香港城市大學
City University of Hong Kong

Hong Kong Institute for Clean Energy
香港清潔能源研究院

Sino-Germany Workshop on Printable Photovoltaics

May 21st – 23rd, Erlangen, Germany

Optical Design of Organic-based Transparent and Tandem Solar Cells

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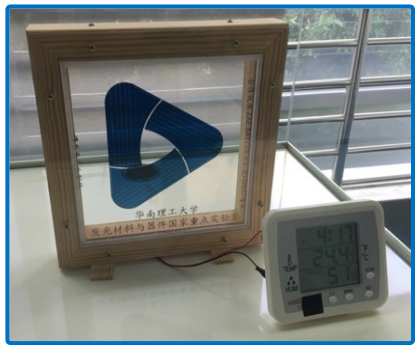
Assoc. Director, Hong Kong Institute for Clean Energy (HKICE)
Dept. of Materials Science & Engineering
School of Energy & Environment
City University of Hong Kong

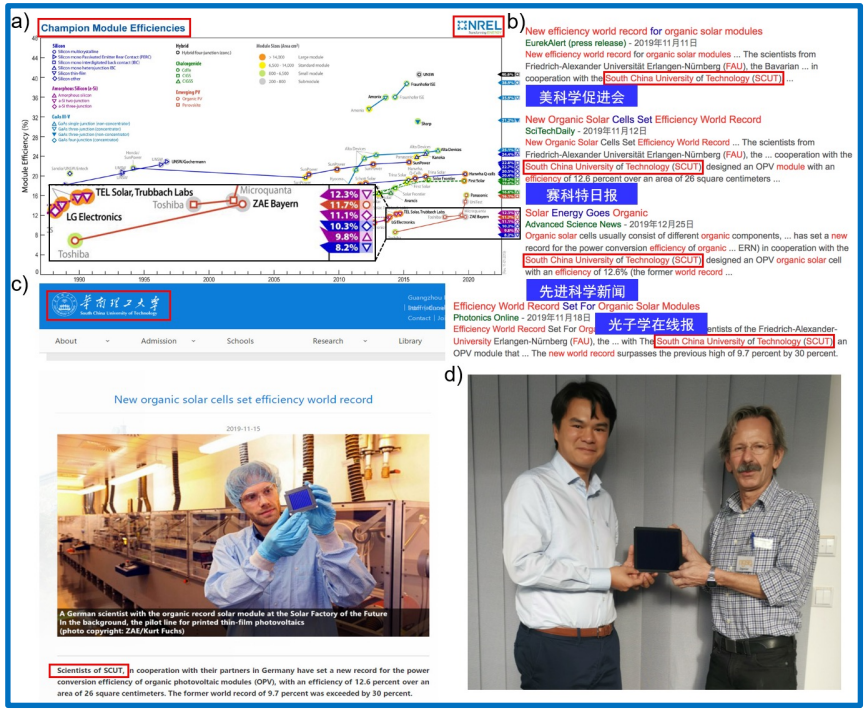
Academic Positions

South China University of Technology (SCUT 2013-2020)

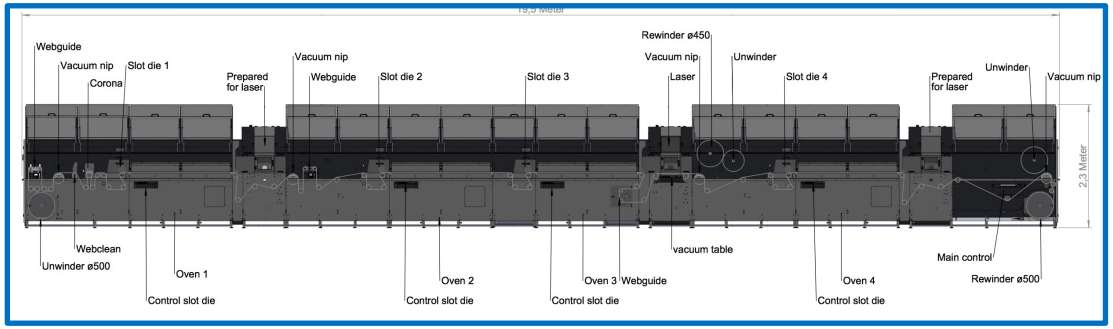
- Professor, School of MSE, State Key Lab of Luminescent Materials and Devices, SCUT- 2013/6-2020/12
- Director, Innovation Center for Printed Photovoltaics, SCUT, 2018/1-2020/12

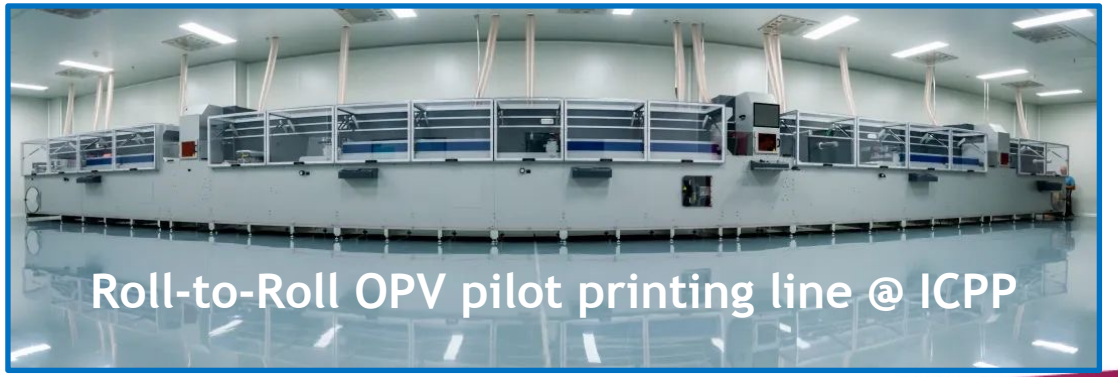
Participated in the certification of Champion OPV Module





Designed and Assembled a R2R OPV pilot printing line





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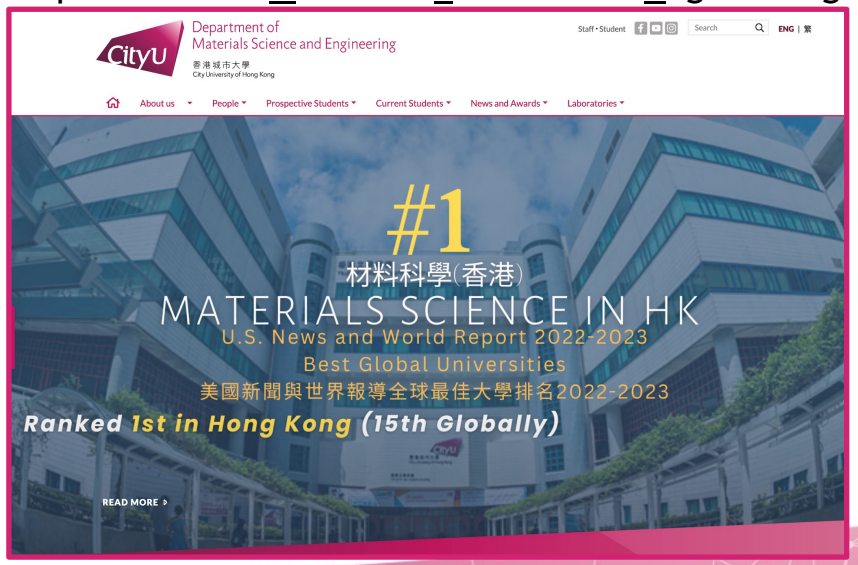
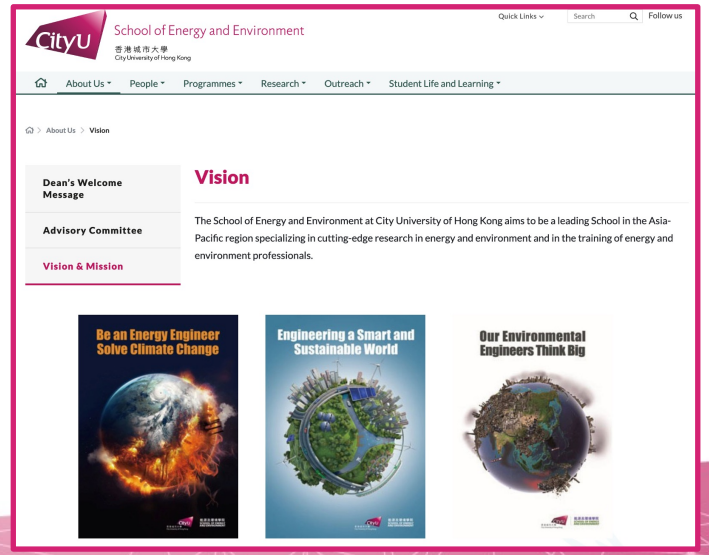
City University of Hong Kong (CityUHK 2021-now)

- Professor, MSE / SEE, City University of Hong Kong- 2021/1-now
- Associate Director, HKICE, City University of Hong Kong- 2022/1-now
- PI (Blue Economy), State Key Laboratory of Marine Pollutions, CityUHK- 2024/1-now

Department of Materials Science and Engineering



School of Energy and Environment

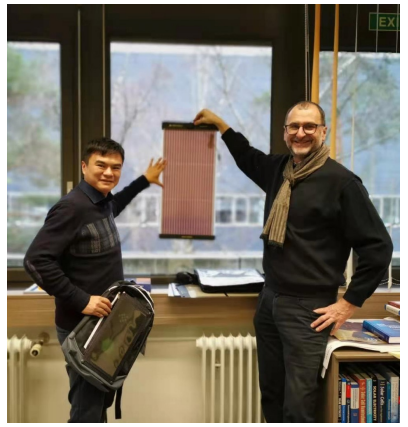


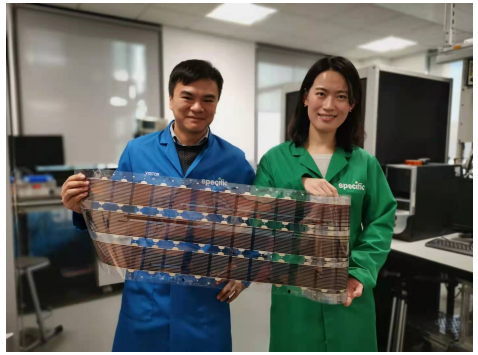
Hong Kong Institute for Clean Energy

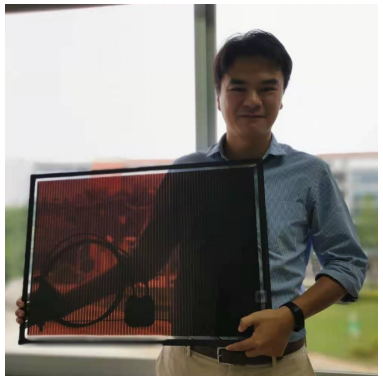
Promoting New PV Technology in HK

Work with local companies & the community to promote green tech

R&D: New Generation Printable PV



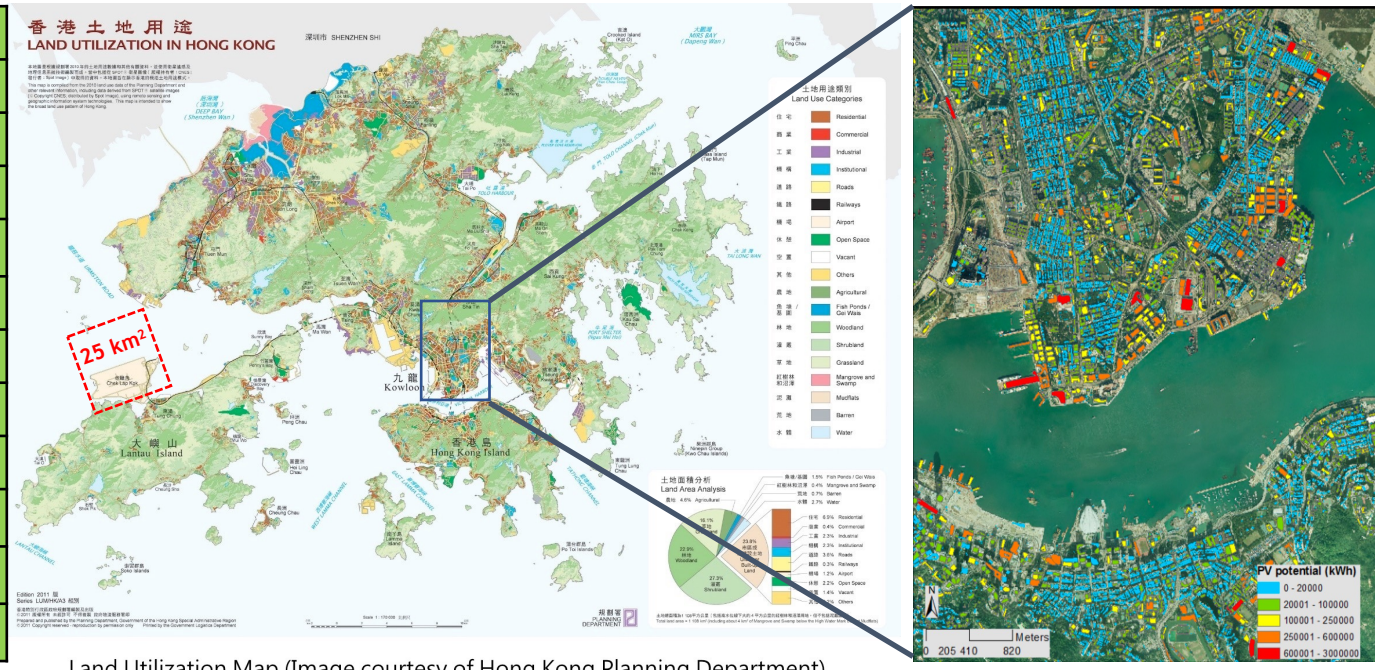




- 【碳中和】都市太陽能
https://www.youtube.com/watch?v=x_FXxaosg1s
- 2021「科學為民」- 香港發展太陽能可再生能源的機遇與挑戰
https://www.youtube.com/watch?v=BZgvhloi2Ac
- Innocarnival 2022-Challenges and Opportunities of Solar Power in HK
https://www.youtube.com/watch?v=u5yq-ihv-HA

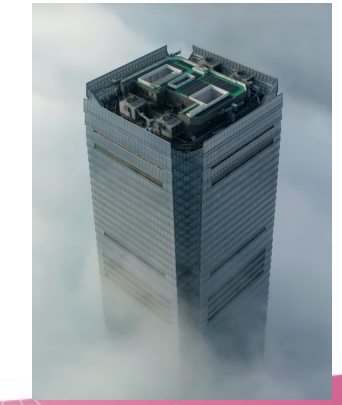
Challenges of Solar Energy Deployment in Urban City

	km²
Residential	78
Commercial	5
Industrial	27
Parks	53
Road	46
Agriculture	50
Fish Ponds	16
Reservoir	25
Mountain	600
Land	1100
Coastal/Sea	1645



Land Utilization Map (Image courtesy of Hong Kong Planning Department)

- HK consumes ~280000 TJ annually
- Now: ~100 MW PV installation -> ~0.2 % energy in HK
- PV: 5 GW x 1500 hr/yr x 60min x 60s = 27000 TJ ~ 10%
- Requires 25 km² covered by 20% PV panels to produce 5GW
- All available building rooftops ~ 0.5-1 GW PV installation



