On the pathway from photons to electrons to bits: introducing the emerging field of ***Photovoltatronics***

Hesan Ziar, Patrizio Manganiello, Olindo Isabella, Miro Zeman

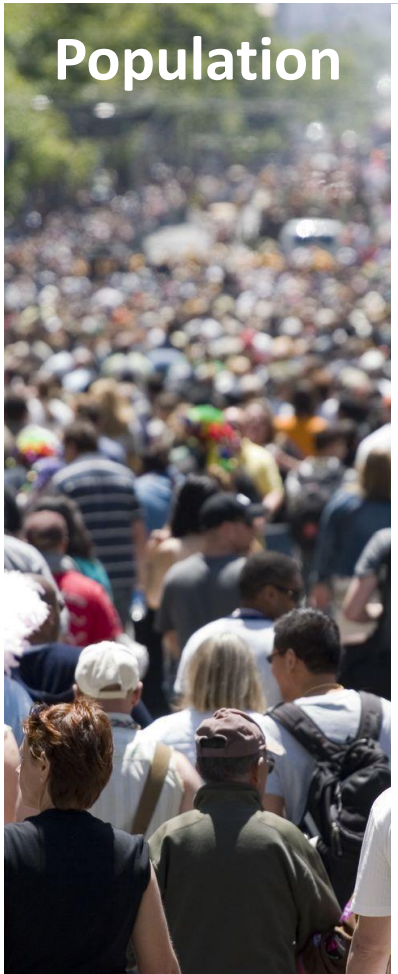
8th of September 2021

EUPVSEC, online

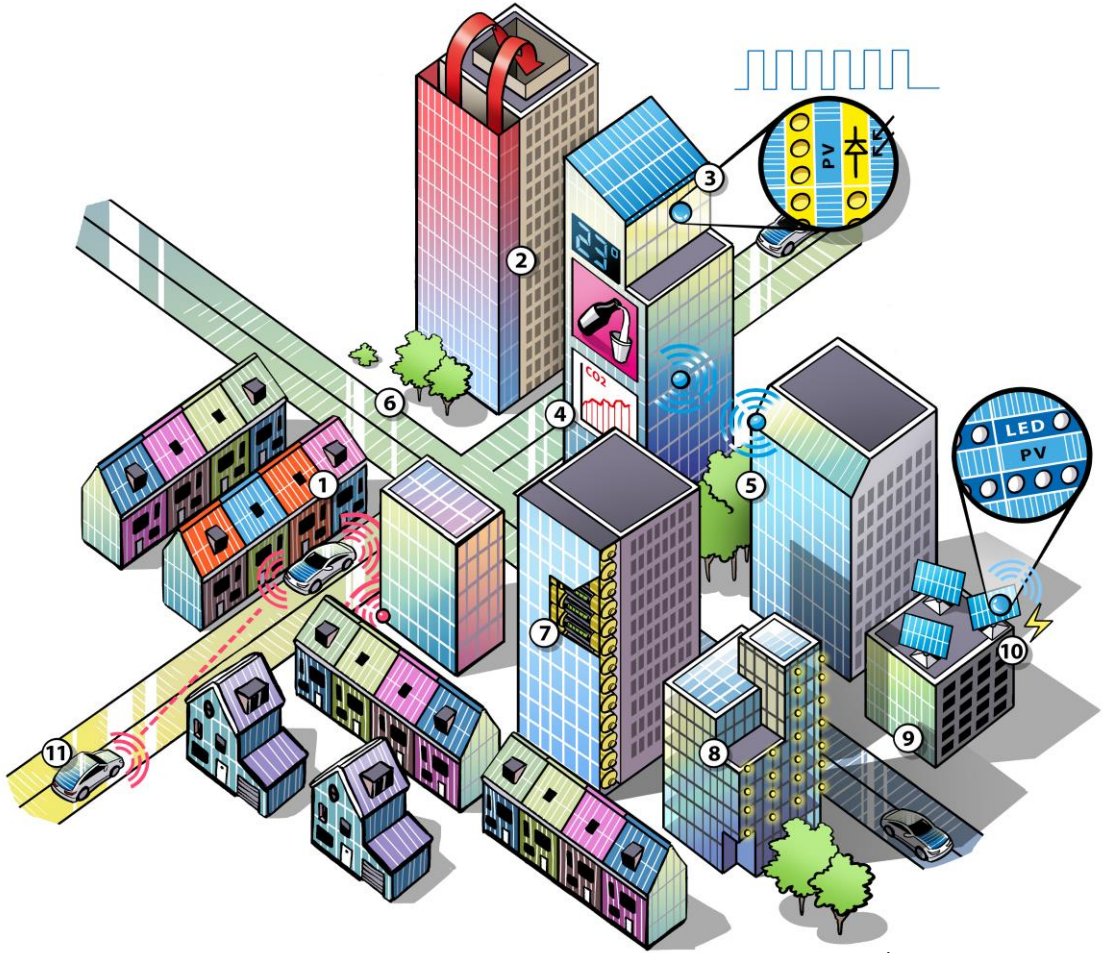
