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Economic Operation of a Multi-Energy System Considering the Impacts of Micro-Mobility

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***Abstract*—The increasing and uncontrolled demand for energy has led to the emergence of a multi-energy system (MES), which is a promising and efficient way of providing multiple energy services to end-users, such as electricity, heating and cooling. The determination of the optimal MES configuration involves a comprehensive assessment of the entire system, including its various components, load demands, and energy prices. This study focuses on an MES that comprises renewable energy sources (RESs), heat pumps (HPs), combined heat and power units (CHPs), community energy storage (CES), micro-mobility such as electric scooters (e-scooters), and multi-energy demands. To optimize the economic operation of the considered MES, several factors need to be taken into account, especially for considering the impacts of micro-mobility. The target of the study is to maximize the efficiency of the system and minimize the operation costs when the load demands are met. The study also evaluates the optimal operation of the MES, taking the time-of-use (TOU) and non-TOU electricity tariff into account and considering the relevant constraints throughout the operation horizon. Additionally, the economic and charging impacts of e-scooters are evaluated on the system. The proposed optimization algorithm is conducted for different case studies and based on the findings, the simulation results clearly demonstrate the effectiveness of the system.**

***Keywords*—Cost minimization, electric scooter, micro-mobility, multi-energy system.**

NOMENCLATURE

The indices, parameters and variables used in the study are given in Tables I-III.

TABLE I. INDICES

e	Index of e-scooters
m,n	Index of CHP/HP units
t	Index of time periods
s,u	Index of PV/wind scenarios

TABLE II. PARAMETERS

chp_hp_m	Integration multiplier for CHP unit *m*
COP_n	Coefficient-of-performance of HP unit *n*
CE^{CES}, DE^{CES}	Charge/ discharge efficiency of CES
EER_n	Energy efficiency ratio of HP unit *n*
N	Sufficiently big number
$P^{CHP,elec,max}_{m,t}$, $P^{CHP,heat,max}_{m,t}$	Maximum power supply / heat power supply of CHP unit *m* in time period *t*
$P^{end-user,cool}_{s,u,t}$, $P^{end-user,elec}_{s,u,t}$, $P^{end-user,heat}_{s,u,t}$	End-user cooling / electricity / heating demand in time period *t* for scenarios *s* and *u*
$P^{HP,cool,max}_{n,t}$, $P^{HP,heat,max}_{n,t}$	Maximum cooling / heating power supply of HP unit *n* in time period *t*
$P^{pv}_{s,t}$, $P^{wind}_{u,t}$	PV/wind power generation in time period *t* for scenarios *s* and *u*
$R^{CES,ch}$	Maximum charging power of CES
$SOE^{CES,ini}$, $SOE^{CES,min}$, $SOE^{CES,max}$	Initial / minimum / maximum energy of CES
λ^{elec}_t	Electricity price in time period *t*
λ^{gas}_t	Cost of natural gas supply in time period *t*
η^{elec}_m, η^{heat}_m	Efficiency of gas-to-electricity / gas-to-heat conversion at CHP unit *m*

TABLE III. DECISION VARIABLES

$P^{CES,ch}_{s,u,t}$, $P^{CES,dis}_{s,u,t}$	Charging / discharging power of CES in time period *t* for scenarios *s* and *u*
$P^{ES}_{e,s,u,t}$	Charging power of *eth* e-scooter in time period *t* for scenarios *s* and *u*
$P^{CHP,elec}_{m,s,u,t}$, $P^{CHP,heat}_{m,s,u,t}$	Electricity / heat production of CHP unit *m* in time period *t* for scenarios *s* and *u*
$P^{CHP,input}_{m,s,u,t}$	Power of CHP unit *m* in time period *t* for scenarios *s* and *u*
$P^{CHPel,end-user}_{m,s,u,t}$, $P^{CHPel,HP}_{m,s,u,t}$	Power from CHP unit *m* to consumer / HP unit in time period *t* for scenarios *s* and *u*
$P^{direct-user}_{s,u,t}$	Power from the grid to the consumer in time period *t* for scenarios *s* and *u*
$P^{elec}_{s,u,t}$	Power from the grid in time period *t* for scenarios *s* and *u*
$P^{elec,HP}_{s,u,t}$	Power from the grid for all the HPs in period *t* for scenarios *s* and *u*
$P^{gas}_{s,u,t}$	Gas from distribution system in time period *t* for scenarios *s* and *u*
$P^{HP,cool}_{n,s,u,t}$, $P^{HP,heat}_{n,s,u,t}$	HP unit *n* cooling / heating power in time period *t* for scenarios *s* and *u*
$P^{HP,input}_{n,s,u,t}$	HP unit *n* power in time period *t* for scenarios *s* and *u*
$SOE^{CES}_{s,u,t}$	CES SOE level in time period *t* for scenarios *s* and *u*
$u^{HP}_{n,s,u,t}$	Binary variable
Δt	Time granularity

