Game-theoretic scheduling in integrated energy system considering energy flexibility from consumers

Xin Li

2023.08

MENUE

Section 1

Introduction

1.1 Overview

Community Energy Management

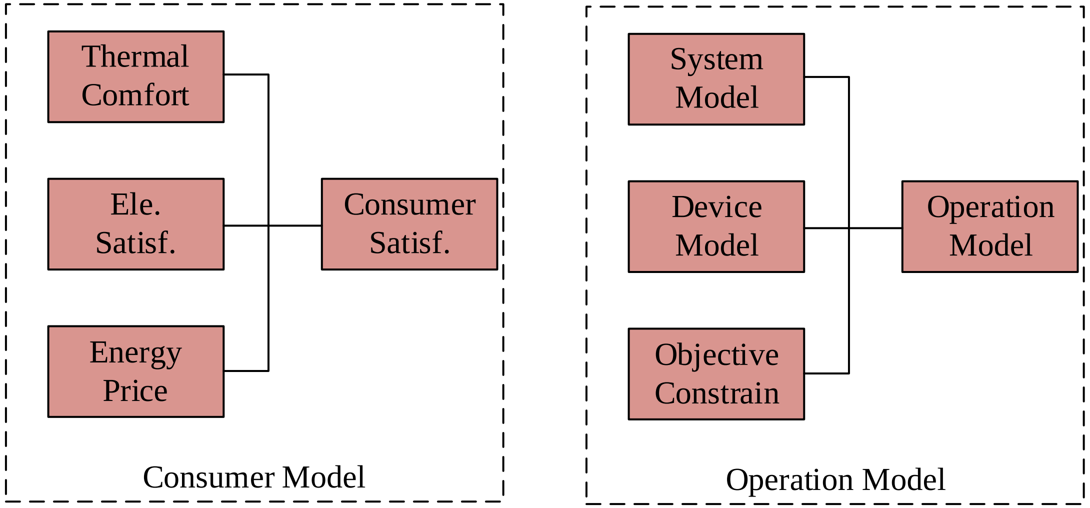
Consumer Comfort

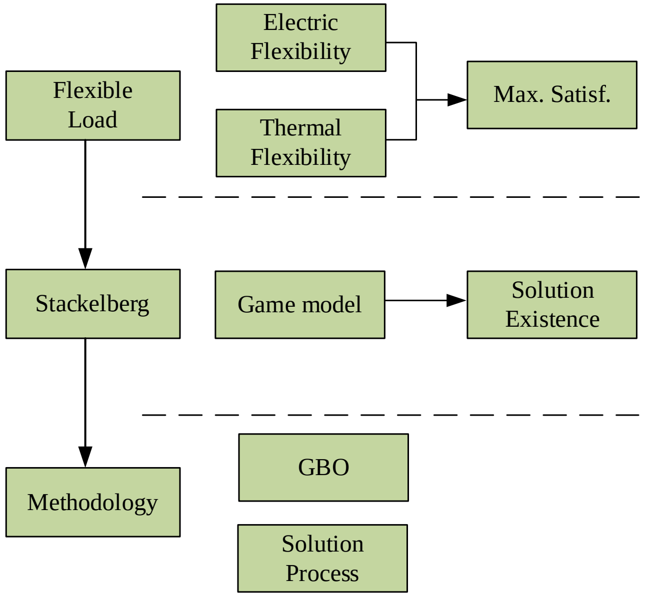
IES Operator

Energy Operation & Flexible Dispatch

Supply & Tariff

Game-theoretic





1.2 Background & Inspiration

- Increasing Energy Demand
  Carbon Reduction Request
  Renewable Energy Penetration
- Integrated Energy Community

- Prosumer Operator
- Economic Revenue
- Energy Supply Tariff

- Energy Management
- Demand Response
- Consumer Comfort

- Game-theoretic Structure
- Flexible Load Scheduling

1.3 Contribution

Consumer satisfaction formulation based on comfort and tariff

Consumer flexible load scheduling model considering comfort and satisfaction

Mechanism designing for distributing the mitigated cost

Comfort modelling formulation based on
Activity, metabolism, temperature

Demand response to optimize the energy operation

System operator –lower cost
Consumer –lower tariff with good comfort

Section2

Consumer Modelling and IES Modelling

2.1 Satisfaction Model and Consumer Model

PMV

$$PMV = (0.303e^{-0.036M} + 0.028)\cdot[(M-W)-E_s-E_b-C_b-H]$$

$$E_s = -3.05\cdot10^{-3}\cdot[5773-6.99\cdot(M-W)-p_a]$$

$$E_b = 1.7\cdot10^{-5}M\cdot(5876-p_a)$$

$$C_b = 0.0014\cdot M(34-t_a)$$

$$H = 3.96\cdot10^{-8}\cdot f_{cl}\cdot[(t_{cl}+273)^4-(t_r+273)^4]-f_{cl}h_c(t_{cl}-t_a)$$

Exist PMV-temperature

$$PMV_{i,t} = a_1\cdot T_{i,t}^{in} + b_1, t\in[T^c, T^d]$$

Thermal Comfort(PTS)

$$T_{i,t+1}^{in} = T_{i,t}^{in} - \frac{\Delta T}{C\cdot R}\cdot[T_{i,t}^{in} - T_{i,t}^{out} - \frac{1.75}{Q^{\max}}u_{i,Q}(t)\cdot R\cdot Q_{i,t} + \frac{1.75}{H^{\max}}u_{i,H}(t)\cdot R\cdot H_{i,t}]$$

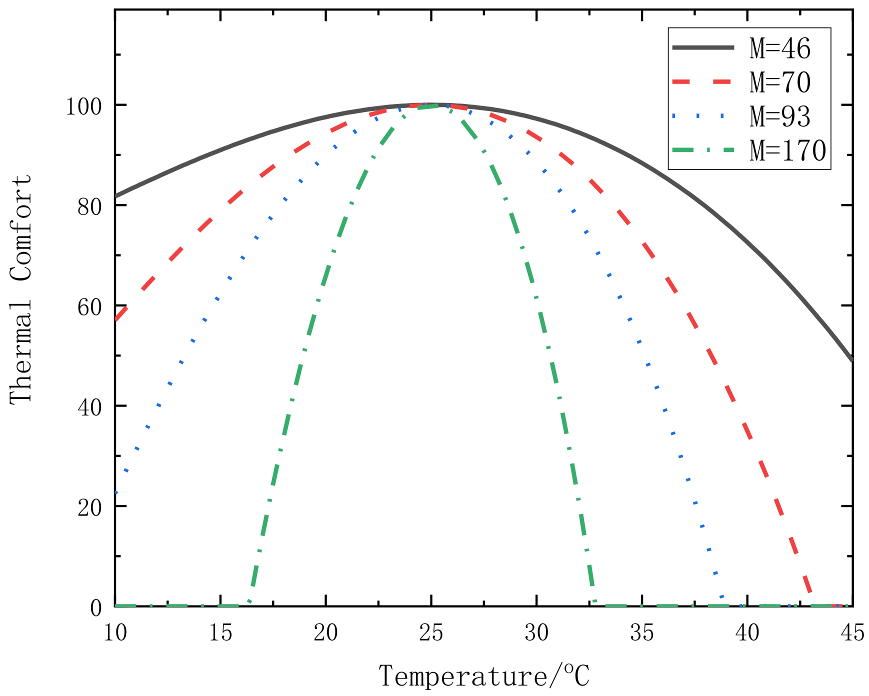
$$PPD(PMV_{i,t})_{i,t} = 100-95\times\exp[-(0.003353\times PMV_{i,t}^4 + 0.2179\times PMV_{i,t}^2)]$$

