forall b, t$$ (24)

$$(P_{b,t}^{\text{line}})^2 = \sum_p Y_p \cdot z_{b,p,t}, \forall b, t$$ (25)
2.2.3. Single level equivalent model of bi-level optimization

Firstly, to transform the lower level problem into Karush-Kuhn-Tucker (KKT) optimality conditions, the Lagrange function which is used to solve the proposed bi-level MILP model should be created as indicated in (26). Furthermore, derivative terms related to the stationarity conditions are indicated in (27)-(30).

\[
\mathcal{L} = \sum_{m} \sum_{t} \lambda_{t}^{\text{grid, buy}} \cdot P_{i,t}^{\text{grid, buy, load}} \cdot \Delta T
\]

\[
+ \gamma_{i,t}^{1} \cdot (-P_{i,t}^{\text{grid, buy, load}})
\]

\[
+ \gamma_{i,t}^{2} \cdot (P_{i,t}^{\text{grid, buy, load}} - P_{i,t}^{\text{net, demand}} - P_{i,t}^{EVPL,tot})
\]

\[
+ \gamma_{i,m,t}^{3} \cdot (-P_{i,m,t}^{EV,ch})
\]

\[
+ \gamma_{i,m,t}^{4} \cdot (P_{i,m,t}^{EV,ch} - CE_{m})
\]

\[
+ \gamma_{i,m,t}^{5} \cdot (SoE_{i,m,t}^{EV} - SoE_{m}^{EV,max})
\]

\[
+ \lambda_{i,m,t}^{1} \cdot (SoE_{i,m,t}^{EV} - SoE_{i,m,t-1} - (P_{i,m,t}^{EV,ch} \cdot CE_{m} \cdot \Delta T)
\]

\[
+ \lambda_{i,t}^{2} \cdot (P_{i,t}^{Load, aux} + P_{i,t}^{EV,ch,tot} + P_{i,t}^{grid, sell, load} - P_{i,t}^{grid, buy, load} - P_{i,t}^{PV,avl})
\]

\[
(26)
\]

\[
\frac{\partial \mathcal{L}}{\partial P_{i,t}^{\text{grid, buy, load}}} = \lambda_{t}^{\text{grid, buy}} \cdot \Delta T - \gamma_{i,t}^{1} + \gamma_{i,t}^{2} - \lambda_{i,t}^{2} = 0, \forall i, t
\]

\[
(27)
\]

\[
\frac{\partial \mathcal{L}}{\partial P_{i,m,t}^{EV,ch}} = -\gamma_{i,t}^{2} - \gamma_{i,m,t}^{3} + \gamma_{i,m,t}^{4} - \gamma_{i,m,t}^{6} \cdot CE_{m} \cdot \Delta T + \lambda_{i,t}^{2} = 0, \forall i, m, t
\]

\[
(28)
\]

\[
\frac{\partial \mathcal{L}}{\partial SoE_{i,m,t}^{EV}} = \gamma_{i,m,t}^{5} + \lambda_{i,m,t}^{1} - \lambda_{i,m,t+1}^{1} = 0, \forall i, m, t \in [T^{a}, T^{d}]
\]

\[
(29)
\]

\[
\frac{\partial \mathcal{L}}{\partial SoE_{m,t}^{EV}} = \gamma_{i,m,t}^{5} + \lambda_{i,m,t}^{1} = 0, \forall i, m, t = T^{a}
\]

\[
(30)
\]

The expressions (31)-(35) identify the complementary slackness conditions. These bilinear terms are linearized by using Big-M method and explained in (36).