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I. INTRODUCTION

A. Motivation

Ensuring an adequate supply of energy is a significant global concern in the modern day. The best use of energy resources requires more attention in the modern era due to the constantly growing demand for energy as well as growing concerns about the environment, the depletion of fossil fuel resources, and the excessive reliance of human lifestyles on energy and technology.

Considering the above concerns, it is necessary and crucial to provide a sustainable energy system having the advantages of being clean, reliable, and affordable. Therefore, providing such a system is one of the main challenges of today. The energy system must undergo a considerable transformation in the upcoming decades to meet this challenge. Thus, integrated energy systems (IESs) might be a promising alternative to the current energy system. Although the initial cost may be higher, an IES can have several advantages over a separate system in terms of energy, environmental effect, cost, and flexibility. Multi-energy systems (MESs), which are crucial in tackling the aforementioned issues, will considerably assist in a seamless transition to a sustainable IES.

MESs represent an IES that optimally combines different energy technologies, where electricity, heating, cooling, fuel and transport interact with each other. This enables the widespread use of renewable energy sources (RESs) and the provision of multiple energy services, which provide better technical, economic and environmental performance. The usage of RESs, which has recently been integrated into MESs in many parts of the world [1], has been expanded to replace fossil energy carriers as a result of growing concerns about negative environmental impacts. MESs can further improve energy efficiency, economy and flexibility, and can also be a very promising future solution for better utilization of primary energy consumption and reduction of greenhouse gas emissions caused by urban energy demand [2]. Additionally, MESs have the benefit of simultaneously supplying electricity, heating, cooling, and residential hot water demands.

B. Relevant Literature

By optimizing the energy flow in an MES, it is possible to enhance the interaction between the energy system and users [3]. Therefore, operation optimization is a key step in ensuring the reliability of the energy supply as well as reducing primary energy consumption, environmental effects, and consumer costs [4].

Environmental problems caused by fuel consumption and fueled vehicles have become much more serious recently [5]. Electric vehicles (EVs) in general, and micro-mobility, which refers to small, lightweight vehicles such as electric scooters (e-scooters) in particular, are typically considered as an integral part of future sustainable transportation systems which are economical and environmentally friendly [6]. Especially, shared micro-mobility is a rapidly growing transportation technology that has numerous benefits [7].

Research on the planning, operation, transaction and evaluation of MESs has flourished [8]. When plug-in EVs (PEVs) are present, the authors of [9] proposed a multi-objective optimization model for managing energy in local MESs. The authors in [10] suggested a review technique toward carbon neutrality by establishing the concept of an MES in terms of its technologies, modeling, configuration, and practicality as a zero-emission tool. To increase the economic advantages, reduce CO_2 emissions, and raise consumption rates of RESs, the study [11] created a multi-objective day-ahead scheduling model of connected multiple regional IES taking energy sharing into account. By considering a combination of RES and energy storage, the authors of [12] implemented a price-based demand response (DR) model. The case study illustrates how the DR model can increase the benefits of a multi-energy microgrid while also significantly lowering the expenses associated with users' energy consumption. The energy hub (EH), where various energy carriers are properly converted, utilized, and stored to meet certain societal economic demands, is an efficient framework for MES modeling and management. The authors of [13] presented a comprehensive overview of the available EH optimization and control experiments.

The authors of [6] made an effort to present a precise and computationally efficient model to forecast an e-scooter's energy consumption within actual driving conditions. The allocation problem for e-scooter chargers was solved in [14] by using a mixed integer linear programming (MILP) model. To minimize the distance traveled by the chargers to pick up the e-scooters, the suggested method distributes the e-scooters to the chargers.

