CHAPTER IV

MULTI-OBJECTIVE OPTIMIZATION USING FMOO FOR OMES-WSPHS INTEGRATION

4.1 General Introduction

This chapter presents a comprehensive multi-objective optimization framework for OMES-WSPHS integration. The proposed optimization methodology employs fuzzy techniques to address multiple objectives, including the minimization of TOC, TCE, and EP. The optimization approach utilizes PSO-LP to achieve an optimal single objective, followed by the construction of a fuzzy-satisfaction membership function (FSMF). PSO is then used to maximize FSMF, ensuring a balanced trade-off among these conflicting objectives. By integrating fuzzy decision-making techniques into the optimization framework, the proposed method ensures a balanced and efficient operation of the MES-WSPHS system, considering cost-effectiveness, environmental sustainability, and energy demand management. Furthermore, the performance of the proposed FMOO technique is benchmarked against WSMO.

4.2 Problem Formulation

4.2.1 TOC Minimization

The proposed method uses the PSO-LP technique to find the optimal scheduling of MES-WSPHS. The multiple energy deliveries are formed as variables on an hourly basis, to find the optimal solution for the system that makes it the minimum operating cost. The analysis considers the TOU tariff throughout the day. Therefore, the objective function is to minimize TOC while accounting for the TOU tariff, with a penalty function incorporated to address any constraints violations, as shown in Eq. (4.1).

$$Minimize\ TOC = \sum_{h=1}^{24} (C_E(h)P_E(h) + C_{NG}(h)P_{NG}(h)) + PNF. \tag{4.1}$$

Subjected to the power balance constraints in (4.2) - (4.3),

$$L_E(h) - P_{FC}(h) - P_{WSP}^i(h) = P_{TR}(h) + P_{MT}^E(h), \tag{4.2}$$

$$L_H(h) = P_{GB}(h) + P_{MT}^H(h), \tag{4.3}$$

and the limit constraints of each conversion device as demonstrated by Eq. (4.4) - (4.9). The initial pressure which is indicated in the content of the HS tank is set to the final pressure when the day is over, as shown in Eq. (4.10). Additionally, penalty function terms can handle some constraints, which can't define a lower and upper boundary such as Eq. (4.9) and (4.10). The penalty function can be defined in Eq. (4.11)

$$0 \le P_{TR}(h) \le P_{TR,rated}, \tag{4.4}$$

$$0 \le P_{MT}^{E,H}(h) \le P_{MT,rated}^{E,H}, \tag{4.5}$$

$$0 \le P_{GB}(h) \le P_{GB,rated}, \tag{4.6}$$

$$0 \le Y_{EL}P_{EL}(h) \le P_{EL,rated}, \tag{4.7}$$

$$0 \le Y_{FC}P_{FC}(h) \le P_{FC,rated}, \text{ and} \tag{4.8}$$

$$p_{\text{tank,min}} \le p_{\text{tank}}(h) \le p_{\text{tank,rated}}. \tag{4.9}$$

$$p_{\text{tank}}(h = initial) = p_{\text{tank}}(h = 24). \tag{4.10}$$

$$PNF = \rho[(p_{\text{tank}}(t) - p_{\text{tank,min}})^2 + (p_{\text{tank}}(t) - p_{\text{tank,max}})^2 + (p_{\text{tank}}(24) - p_{\text{tank}}(\text{initial}))^2] \tag{4.11}$$

The operation of this work procedure, which involves calculating the objective function while handling constraints. This process follows a structured workflow, as depicted in Chapter 3, specifically in Fig. 3.2.

4.2.2 TCE Minimization

The proposed method uses the PSO-LP technique to find the optimal scheduling of MES-WSPHS. The multiple energy deliveries are formed as variables on an hourly basis, to find the optimal solution of the system that makes it the minimum carbon emissions, under the emission factor depending on the generation source. The operation of this work procedure, which involves calculating the objective function while handling constraints, follows the workflow depicted in Fig. 4.1.

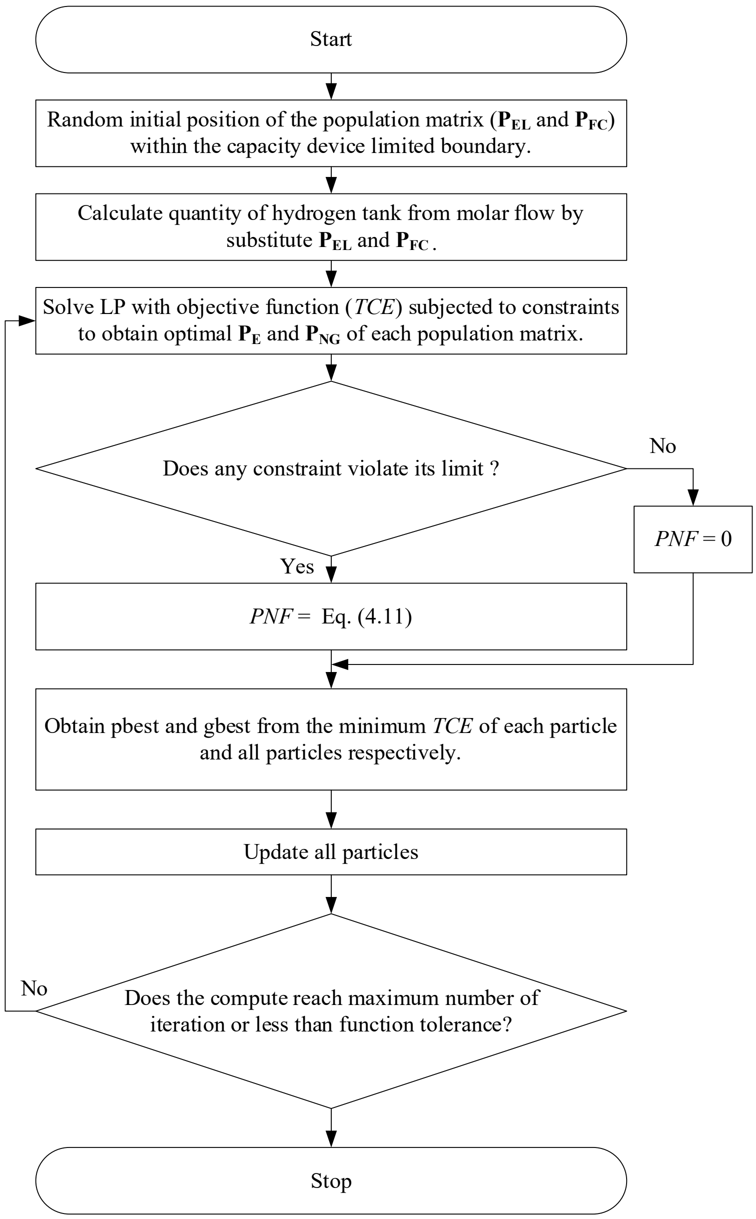


Figure 4.1 The workflow of the PSO-LP technique under TCE

In this model, carbon emissions do not appear in WSP and green HS operations. Therefore, the objective function is to minimize total carbon emissions considering the energy mix from the grid and NG, obtained by Thailand greenhouse gas management organization (TGO), and handle a penalty function for a constraints violation as shown in Eq. (4.12).

$$\text{Minimize } TCE = \sum_{h=1}^{24} [k_{TR}P_{TR}(h) + k_{GB}P_{GB}(h) + k_{MT}^{H}P_{MT}^{H}(h) + k_{MT}^{E}P_{MT}^{E}(h)] + PNF. \quad (4.12)$$

Subjected to the power balance, the limit constraints of each conversion device, and the pressure of the HS tank constraints in Eq. (4.4) – (4.11).

The carbon emissions factor is reported by Thailand Greenhouse Gas Management Organization (Public Organization) (2022). TGO is a public organization under the Ministry of Natural Resources and Environment of Thailand. Its main role is to promote and coordinate efforts to reduce greenhouse gas emissions in Thailand. Therefore, Table 4.1 represents the value of carbon emissions in each energy generation. This work considers two main sources of emission factors including electricity from the grid which is an energy mix and NG which is fueling power to electricity and heat.

Table 4.1 A value of carbon emissions in each energy generation (Thailand Greenhouse Gas Management Organization (Public Organization), 2022)

Source	Variable	Value
Electricity grid to TR	k_{TR}	0.6116
NG to MT produces heat	k_{MT}^{H}	0.3910
NG to MT produces electricity	k_{MT}^{E}	0.4888
NG to GB produces heat	k_{GB}	0.2222

4.2.3 EP Minimization

The proposed method uses the PSO-LP technique to find the optimal scheduling of MES-WSPHS. To find the optimal solution of the system that makes it the minimum EP, under the cooperation multiple energy. The operation of this work procedure, which involves calculating the objective function while handling constraints, follows the workflow depicted in Fig. 4.2.

