Enabling Ubiquitous Solar Photovoltaic Power Through Power Electronics Design

Online Meetings of the Worldwide Energy Network

Dr. Katherine A. Kim

December 28, 2021

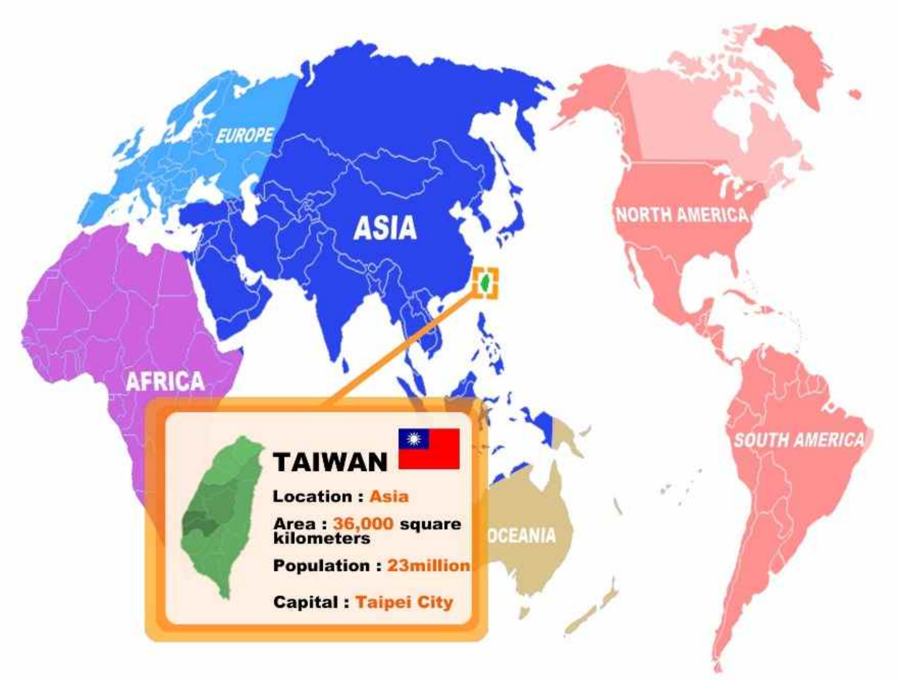
National Taiwan University
國立臺灣大學

PEARS
POWER ELECTRONICS FOR ADVANCED RENEWABLE SYSTEMS LAB

Biography: Katherine A. Kim

- National Taiwan University, Taiwan
  - Associate Professor, Electrical Engineering, 2019-present
  - Power Electronics for Advanced Renewable Systems (PEARS) Lab
- Ulsan National Institute of Science and Technology (UNIST), Korea
  - Assistant Professor, Electrical and Computer Engineering, 2014-2018
- University of Illinois at Urbana-Champaign, IL, USA
  - Ph.D. Electrical and Computer Engineering, 2014
  - M.S. Electrical and Computer Engineering, 2011
- Olin College of Engineering, MA, USA
  - B.S. Electrical and Computer Engineering, 2007
- Industry Experience:
  - Texas Instruments, Dallas, TX, USA, 2008
  - Bluefin Robotics, Cambridge, MA, USA, 2009
- Research Areas: PV Systems, Modeling & Simulation, DC-DC Converter Control, Energy Harvesting Systems

National Taiwan University, Taipei, Taiwan



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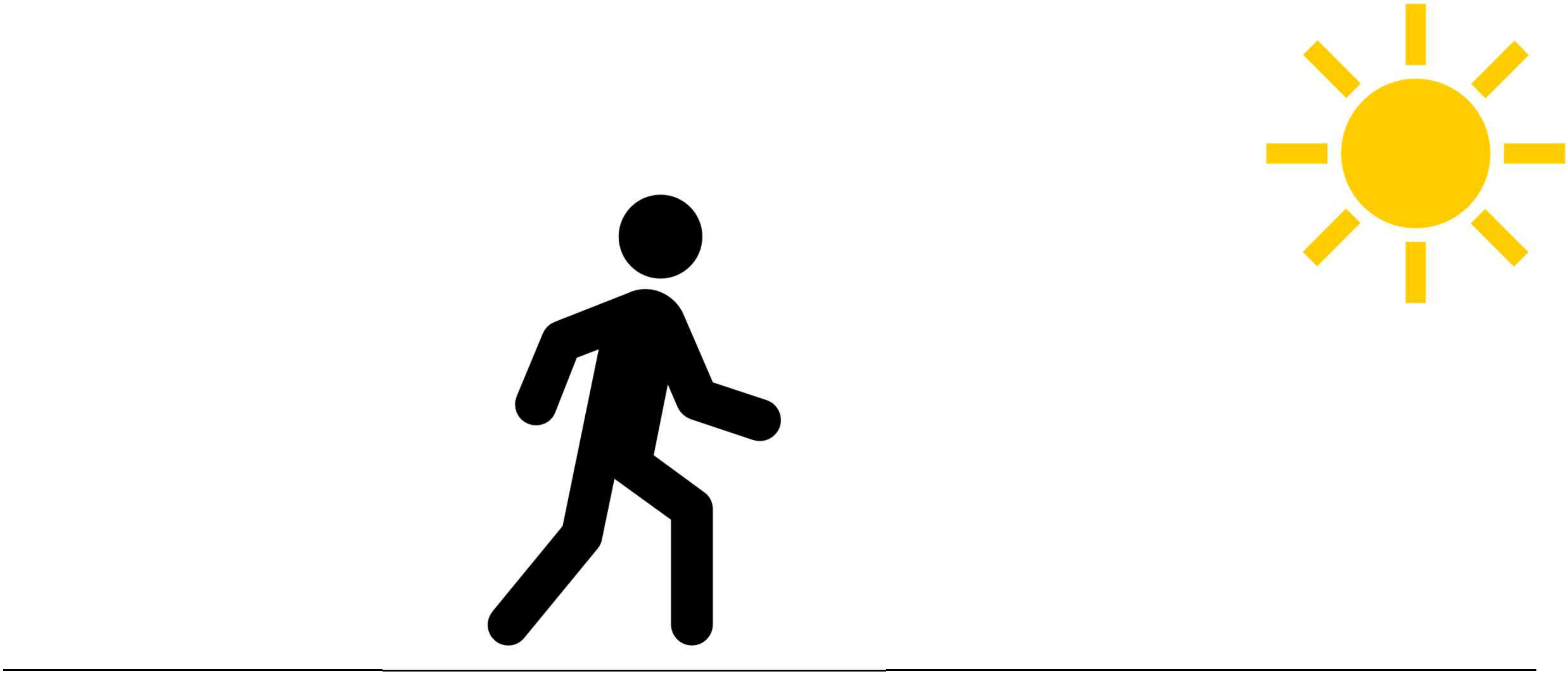

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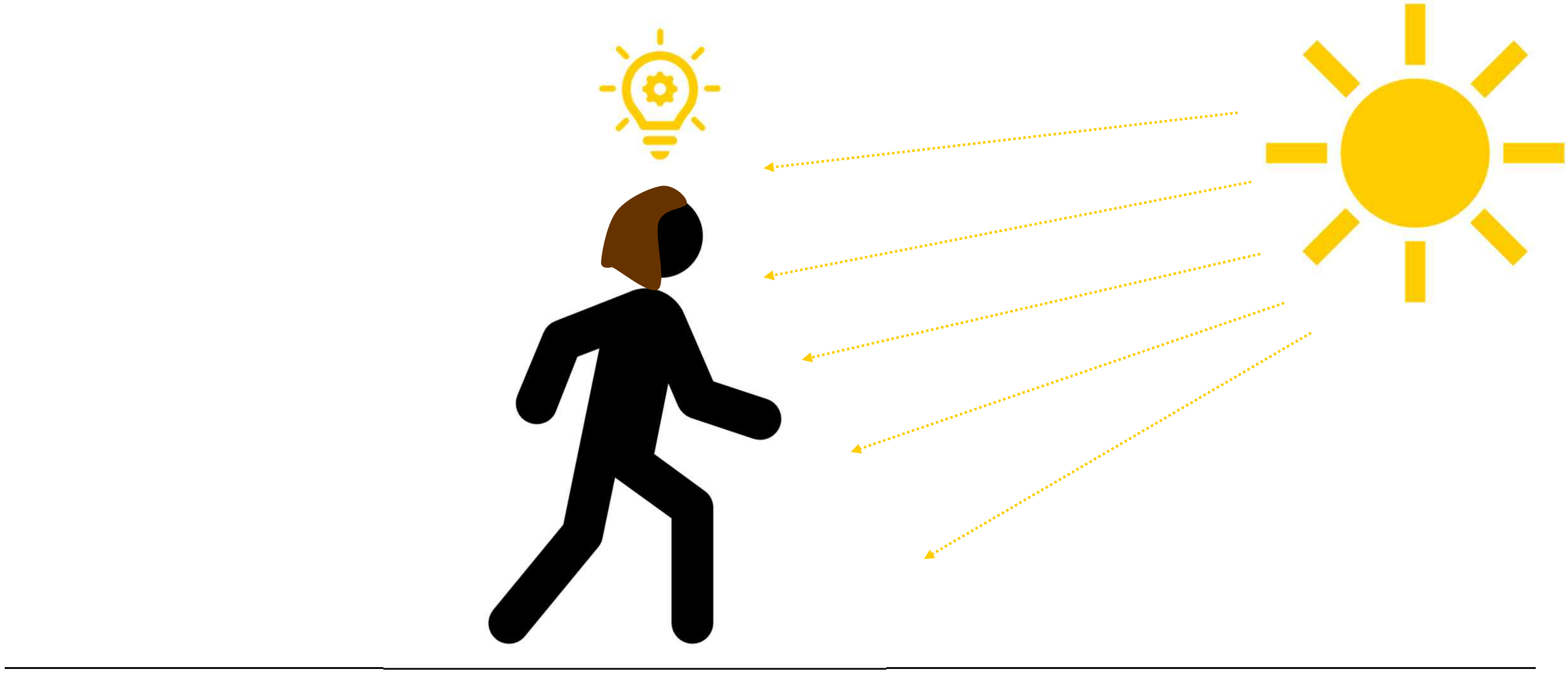

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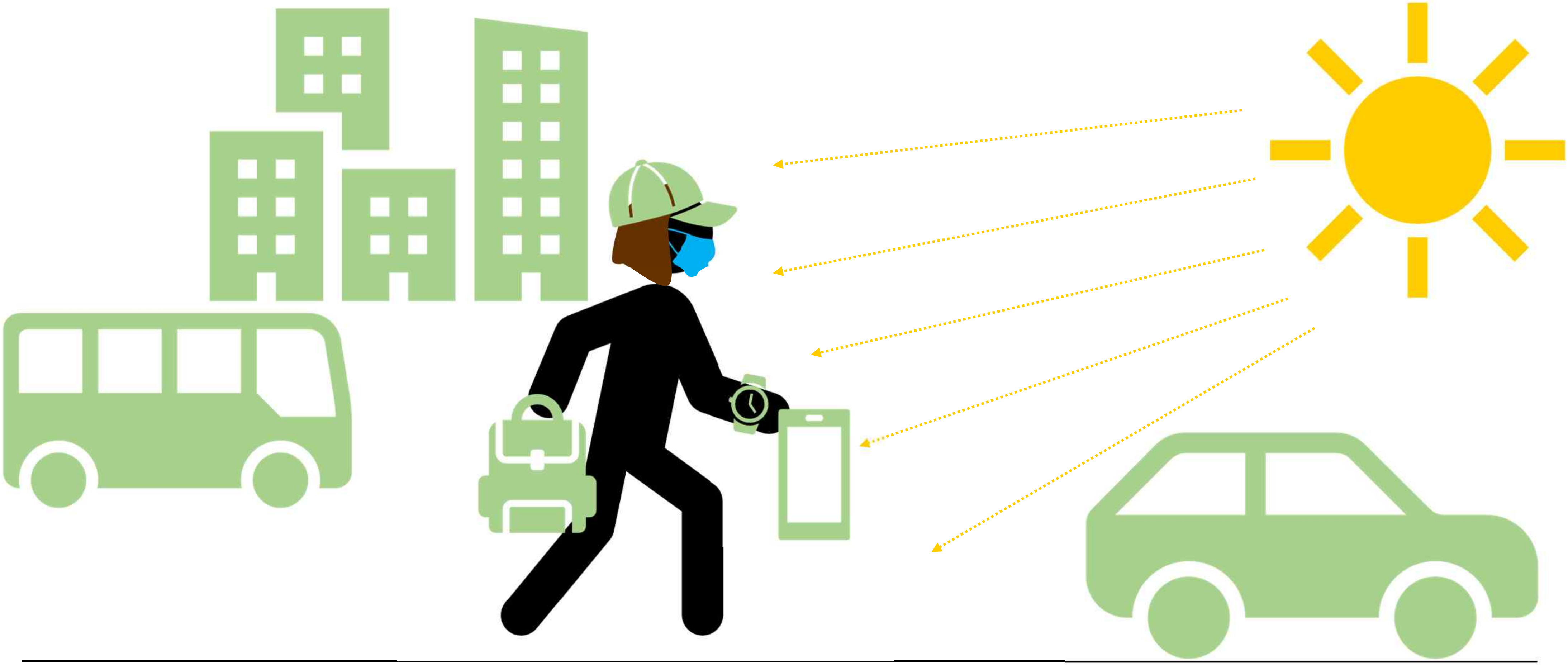

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Product Rating: 6 W

Corner Shaded: 3.5 W (58%)

Half-Shaded: 0.3 W (5%)

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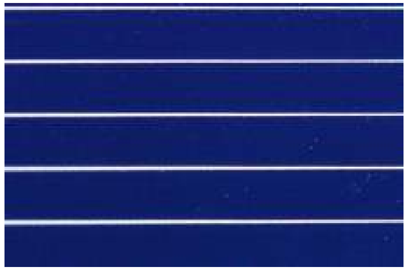
Outline

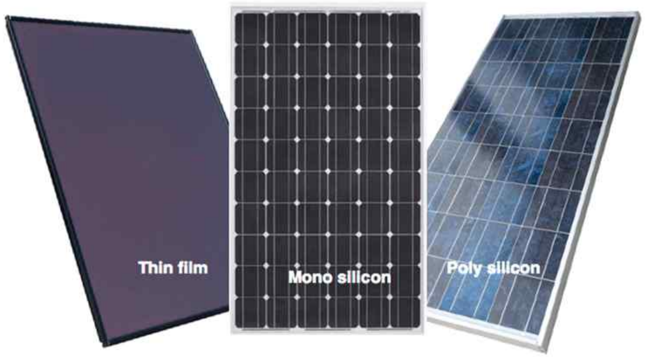
- Solar Photovoltaic Basics
- Emerging Solar PV Applications
- Exploring Parallel Converter Architectures
- Measuring Solar PV Profiles for Wearables
- Maximum Power Point Tracking for Low Power Consumption
- Conclusion

Photovoltaic (PV) Materials

- Crystalline Si
  - Monocrystalline
  - Polycrystalline



- Thin-Film Technologies
  - Copper indium gallium selenide (CIGS)
  - Cadmium telluride (CdTe)
  - Amorphous silicon (a-Si)



[Source: http://www.cleanenergyreviews.info/]

- Multi-junction
  - Double-junction
  - Triple-junction

[Source: http://www.spectrolab.com/]

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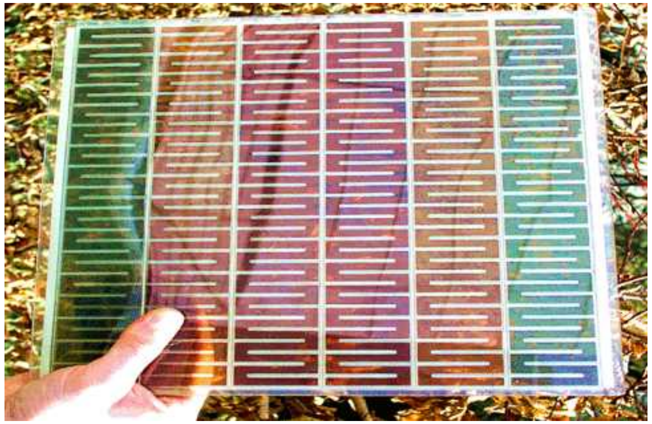
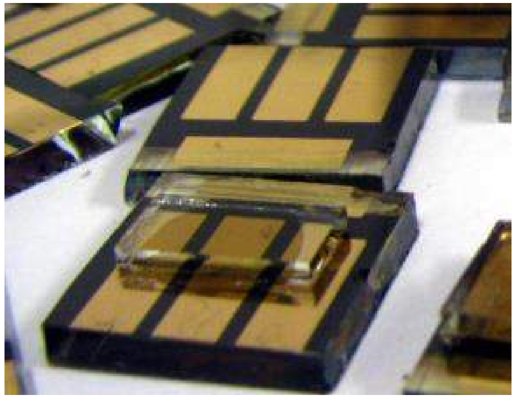
Photovoltaic (PV) Materials

