Economic Analysis and Optimal Design on Microgrids with SS-PVs for Industrial Applications

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Outline

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2. Structure of microgrid with SS-PV PVs
3. Evaluation indices for the microgrid with SS-PVs
4. Optimal design of PV microgrid for industrial applications
5. Case studies
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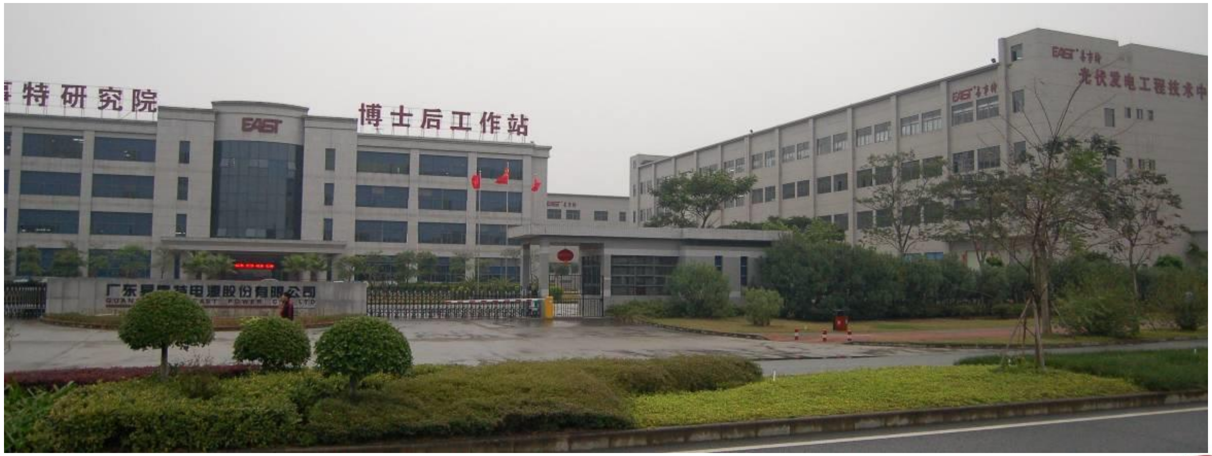


1. Introduction

1.1 Background

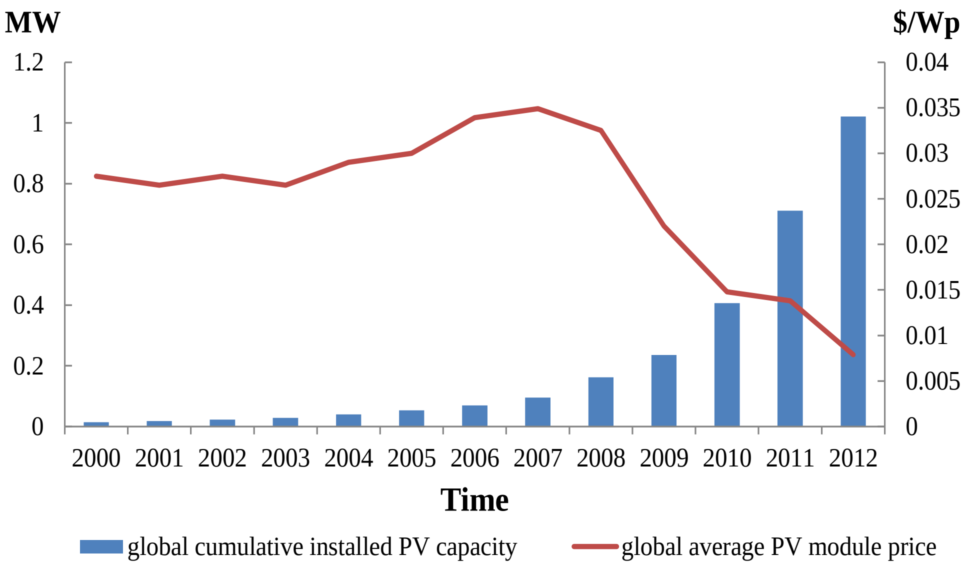
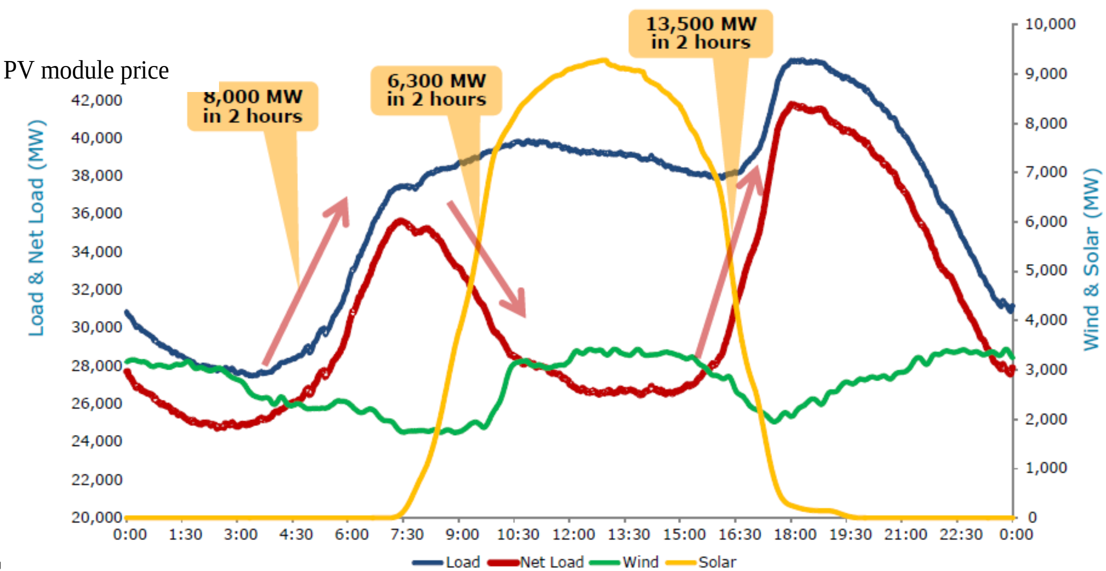


Fig.1 Global PV cumulative installed capacity 2000-2012

The developing trend of PV systems is in two directions :

1. Large-scale grid-connected PV systems(LS-PV)
2. Small-scale PV systems(SS-PV) integrated with other distributed generators in microgrids



1.2 Development of SS-PVs

- 1. Used in remote communities
- 2. Used as distributed generators, including building integrated photovoltaic systems (BIPV)
- 3. Based on the microgrid concept

Advantage

1. Facilitating the integration of renewable energy systems
2. Increasing the reliability and power quality

Disadvantage

1. Low economy efficiency in general

1.3 Some research on microgrids with PVs

➢ On the economic evaluation

Less focus on the economic evaluation of the emission reduction benefits, especially for the non-back-feeding systems.

