THE HONG KONG POLYTECHNIC UNIVERSITY
香港理工大學

香港太陽能學會
Solar Energy Society of Hong Kong

可再生能源建筑应用技术发展与展望

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香港太阳能学会 会长

内容

- ✓可再生能源建筑应用技术简介
- ✓太阳能建筑光热和光电技术应用现状
- ✓太阳能光伏建筑一体化技术的发展与展望
- ✓光伏建筑一体化技术的研究
- ✓地源热泵技术在冬暖下热地区的应用研究
- ✓太阳能干燥除湿空调技术的研究
- ✓结论

可再生能源建筑应用技术简介

- 建筑耗能：中国大陆达47%[1]，香港特区达60%[2]
- 建筑上可再生能源利用技术：
  - 被动式太阳房技术
  - 太阳能热水生产技术
  - 太阳能光伏技术
  - 太阳能辅助制冷，除湿空调技术
  - 风能利用技术
  - 地源热泵技术
  - 废物利用技术，如固体垃圾和污水处理能源再利用等技术

[1] T. Huo et al. (2019), Science of the Total Environment. Volume 650, Pages 427-437. [2] X. Chen, H. Yang (2017). Applied Energy. Volume 206, Pages 541-557.

研究方向：发展以零能耗建筑为目标的电网-建筑-系统能源技术与管理机制

可再生能源-蓄能混合系统对建筑能耗和电网的影响机理和能源管理系统（EMS）设计

1. BIPV applications

-Building integrated Photovoltaics (BIPV)

BIPV： refers to using photovoltaic materials, viz. solar cells and PV modules, to replace conventional building materials in parts of the building envelope such as the roof, skylights, windows or facades where the PV modules simultaneously serving as building envelope material and generating power.

Future trend of solar photovoltaic applications

——Building integrated Photovoltaics (BIPV)

Functions of BIPV

- Power generator
- Part of construction materials
- Water proof
- Shading
- Noise barrier
- Insulation
- Natural lighting

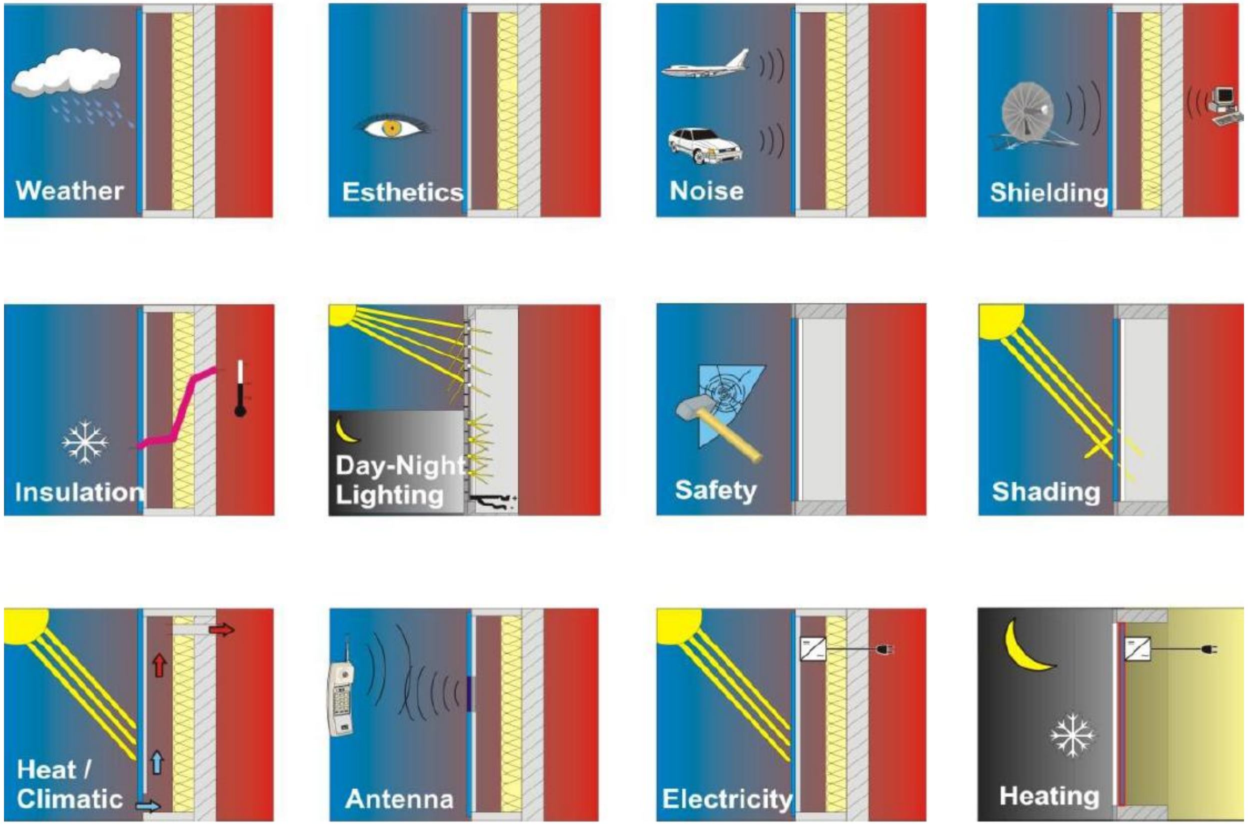
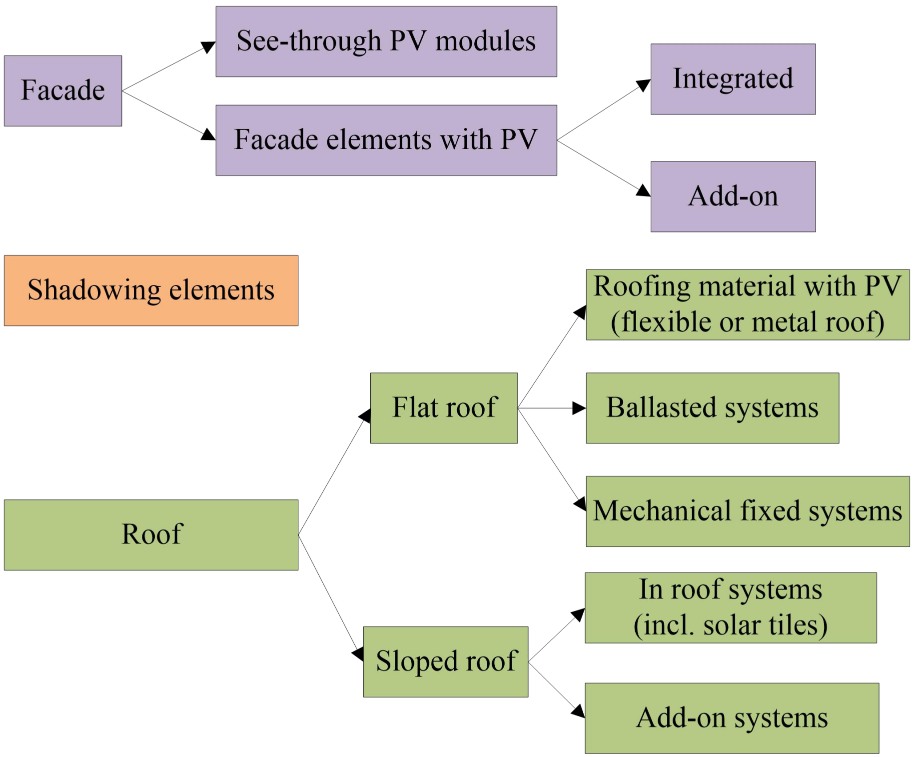
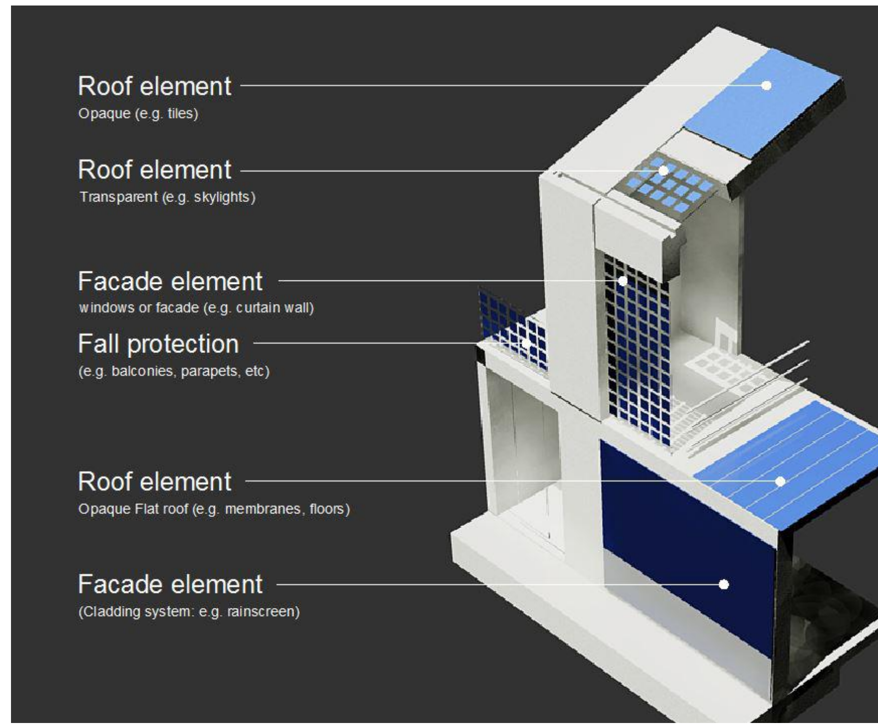


Figure 1. Multiple functions of PV modules. Source: Multielement project

BIPV applications





An overview of applications of PV modules in buildings.

BIPV projects-rooftop

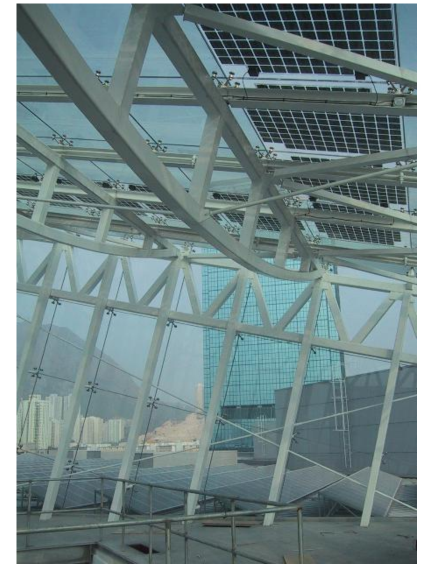
BIPV facade


The Netherlands, Leiden

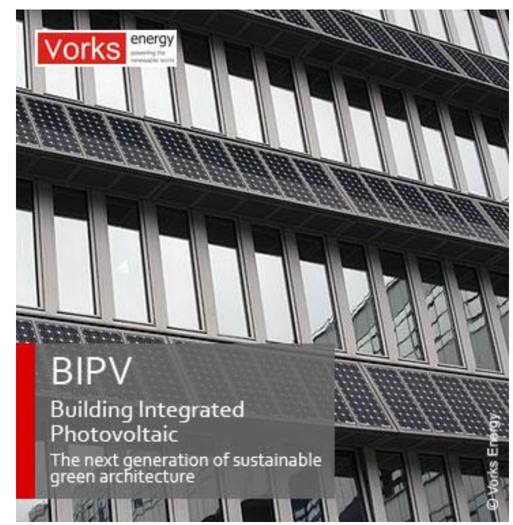

SCHOTT Ibérica SA, Barcelona, Spain • www.gipv.de

BIPV Projects

- Skylight and atrium



- Shading type



BIPV of the South Railway Station in Nanjing

Installation capacity: 10.67 MW.
(The biggest single BIPV project in the world)
PV module type: Poly-Si

Annual energy output: 9.12 GWh
Annual CO_2 emission reduction: 9000 tons

BIPV of the Museum of Natural Science in Jiangxi

Installation capacity: 3.05 MW
PV module type: a-Si hollow PV module
Installation method: BIPV on facades and roof

BIPV of Zhujiang City in Guangzhou

Installation capacity: 185 kW
PV module type: a-Si PV module
Installation method: BIPV on the east and west facades

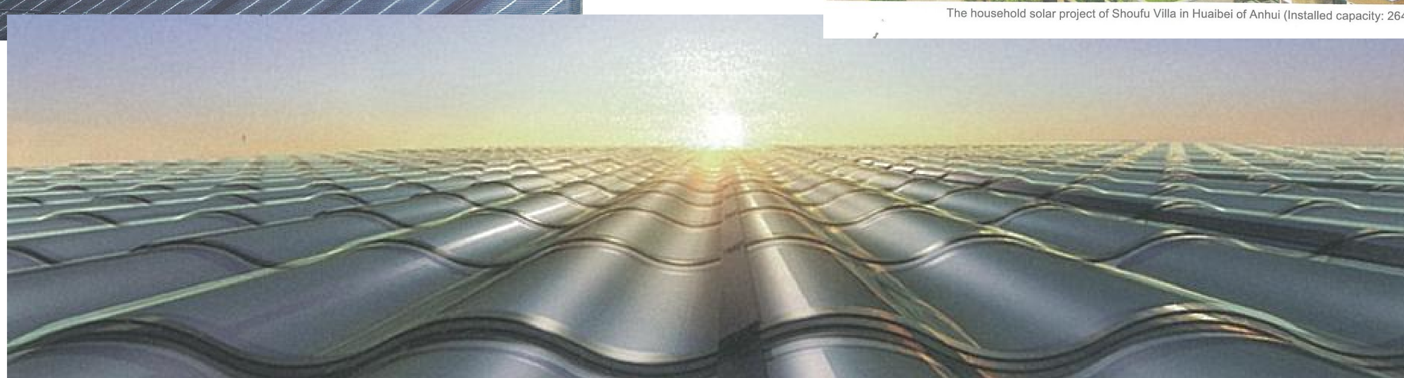
BIPV in Huangshi of Hubei

Installation capacity: 3 MW
PV module type: Poly-Si PV module
Installation method: BIPV on facades, roofs and shading panels

BIPV of Hanergy in Jiangsu

Installation capacity: 67 KW
PV module type: a-Si PV module
Installation method: BIPV on facades
Annual energy output: 33919 kWh
Annual CO_2 emission reduction: 10 tons

New BIPV claddings from Hanergy



BIPV applications in Taiwan

1MWp at Kaohsiung National Stadium (2009)

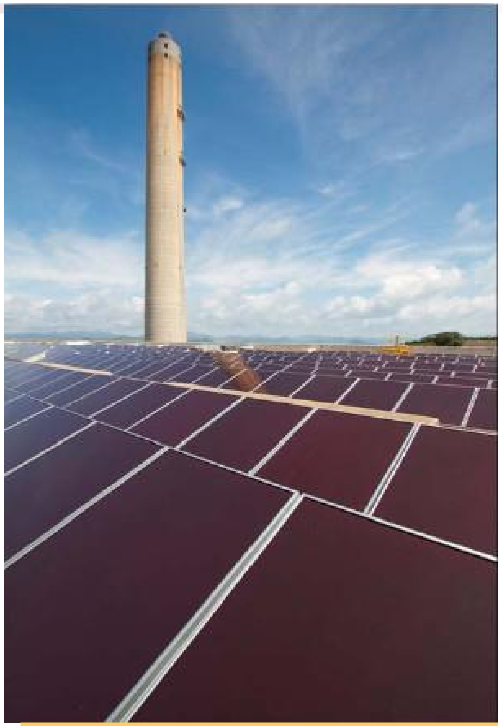
Table 1: Annual radiation comparison across different latitude [12, 13].

	Latitude	Annual solar radiation (Wh/m^2/year)
Taiwan-1 (Max)		1,560
Taiwan-2 (Average)	±23°N	1,059
Taiwan-3 (Min)		801
Sahara	25°00'N	2,500
Israel	33°00'N	2,000
Los Angles, USA	34°30'N	1,816
Athens, G	37°58'N	1,580
Trapani, I	38°00'N	1,800
New York, USA	40°47'N	1,424
Rome, I	41°48'N	1,529
Toronto, C	43°40'N	1,380
Freiburg, D	48°00'N	1,100
London, UK	51°29'N	898
Berlin, G	52°28'N	1,026
Helsinki, FIN	60°00'N	950
Lerwick, UK	60°00'N	775

Solar PV utilizations in Hong Kong

PolyU in 1999

Wai Chai Tower



Lamma Power Plant

EMSD HQ in Hong Kong

Siu Ho Wan Sewage Treatment Plant

- Largest Solar Farm in Hong Kong
- Commissioned in 2016
- Located in North Lantau Island
- Polycrystalline PV panels

Solar Farm Area A & B

Solar Farm Area C

Floating PV in Hong Kong

Two Pilot Projects in Hong Kong

- Shek Pik Reservoir
- Plover Cove Reservoir

Location of FPV System	Annual Power generation (kWh)	Annual Carbon Doxide Reduction (kg)
Shek Pik Reservoir	94,109	66,606
Plover Cove Reservoir	72,227	50,558

Details of the FiT in Hong Kong

Three types of FiT rates will be offered according to the installation capacity of your RE system:

Capacity of the Renewable Energy System	FiT rate (per unit of electricity -kWh)
≤ 10 kW	HK$ 5
> 10 kW - ≤ 200 kW	HK$ 4
> 200 kW - ≤ 1MW	HK$ 3

The rates listed above are effective from 1 Oct 2018 onwards and will be reviewed regularly.

A sample local village house rooftop PV system

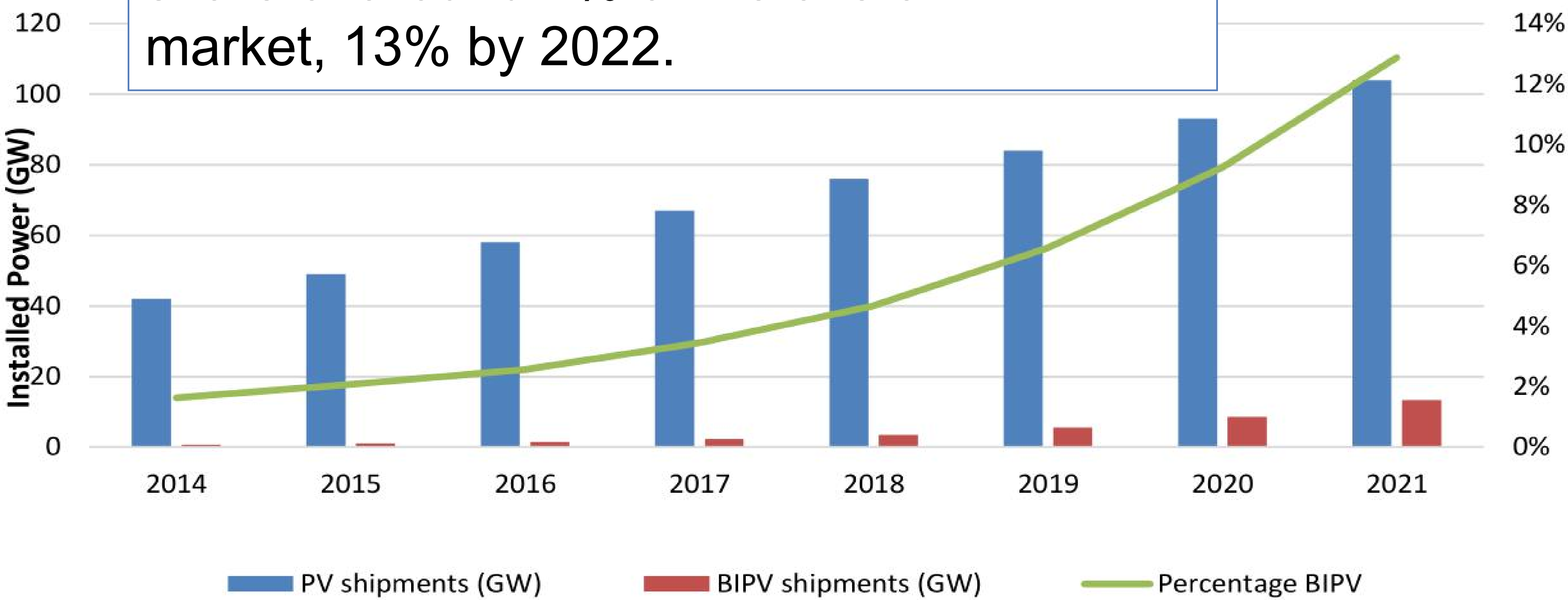
Comparisons of a solar PV on a residential house	
PV installation capacity: 3.0 kWp	
Average net tariff in 2018	HK$1.154 per kWh
Electricity generation by a small solar PV system without FiT	
Installation cost	HK$7900
Annual electricity generation	3,300 kWh
Annual earnings	HK$3808.2
Payback Period	21 years
Electricity generation by a small solar PV system with FiT	
Installation cost	HK$54000
Annual electricity generation	3,300 kWh
FiT tariff	HK$5.0
Annual earnings	HK$16,500
Payback Period	3.3 years

BIPV potential study in Europe

Available Roof Surface					
	Net Available Solar Surface (Km²)	Installable PV "Potential" (GW)	Estimated Electricity production (Twh/year)	Residential Electricity consumption 2006 (TWh/year)	% of PV
Europe (75%: Germany, France, UK, Italy, Spain)	3.723	465,4 (8m²/Kwp)	511,9	859	59%
		161,9 (23m²/KWp)	178,1		20%
USA	4.563	570,4 (8m²/Kwp)	570,4	1351	42%
		198,4(23m²/KWp)	198,4		14%
Japan	1.050	131,3 (8m²/Kwp)	118,1	229	51%
		45,7 (23m²/KWp)	41,1		18%