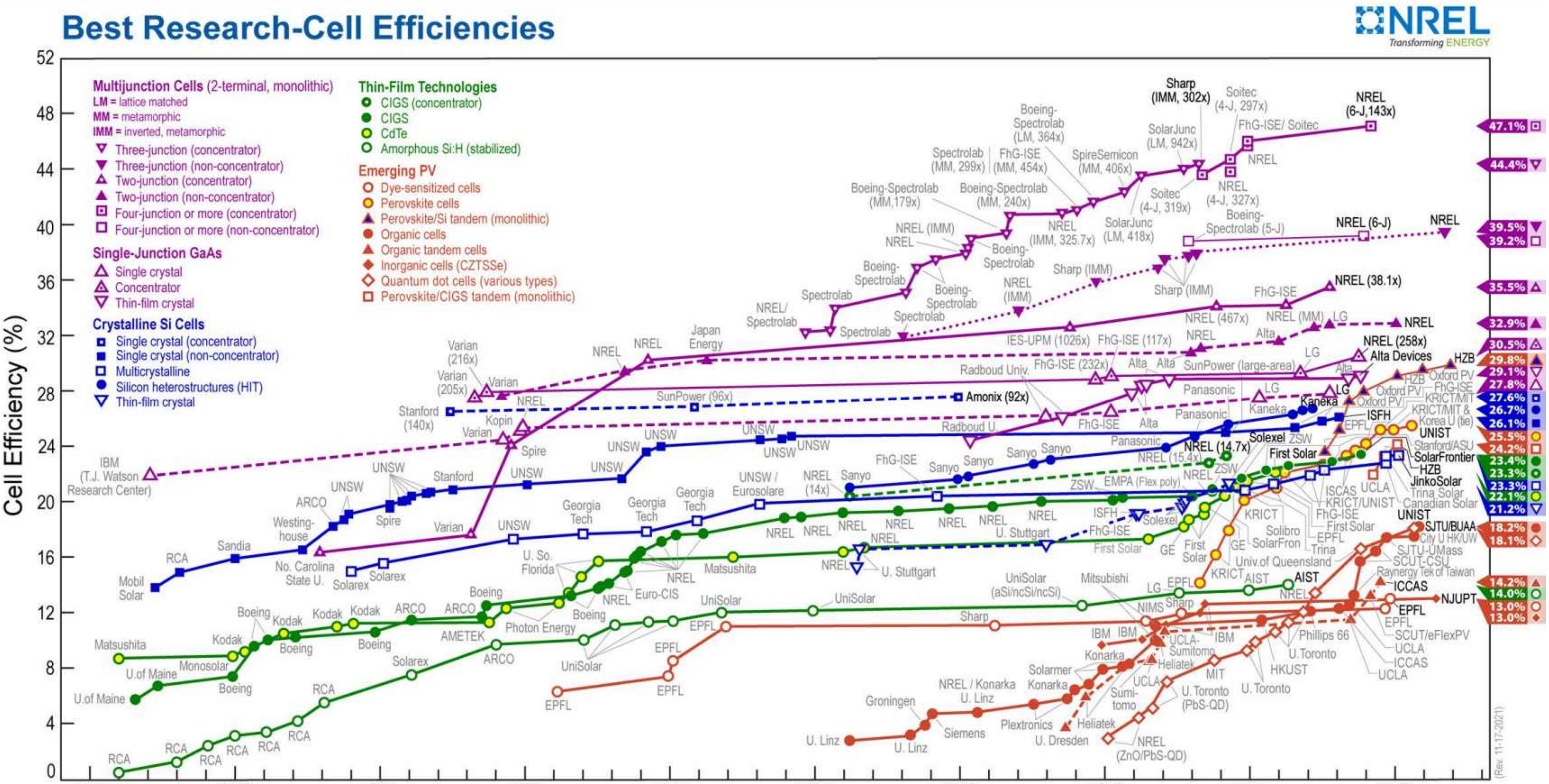
- Emerging PV
  - Dye-Sensitized Cells
  - Perovskite Cells
  - Organic Cells



[Source: http://www.solarisnano.com/]



[Source: www.electronicsweekly.com]



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[Source: http://www.nrel.gov/ncpv/images/efficiency_chart.jpg]

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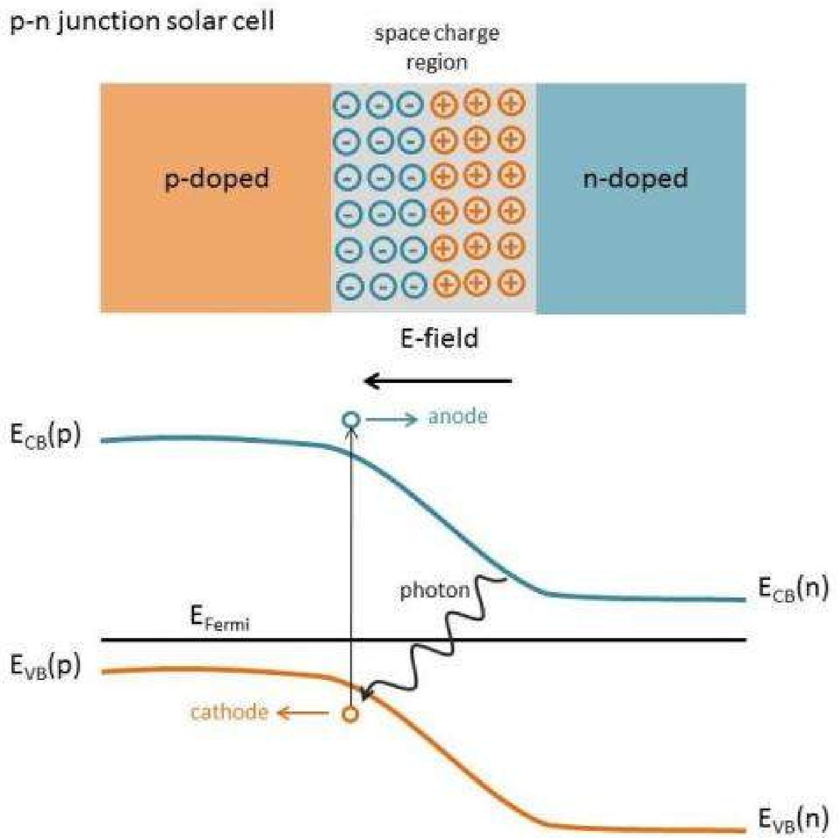
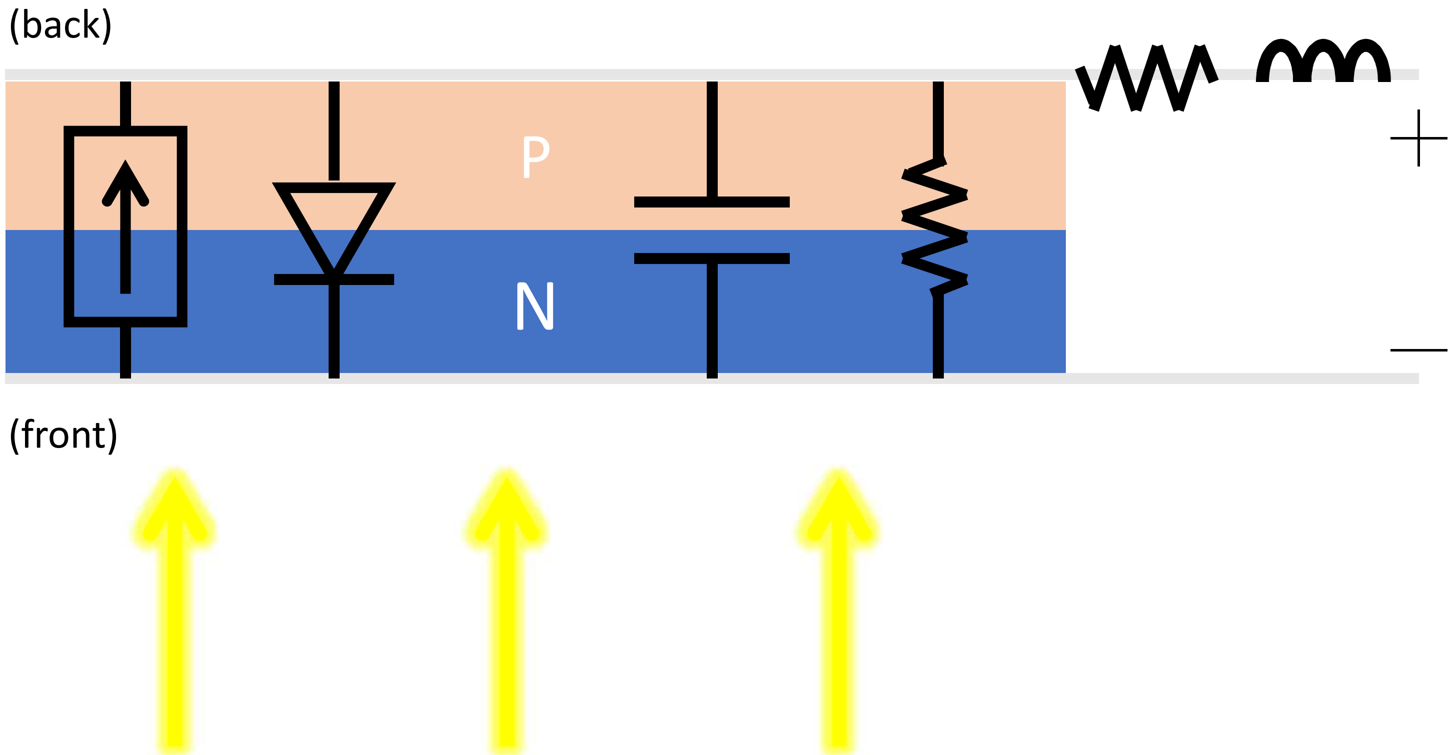
Photovoltaic Electron-Hole Generation

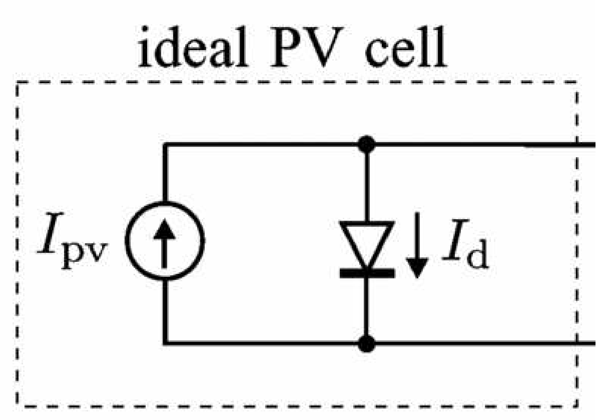


[Source: http://www.science-kick.com]

Photovoltaic Cell Basics

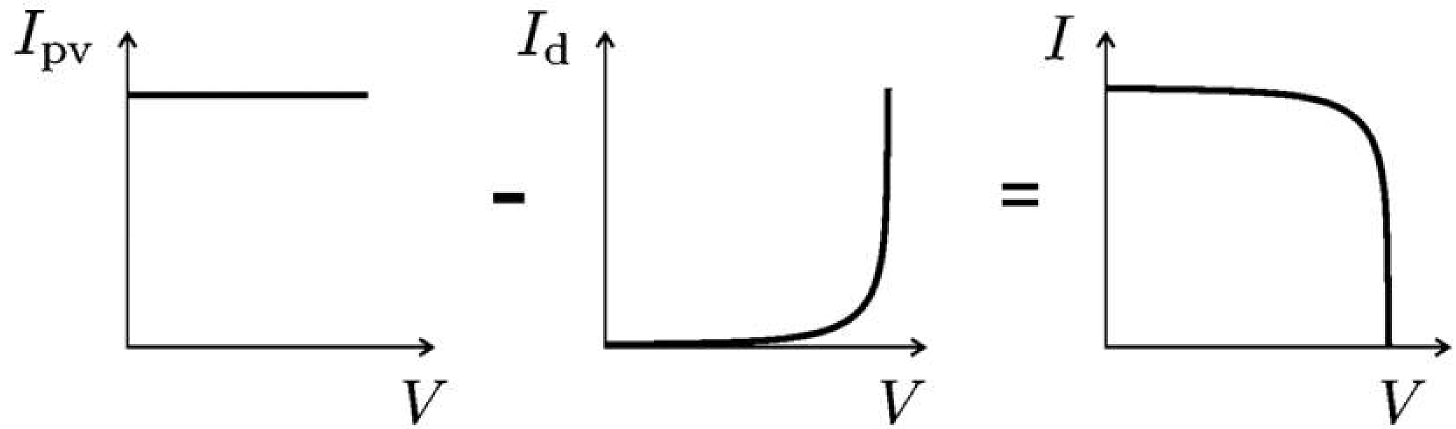


Ideal PV Model



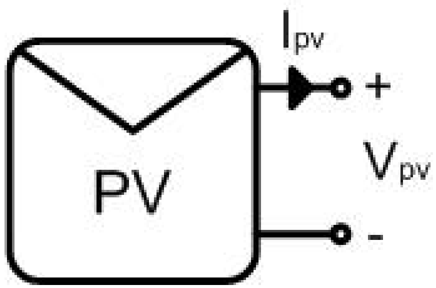
$$I = I_{pv,cell} - \underbrace{I_{0,cell}\left[\exp\left(\frac{qV}{akT}\right) - 1\right]}_{I_d}$$

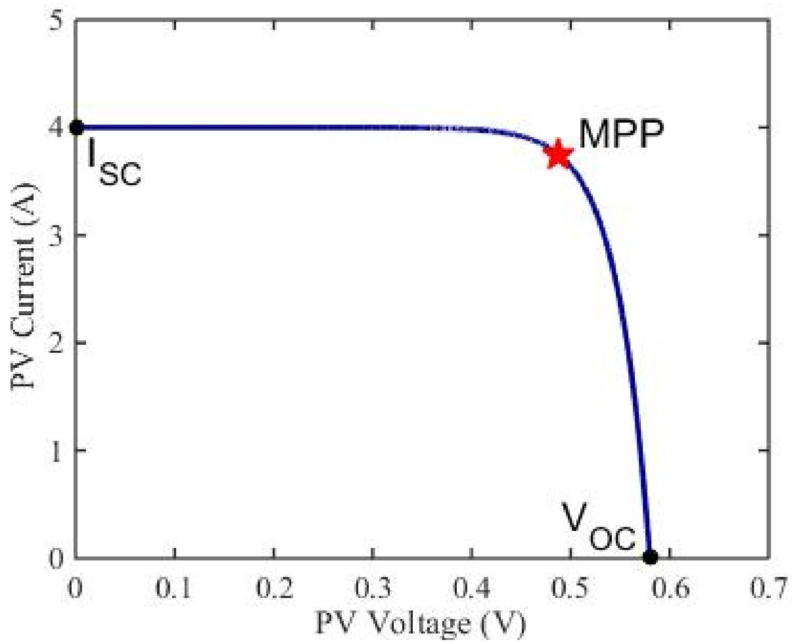
$$I_{pv} = (I_{pv,n} + K_I \Delta_T)\frac{G}{G_n}$$



Villalva, Gazoli, and Filho, "Comprehensive Approach to Modeling and Simulation of Photovoltaic Arrays," IEEE Trans. *Power Elec.,* 2009