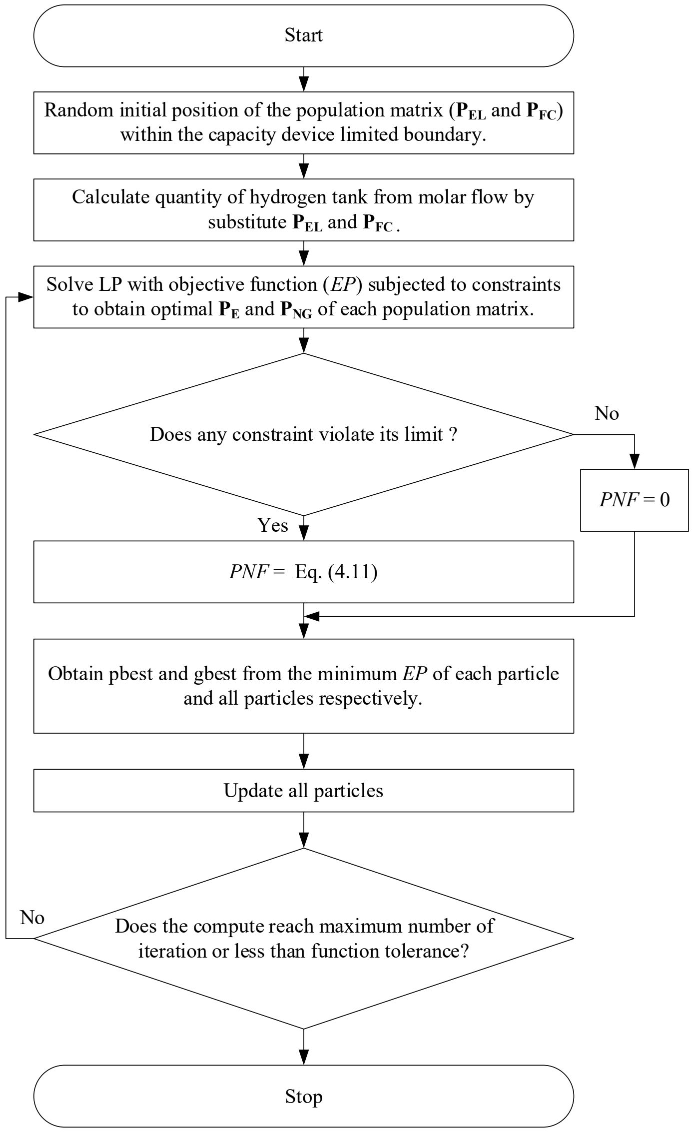


Figure 4.2 The workflow of the PSO-LP technique under EP

Therefore, the objective function is to minimize EP from the grid considering electricity dispatch all day and handle a penalty function for a constraints violation as shown in Eq. (4.13).

$$\text{Minimize } EP = \max([P_E(1), P_E(2), ...P_E(h), ..., P_E(24)]) + PNF. \tag{4.13}$$

Subjected to the power balance, the limit constraints of each conversion device, and the pressure of the HS tank constraints in Eq. (4.4) – (4.11).

4.3 FMOO-based OMES-WSPHS

The optimization of multi-objective functions is carried out to achieve a balanced compromise solution. FMOO-based OMES-WSPHS is employed to solve the optimal scheduling problem. The proposed OMES-WSPHS addresses the following objectives, which can be modeled as a FSMF as displayed in shown in Figs. 4.3, 4.4 and 4.5.

1. Total operating costs (TOC) minimization in Eq. (4.14)

$$\mu_{TOC} = \frac{-1}{TOC_{\max} - TOC_{\min}} TOC + \frac{TOC_{\max}}{TOC_{\max} - TOC_{\min}}. \tag{4.14}$$

2. Total carbon emissions (TCE) minimization in Eq. (4.15)

$$\mu_{TCE} = \frac{-1}{TCE_{\max} - TCE_{\min}} TCE + \frac{TCE_{\max}}{TCE_{\max} - TCE_{\min}}. \tag{4.15}$$

3. Electricity peak from the grid (EP) minimization in Eq. (4.16)

$$\mu_{EP} = \frac{-1}{EP_{\max} - EP_{\min}} EP + \frac{EP_{\max}}{EP_{\max} - EP_{\min}}. \tag{4.16}$$

For decision-making, the multi-objective problem in Eq. (4.14) – (4.16) aim to maximize the total membership function value, which encompasses the membership functions for objectives 1, 2, and 3 respectively. The fuzzy maximization can be represented as Eq. (4.17). The computation concept of the fuzzy decision procedure overview can be illustrated in Fig. 4.3.

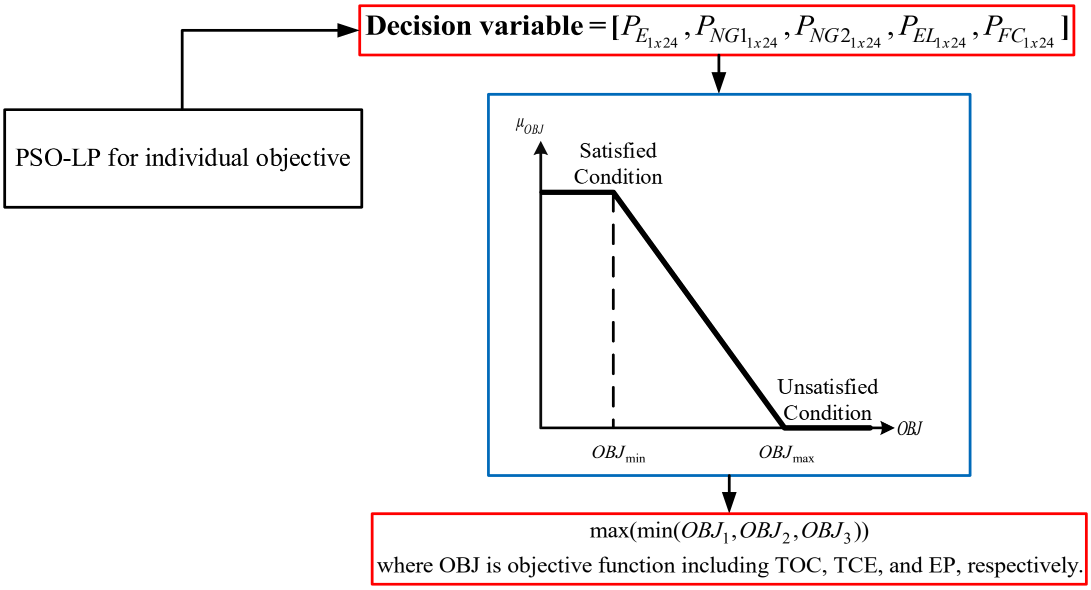


Figure 4.3 The computation concept of the fuzzy decision procedure overview

$$\text{Maximize } \mu_T = \min\{\mu_{TOC}, \mu_{TCE}, \mu_{EP}\} + PNF. \tag{4.17}$$

Subjected to the power balance, the limit constraints of each conversion device, and the pressure of the HS tank constraints in Eq. (4.4) – (4.11).

Where,

$$\mu_{TOC} = \begin{cases} 1 & \text{, for } TOC \leq TOC_{\min} \\ \text{Eq. (4.14)} & \text{, for } TOC_{\min} \leq TOC \leq TOC_{\max} \\ 0 & \text{, for } TOC \geq TOC_{\max} \end{cases} \tag{4.18}$$

$$\mu_{TCE} = \begin{cases} 1 & \text{, for } TCE \leq TCE_{\min} \\ \text{Eq. (4.15)} & \text{, for } TCE_{\min} \leq TCE \leq TCE_{\max} \\ 0 & \text{, for } TCE \geq TCE_{\max} \end{cases} \tag{4.19}$$

$$\mu_{EP} = \begin{cases} 1 & \text{, for } EP \leq EP_{\min} \\ \text{Eq. (4.16)} & \text{, for } EP_{\min} \leq EP \leq EP_{\max} \\ 0 & \text{, for } EP \geq EP_{\max} \end{cases} \tag{4.20}$$