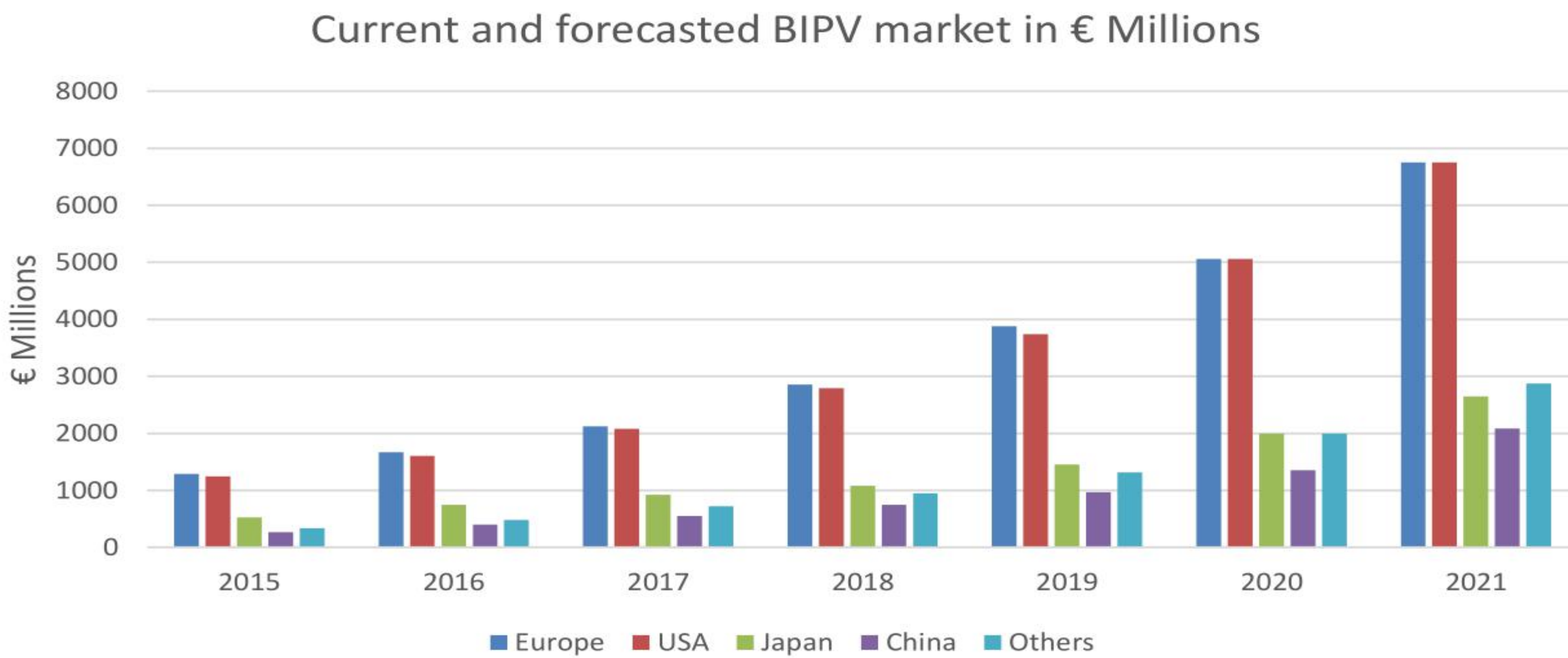
** Facades not included*

The global BIPV sales will triple by 2019, growth by 18.7%;
Currently the BIPV market holds a market share of around 2% of the overall PV market, 13% by 2022.



Source: Nanomarkets , “Nanomarkets report BIPV Market Analysis and Forecast 2014-2021,” 2015.

BIPV market



The most evolved BIPV market regions are Europe and the USA which combined currently account for around 70% of the worldwide market share.

Source: Nanomarkets , “Nanomarkets report BIPV Market Analysis and Forecast 2014-2021,” 2015

2. Our research activities in BIPV applications:

(1) Potential BIPN in Hong Kong

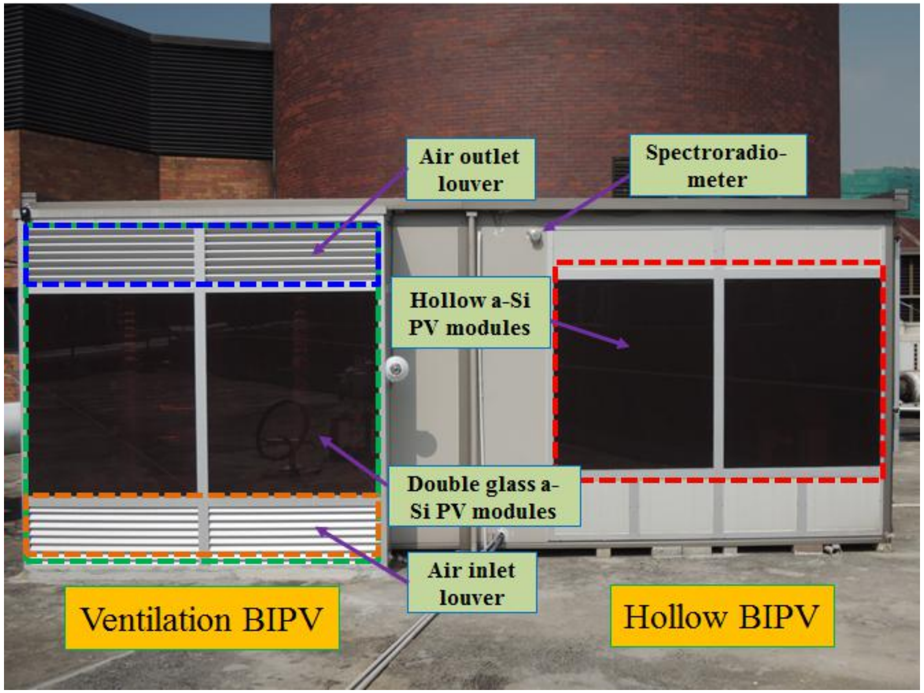
- The potential total active rooftop area of PV modules was calculated as 37.4km². The total potential installation capacity is estimated as 5.97 GWp.

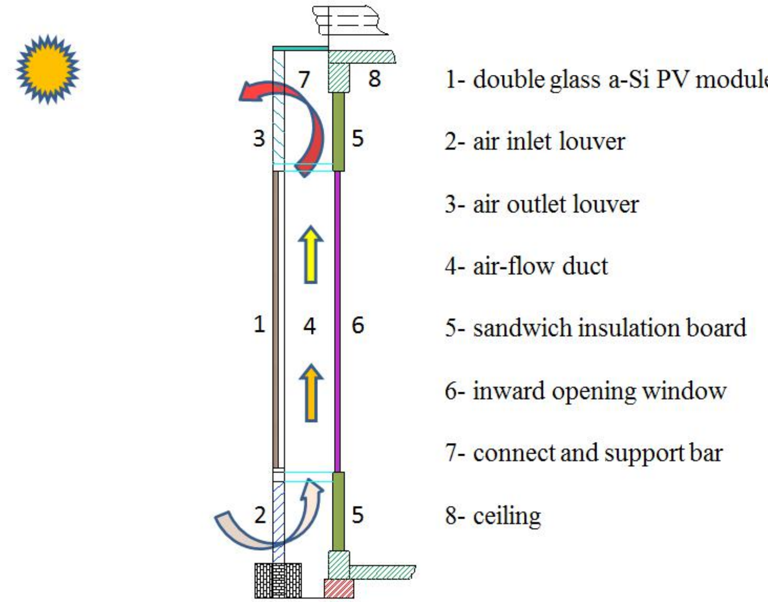
$$A_{act.} = \frac{A_{pot.}}{A_{occu.}} \times A_{pv}$$

$$E_{potential} = A_{act.} \times G_{optimal} \times \eta_{stc} \times \lambda$$

- The potential PV electricity output is about 5,981GWh, accounting for 14.2% of the total electricity use in 2011.
- Reduce the imports of coal and natural gas by 25% and 54% respectively and mitigate about 3 million tons of GHG emissions yearly.

BIPV windows

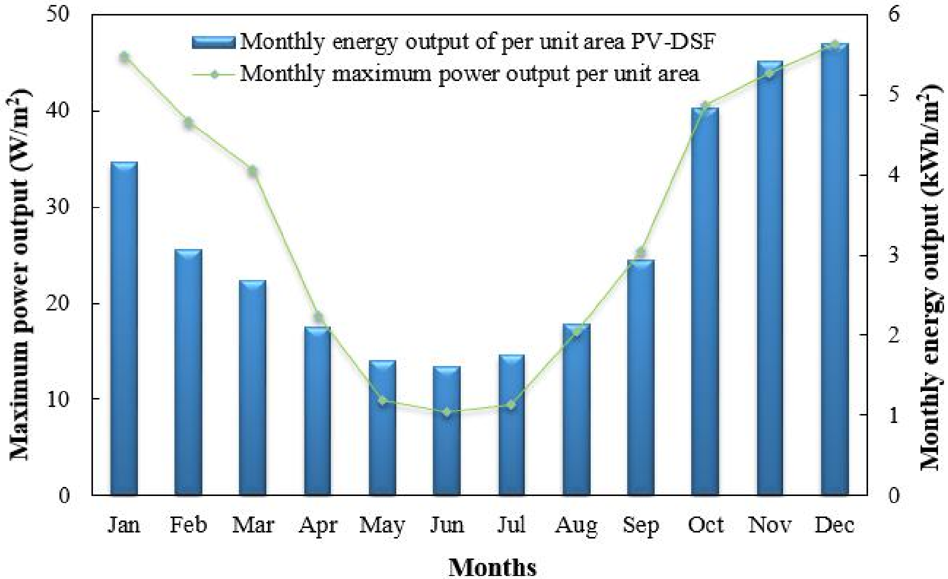


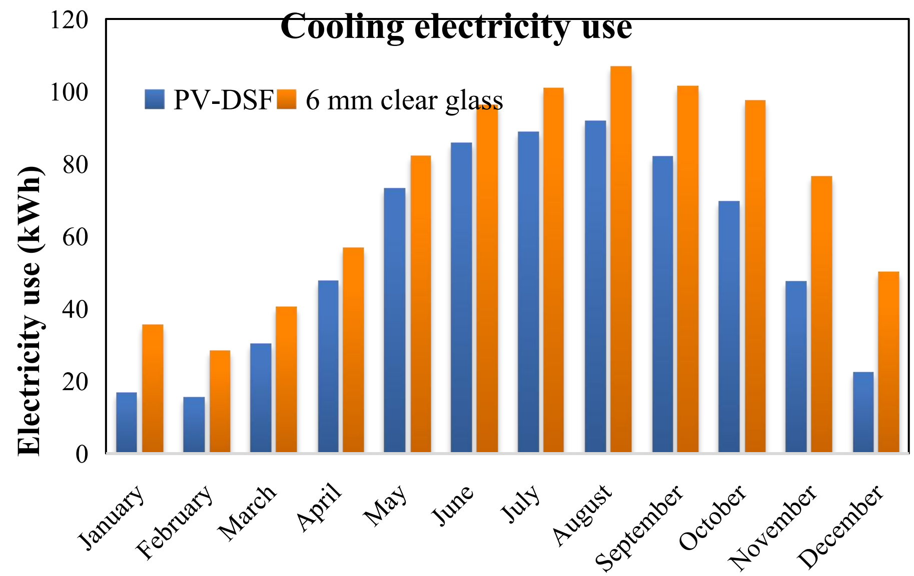


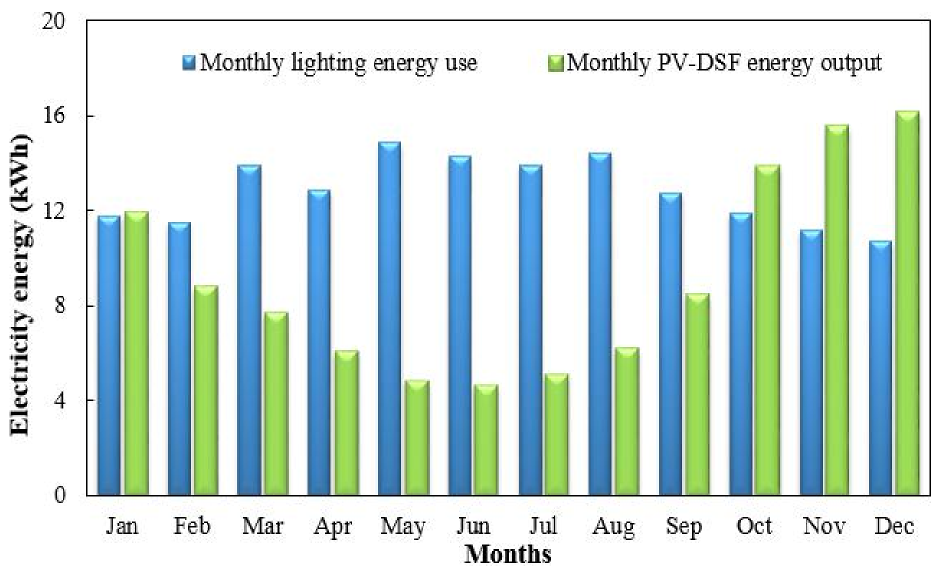
Study of the overall energy performance of BIPV facade:

- real-time power generation performance
- thermal performance
- natural lighting performance

Annual overall performance in Hong Kong







- The maximum monthly energy output : 5.6 kWh/m^2
- Annual energy output: 38 kWh/m^2
- Saving cooling energy use: 70 kWh/m^2/yr.
- Lighting can be powered by the PV-DSF itself in winter.

Experimental studies

BIPV test bed at Tung Chung

PV-IGU

PV-DSF

PV shading

The Housing Authority BIPV project

- Roof integration
- PV walls
- PV windows

Study on semi-transparent solar PV windows
- Data acquisition system

Study on semi-transparent solar PV windows

- Inside views of PV windows

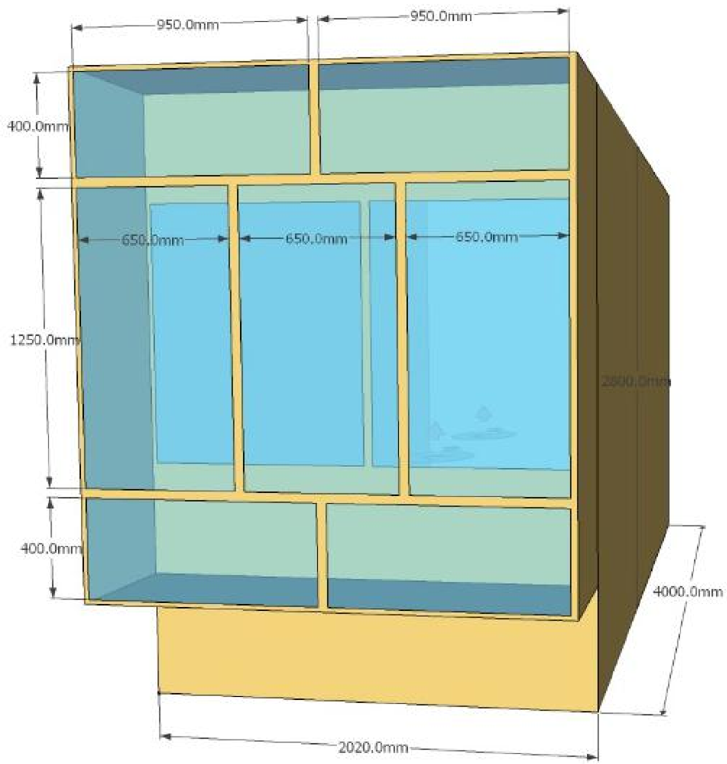
Ventilated PV window

Efficiency: 6.8%
Transmittance: 20%
Rated power: 68W/m²

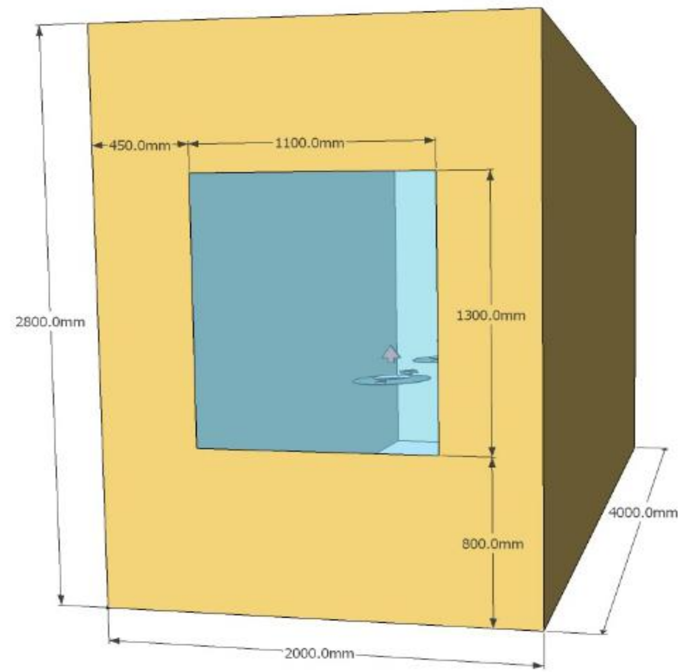
Efficiency: 6.3%
Transmittance: 20%
Rated power: 63W/m²

Hollow PV window

Energy performance of PV DSF and PV IGU



PV double skin façade

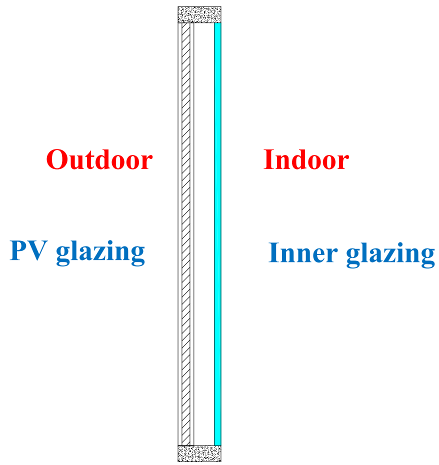


PV insulating glass unit

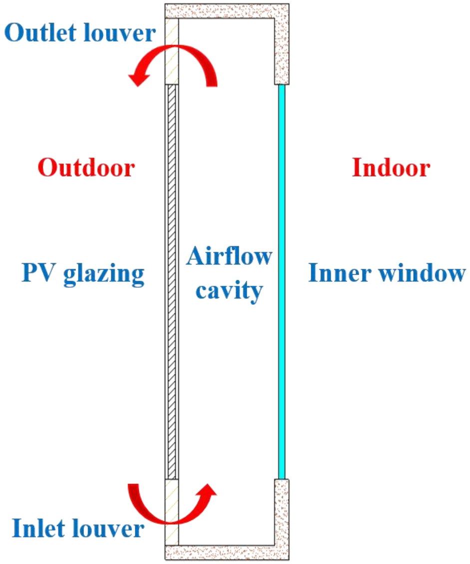
The heat transfer model, daylighting model and PV power generation model in EnergyPlus were adopted to investigate the corresponding performance simultaneously.

