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Comfort violation minimization oriented energy management strategy for a renewable-assisted stand-alone multi-energy electric vehicle service station

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ABSTRACT

In this study, a comfort violation minimization oriented energy management strategy is proposed for a stand-alone electric vehicle (EV) service station serving multiple EV types in a multi-energy manner. The main purpose of this strategy is to minimize the discomfort of EV owners due to insufficient energy supply while considering the fairness among users and optimizing the utilization of renewable energy sources. The criteria for selecting this strategy include: (1) mitigating customer dissatisfaction arising from inadequate energy supply, (2) ensuring fairness in energy distribution among different EV types, and (3) maximizing the use of renewable power sources, such as photovoltaic (PV) units. The developed mixed-integer linear programming (MILP) model comprises a PV unit as the main power source, with an energy storage system (ESS) and an electrolyzer-supported main hydrogen storage unit fulfilling the energy and hydrogen demands of battery electric vehicles (BEVs) and fuel cell electric vehicles (FCEVs), respectively. A comfort violation fairness constraint is also introduced to guarantee a fair service for all EV owners, thereby enhancing the social acceptability of the provided EV service.

Simulation results, obtained under various case studies considering component size changes and comfort fairness constraint relaxation, demonstrate the importance of striking a balance between investing in larger components and allowing for a certain level of customer dissatisfaction. The analysis revealed that relaxation of the fairness constraint led to a reduction in overall comfort violation by up to 15 % for both BEVs and FCEVs combined; however, this relaxation resulted in significant differences in comfort violation among different EV owner types, with variations ranging from a minimum of 0 % to a maximum of >90 %. These findings emphasize the significance of considering fairness in energy distribution to prevent potential dissatisfaction among end-users. Future studies will explore the development of a grid-connected system and compare the stand-alone structure in a techno-economic context, considering the possible impact of different EV types on grid operation during normal and resiliency-oriented conditions.

1. Introduction

1.1. Motivation and background

In recent decades, energy supply has emerged as a primary concern for both developed and developing nations, leading to significant shifts in political, economic, sociocultural, and environmental dynamics worldwide. Environmental considerations have played a key role in these changes, as the global warming crisis has prompted the implementation of stringent policies aimed at reducing the impact of conventional energy sources across various sectors.

Electrifying vehicles has become a critical issue, particularly given the transportation sector's substantial contribution to greenhouse gas (GHG) emissions, which account for 30 % of total emissions in the US, the world's leading GHG emitter [1]. Numerous fully electric transportation solutions, such as battery electric vehicles (SBEVs) and fuel cell EVs (FCEVs), have been developed by leading manufacturers and implemented with support from various stakeholders (e.g., governments, investors) across different industries (e.g., personal transportation, heavy-duty, public transportation, maritime, and aviation). To enhance the environmental benefits of the electrified transportation chain, incorporating renewable energy sources into EV charging infrastructure has gained increasing attention in recent years. Stand-alone renewable-powered solutions, supported by energy storage units, have been developed and are expected to become more prevalent in the future. This approach helps alleviate the need for substantial investments in capacity expansion for both the electric power system and

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Nomenclature

The sets, parameters and decision variables that are used in this paper are alphabetically listed below. Other symbols and abbreviations are defined where they first appear.

A. Sets & indices

k set of FCEVs
m set of SBEVs
t set of time periods

B. Parameters & constants

a_{H2-P} hydrogen amount to electric power conversion constant [kg/kW]
Cap_{elec} electrolyzer capacity [kW]
Cap_{ESS} capacity of common ESS unit [kWh]
$Cap_{FCEV-H2,k}$ capacity of hydrogen tank of FCEV k [kg]
$Cap_{MHSU-H2}$ capacity of main hydrogen storage unit [kg]
$Cap_{SBEV,m}$ capacity of battery of SBEV m [kWh]
$Cap_{SCEV-CS,m}$ charging station capacity of the SBEV m [kW]
CE charging efficiency
DE discharging efficiency
Lim_{ESS} ESS charging/discharging limit [kW]
$m_{FCEV-H2-des,k}$ desired hydrogen amount in FCEV k during departure time [kg]
$m_{FCEV-H2-init,k}$ initial hydrogen amount in FCEV k during arrival time [kg]
$m_{MHSU-H2-init}$ initial hydrogen amount in main hydrogen storage unit [kg]
$m_{MHSU-H2-min}$ minimum hydrogen amount in main hydrogen storage unit [kg]
N sufficiently large positive constant
N_{CV} ratio (≥ 1) between minimum and maximum comfort violation values for all EV owners ensuring a fair comfort violation
$P_{PV,t}$ power production of PV unit in period t [kW]
$SoE_{ESS-init}$ initial state-of-energy of common ESS unit [kWh]
$SoE_{ESS-min}$ minimum allowable state-of-energy of common ESS unit [kWh]
$SoE_{SBEV-des,m}$ desired state-of-energy of SBEV m during departure time [kWh]
$SoE_{SBEV-init,m}$ initial state-of-energy of SBEV m during departure time [kWh]
$T_{a,k}$ arrival time of FCEV k
$T_{a,m}$ arrival time of SBEV m
$T_{d,m}$ departure time of FCEV k
$T_{d,k}$ departure time of SBEV m
ΔT time granularity [h]