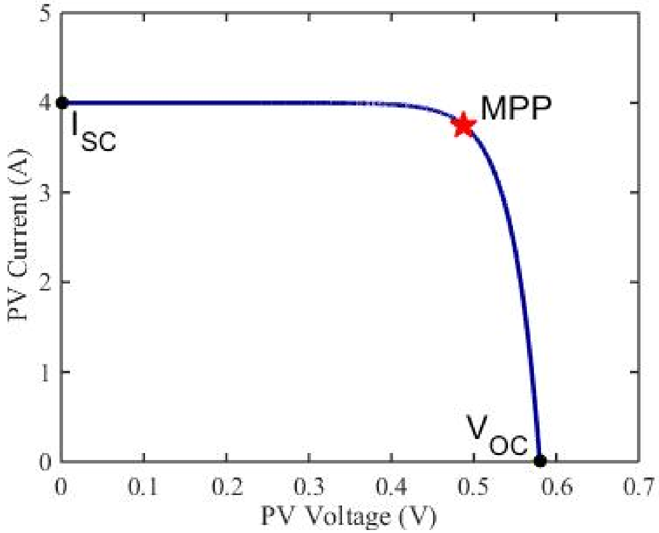
PV I-V Characteristics



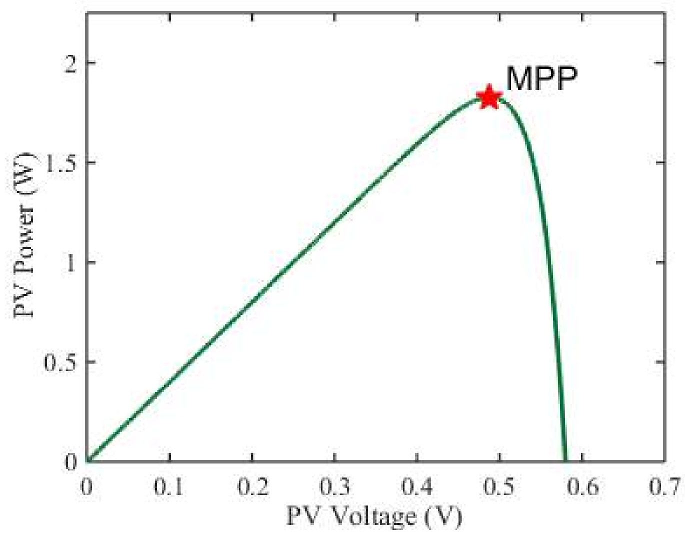


PV Panel Curves

I-V Curve

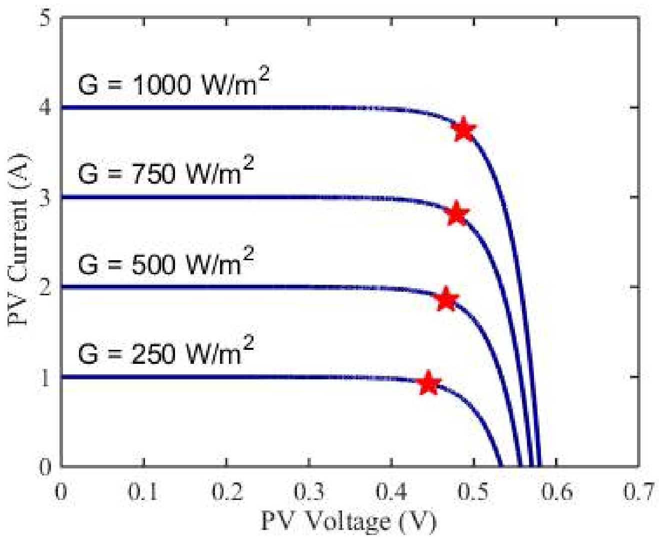


P-V Curve



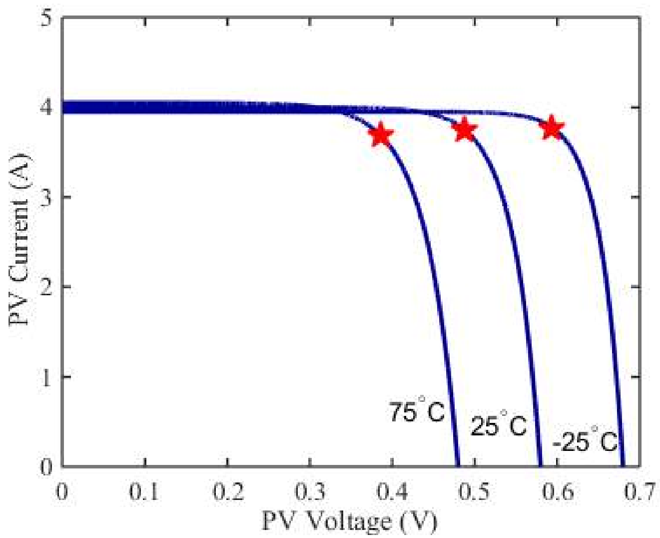
I-V Curve Under Varying Conditions

Irradiance (G) Variations



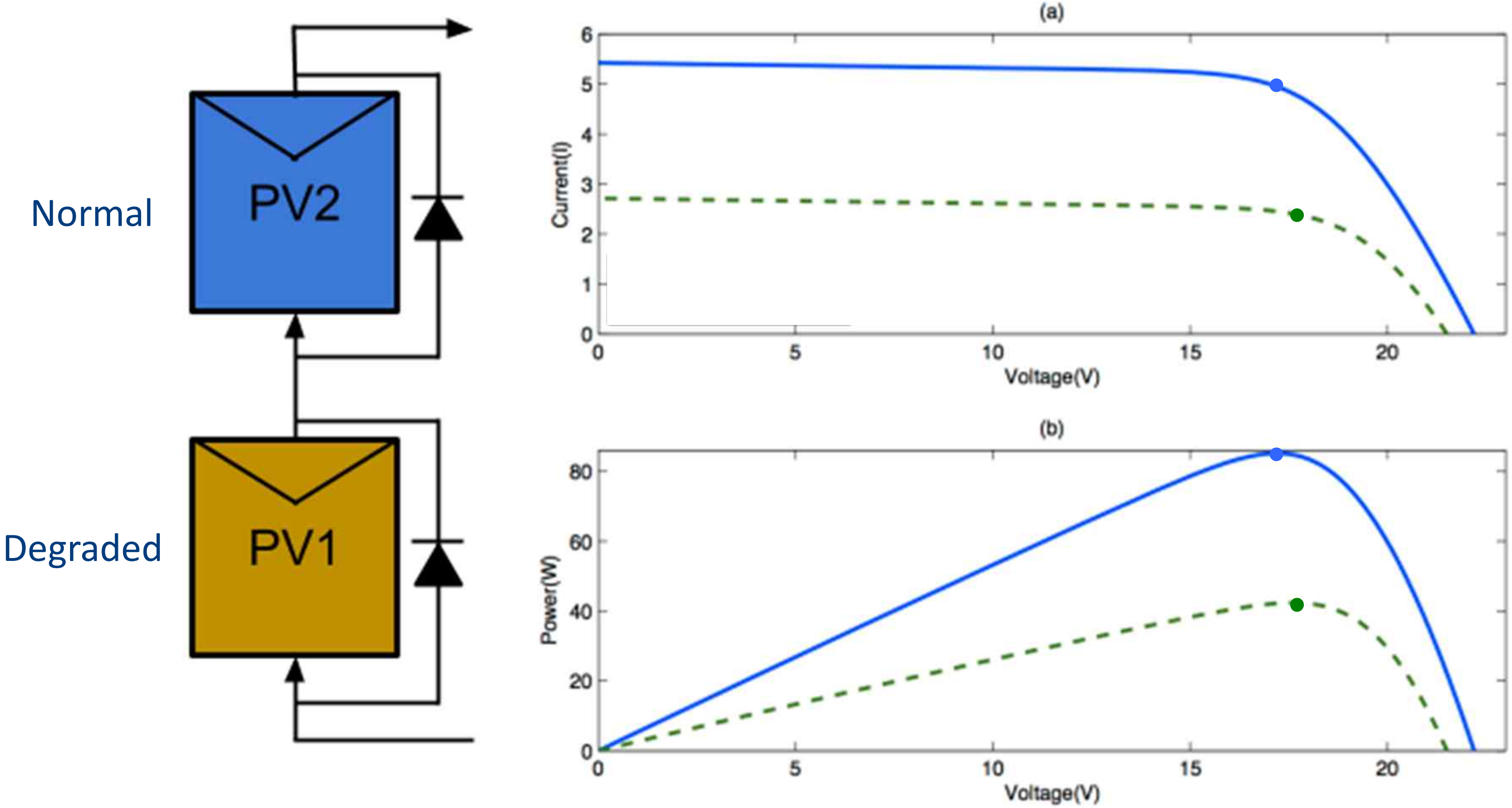
Irradiance directly proportional to **short-circuit current**

Temperature (T) Variation

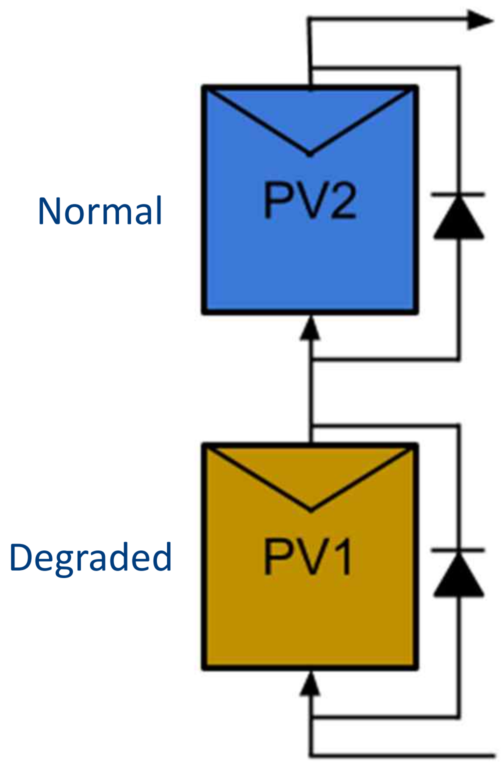


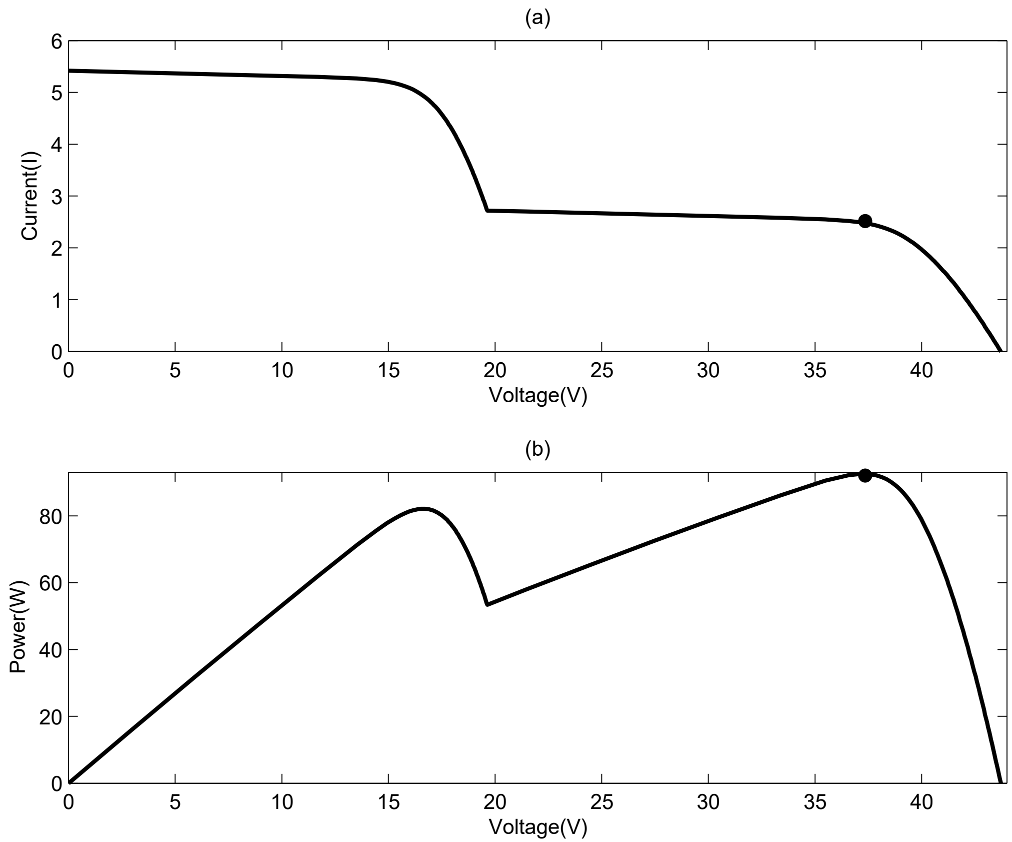
Temperature inversely proportional to **open-circuit voltage**

PV Mismatch: Cell Characteristics



PV Mismatch: String Characteristics





PV Cell Binning

Panel Cleaning

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Research Objective

Question:

- How can we embrace solar photovoltaic cell mismatch while maximizing output power?

Solutions:

- Rethink the system and power converter architecture
- Use intelligent control at the converter level

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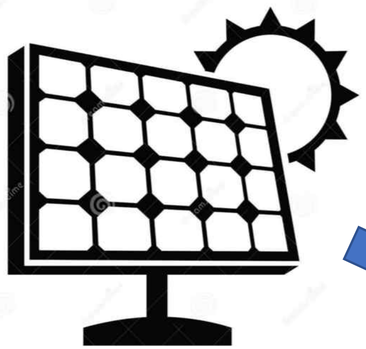
Emerging PV Power Applications



Electric Vehicles

Drones

Solar Electric Cars

Toyota (2019)

[Source: https://www.greencarreports.com/news/1123920_toyota-covers-prius-prime-with-solar-panels-to-test-mileage]

Lightyear One (2021)

[Source:https://lightyear.one/lightyear-one]

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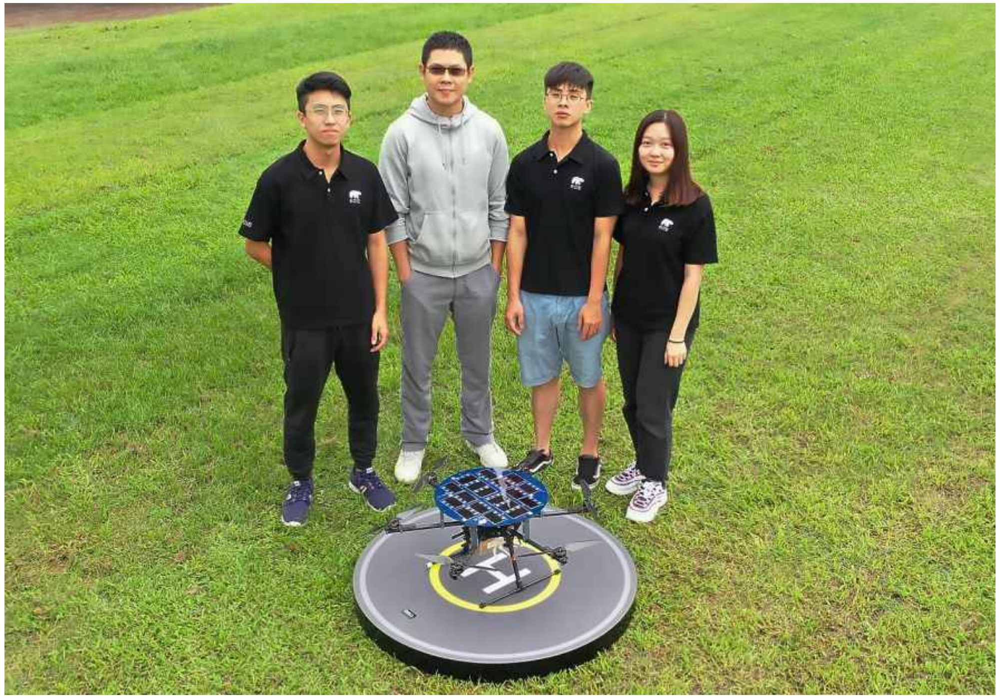
Photovoltaic Solar-Powered Drone

Video: https://youtu.be/-gvolbj536c



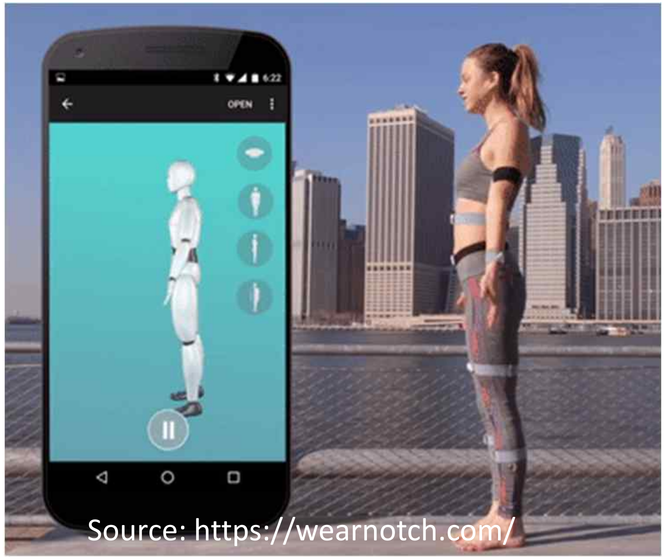
National I-Lan University
ECIE Lab: http://ecie.tech/

Is the Future Wearable?

https://chinese.engadget.com/fitbit-charge-5-ecg-eda-gps-
heart-rate-monitor-fitness-tracker-130036648.html

Wearable activity monitor

- Step count
- Heart rate
- Oxygen rate
- GPS and etc.

