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Abstract*—The application of hydrogen (H2) energy in Microgrids (MGs) is suppressed by the limited energy conversion efficiency between H2 and electricity, even though the energy density of H2 outperforms the electricity storage. This paper proposed a multi-objective energy management system (EMS) to economically operate a hybrid H2-electricity system under the flexible electricity market, considering the energy loss in not only power-to-gas (P2G) and gas-to-power (G2P) conversion but also the energy consumption of H2 pressurization. Particle swarm optimization (PSO) is deployed to perform a day-ahead schedule for the electricity storage system and H2 storage system separately. The global optimal operation is achieved by the proposed method to allocate renewable energy and shift the cheap electricity. The performance of the proposed EMS is verified through numerical experiments based on real-world data. The influence of prediction methods on the proposed MOEMS is further tested and analyzed to improve the reproducibility of the approach. The results indicate that the proposed MOEMS could effectively schedule the operation of the hybrid storage system.

***Index Terms*—Energy management; Energy storage; PSO**

I. Introduction

Renewable energy is promoted rapidly as the public awareness of carbon neutrality. Microgrid (MG) is the fundamental unit to integrate distributed renewable generators. However, renewable energy brings Microgrids uncertainty and intermittence apart from low carbon emissions [1]. To compensate for power oscillation and energy uncertainty of renewable energy sources (RESs), energy storage (ES) systems are deployed, and energy management systems (EMSs) must be implemented.

Batteries are the most popular ES in many applications due to their high efficiency and fast response [2]. Cooperated with EMSs, the oscillation or intermittence caused by the uncertainty from the renewable energy and demand side could be well addressed. Traditional EMSs perform a step-ahead schedule for batteries based on the forecasting of renewable energy generation, power demand, and electricity price [3]. The schedule is solved as a mathematical optimization problem [4]. Numerous optimization algorithms are introduced into this area to achieve the optimal schedule for battery operation. Typical approaches like mixed-integer linearization programming (MILP) [5], particle swarm optimization (PSO) [6], teaching-learning (TL) [7], etc, can well solve the optimization problem based on appropriate system formulation. However, the limited energy density of batteries suppresses their performance in long-term energy-shifting scenarios [8]. To solve this problem, the hydrogen (H2) ES system has been deployed in many studies due to the development of fuel cell (FC) technology. The electrolyzer (EL), compressor, and fuel cell are the fundamental components of the H2 ES system. Benefiting from the chemical characteristics of ES media, the H2 ES system has sustainable energy capacity and considerable energy density [9], however, the energy conversion and pressurization bring unneglectable energy loss, which brings great challenges to EMSs.

EMSs for hybrid electricity-H2 ES systems must consider the features of different ES units. Many optimization methods such as MILP [10], mixed-integer nonlinear programming (MINP) [11], and PSO [12], are deployed to generate the optimal operation of MGs and achieve considerable results. However, caused by the ES units increase, the optimization variables are doubled and the complexity of the optimization problem is greatly enlarged [13]. In [14], a gravitational search algorithm is deployed to solve the optimization problem for an MG suffering from uncertainty caused by electricity price, demand side, and renewable energy. In [15], a day-ahead schedule based on the marine predator algorithm is suggested for the cost-effective energy management of an MG with renewable energy and an H2 storage system. Even though the existing approaches can already solve the optimal operation problem in their applications, there are still some neglected aspects. The efficiency of H2 ES is quite lower than batteries since the energy loss happens not only during the power-to-gas (P2G) and gas-to-power (G2P) conversion but also in the pressurization of H2 storage. Hence, the economical operation of the hybrid ES in a grid-connected MG with flexible electricity price becomes a multi-variable optimization problem with a high proportion of uncertainty.

