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Optimal Sizing of a Community Energy Storage in a Multi-Energy System

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***Abstract*—Multi-energy systems (MESs) offer a promising approach to providing various energy services while integrating renewable energy sources (RESs). However, the variability of RESs necessitates energy storage systems (ESSs) for reliable operation. This work proposes a novel method for integrating a Community Energy Storage (CES) into an MES framework, determining the optimal CES size for minimized operational costs. The optimization algorithm takes all system components and constraints into account to ensure a reliable and efficient energy supply. Several case studies demonstrate significant cost reductions (up to 13.67%) due to optimal CES sizing, highlighting the economic benefits of collaborative community energy management. Moreover, the influence of Time-of-Use (TOU) pricing schemes and the level of RES integration on the optimal CES size are investigated. By enabling cost-effective and sustainable community energy management, this approach paves the way for the widespread adoption of MESs with optimized CES integration, ultimately fostering a more sustainable energy future.**

***Keywords*—Cost optimization, multi-energy system, energy storage.**

Nomenclature

The indices, parameters and variables used throughout this paper are given in Tables I-III.

TABLE I. INDICES

m, n	Index of CHP/HP units
s, w	Index of PV/wind scenarios
t	Index of time intervals

TABLE II. PARAMETERS

CE^{CES}, DE^{CES}	Charging/discharging efficiency of CES
COP_n	Coefficient-of-performance of HP *n*
chp_hp_m	Integration multiplier of CHP *m*
EER_n	Energy efficiency ratio of HP *n*
N	Sufficiently big number
$P_{m,t}^{CHP\_elec\_max}$, $P_{m,t}^{CHP\_heat\_max}$	Max. power supply/heat supply of CHP *m* in time interval *t*
$P_{s,w,t}^{end-user\_cool}$, $P_{s,w,t}^{end-user\_heat}$, $P_{s,w,t}^{end-user\_elec}$	Cooling/heating/electricity demand of end-user in time interval *t* for scenarios *s* and *w*
$P_{n,t}^{HP\_cool\_max}$, $P_{n,t}^{HP\_heat\_max}$	Max. cooling/heating power supply of HP *n* in time period *t*
$P_{s,t}^{pv}$, $P_{w,t}^{wind}$	PV/wind power generation in time interval *t* for scenarios *s* and *w*
R^{CES_ch}	Max. charging power rate of CES
SOE^{CES_ini}, SOE^{CES_min}, SOE^{CES_max}	Initial/minimum/maximum energy of CES
λ_t^{elec}	Electricity price in time interval *t*
λ_t^{gas}	Natural gas supply cost in time interval *t*
η_m^{elec}, η_m^{heat}	Efficiency of gas-to-electricity/gas-to-heat conversion at CHP *m*

TABLE III. DECISION VARIABLES

$P_{s,w,t}^{CES\_ch}$, $P_{s,w,t}^{CES\_dis}$	Charging/discharging power of CES in time interval *t* for scenarios *s* and *w*
$P_{m,s,w,t}^{CHP\_elec}$, $P_{m,s,w,t}^{CHP\_heat}$	Electricity/heat production of CHP *m* in time interval *t* for scenarios *s* and *w*
$P_{m,s,w,t}^{CHP\_input}$	Power of CHP *m* in time interval *t* for scenarios *s* and *w*
$P_{m,s,w,t}^{CHPel\_end-user}$, $P_{m,s,w,t}^{CHPel\_HP}$	Power from CHP *m* to end-user/ HP in time interval *t* for scenarios *s* and *w*
$P_{s,w,t}^{direct-user}$	Power from grid to the end-user in time interval *t* for scenarios *s* and *w*
$P_{s,w,t}^{elec}$	Power from grid in time interval *t* for scenarios *s* and *w*
$P_{s,w,t}^{elec\_HP}$	Power from grid for all the HPs in time interval *t* for scenarios *s* and *w*
$P_{s,w,t}^{gas}$	Gas from outer network in time interval *t* for scenarios *s* and *w*
$P_{n,s,w,t}^{HP\_cool}$, $P_{n,s,w,t}^{HP\_heat}$	HP unit *n* cooling/heating power in time interval *t* for scenarios *s* and *w*
$P_{n,s,w,t}^{HP\_input}$	HP unit *n* power in time interval *t* for scenarios *s* and *w*
$SOE_{s,w,t}^{CES}$	CES state-of-energy level in time interval *t* for scenarios *s* and *w*
$u_{n,s,w,t}^{HP}$	Binary variable
Δt	Time granularity