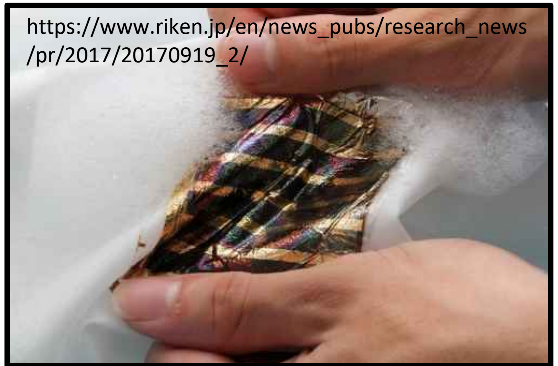


Wearable 3D motion tracker

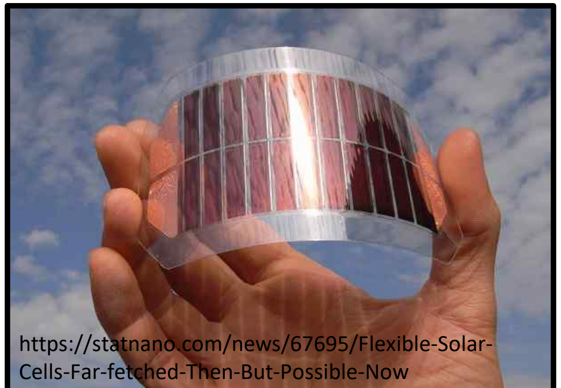
Wearable gesture sensor

Can we power them with Solar Energy?

Solar Powered Applications



Ultra-thin Organic Solar Cells



Flexible Solar Cells

Wearable Solar Coat

https://design-milk.com/wearable-solar-clothing-charges-smartphone/

Solar Backpack

https://inhabitat.com/ecouterre/ralph-lauren-launches-800-solar-powered-waterproof-backack/

Solar Ski Helmet

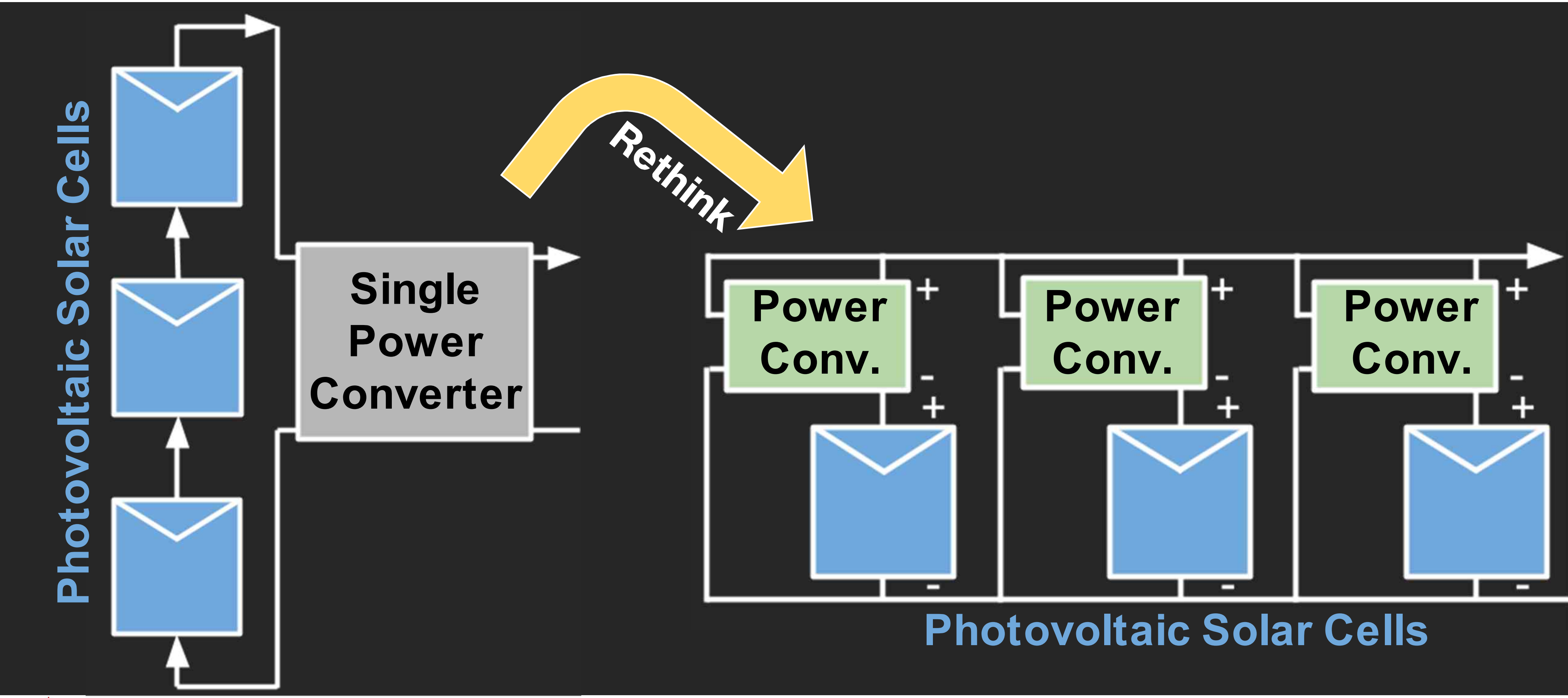
https://www.izm.fraunhofer.de/en/news_events/tech_news/solarhelm_liefertstromaufderskipiste.html

Product Rating: 6 W

Corner Shaded: 3.5 W (58%)

Half-Shaded: 0.3 W (5%)

Power System Design Solutions



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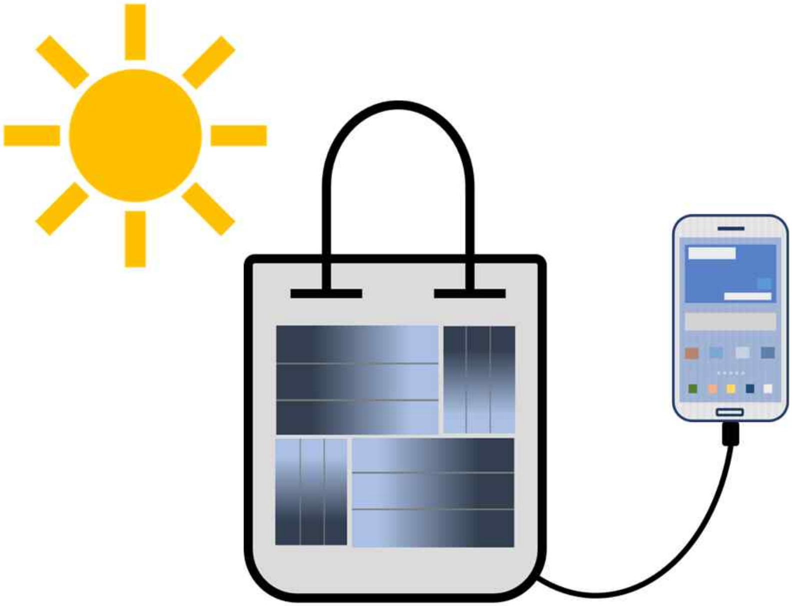
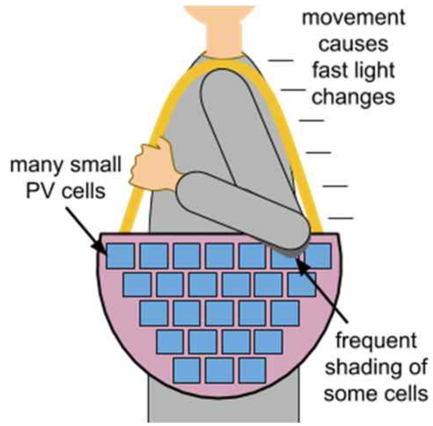
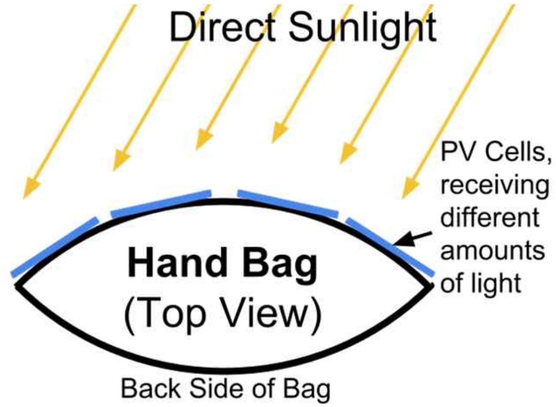
Challenges for Solar-Powered Wearables

PV Powered Bag



Potential Problems





Solution:

Efficient converter design
+
Independent maximum power power tracking (MPPT) of each panel

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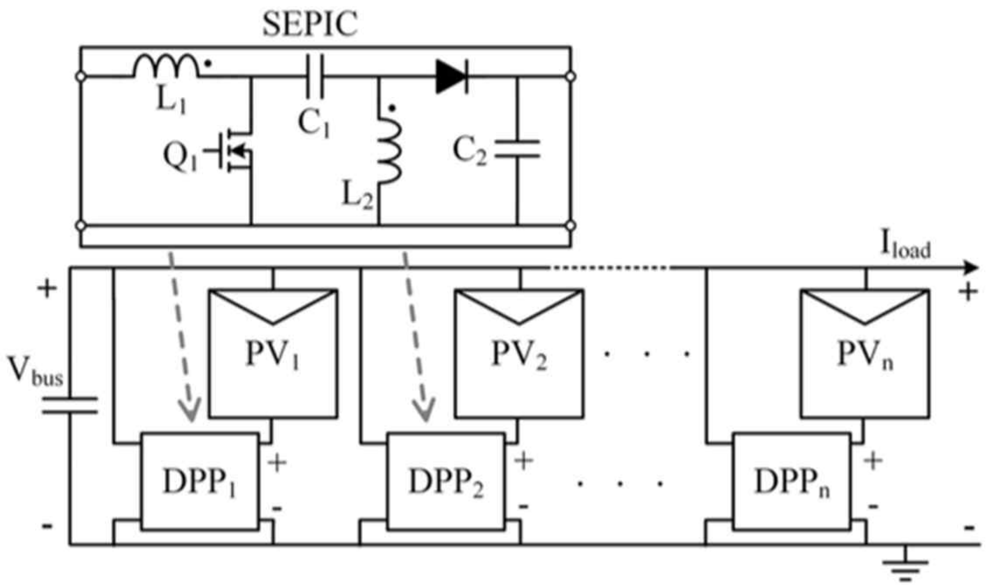
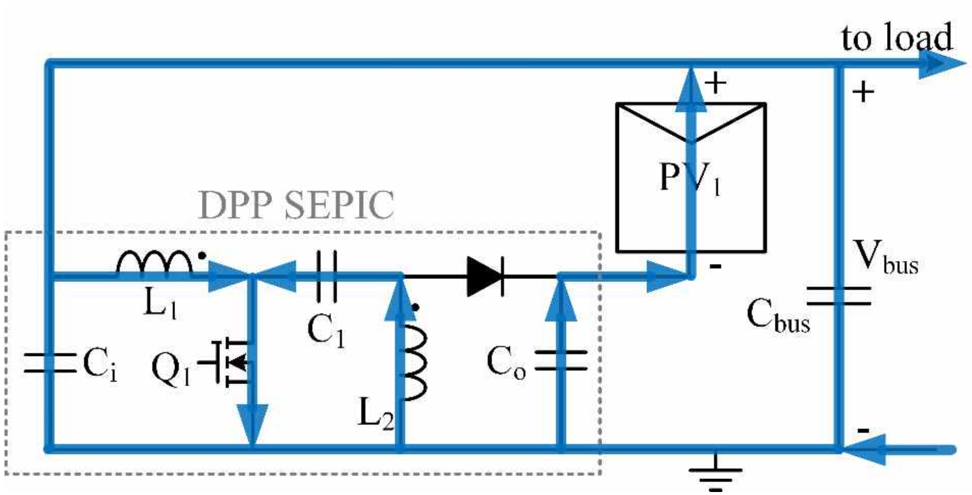
Initial Approach: SEPIC in Parallel DPP Architecture



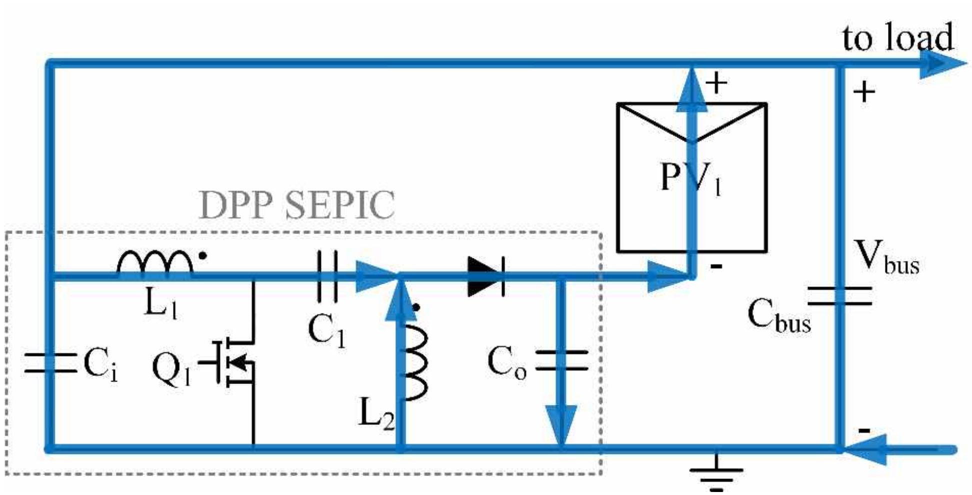
- SEPIC: Single-ended primary-inductor converter
- Coupled inductor is used to reduce magnetics size
- Utilized parallel DPP system architecture
- PV panel voltage is above DPP converter output for the ease of sensor and controller implementation

F. Selin Bagci, et. al. “Low-Power Photovoltaic Energy Harvesting With Parallel Differential Power Processing Using a SEPIC,” IEEE Applied Power Electron. Conf., 2019.

SEPIC DPP Operation



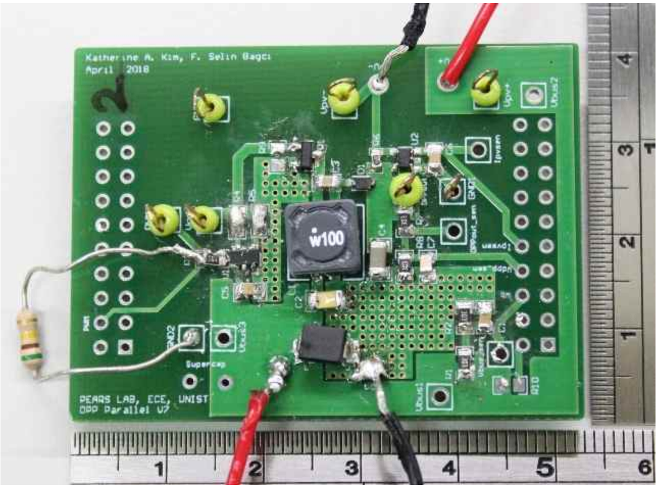
Switch On

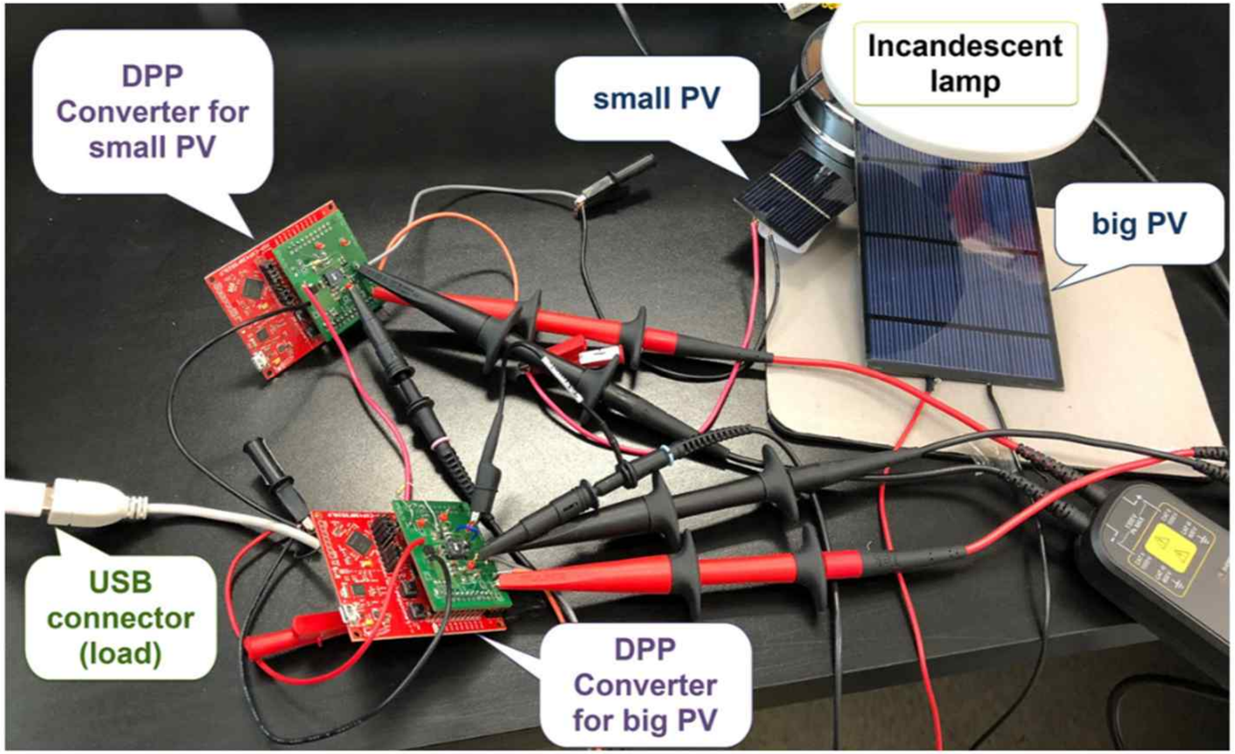


Switch Off

F. Selin Bagci, et. al. “Low-Power Photovoltaic Energy Harvesting With Parallel Differential Power Processing Using a SEPIC,” IEEE Applied Power Electron. Conf., 2019.