C. Contributions and Organization

The key originality of the proposed study is the integration of e-scooters in an MES at a university community level since none of the aforementioned studies has considered this problem before. The proposed optimization algorithm considers all the system components and constraints on both the source and load sides throughout the operational horizon to avoid operational issues, achieve higher energy performances, and ensure optimal operation of the system. The paper is organized into sections covering the proposed scheme and optimization problem, simulation results, and conclusions.

II. METHODOLOGY

A. Overview of the Proposed Scheme

By considering the aforementioned concerns, first, an MES shown in Fig. 1 is considered in the study. The inputs of the considered MES scheme are electricity and natural gas networks while heating and cooling services, and electricity can be simultaneously delivered to the end-users. The main objective of the proposed approach is to effectively manage various multi-energy technologies including combined heat and power (CHP), heat pump (HP), RESs, energy storage, and micro-mobility (e-scooters).

B. Mathematical Formulation

The approach involves a scheduling strategy that prioritizes the cost as the objective for optimization. This requires consideration of all components of the system to determine the optimal configuration.

To minimize the total operational costs and maximize the efficiency as well as satisfy the load demands, a mixed integer linear programming (MILP) formulation is developed to model the optimal operation of the considered MES. Moreover, every unit is modeled to optimize the operation of the MES while considering its operational limits and restrictions. Equations (1)-(23) account for the relevant constraints for each component, which are given below.

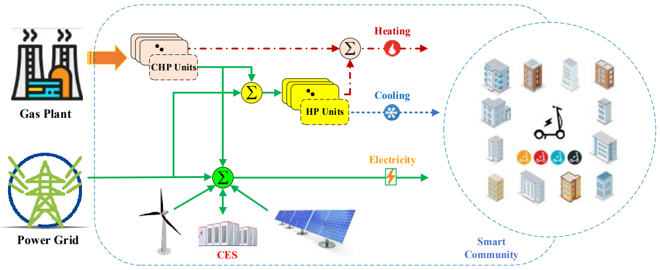

Fig. 1. Proposed scheme of the multi-energy system.

1) Objective function

In the study, it is aimed to minimize the operational cost, which is represented by (1). The total MES cost is determined by the amount of power received from the grid and gas, and the prices of electricity and gas from external networks during time interval t for the scenarios involving RES production.

$$Total\ Cost = \sum_t \sum_s \sum_u \left(P_{s,u,t}^{elec} \cdot \lambda_t^{elec} + P_{s,u,t}^{gas} \cdot \lambda_t^{gas}\right), \quad \forall s, \forall u, \forall t \tag{1}$$

2) Modelling of CHPs

The CHP units receive input from the gas network and convert it into both power and heat. The equations describing these conversions and the relevant parameters are represented in (2-7).

$$P_{s,u,t}^{gas} = \sum_m P_{m,s,u,t}^{CHP,input}, \quad \forall m, \forall s, \forall u, \forall t \tag{2}$$

$$P_{m,s,u,t}^{CHP,input} \leq \frac{P_{m,t}^{CHP,elec,max}}{\eta_m^{elec}} + \frac{P_{m,t}^{CHP,heat,max}}{\eta_m^{heat}}, \quad \forall m, \forall s, \forall u, \forall t \tag{3}$$

$$P_{m,s,u,t}^{CHP,input} = \frac{P_{m,s,u,t}^{CHP,elec}}{\eta_m^{elec}} + \frac{P_{m,s,u,t}^{CHP,heat}}{\eta_m^{heat}}, \quad \forall m, \forall s, \forall u, \forall t \tag{4}$$

$$P_{m,s,u,t}^{CHP,elec} = P_{m,s,u,t}^{CHPel,end-user} + P_{m,s,u,t}^{CHPel,HP}, \quad \forall m, \forall s, \forall u, \forall t \tag{5}$$

$$P_{m,s,u,t}^{CHP,heat} \leq P_{m,t}^{CHP,heat,max} \quad \forall m, \forall t \tag{6}$$

$$P_{m,s,u,t}^{CHP,elec} \leq P_{m,t}^{CHP,elec,max} \quad \forall m, \forall t \tag{7}$$