➢ On optimal design

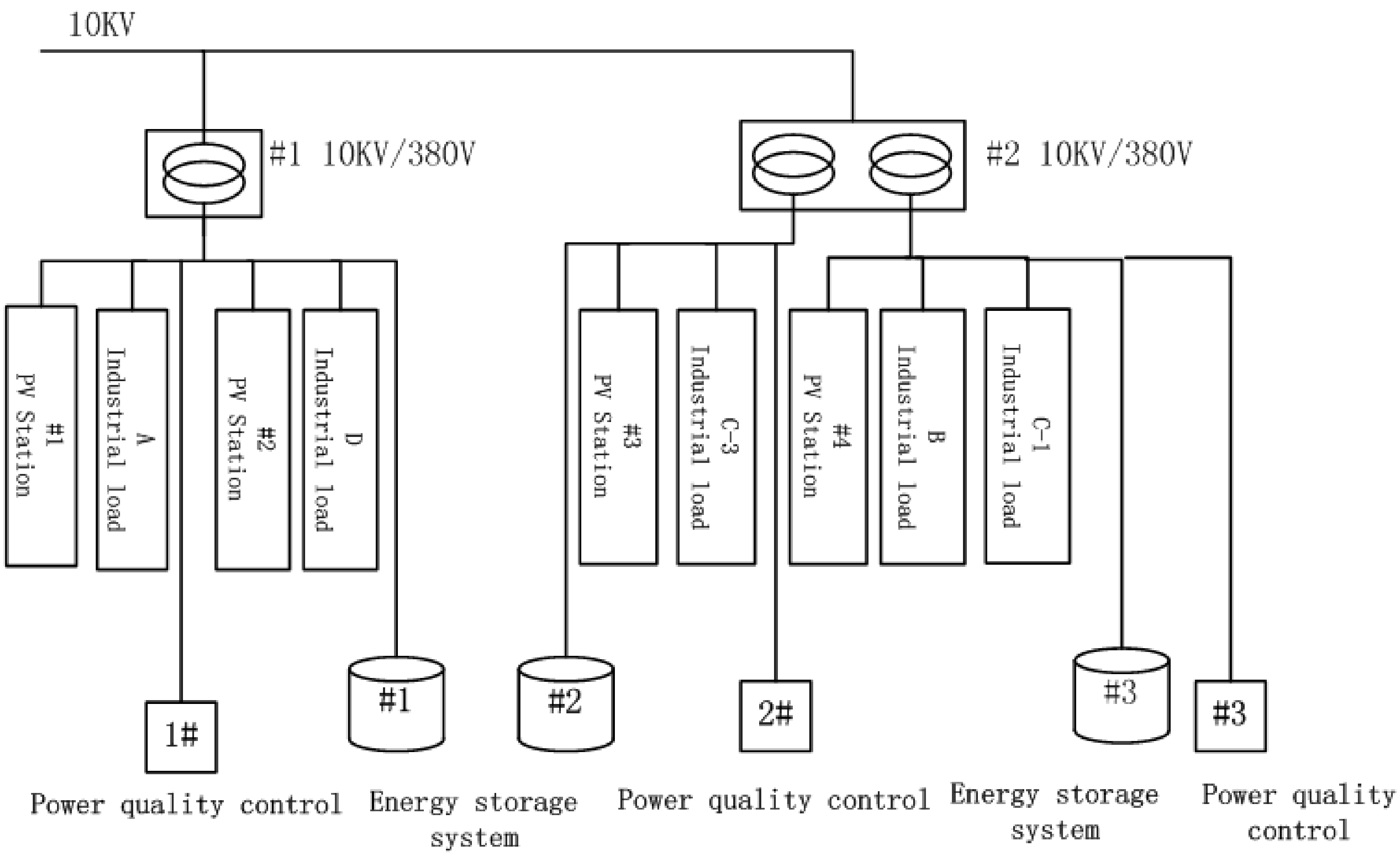
Mostly for the island system, but rarely for grid-connected system

2. Structure of Microgrid with SS-PVs

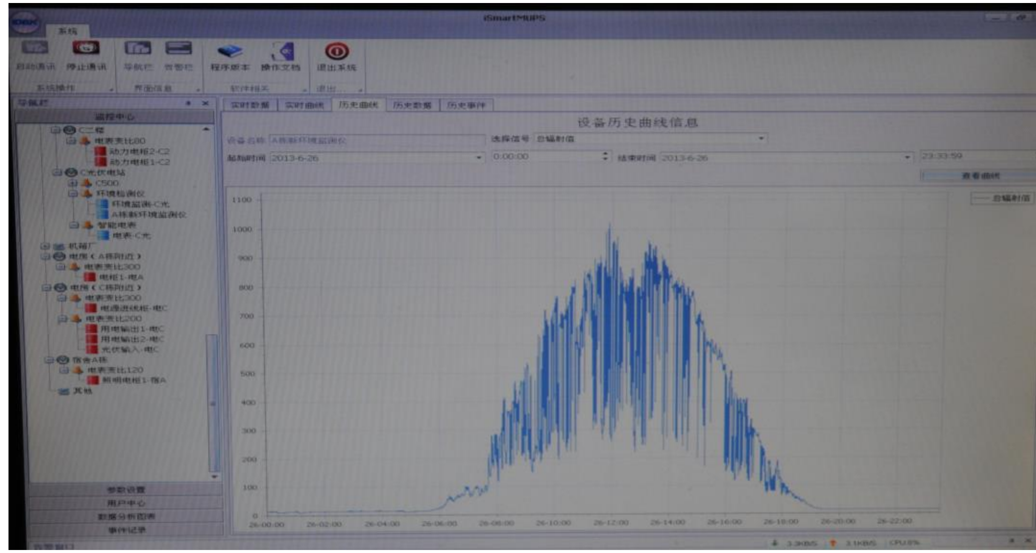
2.1 2MW industrial photovoltaic microgrid installed at EAST