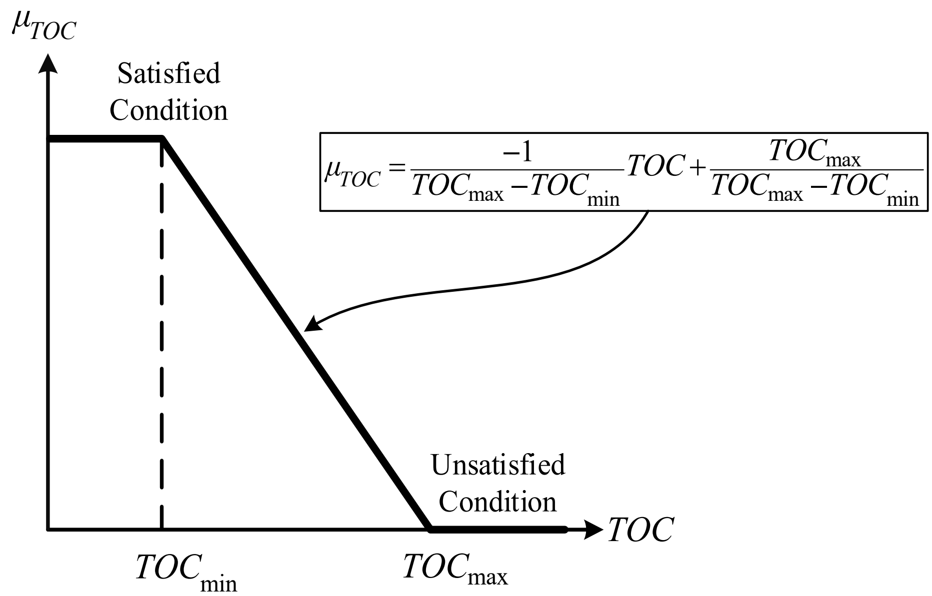


Figure 4.4 FSMF of total operating costs

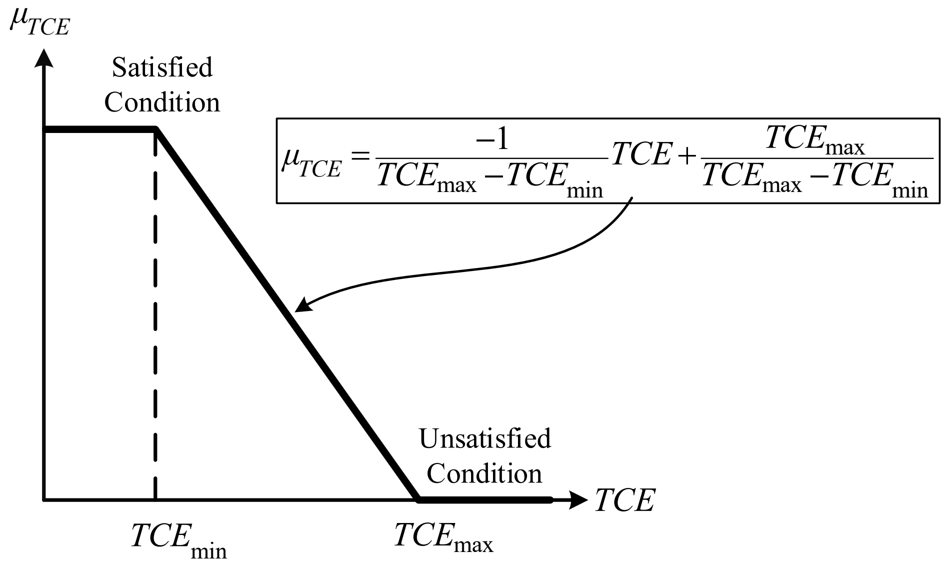


Figure 4.5 FSMF of total carbon emissions

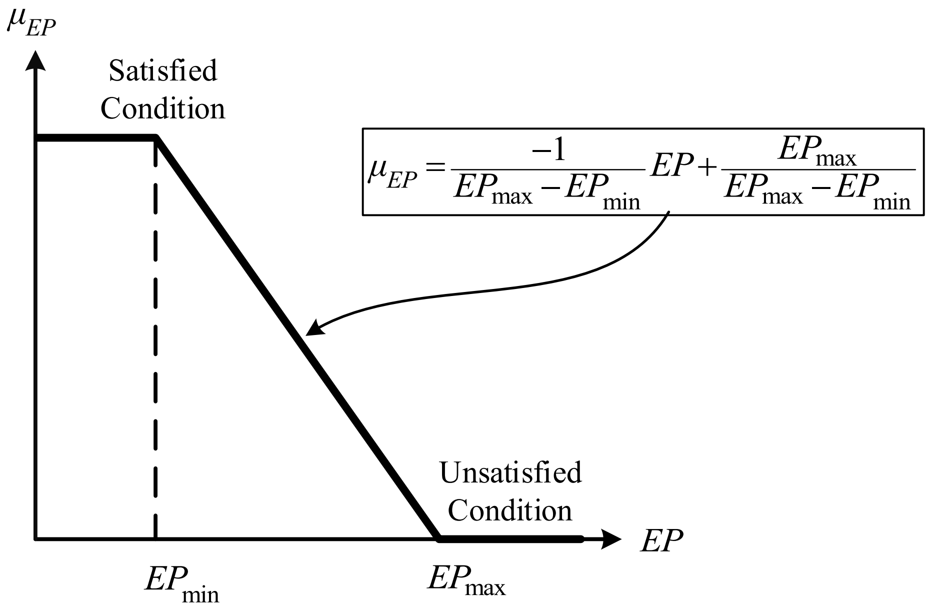


Figure 4.6 FSMF of electricity peak from the grid

4.4 WSMO-based OMES-WSPHS

In this study, WSMO method is applied to solve OMES-WSPHS. The WSMO approach transforms the original multi-objective problem comprising TOC, TCE, and EP into a single-objective function by assigning appropriate weights to each objective based on their relative importance. To enable comparison with the proposed FMOO approach, all three objectives are transformed into equivalent monetary costs. This conversion, as defined in Eq. (4.21), allows the integration of both economic and environmental factors into a unified cost-based objective function, thereby supporting more effective and interpretable decision-making.

$$\text{Minimize Cost}_{normalized} = TOC + (C_{TCE}TCE) + (C_{EP}EP) + PNF. \tag{4.21}$$

Subjected to the power balance, the limit constraints of each conversion device, and the pressure of the HS tank constraints in Eq. (4.4) – (4.11). The cost parameters presented in Table 4.2 have been standardized for consistency across objectives. The carbon cost rate was converted from THB per ton to THB per kilogram, while the peak demand charge was adjusted from a monthly rate to a daily rate by dividing by 30 days/month. These cost coefficients serve as weighting factors in the multi-objective optimization, representing the relative priority assigned to each objective function.

Table 4.2 The cost parameters each objective into monetary units (Provincial Electricity Authority, 2023; Reuters, 2025).

Objective	*Unit*	*Cost parameter*	*Value*	*Description*
TOC	THB	-	-	Already expressed in monetary units
TCE	$kgCO_2$	Carbon cost rate (C_{TCE})	0.2 THB/ $kgCO_2$	Cost of carbon emissions per $kgCO_2$
EP	kW	Peak demand charge (C_{EP})	7 THB/ kW/day	Cost associated with peak electricity demand

4.5 Simulation Results

4.5.1 FMOO-Based OMES-WSPHS Optimization for Each Objectives

To construct the FSMF, the optimal scheduling pattern of HS is determined using PSO, while the scheduling of electricity and NG is optimized using LP. For multi-objective considerations, a satisfaction function must be developed to facilitate the fuzzy decision-making process, ultimately leading to a balanced or compromise solution.

The first objective focuses on minimizing the TOC, as evaluated in Chapter 3, Section 3.4.2. Therefore, Case V, as part of the case study, examines OMES-WSPHS solution for TOC minimization. The decision variables, including the scheduled HS operation and electricity-NG operation, are defined as a pattern for TOC minimization as illustrated in Fig. 4.7.

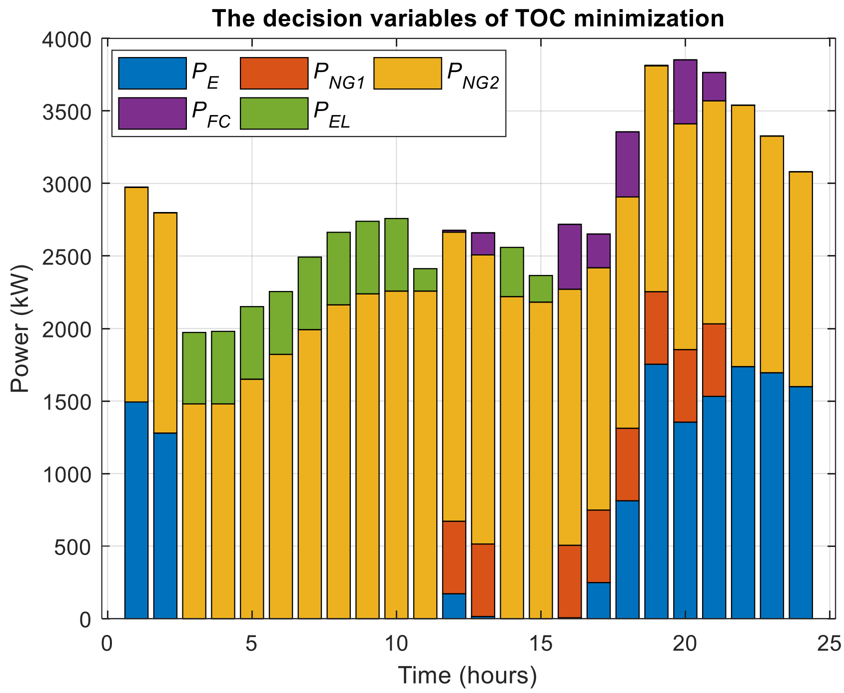
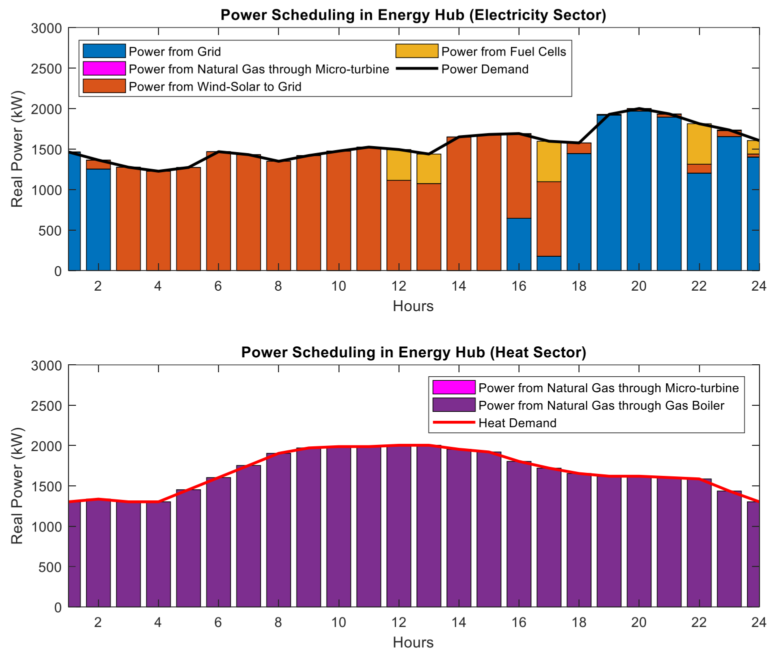
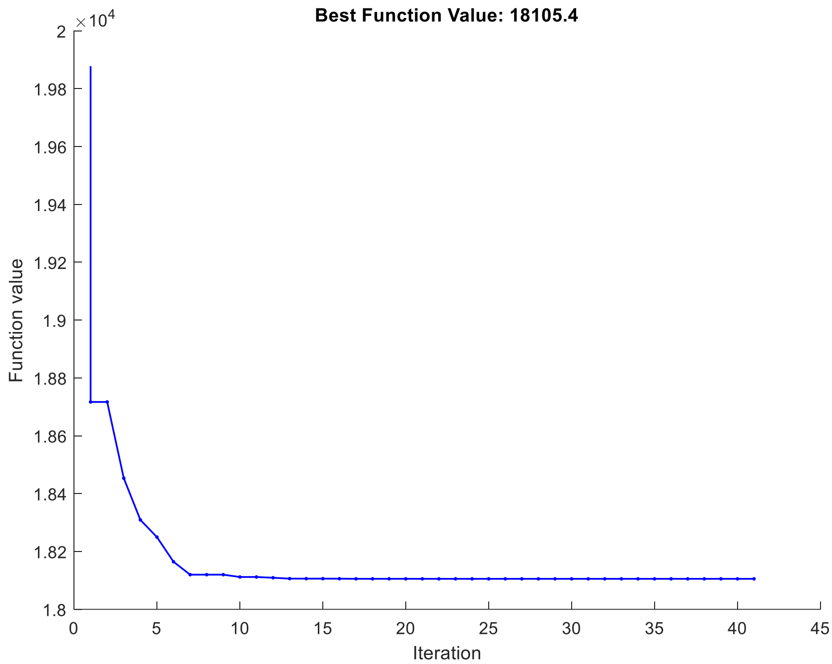