3) Modelling of HPs

HP units receive power from both the main grid and the CHP units. To meet the heating and cooling demands of end-users, they convert the input power into heating and cooling. The CHPs are integrated into the HP units, and the corresponding coefficient (chp_hp_m) is equal to 1. The equations that describe the conversion constraints for the HP units are provided in (8)-(15).

$$P_{s,u,t}^{elec} = P_{s,u,t}^{elec,HP} + P_{s,u,t}^{direct-user}, \quad \forall s, \forall u, \forall t \tag{8}$$

$$\sum_n P_{n,s,u,t}^{HP,input} = \sum_m P_{m,s,u,t}^{CHPel,HP} \cdot chp\_hp_m + P_{s,u,t}^{elec,HP}, \quad \forall m, \forall n, \forall s, \forall u, \forall t \tag{9}$$

$$P_{n,s,u,t}^{HP,input} = \frac{P_{n,s,u,t}^{HP,heat}}{COP_n} + \frac{P_{n,s,u,t}^{HP,cool}}{EER_n}, \quad \forall n, \forall s, \forall u, \forall t \tag{10}$$

$$P_{n,s,u,t}^{HP,input} \leq \frac{P_{n,t}^{HP,heat,max}}{COP_n} + \frac{P_{n,t}^{HP,cool,max}}{EER_n}, \quad \forall n, \forall s, \forall u, \forall t \tag{11}$$

$$P_{n,s,u,t}^{HP,heat} \leq N \cdot u_{n,s,u,t}^{HP}, \quad \forall n, \forall s, \forall u, \forall t \tag{12}$$

$$P_{n,s,u,t}^{HP,cool} \leq N \cdot \left(1 - u_{n,s,u,t}^{HP}\right), \quad \forall n, \forall s, \forall u, \forall t \tag{13}$$

$$P_{n,s,u,t}^{HP,heat} \leq P_{n,t}^{HP,heat,max}, \quad \forall n, \forall s, \forall u, \forall t \tag{14}$$

$$P_{n,s,u,t}^{HP,cool} \leq P_{n,t}^{HP,cool,max}, \quad \forall n, \forall s, \forall u, \forall t \tag{15}$$

4) Modelling of CES

Community energy storage is leveraged to provide electricity to end-users cost-effectively and advantageously. The CES can be charged using the main power grid, as well as the power output from CHP units and the RESs. The mathematical expressions for the state-of-charge (SoC) of the CES, as well as its charging and discharging powers, are outlined in equations (16)-(19).

$$0 \leq P_{s,u,t}^{CES,ch} \leq R^{CES,ch}, \quad \forall s, \forall u, \forall t \tag{16}$$

$$SOE_{s,u,t}^{CES} = SOE^{CES,ini} + CE^{CES} \cdot P_{s,u,t}^{CES,ch} \cdot \Delta t, \quad \forall s, \forall u, \forall t \tag{17}$$

$$SOE_{s,u,t}^{CES} = SOE_{s,u,(t-1)}^{CES} + CE^{CES} \cdot P_{s,u,t}^{CES,ch} \cdot \Delta t - \left(\frac{P_{s,u,t}^{CES,dis}}{DE^{CES}}\right) \cdot \Delta t, \quad \forall s, \forall u, \forall t \tag{18}$$

$$SOE^{CES,min} \leq SOE_{s,u,t}^{CES} \leq SOE^{CES,max}, \quad \forall s, \forall u, \forall t \tag{19}$$

5) Modelling of end-users

The equations representing the balance between the energy supply and demand for end-users, which take into account all the units that generate and consume energy, such as RESs, community energy storage and electric scooters, are presented in (20)-(22).

$$P_t^{end-user,elec} = P_{s,u,t}^{direct-user} + P_{s,t}^{pv} + P_{u,t}^{wind} + \sum_m P_{m,s,u,t}^{CHPel,end-user} + P_t^{CES,dis} - P_t^{CES,ch} - \sum_e P_{e,s,u,t}^{ES}, \quad \forall m, \forall e, \forall s, \forall u, \forall t \tag{20}$$

$$P_t^{end-user,heat} = \sum_m P_{m,s,u,t}^{CHP,heat} + \sum_n P_{n,s,u,t}^{HP,heat}, \quad \forall m, \forall n, \forall s, \forall u, \forall t \tag{21}$$

$$P_t^{end-user,cool} = \sum_n P_{n,s,u,t}^{HP,cool}, \quad \forall n, \forall s, \forall u, \forall t \tag{22}$$