Structures of PV-IGU and PV-DSF

PV-IGU

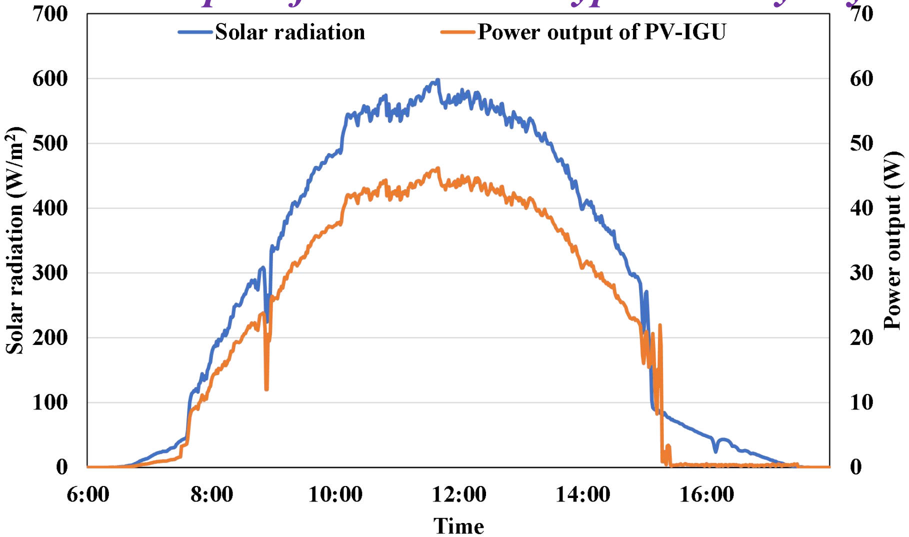


PV-DSF

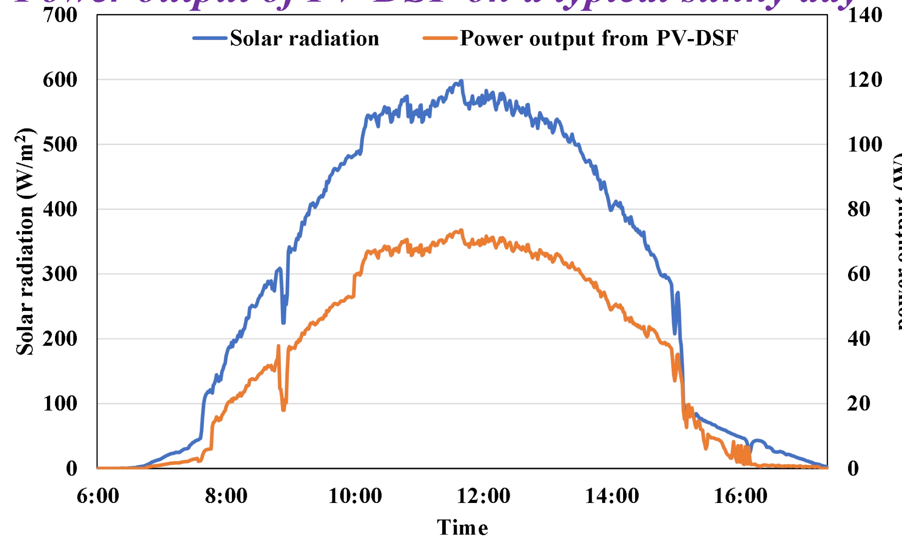


Experimental studies

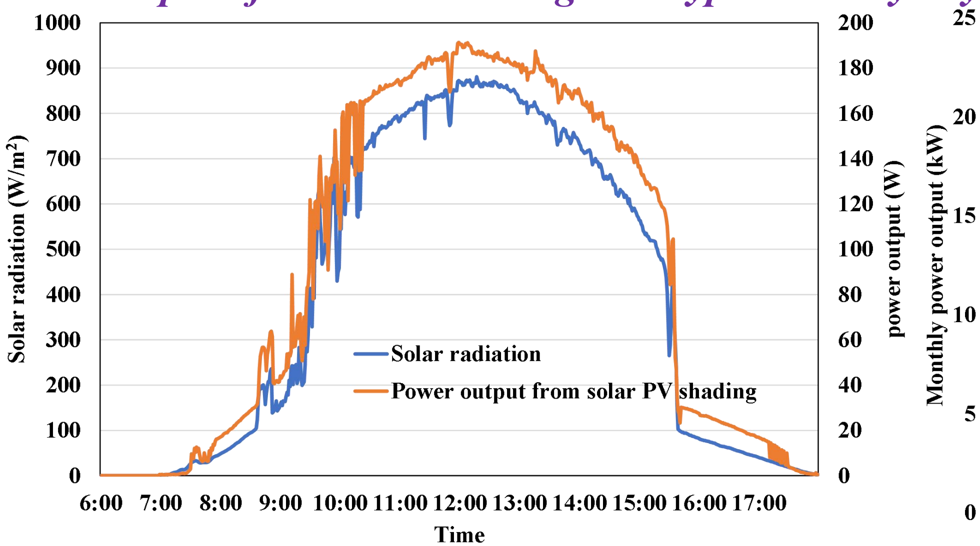
Power output of PV-IGU on a typical sunny day



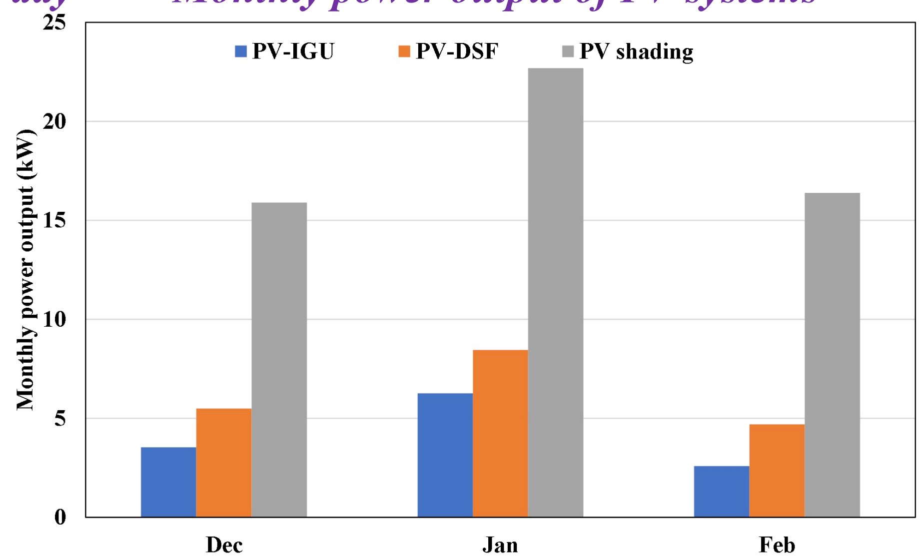
Power output of PV-DSF on a typical sunny day



Power output of solar PV shading on a typical sunny day

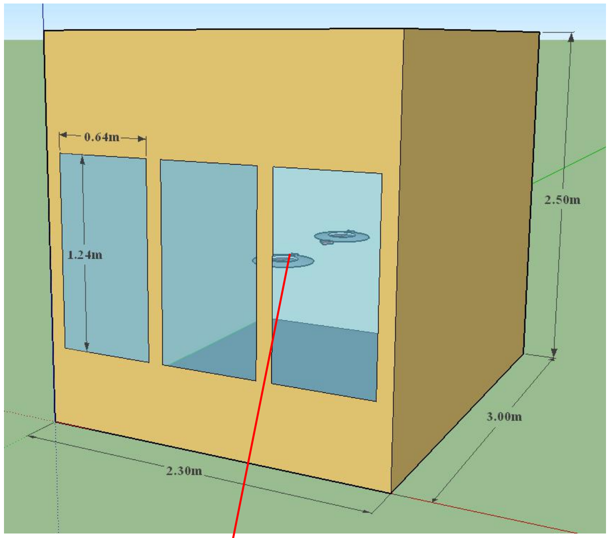


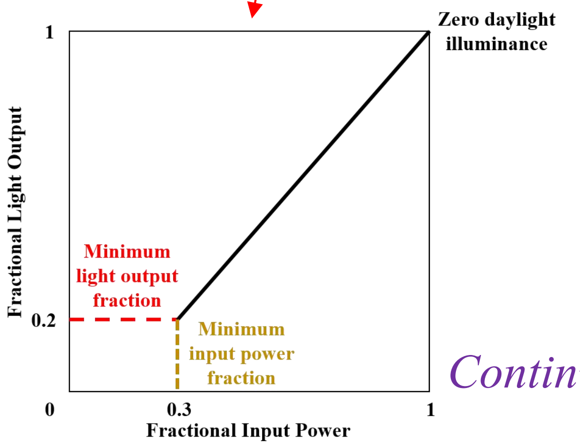
Monthly power output of PV systems



(3) Single-glazed PV glazing VS energy-efficient glazing

A generic representative model

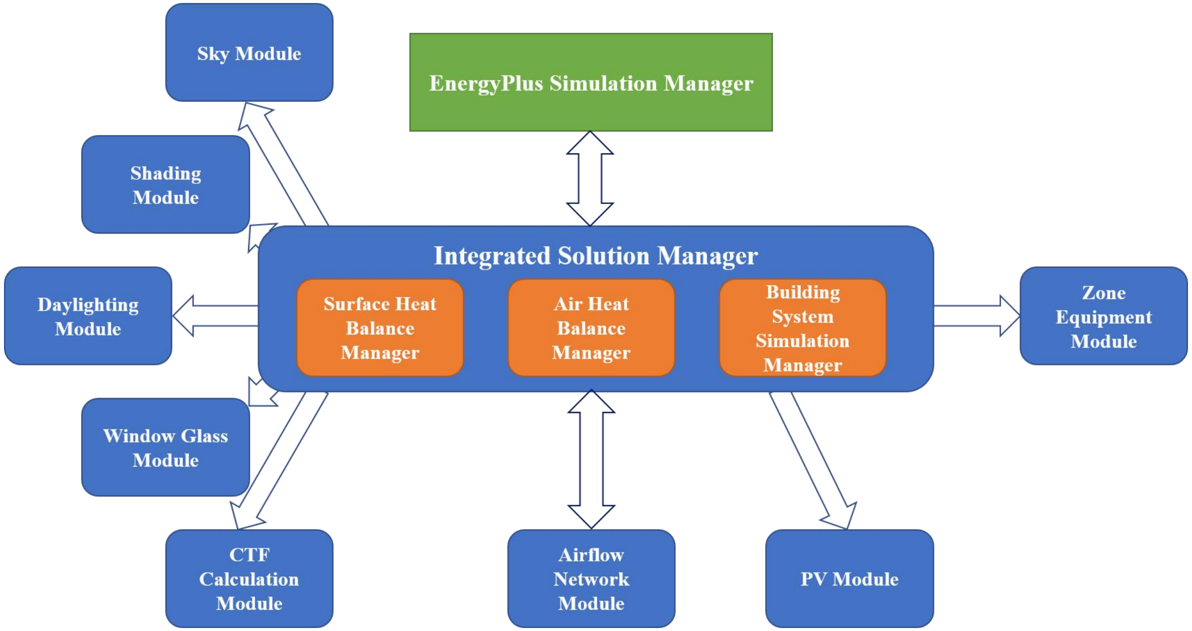




Continuous dimming control

Simulation tools:

Berkeley Lab WINDOW, EnergyPlus

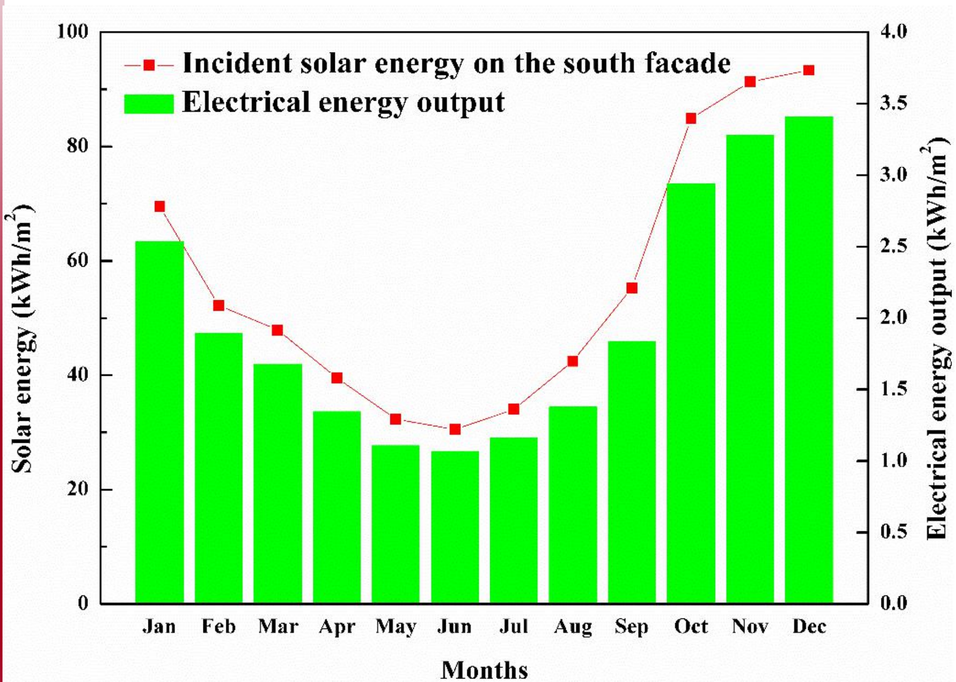


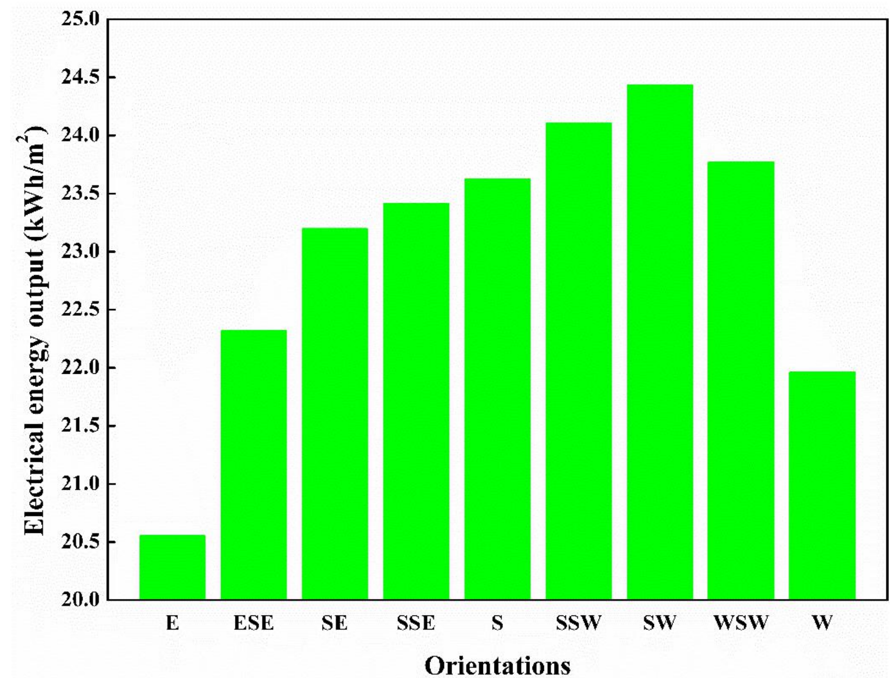
Sandia Array performance Model

- Empirical-based
- More accurate for thin-film solar cells

Single-glazed PV glazing

Power generation performance in Hong Kong





Monthly power output per unit area of south facing solar PV windows

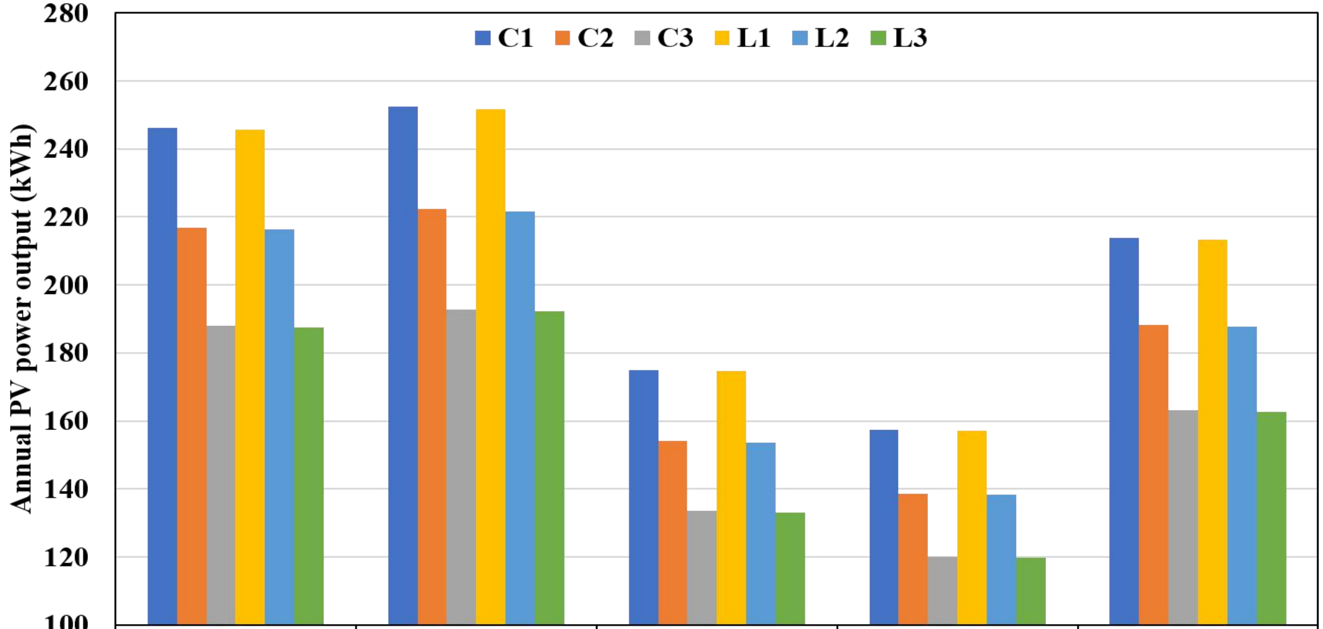
Annual power outputs per unit area of solar PV windows in different orientations

1) Significant difference among different months: more in winter and less in summer.

2) Annual electricity output varies with orientations: SW > SSW > WSW > S > … > E

Energy performance of PV-IGU

Annual PV power output



	Harbin	Beijing	Shanghai	Hong Kong	Kunming
C1	246.2	252.5	175.0	157.4	213.8
C2	216.8	222.4	154.1	138.6	188.3
C3	187.9	192.8	133.5	120.0	163.2
L1	245.8	251.8	174.6	157.0	213.3
L2	216.4	221.7	153.7	138.2	187.8
L3	187.5	192.2	133.1	119.7	162.7

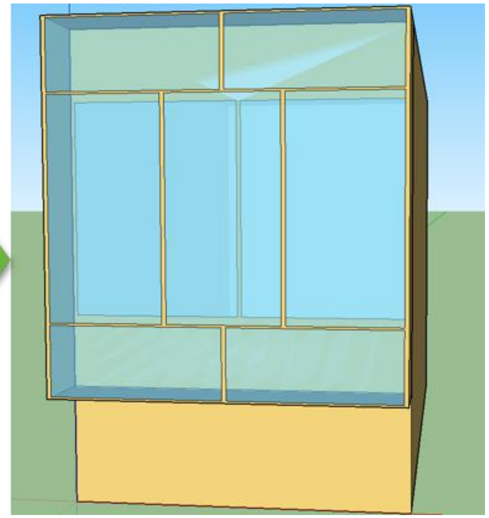
Location: Beijing > Harbin > Kunming > Shanghai > Hong Kong