Testing with Two DC-DC Power Converters

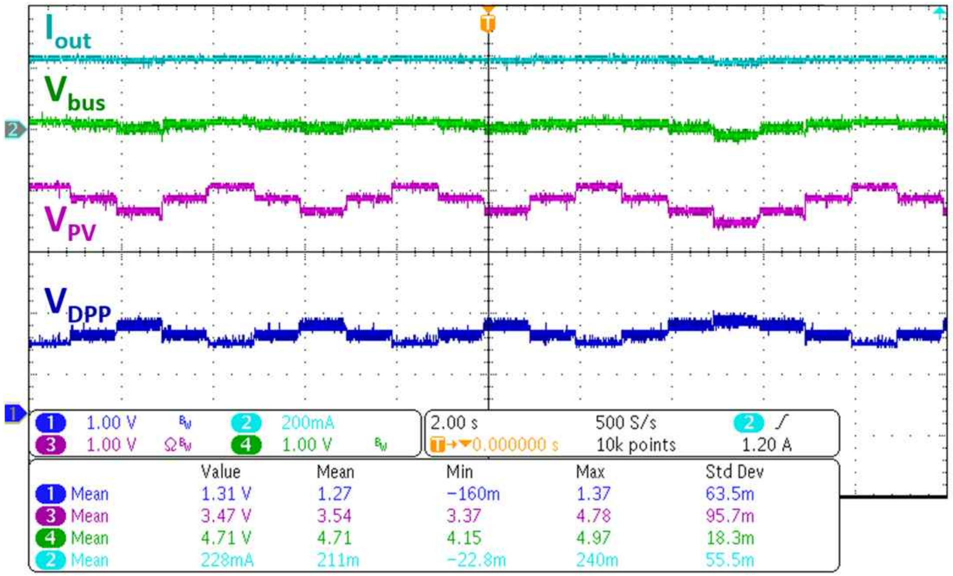




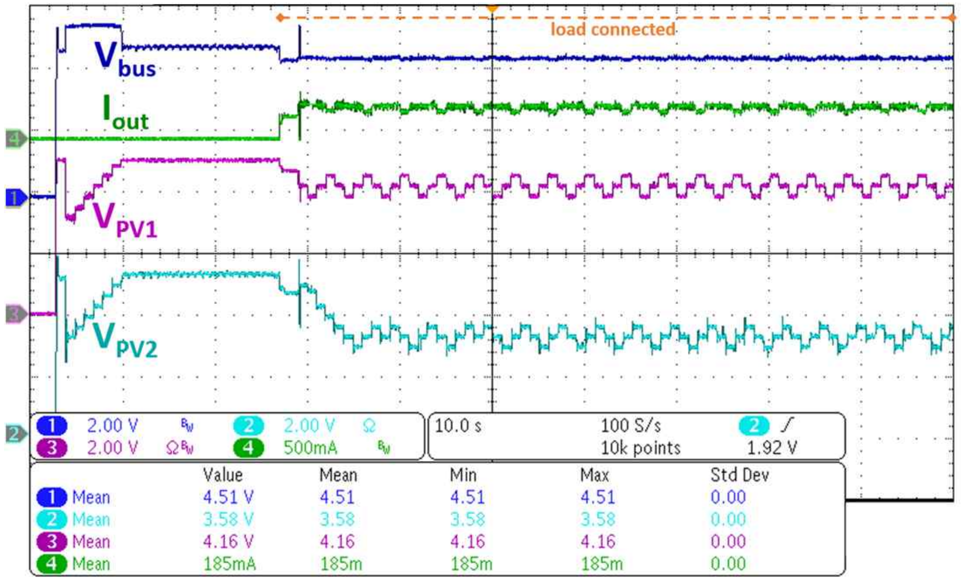
F. Selin Bagci, et. al. "Low-Power Photovoltaic Energy Harvesting With Parallel Differential Power Processing Using a SEPIC," IEEE Applied Power Electron. Conf., 2019.

Converter Operating Waveform

MPP Operation of One PV Panel



MPP Operation After Load Connection



F. Selin Bagci, et. al. “Low-Power Photovoltaic Energy Harvesting With Parallel Differential Power Processing Using a SEPIC,” IEEE Applied Power Electron. Conf., 2019.

Solar Powered Bag: Initial Prototype

F. Selin Bagci, et. al. "Low-Power Photovoltaic Energy Harvesting With Parallel Differential Power Processing Using a SEPIC," IEEE Applied Power Electron. Conf., 2019.

F. Selin Bagci, et. al. “Low-Power Photovoltaic Energy Harvesting With Parallel Differential Power Processing Using a SEPIC,” IEEE Applied Power Electron. Conf., 2019.

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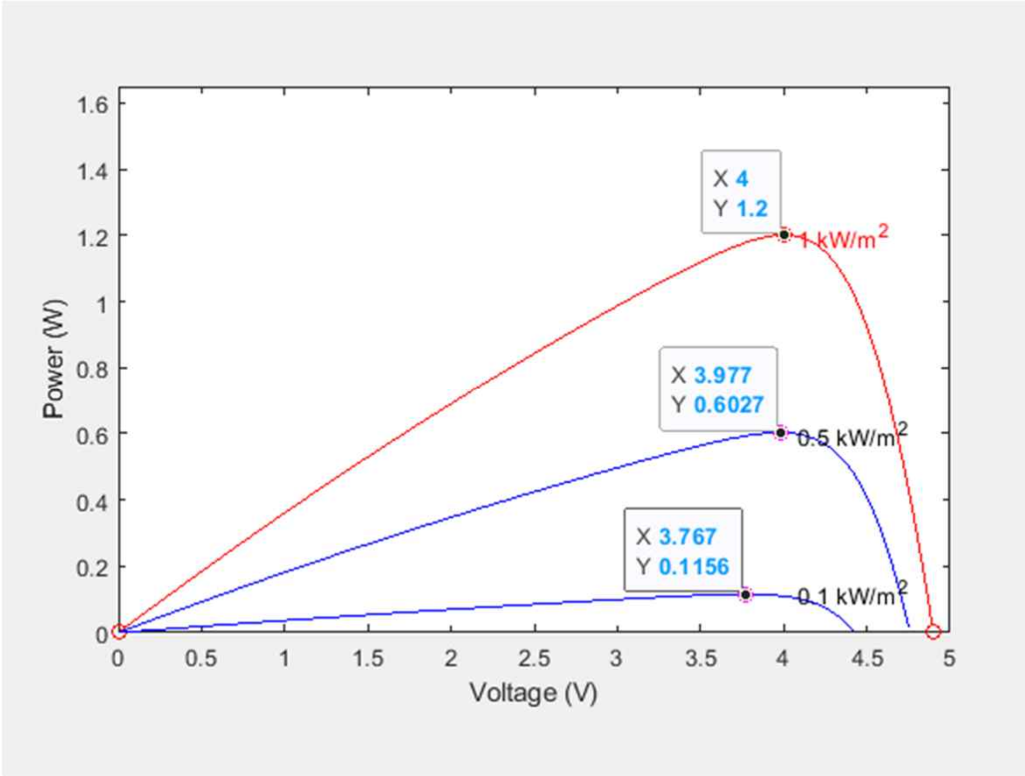
Wearable PV Bag Prototype

FRONT VIEW

- 4 identical panels.

P-V SWEEP OF THE PANEL (Simulated)



- Best case scenario:
  Total input power = 1.2 W x 4 = 4.8 W

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F. S. Bagci, et. al. "Power Profile Measurement and System Design Analysis for a Wearable Photovoltaic Application," *International Power Electronics and Motion Control Conference – ECCE Asia*, Nanjing, China, Dec. 2020, pp. 1469-1474.

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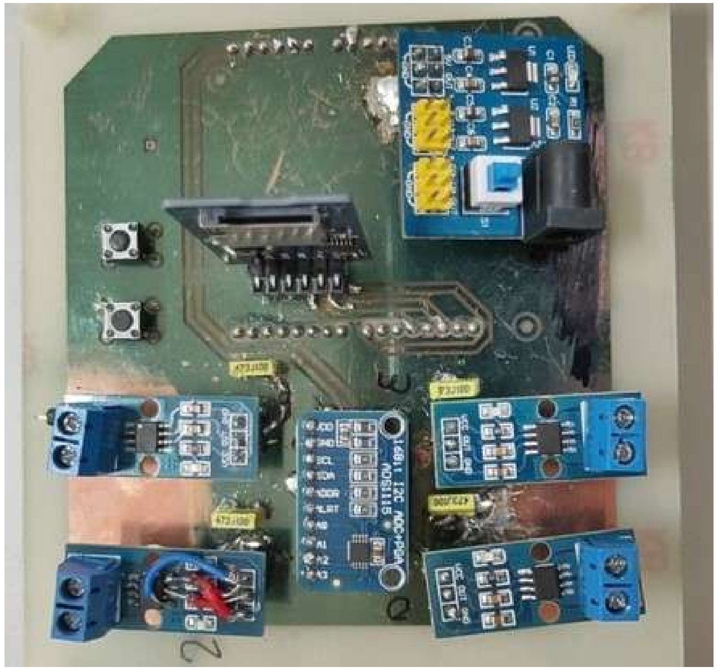
Power Profile Measurement

Measurement Device Hardware



1. PV terminals were shorted to get short-circuit current (I_{sc})
2. I_{sc} data was saved on the SD card
3. Irradiance (G) is calculated since it's proportional to I_{sc}

Video During Experiment

- Taken on a bright day, with no direct shading

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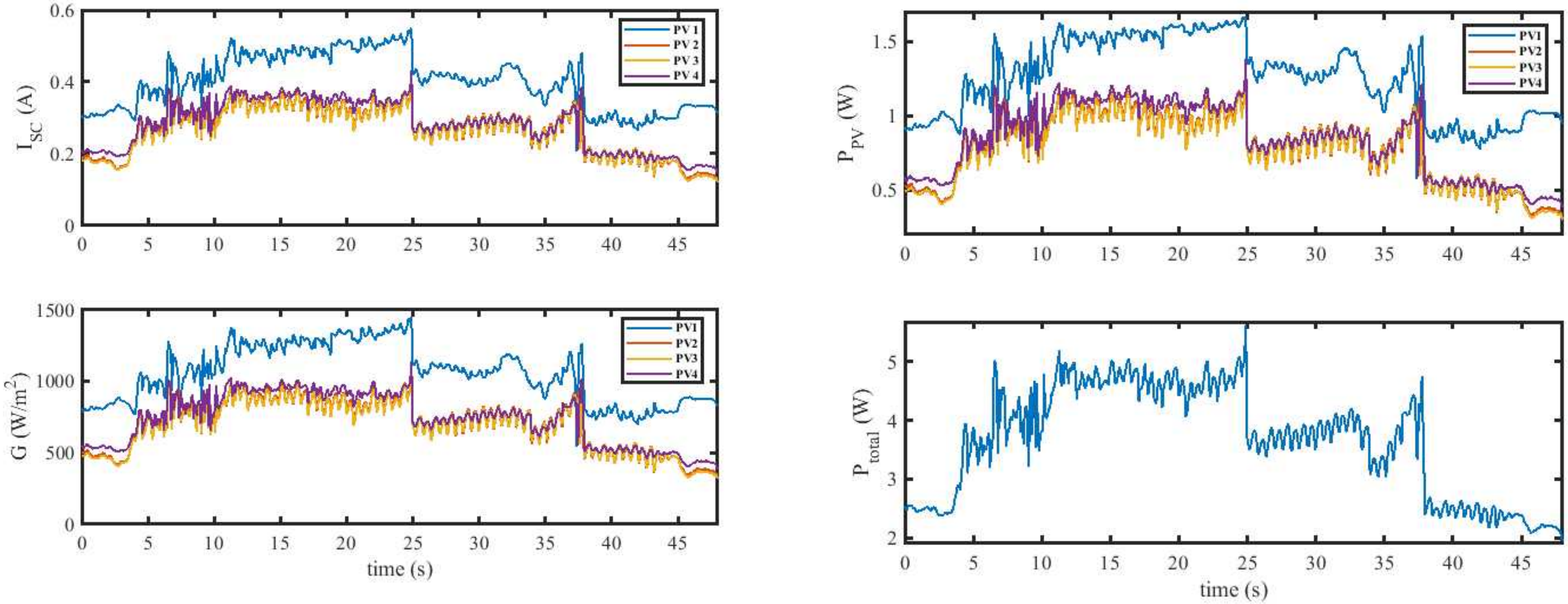
Power Profile Measurement

Case 1: Unshaded (no direct shading)



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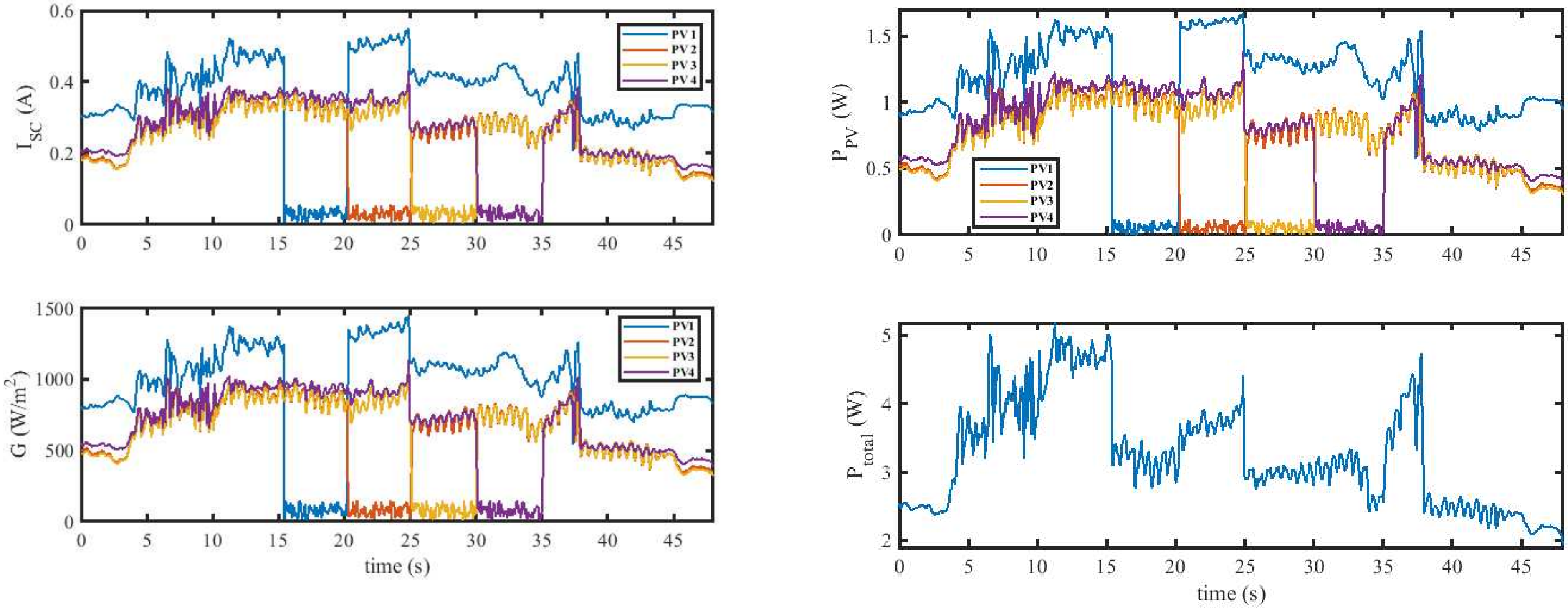
Power Profile Measurement