\[
(0 \leq P_{i,t}^{\text{grid, buy, load}}) \perp (0 \leq \gamma_{i,t}^{1}), \forall i, t \in [T^{a}, T^{d}]
\]

\[
(31)
\]

\[
(0 \leq P_{i,t}^{\text{net, demand}} + P_{i,t}^{EVPL,tot} - P_{i,t}^{\text{grid, buy, load}}) \perp (0 \leq \gamma_{i,t}^{2}), \forall i, t \in [T^{a}, T^{d}]
\]

\[
(32)
\]

\[
(0 \leq P_{i,m,t}^{EV,ch}) \perp (0 \leq \gamma_{i,t}^{3}), \forall i, t \in [T^{a}, T^{d}]
\]

\[
(33)
\]

\[
(0 \leq CR_{m}^{EV} - P_{i,m,t}^{EV,ch}) \perp (0 \leq \gamma_{i,t}^{4}), \forall i, t \in [T^{a}, T^{d}]
\]

\[
(34)
\]
\[(0 \leq \text{SoE}_{m}^{EV_{\text{max}}} - \text{SoE}_{m}^{EV_i,t}) \perp (0 \leq \gamma_i^1, \forall i, t \in [T^n, T^d]) \quad (35)\]

In (36), both decision variable \( (P_{\text{grid},\text{buy,load}}^i,t) \) and related Lagrange multiplier \( (\gamma_i^1) \) should be greater than zero. The decision variable \( (P_{\text{grid},\text{buy,load}}^i,t) \) and Lagrange multiplier \( (\gamma_i^1) \) must be decomposed via the binary variable \( (u_{i,t}^{\text{bigM1}}) \). \( K \) is a sufficiently large number like \( N \).

\[
0 \leq P_{\text{grid},\text{buy,load}}^i,t \perp 0 \leq \gamma_i^1 = \begin{cases} 
P_{\text{grid},\text{buy,load}}^i,t \geq 0 \\
\gamma_i^1 \geq 0 \\
P_{\text{grid},\text{buy,load}}^i,t \leq K \cdot u_{i,t}^{\text{bigM1}} \\
\gamma_i^1 \leq K \cdot (1 - u_{i,t}^{\text{bigM1}})
\end{cases} \quad (36)
\]

The objective function in (13) of the single level model of the problem is to minimize total power losses at distribution level subject to (8)-(11), (15)-(25), (27)-(36).

3. Test and results

3.1. Input data

Seasonal power consumption profiles of the office buildings, roof area for possible PV integration, and number of trucks with arrival and departure durations are obtained from the customs zone management. In addition, solar radiation data of Istanbul, Turkey is integrated for PV generation calculations including seasonal variation. The average daily power consumption of July and January are implemented to calculations to reflect seasonal impact on the power consumption as indicated in Figure 3. While the average daily energy consumption is 403 kWh in January, it reaches to the value of 448 kWh in July due to the consumption generated by air conditioner loads. Furthermore, total roof area for PV installation is considered as 35000 m\(^2\) based on the obtained information from customs zone management. Thus, installation power of PV system which is planned to be integrated is calculated as 6.5 MWp. The irradiation data of summer and winter season in Istanbul is acquired from [38] is indicated Figure 4.

![Figure 3. Auxiliary consumptions of customs zone in winter and summer scenarios](image-url)
Furthermore, technical specifications of electric vehicles and trucks which are foreseen to be users of customs zone are shared in Table 2 and Table 3, respectively. It is assumed that 50% of the office staff will prefer EVs which means 500 EVs will be present at customs zone during working hours. The number of electric trucks that will be present in customs zone are determined as 589 for winter and 700 for summer scenario cases based on actual data obtained from customs zone management. Finally, arrival and departure time intervals of the vehicles in the customs zone are randomly determined by MATLAB software.