Higher transmittance → Lower power output

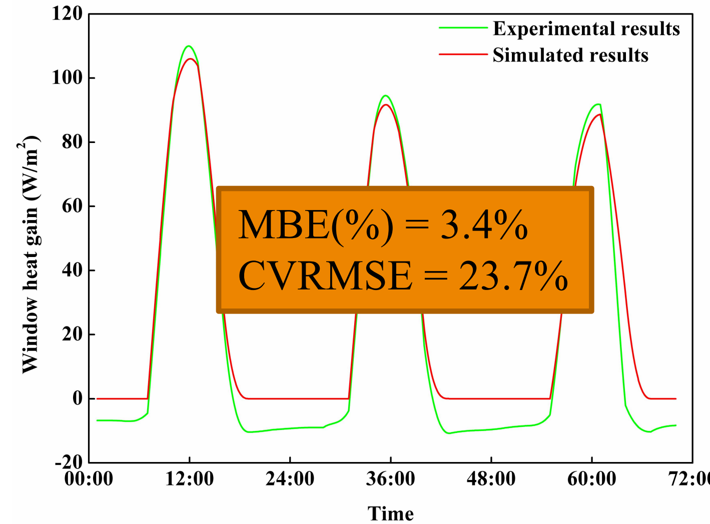
Energy performance of PV-DSF

Model development and validation

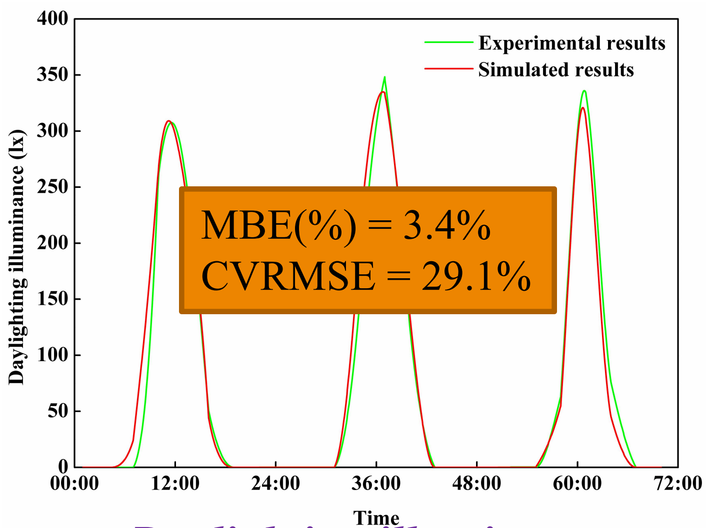
Test bed



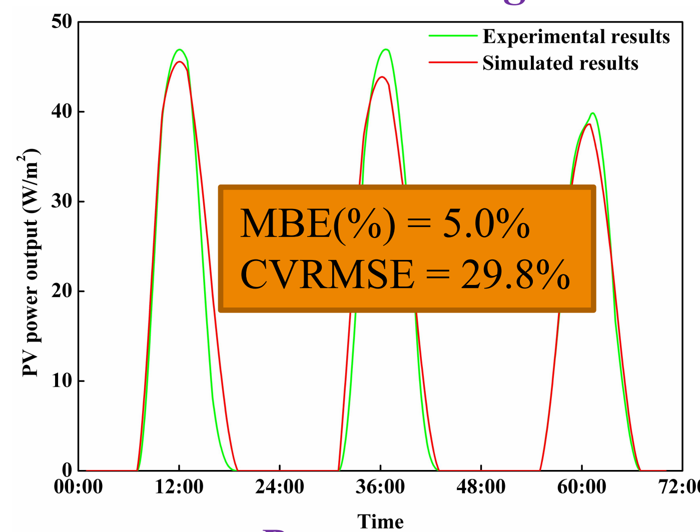
Simulation model



Window heat gain



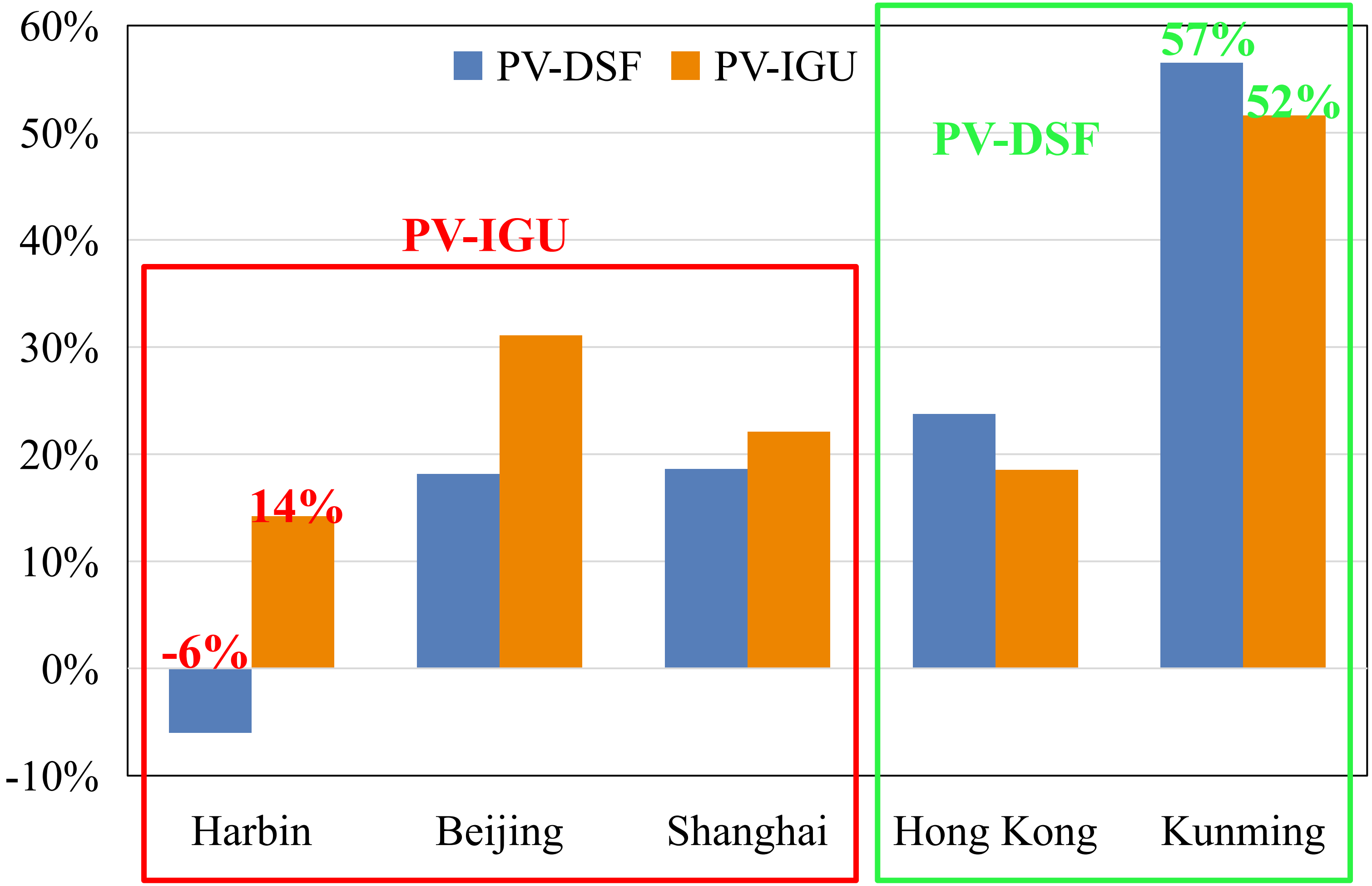
Daylighting illuminance



Power output

Energy performance of PV-DSF

Energy saving potential of PV-DSF and PV-IGU compared to reference window

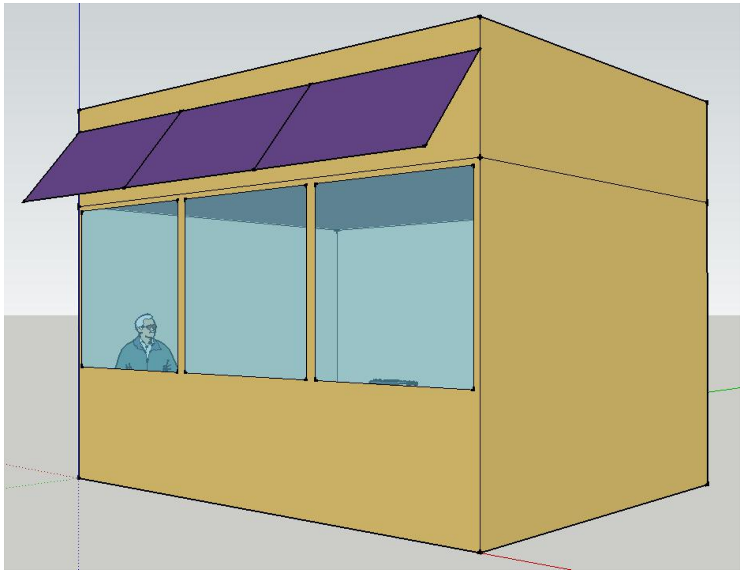


How to improve?
- **Inner glazing**
- **Ventilation mode**

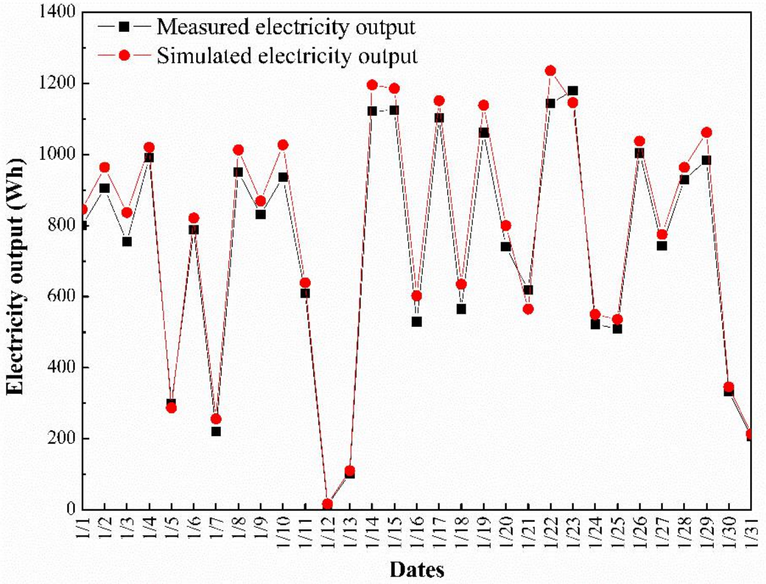
Energy saving potential of solar PV shadings

Research gap

- Daylighting performance is rarely considered in previous studies. However, both external and internal shadings affect the daylighting performance of the room.
- Comparison between external solar PV shadings and interior shading devices has not been reported yet.



Simulation model of solar PV shadings

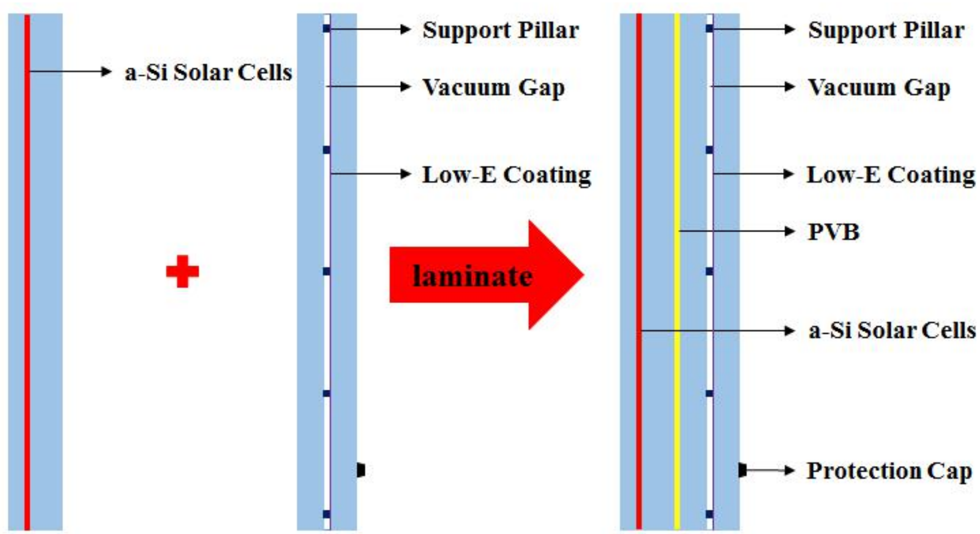


Validation of the electricity output

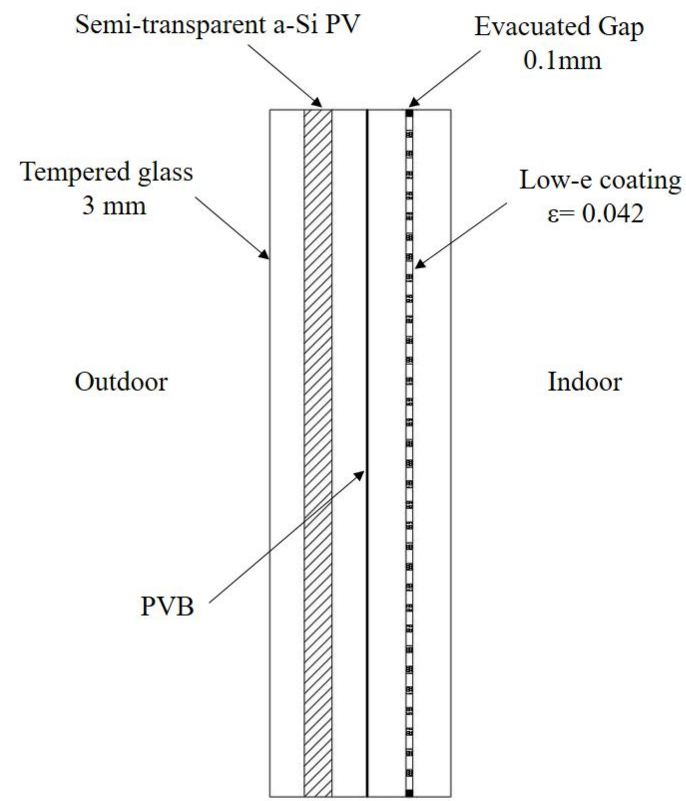
Due south, Tilt angle: 55˚, Error: 5%

(3) Advanced VPV IGU

- A novel vacuum PV insulated glass unit (VPV IGU) is proposed to combine the advantage of the high thermal insulation performance of vacuum glazing and the power generation capability of STPV windows.



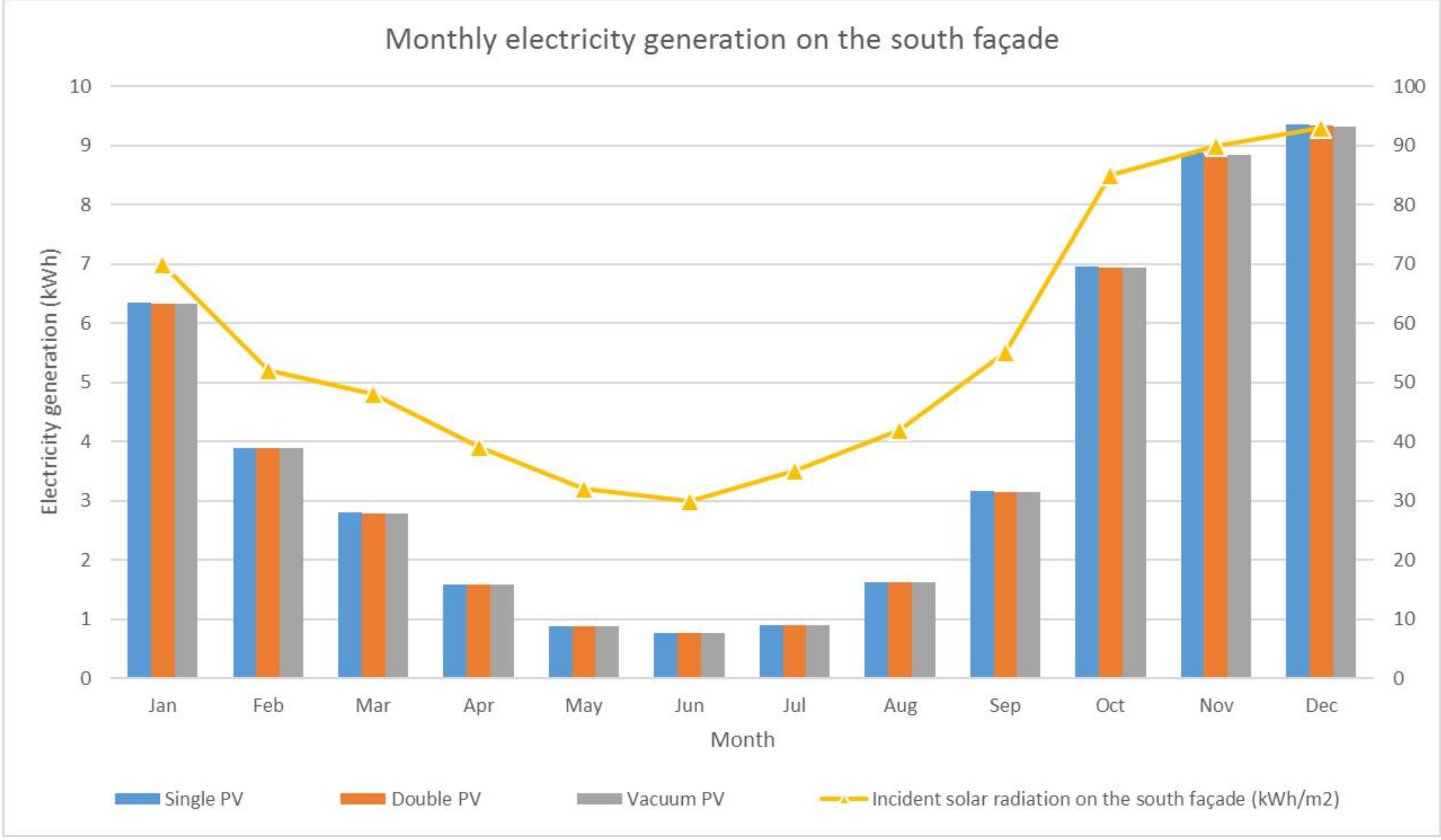
The structural details of VPV IGU



The cross-section of VPV IGU

Power generation Performance

- The difference of the power generation among different BIPV systems is less than 1%, and the single-pane PV glazing produced the most electricity output.

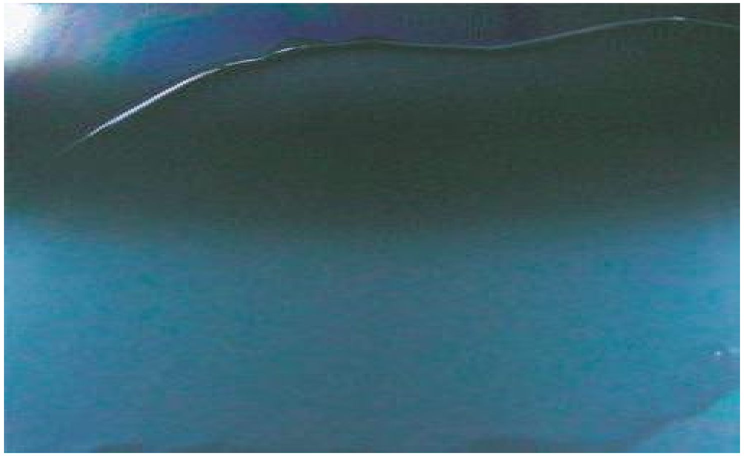


(4) Development of self-cleaning nano-coating for PV

Super-hydrophobic , θ(Lotus leaf):>150°

Super-hydrophobic self-cleaning glass

Super-hydrophilic, θ(clean glass surface) :<10°



Super-hydrophilic self-cleaning glass

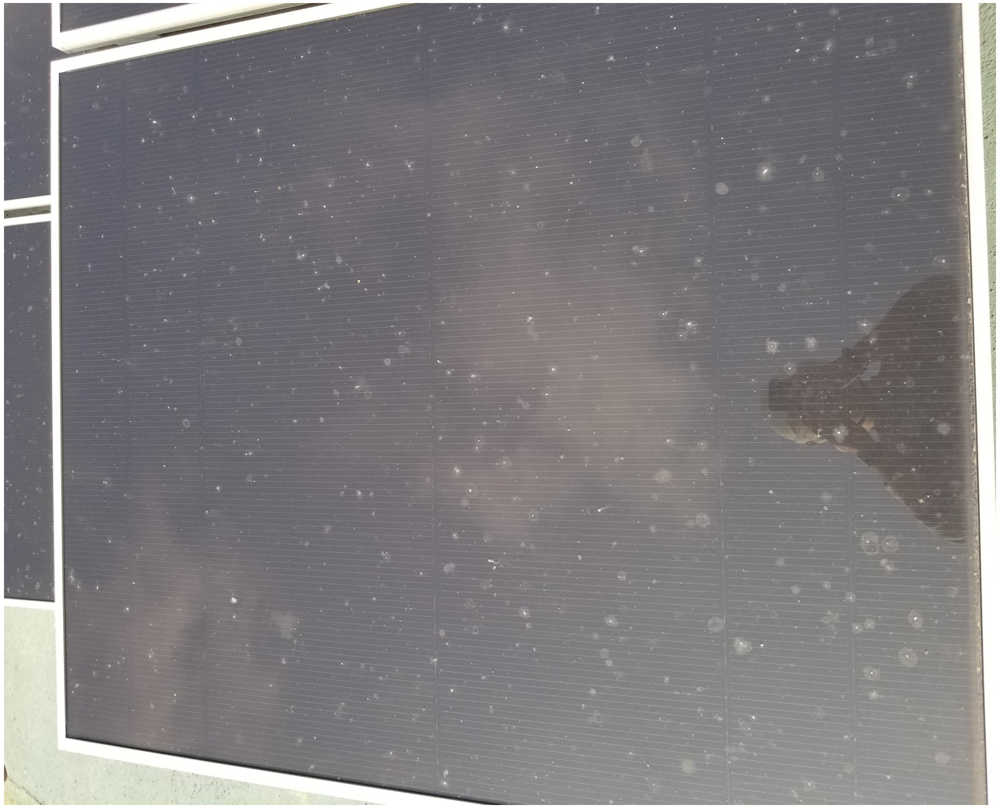
Advantages of our product: Superior self-cleaning property and cheaper cost

The comparison between two PV modules after two months in Shenzhen.
The self-cleaning coating has superior super-hydrophilicity.

Advantages of our product: Superior self-cleaning property and cheaper cost

With self-cleaning coating

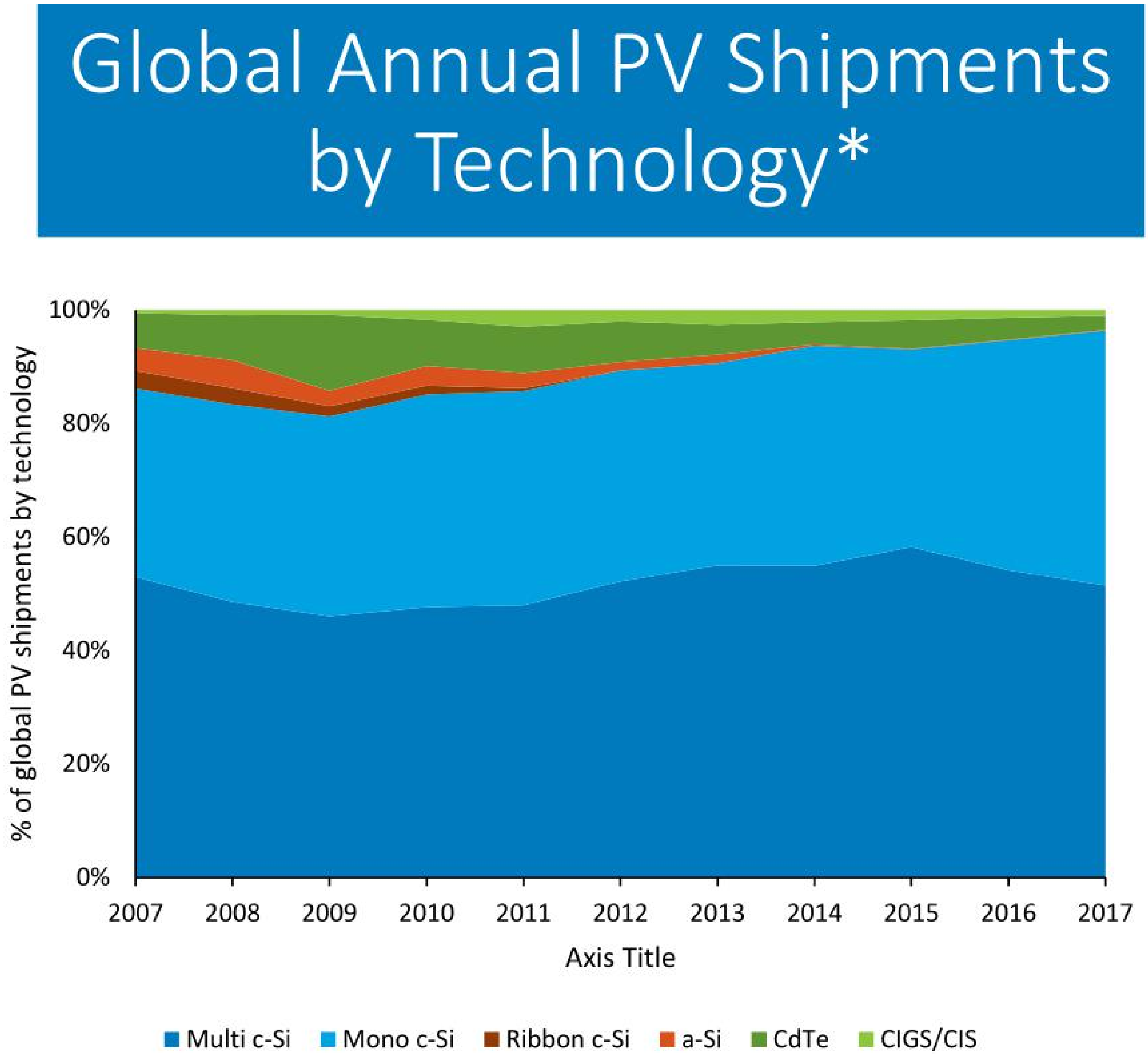
Without self-cleaning coating



Comparisons between two PV modules after about one year in Hong Kong.