Case 2: Partially Shaded (Hypothetical case where PVs were obscured in turn)



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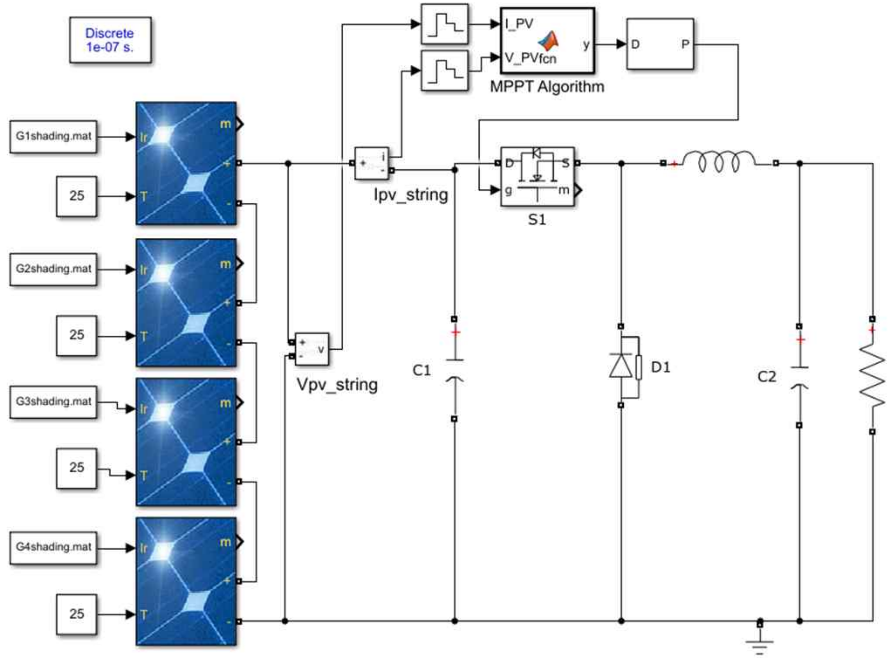
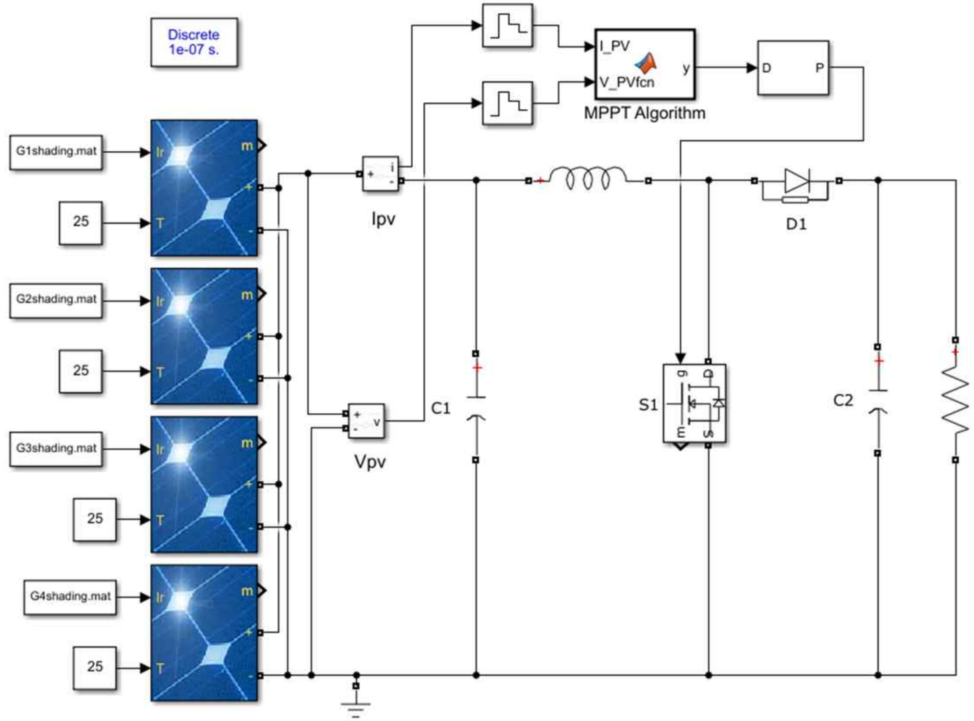
System Configuration Comparison

Series PV configuration + Buck converter



Parallel PV configuration + Boost converter



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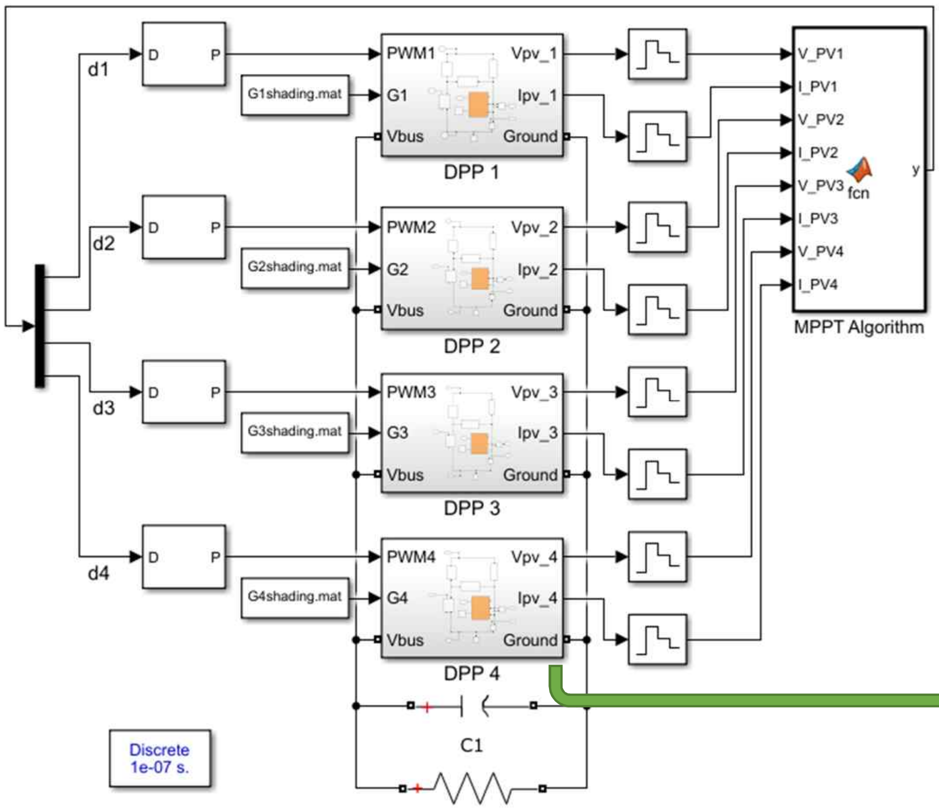
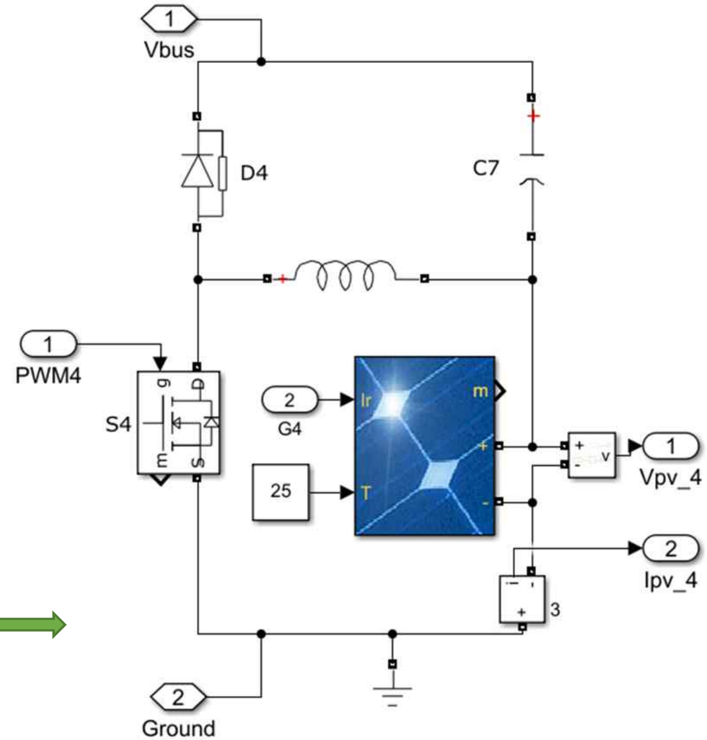
System Configuration Comparison

Parallel DPP





Augmented Boost Converter

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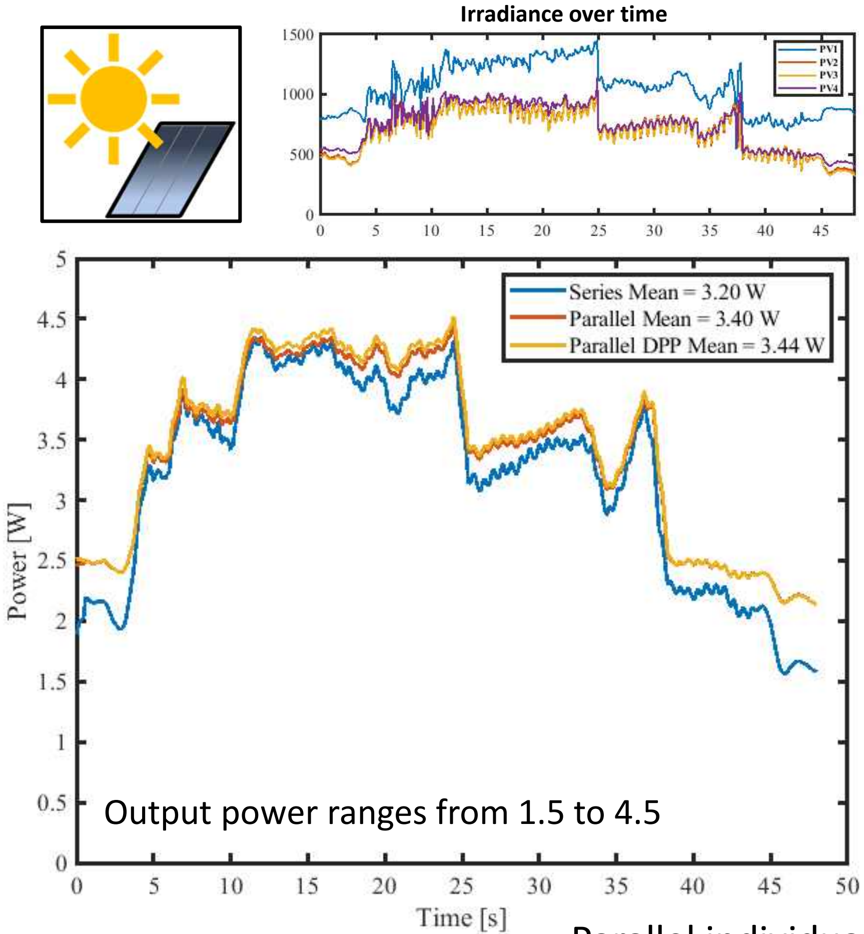
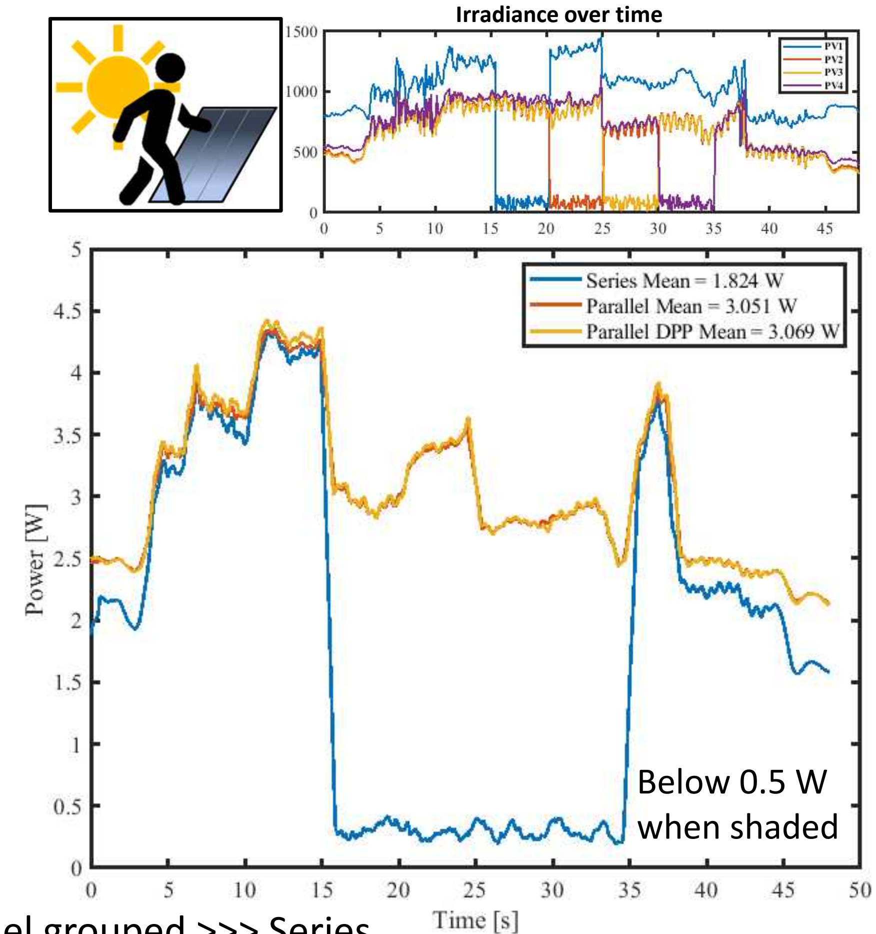
Output Power Comparison

Case 1: Unshaded



Case 2: Partially Shaded



Parallel individual ≈ Parallel grouped >>> Series

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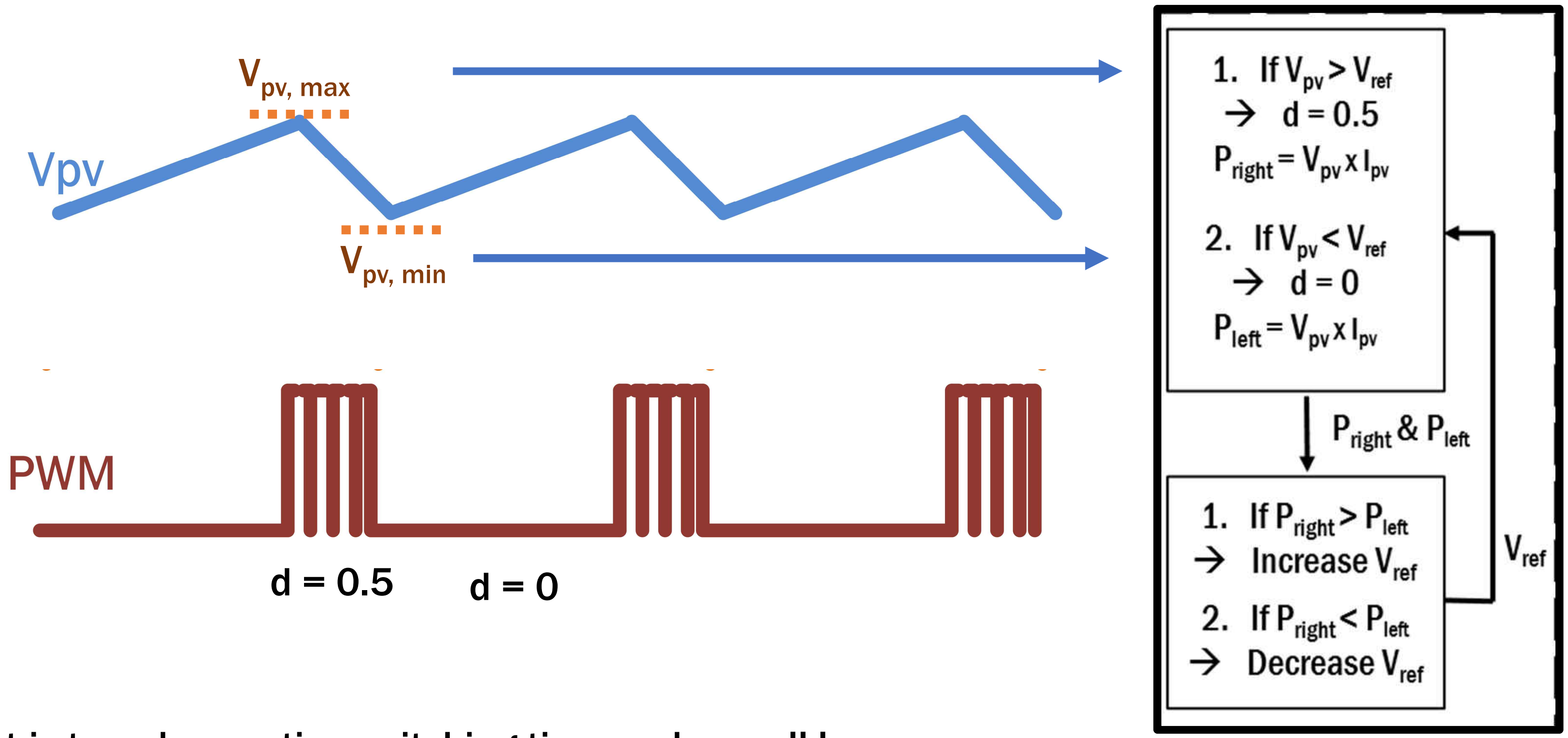
- Conclusion