This paper proposed a multi-objective EMS (MOEMS)

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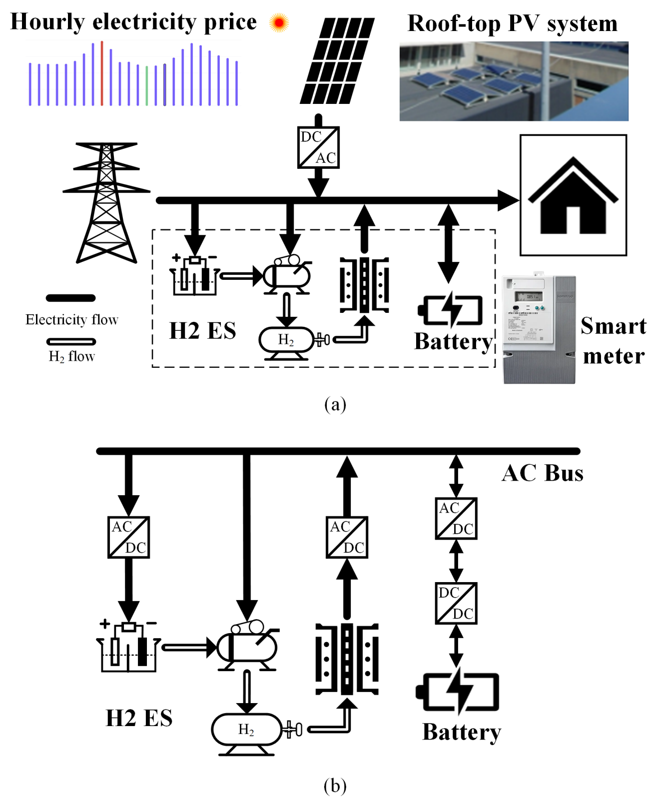

Fig. 1. Architecture of the MG with hybrid ES system

for grid-connected residential MGs (RMGs) to economically allocate renewable energy and shift the loads using the hybrid ES system. The energy conversion efficiency of the ES units is considered separately to implement the day-ahead optimization for the hybrid ES system. The feasibility of the proposed method is verified by real-world data, and the performance is studied under prediction results with different accuracy. The discussion of the performance degradation by prediction accuracy is instructive for the step-ahead schedule-based EMS approaches.

The remainder of the paper is organized as follows. The structure of the target RMG is presented in Section II; Section III expounds the algorithm of the MOEMS; The case study using real-world data from Internet of Things (IoT) Laboratory from AAU CROM is shared in Section IV; A conclusion is drawn in Section V.

II. Architecture of the MG with hybrid ES system

The architecture of the target MG with a hybrid ES system is shown in Fig. 1 (a). A PV system is employed here as the green energy generator. The hybrid ES system is composed of a Lithium-ion battery and an H2 ES unit. The H2 ES unit contains an electrolyzer, a compressor, a high-pressure H2 tank, and a proton exchange membrane (PEM) FC system. The energy consumption of the compressor will be measured and considered in the proposed MOEMS.

The utility grid is connected to the AC bus directly to ensure the power balance of the MG, hence the power shaving of PV system is not activated. To ensure the comfort of consumers, the loads, including two fridges, an oven, TVs, laptops, a microwave oven, coffee machines, and cooking stuff, are not regulated.

The internal topology of the ES system is presented in Fig. 1 (b). The electrolyzer is excited by an AC-DC converter and the FC supports the load through a DC-AC grid-following converter. The battery is connected to the AC bus through a DC-AC grid-following converter and the charging and discharging events are controlled by the bidirectional DC-DC converter. The compressor is connected to the AC bus and works as an AC load. In the H2 ES unit, the charging process is realized by the electrolyzer and the compressor, and the electrical power will be transferred to liquid H2 and stored in the H2 tank. During the discharging process, the FC consumes the H2 in the tank and generates electrical power to support the load.

III. The proposed PSO-based day-ahead optimization

To economically allocate renewable energy and shift the loads, a PSO-based optimization method is proposed to perform the day-ahead schedule for the hybrid ES system.

A. System reformulation

The uncertainty in the MG system comes from not only the RES but also the consumers and greatly affects the supply-demand balance. To enhance the performance of the prediction method, the power demand P_d is introduced to combine the components with uncertainty.

$$P_d = P_{load} - P_{RES}. \tag{1}$$

in which P_{load} donates the load power and P_{RES} represents power generation of RES. The flexible electricity price and its forecasting Pr are provided by the energy supplier.