The self-cleaning coating has superior super-hydrophilicity.

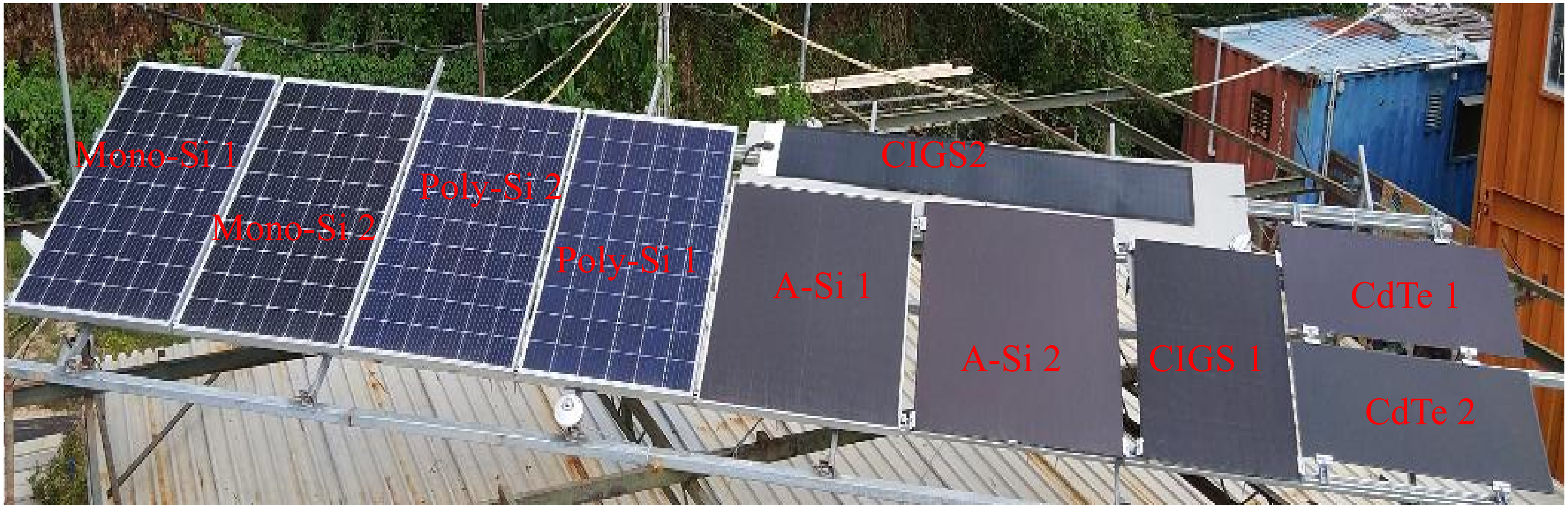
(4) Selection of PV modules



In 2017:

- Monocrystalline: 45%；
- Poly-crystalline: 51%；
- Thin film: 4%。

Experimental study



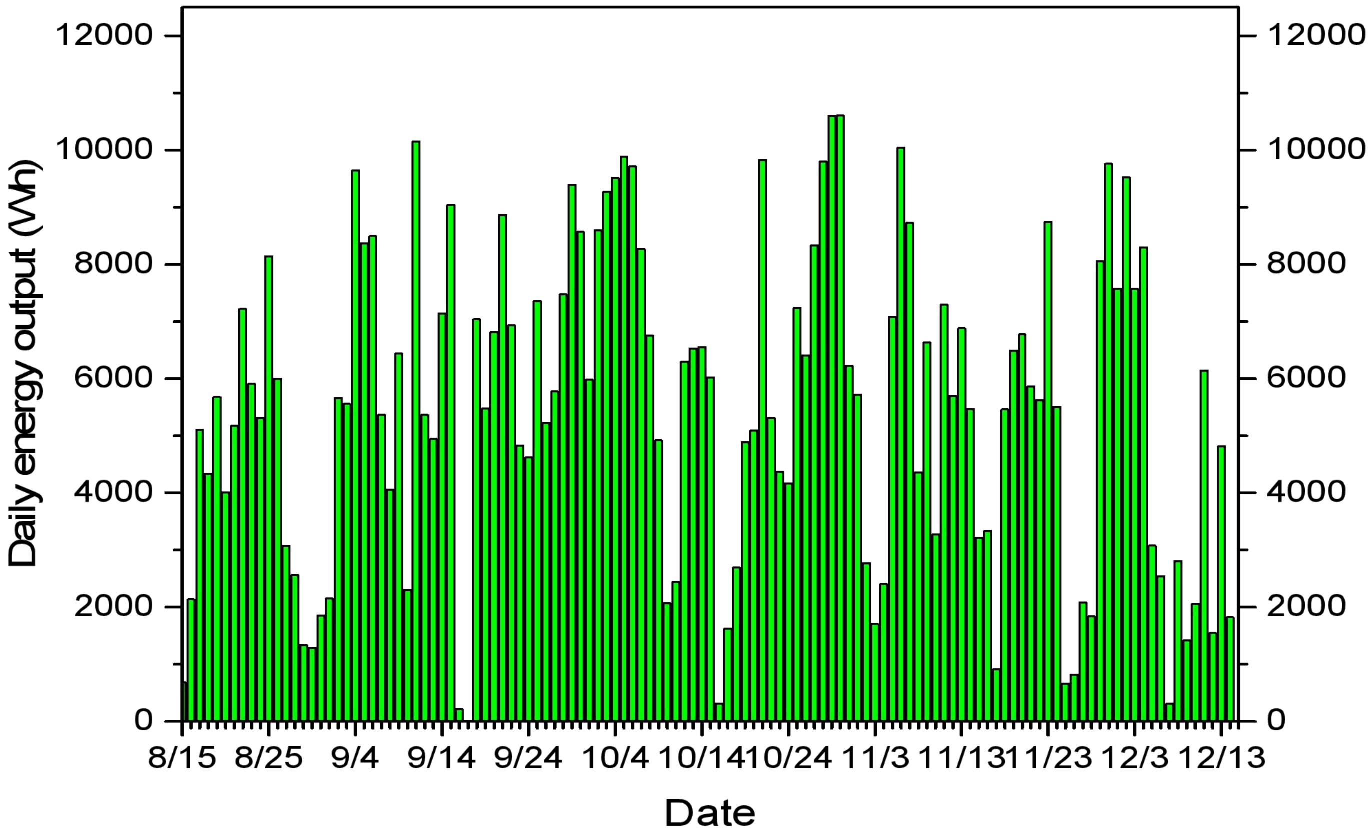
The PV system testing rig in the New Territories

In order to obtain the actual energy performance of PV modules, an on-site test system was developed in Hong Kong. All the ten solar PV panels are installed facing south with a tilt angle of 22°.

Selection of solar PV panels for detailed study -- 5 different types

Solar Cell-technologies	Mono-Si 1	Mono-Si 2	Poly-Si 1	Poly-Si 2	A-Si 1	A-Si 2	CIGS 1	CIGS 2	CdTe 1	CdTe 2
Model										
Nominal Power (W)	305	300	280	275	140	130	140	115	107.5	80
Short circuit current (A)	9.94	9.77	9.37	9.35	5.28	2.65	1.79	4.52	1.75	0.95
Open circuit voltage (V)	40.2	39.76	38.65	38.72	42.3	71	106.7	37.6	86.6	118.9
Current at maximum power (A)	9.24	9.26	8.86	8.77	4.34	2.22	1.62	3.87	1.57	0.85
Voltage at maximum power (V)	33.0	32.41	31.61	31.36	32.2	54	86.5	29.7	68.6	94.1
Maximum system voltage (V)	1000 (IEC)	1000 (IEC) 1000 (UL)	1000/ 1500 DC(IEC)	1000 (IEC) 1000 (UL)	N/A	1000	1000 (IEC) 600 CSA/UL	1000 (IEC) 600 (UL)	1000V (class II) 1500V class 0	N/A
Module Efficiency (%)	18.7	18.0	17.1	16.5	9.6	9.1	14.9	12.0	14.9	11.1
Weight (kg)	18.2	18.8	18.2	18.8	18.3	25	16.5	2.7	12	11.8
Dimension (mm×mm×mm)	1650*991*40	1670*1000*32	1650*991*35	1670*1000*32	1310*1110*40	1300*1100*6.8	1190*790*7.3	2598*370*17	1200*600*6.8	1200*600*6.8

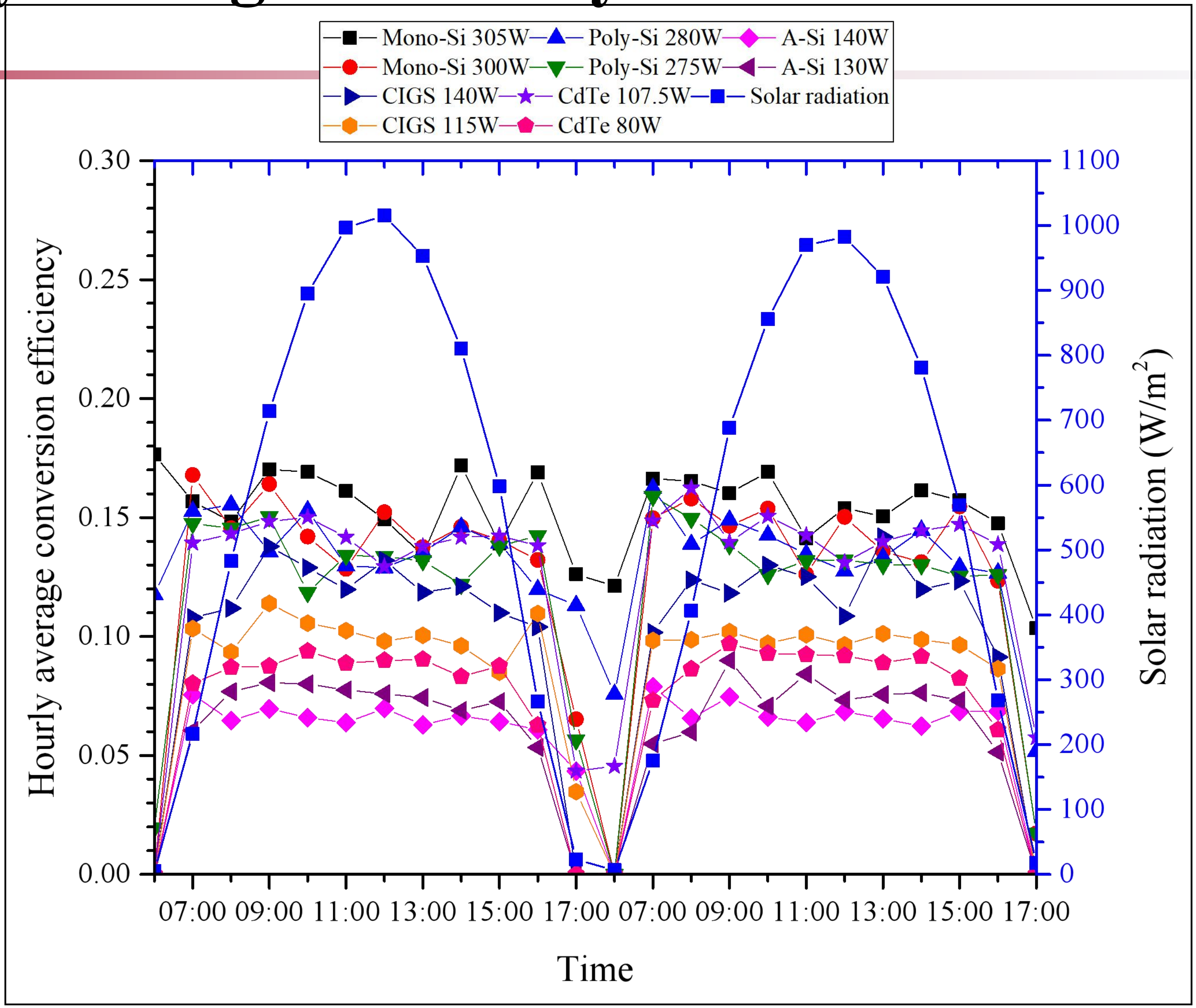
Daily power generation from the whole system



The PV system has been working very well for 10 months. The highest daily energy output is 10.6 kWh on 30th November 2018.

Hourly average efficiency of PV modules

In typical sunny days (30th Oct and 6th Nov 2018):

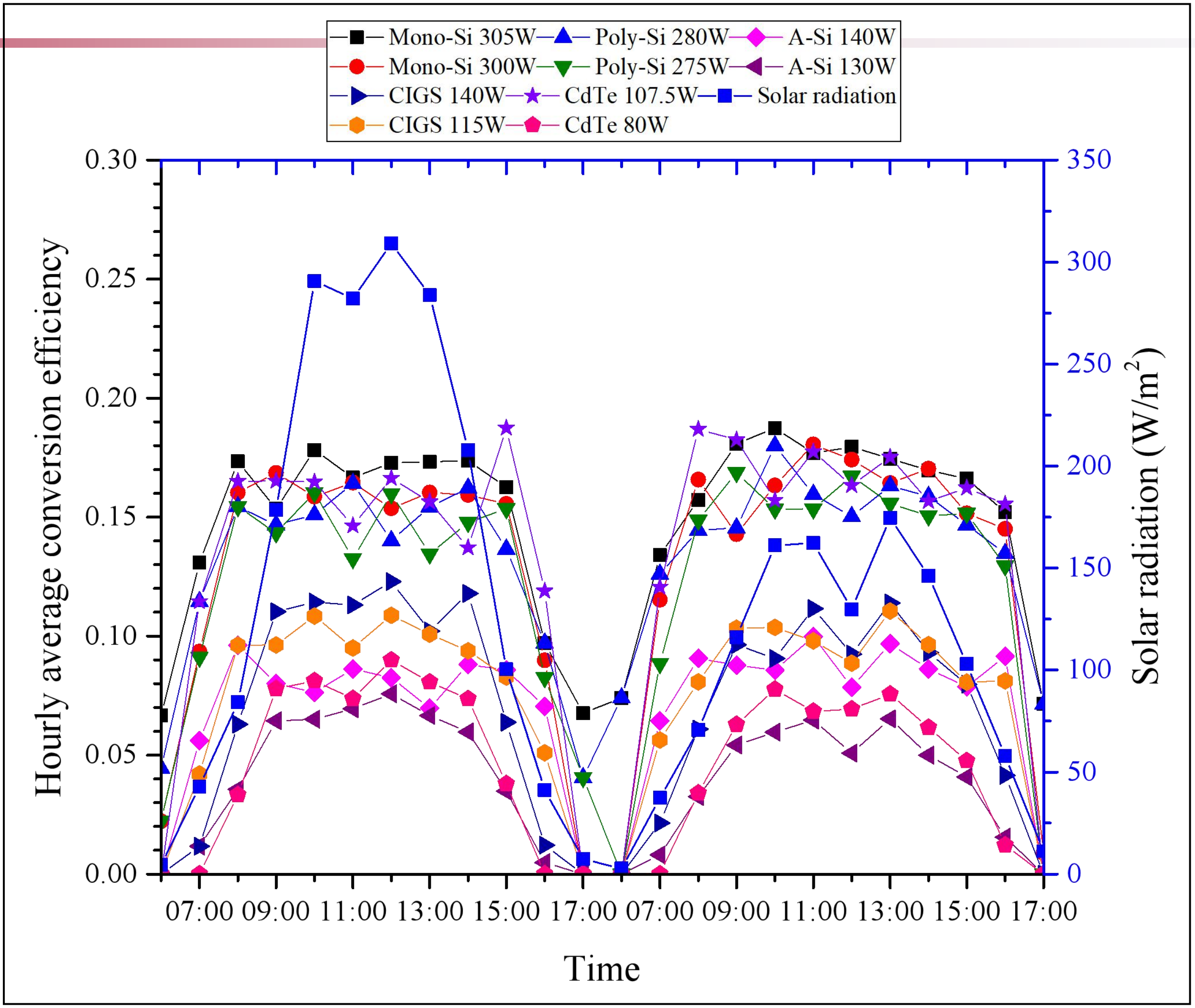


Energy conversion efficiencies:

Mono-Si > CdTe (107.5Wp) >Poly-Si > CIGS >A-Si

Hourly average efficiency of PV modules

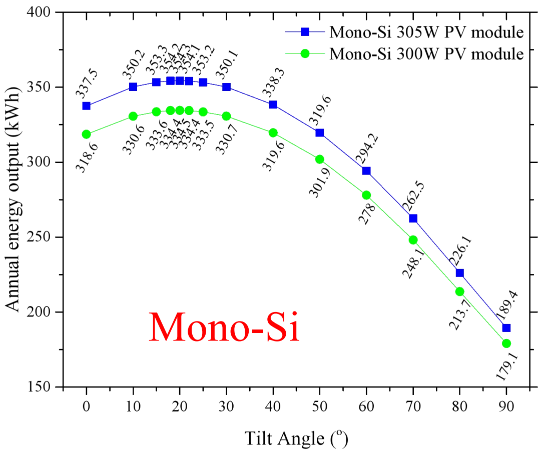
In typical cloudy days (2^{nd} Nov and 3^{rd} Nov 2018):

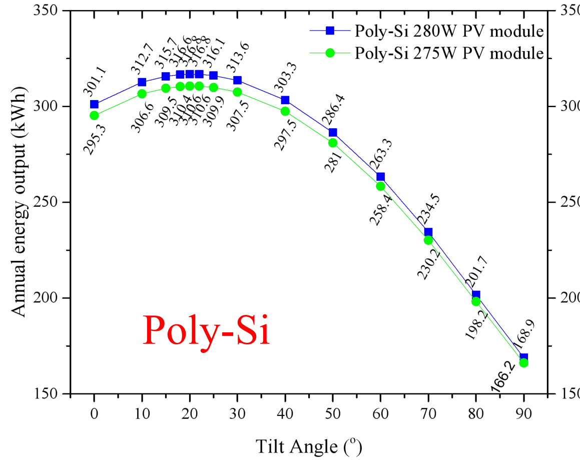


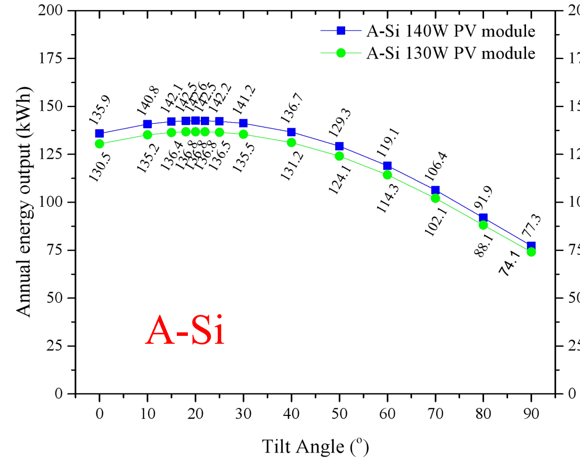
Energy conversion efficiencies:

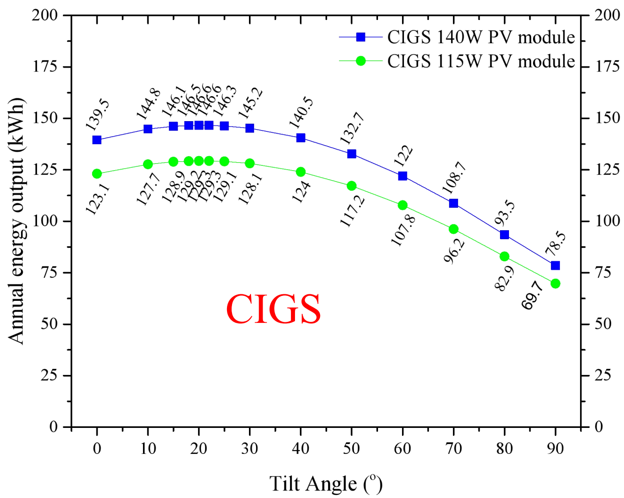
Mono-Si > CdTe (107.5Wp) > Poly-Si > > CIGS >A-Si

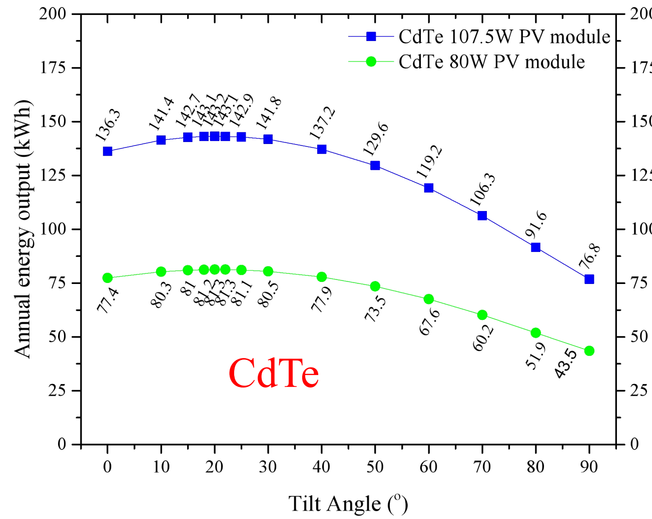
Simulation of annual power generation for different tilt angles (south)











The optimal tilt angles of PV modules are found to be 18-22^{o} depending on local latitude and weather.