I. Introduction

A. Motivation

Multi-energy systems (MESs) offer a promising and efficient way to provide various energy services, such as electricity, heating, and cooling, to consumers. MESs harness renewable energy sources (RESs), empower consumer participation through demand response (DR) and integrate energy storage systems (ESSs). This combination allows communities to rely less on the main grid, maximize economic benefits, and optimize renewable energy use [1].

Recent years have seen a surge in research on MESs, covering all aspects from planning and operation to transactions and evaluation. Optimizing how energy flows within an MES enhances the interaction between the system and its users, making it crucial for a reliable, affordable, and eco-friendly energy supply [2, 3]. The energy hub (EH) as a promising framework for modeling and managing MESs serves as a central point where various energy carriers, such as electricity, gas, and heating, are efficiently converted, utilized, and stored to fulfill societal demands.

The integration of large amounts of renewable energy introduces challenges due to the inherent variability of these sources, necessitating the integration of energy storage systems [4]. From a consumer perspective, ESS offers tangible benefits like reduced electricity bills through minimized peak demand charges and increased self-reliance. However, successfully planning the inclusion of ESS within energy communities requires careful consideration [5].

B. Relevant Literature

Several researches have been conducted on ESSs, which delve into various aspects, including the different technologies available, optimization strategies, and how it all works within communities powered by RESs. The wealth of research available highlights the potential of this approach and paves the way for widespread implementation.

Recognizing the potential of energy storage and diverse RESs, the authors in [6] proposed a two-dimensional, price-based DR model. Their case study demonstrates how this model not only enhances the overall benefits of a multi-energy micro-grid system, but also leads to significant reductions in user energy costs.

The authors of [7] focused on evaluating the operational reliability of urban MESs, specifically considering the inclusion of "equivalent energy storages", which represent a novel concept simplifying the analysis of various components within the MES while capturing their key dynamic relationships. The authors of [8] proposed a new design capable of harnessing diverse energy sources. This innovative MES incorporates natural gas storage (NGS), thermal energy storage (TES), ice energy storage (IES), and hydrogen energy storage (HES).

By employing time-series simulations, the method proposed in [9] optimized the allocation of energy storage capacities within a multi-energy complementary power system. By rewarding users based on their contributions (both energy production and consumption) over time, [10] proposed a "relative contribution-based" approach for sharing community battery energy. To navigate unpredictable energy demands, [11] introduced a novel method for planning energy storage within integrated MESs. Taking into account the size and capabilities of energy storage units, a new optimization model was proposed in [12] that specifically considers the amount of energy lost within the entire MES.

The study [13] explored how the placement and size of a community energy storage system (CES) in a low-voltage grid influence the economic benefits of consumers. To optimize the sizing of a CES for residential districts, [14] proposed a unique clustering approach. By grouping households with similar storage requirements, the method identified the total storage capacity needed for the community.

Successfully optimizing these systems hinges on factoring in the operational limitations on both energy supply and demand sides. Failing to do so can lead to operational issues. By considering these constraints, it is possible to maximize energy performance and achieve truly optimal system operation.