Figure 4.7 The decision variables of TOC minimization

The second objective focuses on minimizing TCE, as calculated in Eq. (4.12). The optimal solution of OMES-WSPHS for TCE minimization is illustrated in Fig. 4.8, where Fig. 4.8(a) presents the power scheduling obtained when considering TCE as the objective, and Fig. 4.8(b) shows the convergence of the solution under TCE minimization. To ensure the best and most reliable result, the optimization process for the second objective function is executed 30 trials, with the results shown in Fig. 4.8(c). Since the optimal solution for the second objective function has been determined, the decision variables scheduling pattern for TCE minimization can be illustrated in Fig. 4.9.

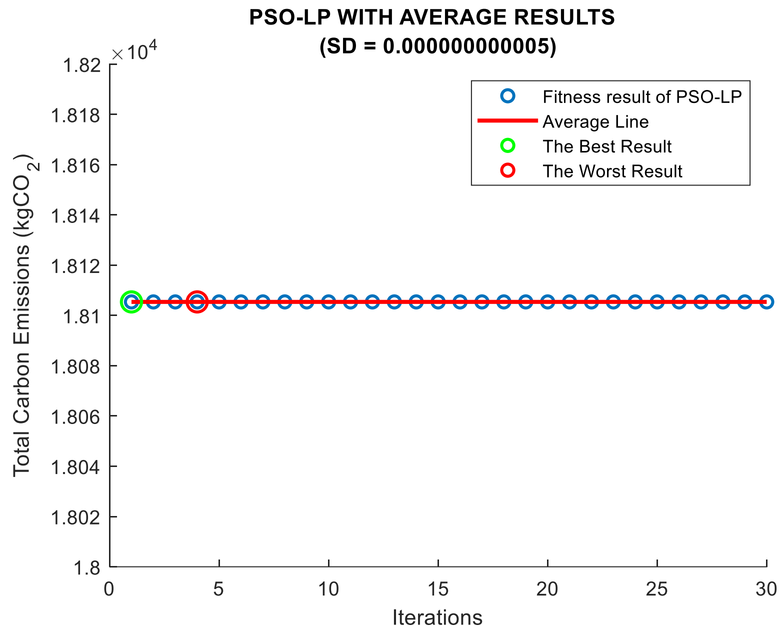


(a)



(b)

Figure 4.8 The optimal solution of OMES-WSPHS for TCE minimization (a) the power scheduling, (b) the convergence of the solution, and (c) The fitness results with 30 trials



(c)

Figure 4.8 The optimal solution of OMES-WSPHS for TCE minimization (a) the power scheduling, (b) the convergence of the solution, and (c) The fitness results with 30 trials (Continued)

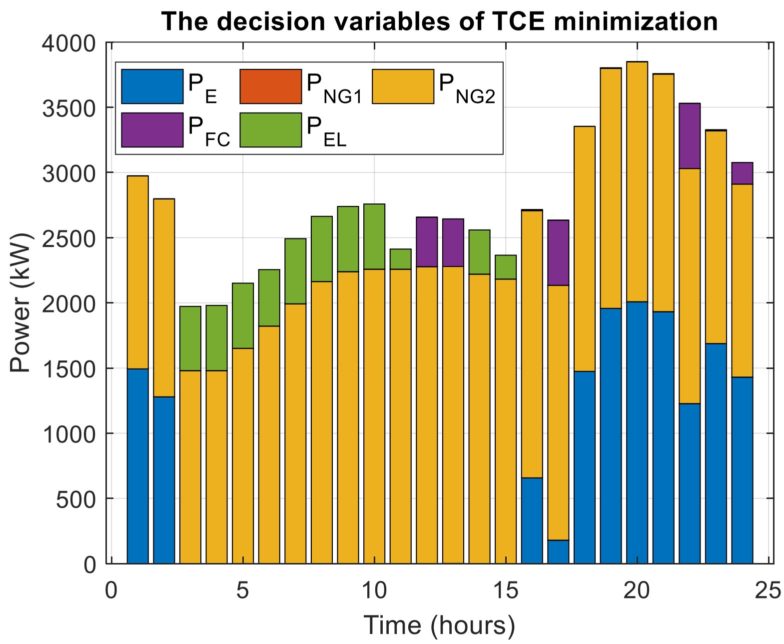
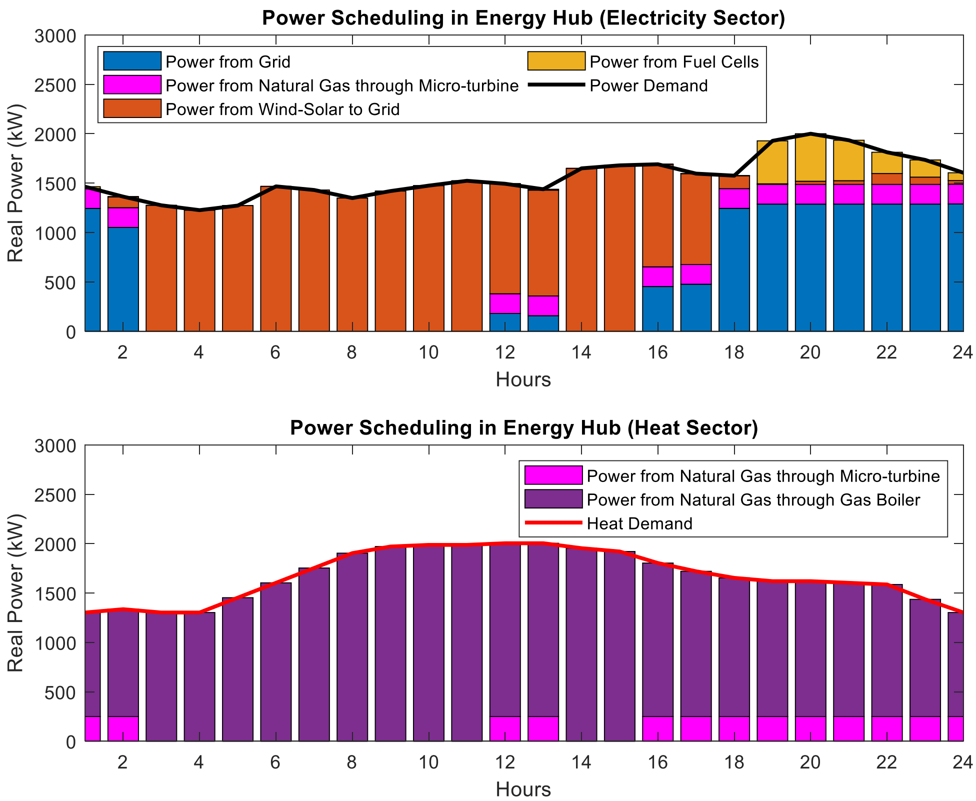