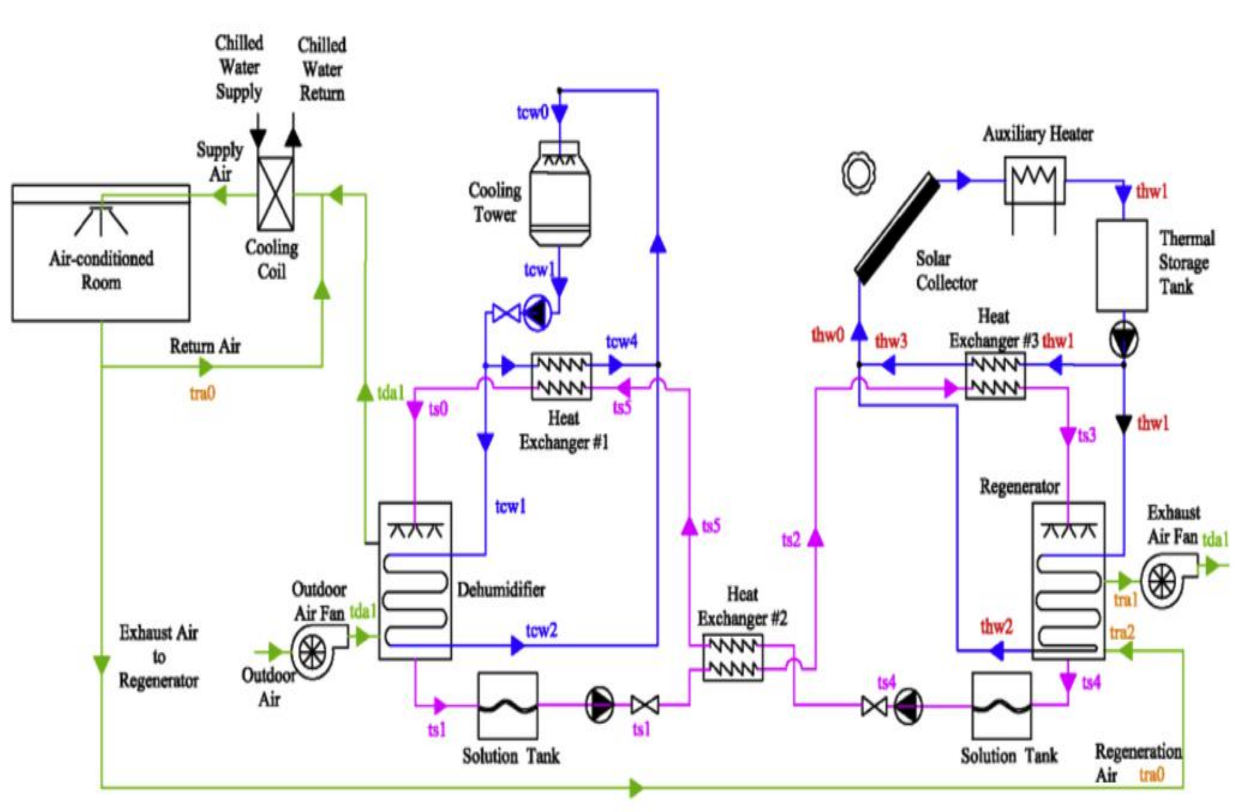
Simulation results: Annual power generation at best position (azimuth=180º, and tilt angle=22º)

Solar PV panel	Mono-Si 305W	Mono-Si 300W	Poly-Si 280W	Poly-Si 275W	A-Si 140W	A-Si 130W	CIGS 140W	Flexible CIGS 115W	CdTe 80W	CdTe 107.5 W
Annual total (kWh)	354.1	334.4	316.7	310.6	142.6	136.8	146.6	129.4	81.3	143.2
Annual output (kWh/m²)	215.9	200.2	193.1	186.0	98.3	95.7	156.0	134.8	112.9	198.9
Annual output (kWh/Wp)	1.16	1.11	1.13	1.13	1.02	1.05	1.05	1.12	1.02	1.33

Per m² (kWh/m²): Mono-Si > CdTe > Poly-Si > CIGS > a-Si

Energy yield (kWh/Wp): CdTe (107.5Wp) > Mono-Si > Poly-Si > CIGS > A-Si

3. Solar liquid desiccant air-conditioning (SLDAC)

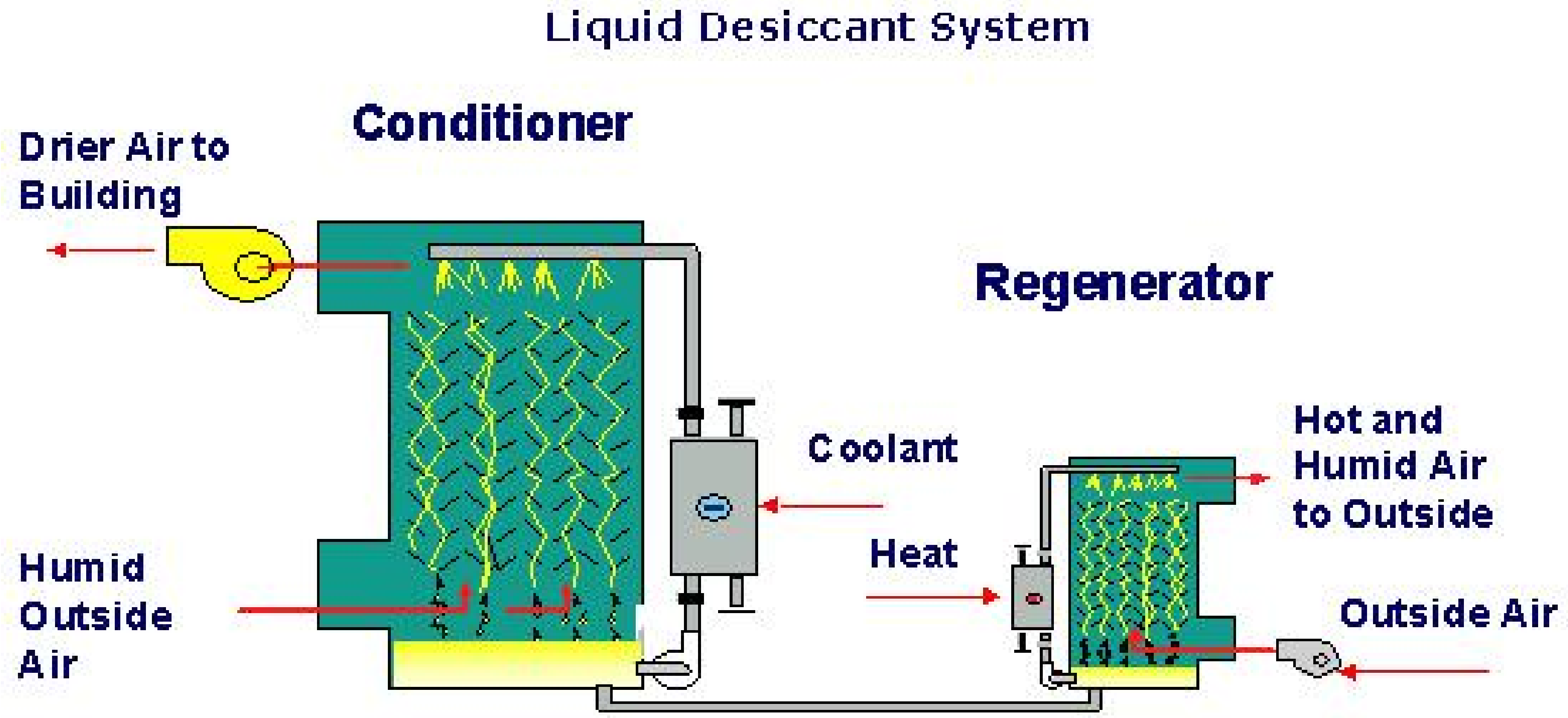


Equipment

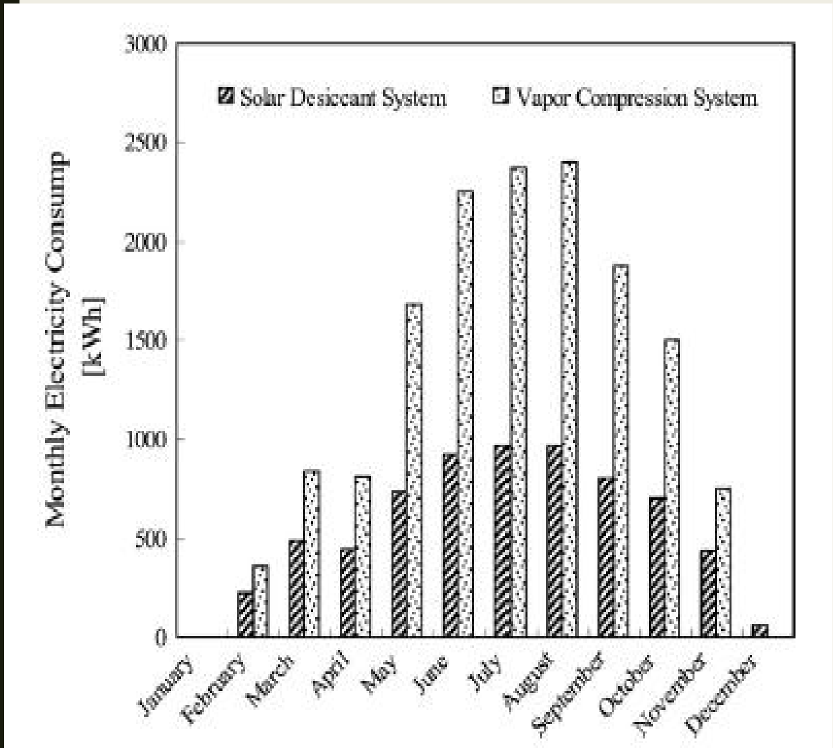
- Dehumidifier
- Solar Collector/ Regenerator
- Solution storage tank
- Heat exchanger

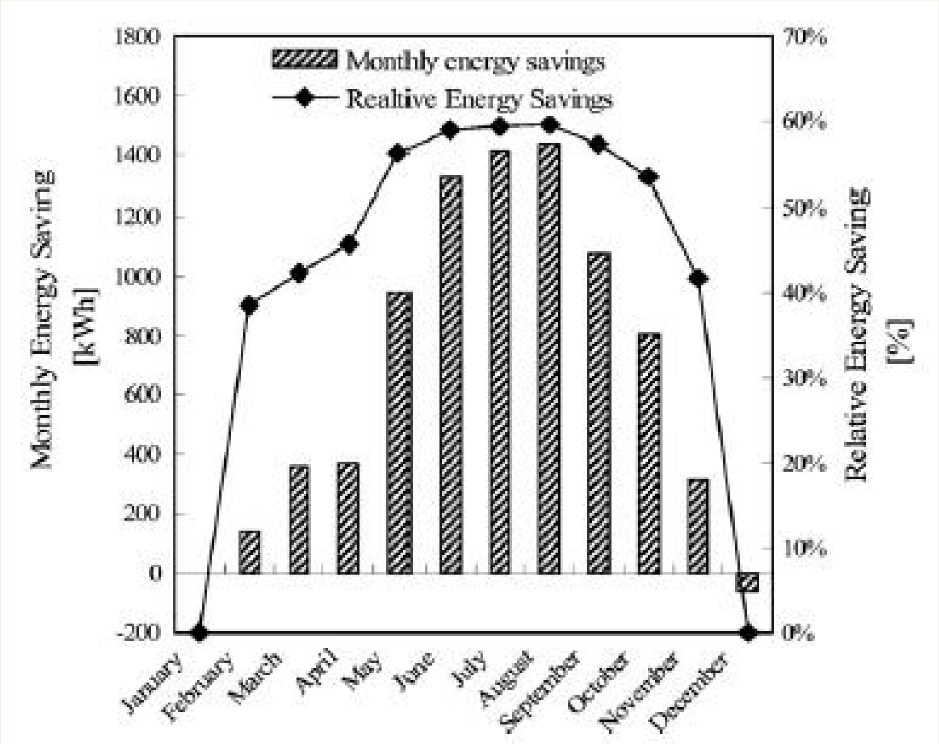
- Green line: Air flow path
  - Supplied by outdoor air fan
  - Moisture is removed in dehumidifier
  - Further cooled by AHU

Possible Configurations of the System



Annual energy performance – bigger share in latent load





Solar Desiccant Air Conditioning

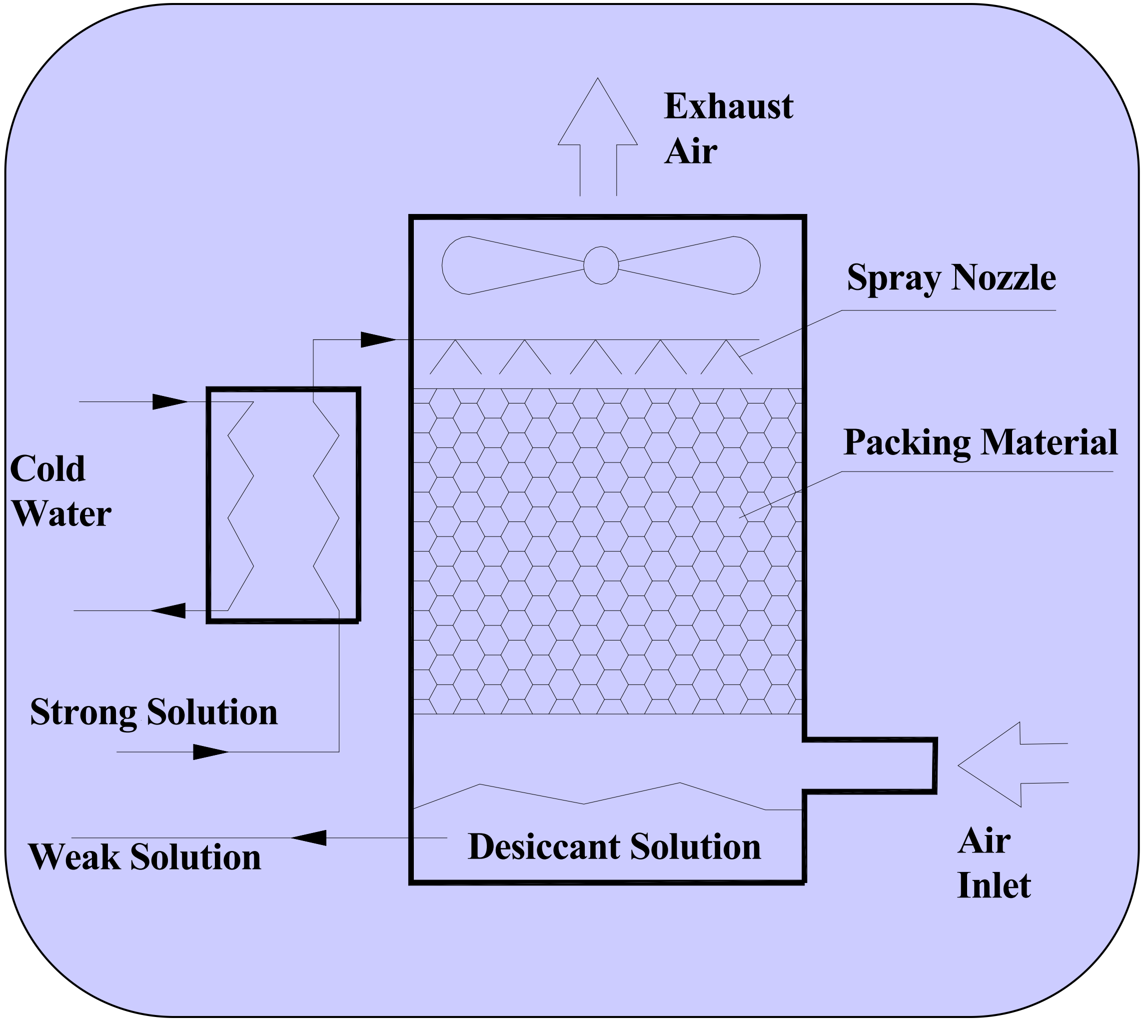
----solar assisted air conditioning

Moisture Control → Desiccant Dehumidification → Latent Load

Temperature Control → Air cooling → Sensible Load

Separate handling of latent and sensible loads.