6) Modelling of electric scooters

The methodology for modelling e-scooters merges a common physics-based vehicle model with the functional features of the main components of an e-scooter to convert the necessary traction power at the wheels to battery power requirements. Taking into account the characteristics and principles of e-scooters as discussed in a previous study cited as [6] is out of the scope of this study, we only present a formula for energy consumption specifically for e-scooters, denoted as formula (23).

$$Rating\ Power = Rating\ Voltage \times Rating\ Current \tag{23}$$

III. TEST AND RESULTS

The performance of the proposed management approach for the smart MES is evaluated using the GAMS environment and the CPLEX solver. The input data and obtained values for different cases are presented in the following subsections. Table IV provides a list and description of the various cases that were analyzed. By taking the Time-of-Use (TOU) and fixed electricity tariffs into account, ten case studies are realized to demonstrate the performance of the optimization algorithm.

A. *Input Data*

The energy purchase costs given in Fig. 2 display the actual prices of electricity and gas. The electricity prices fluctuate depending on the TOU tariff, with rates of 0.068 \$/kWh, 0.134 \$/kWh, and 0.215 \$/kWh, and the real fixed price is 0.138 \$/kWh, which are all calculated based on the data from [15]. The fixed gas price of 0.050 \$/kWh is obtained from [16].

The time-varying prices have an impact on the utilization of components such as CHPs, HPs, CES, as well as the electricity and gas inputs of the MES.

Figure 3 presents the approximated energy demands such as electricity, heating, and cooling for a university community level. The technical details of HPs and CHPs are sourced from [17] and [18], and the technical data are displayed in Table V and Table VI, correspondingly. The MES employs ten HP units with five diverse features and five CHP units with five distinct characteristics.

The installed PV productions supply about 4-5% of the total energy demand [19], also it is assumed to supply the same percentage of energy demand by wind energy. The RES generation corresponds to about 9 to 10 percent of the load, which is shown in Fig. 4.

The technical details of the considered community energy storage system are provided in Table VII. The technical data of a standard e-scooter are given in Table VIII. A total number of 100 e-scooters are considered in the system, which are charged at midnight time and used during the day time.

B. *Simulation Results*

The grid energy consumption levels for pre- and post-integration of RESs are illustrated in Fig. 5. It is observed that the energy consumption experiences a reduction after the RES integration. Notably, the electricity demand of the system remains constant except during the intervals when e-scooters are charging.

Figure 6 displays the electricity balance of the MES, revealing that the net electricity demand fluctuates between 61.92 kW and 284.65 kW. The proposed algorithm determines the optimal time to utilize gas or electricity based on the objective function. The outcomes obtained indicate that the proposed approach can significantly decrease overall operational expenses.

Figures 7 and 8 demonstrate the balance between the generated and consumed heating and cooling energy for Cases 7 and 10, correspondingly. In Case-7, the heating and cooling requirements are fulfilled by HPs, whereas the heating is provided by CHPs in Case-10 except for the time at 1:00 am when the heating is produced by HP units, and the cooling is generated by HP units for all time hours.

TABLE IV. DESCRIPTION OF CONSIDERED CASES

Case #	**Description**
Case_1	Grid and gas networks (fixed prices)
Case_2	Grid and gas networks – Base Case (TOU tariff)
Case_3	Grid, gas and PV generation
Case_4	Grid, gas, and wind generation
Case_5	Grid, gas, PV and wind generations
Case_6	Grid, gas, PV and wind generations, CES
Case_7	Grid, gas, PV and wind, CES and e-scooters - Desired Case
Case_8	Gas price increased by +50% for Case_7
Case_9	Gas price increased by +100% for Case_7
Case_10	Non-TOU electricity tariff for Case_7