$$PTS_{i,t} = 1-PPD_{i,t}/100$$

Formulate PTS-temperature

Activity	$M(\mathrm{W/m^2})$
Sleeping	46
Sedentary	70
Shopping	93
Work	170
Walk	200

Different comfort under different temperature and metabolism M



2.1 Satisfaction Model and Consumer Model

Piecewise linearization

PMV-PTS

$$b_1 \le b_2 \le \ldots \le b_n \le b_{n+1}$$

$$b_1 = PMV_{\min}, b_k = PMV_{\min} + k \cdot \frac{PMV_{\max} - PMV_{\min}}{n}, b_{n+1} = PMV_{\max}, k = 2, \ldots, n$$

$$PMV_{i,t} = \sum_{k=1}^{n+1} b_k \cdot \gamma_{i,t,k}$$

$$PTS_{i,t}^{linear} = \sum_{k=1}^{n+1} [PTS(b_k)_{i,t} \cdot \gamma_{i,t,k}]$$

$$s.t. \begin{cases} \gamma_{i,t,1} \le \kappa_{i,t,1}, \gamma_{i,t,n+1} \le \kappa_{i,t,n+1}, \gamma_{i,t,k} \le \sum_{j=k-1}^{k} \kappa_{i,t,j}, k = 2 \ldots n \\ \sum_{k=1}^{n} \gamma_{i,t,k} = 1 \\ \sum_{k=1}^{n} \kappa_{i,t,k} = 1 \end{cases}$$

Consumer Objective

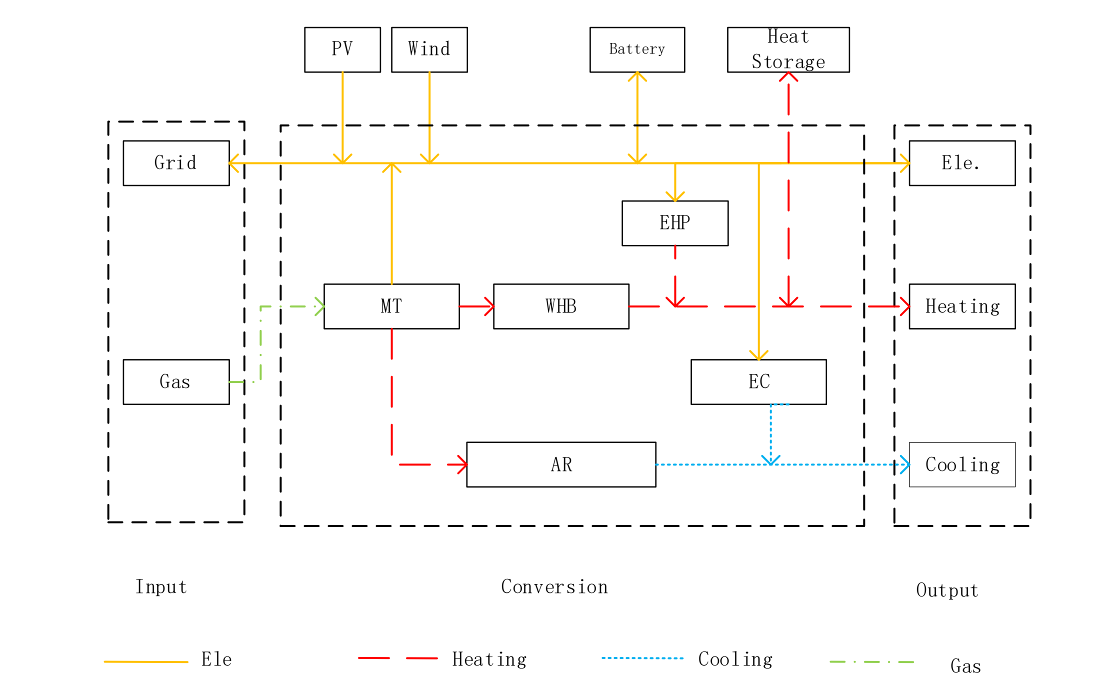
Satisfaction per cost = (**Ele. satisfaction** × **Thermal Comfort**) / (**Ele. cost** × **Thermal Cost**)

Ele. satisfaction

$$PES_{i,t} = P_{i,t}^{E} / E_{i,t}$$

2.2 IES Operation Model

IES Structure



CCHP

Micro Turbine

$$P_{i,s,t}^{\mathrm{MT}} = \frac{\eta_{i,s,t}^{\mathrm{MT}} C_{i,s,t}^{\mathrm{MT}}}{R_{\mathrm{gas}}} \cdot LH$$

Absorption Refrigeration

$$Q_{i,s,t}^{\mathrm{AR}} = \frac{P_{\mathrm{MT}}(t)}{\eta_{i,s,t}^{\mathrm{MT}}} \cdot \xi_{i,s,t}^{\mathrm{AR}} (1-\eta_{i,s,t}^{\mathrm{MT}} - \eta_l) \cdot COP_{i,s,t}^{\mathrm{AR}}$$

Waste Heat Boiler

$$H_{i,s,t}^{\mathrm{WHB}} = \frac{P_{\mathrm{MT}}(t)}{\eta_{i,s,t}^{\mathrm{MT}}} \cdot \xi_{i,s,t}^{\mathrm{WHB}} (1-\eta_{i,s,t}^{\mathrm{MT}} - \eta_l) \cdot COP_{i,s,t}^{\mathrm{WHB}}$$

Heat Pump

Cooling

$$Q_{i,s,t}^{\mathrm{EC}} = P_{i,s,t}^{\mathrm{EC}} \cdot COP_{i,s,t}^{\mathrm{EC}}$$