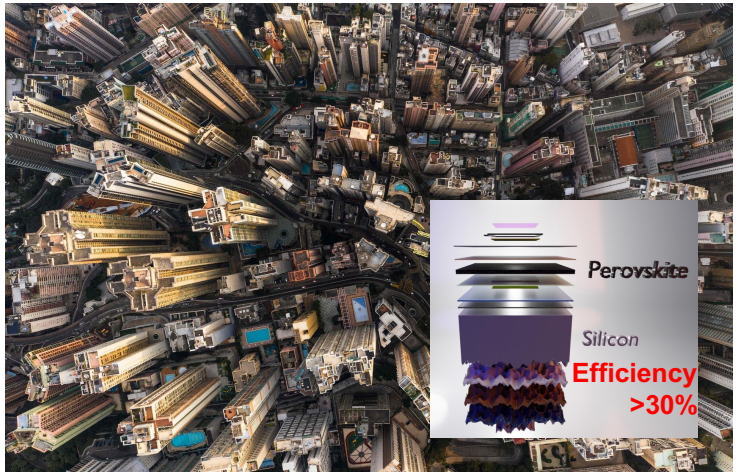
Majority of Solar Energy in HK is from Rooftop PV

http://www.lsgi.polyu.edu.hk/rsl/lsw/solarenergyHK/index.html
https://www.pland.gov.hk/pland_tc/info_serv/statistic/landu.html

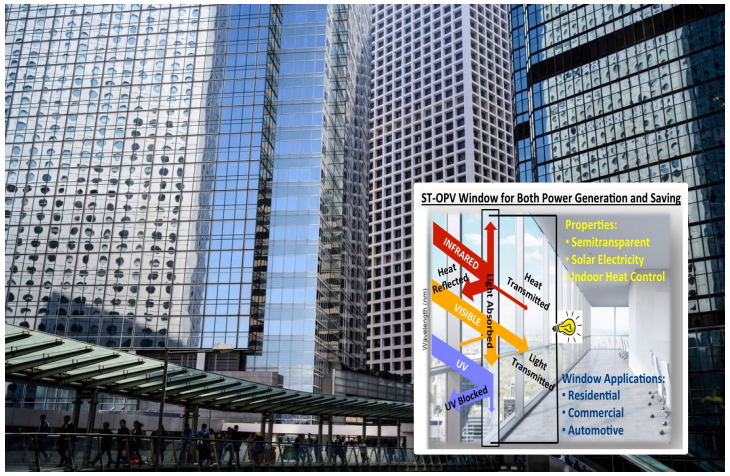
Innovative PV Technology with Broaden Applications

- Solar cells with new form factors for easy application integration

Rooftops



Facades & Windows



Roads

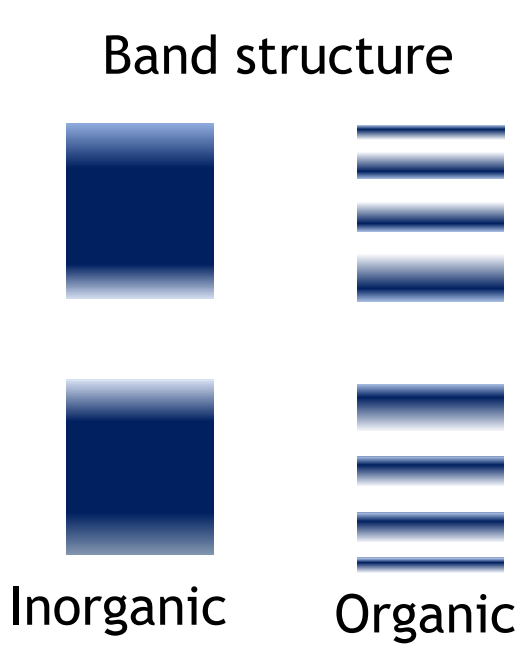
Automobiles

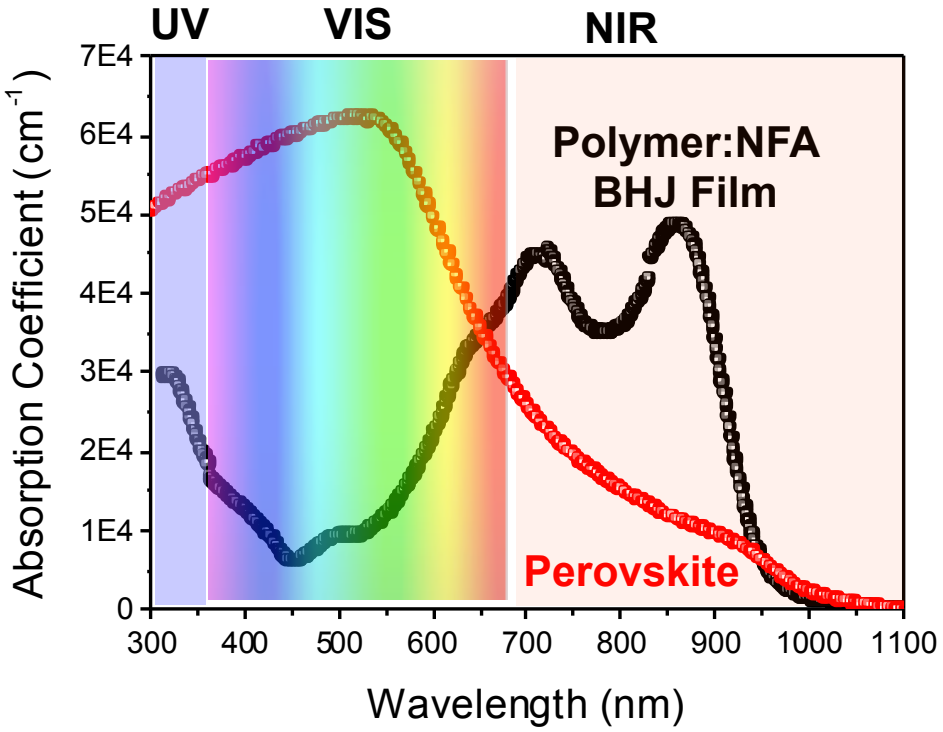
Agriculture & Fisheries

Mountain & Sea

Unique Optical Properties of Organic Semiconductors

- Tunable optical absorption is ideal for transparent PV applications
- Bandgap can be readily adjusted to suit tandem solar cells



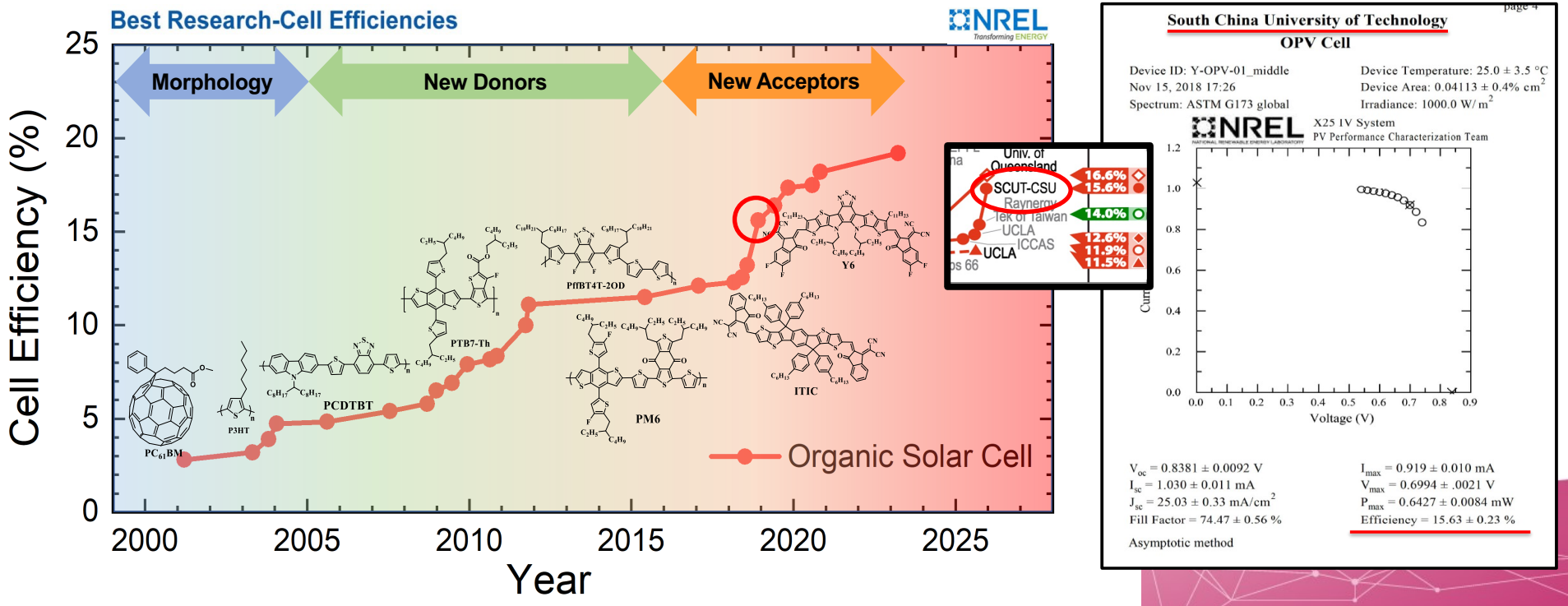


Outline

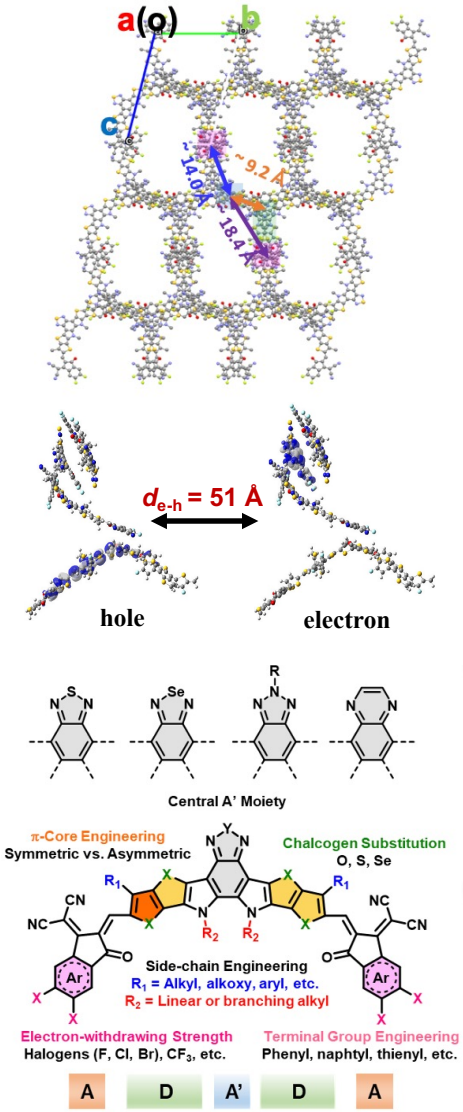
- Key material development for OPV
- Target-oriented high-throughput optical modeling for designing multifunctional transparent solar cells
- Commercialization of new generation PV

Key OPV Materials Breakthroughs

- In 2019, reported OPV "Star molecule-Y6" with NREL-certified efficiency of 15.6%.
  - Yip, Zou et al, ***Joule*** **2019**, *3*, 1140 **(Citation > 4500) Highly cited paper**
- In 2020, reported the "crystal structure-charge generation" relationship of the Y6.
  - Yip, et al, ***Nat. Commun.*** **2020**, *11*, 3943 **(Citation > 400) Highly cited paper**
- In 2022, published "Renewed Prospects of Organic Photovoltaics" in *Chem. Rev*
  - Yip, et al, ***Chem. Rev.*** **2022**, *122*, 14180 **(Citation > 350) Highly cited & Hot paper**



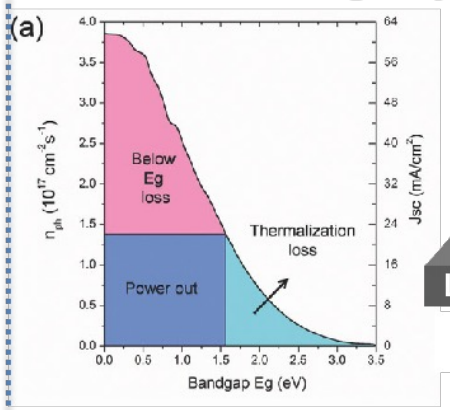
Structure-property study inspires OPV to reach 20 % efficiency

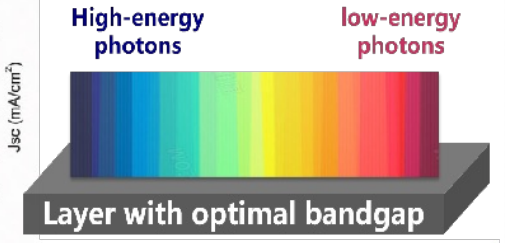


Low bandgap NFA Development

Develop novel narrow bandgap non-fullerene acceptors (NFAs) with strong NIR absorption

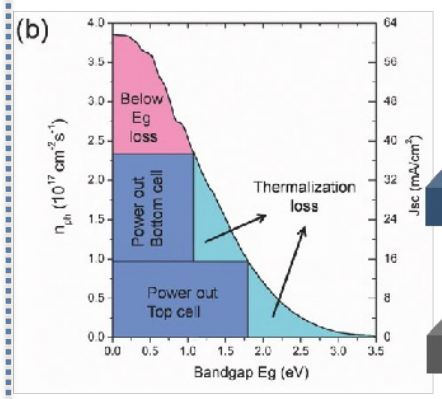
single-junction

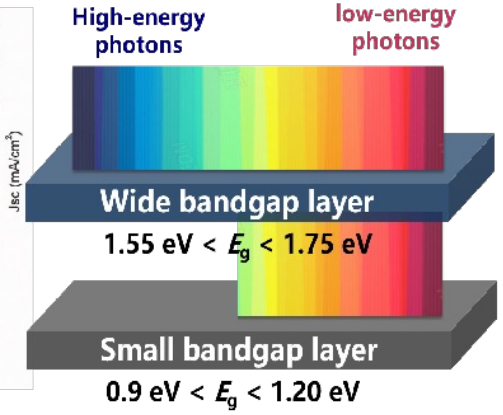




Efficiency potential: 33.7%

tandem





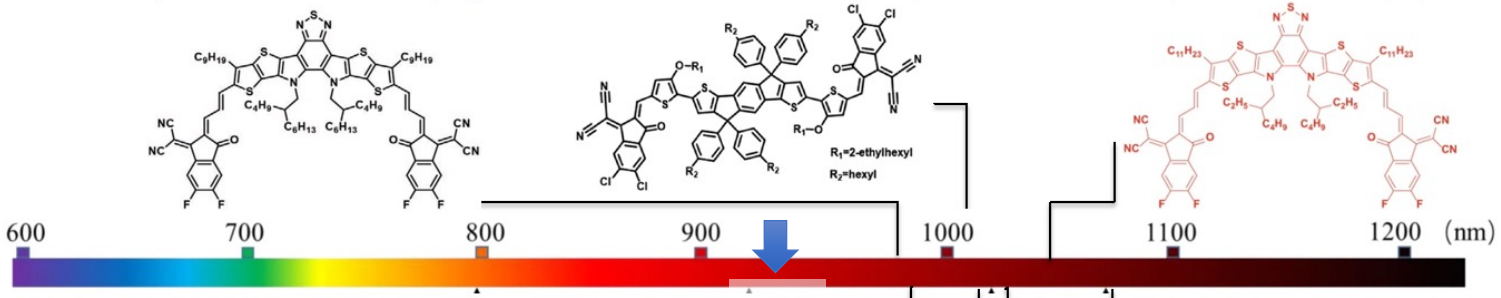
Huang, J., *Adv. Energy Mater.* **2017**, *7*, 1602400.