The Desiccant Dehumidifier

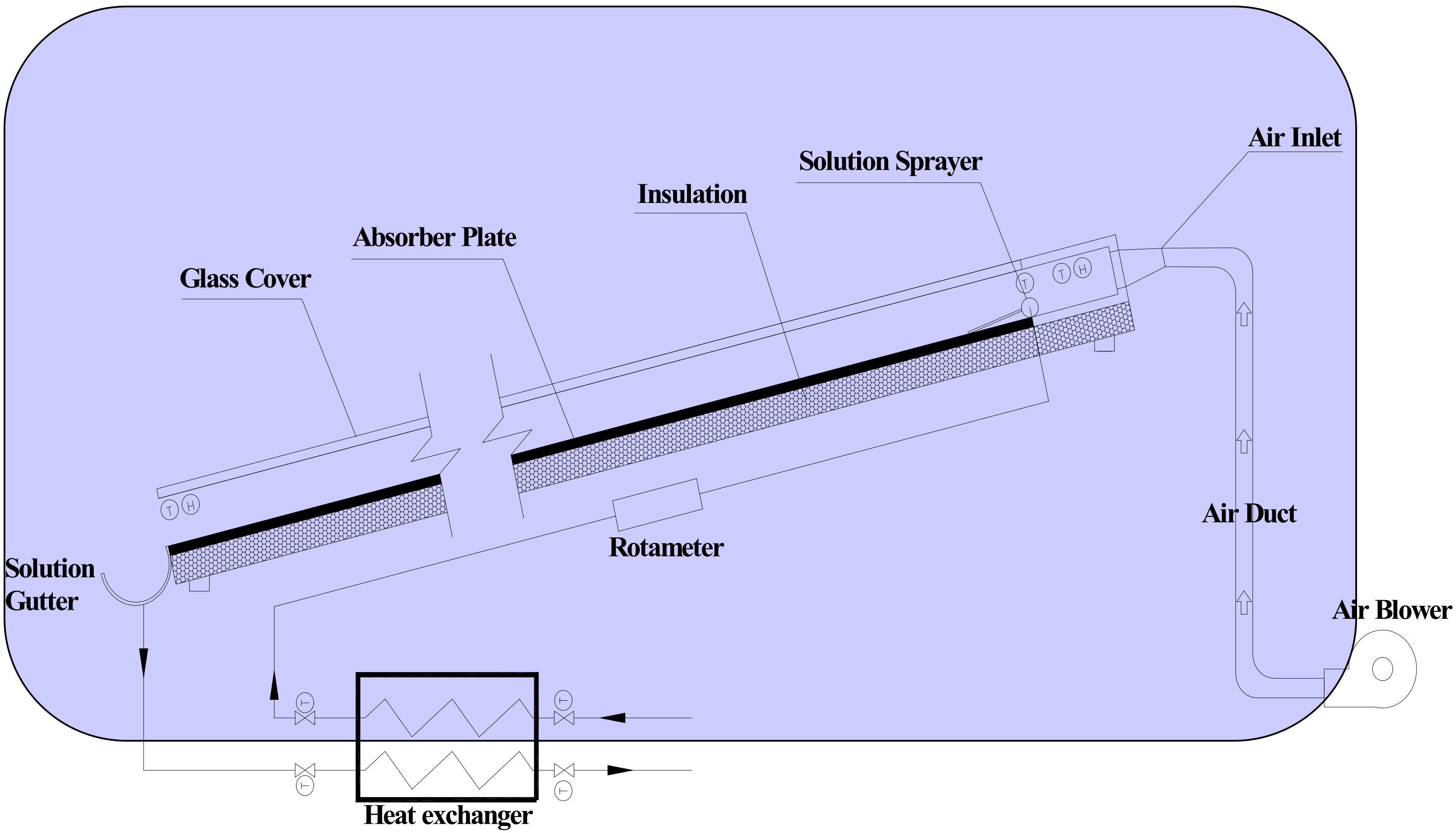


Raschig Ring

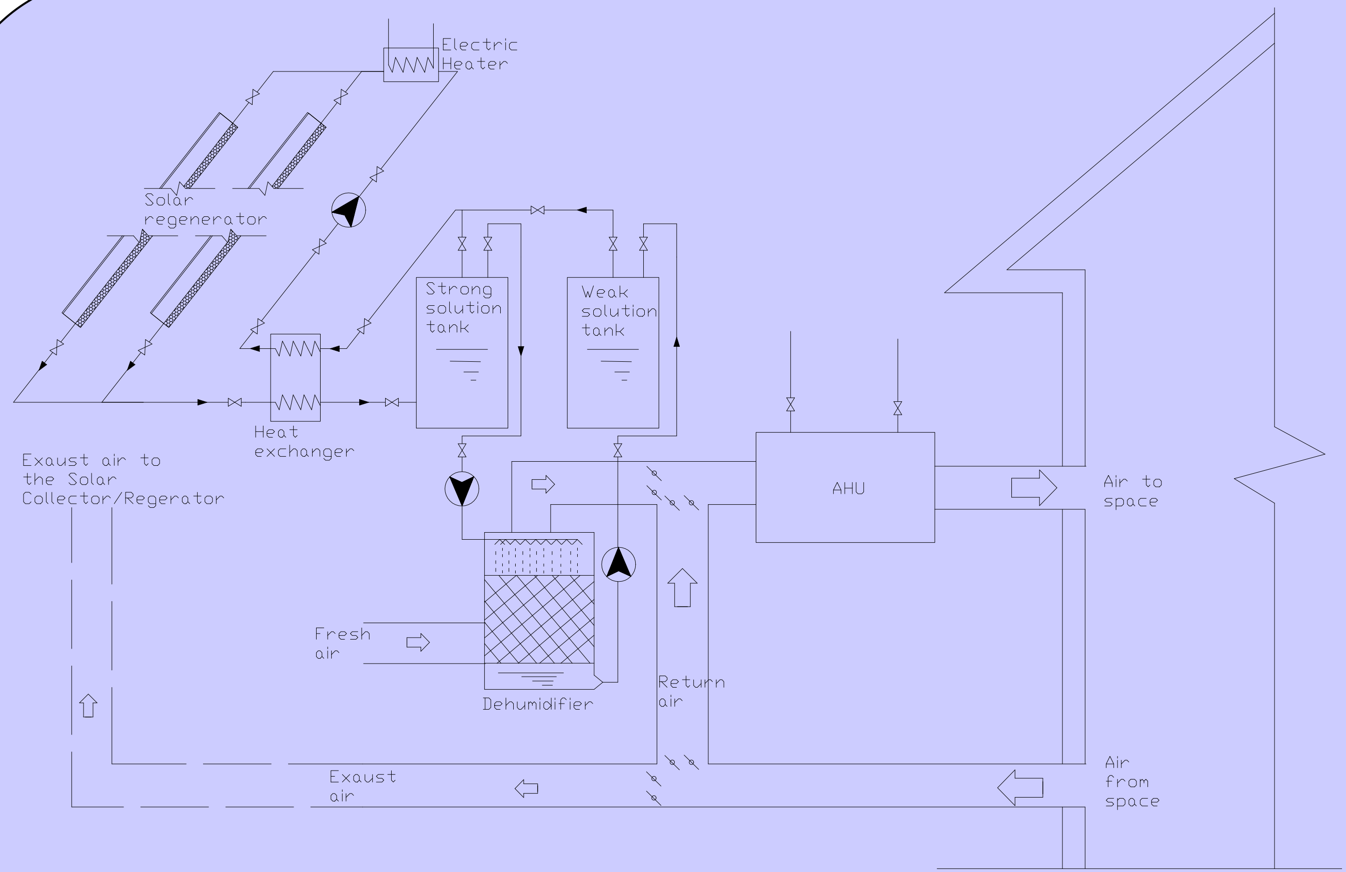
Berl Saddlen

Pall Ring

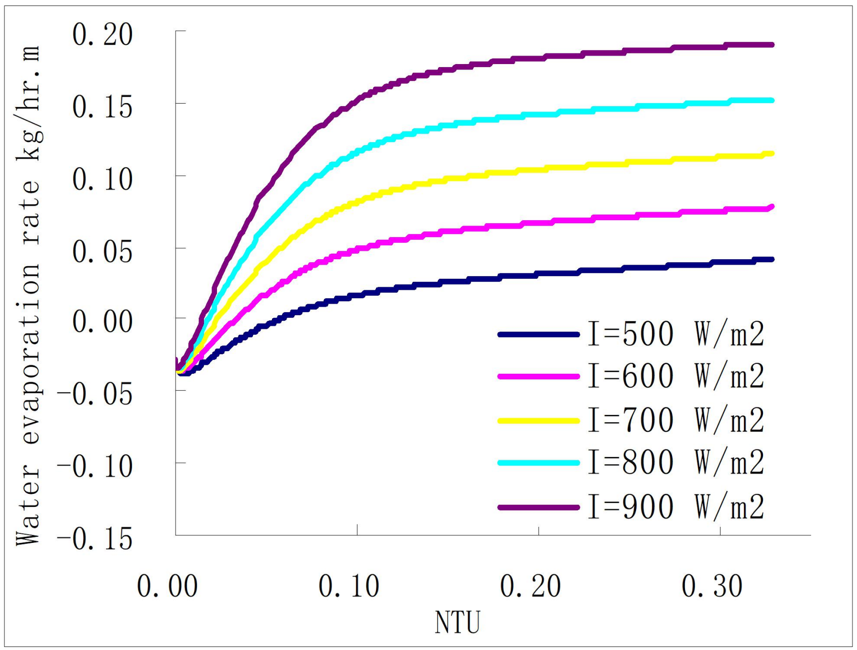
The Open Cycle Solar Collector/Regenerator



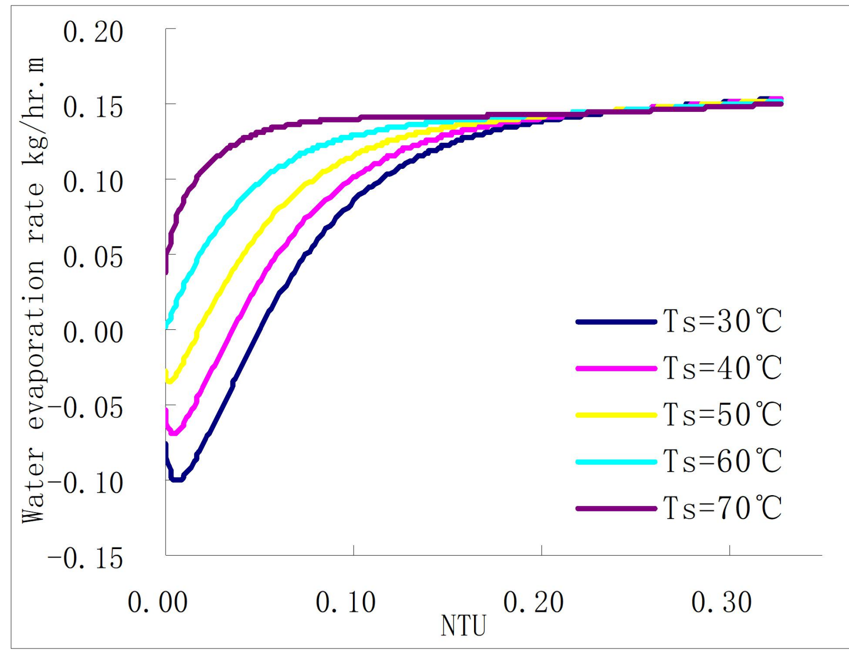
Possible Configurations of the System



Parametric analysis



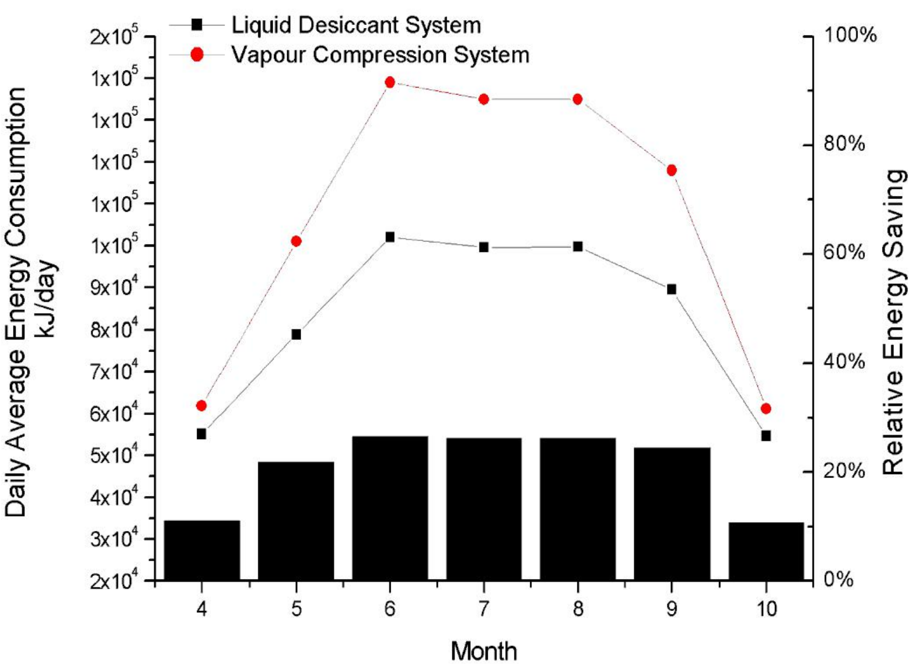
(a) Solar radiation



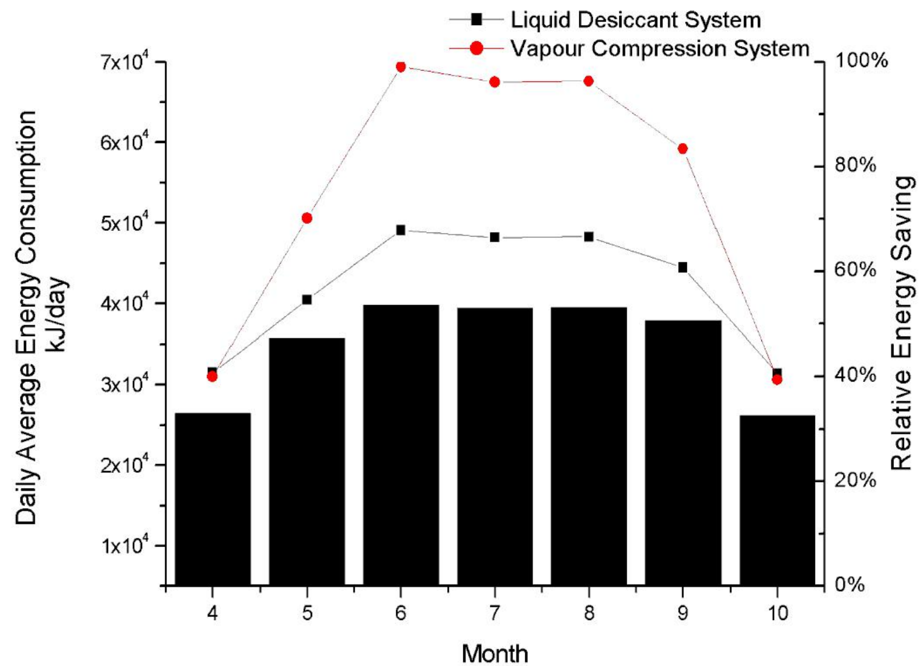
(b) Solution temperature

Effects of the main parameters on a solar C/R

System Performance on Design Day



Energy savings for low latent load condition (SHF=0.8)



Energy savings for high latent load condition (SHF=0.6)

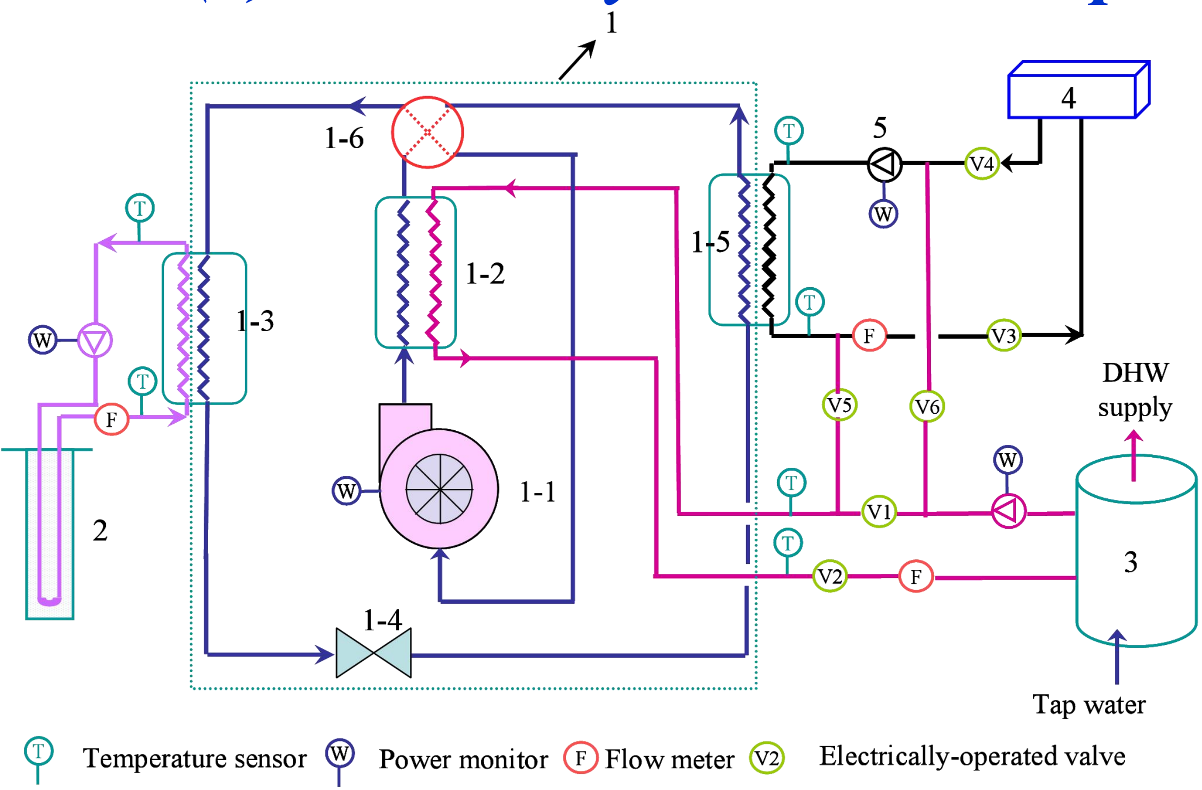
4. Study on hybrid GCHP systems for areas with unbalanced cooling and heating loads

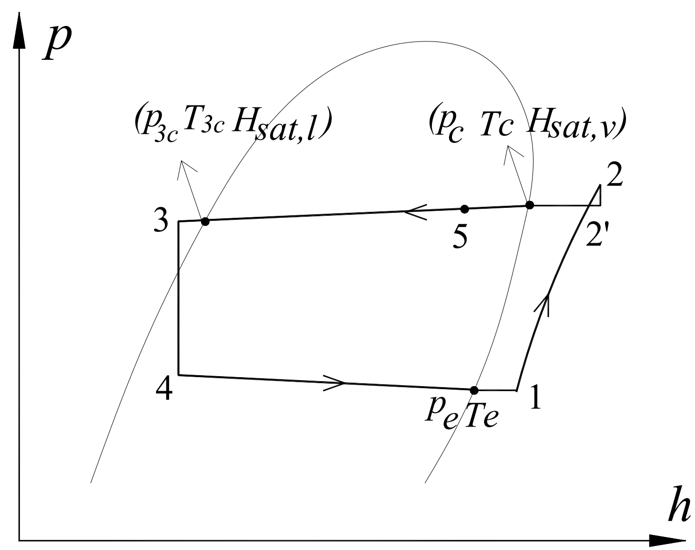
4.1. Research in GCHP system for cooling load dominated buildings

- Hybrid GCHP (HGCHP) system with desuperheater
- HGCHP system with cooling tower
- HGCHP system with nocturnal cooling radiator

Research in GCHP system for cooling load dominated buildings

(1) HGCHP system with desuperheater

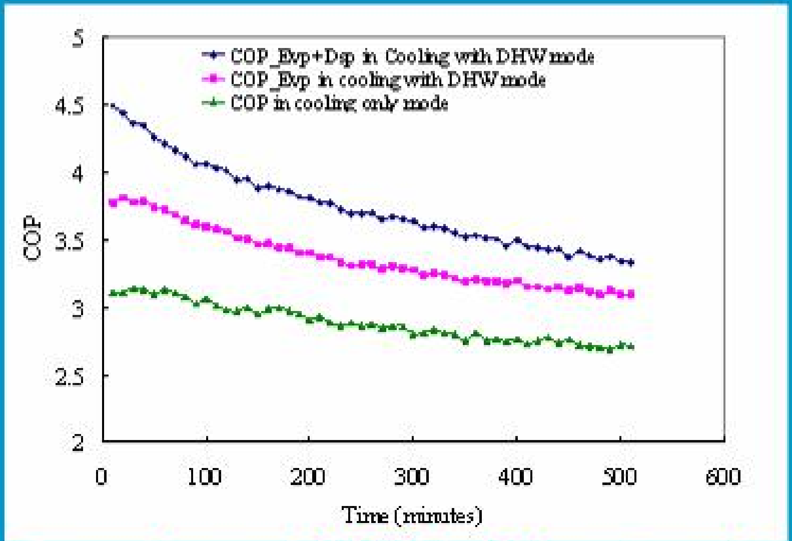




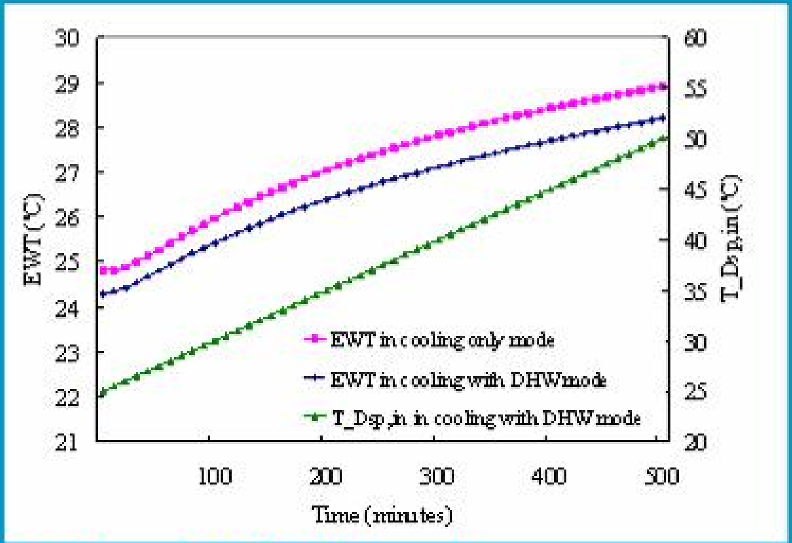
Cooling or heating only mode:	V3 and V4 on; V1, V2, V5 and V6 off;
Cooling with DHW heating mode:	V1, V2, V3 and V4 on; V5 and V6 off
Heating with DHW heating mode:	V1, V2, V3 and V4 on; V5 and V6 off
DHW heating mode:	V2, V5 and V6 on; V1, V3 and V4 off

- Operating mode： Cooling/Heating/ DHW heating

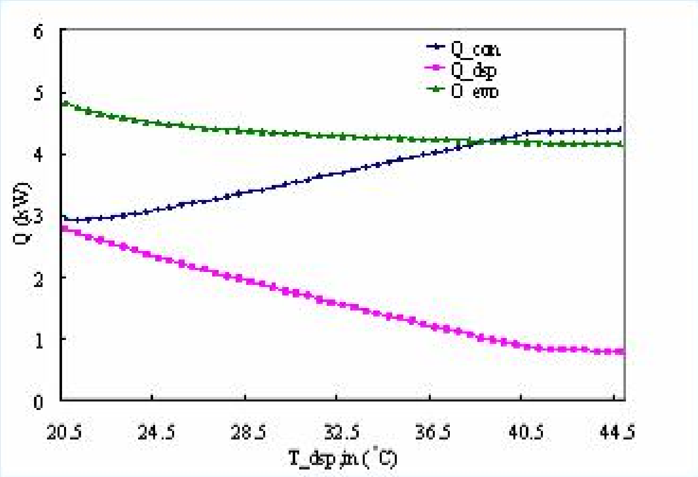
Simulation Results of HGCHP system (1)