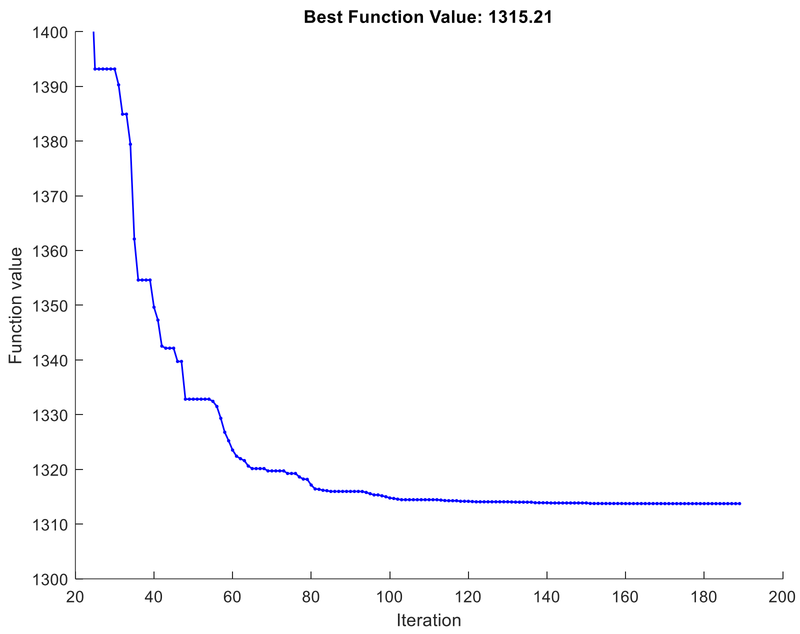
Figure 4.9 The decision variables of TCE minimization

The third objective focuses on minimizing EP, as calculated in Eq. (4.13). The optimal solution of OMES-WSPHS for EP minimization is illustrated in Fig. 4.10, where Fig. 4.10(a) presents the power scheduling when considering EP as the objective, and Fig. 4.10(b) shows the convergence of the solution under EP minimization. Similar to the second objective, the optimization process for the third objective function is executed 30 trials to ensure the best and most reliable results, with the results shown in Fig. 4.10(c). Once the optimal solution for EP minimization has been determined, the decision variables scheduling pattern for EP minimization can be illustrated in Fig. 4.11.



(a)

Figure 4.10 The optimal solution of OMES-WSPHS for EP minimization (a) the power scheduling, (b) the convergence of the solution, and (c) The fitness results with 30 trials



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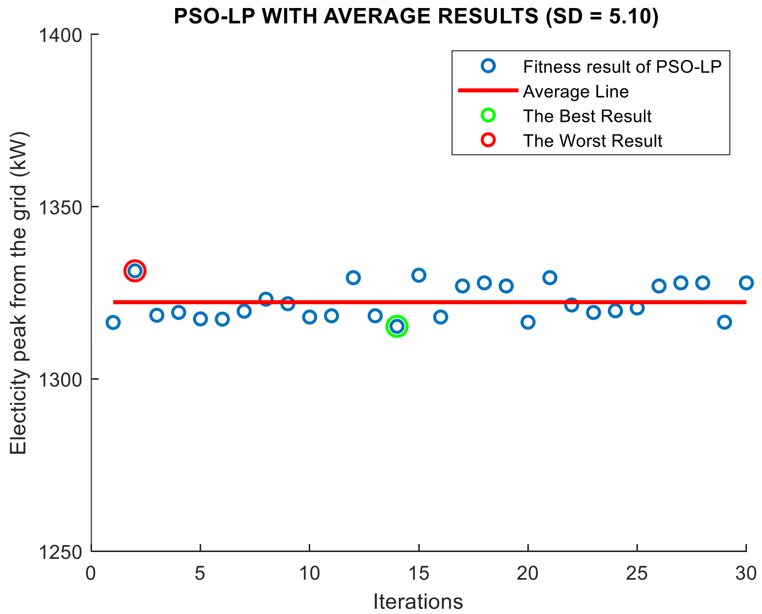


(c)

Figure 4.10 The optimal solution of OMES-WSPHS for EP minimization (a) the power scheduling, (b) the convergence of the solution, and (c) The fitness results with 30 trials (Continued)

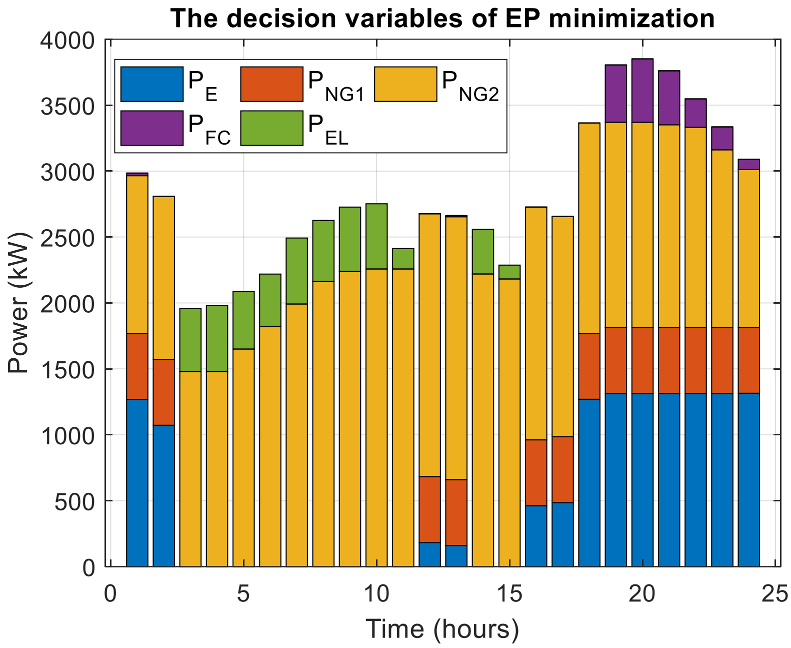


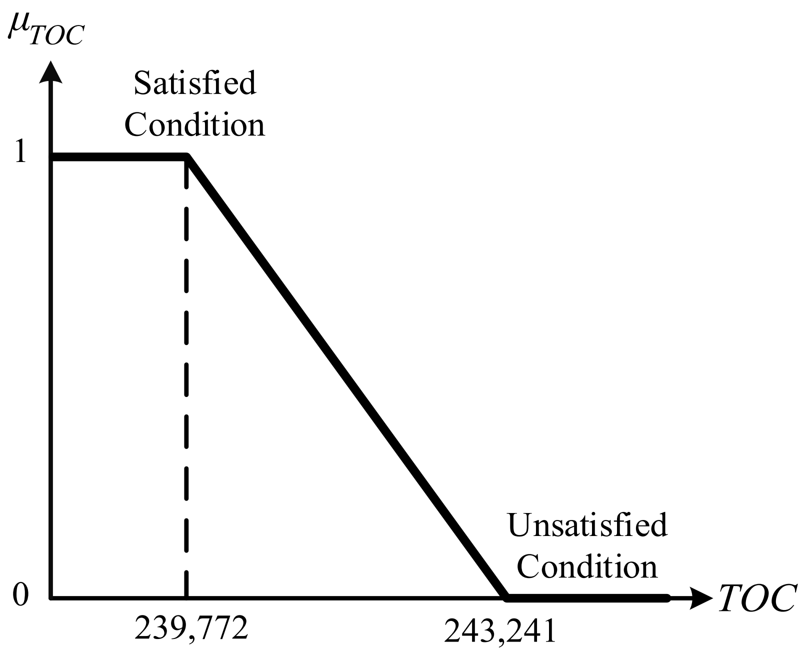
Figure 4.11 The decision variables of EP minimization

To effectively balance these objectives, FSMF is constructed to quantify the degree of satisfaction for each solution. This function assigns membership values between 0 and 1, representing the desirability of different scheduling patterns. By integrating this function into the decision-making framework, a compromise solution that considers all objectives can be achieved. The systematic approach involves optimizing each objective separately, normalizing the results for comparability, defining a fuzzy membership function for each objective follows the Eq. (4.18) – (4.20) respectively, and aggregating the satisfaction levels to determine an optimal scheduling pattern that balances TOC, TCE, and EP. This study defines the A scheduling pattern as the pattern for TOC minimization, the B scheduling pattern as the pattern for TCE minimization, and the C scheduling pattern as the pattern for EP minimization. By utilizing all three patterns to evaluate the objectives, the minimum and maximum values for each objective can be determined as shown in Table 4.3, which then allows for the creation of a FSMF to aid in the decision-making process. Each FSMF in is illustrated in 4.12 (a) TOC minimization, (b) TCE minimization, and (c) EP minimization.

Where the green highlight indicates the minimum value of each objective, while the orange highlight also represents the maximum value of each objective.