Efficiency potential: 46.1%

BTPV-4F-eC9
(E_g=1.25 eV)
Li et al, *Adv. Funct. Mater.* **2021**, *31*, 2102361

IEICO-4Cl
(E_g=1.23 eV)
Hou et al, *Adv. Mater.* **2017**, *29*, 1703080

BTPV-4F
(E_g=1.21 eV)
Li et al, *Nat Commun* **2021**,*12*, 178



EHBZs-4F
(E_g=1.24 eV)
Jen et al, *ACS Energy Lett.* **2021**, *6*, 9−15

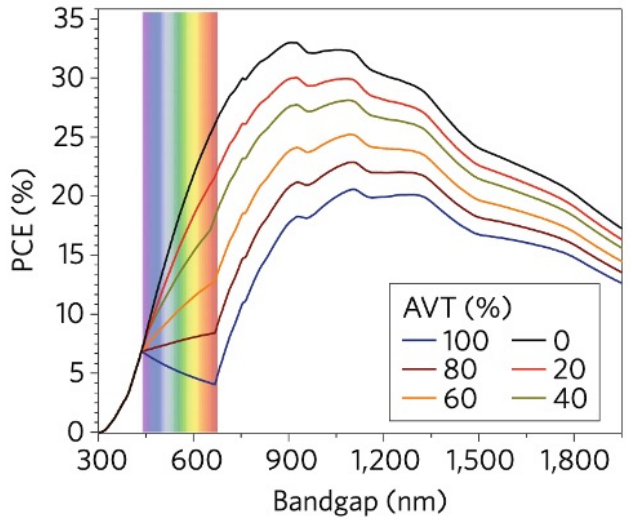
BTPV-4Cl-eC9
(E_g=1.22 eV)
Li et al, *Adv. Mater.* **2022**, *34*, 2108829

DTPC-DFIC
(E_g=1.21 eV)
Jen et al, J. Am. Chem. Soc. **2018**, *140*, 2054−2057

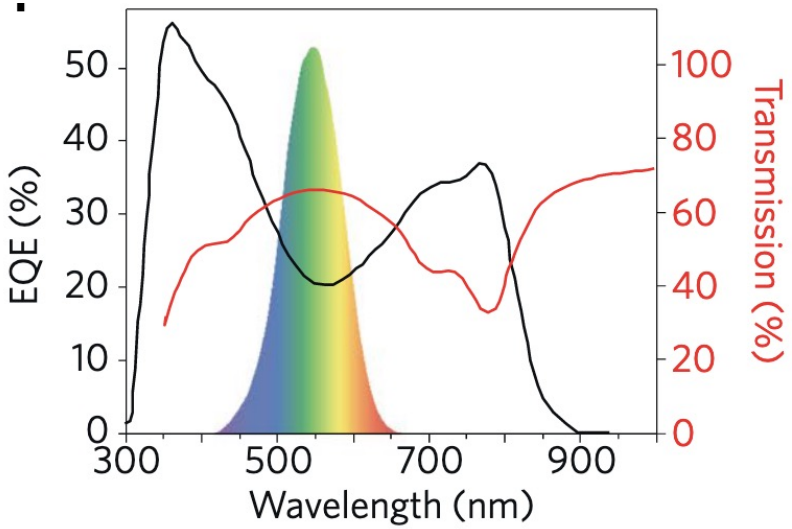
BTPSeV-4F
(E_g=1.17 eV)
Li et al, *Nat Commun* **2023**, *14*, 1236

Evaluation Criteria for Transparent PV

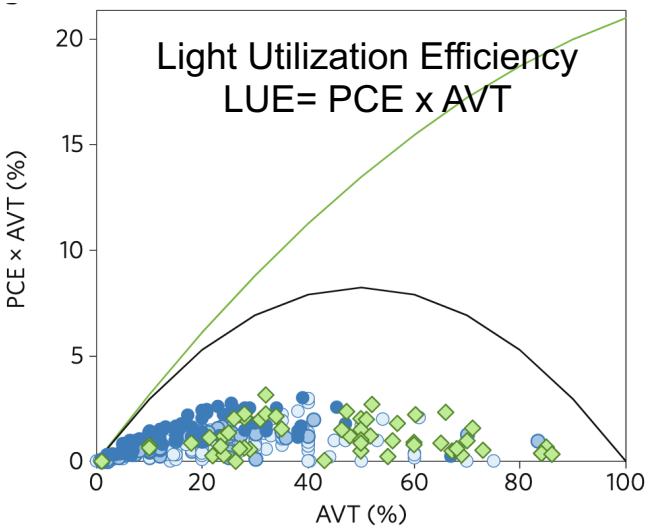
PCE



AVT

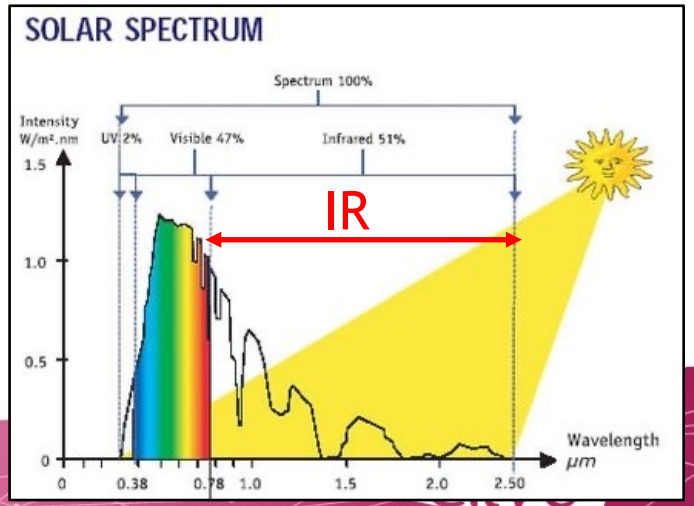


LUE



Colored or High CRI

IRR

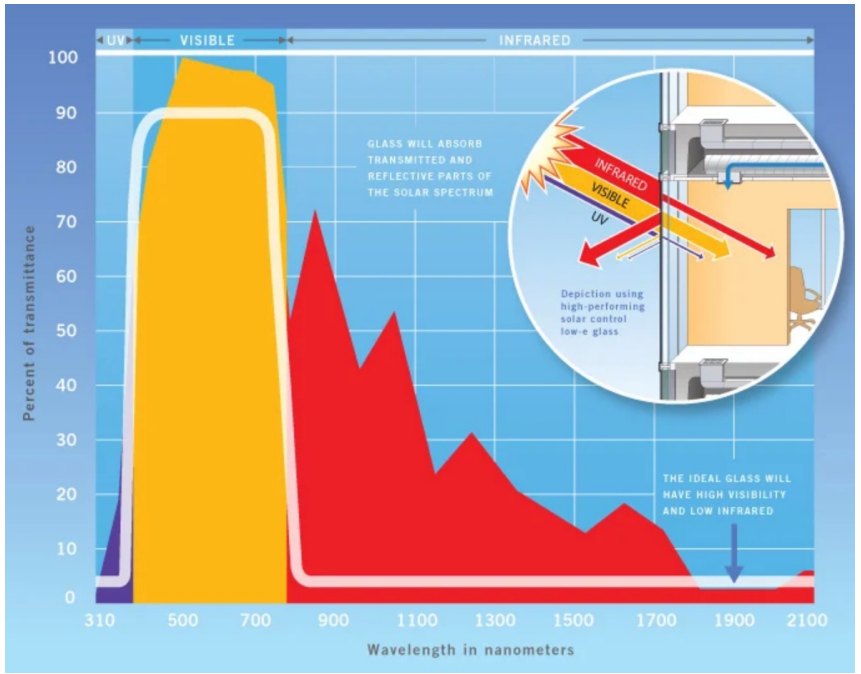


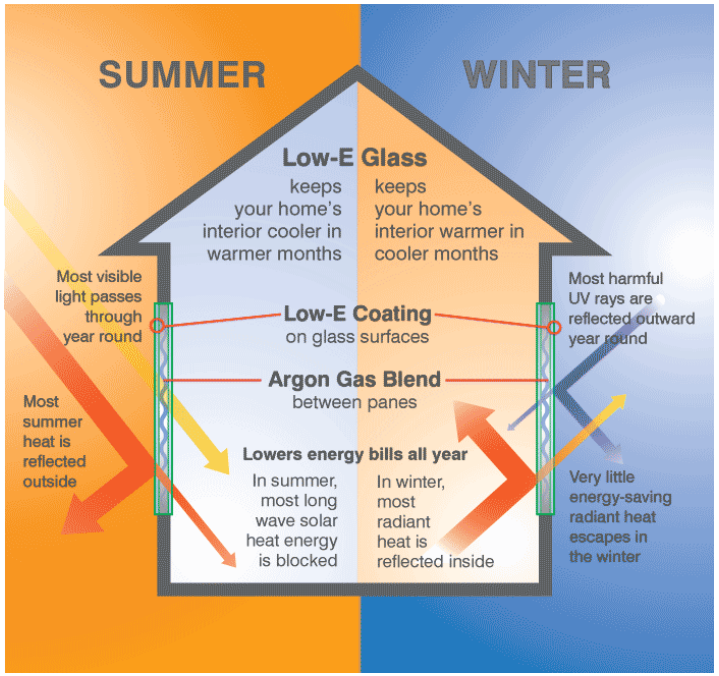
Richard Lunt, et al , *Nature Energy* , **2**, 849–860 (2017)

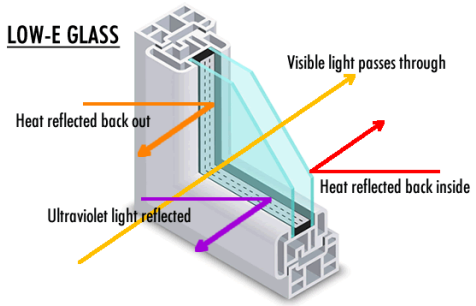
Current Technology – Low-E Windows

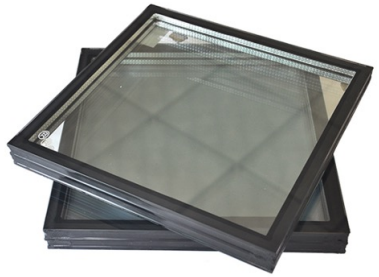
Low-Emissivity Glass Window

Energy saving – control cooling and heating









Energy saving:
Up to 200 kWh/m^2/yr **+**

Energy Generation:
20% PV Panel, 1500 hr/yr
Produce ~ 300 kWh/m^2/yr

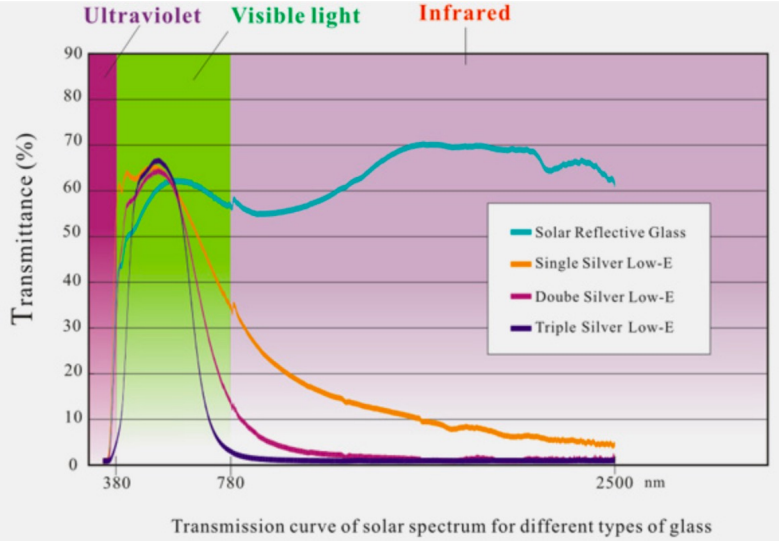
www.glassed.vitroglazings.com

Current Technology – Low-E Windows

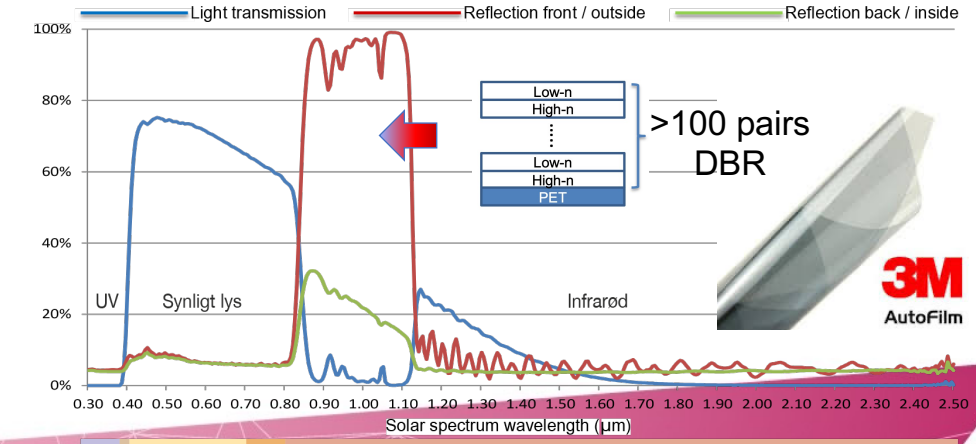
Low-E coating design on glass

Oxide
SiN
primer
UTMF (Ag)
primer
Oxide
primer
UTMF (Ag)
SiN
Oxide
UTMF (Ag)
Oxide
SiN
Glass

Low-E coating on film



Transmission curve of solar spectrum for different types of glass



Current Technology – Low-E Windows

Low-E coating design on glass

Low-E coating on film

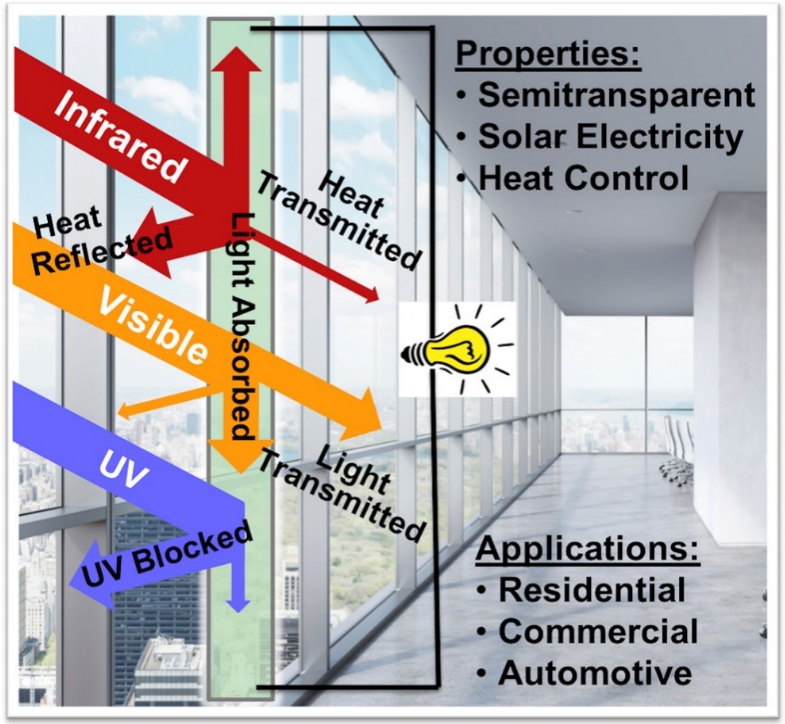
OPV structure

MoO_3	0:10:100 nm
LiF	0:10:100 nm
MoO_3	0:10:100 nm
LiF	0:10:100 nm
Ag	20 nm
MoO_3	10 nm
PM6:Y6:PCBM	100 nm
ZnO	30 nm
ITO	150 nm
Glass	0.7 mm

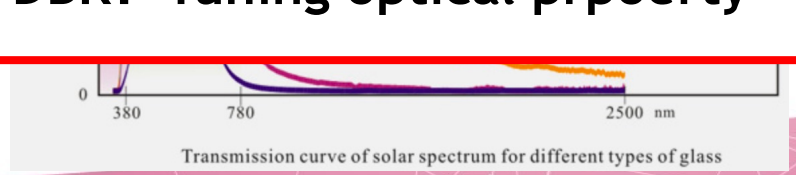
UTMF: TE, IR reflection

DBR：Tuning optical prpoerty

Dual-function STOPV



Yip, at el, Joule, **2018**, *2,* 1816



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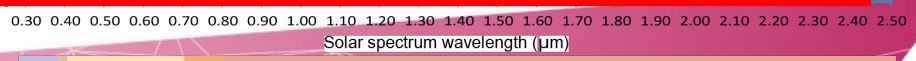


New Modeling Concept

- Introduced the concept of *'Optical Genome Engineering,'* a new and novel approach utilizing high-throughput screening to design organic solar cell architectures with optimized properties.