Heating

$$H_{i,s,t}^{\mathrm{EHP}} = P_{i,s,t}^{\mathrm{EHP}} \cdot COP_{i,s,t}^{\mathrm{EHP}}$$

Storage

Battery

$$E_{i,s,t}^{ba} = E_{i,s,t_0}^{ba} + \eta_{i,s,t}^{ba\_in} E_{i,s,t}^{ba\_in} - \eta_{i,s,t}^{ba\_out} E_{i,s,t}^{ba\_out}$$

Heat Storage

$$H_{i,s,t}^{hs} = H_{i,s,t_0}^{hs} + \eta_{i,s,t}^{hs\_in} E_{i,s,t}^{hs\_in} - \eta_{i,s,t}^{hs\_out} E_{i,s,t}^{hs\_out}$$

DER

PV

$$P_{i,s,t}^{\mathrm{pv}} = A_{i,s,t}^{\mathrm{pv}} \times \eta_{s,t}^{\mathrm{pv}} \times SRI_{s,t}$$

Wind turbine

$$P_{i,s,t}^{\mathrm{wt}} = \begin{cases} 0 & v_{i,s,t} < v_{ci} \\ k_1 v_{i,s,t} + k_2 & v_{ci} < v_{i,s,t} < v_r \\ P_r & v_{i,s,t} > v_r \end{cases}$$

2.2 IES Operation Model

Objective

revenue = Consumer Cost − Operation Cost

$$\max F=\sum_t[RE_t-C_t^{fd}-C_t^{wh}]$$

$$RE_t=CE_{jm,t}+CT_{jm,t}+CE_{gy,t}+CT_{gy,t}+CE_{sy,t}+CT_{sy,t}$$

$$C_t^{fd}=C_{i,s,t}^{\mathrm{MT}}+P_{i,s,t}^{gr}\cdot G_t^{gr}$$

$$C_t^{wh}=\sum\theta_{i,s,t}^{\varphi}\cdot P_{i,s,t}^{\varphi},\varphi=MT,AR,WHB,EHP,wt,pv,ba,hs$$

Constraints

Energy Balance

$$\sum_i P_{i,t}^{E}=\sum_i P_{i,s,t}^{\mathrm{MT}}-\sum_i P_{i,s,t}^{\mathrm{EHP}}-\sum_i P_{i,s,t}^{\mathrm{EC}}+\sum_i P_{i,s,t}^{\mathrm{wt}}+\sum_i P_{i,s,t}^{\mathrm{pv}}+\sum_i E_{i,s,t}^{ba\_out}-\sum_i E_{i,s,t}^{ba\_in}+\sum_i P_{i,s,t}^{gr}$$

$$\sum_i H_{i,t}=\sum_i H_{i,s,t}^{\mathrm{WHB}}+\sum_i H_{i,s,t}^{\mathrm{EHP}}+\sum_i E_{i,s,t}^{hs\_out}-\sum_i E_{i,s,t}^{hs\_in}$$

$$\sum_i Q_{i,t}=\sum_i Q_{i,s,t}^{\mathrm{AR}}+\sum_i Q_{i,s,t}^{\mathrm{EC}}$$

Device Constraints

$$P_{\min}^{\varphi}\le P_{i,s,t}^{\varphi}\le P_{\max}^{\varphi},\varphi=MT,AR,WHB,EHP,wt,pv,ba,hs$$

Section3

Game-theoretic Scheduling Model

3.1 Flexible Load

Initial Satisfaction Function

$$SA_{i,t}^{0} = \frac{PES_{i,t}^{0}}{CE_{i,t}^{0}} \cdot \frac{PTS_{i,t}^{0}}{CT_{i,t}^{0}}$$

Thermal Flexible Load

Satisfaction/cost

Thermal Comfort

Thermal Cost

$$\begin{cases} SA_{i,t}^{'} = \frac{PES_{i,t}}{CE_{i,t}} \cdot \frac{PTS_{i,t}^{'}}{CT_{i,t}^{'}} \\ SA_{i,t}^{'} \geq SA_{i,t}^{0} \\ PTS_{i,t}^{'} < PTS_{i,t}^{0} \\ CT_{i,t}^{'} < CT_{i,t}^{0} \end{cases}$$

Ele. Flexible Load

Satisfaction/cost

Ele. Comfort

Ele. Cost

$$\begin{cases} SA_{i,t}^{''} = \frac{PES_{i,t}^{''}}{CE_{i,t}^{''}} \cdot \frac{PTS_{i,t}^{0}}{CT_{i,t}^{0}} \\ SA_{i,t}^{''} \geq SA_{i,t}^{0} \\ PES_{i,t}^{''} < PES_{i,t}^{0} \\ CE_{i,t}^{''} < CE_{i,t}^{0} \end{cases}$$

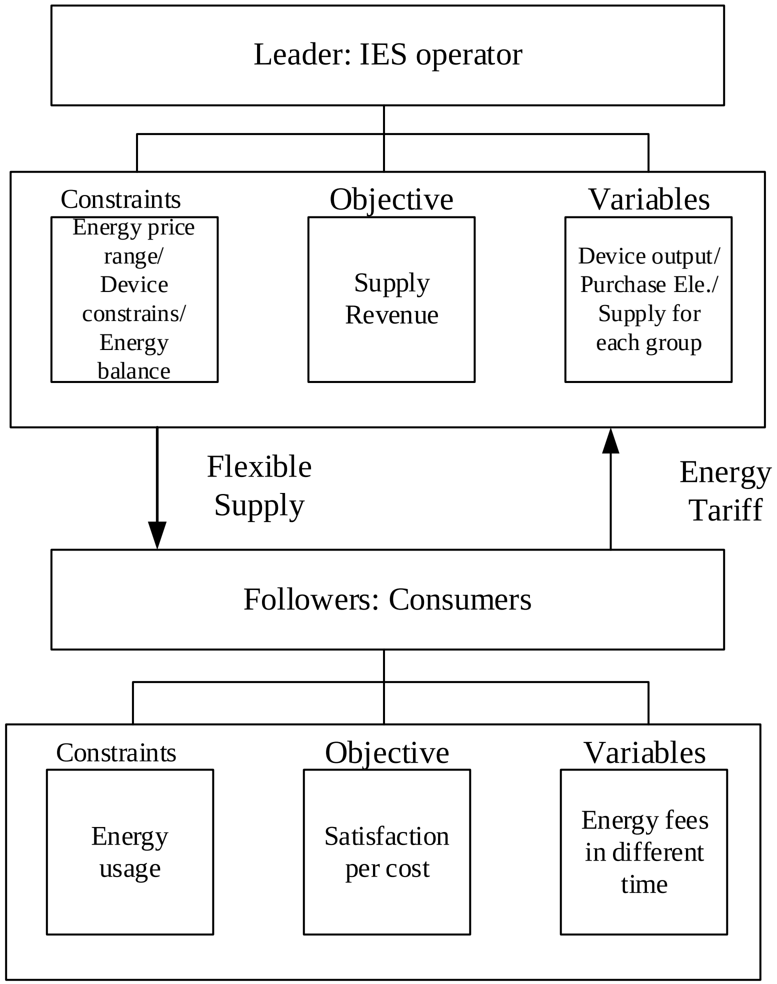
3.2 Game Model

Stackelberg

$$\begin{cases} \min F(x,\bar{y}) \\ s.t.\ \ G(x,\bar{y}) \le 0 \\ H(x,\bar{y}) = 0 \\ \bar{y} \in S(x) \end{cases} \quad leader$$