PVMD Delft University of Technology

TU Delft

Motivation *(importance of a surface)*



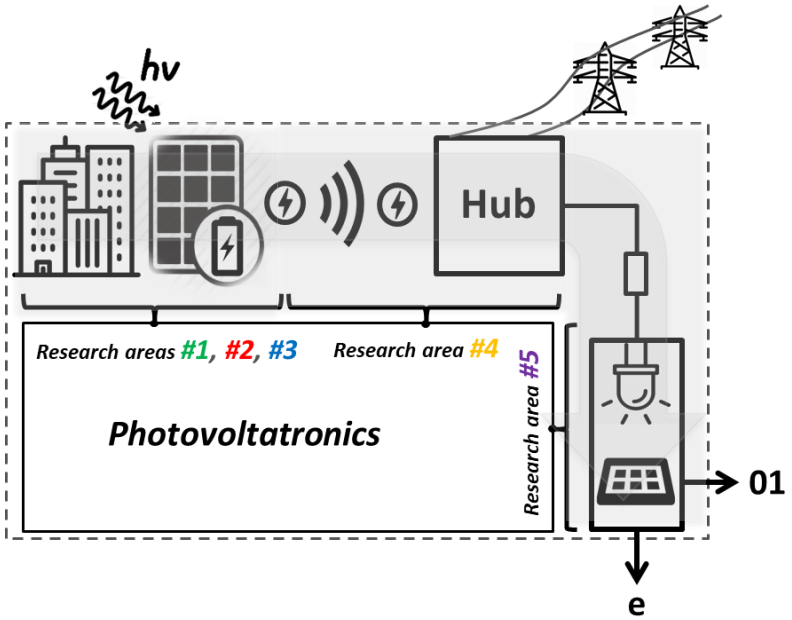
Comprehensive vision



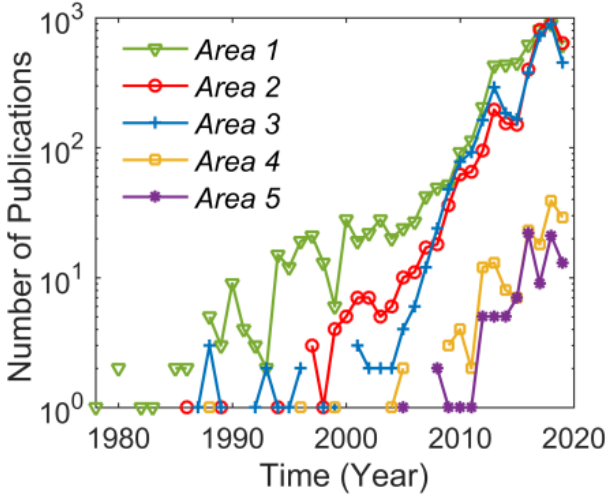
H. Ziar, et al., *Energy Environ. Sci.*, 2020, DOI: 10.1039/D0EE02491K.