High-Throughput Optical Screening for Device Design of OSCs

Input Required Property

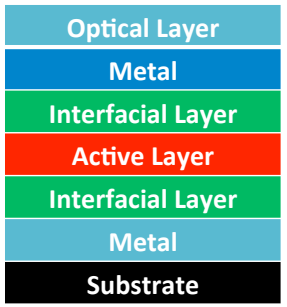
Single-junction
- Max. Jsc

Tandem cells
- Double-Junctions
- Triple-Junctions

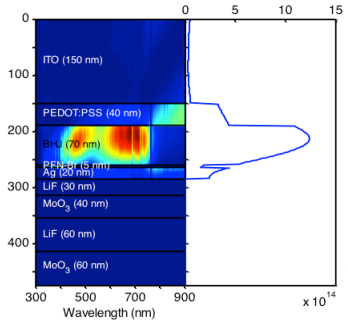
Semitransparent cells
- AVT vs Luminosity
- Specific Colors
- Color Neutral
- Green House specific
- Indoor vs Outdoor
- Heat Isolation

Complex patterns

Materials Database



High-Throughput Modeling



Optical Constant Database
- >250 Active Layers
- >20 Interfacial Layers
- >20 Other Layers

\+

Electrical Property Database

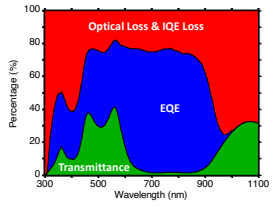
Optical Simulation
- 10000X speed
- Multi-objective & Multi-layer Thickness Optimization

Best Materials Choice & Device Structure

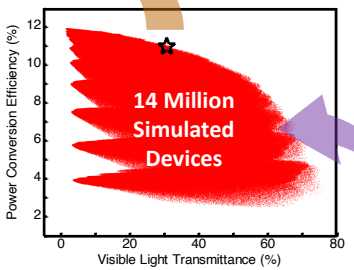
Yip's group

Simulation Guided Device Fabrication

MoO_3	110 nm
LiF	110 nm
MoO_3	60 nm
LiF	170 nm
Ag	20 nm
PFN-Br	5 nm
BHJ	110 nm
PEDOT:PSS	40 nm
ITO	150 nm
Glass	0.7 mm



Optimized Device Architecture



Human Eye Perception

Photonic Crystals

MoO_3	0:10:200 nm
LiF	0:10:200 nm
MoO_3	0:10:200 nm
LiF	0:10:200 nm

Basic STOSC

Ag	10:5:40 nm
PFN-Br	5 nm
BHJ	30:10:150 nm
PEDOT:PSS	40 nm
ITO	150 nm
Glass	0.7 mm

Optical Simulation

Optimize

Optimize

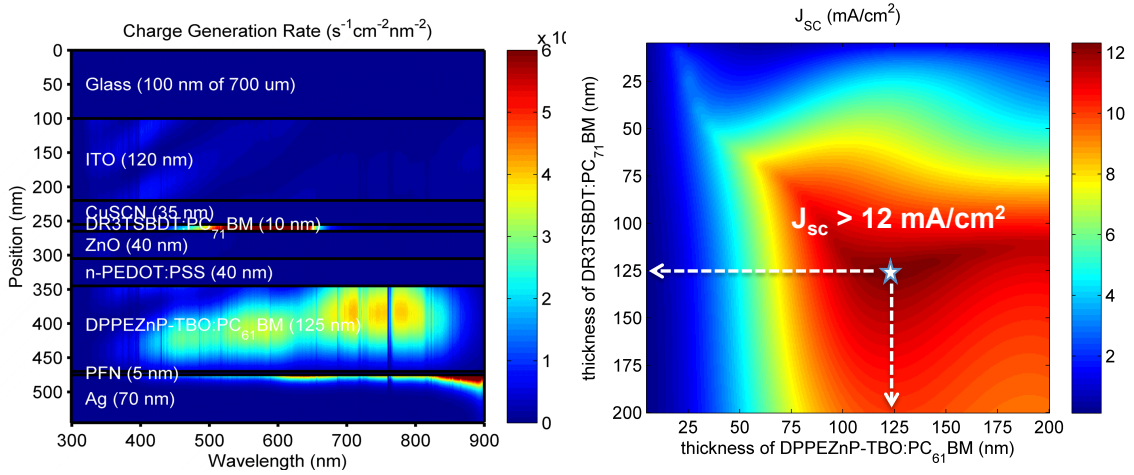
Efficiency

High-Throughput Optical Simulation

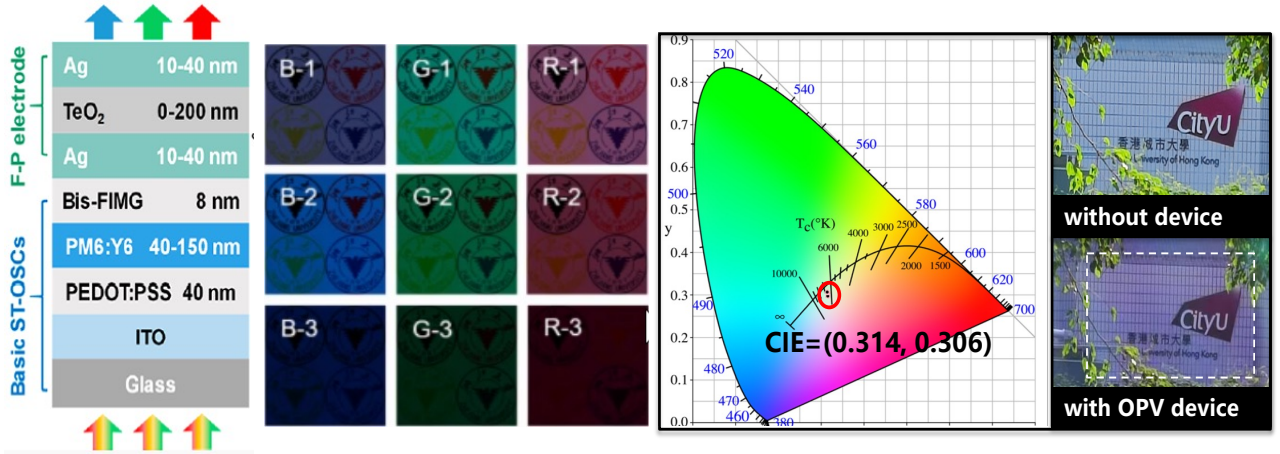
Yip, et al. *Joule* 2019, 3, 2241

Optical Model-Assisted Device Design

Modeling-Guided Design of Tandem Cells



Modeling-Guided Design of Transparent Cells

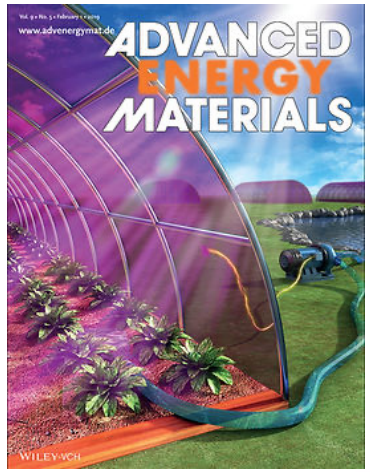


Collaboration leads to tandem OPV breakthrough

- Yip et al, ***Adv. Mater.,*** 2016, *28*, *4817* **(SCUT, PCE>11%)**
- Wan *et al*, ***Nat. Photonics***, 2017, *11*, 85 **(Nankai, PCE>12%)**
- Zhang *et al*, ***Adv. Energy Mater***. 2018, 1703180 **(SCUT)**
- Chen *et al*, ***Adv. Mater.*** 2018, 1707508 **(Nankai, PCE>14%)**
- Zhang *et al*, ***Adv. Mater.*** 2018, 1803166 **(SCUT, All-polymer)**
- Li *et al*, ***Adv. Mater.***, *2018*, *30*, 1803769 **(ZJU, PCE>14.5%)**
- Li *et al*, ***ACS Energy Lett.***, 2020, *5*, 1771**(ZJU, Triple-Tandem)**
- Chen, Ding *et al*, ***Science***, 2018, *361*, 1094 **(Nankai, PCE>17%)**
- Zhang *et al*, ***Adv. Funct Mater***, 2021, *31*, 2103283 **(PCE>18.7%)**

Collaboration on semitransparent OPV

- Yip, et al, ***Adv. Energy Mater***. 2019, *9*, 1803438
- Yip, Sun *et al*, ***Small Methods***, 2020, *3*, 1900424.
- Yip, Sun *et al*, ***Adv. Funct. Mater.***, 2020,*30*, 2002181
- Yip, Li, Chen *et al*, ***ACS Energy Lett.***, 2020, *5*, 1771
- Yip, Li, Chen *et al*, ***ACS Energy Lett.***, 2020, *5*, 3115
- Yip, Li, *et al*, ***Adv. Mater.***, 2020, *32*, 2001621
- Yip, Li, *et al*, ***Energy Environ. Sci,*** 2022,*15*, 2629
- Yip, Zou et al, ***Adv. Funct. Mater.***, 2023,*33*, 2305017

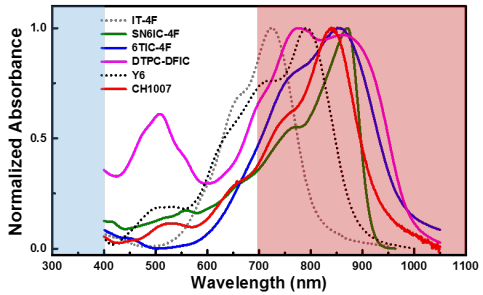


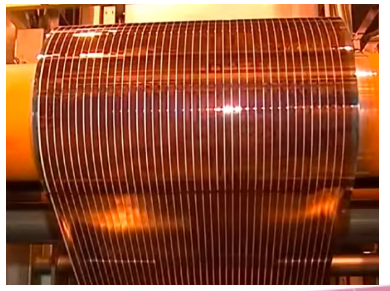
Partnering with Leading Window Manufacturer

"New Window Technology with Combined Energy Generation and Energy Saving Functions"

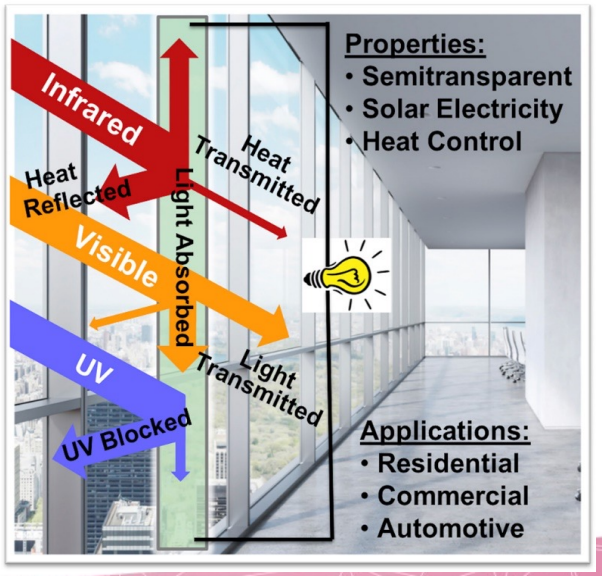
Highly Efficient Thin-Film OPVs → ***High Throughput Optical Model*** ← ***Commercialized Low-E Glass***

- High efficiencies (>20%)
- High transmittance
- Good color-tunability
- Light-weight, flexible, printable
- Low primary energy demand





Heat-Insulating Power-Generating ST-OPV Glass



Yip, at el, Joule, **2018**, *2*, 1816

- Low-E property
- Heat- and noise-insulating
- Cost-performance balance

China Resources Tower, Shenzhen

New World Centre, HK.

PKX "The Starfish", Beijing.

Target-Oriented Optical Modeling

Model function

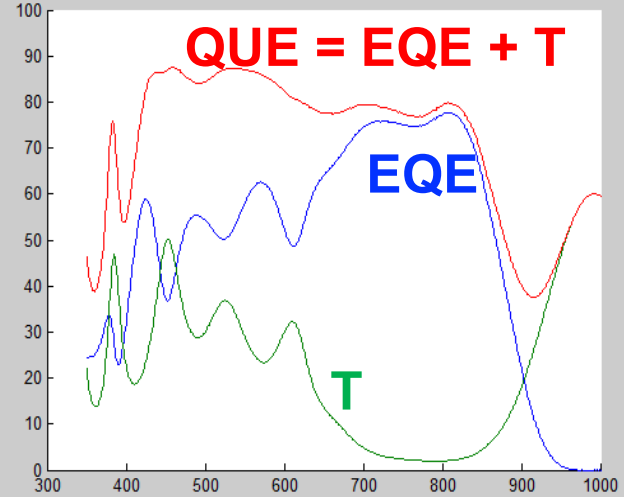
$$(PCE, VLT, CRI) = F(t_{BHJ\&Ag\&PC})$$

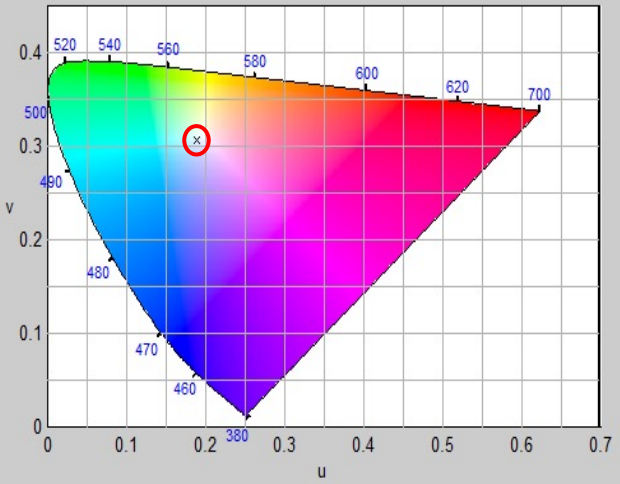
Setting: CRI>90, VLT>20%

MoO_3	120 nm
LiF	120 nm
MoO_3	90 nm
LiF	150 nm
MoO_3	70 nm
LiF	165 nm
Ag	15 nm
MoO_3	12 nm
BHJ	70 nm
ZnO	30 nm
ITO	150 nm
Glass	0.7 mm