The battery model is defined by,

$$SoC = \frac{\int -P_{Bat}dt}{C_{bat}}; \tag{2}$$

where SoC is battery state of charge, the P_{Bat} is the battery output power, and C_{bat} is the capacity of battery. In the proposed scenario, constraints for SoC and P_{Bat} are set for the battery ES unit.

The H2 ES unit is designed as,

$$SoF = \begin{cases} \dfrac{\eta_E \eta_C \int -P_{H2}dt}{C_{H2}}, & 0 \geq P_{H2}, \\ \dfrac{\int -P_{H2}dt}{\eta_F C_{H2}}, & 0 < P_{H2}. \end{cases} \tag{3}$$

in which SoF represents the state of fuel of the H2 ES unit; η_E, η_C, η_F donates the efficiency of the electrolyzer, compressor, and fuel cell, separately; P_{H2} is the total output power of the H2 ES unit; C_{H2} is the total capacity of H2 ES unit in kWh. Some constraints are set for the H2 ES unit as well.

Constraints are defined for both ES units to ensure the health of devices.

$$\begin{cases} 0.1 \leq SoC \leq 0.95, \\ 0.1 \leq SoF \leq 0.95, \\ -2.5 \leq P_{Bat} \leq 2.5, \\ -2.5 \leq P_{H2} \leq 2.5. \end{cases} \tag{4}$$

Based on the formulation of the MG, the day-ahead optimization using PSO is performed to figure out the optimal output power for the ES units separately.

B. PSO-based optimization algorithm

PSO is a concept for the optimization of nonlinear functions [16]. The interracial algorithm of the PSO is presented in Algorithm 1. The input of the algorithm is the state space of the MG, the output is the SoC sequence for the battery, and SoF sequence for the H2 ES. The superscript represents the size of the matrix. The velocity matrix v, the neighborhood size N, the inertia W, and stall counter c are initialized before the iterations. During the iterations, the particle and the related position are recorded as i and $x(i)$. In each iteration, the subset is chosen randomly and the local best position can be found. u_1, u_2 uniformed between 0 and 1 are introduced to update the velocities using a weighted sum of the previous velocities, the difference between the current position and the best position within the particle, and The difference between the current position and the best position in the current neighborhood. Based on the new velocities, the positions can be updated. After enhancing the bounds of the positions and velocities, the objective function can be evaluated. The best position has been seen, marked as p, is updated first, then the best objective function b in the swarm and the best location d are updated. The current function output is compared with that in the past iteration. If current output is lower, the moving direction will be accepted and the moving speed will be decreased accordingly. If it is higher, the search step will be enlarged to find the lower region.

The optimal SoC and SoF sequences for the next day will be calculated by the PSO algorithm based on the reformulation of the MG system.

IV. NUMERICAL EXPERIMENTS

The performance of the proposed MOEMS is verified through realistic data from a real-world IoT laboratory. Considering that the step-ahead schedule approaches highly relied on the prediction methods, the performance of the proposed MOEMS fed with different prediction results is studied.

The input sequences of the power demand and electricity price are presented in Fig. 2. Five-day data is deployed to validate the proposed MOEMS. Different weathers are included in the scenario. The electricity price changes hourly. The uncertainty from renewable generation, demand side, and energy market is introduced into the research through the dataset. The MOEMS is activated at the beginning of each day to generate the 24-point SoC and SoF sequences for the ES units, and the initial state of the optimization is reset according to the last status of the previous day.