C. Decision variables

CV_{max} maximum comfort violation value among different EV owners [%]
CV_{min} minimum comfort violation value among different EV owners [%]
$m_{FCEV,k,t}$ amount of hydrogen injected to the hydrogen tank of FCEV k from the main hydrogen storage unit in period t [kg]
$m_{FCEV-H2,k,t}$ hydrogen amount in the hydrogen tank of FCEV k in period t [kg]
$m_{FCEV-H2-dev,k}$ deviation of hydrogen level of FCEV k from the desired level [kg]
$m_{MHSU-H2,t}$ hydrogen amount in main hydrogen storage unit in period t [kg]
$m_{MHSU-H2-prod,t}$ hydrogen amount produced by the electrolyzer unit in period t [kg]
$P_{elec,t}$ electrolyzer power in period t [kW]
$P_{ESS-ch,t}$ charging power of CESS unit in period t [kW]
$P_{ESS-disch,t}$ discharging power of CESS unit in period t [kW]
$P_{SBEV-ch,m,t}$ charging power of SBEV m in period t [kW]
$P_{SBEV-ch-total,t}$ total charging power of SBEVs in period t [kW]
$SoE_{ESS,t}$ state-of-energy of common ESS unit in period t [kWh]
$SoE_{SBEV,m,t}$ state-of-energy of SBEV m in period t [kWh]
$SoE_{SBEV-dev,m}$ deviation of state-of-energy of SBEV m from the desired level [kWh]
u_t binary variables to prevent simultaneous occurrence of charging and discharging conditions of common ESS unit
$\%m_{FCEV-H2-dev,k}$ percentage of deviation of hydrogen level of FCEV k from the desired level [%]
$\%SoE_{SBEV-dev,m}$ percentage of deviation of state-of-energy of SBEV m from the desired level [%]

other service infrastructures.

1.2. Literature overview

Numerous studies have been conducted on grid-connected service infrastructure provision, particularly for SBEVs. A game-theoretic approach to model the interactions between the grid operator, the parking lot operator, and the EV owners was proposed in [2] with the aim of maximizing the monetary benefits of the parking lot operator. However, this study did not consider renewable energy integration or EV user comfort. A management strategy for multi-parking lots operated by the same entity was proposed in [3], enabling an energy exchange capability between parking lots to maximize the entity's profit. While this approach offered an innovative solution for energy exchange, it did not specifically address distributed generation units or user comfort.

There has been a growing number of studies specifically dealing with the role of distributed generation units, especially photovoltaic (PV) systems, in EV interconnection to electric power systems from single or multiple charging points. For instance, a model predictive control methodology for a grid-connected multiple EV charging station supported by PV, FC, electrolyzer, hydrogen storage, and ESS was proposed in [4]. This study provided a comprehensive solution for renewable integration but did not address EV user comfort or fairness. An economic and environmental analysis of a PV and ESS supplied grid-connected SBEV parking lot was conducted in [5], which covered the environmental aspects but did not consider user comfort or fairness constraints.

Several review studies have focused on PV integrated EV charging solutions, such as the studies by Bhatti et al. [6], Nunes et al. [7], and Yap et al. [8]. These studies provided valuable insights into the state of the art but did not specifically address comfort or fairness issues. Eltoumi et al. [9] studied the usage of hybrid power sources, including PV, battery-based energy storage systems (ESS), electrolyzer-FC combined hydrogen-electric chain-based power sources, etc., for supplying SBEV charging requirements in both grid-connected and stand-alone applications. This study expanded the potential power sources but did not consider user comfort or fairness.

Regarding stand-alone solutions, Afshar et al. [10] reviewed mobile EV charging service solutions with practical evidence. Although this study provided valuable information on stand-alone solutions, it did not address user comfort or fairness. Ghotge et al. [11] specifically proposed an optimal management strategy for PV-powered stand-alone SBEV charging service points without the implementation of an onsite ESS unit. However, this study did not consider multiple types of EVs, user comfort, or fairness.

Table 1
The taxonomy regarding the contribution of the proposed study.

Study	Multi-types of EVs	Comfort violation consideration	Fairness constraint	Stand-alone structure	PV & ESS integration
[2]	×	×	×	×	×
[3]	×	×	×	×	×
[4]	×	×	×	×	✓
[5]	×	×	×	×	✓
[6]	×	×	×	×	✓
[7]	×	×	×	×	✓
[8]	×	×	×	×	✓
[9]	✓	×	×	✓	✓
[10]	×	×	×	✓	×
[11]	×	×	×	✓	✓
[12]	×	×	×	×	×
[13]	×	×	×	×	✓
[14]	×	×	×	×	×
[15]	✓	×	×	✓	✓
[16]	✓	×	×	×	✓
[17]	✓	×	×	×	✓
[18]	✓	×	×	✓	✓
[19]	✓	×	×	✓	✓
[20]	×	✓	×	×	×
This paper	✓	✓	✓	✓	✓

Several studies have aimed to find better solutions for serving FCEVs. The role of electrolyzers to provide grid flexibility was analysed in [12], considering the use of the produced hydrogen for FCEV refueling. A model predictive control approach was proposed in [13] for a wind power-assisted grid-connected service station supplying the refueling requirements of FCEVs via an electrolyzer unit-based hydrogen production. A distribution system operator point-of-view was proposed in [14] for solely grid-supplied electrolyzer units supplying the refueling requirements of FCEVs, including a risk-averse techno-economic minimization problem. These studies provided valuable insights into FCEV servicing but did not consider user comfort, fairness, or integration with SBEVs.

Recent studies have focused on serving multiple types of EVs at a single service point. Guo and Gong [16] proposed a deep reinforcement learning-based energy management strategy for a PV and ESS supported grid-connected service point for both SBEVs and FCEVs. Çiçek [17] provided a cost-minimization-oriented energy management strategy for a PV-supported grid-connected all-in-one service point, including FCEV refueling and SBEV charging/swapping. Stand-alone service points for both FCEVs and SBEVs, supported by PV, diesel generator, and FC-based units, were proposed in [18], which also considered the risk-based optimal sizing of the components. A similar structure to [18] was proposed in [19], focusing on a stand-alone application based on PV, diesel generator, and FC to supply FCEVs and SBEVs, considering optimal design and coordination processes. These studies provided applicable concepts for renewable-supported EV service points; however, they did not consider EV owner comfort violations due to insufficient supply of the desired charging and refueling levels. This issue is particularly important for stand-alone service points.