C. Contributions and Organization

This work offers a novel contribution to the domain of MESs. It proposes the integration of CES into an MES framework, encompassing the determination of the optimal CES size within the system. The optimization algorithm specifically addresses all system components and their associated constraints to ensure both supply and demand dynamics across the operational timeframe. This approach strives to achieve four primary objectives: preventing operational issues, enhancing energy performance metrics, identifying optimal CES size, and ultimately ensuring optimal system operation. This work is structured into distinct sections, which initially detail methodology. Subsequently, section III presents the test and results. Finally, the concluding section meticulously summarizes the key findings.

II. Methodology

A. Overview of the Proposed Scheme

This study tackles the optimization of an MES by proposing a novel approach presented in Figure 1. The system considered in the study draws electricity and natural gas from external networks and delivers electricity, heating, and cooling to end-users. The main objective of the approach lies in managing interconnected technologies like heat pumps (HPs), combined heat and power units (CHPs), RESs and CES. The management algorithm aims to maximize efficiency, minimize operational costs, and reliably meet user energy demands. This model will take various economic considerations into account and identify the optimal size of the CES among the proposed different CES' sizes for maximum cost-effectiveness. The effectiveness of the proposed optimization algorithm is validated through diverse case studies.

B. Mathematical Formulation

This study proposes an optimization-based approach for determining the optimal size of the CES within the MES framework. The core objective of this strategy is to minimize operational costs. To address this challenge and optimize MES operation alongside CES sizing, a mixed-integer linear program (MILP) optimization model is developed. This model prioritizes both economic efficiency, achieved through cost minimization, and overall system efficiency. It simultaneously guarantees that all demand profiles across various scenarios are met. The model achieves this comprehensive consideration by incorporating every unit within the MES and capturing its unique operational characteristics and associated constraints.

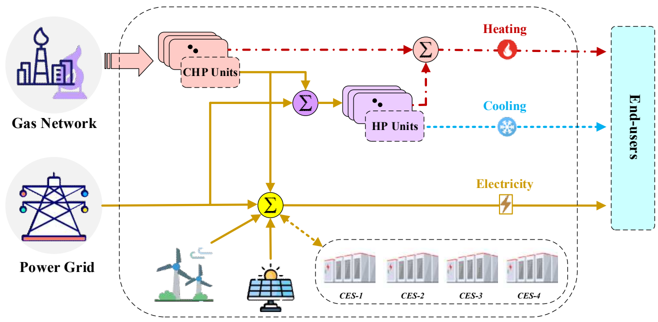


Fig. 1. The multi-energy system proposed scheme.

The following equations (1) to (22) explicitly detail these constraints governing the operation of each individual component.

1) Objective function

This research prioritizes minimizing the operational cost of the MES, mathematically represented by Equation (1). The total cost is influenced by two factors: 1) the amount of electricity and gas procured from external networks, and 2) the corresponding pricing of these utilities during each time interval (t) which equals to an hour within scenarios that incorporate RESs production.

$$TOC = \sum_{t}\sum_{s}\sum_{w}\left(P_{s,w,t}^{elec}\cdot\lambda_t^{elec} + P_{s,w,t}^{gas}\cdot\lambda_t^{gas}\right), \quad \forall s,\forall w,\forall t \tag{1}$$

2) Modelling of CHPs

The CHP units utilize natural gas procured from the external network as input fuel. These CHP units undergo a conversion process enabling the simultaneous generation of both electrical power and heat. Equations (2) to (7) comprehensively capture the mathematical relationships that govern these conversion processes.

$$P_{s,w,t}^{gas} = \sum_{m} P_{m,s,w,t}^{CHP\_input}, \quad \forall m,\forall s,\forall w,\forall t \tag{2}$$

$$P_{m,s,w,t}^{CHP\_input} \le \frac{P_{m,t}^{CHP\_elec\_max}}{\eta_m^{elec}} + \frac{P_{m,t}^{CHP\_heat\_max}}{\eta_m^{heat}}, \quad \forall m,\forall s,\forall w,\forall t \tag{3}$$