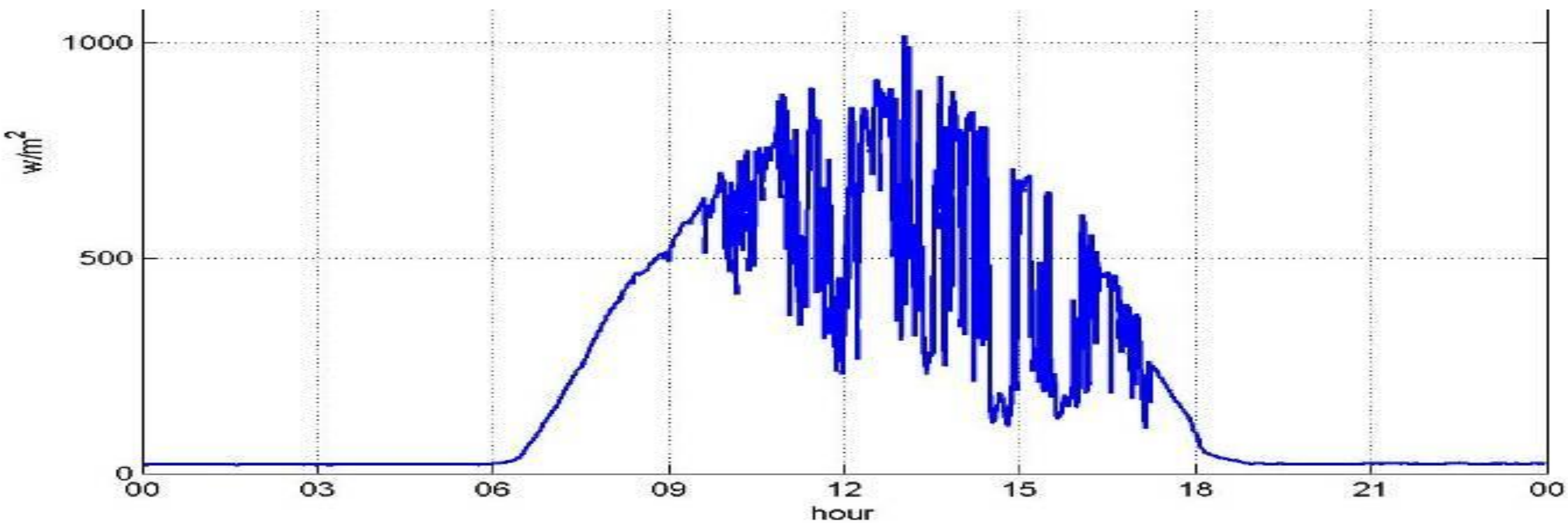
Total installed capacity：2MW
(500KW completed)

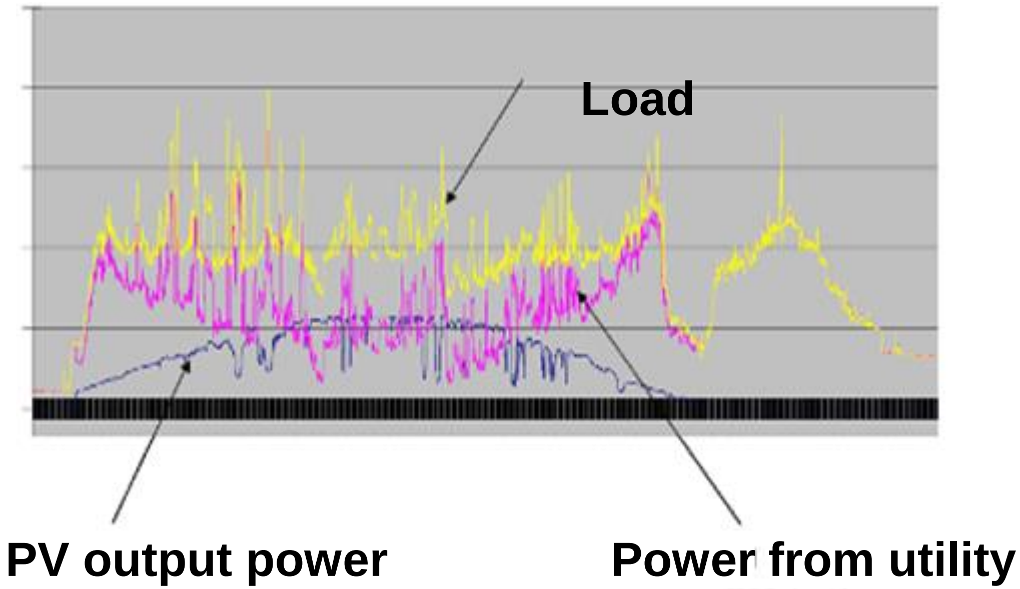
Configuration of Microgrids with SS-PVs installed at EAST



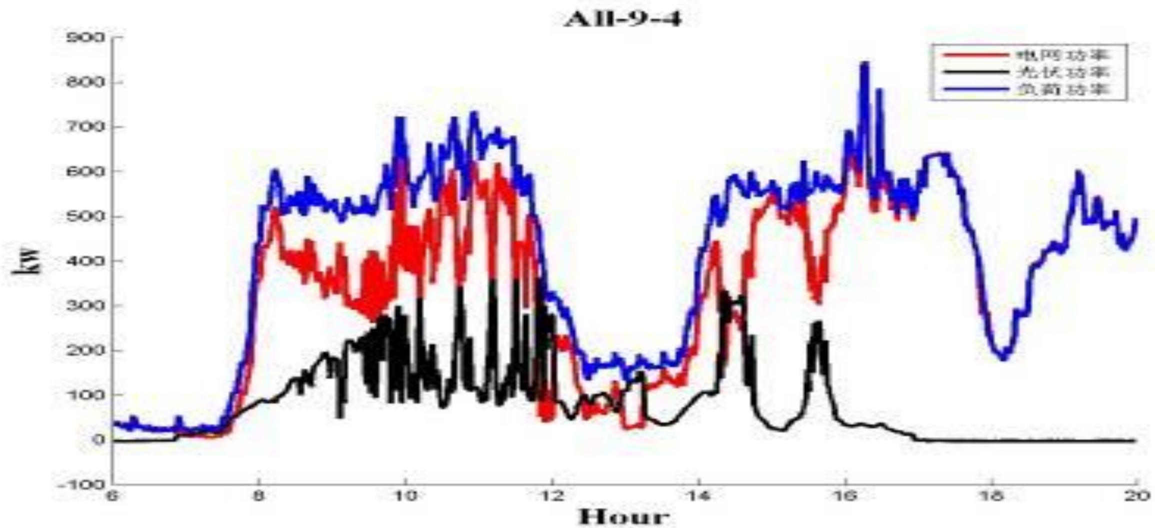
Normal PV output power characteristic in coastal areas：fluctuate frequently and drastically