$$\begin{cases} \bar{y}^i = arg\ \min f_i(x, y^i, y^{-i}) \\ s.t.\ \ g_i(x, y^i) \le 0 \\ h_i(x, y^i) = 0 \end{cases} \qquad follower : \forall i$$

Structure



Equilibrium

$$G = \begin{Bmatrix} \{IER \cup users\}; \\ \{\rho_{IER}\}; \{C_{users}\}; \\ F; SA_{users} \end{Bmatrix}$$

$$users = \{user\_jm \cup user\_gy \cup user\_sy\}$$

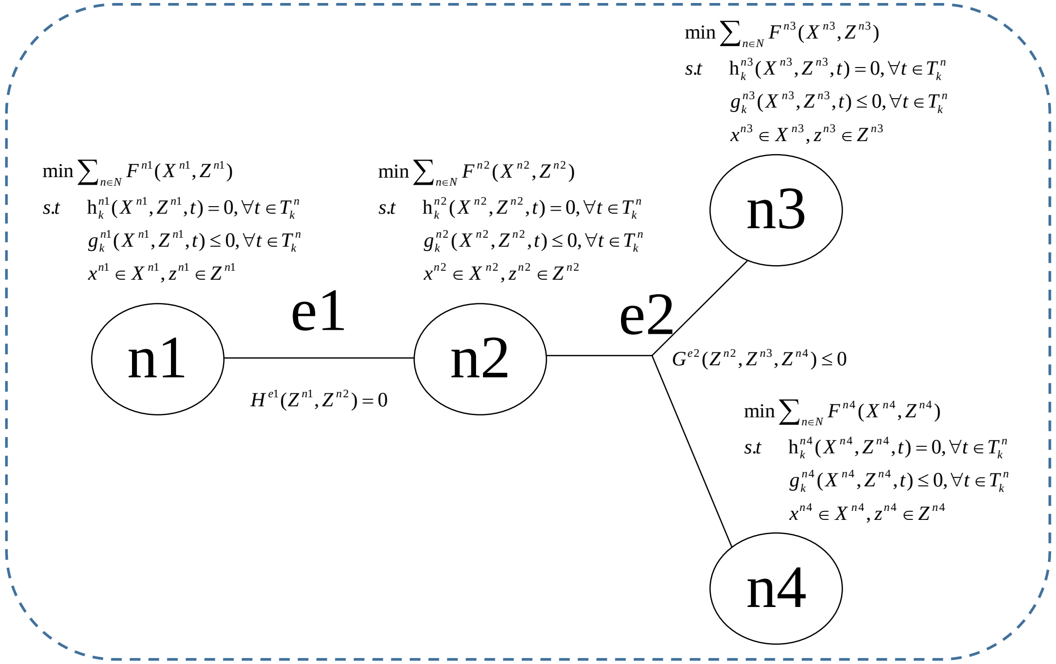
$$SA_{users} = \{SA_{jm}, SA_{sy}, SA_{gy}\}$$

$$\begin{cases} F(\rho_{IES}{}^{*}, C_{users}{}^{*}) \ge F(\rho_{IES}, C_{users}) \\ SA_{users}(\rho_{IES}{}^{*}, C_{users}{}^{*}) \ge SA_{users}(\rho_{IES}, C_{users}) \end{cases}$$