$$P_{m,s,w,t}^{CHP\_input} = \frac{P_{m,s,w,t}^{CHP\_elec}}{\eta_m^{elec}} + \frac{P_{m,s,w,t}^{CHP\_heat}}{\eta_m^{heat}}, \quad \forall m,\forall s,\forall w,\forall t \tag{4}$$

$$P_{m,s,w,t}^{CHP\_elec} = P_{m,s,w,t}^{CHPel\_end-user} + P_{m,s,w,t}^{CHPel\_HP}, \quad \forall m,\forall s,\forall w,\forall t \tag{5}$$

$$P_{m,s,w,t}^{CHP\_heat} \le P_{m,t}^{CHP\_heat\_max} \qquad \forall m,\forall t \tag{6}$$

$$P_{m,s,w,t}^{CHP\_elec} \le P_{m,t}^{CHP\_elec\_max} \qquad \forall m,\forall t \tag{7}$$

3) Modelling of HPs

The HP units serve to satisfy the end-users' heating and cooling requirements by converting the received electrical power into thermal energy for these purposes. Notably, the CHPs are seamlessly integrated with the HP units, resulting in a coefficient of integration (chp_hp_m) equal to 1. Equations (8) to (15) are the mathematical relationships that restrict the energy conversion processes occurring within the HP units.

$$P_{s,w,t}^{elec} = P_{s,w,t}^{elec\_HP} + P_{s,w,t}^{direct-user}, \qquad \forall s,\forall w,\forall t \tag{8}$$

$$\sum_{n} P_{n,s,w,t}^{HP\_input} = \sum_{m} P_{m,s,w,t}^{CHPel\_HP}\cdot chp\_hp_m + P_{s,w,t}^{elec\_HP}, \quad \forall m,\forall n,\forall s,\forall w,\forall t \tag{9}$$

$$P_{n,s,w,t}^{HP\_input} = \frac{P_{n,s,w,t}^{HP\_heat}}{COP_n} + \frac{P_{n,s,w,t}^{HP\_cool}}{EER_n}, \qquad \forall n,\forall s,\forall w,\forall t \tag{10}$$

$$P_{n,s,w,t}^{HP\_input} \le \frac{P_{n,t}^{HP\_heat\_max}}{COP_n} + \frac{P_{n,t}^{HP\_cool\_max}}{EER_n}, \quad \forall n,\forall s,\forall w,\forall t \tag{11}$$

$$P_{n,s,w,t}^{HP\_heat} \le N\cdot u_{n,s,w,t}^{HP}, \qquad \forall n,\forall s,\forall w,\forall t \tag{12}$$

$$P_{n,s,w,t}^{HP\_cool} \le N\cdot\left(1-u_{n,s,w,t}^{HP}\right), \qquad \forall n,\forall s,\forall w,\forall t \tag{13}$$

$$P_{n,s,w,t}^{HP\_heat} \le P_{n,t}^{HP\_heat\_max}, \qquad \forall n,\forall s,\forall w,\forall t \tag{14}$$

$$P_{n,s,w,t}^{HP\_cool} \le P_{n,t}^{HP\_cool\_max}, \qquad \forall n,\forall s,\forall w,\forall t \tag{15}$$

4) Modelling of CES

Community energy storage (CES) presents a cost-effective and beneficial approach for storing and delivering electricity to local end-users. A distinguishing feature of CES is its inherent flexibility, enabling it to be charged from diverse sources. This multifaceted charging capability offers the potential to bolster energy security, lessen dependence on conventional grid-supplied electricity, and promote greater utilization of RESs. Equations (16) to (19) mathematically model the relationships that govern the State-of-Charge (SoC) of the CES, along with its corresponding charging and discharging power capabilities.