The PV provides almost 50% total power consumption at EAST



The profiles of the utility, PV and load

2.2 Operation strategies of the microgrid with SS-PVs

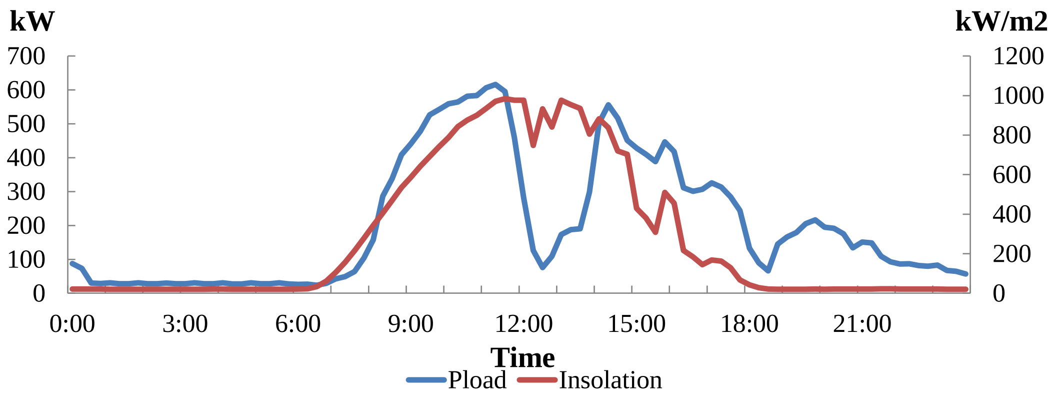


Fig.3 Typical daily load curve of the factory

In order to reduce the cost of electricity, an effective way is needed to minimize the difference of the electricity demand between the peak and valley in different periods every day.

- Calculating the evaluation indices of the system
- Economic analysis based on an optimized design model
- Energy management strategy for the PV system
- Sensitivity analysis of the impact of different installation sites on the system

3. Evaluation indices for the microgrid with SS-PVs

3.1 Levelized Energy Cost (LEC)

$$C_{LEC}=\frac{C_{tot}\cdot\frac{r(1+r)^N}{(1+r)^N-1}+C_{rep}+C_{om}+C_{buy}-C_{ERB}}{E}$$

C_{tot}	the total initial investment of the system
C_{rep}	the annual replacement cost
C_{om}	the operation and maintenance cost
C_{buy}	the annual cost of electricity purchase
C_{ERB}	the benefits of emission reduction
E	the annual energy output of the system
r	the interest rate
N	the life circle of the system

3.2 Emission Reduction Benefit (ERB)

$$C_{ERB} = \sum_{i=1}^{4} (E_{PV} * \mathrm{Emi}_i * Env_i)$$

E_{PV}	the annual power output of PV in the microgrid
Emi_i	the emission of four different pollutants in producing 1 kWh of electricity
Env_i	the corresponding environment cost

3.3 Payback Period (PBP)

$$PBP = \frac{C_{tot}}{Q} \qquad Q = \left(p \cdot E - C_{rep} - C_{om} \right)$$

Q	annual cash flow of the system
p	the electricity price
E	the annual energy output of the system

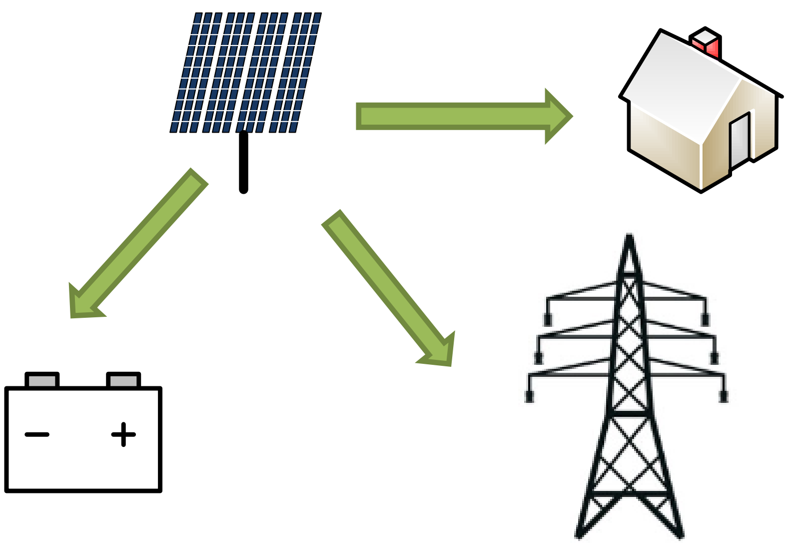
4. Optimal design of PV microgrid for industry

- 4.1 Energy Scheduling Strategy

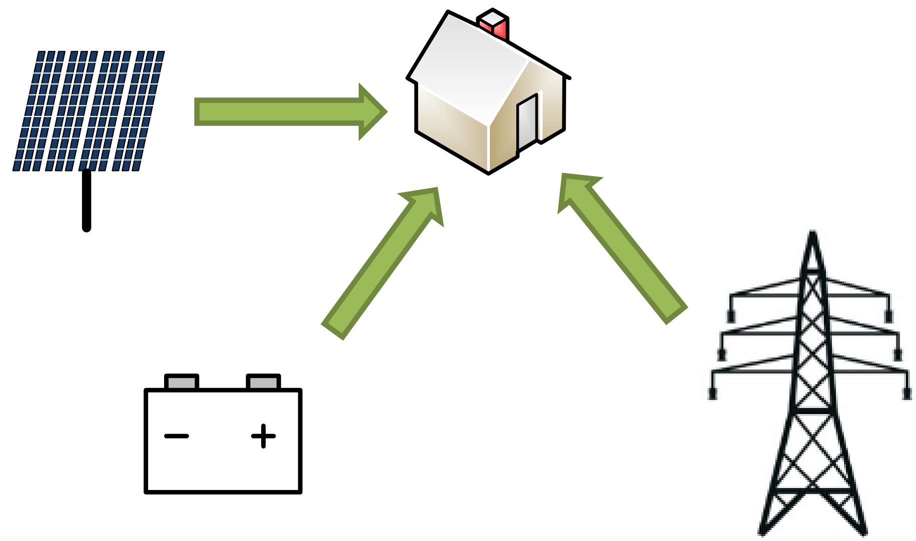
1) If it is allowable to sell the electricity to the utility:

(a) During the peak period

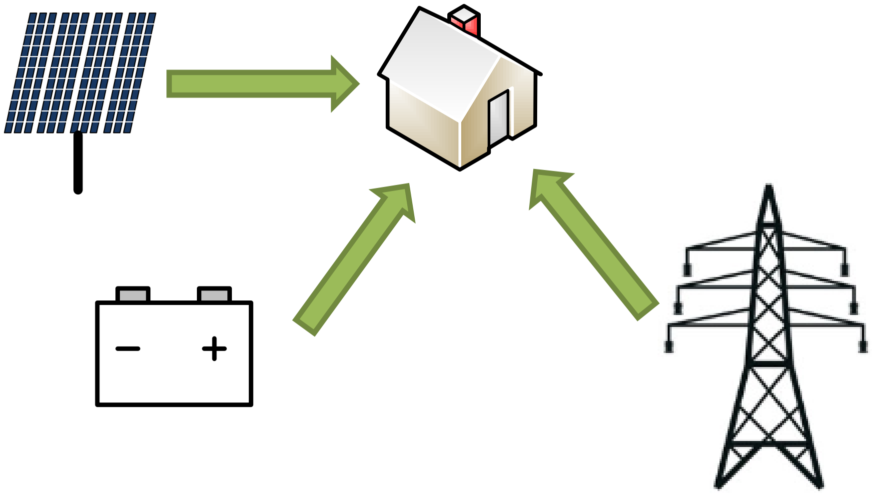
If the solar energy is sufficient



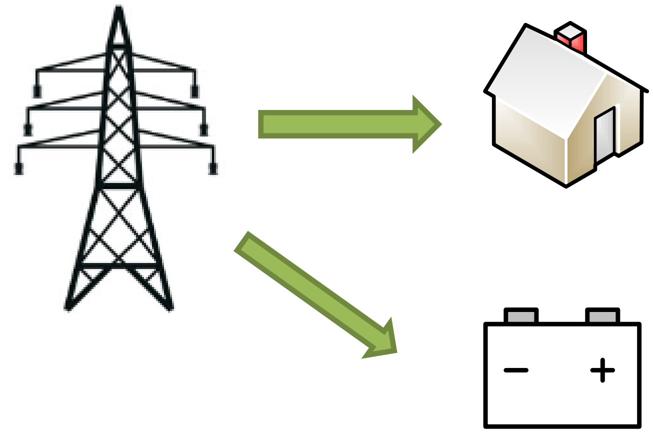
If the solar energy is insufficient



(b) During the flat period

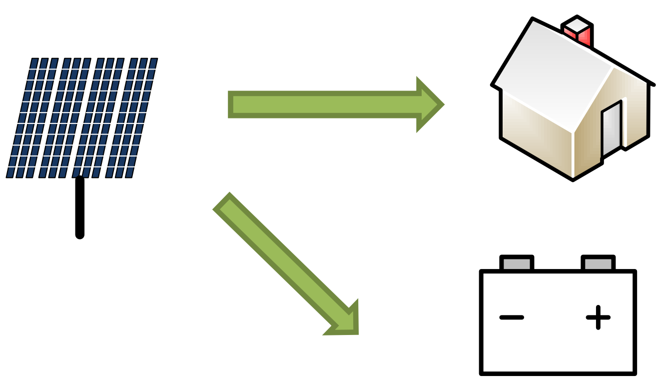


(c) During the valley period

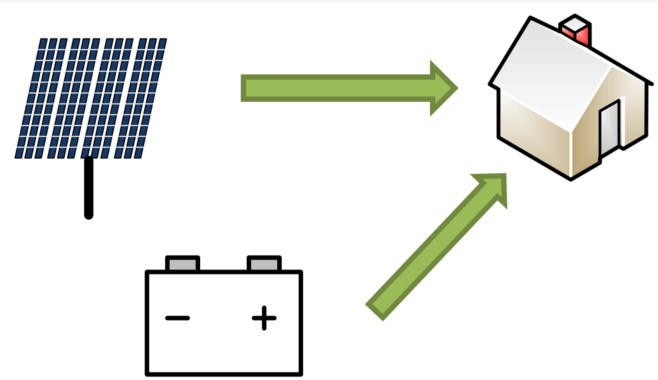


2) If it is not allowable to sell the electricity to the utility

If the solar energy is sufficient



If the solar energy is insufficient



4.2 Optimal design model

1) The objective function

$$f_{\min} = C_{tot} \cdot \frac{r(1+r)^N}{(1+r)^N - 1} + C_{rep} + C_{om} + C_{buy} - C_{ERB}$$

C_{tot}	The total initial investment of the system
r	The bank interest rate
N	The life circle of the system
C_{rep}	The replacement cost
C_{buy}	The electricity purchasing cost
C_{ERB}	The benefits of emission reduction

2) Constraints

$$P_{PV} + P_{Bat} + P_{buy} = P_{load}$$

$$0 \le P_{PV} \le P_{MPP}$$

$$I_{d,\max} \le I_{Bat} \le I_{c,\max}$$

$$\begin{cases} SOC_{\min} \le SOC \le SOC_{\max} & during\ \ peak\ and\ vallay\ period \\ SOC_{low} \le SOC \le SOC_{\max} & during\ \ flat\ period \end{cases}$$

$$\eta \ge \eta_{Desired}$$

P_{PV}	the output power of photovoltaic array
P_{Bat}	charge or discharge power of the battery
P_{buy}	the purchased electricity of the system
P_{load}	the load power
I_{Bat}	charge or discharge current of the battery
SOC	the state of the charge of the battery
SOC_{min}	the minimum SOC of the battery
SOC_{low}	a set value which avoids that the battery is over discharged during the flat period
η	the self-sufficiency ratio during the peak period