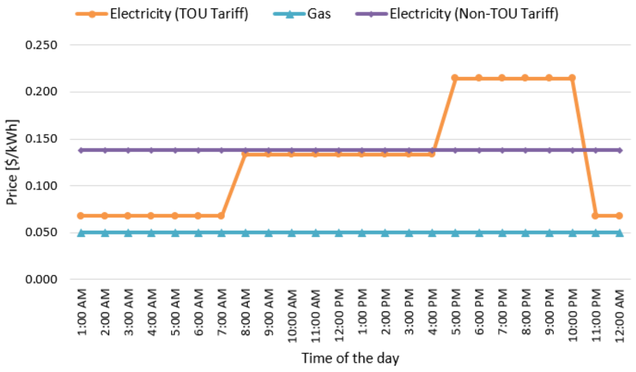

Fig. 2. Energy purchase prices.

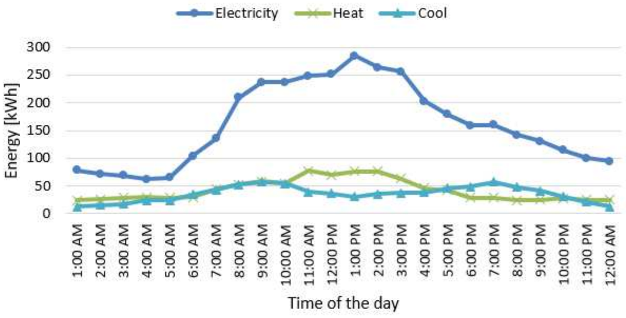

Fig. 3. Electricity, heating and cooling energy demands.

TABLE V. TECHNICAL DATA OF HP UNITS

	Heating		**Cooling**	
Unit Type	**Power (kW)**	**COP**	**Power (kW)**	**EER**
HP-1	10.3	3.5	9	3.24
HP-2	9	3.53	7.8	3.31
HP-3	8	3.83	7.1	3.53
HP-4	6.8	4.07	6	3.77
HP-5	6	3.7	5	3.79

TABLE VI. TECHNICAL DATA OF CHP UNITS

	Electrical		**Heating**	
Unit Type	**Power (kW)**	**Efficiency (%)**	**Power (kW)**	**Efficiency (%)**
CHP-1	30	32.4	58.1	62.8
CHP-2	50	34.2	88.5	60.6
CHP-3	85	33.7	141	56.1
CHP-4	104	34.7	166	55.3
CHP-5	124	36.6	182	53.6

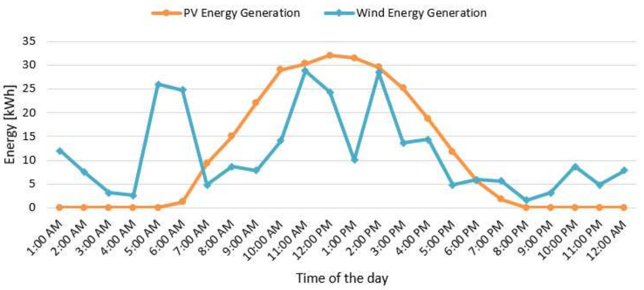

Fig. 4. PV and wind profile generations.

TABLE VII. CHARACTERISTICS OF CES

Parameters	**Value [Unit]**
Minimum Capacity	90 [kWh]
Maximum Capacity	600 [kWh]
Initial Energy State	270 [kWh]
Charging Rate	90 [kW]
Discharging Rate	90 [kW]
Charging Efficiency	95 [%]
Discharging Efficiency	95 [%]

TABLE VIII. CHARACTERISTICS OF E-SCOOTERS

Type of e-scooter	**Rating Voltage (V)**	**Rating Current (Ah)**	**Max. Speed (km/h)**	**Range (km)**
Navee N65 500W	48	12.5	25	65

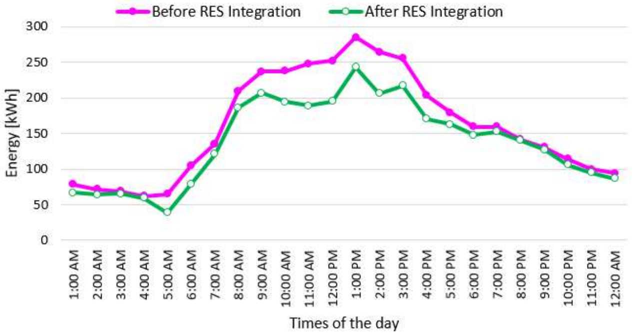

Fig. 5. End-users electricity consumption from the main grid.