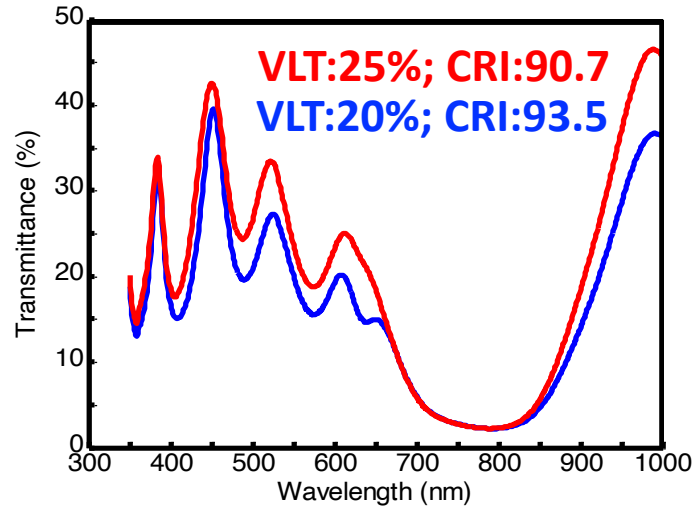
Ag=15nm
PRR=82.1%
VLT=29.0%
CRI=95.1

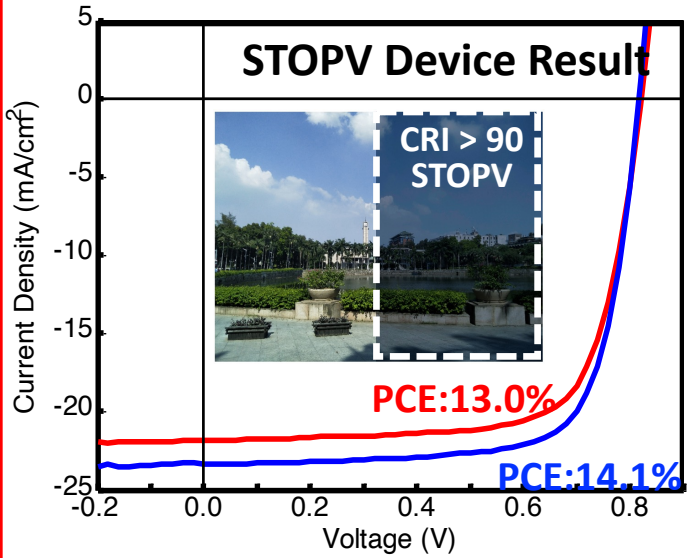
Simulated result





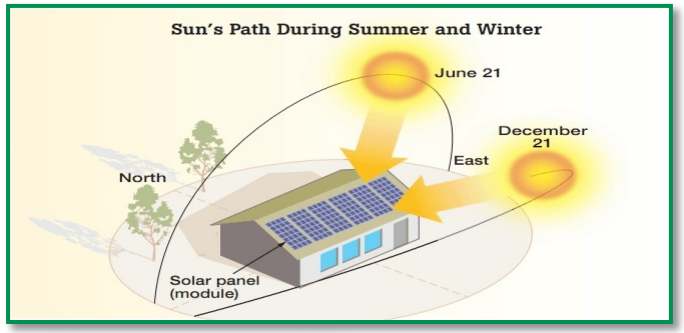
Experimental result

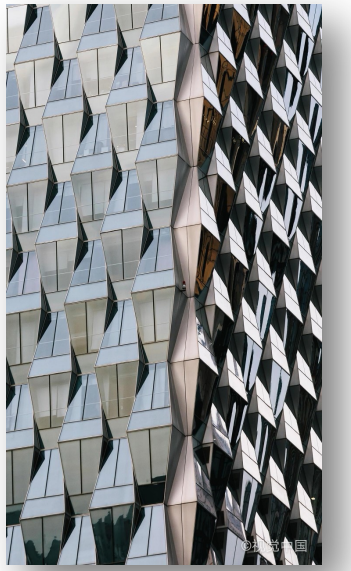




Unpublished result

Modeling of Angle-dependent properties in STOPV





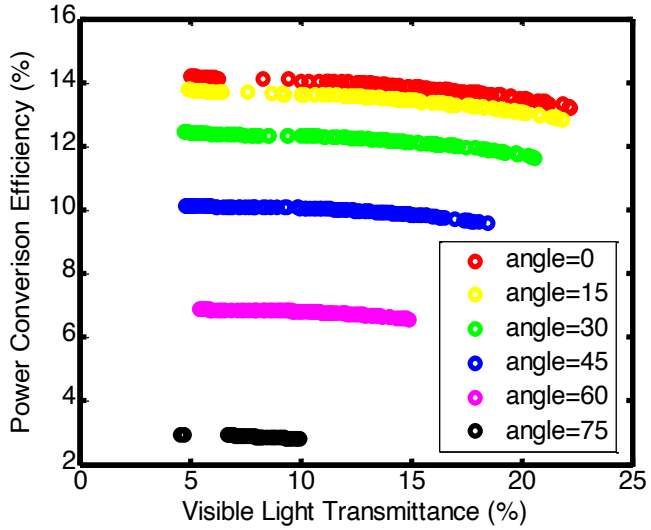
MoO_3	0:10:100 nm
LiF	0:10:100 nm
MoO_3	0:10:100 nm
LiF	0:10:100 nm
Ag	20 nm
MoO_3	10 nm
PM6:Y6:PCBM	100 nm
ZnO	30 nm
ITO	150 nm
Glass	0.7 mm

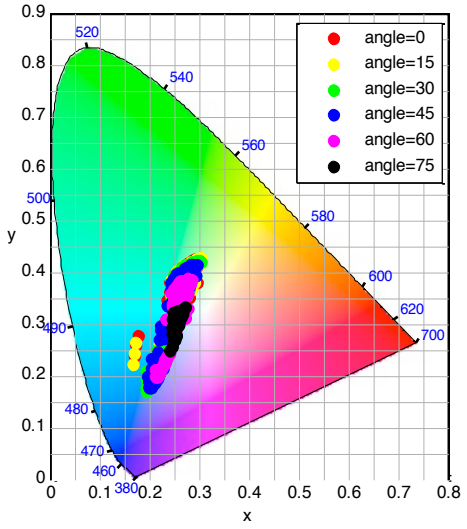
BIPV

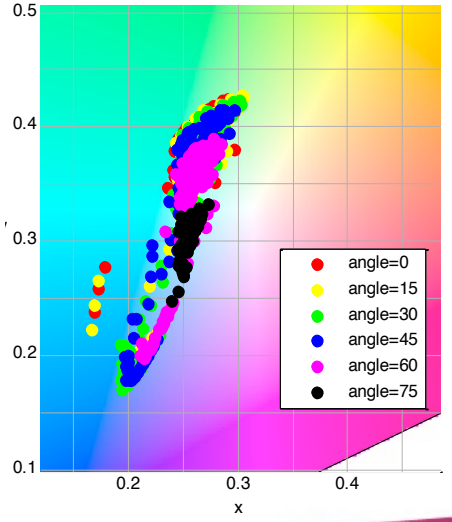
↑ Θ

$\Theta = 0, 15, 30, 45, 60, 75$

$(PCE, VLT, (x,y)) = F(\Theta, t_{PCs})$





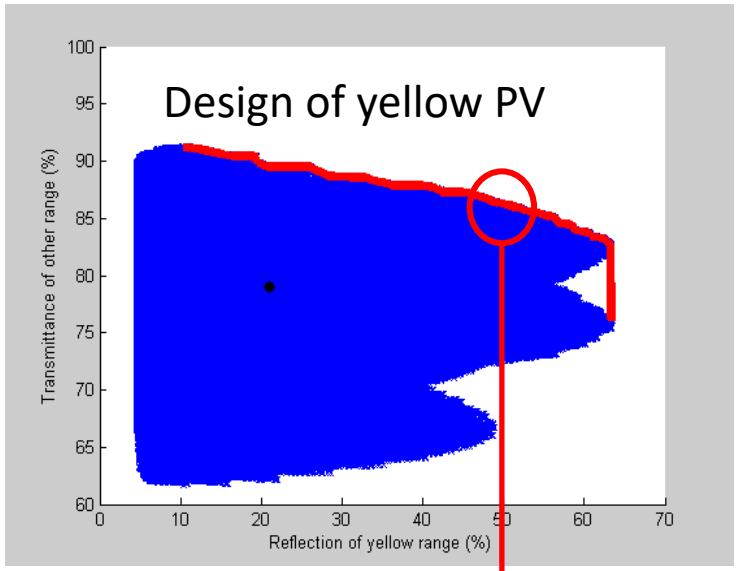


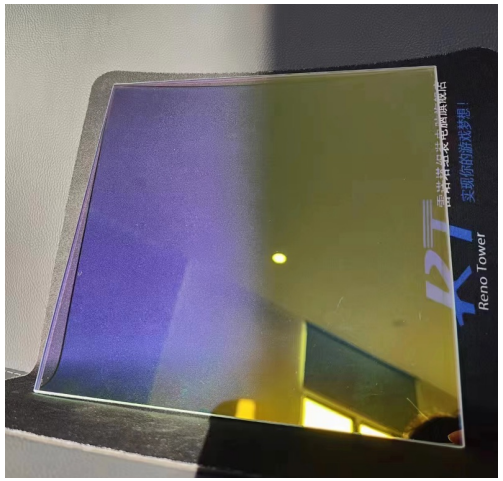
PCE, VLT, and color are all angle-dependent properties in STOSC.

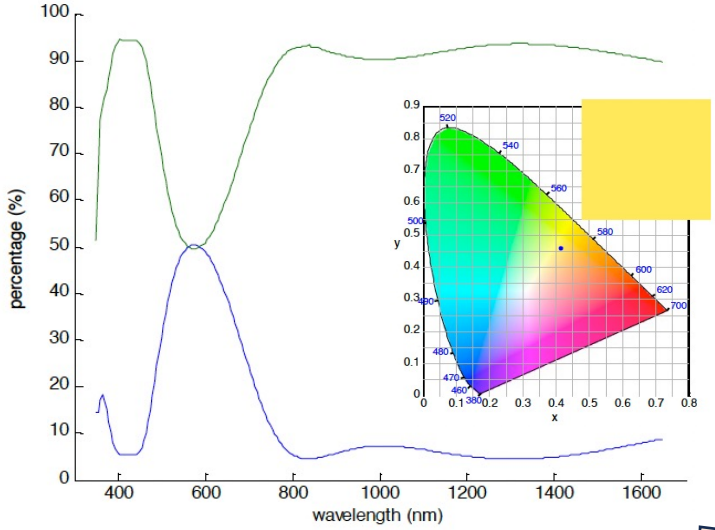
Enhancing Si PV Panels with Tailored Optical Coating

Optical Model:

- Optical film reflects desired visible light for color customization
- Allows high PV efficiency with optimal layer design
- Blocks infrared to reduce thermal load

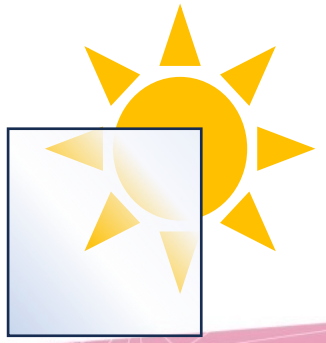


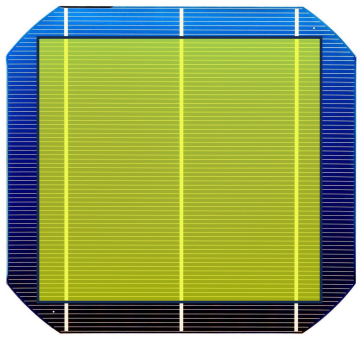


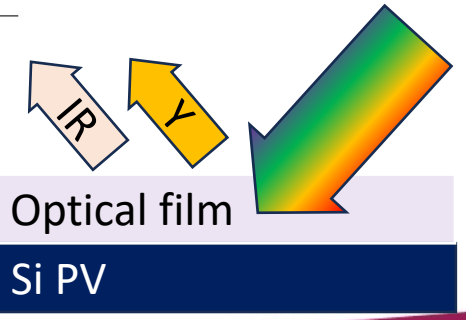


SiO_2 200nm
TiO_2 80nm
SiO_2 40nm
TiO_2 90nm
SiO_2 30nm
Glass

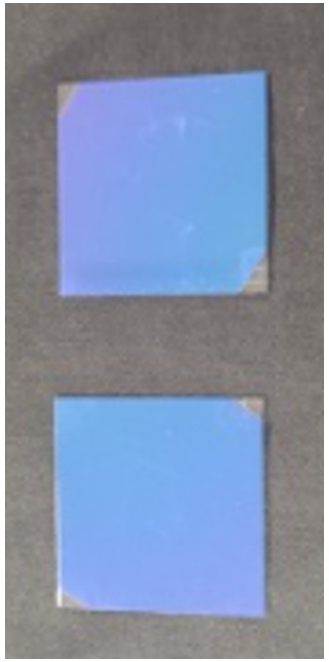
R = 50.1% , T = 86.3%





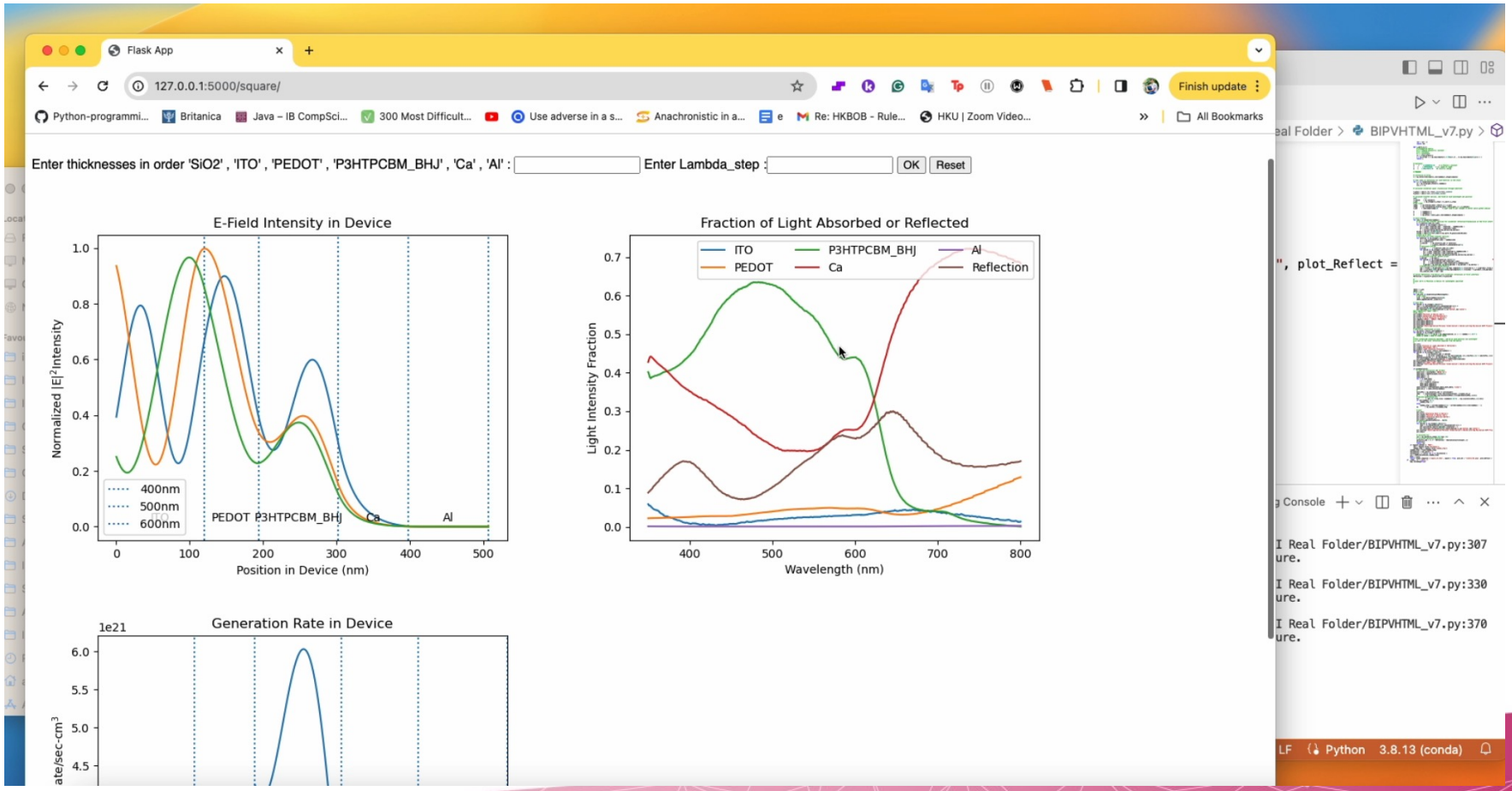


Tailoring Colors for specific applications



Developing a Publicly Accessible Modeling Platform

1. Accelerated Design: Streamlines device prototyping and testing.
2. Material Optimization: Enhances material selection for improved efficiency.
3. Global Collaboration: Enables knowledge sharing across research communities.