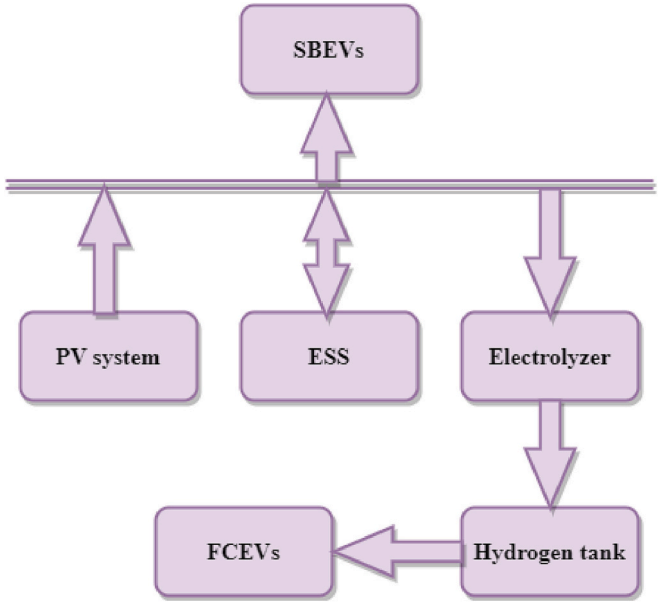

Fig. 1. A general diagram of the proposed structure.

A comfort calculation was previously proposed in [20] only for SBEVs in a grid-connected structure, considering a completely different concept without any fairness limitation. This study served as an inspiration to expand the concept to multiple EV types with different modeling details and service station structures. However, the comfort and fairness considerations in this study were limited to SBEVs and did not address the needs of FCEVs.

In summary, the existing literature provides valuable insights into various aspects of EV service infrastructure provision, including renewable energy integration, energy exchange between parking lots, and stand-alone solutions. However, none of these studies have comprehensively addressed the issue of EV owner comfort and fairness constraints, particularly for service points catering to both SBEVs and FCEVs. The current paper aims to fill this gap by providing a novel approach that takes into account user comfort and fairness for multiple types of EVs in a single service point, thus offering a more holistic and efficient solution for EV service infrastructure provision.

1.3. Content and contribution of the study

In this study, the Author proposes a comfort violation minimization oriented energy management strategy for a stand-alone service station catering to multiple types of EVs. The primary power source is a PV system, supplemented by an ESS unit and an electrolyzer that generates hydrogen for a main hydrogen storage unit, which together meet the electric energy and hydrogen needs of SBEVs and FCEVs, respectively. Comfort violation is defined as the deviation from desired energy and hydrogen levels for SBEV and FCEV owners, respectively. A Mixed-Integer Linear Programming (MILP) model is presented to facilitate a detailed analysis of system component sizes and comfort violation fairness limits among EV owners through case studies.

The contributions of the proposed concept are twofold considering also the taxonomy provided in Table 1:

- The model offers a fully renewable, stand-alone supply structure that caters to the distinct requirements of both SBEVs and FCEVs, while considering comfort violations.
- The importance of comfort violation fairness among different EV owners is emphasized as a crucial aspect of customer satisfaction from the service operator's perspective.

1.4. Paper organization

The remainder of this study is organized as follows: Section 2 deals with the mathematical modeling details of the proposed methodology. Then, Section 3 presents the case studies based analyses and the relevant obtained results. Finally, Section 4 provides the concluding remarks.

2. System description and methodology

The proposed system comprises a single service point that caters to both SBEVs and FCEVs, aiming to optimize user comfort and fairness among different types of EVs while minimizing energy management costs as shown in Fig. 1. This service point is connected to a PV system as a renewable energy source. Additionally, an energy storage system (ESS) is integrated to store excess energy generated from the PV system and to provide support during periods of high demand. The service point is also equipped with an electrolyzer unit, which generates hydrogen for FCEV refueling using electricity from the grid, PV system, or ESS. The hydrogen produced is stored in a hydrogen storage system, which is then used to refuel FCEVs at the service point. For SBEVs, the service point provides charging services through multiple charging stations. The energy management system coordinates the power flow among the PV system, ESS, electrolyzer, hydrogen storage, and charging stations to maximize user comfort and maintain fairness while minimizing overall energy management costs.

Here, the comfort variation is defined as the deviation of the energy and hydrogen levels of respectively SBEV and FCEVs from their desired level at the time of departure from the service station. The average value of the mentioned individual comfort violation values for SBEV and FCEVs is minimized as depicted in (1):

$$MinimizeAverage-CV=\frac{\sum_{m}\%SoE_{SBEV-dev,m}}{card(m)}+\frac{\sum_{k}\%m_{FCEV-H2-dev,k}}{card(k)} \tag{1}$$

The power balance is given in (2) composed of PV power production, ESS discharging power on one hand and total SBEV charging power, ESS charging power and electrolyzer power on the other hand.

$$P_{PV,t}+P_{ESS-disch,t}=P_{SBEV-ch-total,t}+P_{ESS-ch,t}+P_{elec,t},\forall t \tag{2}$$

The logical constraints in (3) and (4) hinder the simultaneous occurrence of the discharging and charging transactions of ESS unit. The state-of-energy variation of the ESS unit is defined as in (5) dependent on ESS charging and discharging power values and efficiencies. The initialization of ESS state-of-energy is provided by (6) while state-of-energy of ESS unit is lower and upper bounded by (7). The state-of-energy value should be greater than its initial value at the end of the evaluation horizon as ensured by (8).