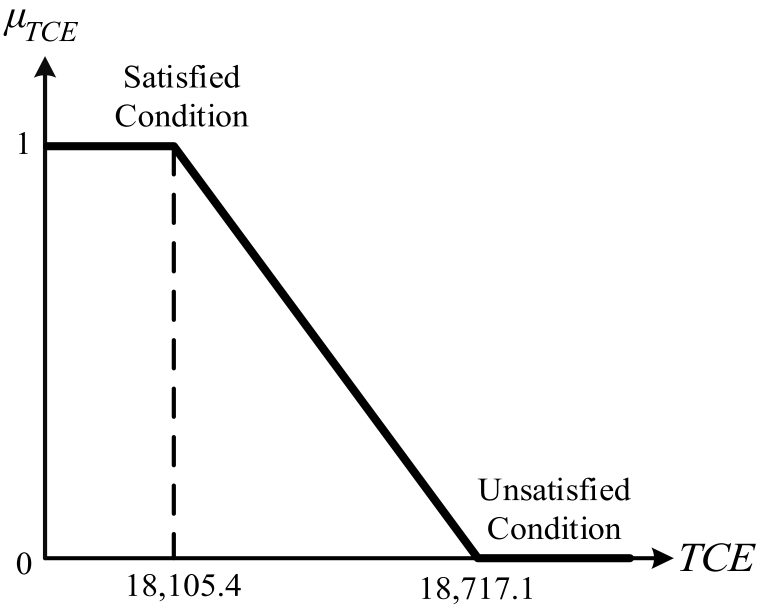
Table 4.3 The scheduling pattern for TOC, TCE, and EP

Objectives / *Pattern of Scheduling*	*TOC* (THB)	*TCE* ($kgCO_2$)	*EP* (kW)
A (min TOC as objective)	239,772	18,442.1	1,753.96
B (min TCE as objective)	242,935	18,105.4	2,008.61
C (min EP as objective)	243,241	18,717.1	1,315.21



(a)

Figure 4.12 Each FSMF (a) TOC minimization, (b) TCE minimization, and (c) EP minimization



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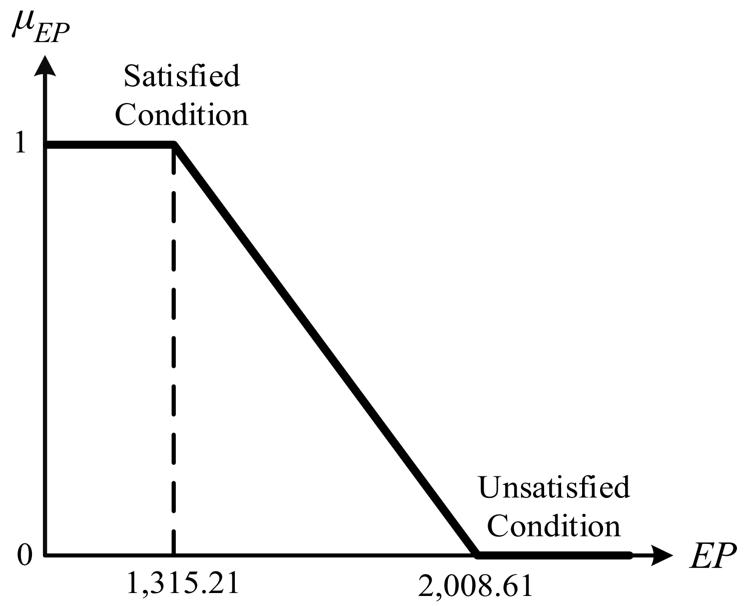


(c)

Figure 4.12 Each FSMF (a) TOC minimization, (b) TCE minimization, and (c) EP minimization (Continued)

4.5.2 FMOO-Based OMES-WSPHS Optimization for Total FSMF

According to Section 4.5.1, FSMF is individually defined for each objective. Consequently, the total FSMF represents overall satisfaction by capturing the maximum satisfaction among the minimum satisfaction levels of the three combined objective functions. The maximin principle is applied to maximize the minimum outcome among the three objectives, ensuring that the worst-case scenario is as favorable as possible. This approach guarantees a balanced and compromised solution that considers all objectives. By maximizing FSMF, the scheduling pattern of HS and the electricity-NG dispatch can be determined for the optimal compromise solution. The total FSMF solution is illustrated through the convergence plot in Fig. 4.13, while Fig. 4.14 presents the fitness total FSMF results over 30 trials.

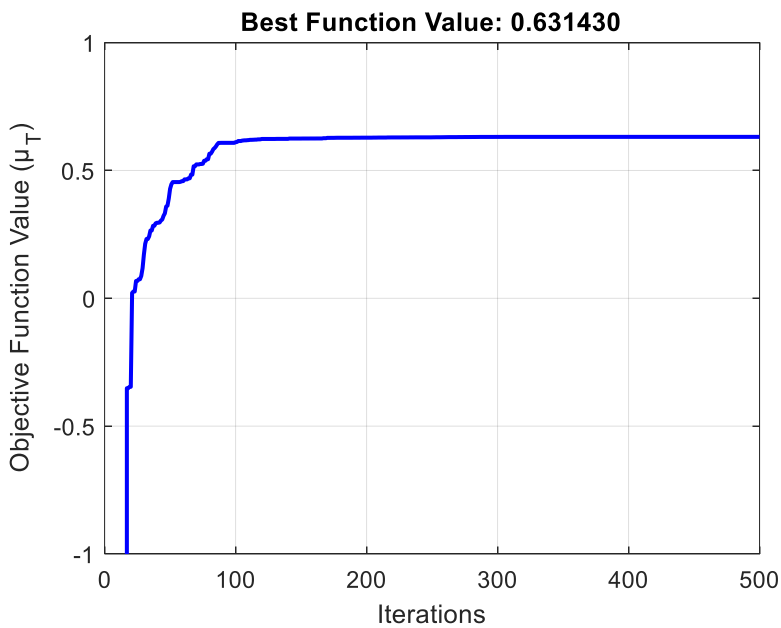


Figure 4.13 The convergence plot of the total FSMF solution

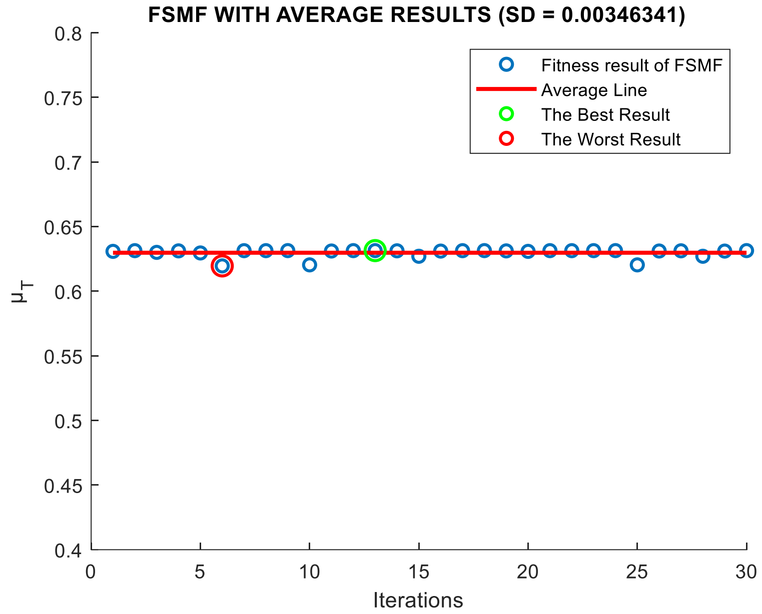
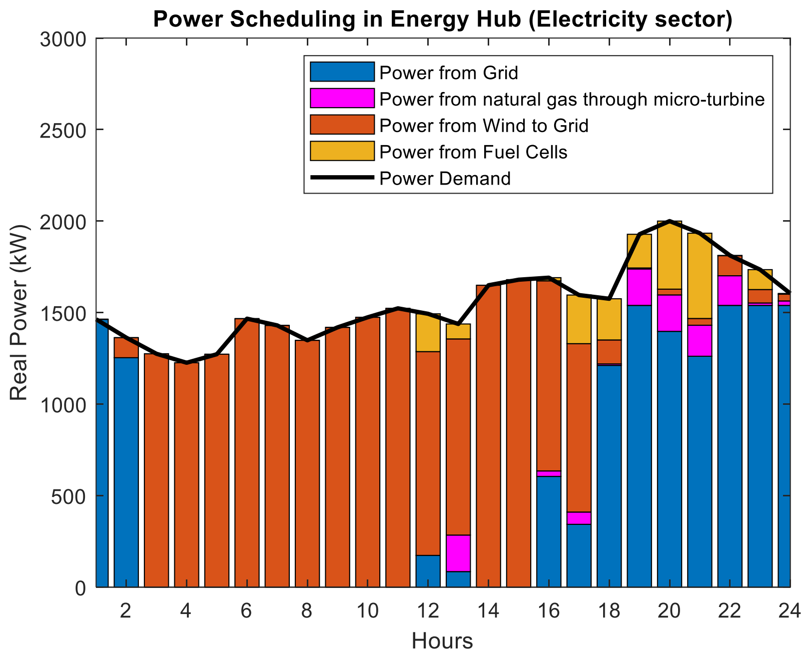


Figure 4.14 The fitness total FSMF results with 30 trials

For this proposed procedure, Fig. 4.15 illustrates the power scheduling for each energy sector which (a) electricity and (b) heat, ensuring a balanced trade-off among multiple objectives. In the electricity sector (Fig. 4.15 (a)), the microturbine operates mainly during 12:00–2:00 p.m. and 6:00–10:00 p.m., with fuel cells contributing intermittently in the same periods. In the heat sector (Fig. 4.15 (b)), heat demand is primarily met by a gas boiler, while the microturbine provides additional heat during 12:00–2:00 p.m. and 6:00–10:00 p.m. The HS scheduling and state of the tank can be demonstrated in Fig. 4.16 (a) and (b), respectively. For each objective function, the best and worst values are determined based on the optimization goal. For FSMF, the best value is the maximum, as a higher fuzzy satisfaction level indicates a more optimal solution, while the worst value is the minimum. Conversely, for TOC, TCE, and EP, the best values correspond to the minimum, as reducing total operating costs, total carbon emissions, and electricity peaks is desirable. In contrast, the worst values for these objectives are the maximum, as they represent higher costs, emissions, and peak loads, which are less favorable. These results highlight the trade-offs between different objectives in MES-WSPHS optimal scheduling. Table 4.4 contains the results which show average value, best value, and worst value of FSMF, TOC, TCE, and EP.