$$0 \le P_{s,w,t}^{CES\_ch} \le R^{CES\_ch}, \qquad \forall s,\forall w,\forall t \tag{16}$$

$$SOE_{s,w,t}^{CES} = SOE^{CES\_ini} + CE^{CES}\cdot P_{s,w,t}^{CES\_ch}\cdot\Delta t, \quad \forall s,\forall w,\forall t \tag{17}$$

$$SOE_{s,w,t}^{CES} = SOE_{s,w,(t-1)}^{CES} + CE^{CES}\cdot P_{s,w,t}^{CES\_ch}\cdot\Delta t - \left(\frac{P_{s,w,t}^{CES\_dis}}{DE^{CES}}\right)\cdot\Delta t, \qquad \forall s,\forall w,\forall t \tag{18}$$

$$SOE^{CES\_min} \le SOE_{s,w,t}^{CES} \le SOE^{CES\_max}, \quad \forall s,\forall w,\forall t \tag{19}$$

5) Modelling of end-users

Equations (20) to (22) mathematically present the critical equilibrium between energy supplied to and demanded by the community's end-users. These equations comprehensively account for all entities that contribute to or consume energy within the system.

$$P_t^{end-user\_elec} = P_{s,w,t}^{direct-user} + P_{s,t}^{pv} + P_{w,t}^{wind} + \sum_{m} P_{m,s,w,t}^{CHPel\_end-user} + P_t^{CES\_dis} - P_t^{CES\_ch}, \qquad \forall m,\forall s,\forall w,\forall t \tag{20}$$

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

$$P_t^{end-user\_cool} = \sum_n P_{n,s,w,t}^{HP\_cool}, \qquad \forall n, \forall s, \forall w, \forall t \tag{22}$$

III. Test And Results

This study employed a General Algebraic Modeling System (GAMS) and CPLEX solver-based approach to meticulously evaluate the effectiveness of the proposed management strategy for the smart MES. Table IV presents a detailed listing and description of the various cases analyzed in this study, each case is conducted under two scenarios A and B. The detailed results presented in the following sections provide valuable insights into the effectiveness of this approach for optimizing energy usage and optimal sizing of CES within an MES framework.

TABLE IV. Cases Considered in the Study

Case #	Description	Scenario
Case-1	Grid, gas, RESs (PV, wind)	A, B
Case-2	Grid, gas, RESs, and CES-1	A, B
Case-3	Grid, gas, RESs, and CES-2	A, B
Case-4	Grid, gas, RESs, and CES-3	A, B
Case-5	Grid, gas, RESs, and CES-4	A, B
Note	Scenario A: RESs production Scenario B: RESs production decreased by 25%	

A. Input Data

Figure 2 illustrates the actual energy procurement costs, reflecting the current market prices for electricity and natural gas. Electricity costs follow a Time-of-Use (TOU) tariff structure, resulting in variable rates of 0.068 \$/kWh, 0.134 \$/kWh, and 0.215 \$/kWh. These values are substantiated by the data presented in [15]. The natural gas price, as referenced in [16], remains fixed at 0.050 USD/kWh. Fluctuations in energy prices over time demonstrably exert a significant influence on operational decision-making processes within the MES. These decisions concern the utilization of critical components such as CHPs, HPs, and the CES.

Figure 3 shows the approximated energy demand for electricity, heating, and cooling at a MES community level. The technical specifications of HP and CHP units are documented in [17] and [18], with comprehensive details provided in Tables V and VI, respectively. The considered MES incorporates ten HP units, characterized by five distinct types, and five CHP units, each defined by unique parameters.

Figures 4 and 5 depict the generation profiles of photovoltaic (PV) and wind energy sources, for scenarios A and B, respectively. The only difference between scenario A and B is in the amount of RESs production, thus, scenario B has a 25% lower production than scenario A. As referenced in [19], PV generation contributes approximately 4-5% to the total energy consumption of the system. Wind energy is projected to make a similar contribution. Collectively, these renewable energy sources (RESs) generate roughly 9-10% of the overall energy load, emphasizing their significant role in meeting the energy demands within the considered system.

The technical specifications of CESs are given in Table VII. To determine the optimal size of the CES, four energy storage sizes under different case studies for scenarios A and B are tested in the system.