$$P_{ESS-disch,t}\le Lim_{ESS}\cdot u_t,\forall t \tag{3}$$

$$P_{ESS-ch,t}\le Lim_{ESS}\cdot(1-u_t),\forall t \tag{4}$$

$$SoE_{ESS,t}=SoE_{ESS,t-1}+P_{ESS-ch,t}\cdot\Delta T\cdot CE-\frac{P_{CESS-disch,t}\cdot\Delta T}{DE},\forall t>1 \tag{5}$$

$$SoE_{ESS,t}=SoE_{ESS-init},if\ t=1 \tag{6}$$

$$SoE_{ESS-min}\le SoE_{ESS,t}\le Cap_{ESS},\forall t \tag{7}$$

$$SoE_{ESS,t}\ge SoE_{ESS-init},if\ t=T_{final} \tag{8}$$

The total SBEV power demand is calculated via the summation of each SBEV's charging power as in (9) where the charging power of each SBEV is limited by (10). The state-of-energy variation of each SBEV is calculated depending on the SBEV charging power and efficiency as in (11). The initialization and upper bound of SBEV state-of-energy are defined respectively in (12) and (13). The final desired state-of-energy level of each SBEV is depicted in (14) together with the possible deviation from this level leading to the percentage of this deviation calculated in (15).

$$P_{SBEV-ch-total,t}=\sum_{m}P_{SBEV-ch,m,t},\forall t \tag{9}$$

$$P_{SBEV-ch,m,t}\le Cap_{SCEV-CS,m},\forall t \tag{10}$$

$$SoE_{SBEV,m,t}=SoE_{SBEV,m,t-1}+P_{SBEV-ch,m,t}\cdot\Delta T\cdot CE,\forall m,\forall t>T_{a,m} \tag{11}$$

$$SoE_{SBEV,m,t}=SoE_{SBEV-init,m},\forall m,if\ t=T_{a,m} \tag{12}$$

$$SoE_{SBEV,m,t}\le Cap_{SBEV,m},\forall m,\forall t \tag{13}$$

$$SoE_{SBEV,m,t}+SoE_{SBEV-dev,m}\ge SoE_{SBEV-des,m},\forall m,if\ t=T_{d,m} \tag{14}$$

$$\%SoE_{SBEV-dev,m}=100\cdot\frac{SoE_{SBEV-dev,m}}{Cap_{SBEV,m}},\forall m \tag{15}$$

The calculation of the hydrogen amount produced by the electrolyzer power limited by (16) is given in (17). The hydrogen amount variation within the main hydrogen storage unit of the service station is depicted in (18) considering the produced hydrogen and the hydrogen demand of the FCEVs. The initial hydrogen amount in the main hydrogen storage unit is defined in (19) and bounded by lower and upper limits as in (20). The hydrogen amount in the main hydrogen storage unit should be greater than its initial value at the end of the evaluation horizon as ensured by (21).

$$P_{elec,t}\le Cap_{elec},\forall t \tag{16}$$

$$m_{MHSU-H2-prod,t}=P_{elec,t}\cdot\Delta T\cdot a_{H2-P},\forall t \tag{17}$$

$$m_{MHSU-H2,t}=m_{MHSU-H2,t-1}+m_{MHSU-H2-prod,t}-\sum_{k}m_{FCEV,k,t},\forall t>1 \tag{18}$$

$$m_{MHSU-H2,t}=m_{MHSU-H2-init},if\ t=1 \tag{19}$$

$$m_{MHSU-H2-min}\le m_{MHSU-H2,t}\le Cap_{MHSU-H2},\forall t \tag{20}$$

$$m_{MHSU-H2,t}\ge m_{MHSU-H2-init},if\ t=T_{final} \tag{21}$$

The hydrogen amount variation in each FCEV's hydrogen tank is depicted in (22) while the hydrogen value at the hydrogen tank of each FCEV is initiated by (23) and upper bounded by (24). Each FCEV is expected to leave the residential community with a hydrogen level greater than a predefined desired value considering the deviation possibility from this level as in (25). This percentage of this deviation for each FCEV is calculated by (26).

$$m_{FCEV-H2,k,t}=m_{FCEV-H2,k,t-1}+m_{FCEV,k,t},\forall k,t>T_{a,k} \tag{22}$$

$$m_{FCEV-H2,k,t}=m_{FCEV-H2-init,k},\forall k,t=T_{a,k} \tag{23}$$

$$m_{FCEV-H2,k,t}\le Cap_{FCEV-H2,k},\forall k,\forall t \tag{24}$$

$$m_{FCEV-H2,k,t}+m_{FCEV-H2-dev,k}\ge m_{FCEV-H2-des,k},\forall k,t=T_{d,k} \tag{25}$$

$$\%m_{FCEV-H2-dev,k}=\frac{m_{FCEV-H2-dev,k}}{Cap_{FCEV-H2,k}},\forall k \tag{26}$$

Finally, the fairness of the comfort violation among different types of EV owners is ensured by (27)–(29). This concept inspired from [21] (the