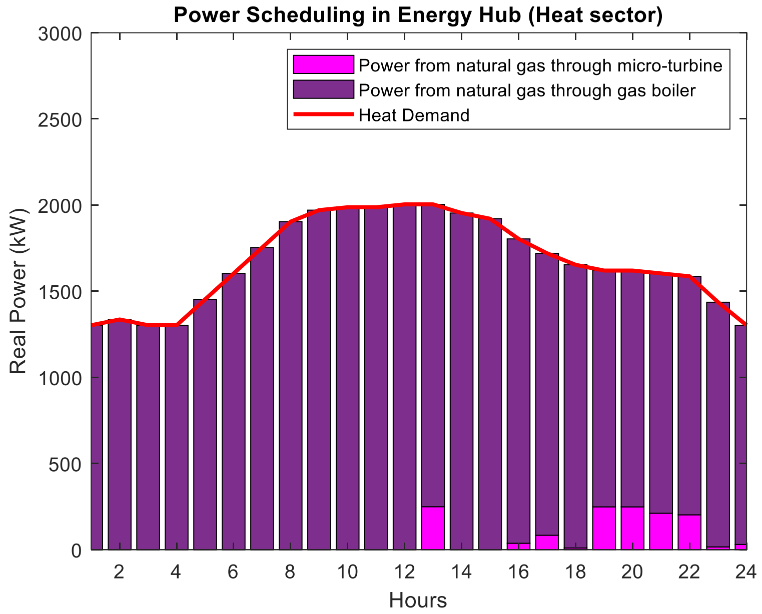
Table 4.4 The results of statistics data for FSMF, TOC, TCE, and EP.

	BEST	AVERAGE	WORST
TOC	241,049.03	241,114.21	242,508.97
TCE	18,317.69	18,331.56	18,358.05
EP	1,570.8	1,579.3	1,731.5
μ_T	0.6314	0.6298	0.6196



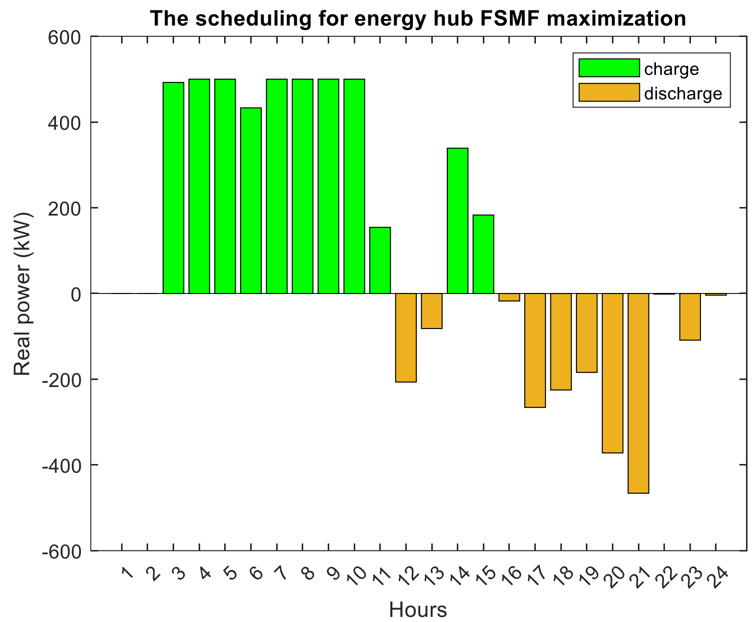
(a)

Figure 4.15 The total FSMF maximization for the power scheduling (a) electricity and (b) heat



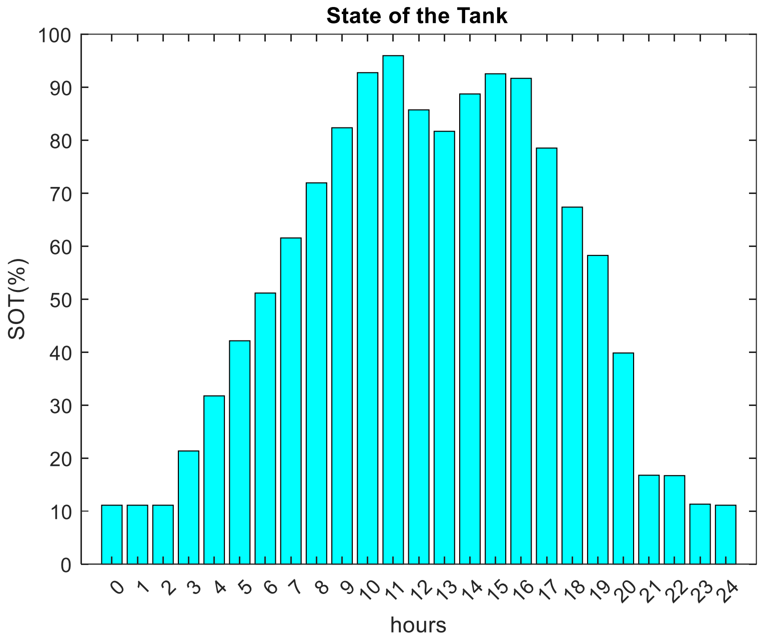
(b)

Figure 4.15 The total FSMF maximization for the power scheduling (a) electricity and (b) heat (Continued)



(a)

Figure 4.16 The total FSMF maximization for (a) The HS scheduling and (b) state of the tank

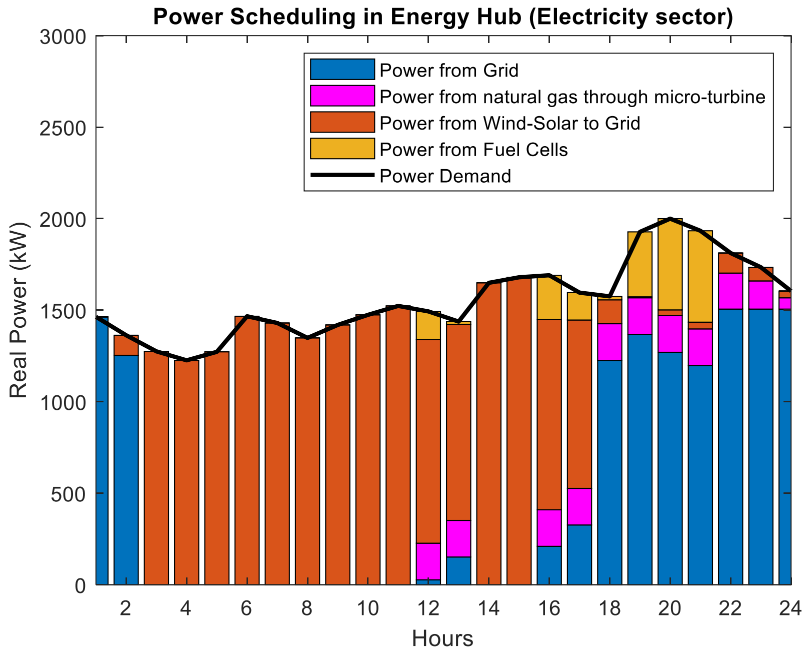


(b)