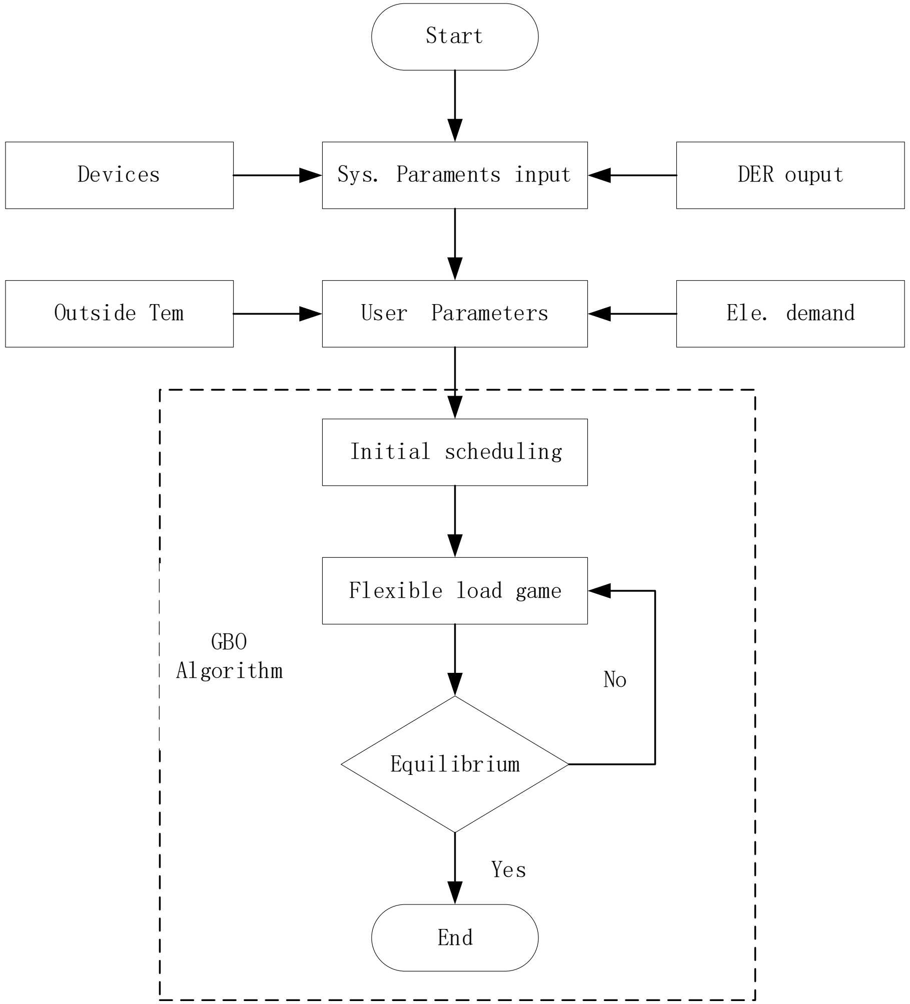
3.3 Algorithm and Process

GBO

$$
\begin{aligned}
\min & \sum\nolimits_{n\in N} F^{n}(X^{n},Z^{n}) \\
s.t \quad & \mathrm{h}_{k}^{n}(X^{n},Z^{n},t)=0,\forall t\in T_{k}^{n} \\
& g_{k}^{n}(X^{n},Z^{n},t)\le 0,\forall t\in T_{k}^{n} \\
& H^{e}(Z^{e})=0,\forall e\in \varepsilon \\
& G^{e}(Z^{e})\le 0,\forall e\in \varepsilon \\
& x^{n}\in X^{n},z^{n}\in Z^{n},\forall n\in N
\end{aligned}
$$



Process

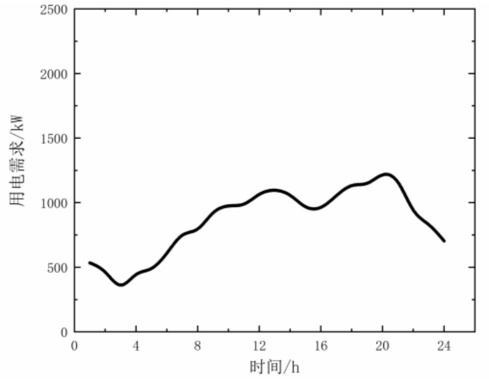


Section4

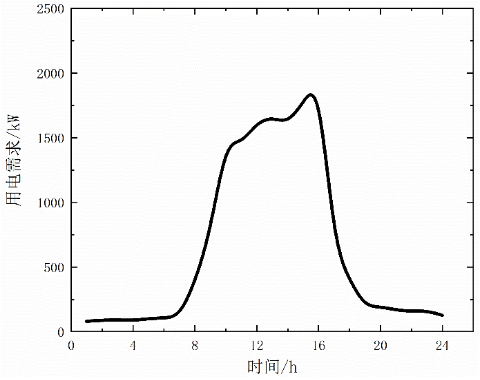
Case Study

4.1 System Parameters

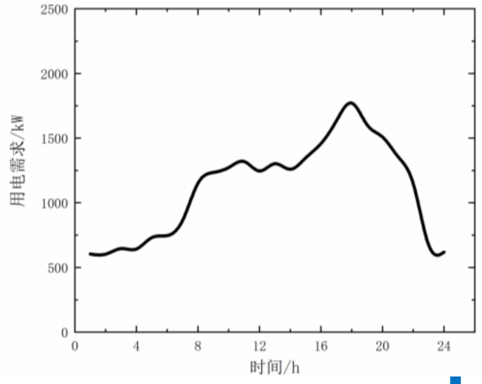
Electricity Demand



Residential



Industrial

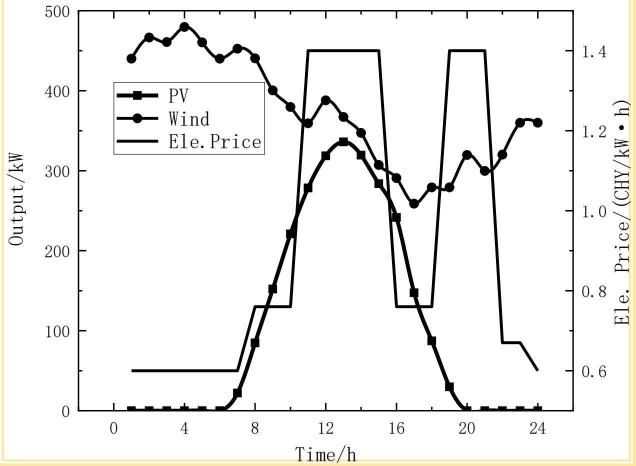


Commercial

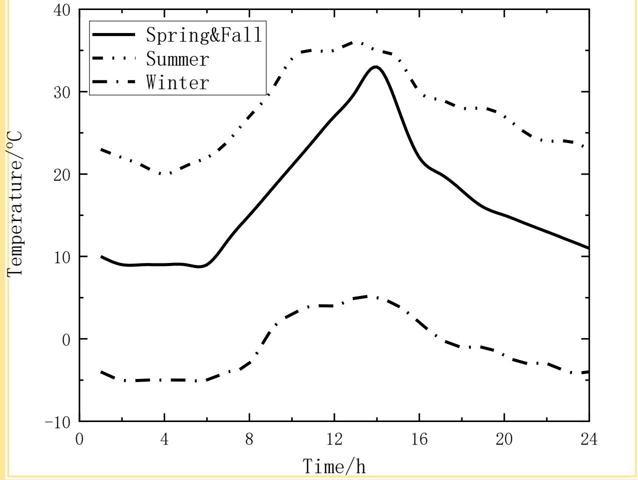
Device Parameters

Device	capacity(kW)	maintenance(CHY/kW)	Efficiency
MT	5000	0.03	0.73
EHP	1500	0.02	2
AR	2000	0.015	2.5
EC	2000	0.015	2.5
WHB	1000	0.02	1.5
Battery	3000	0.01	0.95
HS	4000	0.005	0.98