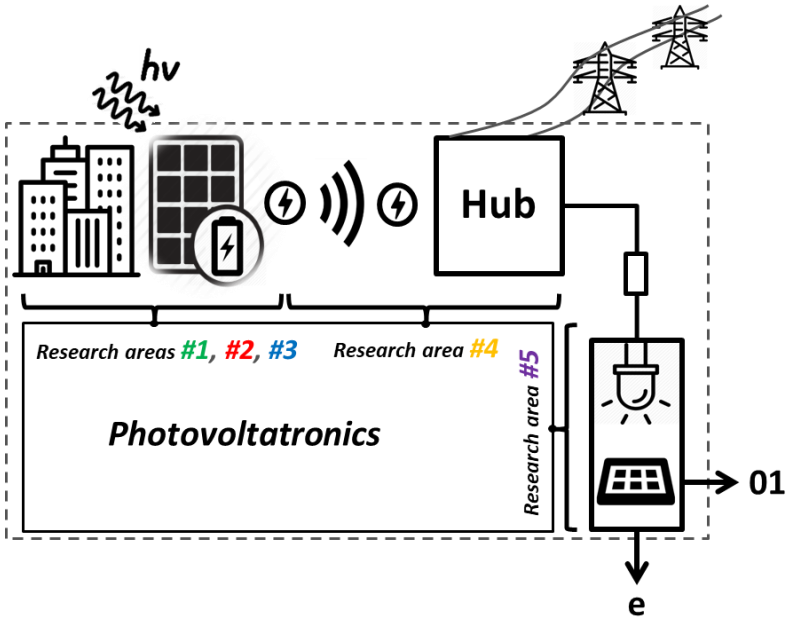
Photovoltatronics

1. Modelling and multi-layer mapping
2. PV-based intelligent energy agents
3. Energy output stabilization
4. Wireless power transfer
5. Light-based communication