5. Case studies

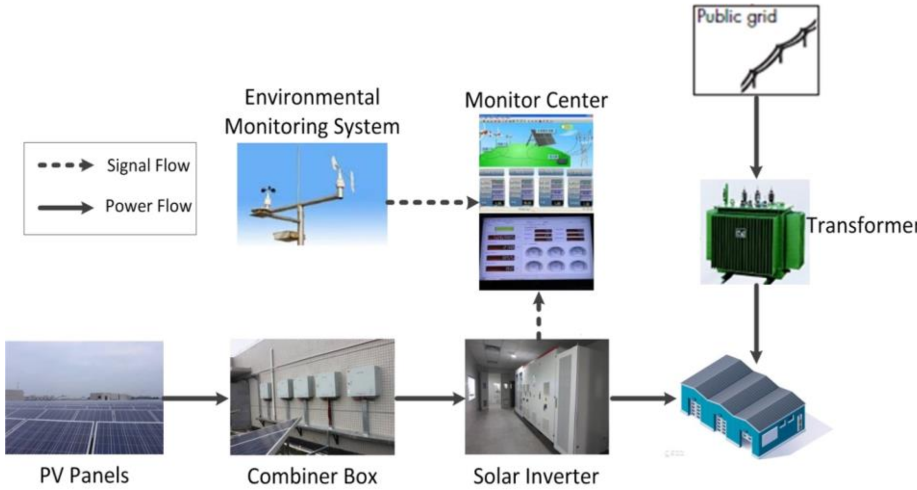


Fig.4 The studied system at EAST, China

Table1.Time-of-use electricity price policy

Load period	Hour(h)	Electricity price ($/kWh)
peak period	9:00-12:00, 19:00-22:00	0.13
valley period	0:00-8:00	0.03
flat period	8:00-9:00,12:00-19:00, 22:00-24:00	0.08

Table 2. Optimization result of the 500kW PV microgrid for industries

Units	Capacity	Ctot($)	Crep($/year)
PV	500kW	500000	0
Capacity of Batteries for the non-back feeding system	1150kWh	110000	35000
Capacity of Batteries for the back-feeding system	1430kWh	138000	43800