PV&WT&Ele. Price

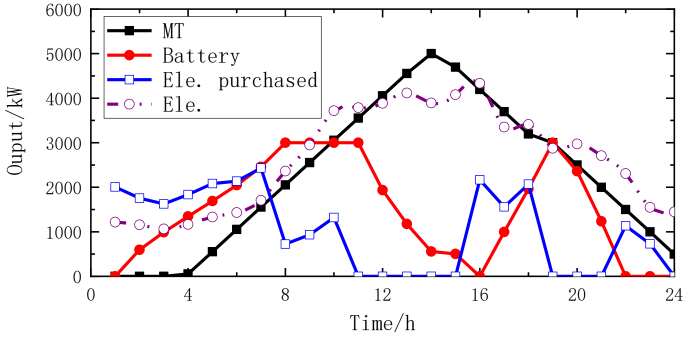


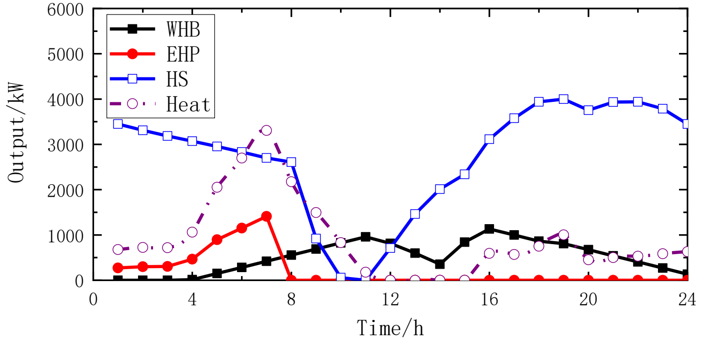
Temperature in seasons

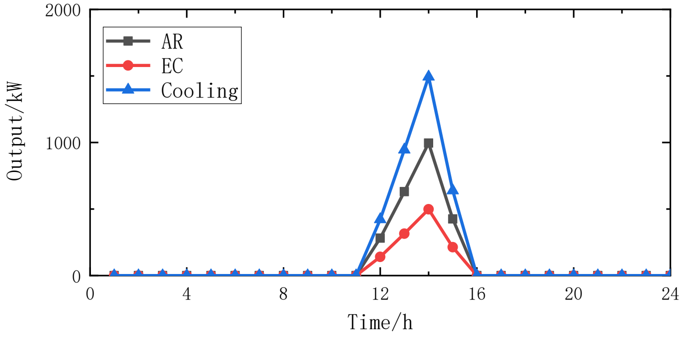


4.2 Results and Analysis

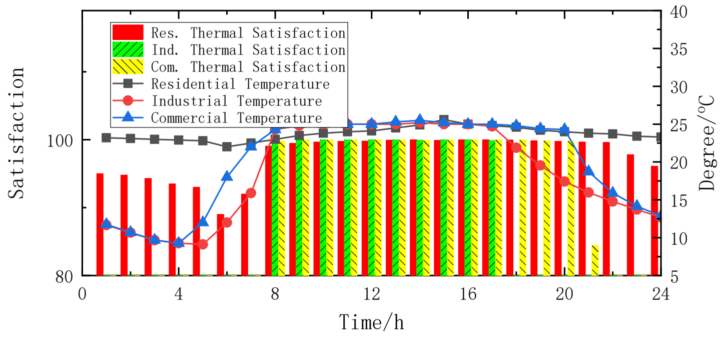
Scheduling Result in Spring&Fall

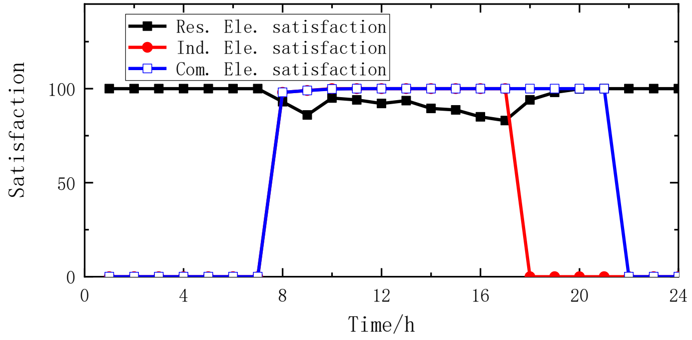






Consumer satisfaction & indoor Tem.