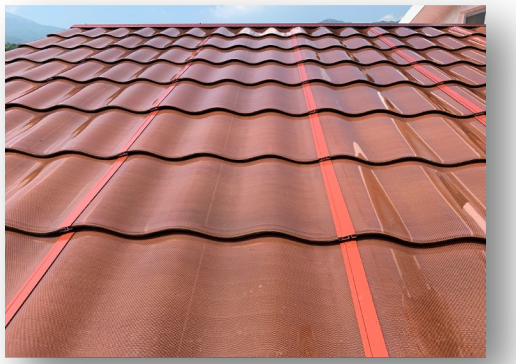


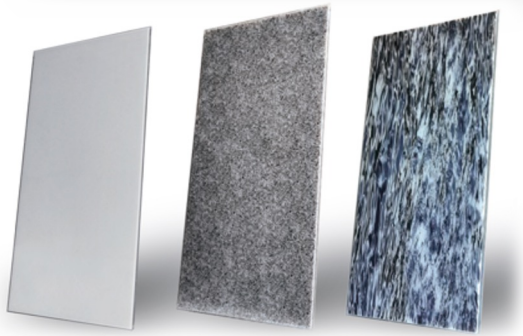
Promote New PV Applications with Local Green Tech Companies

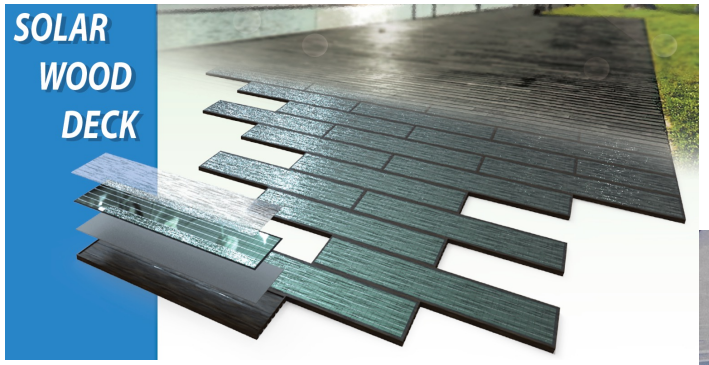
Solar Windows, Tiles, Roads, Walls, Bricks, Wood Decks

A-GRADE ENERGY

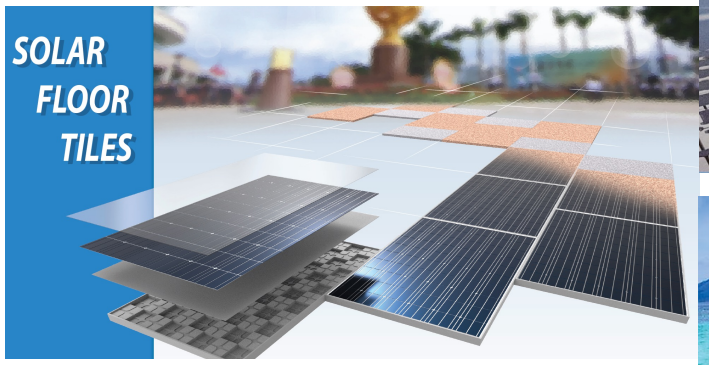
MONDO GREEN ENERGY 天地綠色能源

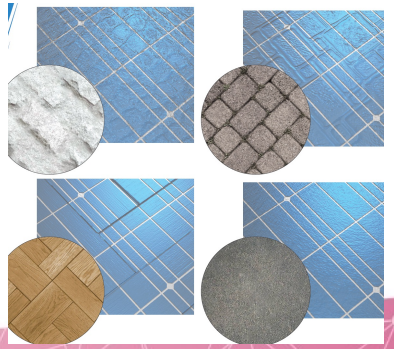


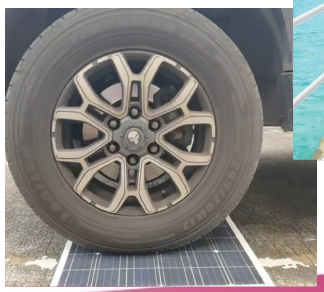




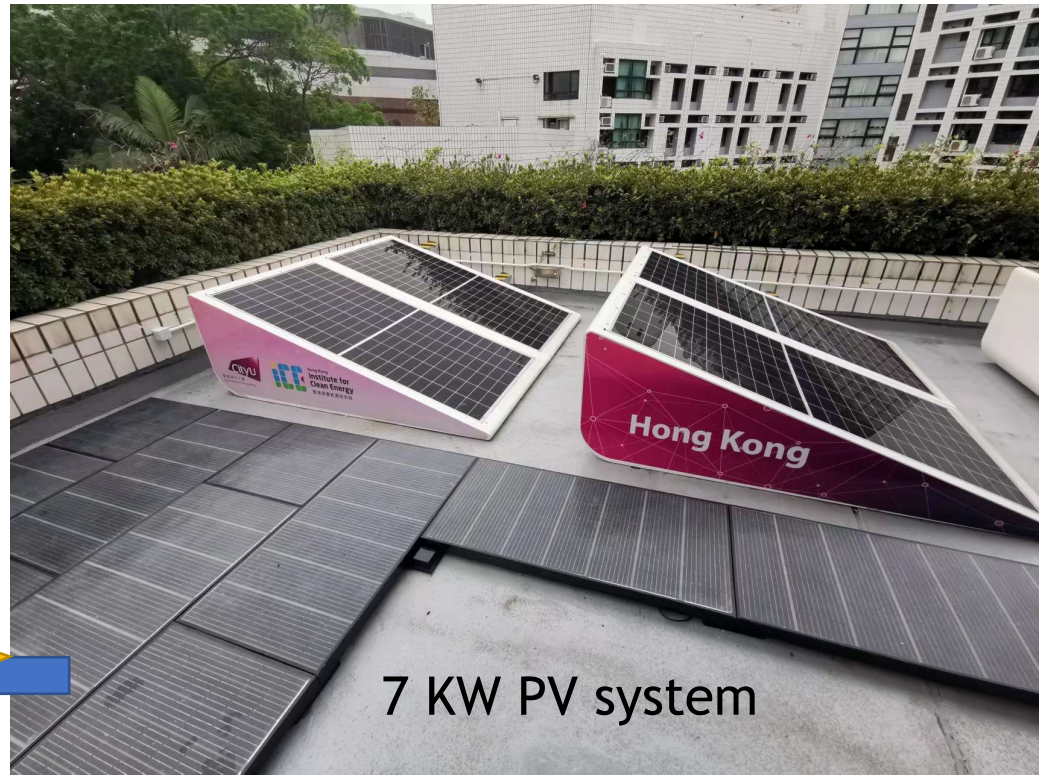
ABES Technology Group Limited

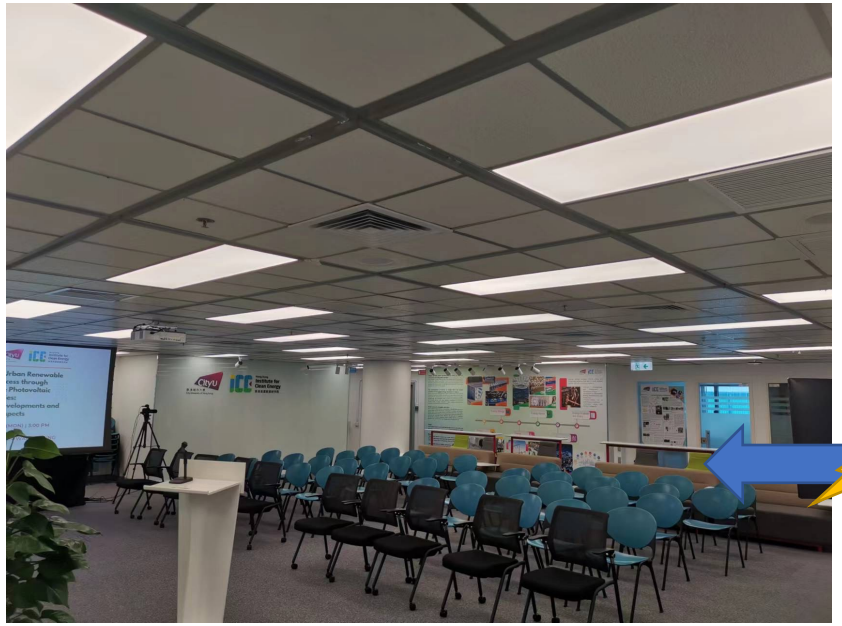






Integrated Power Generation-Storage-Saving Project





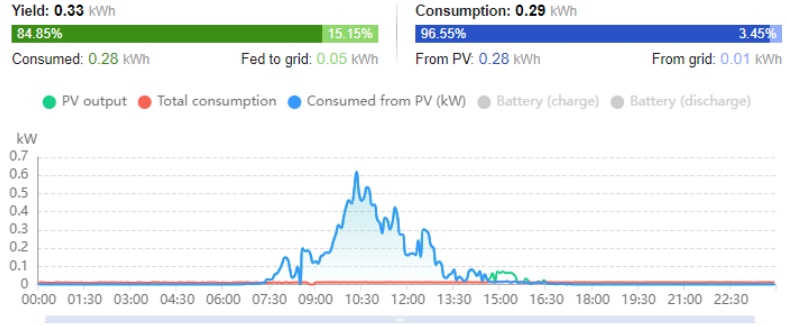
LED Lighting for energy saving

10 KWh storage

HKICE's PV systems endured the recent extreme weather conditions

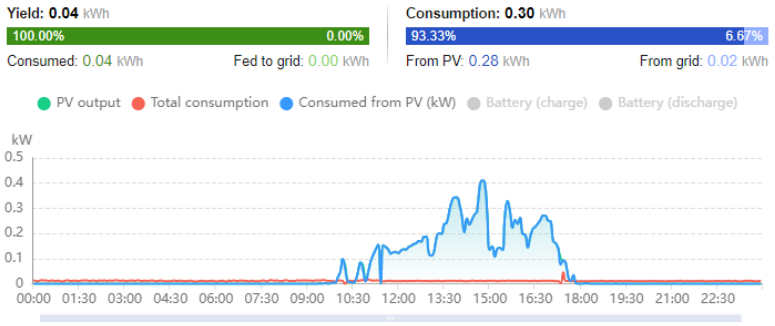
Energy Management

2023-09-01
(Super Typhoon Saola)



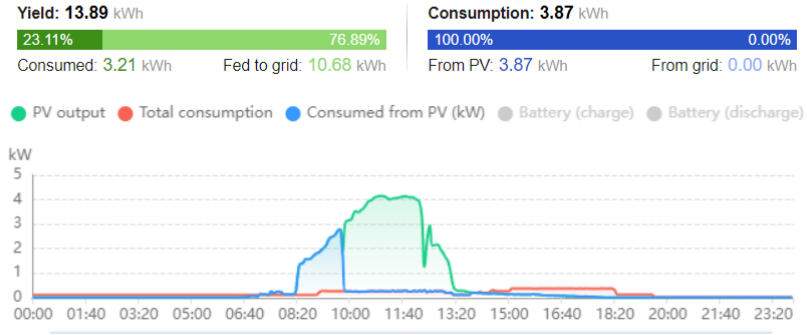
Energy Management

2023-09-07
(Record-breaking Rainstorm)



Energy Management

2023-09-18
(After two extreme Weather Conditions)