5.1 The simulation results in four scenarios

1) Non-Back-Feeding System Without Batteries

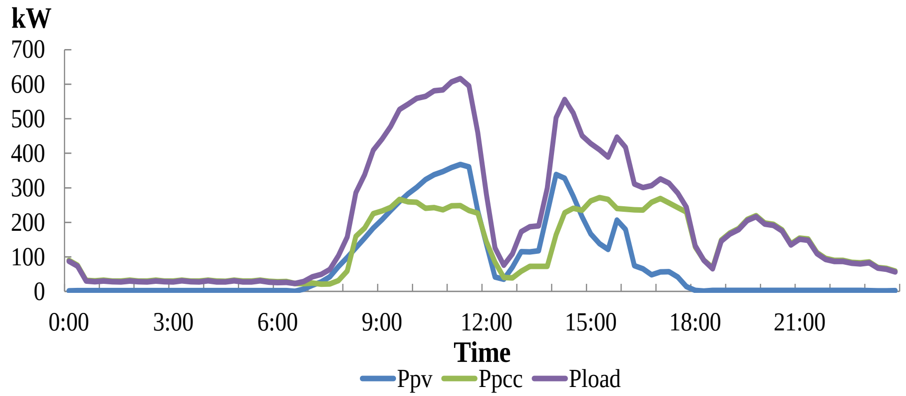


Fig.5 Output power of the units

2) Non-Back-Feeding System With Batteries

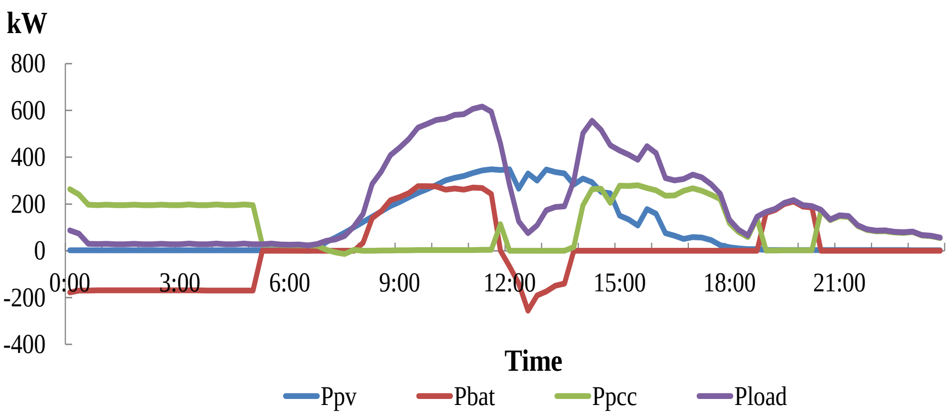


Fig.6 Output power of the units

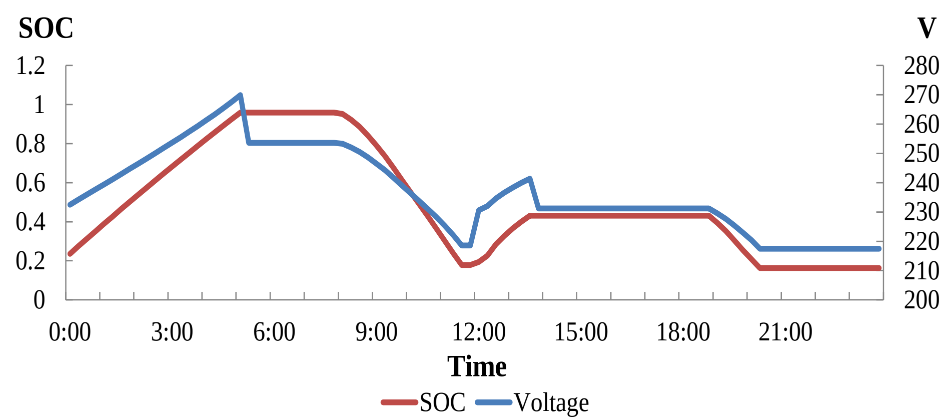


Fig.7 SOC and voltage of the battery

3) Back-Feeding System Without Batteries

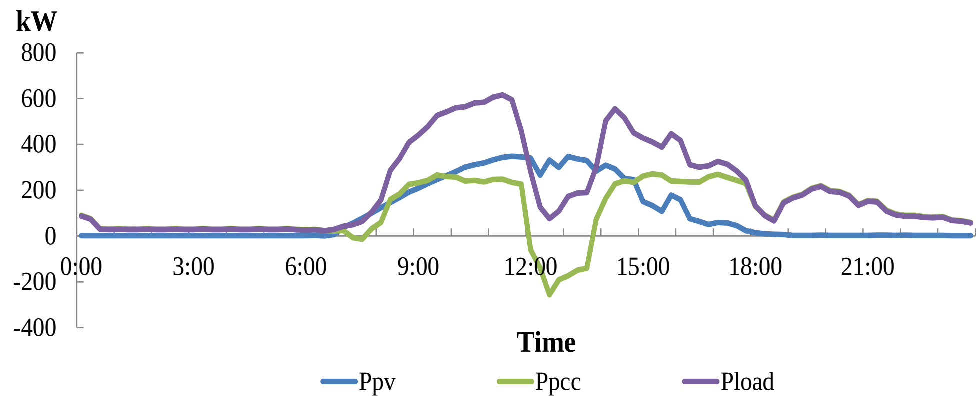
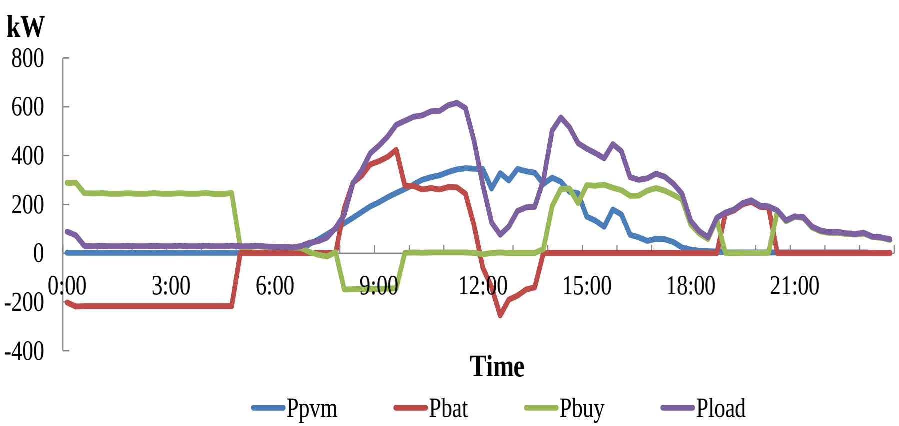