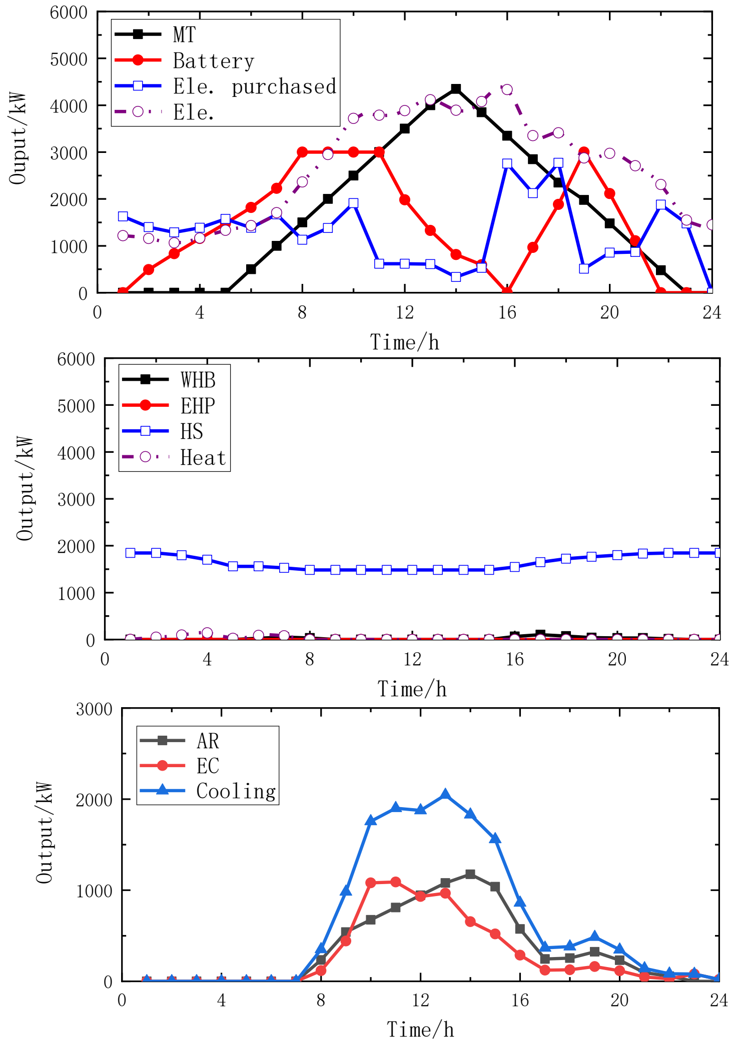




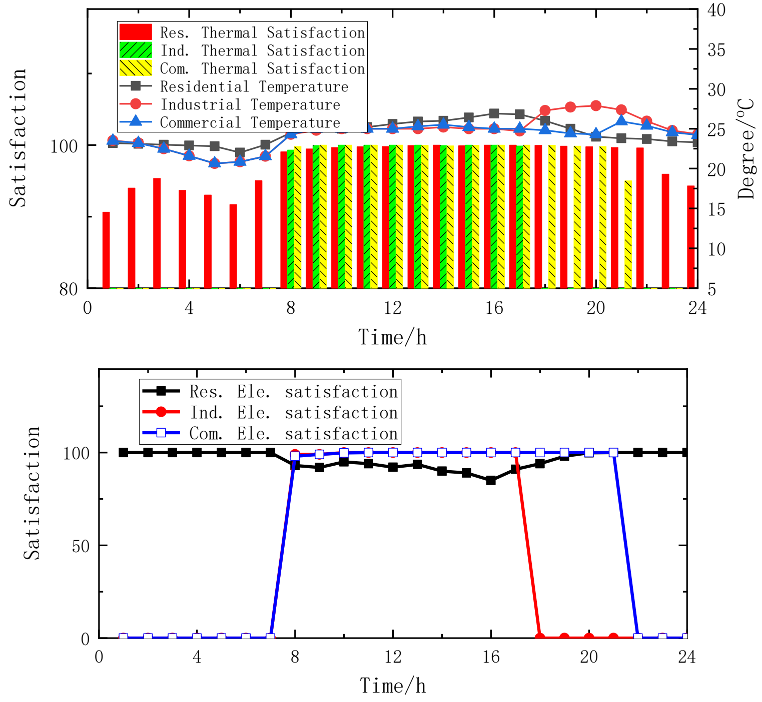
- **MT 5000kW during the peak**
- **HS absorb day,release night**
- **AR main cooling**

4.2 Results and Analysis

Scheduling Result in Summer



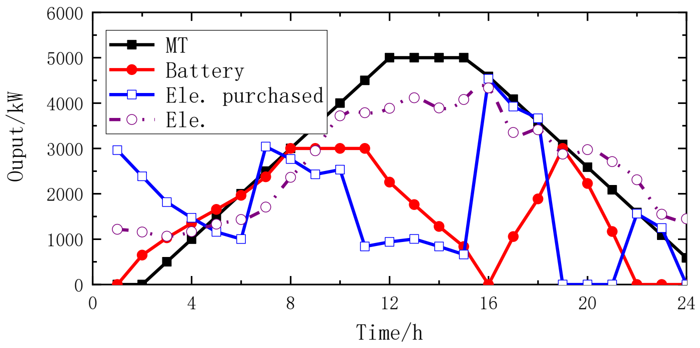
Consumer satisfaction & indoor Tem.

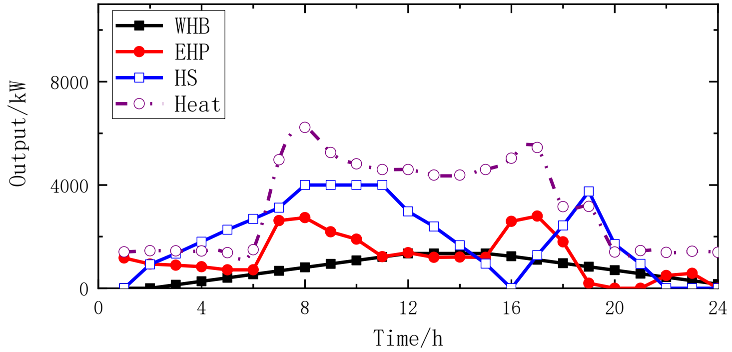


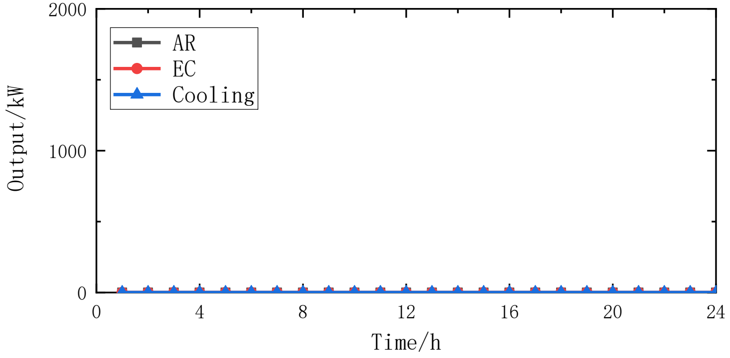
- ◆ **MT 4000kW during the peak**
- ◆ **WHB, HS no work**
- ◆ **EC, AR for cooling**

4.2 Results and Analysis

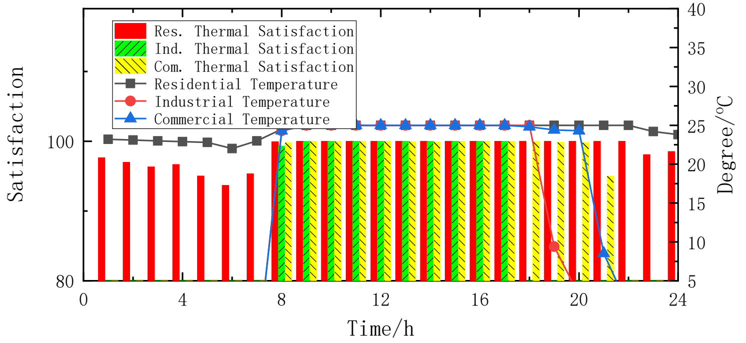
Scheduling Result in Winter

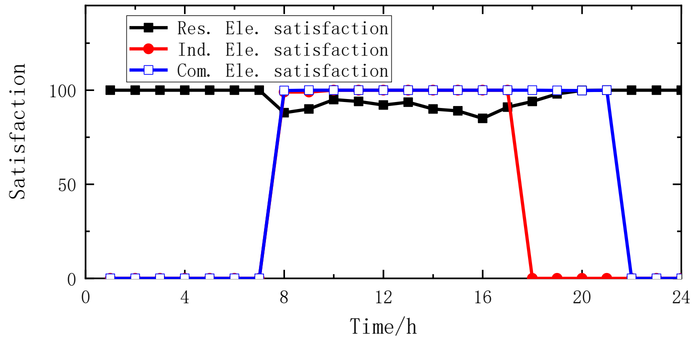






Consumer satisfaction & indoor Tem.