TABLE V. Technical Specification of HP Units

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

TABLE VI. Technical Specification of CHP Units

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

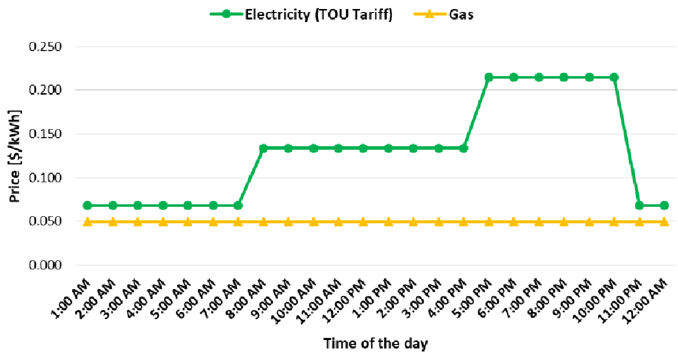


Fig. 2. The electricity and gas purchase prices.

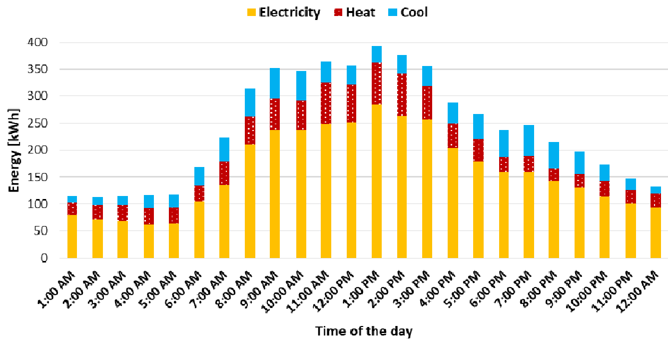


Fig. 3. Total energy demands of electricity, heating and cooling.

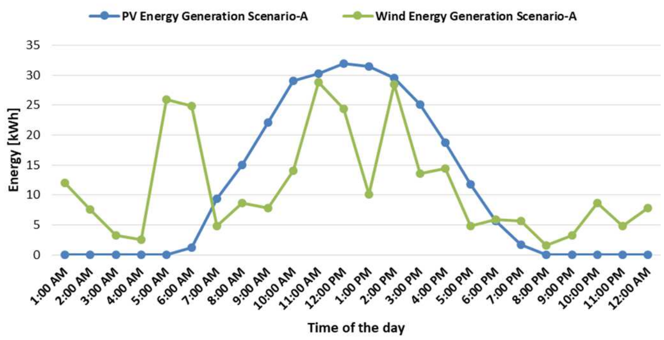


Fig. 4. The PV and wind generation Scenario-A.

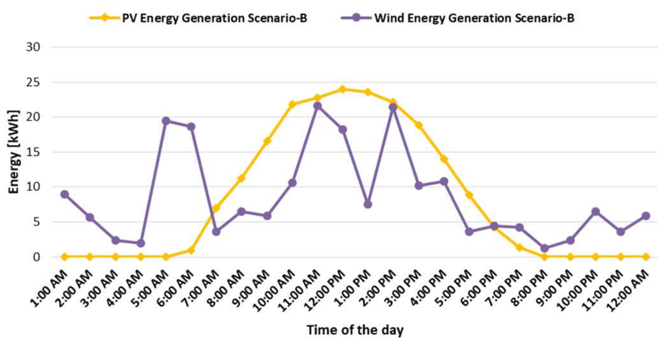


Fig. 5. The PV and wind generation Scenario-B (25% reduction).