Fig.8 Output power of the units

4) Back-Feeding System With Batteries



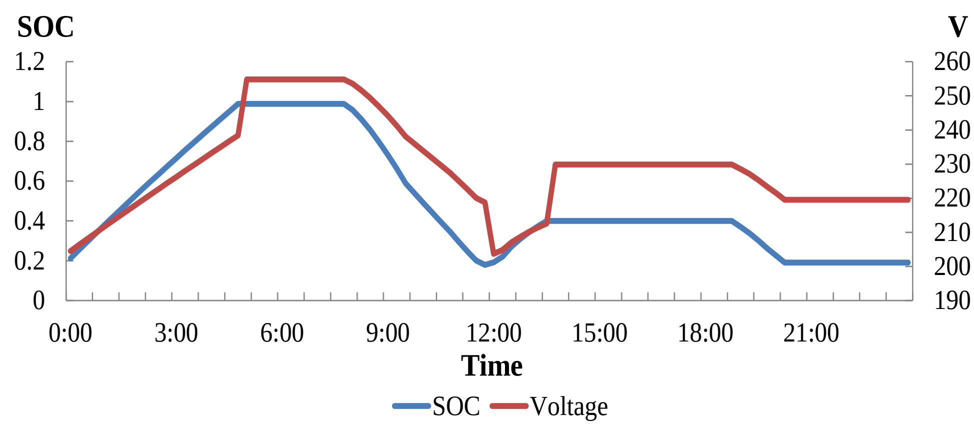


Fig.9 SOC and voltage of the battery

Fig.10 Output power of the units

5.2 Three evaluation indexes

1) *LEC*

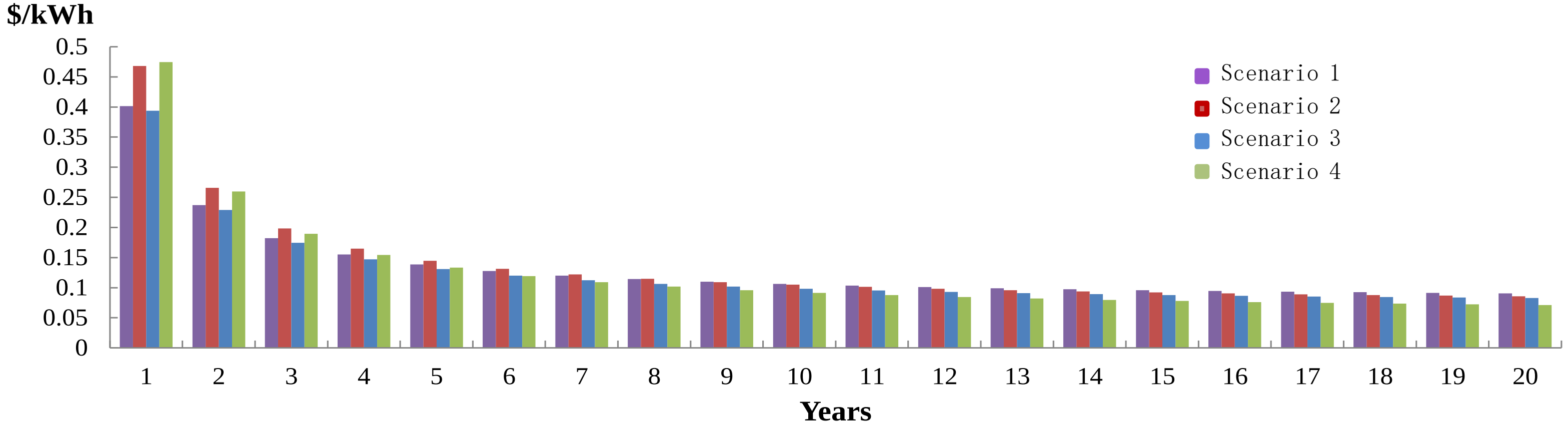


Fig.11 *LEC* of the system at different scenarios

2)*ERB*

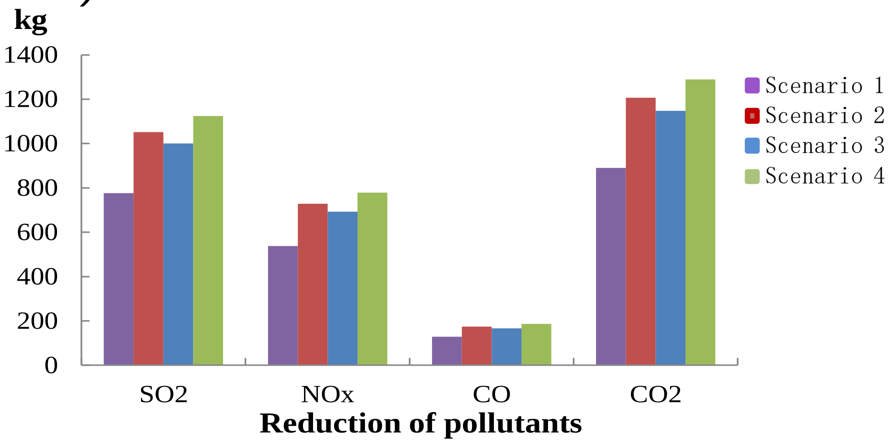


Fig.12 Reduction of pollutant emission of the system before and after the introduction of the battery

3)*PBP*

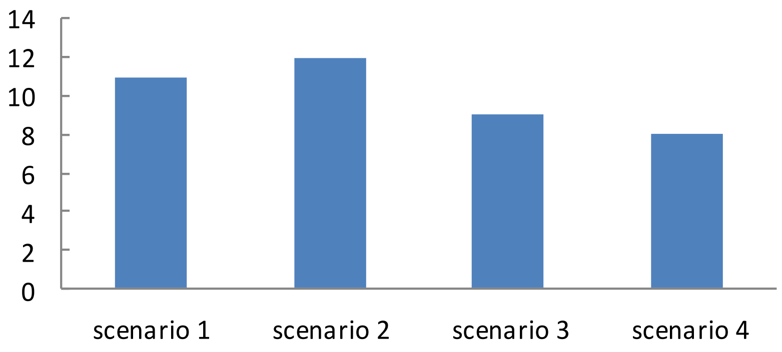


Fig.13 *PBP* of the system at different scenarios

• 5.3 Sensitivity analysis

Table 3. Summary of the sensitivity analysis

Parameter	Base value	Changed to	change in LEC (%)	change in PBP (%)
Initial investment cost	500000 $	475000$(-5%)	-1.62	-4.05
		450000$(-10%)	-3.25	-8.1
Operation and maintenance cost	0.8 $/kW	0.74$/kW(-10%)	-0.04	-0.09
		0.88$/kW(+10%)	+0.04	+0.11
Battery cost	96.77 $/kWh	91.93(-5%)	-1.25	-2.11
		87.1(-10%)	-3.45	-4.21
Cycle efficiency	80%	70%	+2.34	+0.03
		90%	-1.87	-0.04
FiT	0.19 $/kWh	0.21(+10%)	-3.14	-3.99
		0.23(+20%)	-6.25	-7.58
Allowable level of reverse power (% of the installed system capacity)	20%	10%	+7.02	+10.31
		30%	-2.06	-5.41

- 5.4 Calculation results for microgrids installed at different sites

Table 4. Region classification by distribution of solar energy resource in china

Class of Regions	Total annual insolation（MJ/m²）	Daily solar insolation（kWh/m²）	Regions
First level	6680 ~8400	5.1 ~6.4	Ningxia, Gansu, northern Xinjiang, western Tibet
Second level	5850 ~6680	4.5 ~5.1	Hebei, Shanxi, northern, central Gansu
Third level	5000 ~5850	3.8 ~4.5	Guangdong, Shandong, Liaoning, Jiangsu, northern Anhui
Forth level	4200 ~5000	3.2 ~3.8	Hunan, Hubei, Zhejiang, southern Anhui
Fifth level	3350 ~4200	2.5 ~3.2	Sichuan, Guizhou

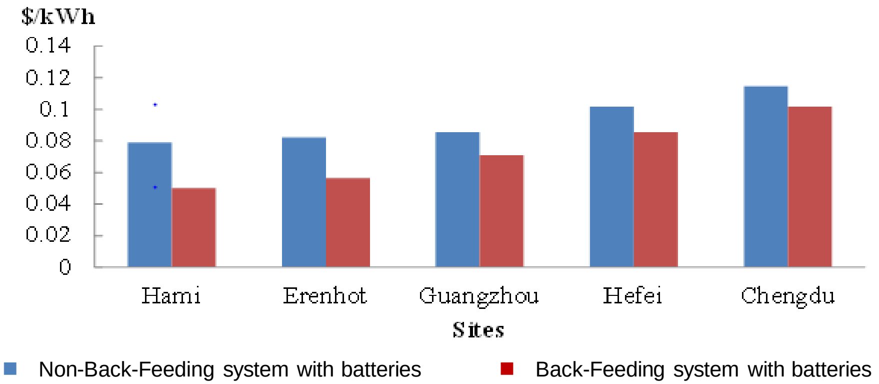


Fig.14 The LEC of microgrids installed at different sites

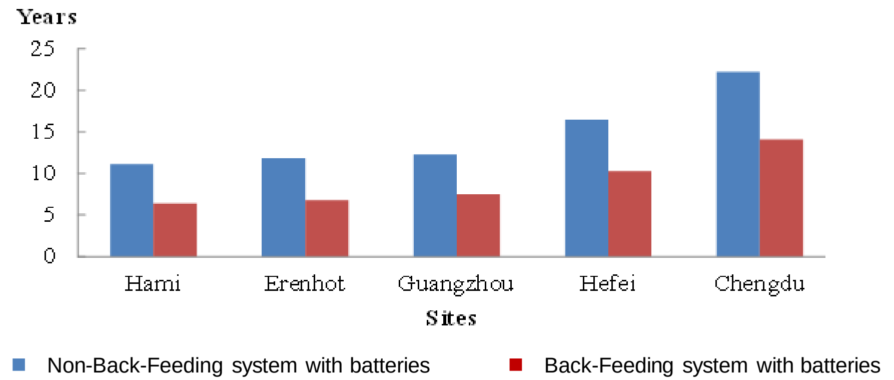


Fig.15 The PBP of microgrids installed at different sites

6. Conclusion

- The optimized back-feeding microgrid with SS-PVs and batteries can bring the most economic and emission reduction benefits to the customers and society.
- The sensitivity analysis of the impact of various parameters and different installed sites for the microgrid system has also been performed in this study.
- The economic analysis and optimal design of the PV microgrid for industrial applications provided a reference for the application of similar projects.