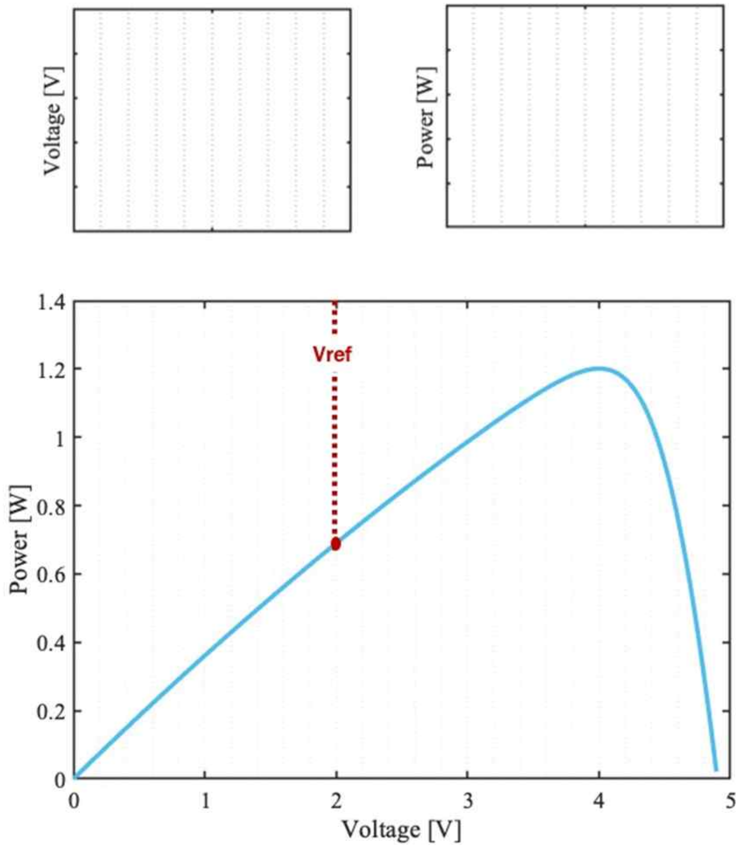
Burst-Mode MPPT Algorithm



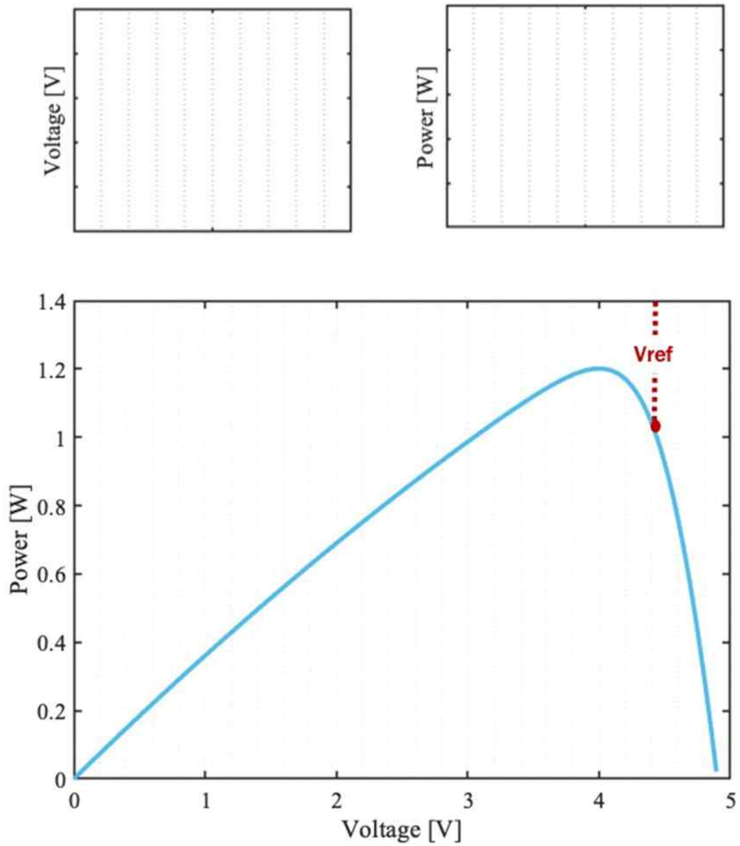
- **Target is to reduce active switching time and overall losses**

F. S. Bagci and K. A. Kim, "Performance Comparison of Burst-Mode MPPT and Perturb and Observe MPPT Algorithms for Photovoltaic Energy Harvesting Applications," *IEEE ECCE*, Vancouver, BC, Canada, Oct. 2021.

Burst-Mode MPPT Algorithm Core Concept



Voltage below MPP

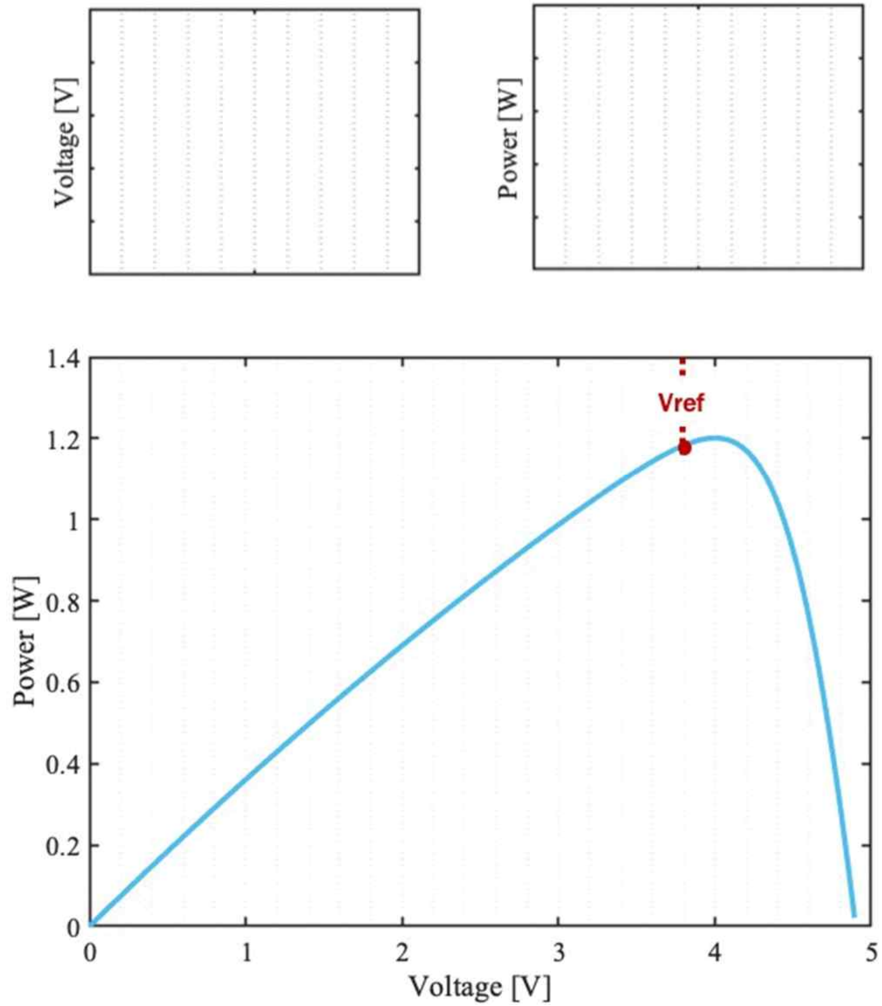


Voltage above MPP

F. S. Bagci and K. A. Kim, "Performance Comparison of Burst-Mode MPPT and Perturb and Observe MPPT Algorithms for Photovoltaic Energy Harvesting Applications," *IEEE ECCE*, Vancouver, BC, Canada, Oct. 2021.

Burst-Mode MPPT Algorithm Core Concept

At MPP



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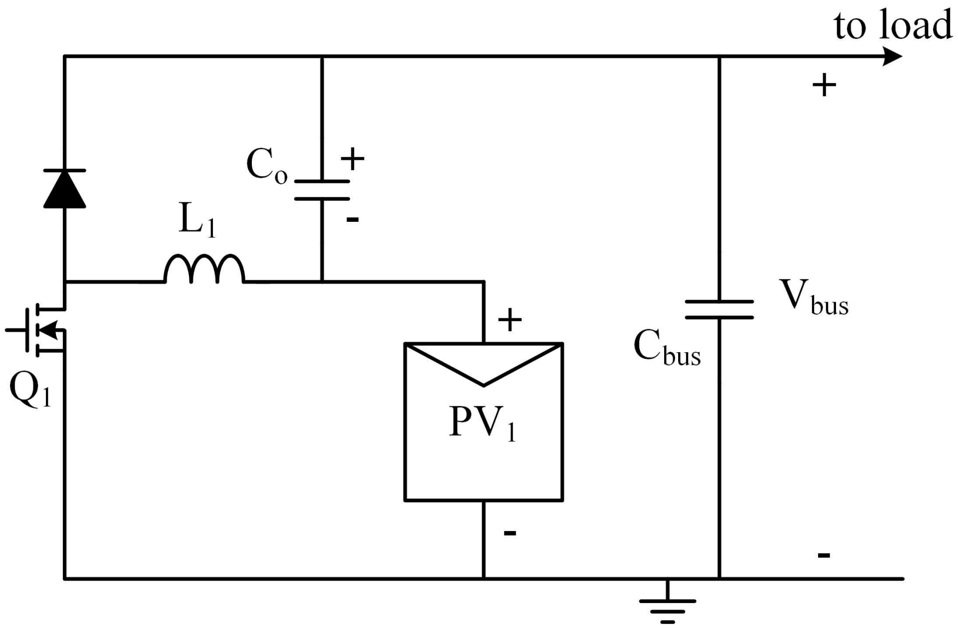
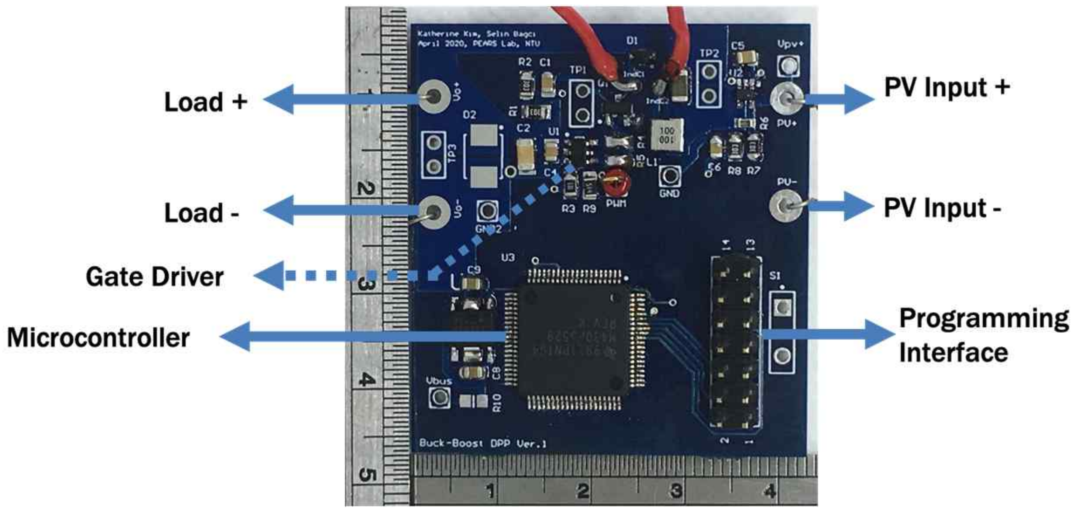
Augmented Boost Converter Topology





Size: 4.5 x 4.3 cm

- PV voltage → increases when the converter is off.
  decreases when the converter is on.

- Hardware implementation

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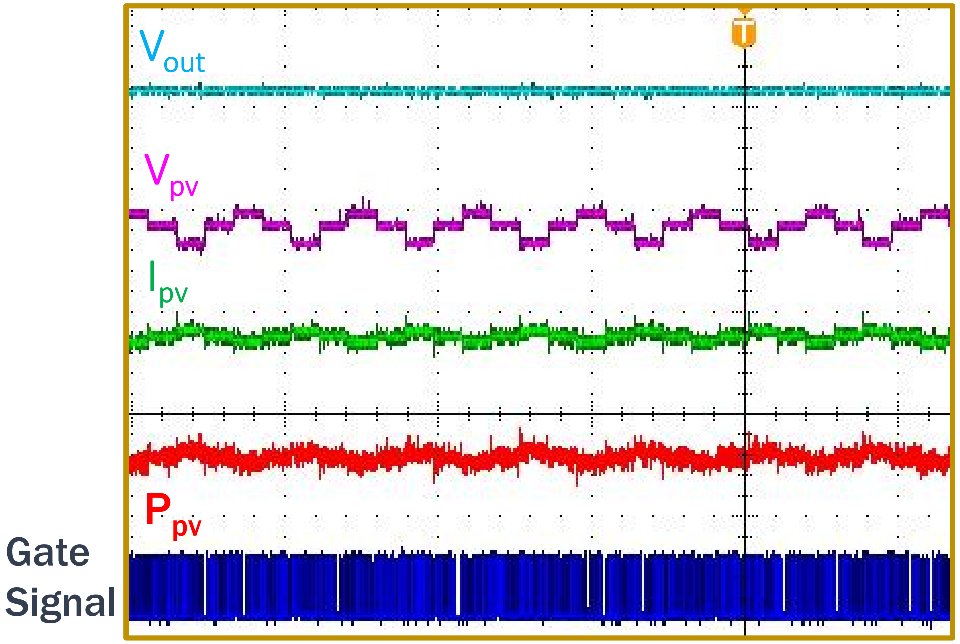
Conventional P&O MPPT vs. Burst-Mode MPPT

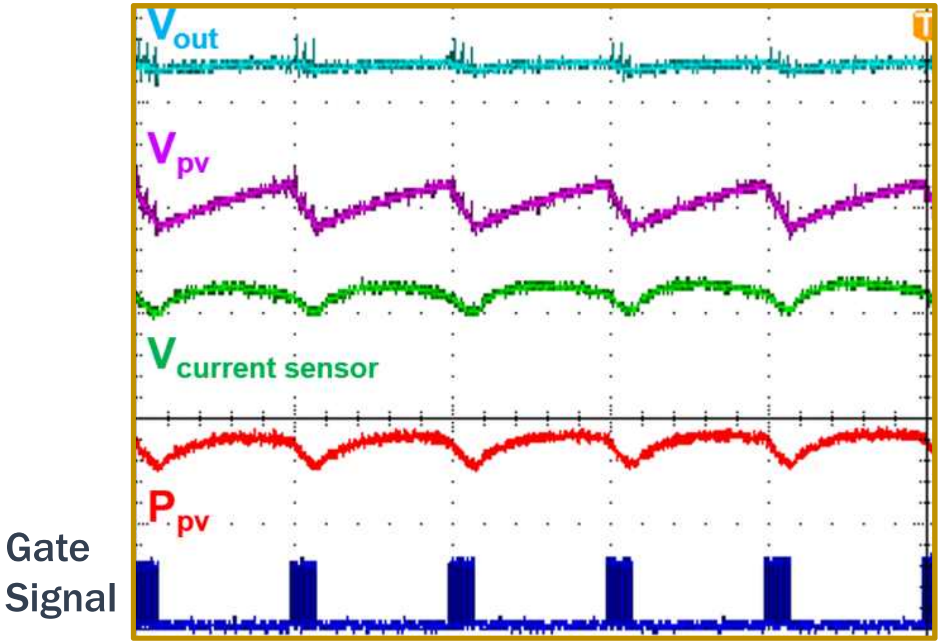
Conventional P&O MPPT at MPP:



- Duty ratio is incrementally adjusted

→ Switch is constantly ON

Burst-Mode MPPT at MPP:



- Actively switching ONLY when $V_{pv} \geq V_{ref}$

→ Reduced ON time

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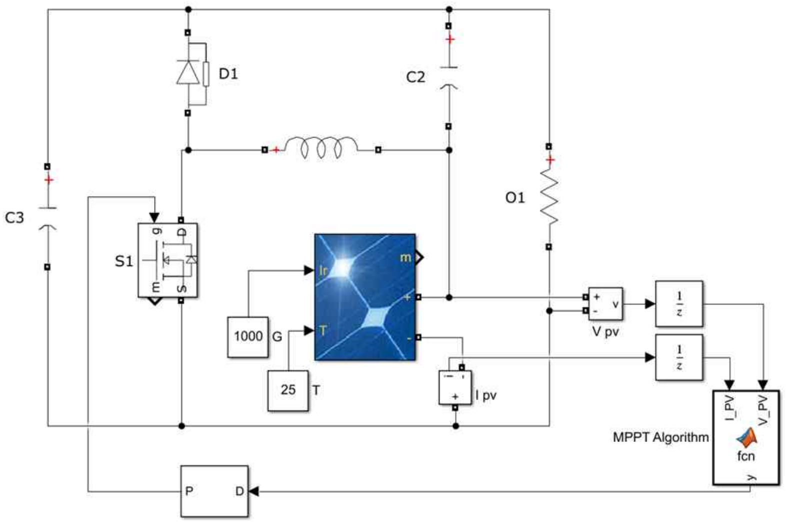
Simulation Setup

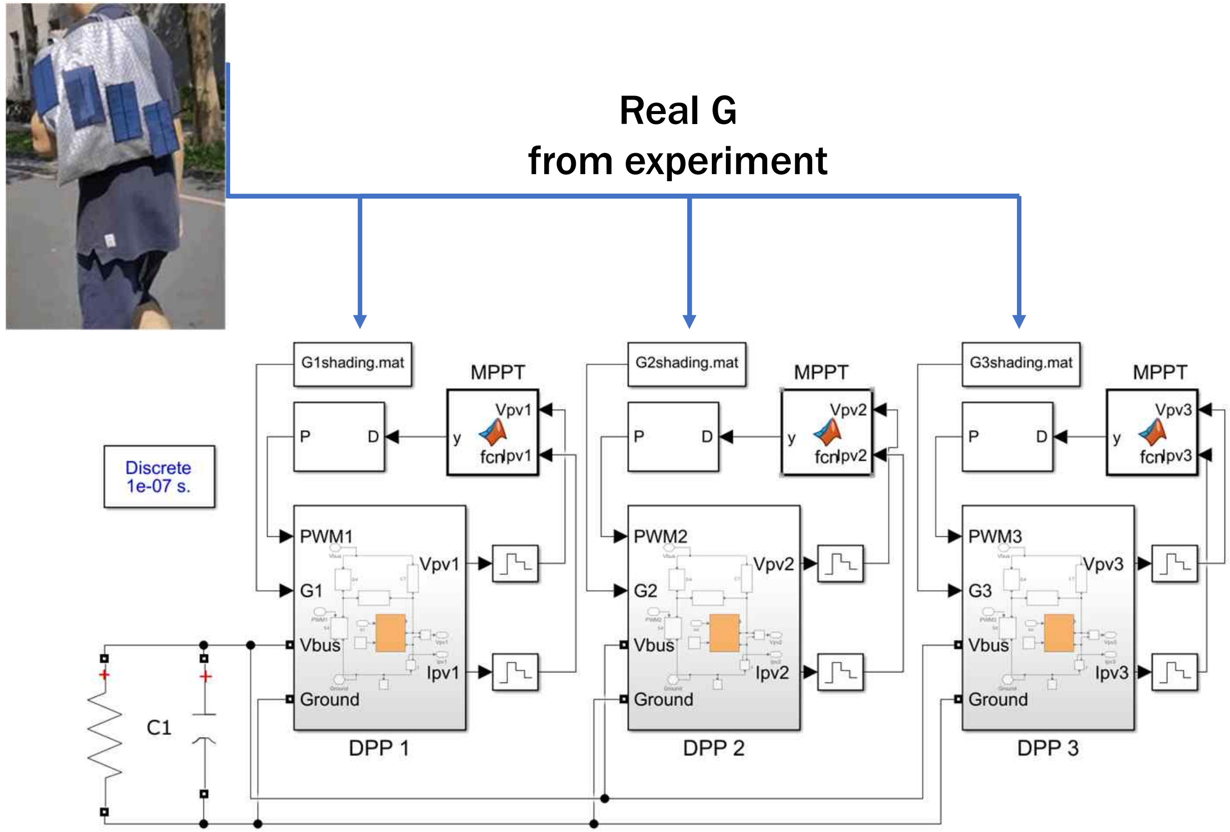
Single-PV/Single-Converter System:



- Converter Switching Frequency = 500 kHz

High switching frequency → Smaller passive components

3-PV/3-Converter System:



- Parallel configuration

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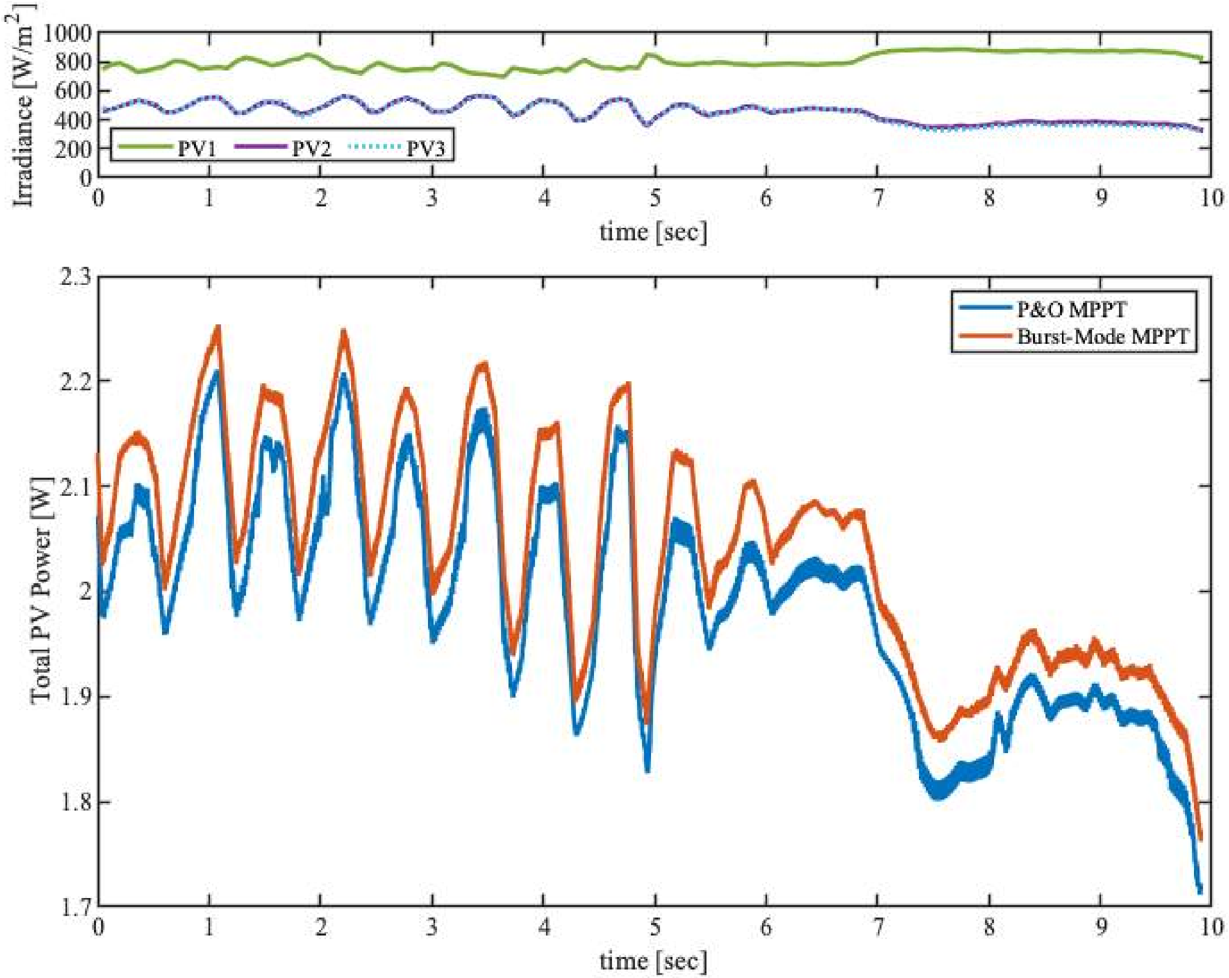
P&O vs. Burst-Mode MPPT (with 3-PV/3-Converter System)



Irradiance between 400 – 1000 W/m^2

P_{burst} = 2.041 W
$P_{P\&O}$ = 1.987 W
$P_{burst} - P_{P\&O}$ = 54 mW

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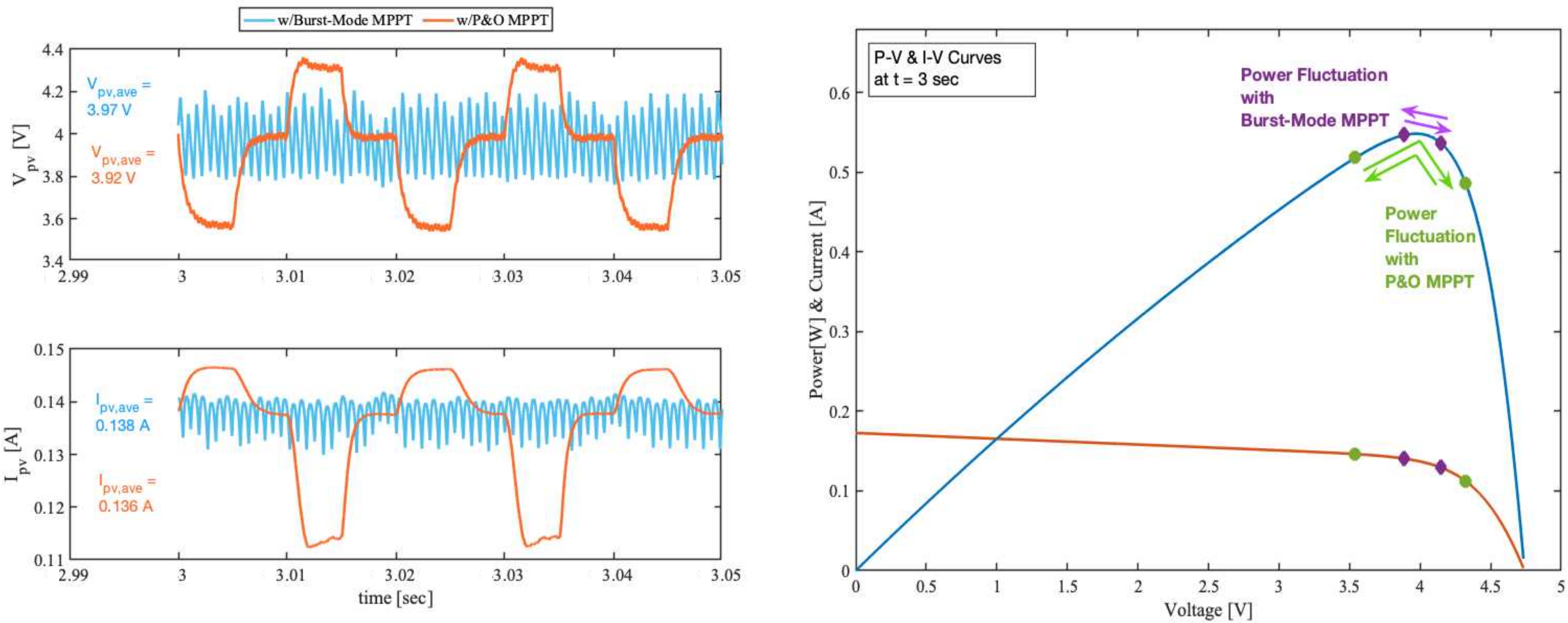
Tracking Efficiency Comparison



With burst-mode MPPT:

- PV current and voltage mean closer to the real MPP values
- Narrower power fluctuation range

Outline

- Solar Photovoltaic Basics
- Emerging Solar PV Applications
- Exploring Parallel Converter Architectures
- Measuring Solar PV Profiles for Wearables
- Maximum Power Point Tracking for Low Power Consumption
- Conclusion

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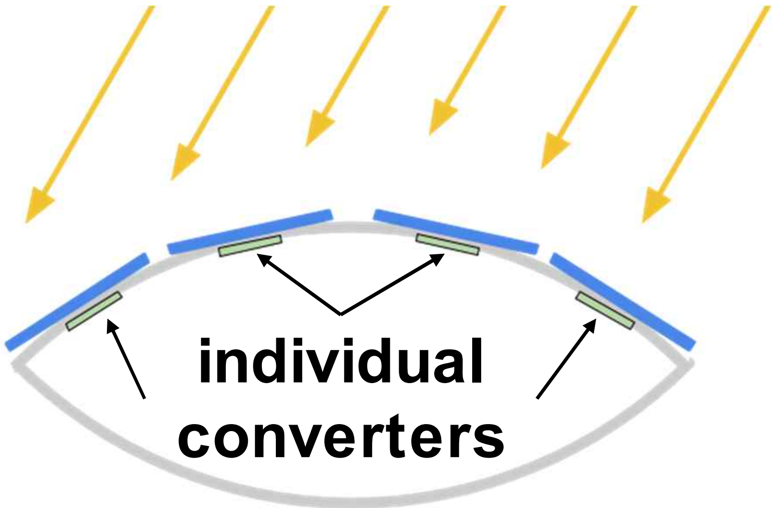
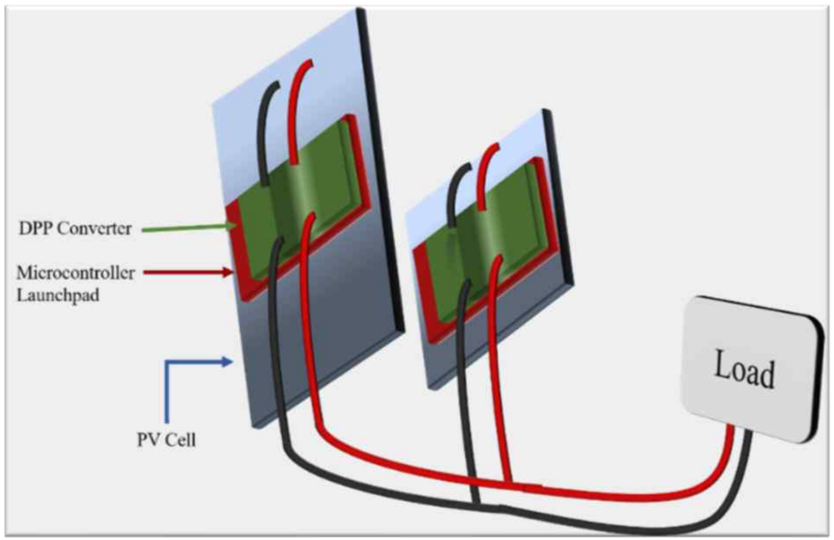
Future Directions:
One DPP Converter Per Panel & Flexible PV/PCB





Conclusion

- Future PV applications include: vehicles, drones, wearables, and many more
- Solar PV characteristics change with irradiance (light intensity) and temperature
- In emerging solar applications, the inherent challenge is that PV characteristics are uneven
  - Parallel connection and individual converters can optimize output power
  - In wearable applications, the incoming light varies quickly
  - Individual MPPT control algorithms are needed to maximize power under various conditions
  - Controllers/algorithms for the converters must have low power consumption
  - Boost-mode MPPT algorithms have potential for small-sized converters
  - Future work on flexible converters will be key to enabling wearable PV applications
- With more research, various applications can be powered with solar