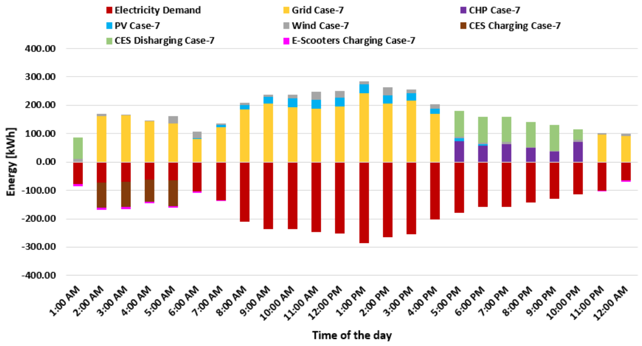

Fig. 6. The electricity balance between demand and supply for Case-7.

The SoC and charging/discharging power of the CES for the desired case are illustrated in Fig. 9, which states that it is charging when the prices are cheap and discharging during the peak hours. Figure 10 shows the total charging power of e-scooters for Cases-7 to Case-10, which only adds a few kilowatt-hours to the demand. It is suggested to charge the e-scooters during the midnight hours, and optimally it takes 5-6 hours to be fully charged. Using e-scooters at a campus level with thousands of students might be very useful for transportation inside the campus and brings benefits in terms of economy and environment.

Figure 11 illustrates the external gas and power inputs of the MES for Cases 7-10. Cases 8-10 were conducted to assess the variation of the process to the fuel prices. The findings revealed that an increase in gas prices results in increased electricity inputs and decreased gas inputs in the MES.

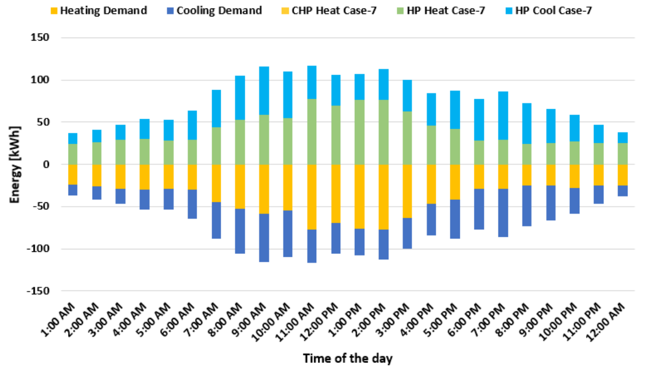

Fig. 7. Heating and cooling balance between demand and supply for Case-7.

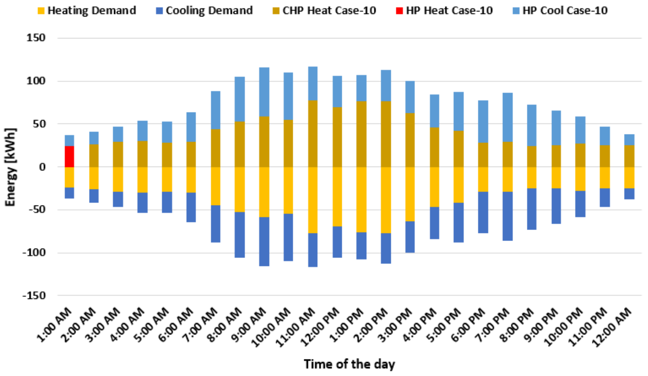

Fig. 8. Heating and cooling balance between demand and supply for Case-10.

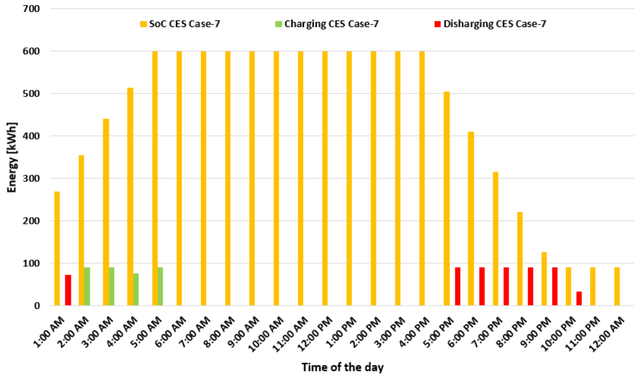

Fig. 9. State-of-Charge, charging and discharging power of CES.