Algorithm 1 Multi-variable PSO Algorithm for MOEMS

Input: System state space: $Pr^{1\times24}$, $P_d^{1\times24}$, SoC_0, SoF_0.
Constraints: SoC_{min}, SoC_{max}, SoF_{min}, SoF_{max}.
Output: SoC matrix: $SoC^{1\times24}$; SoF matrix: $SoF^{1\times24}$.
Initialize particle velocities v within the constraints;
Initialize the neighborhood size $N = N_{MIN} = floor(Z * MNF)$;
  Z: Swarm size;
  $MNF \subset (0,1)$: Minimum Neighborhoods Fraction;
Initialize the inertia $W = W_{MAX}$;
Initialize the stall counter $c = 0$;
for particle = i, position = $x(i)$ **do**
  Choose a random subset S of N particles other than i;
  Find the best objective function $fbest(S)$ and the position $g(S)$;
  for Random $u_1, u_2 \subset (0,1)$ **do**
    Update the velocities:
    $v(i) = Wv(i-1) + y_1 u_1.*(p-x) + y_2 u_2.*(g-x)$;
    y_1: Self-adjustment weight;
    y_2: Social-adjustment weight;
    p: The best position of the particle;
    g: The best position in the current neighborhood.
  end for
  Update the position $x(i+1) = x(i) + v(i)$;
  Enforce the bounds;
  Evaluate the objective function $f = fun(x)$;
  if $f < fun(p)$ **then**
    $p = x$;
  end if
  if $f < b$ **then**
    $b = f$;
    $d = x$;
  end if
  if $f(i) < f(i-1)$ **then**
    $c = MAX(0, c-1)$;
    $N = N_{MIN}$;
    if $c < 2$ **then**
      $W = 2 * W$;
    else if $c > 5$ **then**
      $W = 0.5 * W$;
    else
      $W = W$;
    end if
  else
    $c = c + 1$;
    $N = MIN(N + N_{MIN}, Z)$;
  end if
end for

A. Schedule results with accurate prediction

The hourly results in 5 days are shown in Fig. 3. The P_{H2} and P_{bat} are stacked. The power purchasing from the

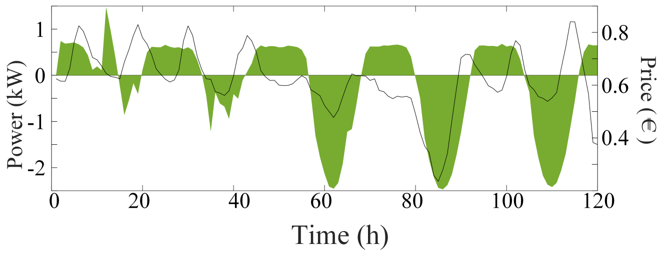

Fig. 2. Performance of the MOEMS with different prediction results

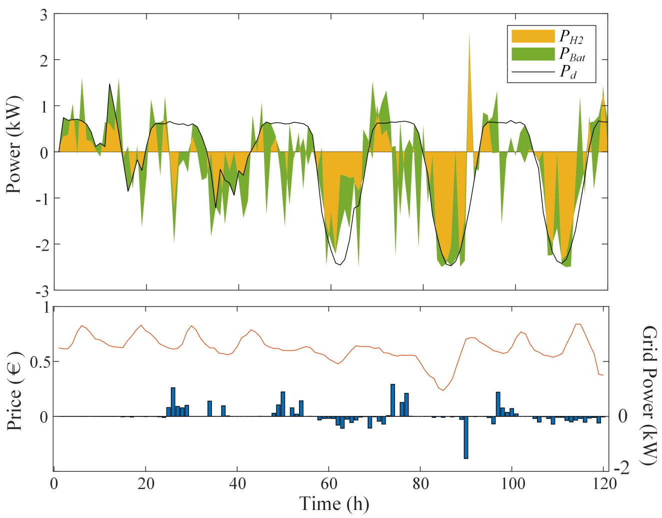

Fig. 3. Detailed schedule of the MOEMS in the RMG application

utility grid is shown in the figure below together with the electricity price. It can be found from the figure that the hybrid ES system could cover the power demand and absorb the exceeding energy in most cases. Power purchasing is regulated to achieve the lowest economic cost. Hence power purchasing always happens in the price valley or just after the peak.

The priority of the ES units is distinguished by the proposed MOEMS considering the energy conversion efficiency. The H2 ES unit has low energy efficiency and high energy density, while the battery is superior for the fast response. Hence, the battery is activated to absorb the power oscillation in most cases and the H2 ES unit works as a backup supply.

Benefiting from the accurate prediction, the output power of the hybrid ES system can well track the power demand to suppress the power purchasing from the utility grid. However, the accuracy is unavailable in real-world applications, and inaccurate prediction will always generate extra expense for power purchasing.