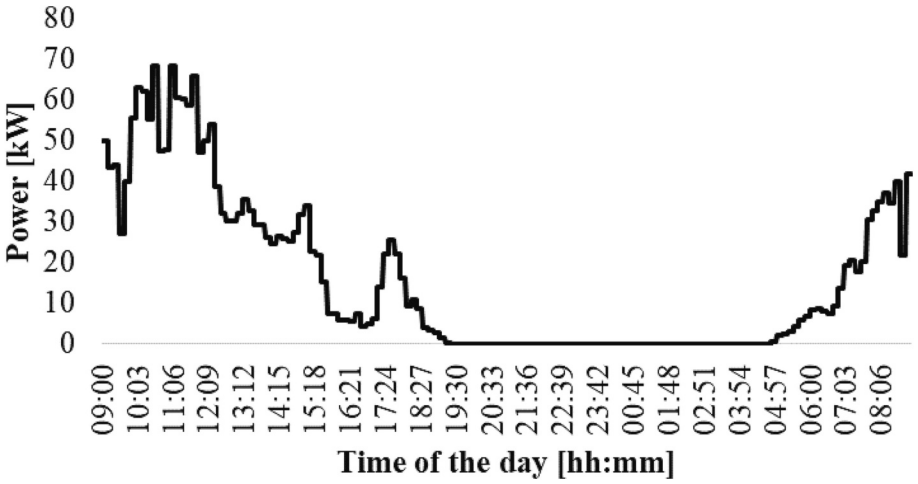

Fig. 2. PV power production per 100 kW installation.

mentioned study mainly provided insights for the fairness among end-users enrolled in a thermostatically controllable loads oriented demand response program, which has no relevance to the concept proposed in this study) provides a basis to ensure an acceptable similarity between the comfort violation levels those EV owners will likely. Here, defining N_{CV} exactly as 1 means all the EV owners should face the same level of comfort violation. Defining this parameter close to 1 will ensure a greater fairness, however this may result in an infeasible problem. Thus, this brings an interesting point in terms of sensitivity of the energy management system's decisions on the value of this parameter.

$$CV_{min} \leq \%m_{FCEV-H2-dev,k} \leq CV_{max} \tag{27}$$

$$CV_{min} \leq \%SoE_{SBEV-dev,m} \leq CV_{max} \tag{28}$$

$$CV_{max} \leq N_{CV} \cdot CV_{min} \tag{29}$$

Before proceeding with the specific implementation details, the overall workflow of the proposed approach consisting of the following steps is depicted with the aim to help readers gain a clear understanding of the main components of the proposed approach and their interactions:

- Collect input data, including PV generation profile, power generation capability of the FC system, ESS state-of-energy, hydrogen storage levels, and user preferences for SBEVs and FCEVs.
- Process the input data and determine the initial energy management parameters, such as energy demand, available resources, and constraints, for the stand-alone operation mode.
- Apply the comfort violation minimization algorithm, which incorporates a fairness limitation, to optimize energy allocation among the different components of the service point, ensuring that the charging and refueling demands of SBEVs and FCEVs are met as efficiently and fairly as possible.
- Generate reports and visualizations to illustrate the performance of the proposed approach in terms of minimizing comfort violations and maximizing user satisfaction.

3. Test and results

The problem of the comfort violation minimization oriented energy management strategy is created through MILP approach. The proposed structure is tested with the GAMS v.24.1.3 software and CPLEX v.12 solver. Input data and simulation results are presented in the subsections of this section, respectively.

Table 2
The clarification of the case studies.

Case	PV [kW]	ESS [kWh]	Electrolyzer [kW]	Main hydrogen storage unit [kg]	N_{CV}
Case-1	3000	3000	3000	300	1.1
Case-2	2000	2000	2000	200	1.1
Case-3	1000	1000	1000	100	1.1
Case-4	1000	1000	1000	100	Inf

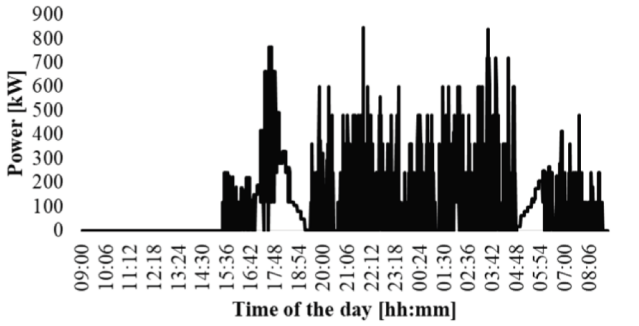

Fig. 3. Total charging power of SBEVs for Case-1.

3.1. Input data

The input data for a sample 100 kW installation is depicted in Fig. 2. As seen, the variation belongs to a cloudy day with a varying production profile enabling the analysis of the system performance under relatively harsh conditions.

The hydrogen amount to electric power conversion constant is considered as 0.02 kg/kWh considering the data given in [22]. The hydrogen storage capacity of each FCEV is defined as 5 kg [23] while 100 kWh battery capacity is defined for SBEVs.

Here it should be noted that the initial and minimum levels of energy and hydrogen respectively for ESS and main hydrogen storage unit are defined as 50 % and 10 % of the relevant storage capacities. The time granularity is considered as 1 min (0.0167 h). It is also assumed that the desired levels of energy and hydrogen are equal to the battery and hydrogen storage unit capacities respectively for SBEVs and FCEVs.

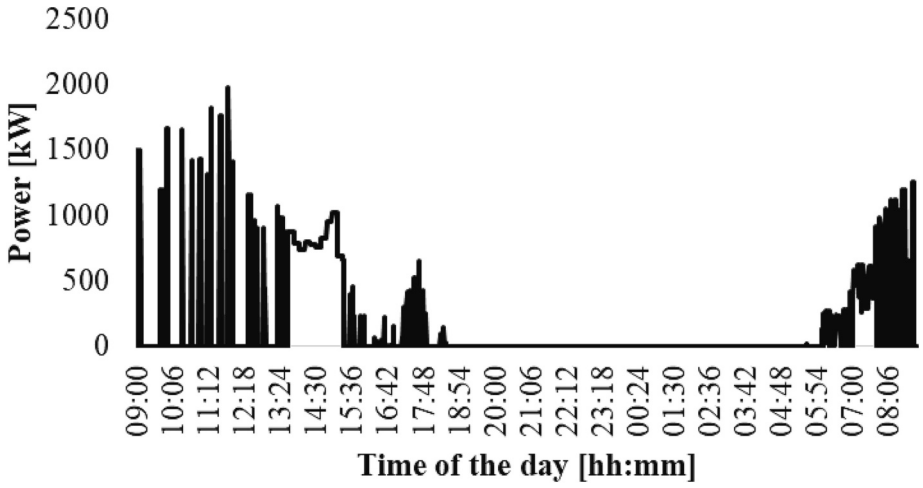

Fig. 4. ESS charging power for Case-1.