TABLE VII. CHARACTERISTICS OF CES

Parameters	CES-1	CES-2	CES-3	CES-4	Value [Unit]
Max. Capacity	200	400	600	800	[kWh]
Min. Capacity	30	60	90	120	[kWh]
Int. Energy State	90	180	270	360	[kWh]
Charging Rate	30	60	90	120	[kW]
Discharging Rate	30	60	90	120	[kW]
Charging Eff.	95	95	95	95	[%]
Discharging Eff.	95	95	95	95	[%]

B. *Simulation Results*

Figure 6 visually compares grid energy consumption patterns observed before and following the integration of RESs for scenarios A and B. The data suggests a statistically significant decrease in total energy consumption after RESs implementation. Interestingly, the electrical demand on the system also exhibits a marked improvement in stability.

Figures 7, 8, 9, and 10 illustrate the state-of-charge and charging/discharging patterns of the CES for Case-2, 3, 4, and 5 under both scenarios A and B. The actual values of Scenario B are not negative. Only, for better understanding and comparison of scenarios A and B, it is given in the same graph. The data evidently demonstrates that the CES participates in energy arbitrage. This strategy involves acquiring energy from the grid at times of lower electricity prices (off-peak periods) and generally discharging it during peak hours or any time needed to satisfy demand and potentially achieve greater economic benefit.

Scenario-B, for Cases 1-5, was configured as a sensitivity analysis. This methodology is specifically employed to investigate and quantify the system's response to variations in renewable energy generation, as well as to determine the optimal size of the CES within the MES.

Figure 11 depicts the total operational costs (USD) for all five cases evaluated under Scenarios A and B. Case-5 demonstrates the lowest cost across both scenarios. While Case-4 exhibits reasonable costs under Scenario A, but its performance deteriorates under Scenario B, because the total operation cost is much higher than in Case-5 scenarios A and B. Notably, the data provides robust evidence for the effectiveness of the proposed approach, as reflected in the demonstrably reduced overall operational expenditures. Furthermore, the attained cost levels remain within acceptable economic feasibility boundaries, thus substantiating the practical implementation potential of the proposed approach.

Considering the tests and simulation results the CES-4 under Case-5 for both Scenarios A and B, provides the most economic benefits in the MES. Therefore, the optimal size of the community energy storage in the proposed MES is the CES-4 having a maximum capacity of 800kWh.

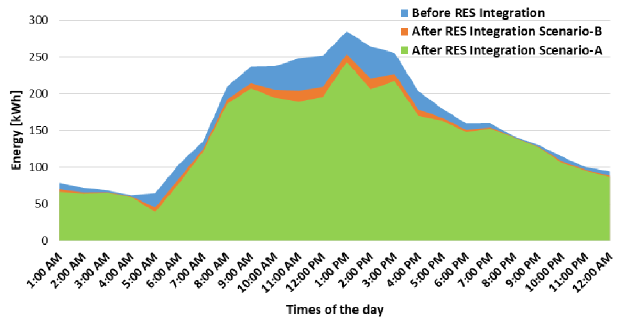


Fig. 6. The electricity consumption of end-users from the main grid before and following the integration of RESs.

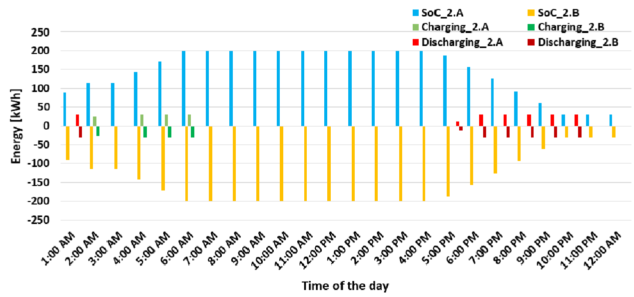


Fig. 7. SOC, charging and discharging power of CES for Case-2 Scenarios A and B.

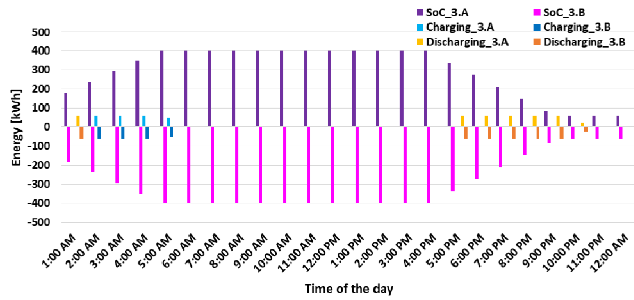


Fig. 8. SOC, charging and discharging power of CES for Case-3 Scenarios A and B.