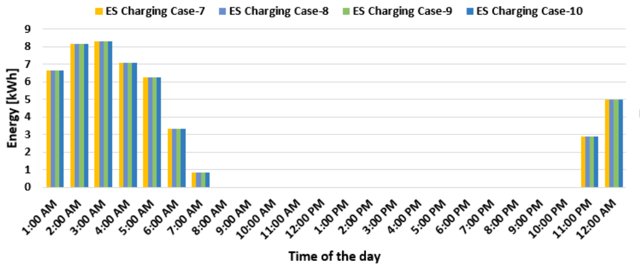

Fig. 10. Charging power of e-scooters.

In Case-10, the use of a non-TOU tariff led to an increase in gas inputs and a decrease in electricity inputs from the power grid. Not only for Case-10, but it is also applicable to the other cases, as analyzed. The results show that the power input from the grid during the peak hours is generally zero and there are gas inputs. The algorithm selects a more cost-effective input and decreases the use of the alternative option.

The total operational costs ($) and their respective changes (%) are depicted in Fig. 12 for all ten cases. The findings show that the proposed approach is effective and the results costs are acceptable.

The results show that Case-1 has the highest operational cost due to the fixed prices of both electricity and gas. Compared to Case-1, Case-2, which is the Base Case, has a lower cost, which is due to the application of the TOU electricity tariff. Additionally, the Base Case is more cost-effective than Case-10 in which the non-TOU tariff is applied. However, by integrating the RESs (PV and wind) in Case-3 and Case-4 individually, and both together in Case-5, the costs are decreased compared to Case-2. The introduction of CES in the system in Case-6 leads to the lowest operational cost of 414.77$, which is 21.59% lower than Case-2. The cost of Case-7 (Desired Case) with added e-scooters consumption is 417.62$, which is 21.05% lower than Case-2 and only about 3$ higher than Case-6 due to the e-scooters in the system.

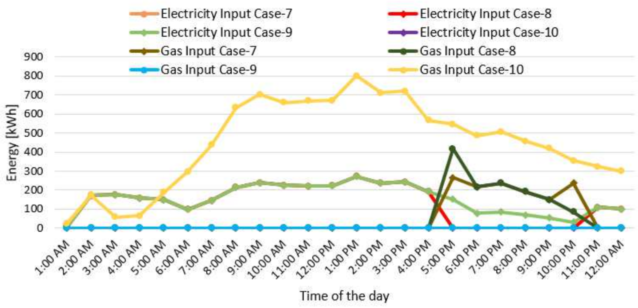

Fig. 11. Electricity and gas inputs of MES for Cases 7-10.

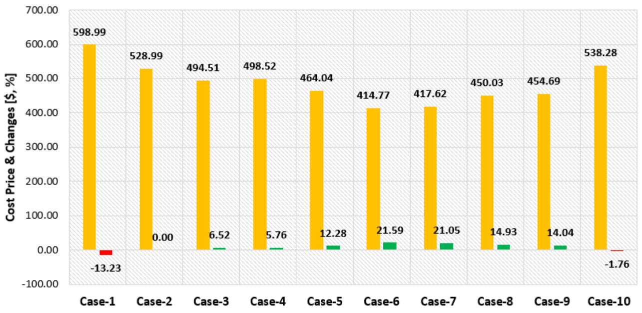

Fig. 12. The total operational costs of the evaluated cases.

IV. CONCLUSIONS

This paper presents the economic operation of an MES that meets the energy demands of end-users while minimizing operational costs. The study also considers the charging and cost impacts of micro-mobility such as e-scooters on the system. The optimal MES configuration is determined by considering the entire system, including its components, load demands, and energy prices. The proposed optimization algorithm is evaluated through various case studies, and the simulation results clearly demonstrate its effectiveness in maximizing efficiency and reducing operational costs. The future work will address the uncertainties related to the system and its components.

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