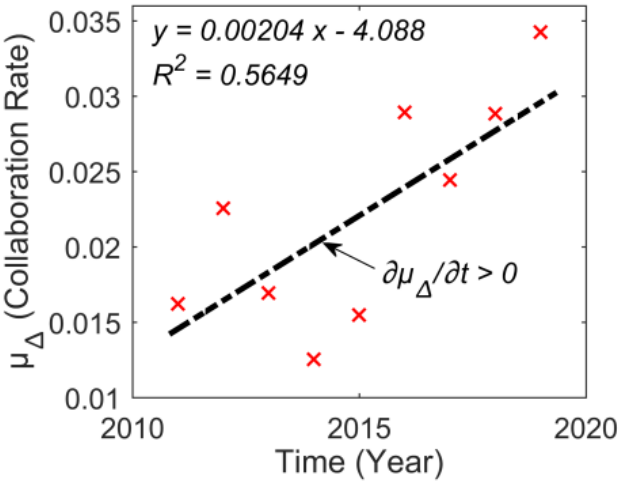
Photovoltatronics

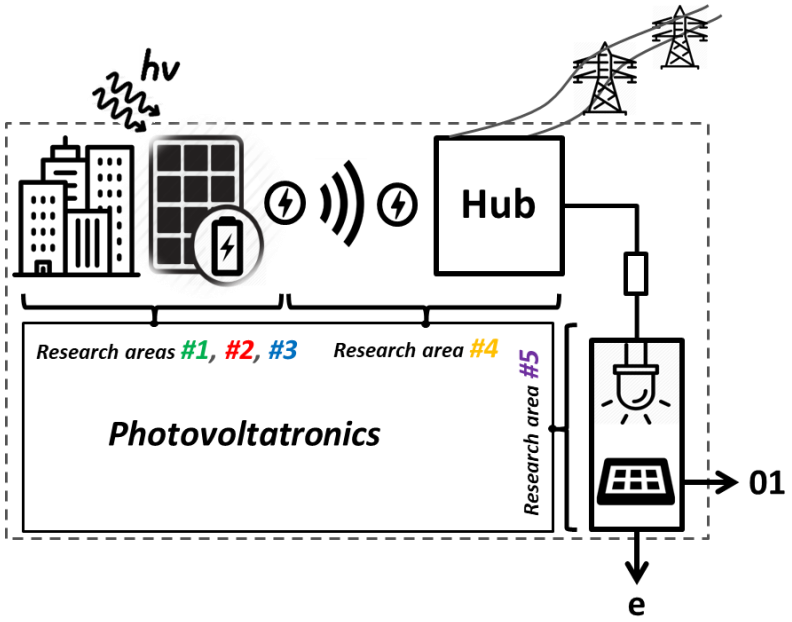




A. A. Salatino, et al., "How are topics born?" *PeerJ Computer Science* 3 (2017): e119