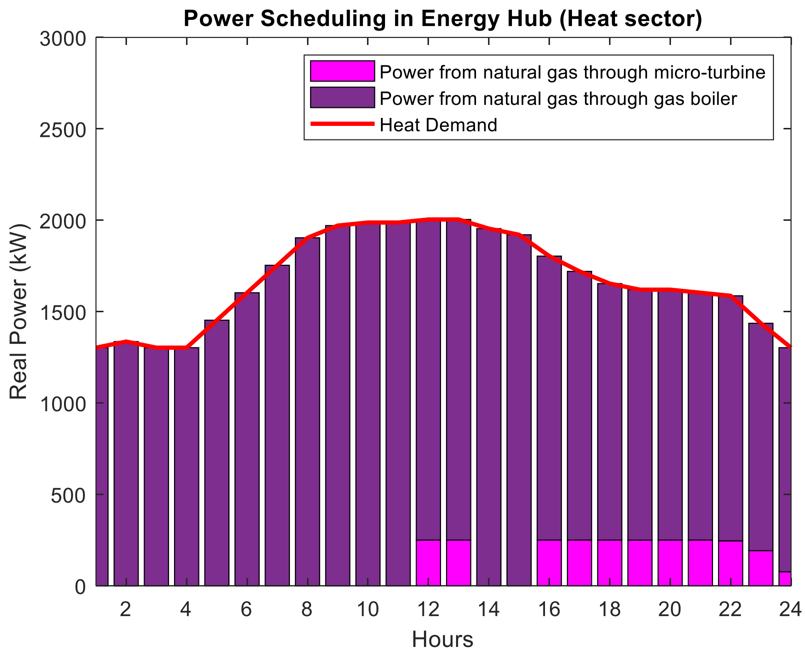
Figure 4.16 The total FSMF maximization for (a) The HS scheduling and (b) state of the tank (Continued)

4.5.3 WSMO vs. FMOO Optimization in OMES-WSPHS

This section demonstrates the effectiveness of the WSMO method in identifying alternative solutions for the multi-objective optimization problem. Unlike the FMOO approach, WSMO provides a more straightforward mechanism by allowing decision-makers to assign weights to each objective based on their relative importance. To ensure that can consider all objectives with different units, normalization is required. Accordingly, in this study, all objectives are converted into cost-equivalent units, as described in Eq. (4.21). The performance of WSMO is illustrated in Fig. 4.17, which shows the power scheduling across each energy sector while maintaining the power balance constraint. Complementing this, Fig. 4.18 presents the scheduling of HS along with the corresponding SOT. Additionally, Fig. 4.19 displays the convergence behavior of the WSMO algorithm, further confirming the stability of the obtained results.

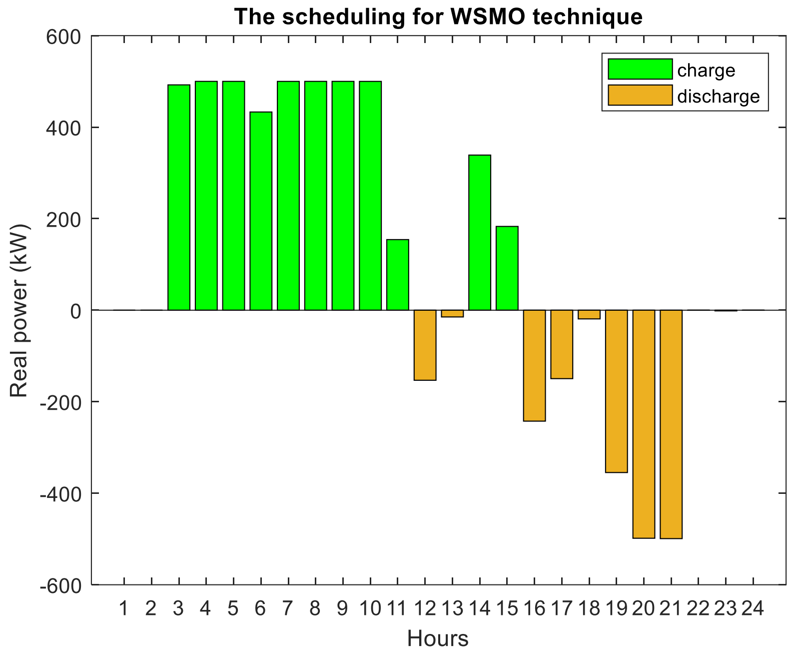


(a)

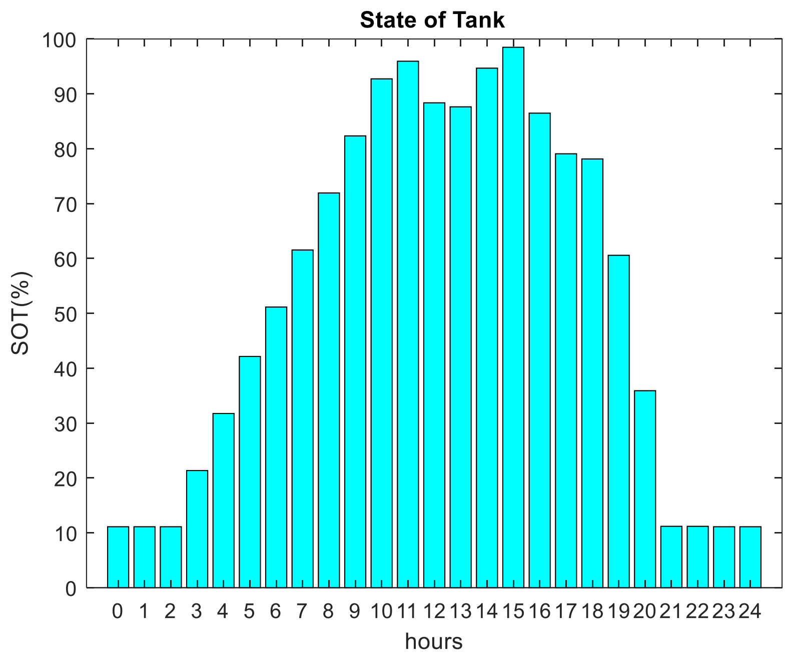


(b)

Figure 4.17 The WSMO performance for (a) electricity sector (b) heat sector



(a)



(b)

Figure 4.18 The WSMO performance for (a) The HS scheduling and (b) SOT

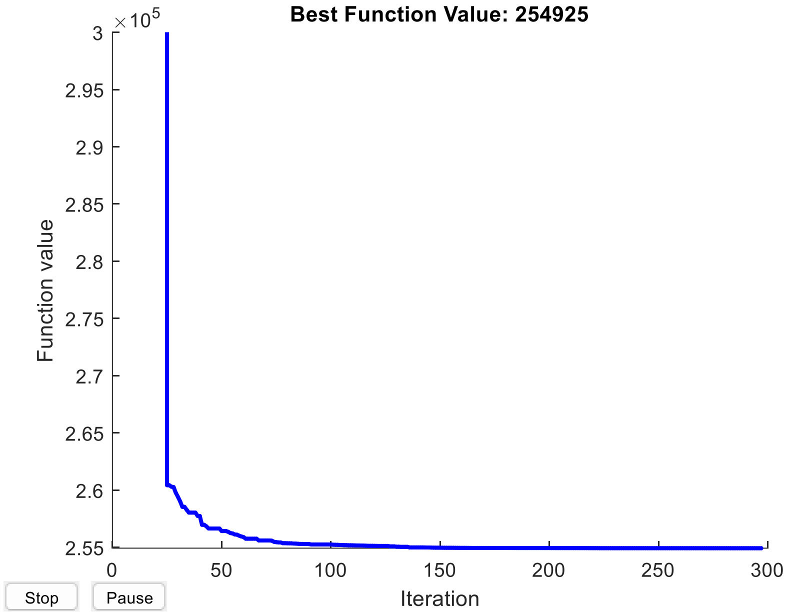


Figure 4.19 The convergence plot for WSMO technique

Table 4.5 A summary of the improvements achieved between WSMO and FMOO

Method	Objective functions		
	TOC	TCE	EP
WSMO	240,467.46	18,528	1,536.9
FMOO	241,049.03	18,317.69	1,570.8
Percentage Difference (%)	0.24%	1.13%	2.2%

Within the OMES-WSPHS framework, WSMO successfully generates a set of compromise solutions. However, when compared to FMOO, the FMOO approach proposes enhanced outcomes in certain objectives due to its ability to better balance competing trade-offs through fuzzy decision-making. Therefore, although WSMO achieves slightly better results in terms of TOC and EP, FMOO offers a more balanced compromise by significantly reducing carbon emissions while only slightly increasing cost and peak load. This highlights FMOO's superior capacity for handling trade-offs in multi-objective scheduling problems under the OMES-WSPHS framework. A summary of the improvements achieved by each method is provided in Table 4.5.

4.6 Chapter Summary

This chapter introduced the FMOO framework for the OMES-WSPHS, considering three key objectives including TOC, TCE, and EP minimization. The optimization process for single objective is conducted using a PSO-LP approach, and the FMOO technique is employed to evaluate trade-offs among competing objectives. The simulation results demonstrated that the proposed methodology effectively balances cost, environmental impact, and peak energy from grid generation. By constructing FSMF for each objective, a systematic decision-making approach is implemented to determine an optimal scheduling pattern that maximizes overall system performance. The findings highlight the effectiveness of fuzzy optimization in handling multi-objective problems within energy systems, ensuring an optimal compromise solution that enhances system efficiency and sustainability. Compared to the WSMO method, the FMOO approach provides more balanced and adaptable solutions by eliminating the bias introduced by predefined weighting factors. Instead, it evaluates the relative satisfaction levels of each objective, enabling the system to operate in a more compromise-oriented and practical manner, particularly under conflicting operational conditions. The results indicate that FMOO achieves a superior balance across all objectives. While TOC and EP exhibit slight increases, these changes occur as a trade-off to significantly reduce the conflicting objective—TCE. Therefore, from the perspective of multi-objective compromise, FMOO demonstrates a more effective and harmonious performance.