B. Total cost with inaccurate prediciton

To analyze the feasibility of the proposed MOEMS, the influence of prediction accuracy is discussed. Mean absolute percent error (MAPE) is deployed to evaluate the prediction accuracy. The MOEMS is fed with power demand prediction results with distinct accuracy to modify the realistic application based on renewable energy and load forecasting. Considering that the electricity price forecasting for a residential MG

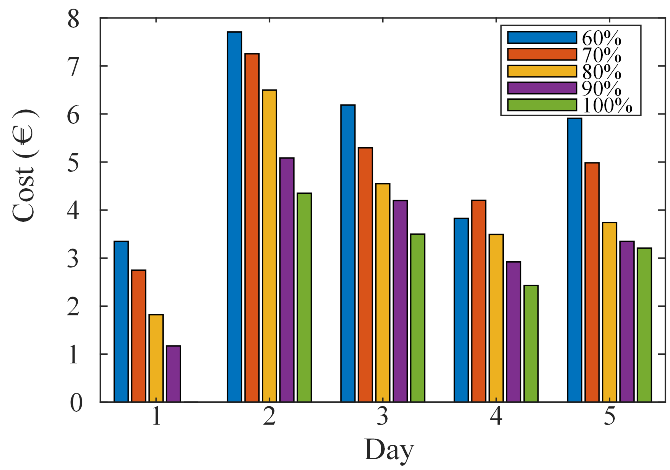

Fig. 4. Performance of the MOEMS with different prediction results

TABLE I
DAILY ENERGY COST (€) OF THE PROPOSED MOEMS WITH DIFFERENT PREDICTION RESULTS.

Precision	60%	70%	80%	90%	100%
Day 1	3.35	2.75	1.82	1.17	0
Day 2	7.71	7.25	6.50	5.08	4.35
Day 3	6.19	5.30	4.55	4.20	3.50
Day 4	3.83	4.20	3.49	2.92	2.43
Day 5	5.91	4.98	3.74	3.35	3.21
Total	26.99	24.49	20.1	16.72	13.49

is available from many energy suppliers, the inaccurate price is not discussed in this research.

The daily cost using prediction results with accuracy of 60%, 70%, 80%, 90%, and 100% is shown in Fig. 5. In each case, the total cost is calculated by the average of ten optimization results. The statistical data is presented in TABLE. I. Compared with the ideal scenario, 90% accuracy leads to a 24% increase in total expense. The total expense with 80% accuracy is 20% more than that with 90% prediction results and 49% increase by the ideal case. Generally, with 10% degradation of the prediction precision, the total expense increases by around 20%. If the prediction accuracy is less than 80%, random errors appear in the schedule and the optimization might be invalid as the results of Day 4 show, the performance with 60% prediction accuracy outperforms that with 70% accuracy.

To further analyze the influence of prediction accuracy, the detailed schedule results are presented in Fig. 5. Compared with the ideal case shown in Fig. 3, the MOEMS with high prediction accuracy (90% and 80%) can generate a valid schedule for a hybrid ES system. The increasing expense for these cases is caused by the power tracking error. In low prediction accuracy (70% and 60%) cases, the random errors are enlarged and significantly affect the schedule results of the MOEMS. The oscillation of grid power in Fig. 5 (c), (d) indicates the stochastic power purchasing event caused by the degradation of prediction results.