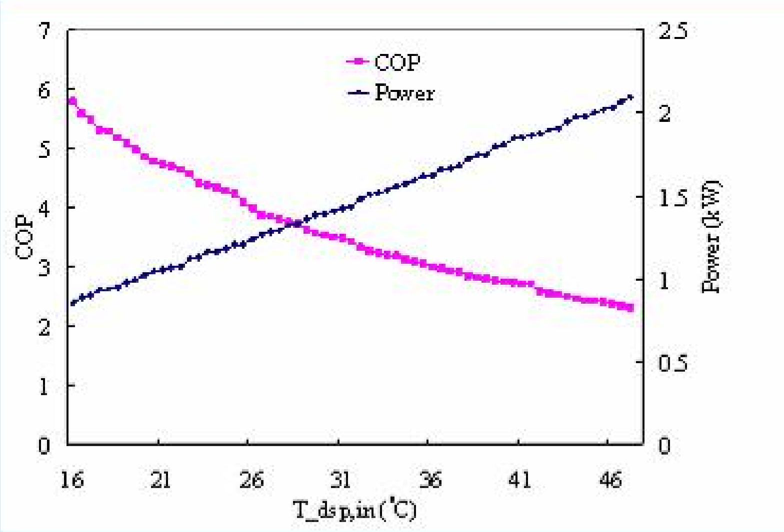
Comparisons of *COP* in different modes



Cooling with DHW mode

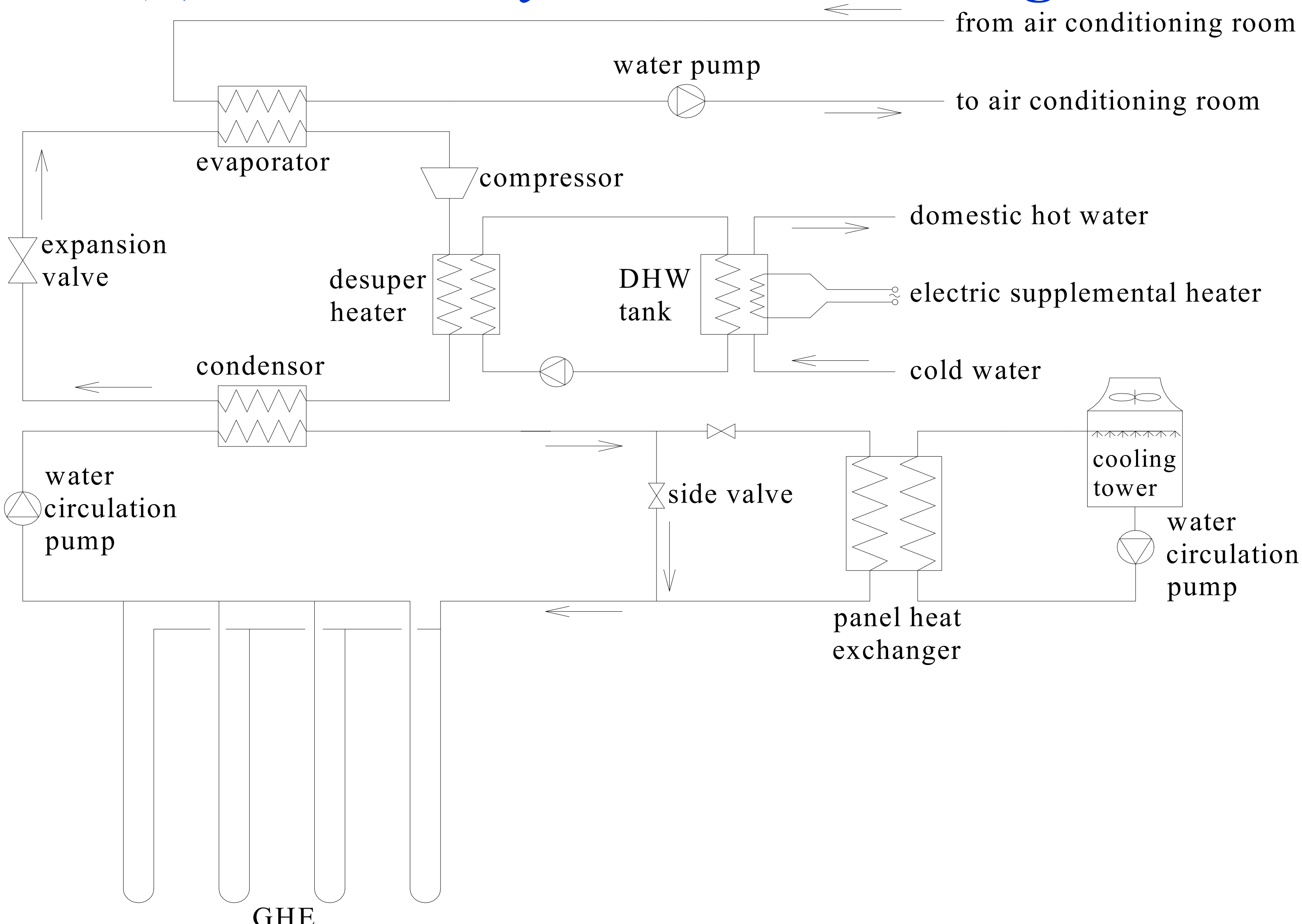


Heating with DHW mode



DHW heating mode

(2) HGCHP system with cooling tower

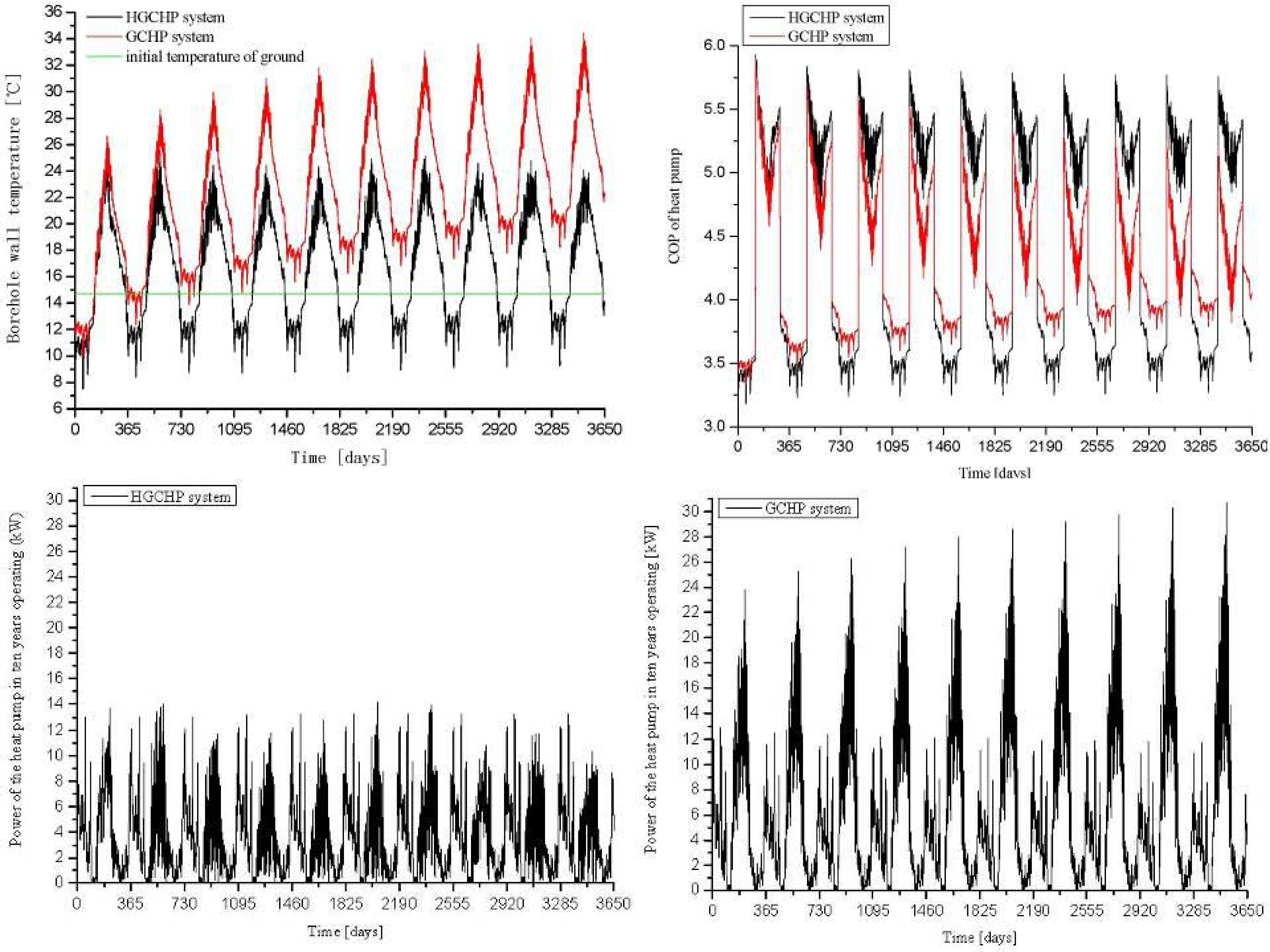


- Cooling tower works as supplemental heat rejecter to reject the unbalanced cooling load, to prevent the heat accumulation around GHE and to ensure the system energy efficiency

Comparisons of energy consumptions between HGCHP system (2) and GCHP system (for office building with unbalance ratio of 1.59)

Item	HGCHP system				GCHP system
	Control strategy 1	Control strategy 2	Control strategy 3	Control strategy 4	
Annual operating time of CT（h）	290	555	1194	830	none
Highest temperature of water entering the heat pump（℃）	31.77	31.6	27.23	31.49	31.3
Annual energy consumption (kWh）	106794	101385	93577	111465	113034
Annual operating cost（$）	6675	6337	5849	6967	7065
Borehole number of GHE	30				50
Initial cost of GHE（$）	30000				50000
Initial cost of CT（$）	312.5				none
Initial cost of heat pump and circulation pump（$）	25625				
System initial cost（$）	55938				75625
Sum of Initial cost and ten years operating cost（$）	122684	119303	114423	125603	160247

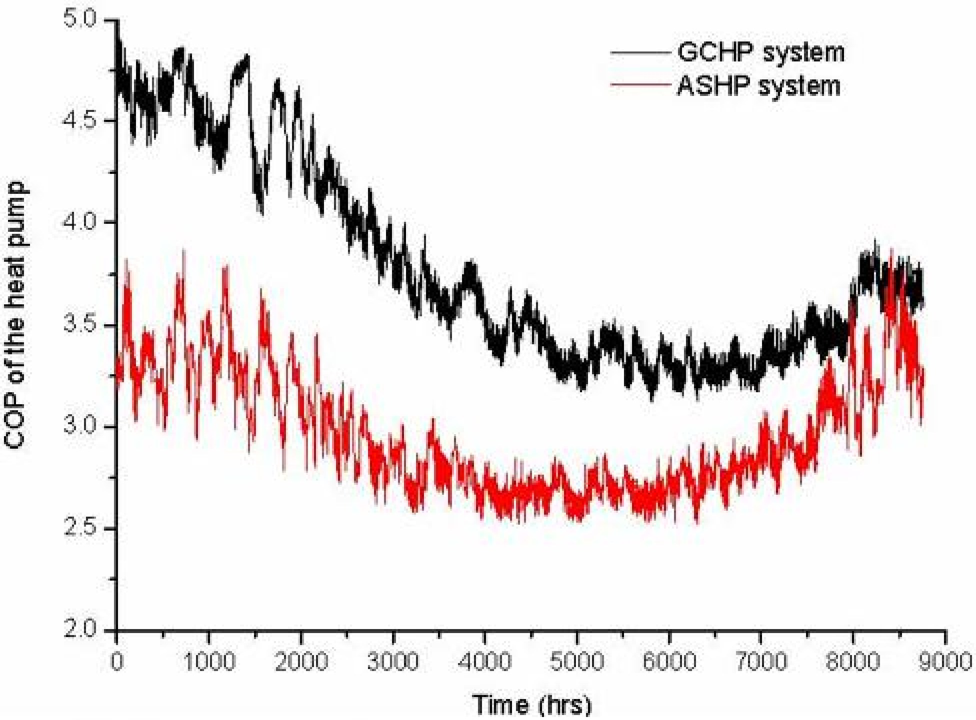
- The optimal control strategy is the temperature difference control strategy.
- The optimal HGCHP system can reduce **35%** initial cost and **20.79%** operating cost in the first year operating, and can save **44.69%** operating cost and **40.05%** total cost in ten years operating compared with the common GCHP system

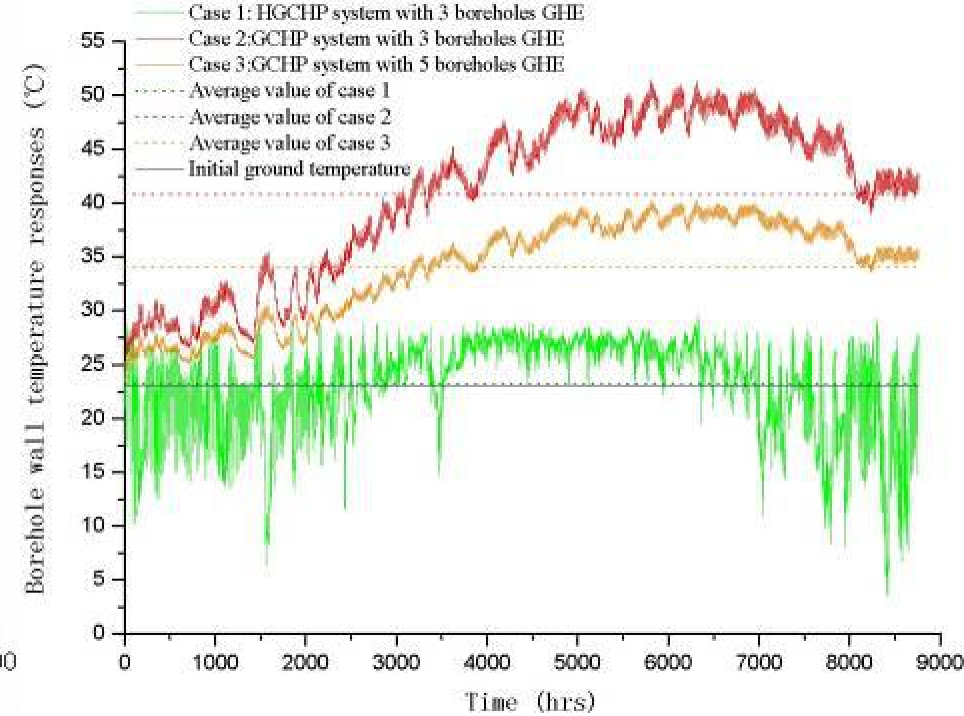

HGCHP system
GCHP system
initial temperature of ground
Borehole wall temperature [°C]
Time [days]
COP of heat pump
Time [days]
HGCHP system
Power of the heat pump in ten years operating (kW)
Time [days]
GCHP system
Power of the heat pump in ten years operating [kW]
Time [days]
0
365
730
1095
1460
1825
2190
2555
2920
3285
3650

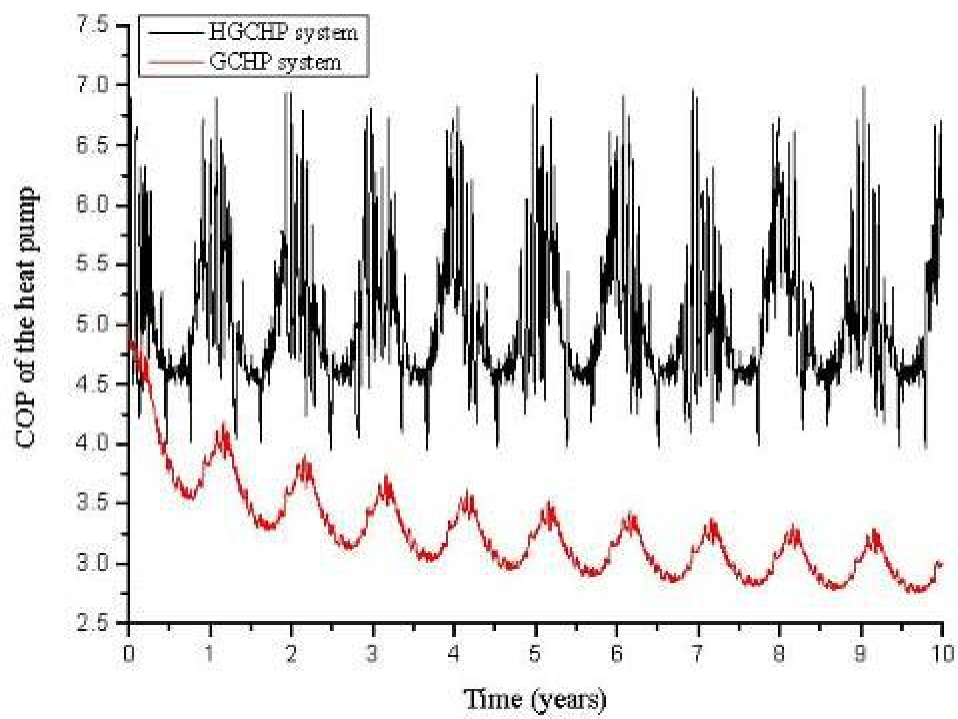
Comparisons of energy consumptions between HGCHP system (2) and GCHP system (for heavy cooling-dominated residential building)

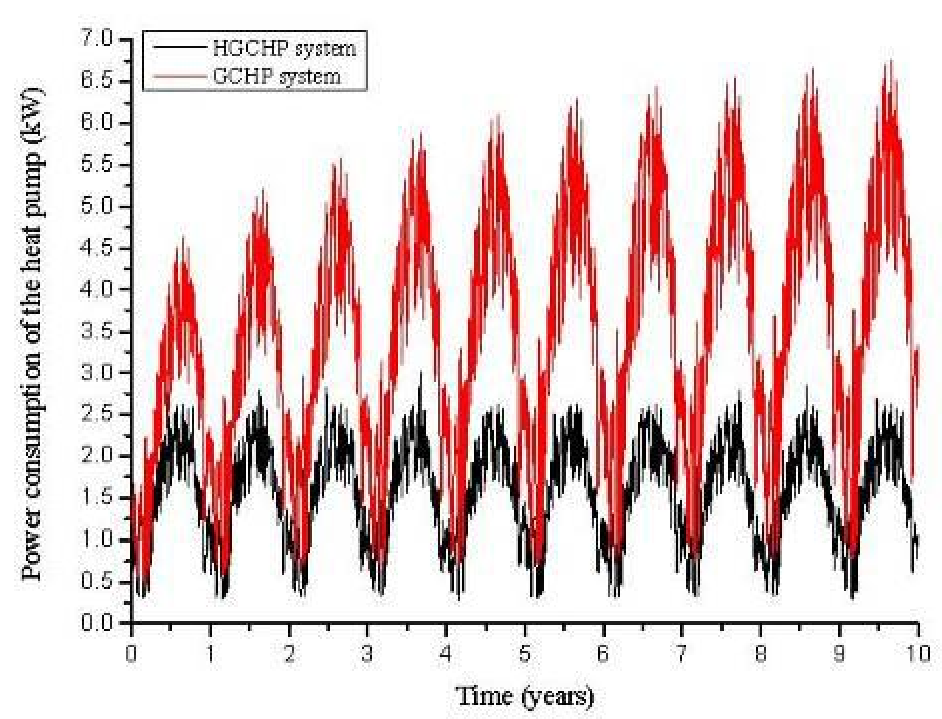
Items	HGCHP system	GCHP system
Borehole length of the GHE (m)	240	400
Initial costs of the GHE (U.S. dollar)	9600	16 000
Initial costs of the CT (U.S. dollar)	50	NA
Initial costs of the heat pump and circulation pumps (U.S. dollar)	2500	2500
Initial costs of the whole system (U.S. dollar)	12 150	18 500
Annual energy consumption (kW)	14 300.57	18 536.93
Annual operating costs (U.S. dollar)	1735.06	2249.05
Ten years' energy consumption (kW)	143 076.41	308 272.62
Ten years' operating costs (U.S. dollar)	17 359.21	37 402.17
Sum of the initial and ten years' operating costs (U.S. dollar)	29 509.21	55 902.17

- The optimal control strategy is to activate the CT when the wet bulb temperature of ambient air is low.
- HGCHP system can save **34.32%** initial costs and **22.85%** operation costs in the first year running, and can save **53.59%** operating costs and **47.21%** total costs during ten years' operation compared with the GCHP system.


GCHP system
ASHP system
COP of the heat pump
Time (hrs)
2.0
2.5
3.0
3.5
4.0
4.5
5.0
0
1000
2000
3000
4000
5000
6000
7000
8000
9000


Case 1: HGCHP system with 3 boreholes GHE
Case 2:GCHP system with 3 boreholes GHE
Case 3:GCHP system with 5 boreholes GHE
Average value of case 1
Average value of case 2
Average value of case 3
Initial ground temperature
Borehole wall temperature responses (℃)
Time (hrs)
0
5
10
15
20
25
30
35
40
45
50
55
0
1000
2000
3000
4000
5000
6000
7000
8000
9000


HGCHP system
GCHP system
COP of the heat pump
Time (years)
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
7.5
0
1
2
3
4
5
6
7
8
9
10


HGCHP system
GCHP system
Power consumption of the heat pump (kW)
Time (years)
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
4.0
4.5
5.0
5.5
6.0
6.5
7.0
0
1
2
3
4
5
6
7
8
9
10

Conclusions

- Solar photovoltaic application develops very fast. The cost is nearly close to traditional energy resources for power generation.
- BIPV represents the future of renewable power generation in urban areas.
- Introduction of the FiT leads to bright future for BIPV in Hong Kong, but long-time policy is needed.
- Solar desiccant dehumidification is an effective way to produce cooling for air-conditioning.
- Research in hybrid GCHP systems can enhance the adaptability of GCHP technology, and can prompt the application of GCHP system in areas with unbalanced cooling and heating loads.

Thank you for your attention !

Q & A