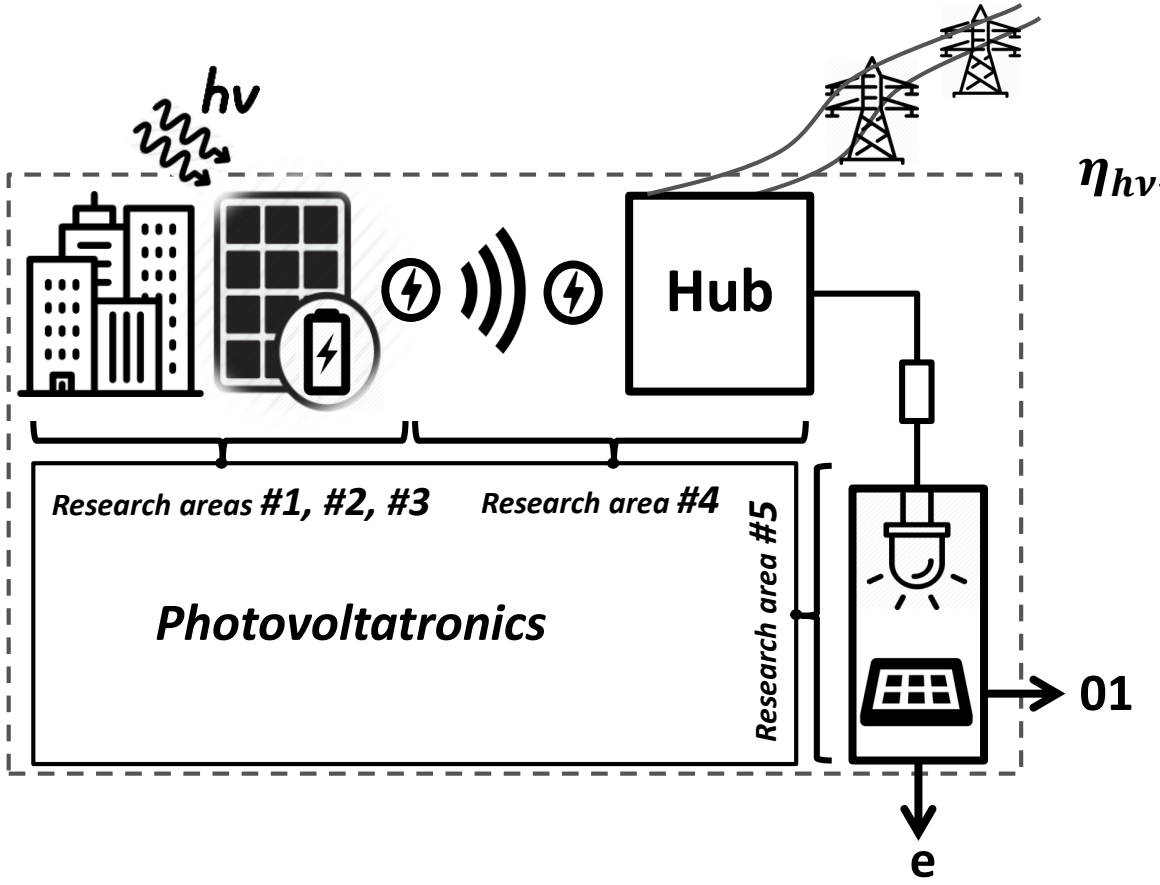
Photovoltatronics





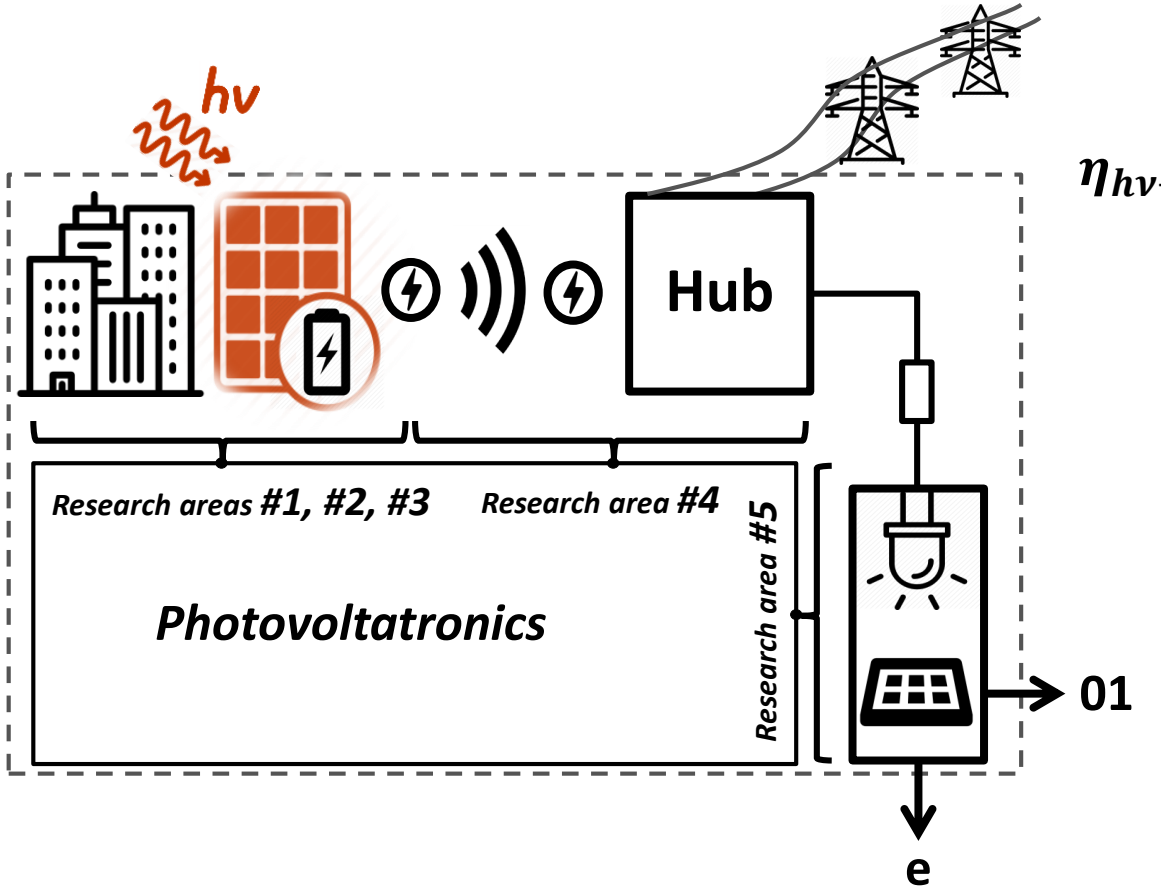
Ultimate conversion efficiency of Photons-to-bits pathway