Overall, the proposed MOEMS can generate a valid sched-

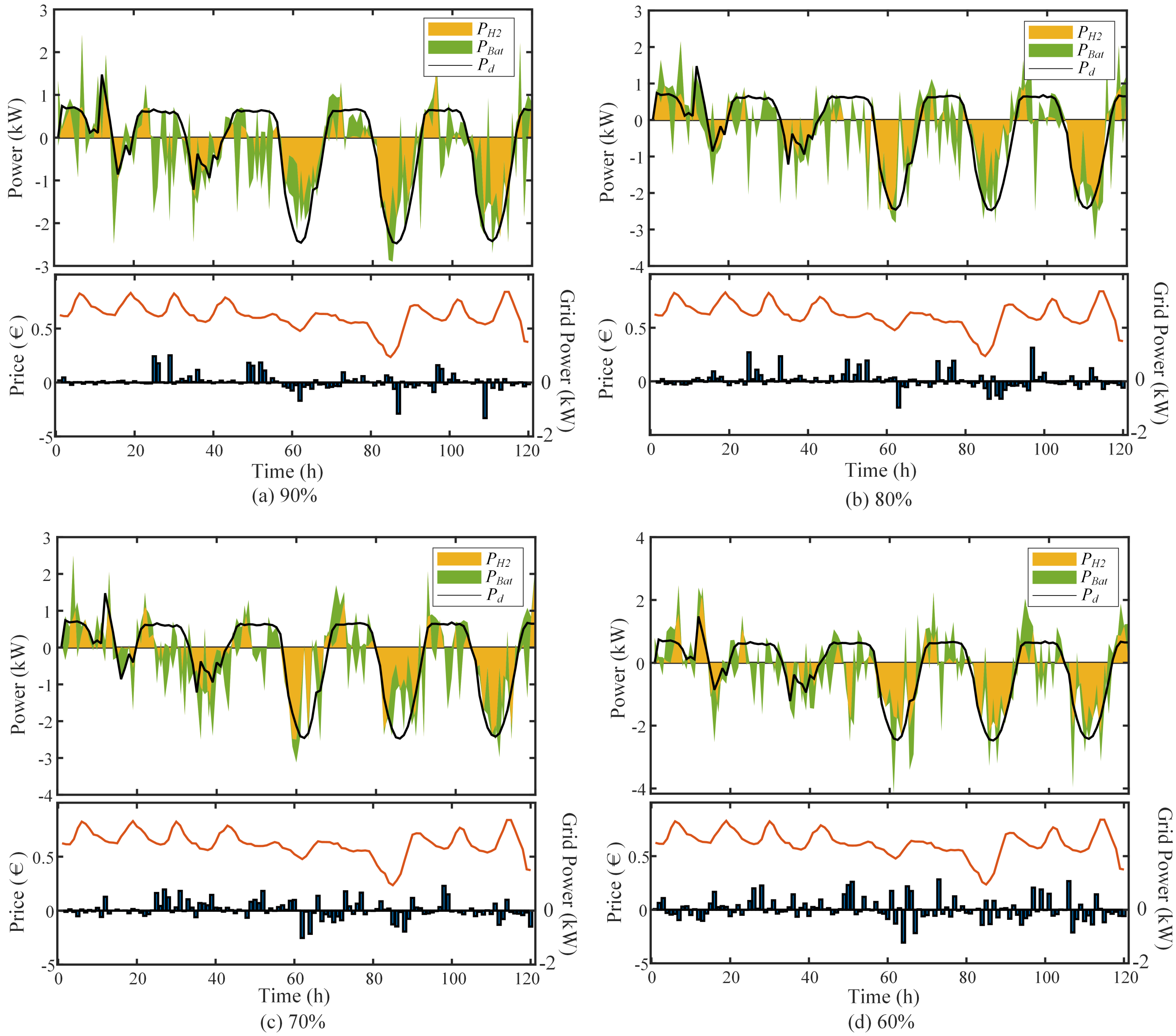

Fig. 5. The schedule results with different prediction accuracy, a) 90% b) 80% c) 70% d) 60%

ule for the hybrid electricity-H2 ES system to achieve a cost-effective operation. However, a prediction method with an accuracy higher than 80% is suggested to cooperate with the proposed MOEMS. Based on the analysis conducted in this research, it can be concluded that there will be a 20% increase in the total economic expense as the prediction accuracy degrades by 10%.

V. Conclusion

A MOEMS is proposed in the paper to realize the intelligent schedule of a hybrid electricity-H2 ES system. PSO-based optimization is established for the optimal day-ahead schedule problem. The main works of the paper can be summarized as.

1) The PSO-based MOEMS considering different efficiency of the ES units is proposed and validated in a multi-energy RMG architecture. Uncertainty from the renewable generation, demand side, and flexible electricity market is introduced into the research through real-world datasets.
2) The influence of prediction results is analyzed to enhance the reproducibility of the work. The performance of the proposed MOEMS under different prediction accuracies is studied and the acceptable precision range is discussed based on the schedule results.
3) Comprehensive numerical experiments based on realistic datasets are implemented to validate the proposed MOEMS and test the optimization degradation by the prediction accuracy.

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