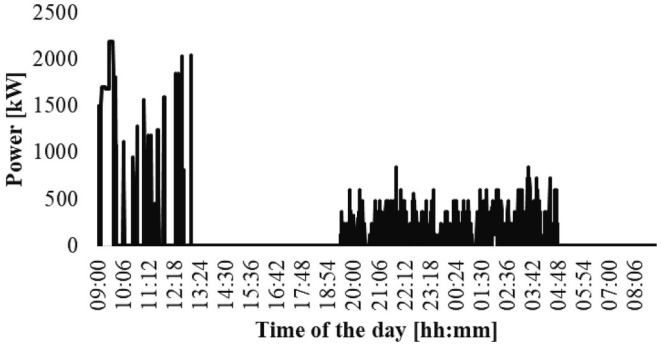

Fig. 5. ESS discharging power for Case-1.

3.2. Simulation results and comparison

The case studies aim to assess the system decisions and relevant outcomes under different component sizes and consider fairness among different EV owners. The main cases are clarified in Table 2, and the corresponding results are illustrated in Figs. 3–11. A summary of the obtained results is provided in Table 3.

As illustrated in Fig. 3, the charging transactions generally shift to later hours of the evaluation period. This is because more renewable PV power is harnessed for storage purposes during the initial times, ensuring that there is a sufficient supply of energy to meet the EV needs in later periods. The ESS serves as a buffer for the electrolyzer unit during the early hours of the day, as demonstrated in Figs. 4 and 5. This allows the system to adequately cover both the PV production and the upcoming FCEV loads, which demand more electric energy compared to SBEVs.

Some power variations, particularly during the first periods of the evaluation period, have significantly short durations. These fluctuations

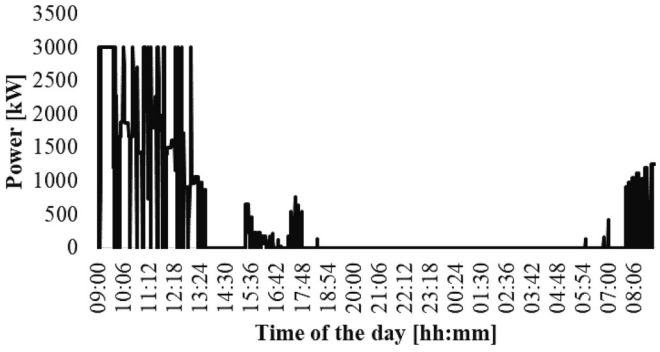

Fig. 7. Electrolyzer power for Case-1.

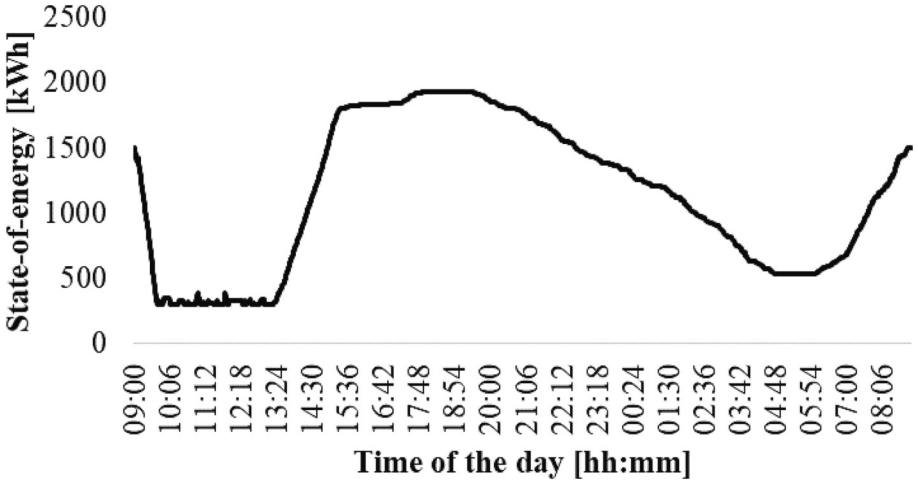

Fig. 6. ESS state-of-energy for Case-1.

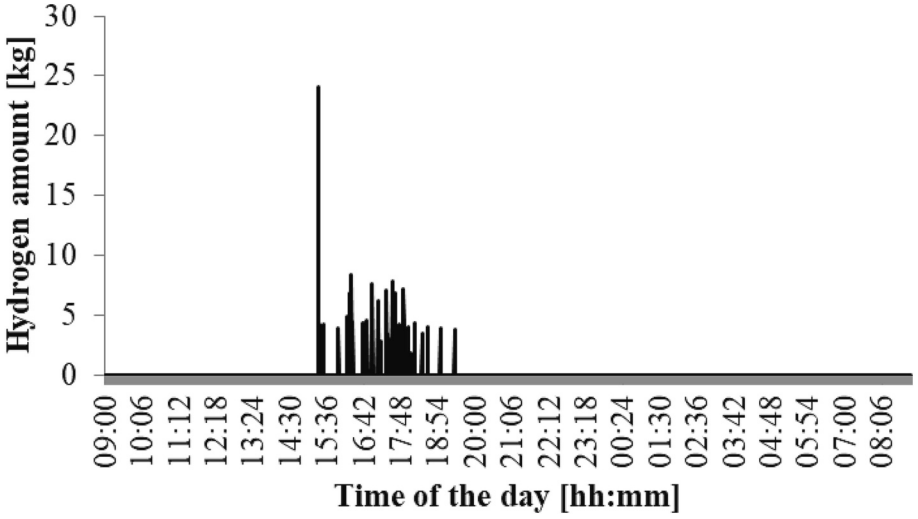

Fig. 8. Total amount of hydrogen injected to FCEVs for Case-1.