- MT afternoon 5000kW
- Large Heating 8-9am &sunset
- EHP main in peak time

4.2 Results and Analysis

Economic Result with Flexible Load

	Spr.&Fall	Summer	Winter
IES Operation(CHY)	51433.08	51034.08	72051.99
Res. Cooling (CHY)	380.01	1747.22	0.00
Ind. Cooling (CHY)	879.32	3509.04	0.00
Com. Cooling (CHY)	624.24	2992.68	0.00
Res. Heating (CHY)	3321.51	166.83	10758.28
Ind. Heating(CHY)	2332.34	0.00	8996.12
Com. Heating(CHY)	2776.61	0.00	9777.35
Res. Ele. (CHY)	11993.33	11993.33	11993.33
Ind. Ele. (CHY)	11564.08	11564.08	11564.08
Com. Ele. (CHY)	19509.41	19509.41	19509.41
Cooling Fees (CHY)	1883.57	8248.92	0.00
Heating Fees(CHY)	8430.45	166.83	29848.17
Ele. Fees(CHY)	43066.83	43066.83	43066.83
All Fees(CHY)	53380.86	51482.59	72915.01
Net Revenue(CHY)	1947.77	448.51	863.02

Operation Reduction

Spr.&Fall 15.97%
Summer 11.42%
Winter 20.65%

Consumer Cost Reduction

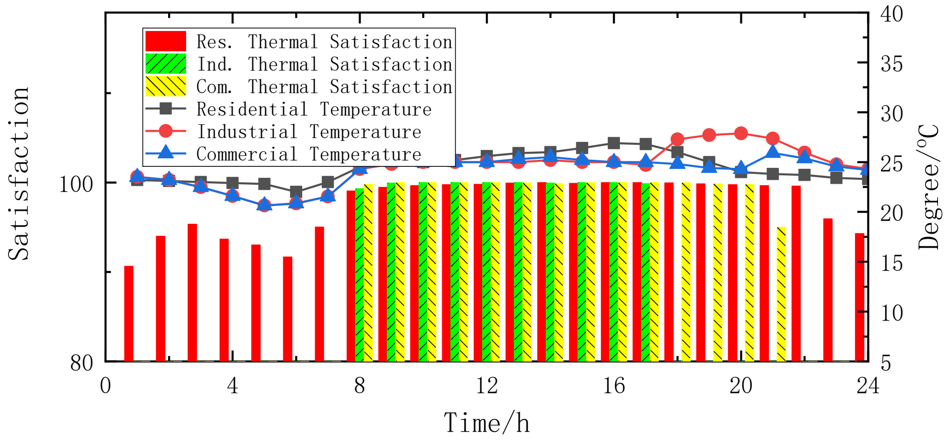
Spr.&Fall 13.32%
Summer 8.25%
Winter 20.21%

Result without Flexible Load

	Spr.&Fall	Summer	Winter
IES Operation(CHY)	61205.38	57618.96	90812.91
Res. Cooling (CHY)	470.49	2163.2	0.00
Ind. Cooling (CHY)	879.32	3509.04	0.00
Com. Cooling (CHY)	636.48	3051.36	0.00
Res. Heating (CHY)	5504.24	276.46	18352.36
Ind. Heating(CHY)	3145.95	0.00	12423.21
Com. Heating(CHY)	3834.35	0.00	13502.06
Res. Ele. (CHY)	15508.62	15508.62	15508.62
Ind. Ele. (CHY)	11564.09	11564.09	11564.09
Com. Ele. (CHY)	20043.92	20043.92	20043.92
Cooling Fees (CHY)	1986.29	8723.60	0.00
Heating Fees(CHY)	12484.51	276.46	44277.64
Ele. Fees(CHY)	47116.63	47116.63	47116.63
All Fees(CHY)	61587.44	56116.71	91394.27
Net Revenue(CHY)	382.06	-1502.26	581.36

4.3 Sensitivity Analysis

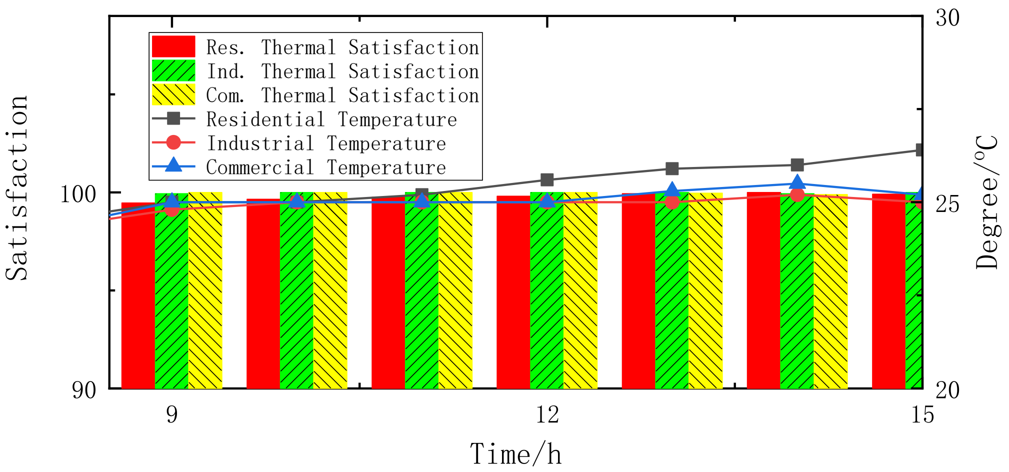
Thermal comfort & Temperature in Sum.



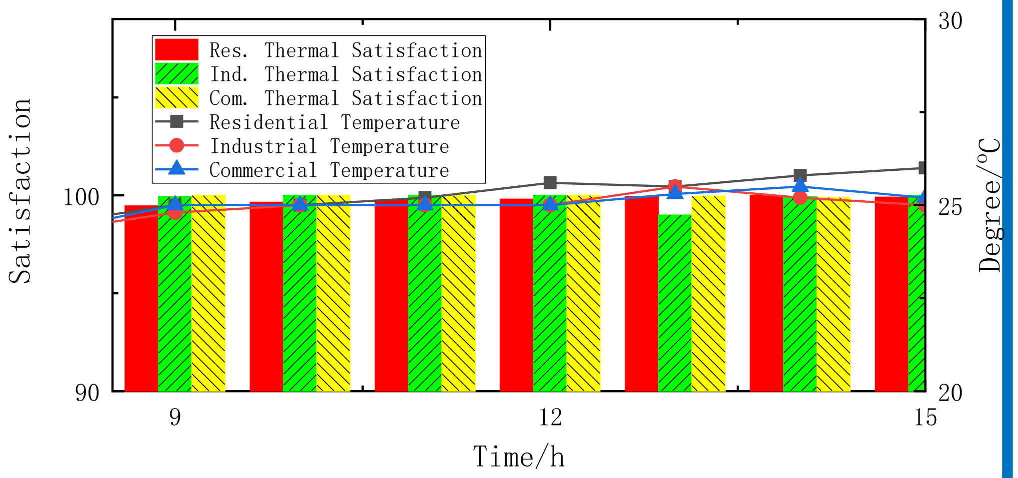
Metabolic M

Summer Industrial Noon break

Without Noon Break



With Noon Break



Section5

Conclusion

5.1 Conclusion

- Formulate the consumer satisfaction function to describe the perceived satisfaction of customers

- Personal condition affect the energy flexibility of consumer

- Revenue distributed based on consumer urgency and condition

5.2 Future Work

- Refine consumer behavior pattern and satisfaction model

- Long-term operation optimization &Optimal planning

- Future participation in the power market

Thank you