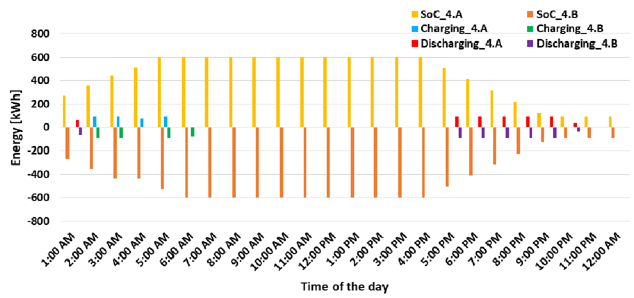


Fig. 9. SOC, charging and discharging power of CES for Case-4 Scenarios A and B.

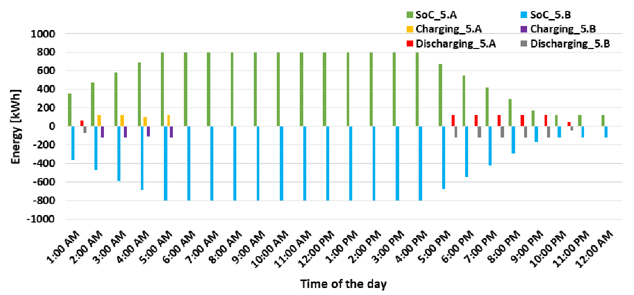
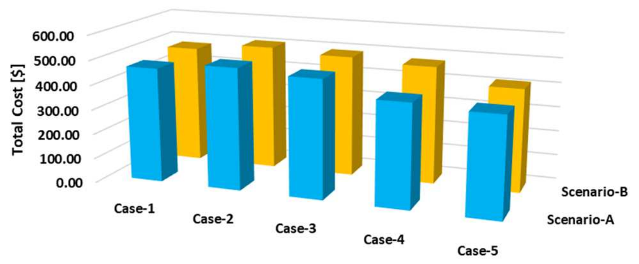


Fig. 10. SOC, charging and discharging power of CES for Case-5 Scenarios A and B.



	Case-1	Case-2	Case-3	Case-4	Case-5
Scenario-A	464.04	492.24	476.01	414.77	400.57
Scenario-B	480.28	508.48	492.24	477.38	416.61

Fig. 11. The total operational cost of considered cases for scenarios A and B.

Evaluating operational costs across diverse scenarios offers valuable insights regarding the influence exerted by pricing structures, integration of RESs, and introduction of CESs on overall system economics. Case 5 achieves the most significant cost optimization due to the optimal sizing of the CES. This translates to the lowest operational costs of $400.57 and $416.61, representing reductions of 13.67% and 13.25% compared to the baseline (Case-1) under Scenarios A and B, respectively. This finding emphasizes the significant economic advantages attainable through collaborative energy management at the community level. The algorithm prioritizes cost-effectiveness by strategically selecting the most economical energy source at any given time. This strategy minimizes dependence on the less economical alternative.

IV. Conclusions

This study investigated the optimal sizing of a Community Energy Storage (CES) within a Multi-Energy System (MES) framework. The proposed approach utilizes a mixed-integer linear program (MILP) to minimize operational costs while ensuring reliable energy supply across diverse scenarios. The results reveal that optimal CES sizing significantly reduces operational costs compared to baseline scenarios. This approach offers valuable insights into the influence of pricing structures, RES integration, and CES implementation on overall system economics. The findings emphasize the economic advantages of collaborative energy management at the community level, achieved through strategic energy source selection based on cost-effectiveness. The future studies will address the practical implementation challenges and considerations at the campus level.

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