**Table 2.** Technical specifications of electric cars

<table>
<thead>
<tr>
<th>Car Brand</th>
<th>Battery Capacity (kWh)</th>
<th>Charging Power (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dacia Spring Electric</td>
<td>26.8</td>
<td>6.6</td>
</tr>
<tr>
<td>Renault Twingo Electric</td>
<td>21.3</td>
<td>22</td>
</tr>
<tr>
<td>Seat Mii Electric</td>
<td>32.3</td>
<td>7.2</td>
</tr>
<tr>
<td>Fiat 500e</td>
<td>37.3</td>
<td>11</td>
</tr>
<tr>
<td>Opel Mokka-E</td>
<td>45</td>
<td>7.4</td>
</tr>
<tr>
<td>Kia E-Soul</td>
<td>64</td>
<td>7.2</td>
</tr>
<tr>
<td>Hyundai Kona Electric</td>
<td>67.5</td>
<td>11</td>
</tr>
<tr>
<td>Tesla Model Y</td>
<td>75</td>
<td>11</td>
</tr>
<tr>
<td>Tesla Model S</td>
<td>90</td>
<td>16.5</td>
</tr>
<tr>
<td>BMWiXxDrive 50</td>
<td>110</td>
<td>11</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Truck Brand</th>
<th>Battery Capacity (kWh)</th>
<th>Charging Power (kW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Man eTGM</td>
<td>185</td>
<td>22</td>
</tr>
<tr>
<td>Mercedes-Benz e-Actros</td>
<td>240</td>
<td>20</td>
</tr>
<tr>
<td>DAF LF Electric</td>
<td>282</td>
<td>23.5</td>
</tr>
<tr>
<td>Scania BEV</td>
<td>300</td>
<td>25</td>
</tr>
<tr>
<td>Volvo FM Electric</td>
<td>490</td>
<td>43</td>
</tr>
</tbody>
</table>
3.2. Simulation results

Proposed bi-level MILP based mathematical model is solved in CPLEX v.12 commercial solver of GAMS v.24.1.3. In addition, different case studies under seasonal effects are carried out in order to prove the effectiveness of the model as stated below:

- Case-1: Winter scenario without PV
- Case-2: Winter scenario with PV
- Case-3: Summer scenario without PV
- Case-4: Summer scenario with PV

Power losses and total costs for each case in bi-level model and single level cost minimization model are shared with the Table 4. Significant reduction in power losses for summer scenarios which is the upper level problem of bi-level model are obtained. While total energy bought from the grid is decreased from the value of 88.680 MWh to the value of 8.476 MWh, total grid losses are reduced from 12.510 MWh to 0.313 MWh thanks to the integration of PV system to the customs zone. In this regard, it is expected that total energy losses are 14.11% without PV system due to the impact of the high charging power of electric trucks. However, total energy losses are calculated as 3.69% thanks to the PV generation. In terms of winter scenarios, while total energy bought from the grid and the related energy losses are 77.026 MWh and 9.758 MWh, respectively for Case-1, the values are reduced to 23.127 MWh and 1.032 MWh, respectively for Case-2. The winter scenarios present the results of reduction of line losses from 12.66% to 4.46%. According to the results of the minimization of total cost which is the lower level problem of bi-level model, despite the increment in the vehicle density and auxiliary consumption, the total energy cost and power losses are significantly decreased. Total operational cost is calculated as 3789.64 TL without PV generation for Case-1 and 1180.11 TL for Case-2. In terms of winter scenarios, while total cost is 4293.28 TL for Case-3, it is reduced to the value of 316.29 TL with PV generation for Case-4. The main factor is the high, PV generation in summer and possibility of selling the excess power back to grid. It is observed that 0.746 MWh excess energy is sold back to the grid for Case-4. Furthermore, comparisons of power losses and total costs under bi-level model and single level cost minimization model are also depicted in the table. While both power losses and operational costs are considered in the bi-level model, single level cost minimization only takes into account the operational costs. Therefore, total cost increases under the bi-level model compared to the single level model because of the consideration of two opposite factors. However, power losses significantly decrease along with the bi-level model, and it is observed that the power efficiency of the grid as well as the economic gain is ensured.