Solar panels in Cheung Sha Wan blown away by Super Typhoon Saola on 1 Sep 2023

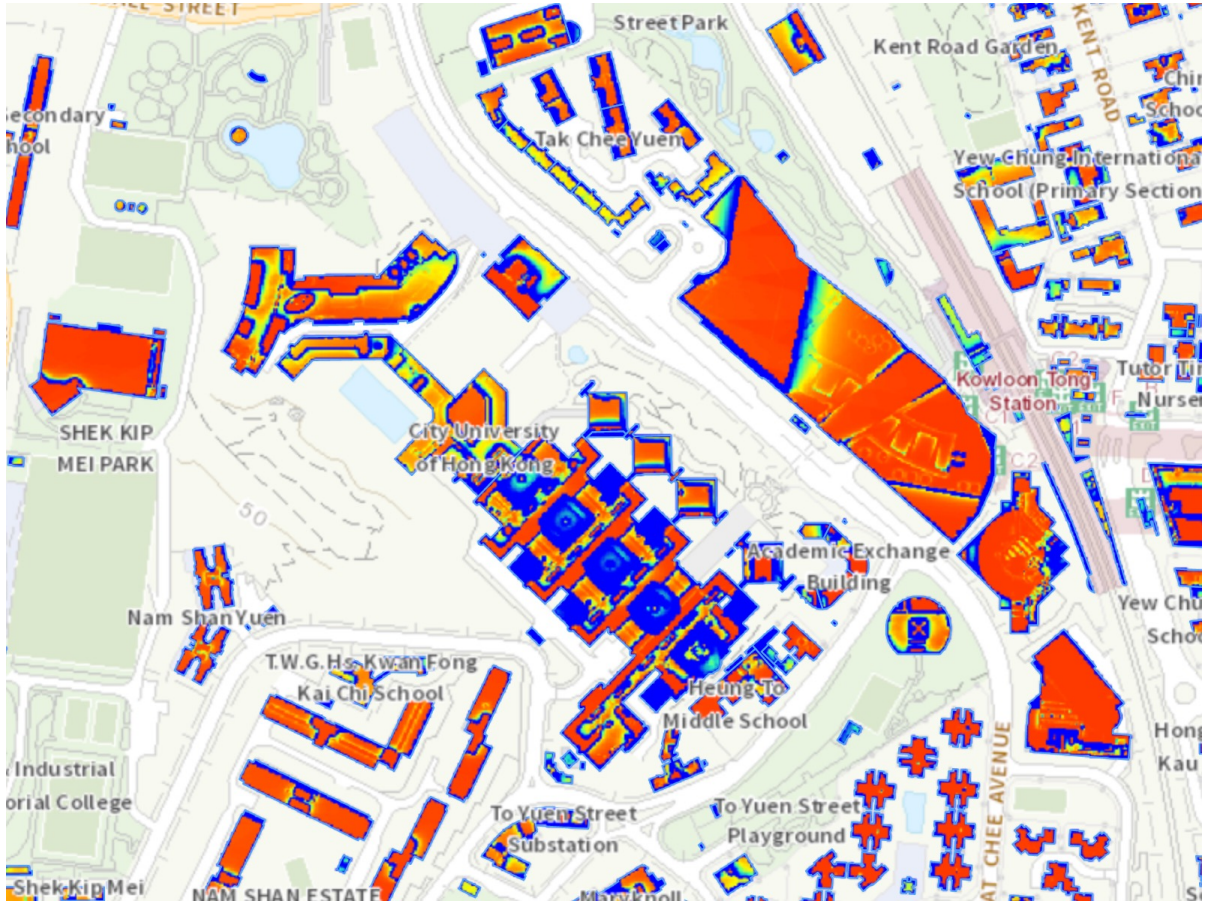
Record-breaking rainstorm on 7 Sep 2023

HKICE's demo display site remained unharmed

Solar Panels before and after Extreme Weather in Mid Sep 2023

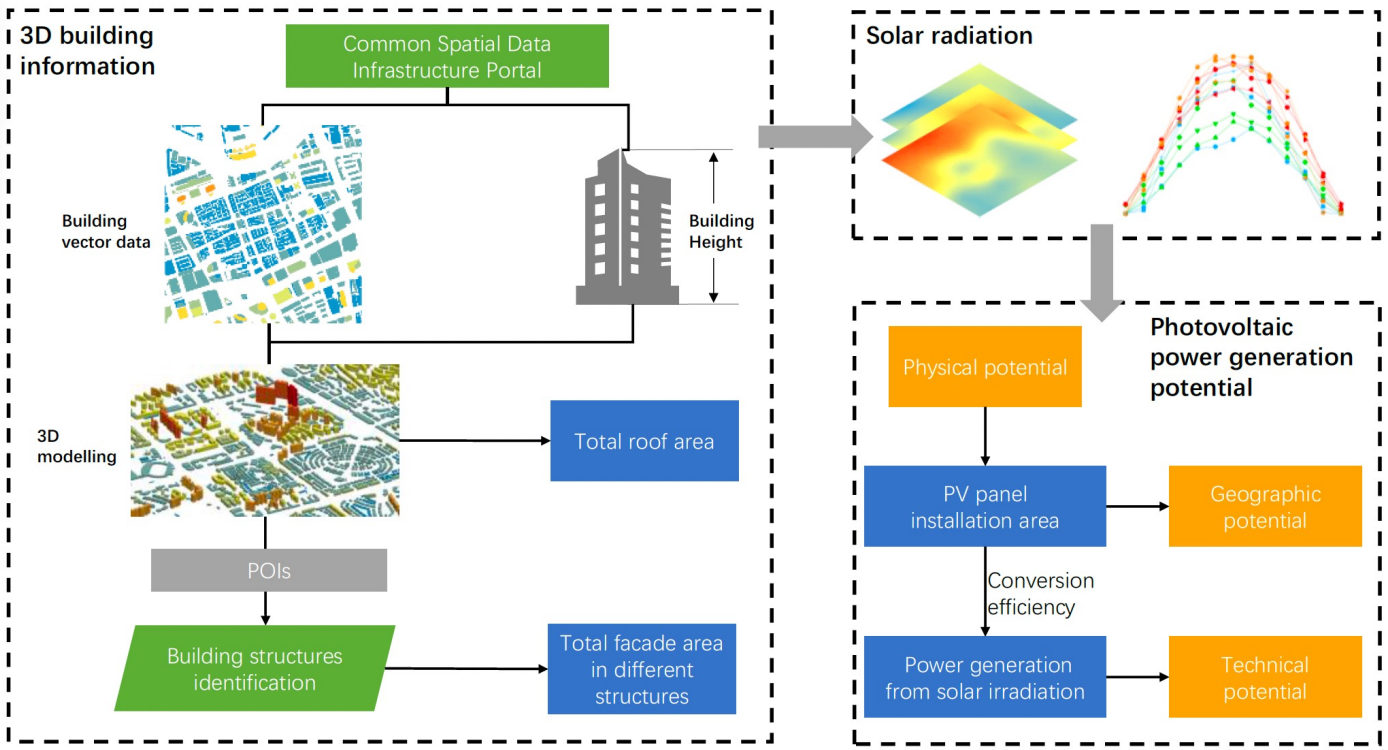
Deployment of Sustainable Green Campus

Promotion to the whole campus > 3MW capacity

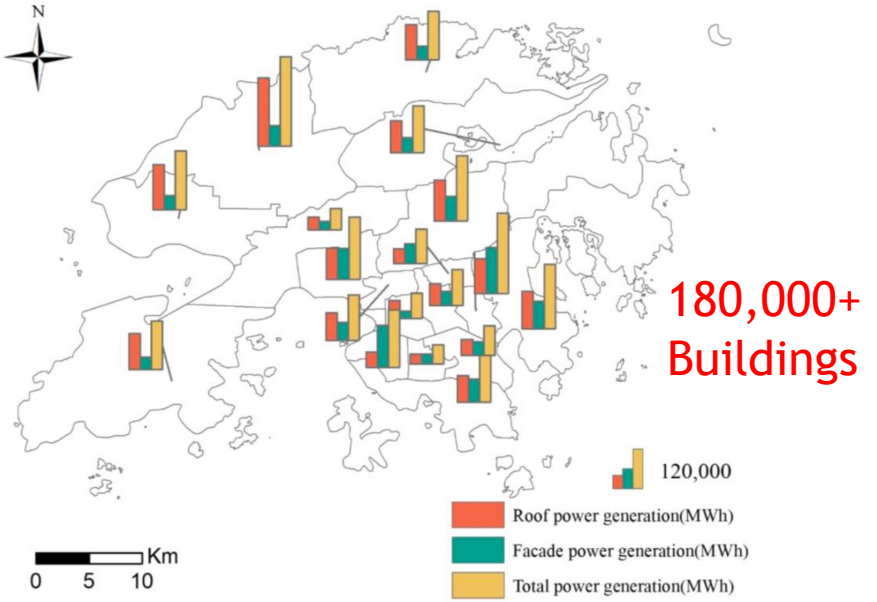


CityU Sustainable Green Campus

Future Goals:
Establish Model to Evaluation Solar Energy Potential in HK



Unleashing the Green Potential: Assessing Hong Kong's Building Solar PV Capacity



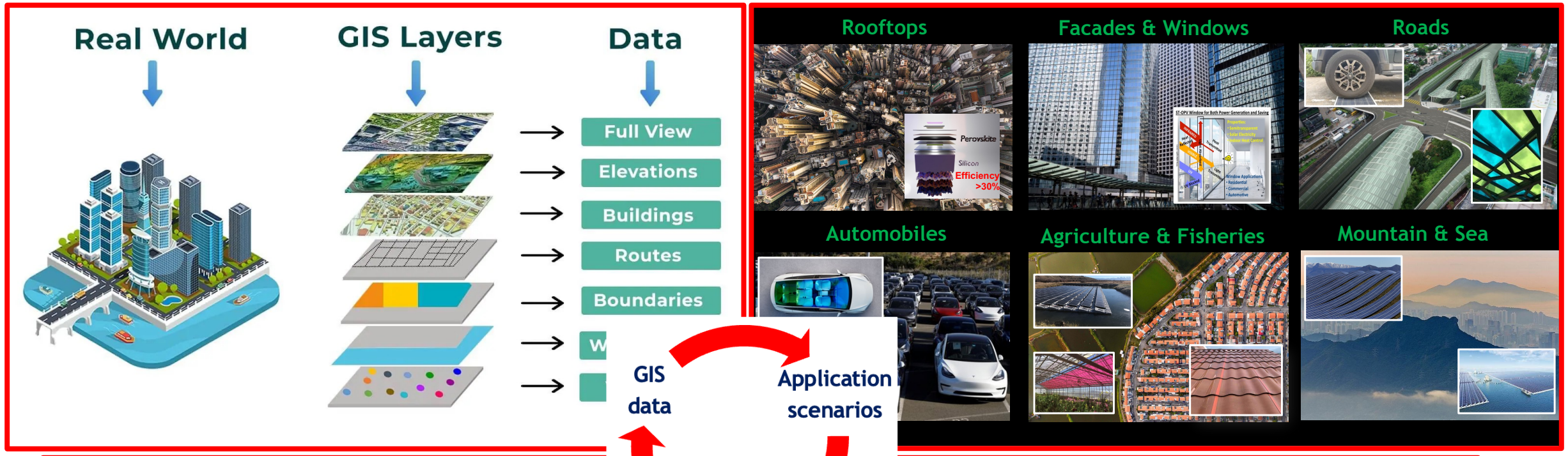
180,000+ Buildings

In collaboration with Prof. LIANG Dong (SEE CityU)
Submitted (http://dx.doi.org/10.2139/ssrn.4753774)

Solar Energy Potential Model Expansion

- **Current Model**: Established for BIPV solar potential in Hong Kong.
- **Next Steps**: Expand to assess solar energy in coastal regions, roads, agriculture, and fisheries.
- **Guideline Development**: To provide comprehensive guidance for solar energy deployment.

Future Goals:
Establish Model to Evaluation Solar Energy Potential in HK



PV Technologies for Oceanic Applications

State Key Lab of Marine Pollution

CityUHK's own Fish Rack in Saigon

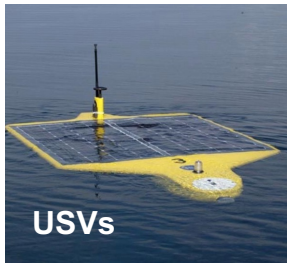
CityU 香港城市大學 City University of Hong Kong

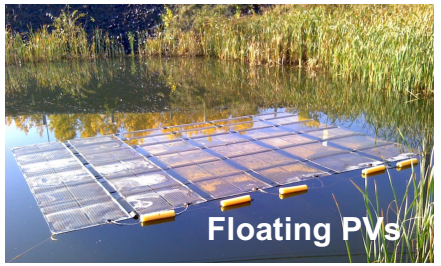
SKLMP 海洋污染國家重點實驗室

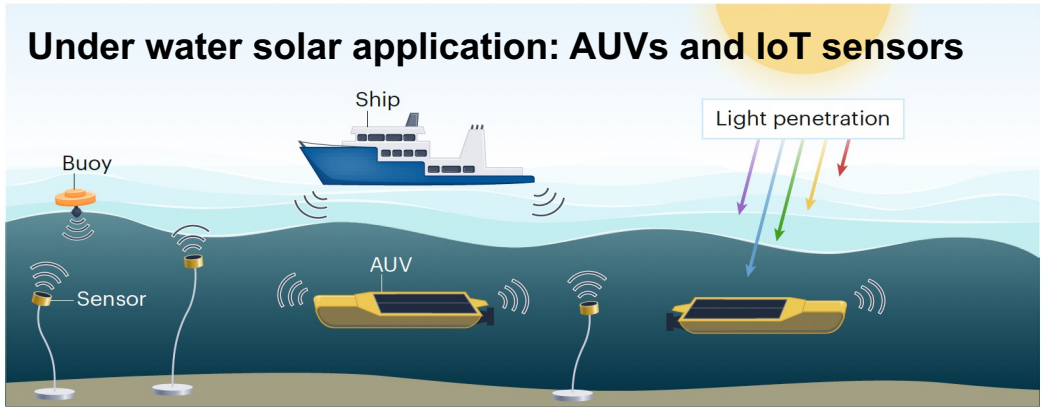
ABES

Innovative PV Technologies for Oceanic Applications

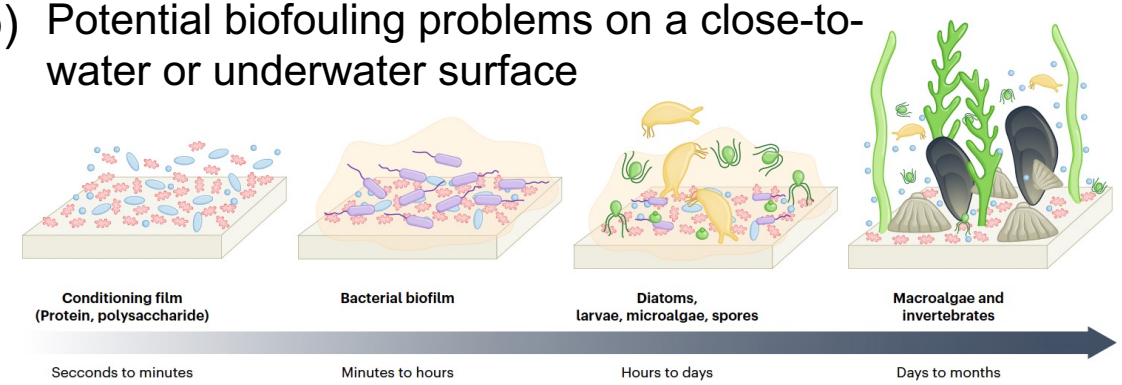
(a)



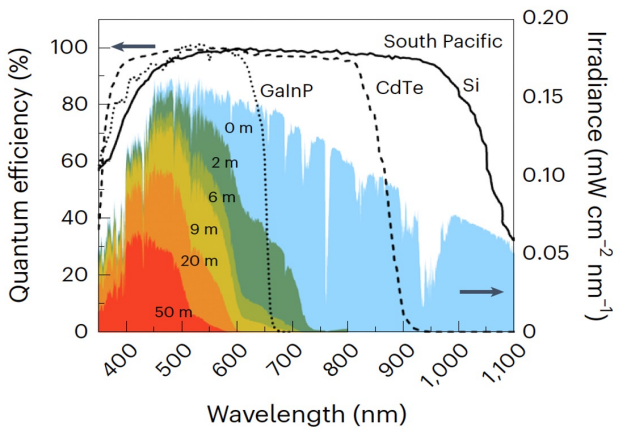


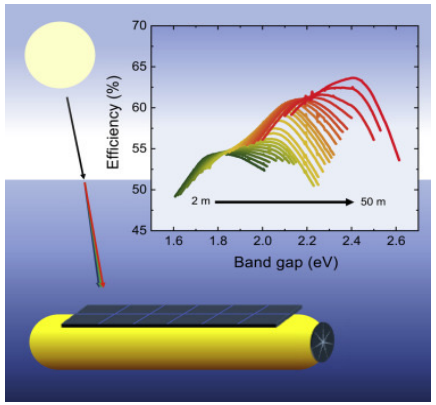


(b) Potential biofouling problems on a close-to-water or underwater surface



Sunlight spectra under water, and PCE vs bandgap



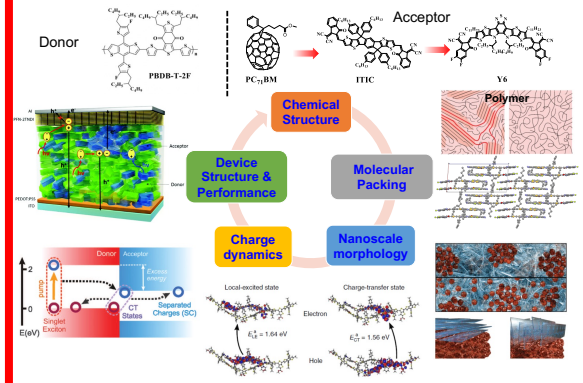


CityU 香港城市大學 City University of Hong Kong

Hong Kong Institute for Clean Energy 香港清潔能源研究院

Research: Development of new generation printable optoelectronic devices, integrating materials innovation, device optimization, upscaling & commercialization.

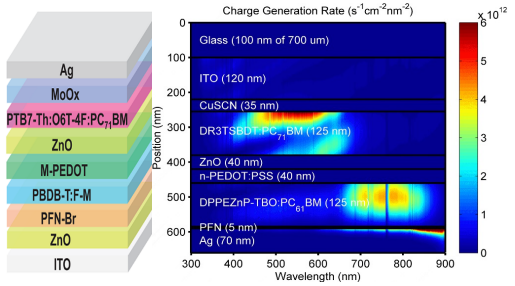
Organic Solar Cells



Highlighted publications:

Adv. Mater. 2023, *35, 2302861*
J. Am. Chem. Soc. 2023, *145, 5909*
ACS Energy Lett. 2022, *7, 2196*
Chem. Rev. 2022, *122, 14180*
***Adv. Mater.* 2021,** *33, 2008158*
***Adv. Mater.* 2020**, *32, 2001621*
***Adv. Energy Mater.* 2019**, *9*, 1803438
***Adv. Energy Mater.* 2018**, *8*, 1801609
***Energy Environ. Sci.* 2017,** *10, 1784*
***Energy Environ. Sci.* 2018,** *11, 1688*
***Energy Environ. Sci.* 2022,** *15, 2629*
***Energy Environ. Sci.* 2022,** *15*, 2958
***J. Am. Chem. Soc.* 2016**, *138, 2004*
***Joule* 2019**, *3*, 2241
***Joule* 2018**, *2*, 1816
***Nat. Commun.* 2019**, *10*, 4100
***Nat. Commun.* 2020,** *11*, 3943

Tandem Solar Cells



Highlighted publications:

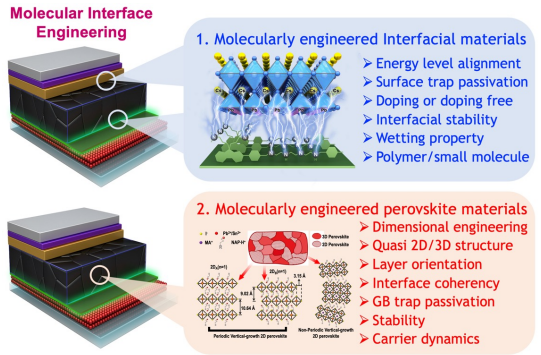
Organic/Organic Tandem Cells:

***Science*, 2018**, *361*, 1094
***Nat. Photonics*, 2017**, *11*, 85
***Adv. Mater.*, 2016**, *28, 4817*
***Adv. Mater.* 2018**, *30*, 1707508
***Adv. Mater.* 2018,** *30, 1803166*
***Adv. Mater.*, 2018**, *30*, 1803769
***Adv. Energy Mater*. 2018**, *8*, 1703180
***ACS Energy Lett.*, 2020,** *5*, 1771
***Adv. Funct Mater,* 2021,** *31, 2103283*

Perovskite/Organic Tandem Cells:

***Adv. Mater,* 2023**, 2306568
Adv. Energy Mater, 2023, *13*, 2204347
***Adv. Funct. Mater*, 2023**, *33*, 2212599
***Small Methods* 2023**, *7*, 2201255
***Adv. Funct. Mater*, 2022**, *32*, 2112126
***J. Energy Chem.*, 2022**, *71*, 12
***Nano Select,* 2021**, *2*, 1266
***Nano Energy,* 2020**, *78*, 105238

Perovskite Solar Cells

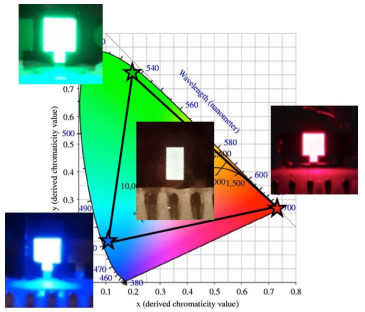


Highlighted publications:

J. Am. Chem. Soc. 2023, *145*, 5920
***Adv. Energy Mater*. 2022**, *12*, 2270004
***Adv. Energy Mater*. 2021**, *11*, 2100784
***Adv. Mater.* 2020,** *32*, 1908011
***Adv. Mater.* 2020,** *32*, 2000571
***Adv. Mater.* 2019,** *31,* 1901152
***Adv. Mater.* 2018**, *30*, 1802509
***Adv. Energy Mater*. 2021**, *11*, 2100784
***Adv. Energy Mater*. 2019**, *9*, 1803572
***Adv. Energy Mater*. 2017**, *7*, 1602333
***Adv. Energy Mater*. 2016**, *6*, 1501534
***Adv. Funct. Mater.* 2018,** *28*, 1707444
***Angew. Chem. Int. Ed.* 2019,** *58*, 49
***J. Phys. Chem. Lett.* 2021**, *12*, 4882
***iScience* 2018,** *9*, 337
***Nat. Commun.* 2020,** *11*, 177
***Joule* 2021,** *3*, 1900265

Perovskite LEDs

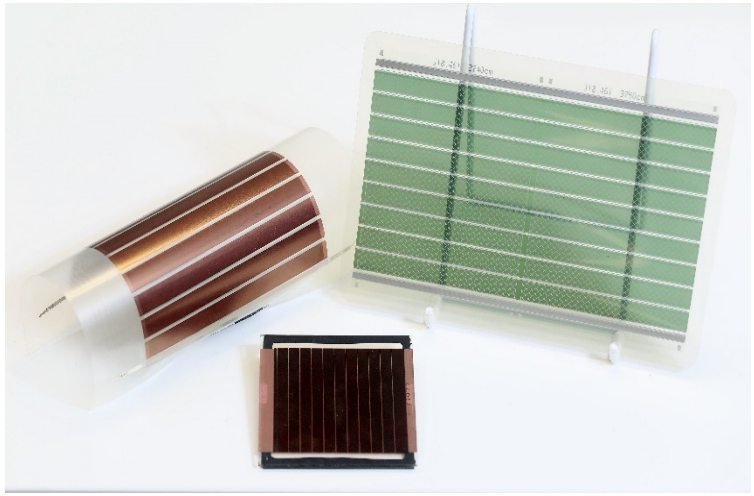
- **RGB & White Perovskite LEDs**
- **Carrier Dynamics Study**



Highlighted publications:

***Nat. Commun.* 2019,** *10*, 1027
***Nat. Commun.* 2023,** *14*, 6441
***Joule* 2021**, *5*, 456-466
***JACS* 2022**, *144*, 12102-12115
***Adv. Mater.* 2017,** *29*, 1603157
***Adv. Mater.* 2018,** *30*, 1801370
***Adv. Mater.* 2021,** *33, 2103286*
***Adv. Funct. Mater.* 2020,** *30*, 1910167
***Adv. Funct. Mater.* 2021,** *31*, 2103219
***Adv. Funct. Mater.* 2021,** *31*, 2106691
***Adv. Funct. Mater.* 2022,** *32*, 2201123
***Adv. Sci* 2022,** *9,* 2201844
***Adv. Sci* 2022,** *9,* 2200393
***Adv. Opt. Mater.* 2022,** *10*, 2201123
***RSC Adv.*, 2019,** *9*, 27684
***Rep. Prog. Phys.* 2021**, *84*, 046401

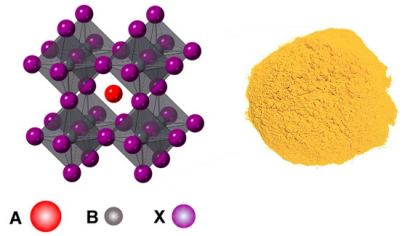
CityU's spin-out to commercialize new PV Technologies

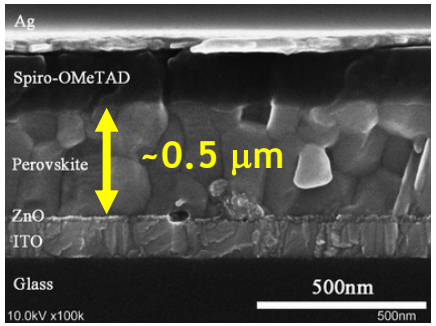


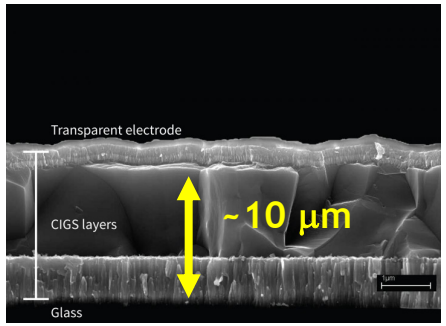
HKTech Solar
滙科光能

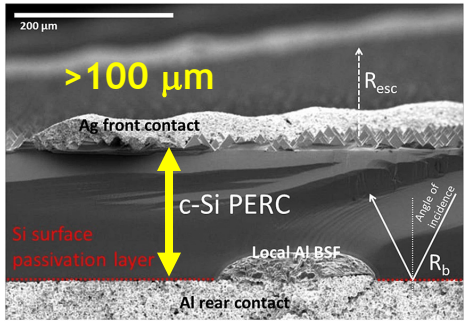
Printable Solar Technology: Perovskite Solar Cells

<3 g/m² — Less Material & Energy Consumption — >1 kg/m²



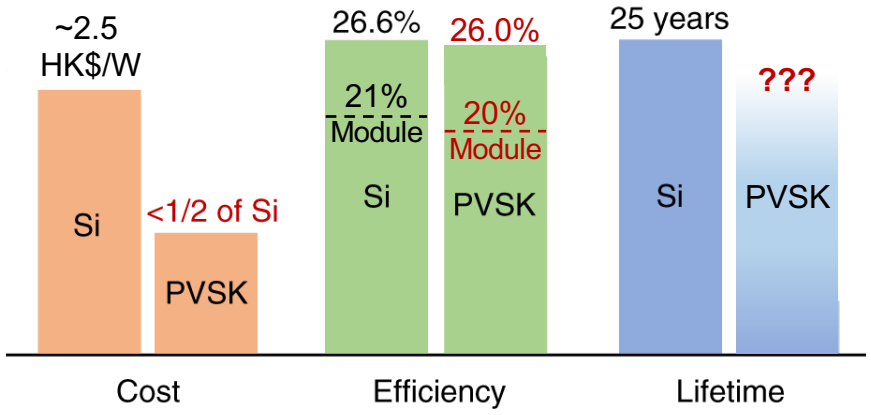


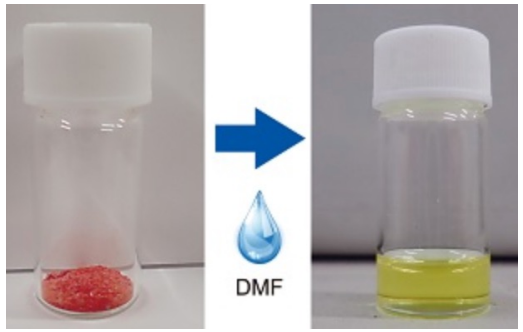




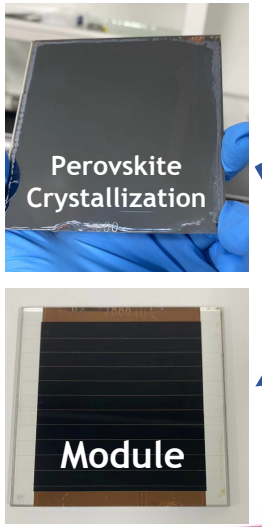
PbI_2<100 HK$/kg | Perovksite: ~0.5 μm | CIGS: ~10 μm | c-Si: >100 μm | Si wafer>1500 HK$/kg

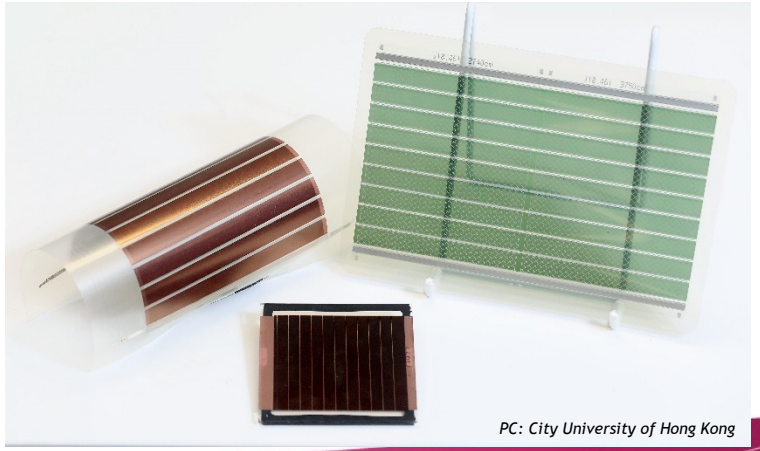
Cheaper Precursors & Scalable Processing Methods





Raw Materials — Perovskite Ink





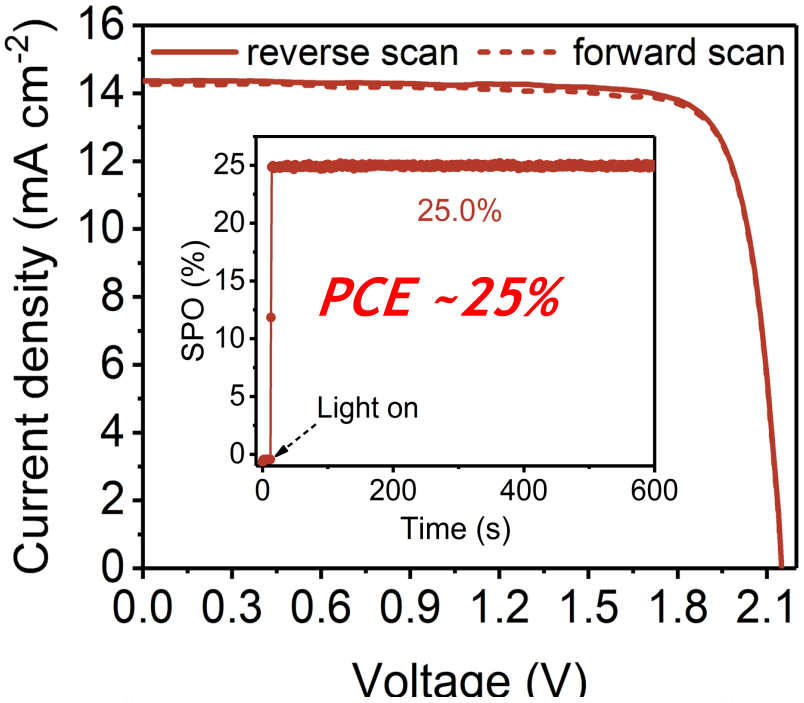
PC: City University of Hong Kong

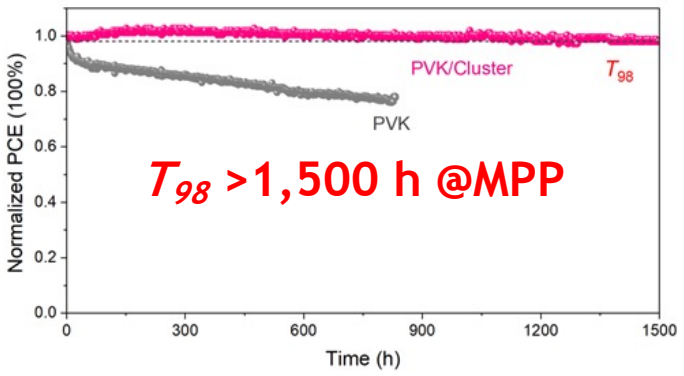
*Modified from *Nature Comm.* 2018, *9*, 5265.

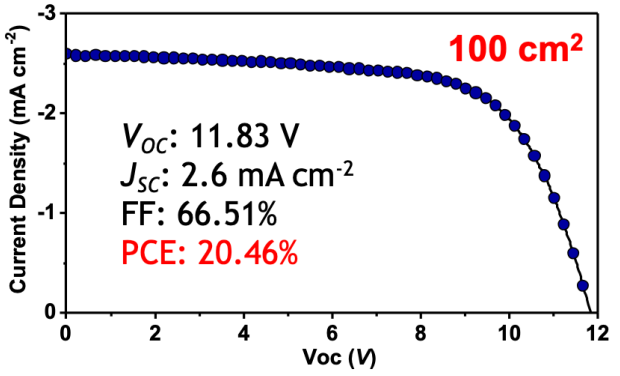
Scalable Printing Technology

Commercialization: From Research Lab to Market

Current Results







R&D
Research Cell
PCE >27%

Tech Transfer
Key Materials

Product Design
Tandem Cells

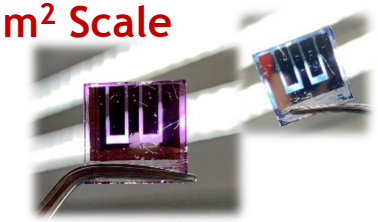
Market

Material Design
Device Engineering
Encapsulation

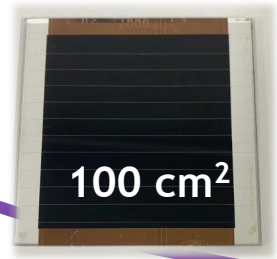
Scalable Production
Product Development

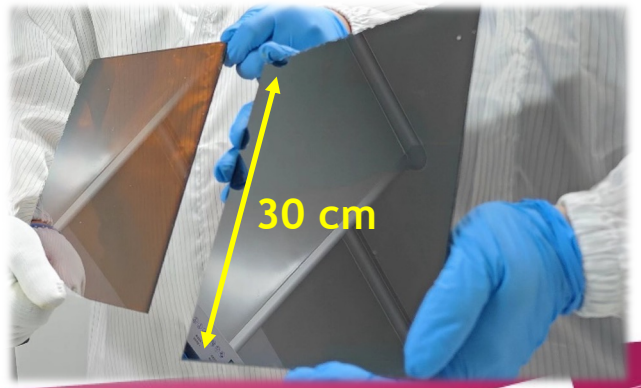
High-power Applications
Flexible Electronics

mm² Scale



Efficiency → Stability → Safety → Scalability





South China University of Technology (2013-20)

City University of Hong Kong (2021-NOW)

CityU 香港城市大學 City University of Hong Kong

NSFC National Natural Science Foundation of China

UGC 大學教育資助委員會 University Grants Committee

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Green Tech Fund 低碳绿色科研基金

华南理工大学发光材料与器件国家重点实验室
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Thank you!

Hong Kong Institute for Clean Energy

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