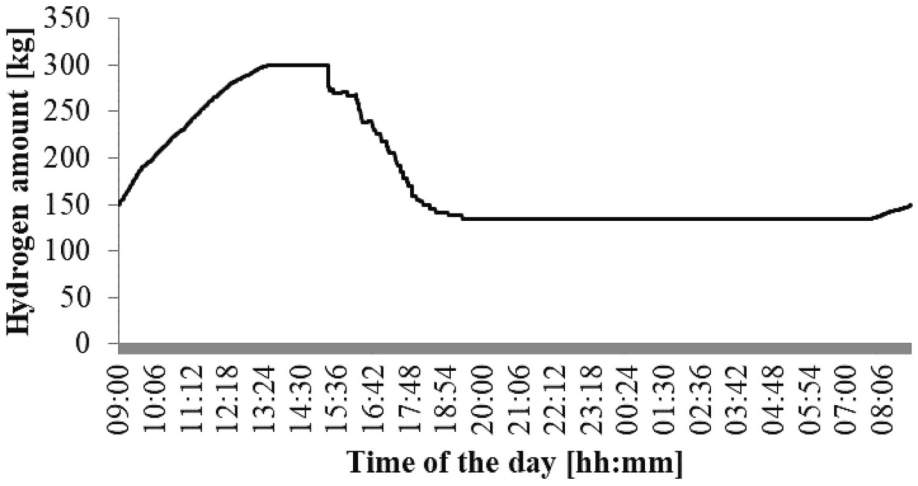

Fig. 9. Hydrogen amount in main hydrogen storage unit for Case-1.

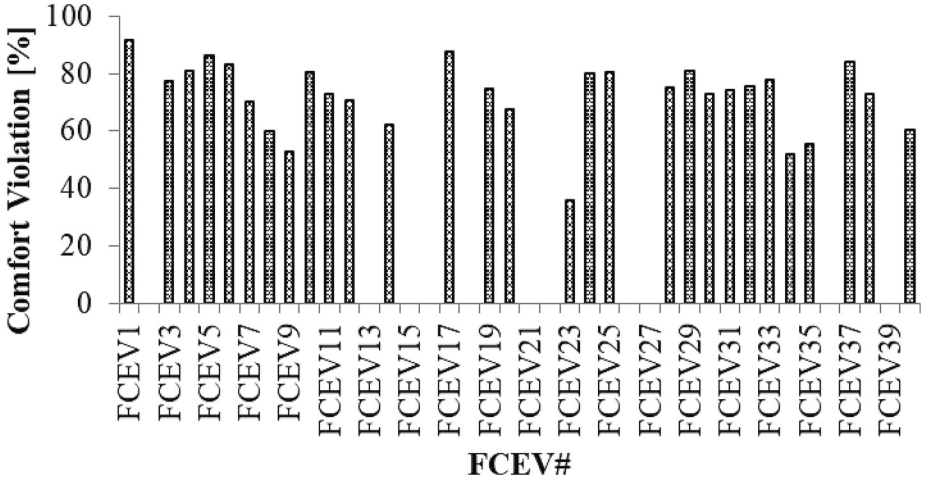

Fig. 10. The variation of comfort violation among FCEVs for Case-4.

lead to a state-of-energy variation illustrated in Fig. 6. After the daily operation concludes, the state-of-energy of the ESS unit returns to its initial value by the end of the evaluation period. This ensures the system is prepared for any subsequent evaluation periods, enabling a fair analysis.