<table>
<thead>
<tr>
<th></th>
<th>Power losses (MWh)</th>
<th>Total cost (TL)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Single level</td>
<td>Bi-level</td>
</tr>
<tr>
<td>Case 1</td>
<td>12.043</td>
<td>9.758</td>
</tr>
<tr>
<td>Case 2</td>
<td>3.427</td>
<td>1.032</td>
</tr>
<tr>
<td>Case 3</td>
<td>14.047</td>
<td>12.510</td>
</tr>
<tr>
<td>Case 4</td>
<td>1.473</td>
<td>0.313</td>
</tr>
</tbody>
</table>

Total energy bought from the grid for each case is depicted in Figure 5. It can be stated that total energy consumed at noon time is more than others due to the vehicle density and auxiliary consumption. Energy bought from the grid is reduced with the impact of PV generation in both winter and summer scenarios. However, reduction in summer scenarios are much more higher compared with winter scenarios due to the impact of PV generation. Renault Twingo Electric (REN), Seat Mii Electric (SEAT), and Tesla Model S (TES-S) are the EVs
used for simulations where Man eTGM (MAN), Mercedes-Benz e-Actros (MER), and Volvo FM Electric (VOL) are the trucks used for simulations and SoE values are indicated in Figures 6 and 7, respectively. Additionally, it can be stated that all the vehicles leave from the charging station by reaching maximum SoE.

![Figure 5. Total energy bought from the grid for each case](image)

![Figure 6. SoE levels of electric cars](image)

The customs zone and grid model are integrated in Electrical Transient Analyzer Program (ETAP) environment to simulate and investigate the impact of ETCS equipped with PV generating units on the existing network. The simulations are conducted using Newton-Raphson methodology. The voltage regulation is investigated for the impact of electric truck demand alone and simultaneous impact of electric trucks and PV units. The sub scenario of the mentioned variation is considered as the seasonal impact of truck consumption and PV generation. The first scenario consists of the comparison of electric truck consumption and PV generation impact on the voltage regulation of customs zone switchgear under winter conditions. The electric truck traffic information based on seasonal data is obtained from Istanbul Muratbey Customs Zone Directory where the total PV generation is calculated by winter average solar radiation data of Istanbul, Turkey. The voltage regulation of
the Customs Zone Switchgear is aimed to keep in the range of ±4%. The impact of electric truck consumption and PV generation is indicated in Figure 8.

As the second scenario of voltage regulation study case, the customs zone is investigated for summer average PV generation and electric truck consumption. The number of electric trucks are determined using the actual data obtained from customs zone directory where the truck battery capacities are obtained from manufacturer data as indicated in Table 3. Total PV generation based on hourly variation is calculated using the average solar radiation data of Istanbul, Turkey. The simulation results of summer grid voltage regulation are presented in Figure 9.

The obtained results indicate that the voltage regulation is kept in the range of ±4% with the impact of PV generated power. Two scenarios for summer and winter average consumption and generation data indicate that the voltage level is stabilized as aimed.
4. Conclusions

In this paper, bi-level charging management system is proposed for ETCS considering power losses. In accordance with the results, there are considerable impacts of the electric trucks on power grid due to the high charging power demand. Especially, it is observed that both grid losses and operational costs are quite high in the absence of distributed generation as seen in Table 4. Moreover, inclusion of distributed energy resources like PV system which is used in this paper presents economic profit to the parking lot management and increases the reliability of ETCS. It was expected that total energy losses are 12.66% and 14.11% without PV system in winter and summer scenarios, respectively. However, losses are calculated as 4.46% and 3.69% thanks to the PV generation in winter and summer scenarios, respectively. In addition, total cost is significantly reduced by 68.85% for winter and by 92.63% for summer study cases. Consequently, the proposed solution prevents the modification requirement for primary equipment of grid connection section such as transformers and transmission lines in case of ETCS installation at customs zone. Furthermore, it was observed that more advantages are available in summer based case studies due to the seasonal impact of the PV generation. Finally, the PV system generates 45,172 MWh/day for winter scenario and 70,468 MWh/day for summer scenario. Therefore, related total $CO_2$ emissions are reduced by 40,654 kg/day for winter and by 63,421 kg/day for winter. As a future study, a hybrid system consists of PV, wind power plant, and community energy storage for high vehicle capacity charging stations will be investigated.

References