The electrolyzer power variation, presented in Fig. 7, along with the

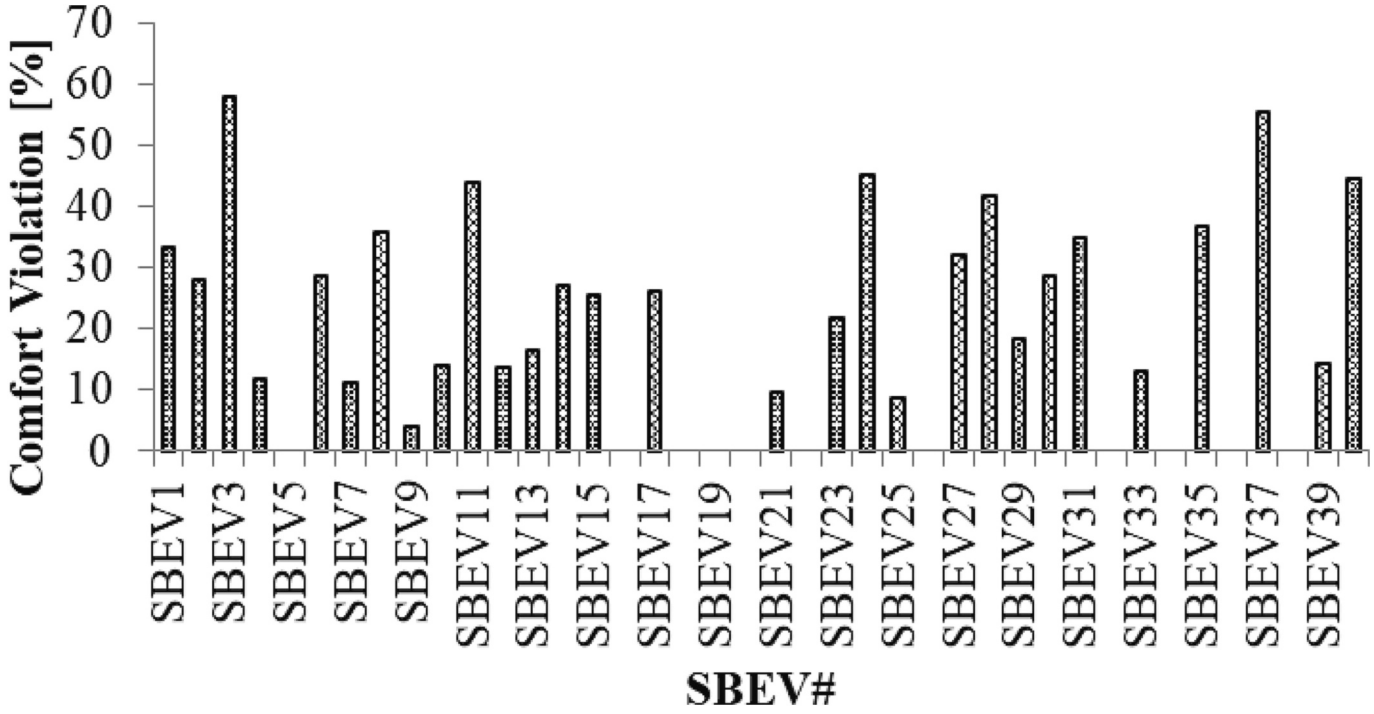

Fig. 11. The variation of comfort violation among SBEVs for Case-4.

Table 3
The summary of the obtained results.

Case	Average of $\%m_{FCEV-H2-dev,k}$	Average of $\%SoE_{SBEV-dev,m}$
Case-1	0	0
Case-2	16.45	14.95
Case-3	43.83	39.84
Case-4	52.41	19.60

total FCEV hydrogen demand depicted in Fig. 8, results in a hydrogen amount fluctuation in the main hydrogen storage unit, as demonstrated in Fig. 9. The hydrogen level reaches its full storage capacity shortly after 15:00 and is then used to supply the FCEV hydrogen demand until evening hours. To return the hydrogen level to its initial value, the remaining hydrogen need is supplied by the hydrogen produced during the early hours of the next day as the evaluation period comes to an end.

Upon analysing the results of Case-2 and Case-3, the impacts of the component sizes on comfort violation become evident. By enabling some levels of comfort violation instead of fully supplying the storage capacities, it is possible to maintain acceptable driving ranges while utilizing a smaller supply structure. Due to the high electric energy equivalence of hydrogen demand for FCEVs, attempts to maintain fair comfort violations among all types of end-users lead to significant negative effects on the comfort violation for SBEV owners.

This issue becomes more pronounced when comparing the results of Case-3 and Case-4. When the comfort violation fairness limit is relaxed, a sharp drop in the average comfort violation for SBEVs can be observed. Furthermore, relaxing the fairness constraint reduces the overall comfort violation for both SBEVs and FCEVs. However, the negative impacts of this constraint relaxation are evident in Figs. 10 and 11.

The comfort violation among both FCEV and SBEV owners varies significantly, especially for the FCEV case, with variations ranging from a minimum of 0 % to a maximum of >90 %. This variation poses a potential barrier to further service demand, particularly for unfairly served EV owners, hindering the social positive acceptance of service quality more than the condition of a more, but fair comfort violation. Consequently, the importance of considering fairness among enrolled EV owners is emphasized through this evaluation.

By looking closely at Tables 2 and 3, we can further understand the relationships between different cases and the associated comfort violations. The average comfort violation for FCEVs in Case-2 is 16.45 %, and for SBEVs, it is 14.95 %. In Case-3, with reduced component sizes, the average comfort violation increases to 43.83 % for FCEVs and 39.84 % for SBEVs. As mentioned earlier, relaxing the fairness constraint in Case-4 leads to a reduction in the average comfort violation for SBEVs to 19.60 %, while the average comfort violation for FCEVs increases slightly to 52.41 %. This demonstrates the trade-offs involved in maintaining fairness and the challenges faced in achieving acceptable comfort violations for both types of EV owners.

4. Conclusions

In this study, an EV owner comfort minimization oriented energy management strategy for a stand-alone EV service station serving multiple EV types in a multi-energy manner was proposed. The developed MILP model included PV unit as the main power source while an ESS as well as an electrolyzer supported main hydrogen unit held the main roles for the supply of the SBEV and FCEV energy and hydrogen requirements. Here, a comfort violation fairness oriented constraint was also added to ensure a fair operation in the service point for all users to increase the social acceptability of the provided EV service.

The results were analysed under several case studies considering the component size changes as well as comfort fairness constraint relaxation. Firstly, the level of comfort violation mitigation decreases when the component capacities are lower as expected. However, the EV owner could still leave the service point with a considerable amount of energy and hydrogen depicting the importance of finding a balance between investing in larger components and allowing some room for a portion of customer dissatisfaction which cannot be totally avoided if longer terms could be considered in such a stand-alone structure. Afterwards, the impacts of the comfort violation fairness constraint relaxation could be analysed. Even though a considerable amount of reduction in total comfort violation could be obtained, the vital differences between different EV owner types may be a vitally negative factor for the end-

users leaving the service point with dissatisfaction. Thus, the consideration of the fairness is very important as clearly depicted in the conducted analyses.

In future studies, it is aimed to develop a grid-connected system and further compare the obtained results with the stand-alone structure in a technoeconomic manner while considering the possible role of different EV types on grid operation during both normal and resiliency oriented conditions.

CRediT authorship contribution statement

Conceptualization, Methodology, Software, Writing – F. G. Erdinç.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

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