Photovoltatronics energy-information efficiency chain



$$\eta_{h\nu \to e} = \cdots$$

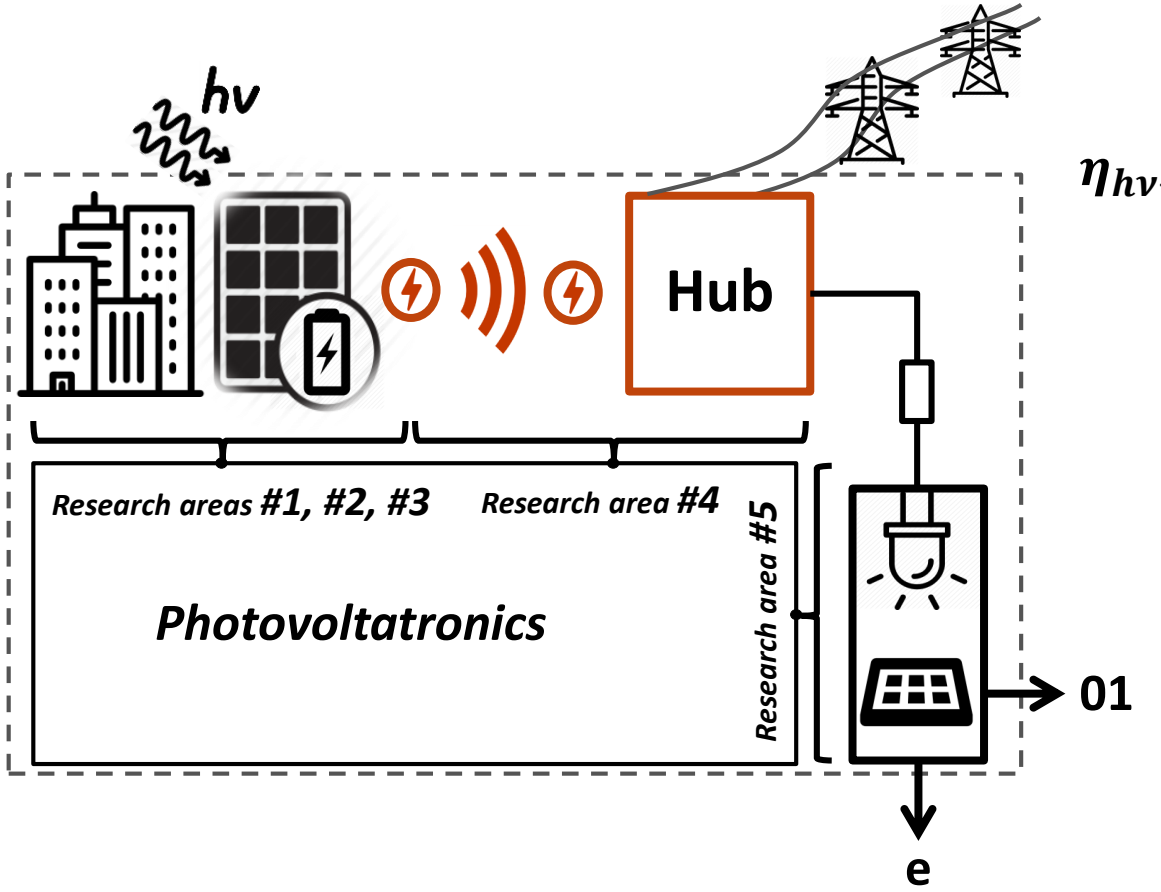
Photovoltatronics energy-information efficiency chain



$$\eta_{h\nu \to e} = \eta_{PV} \cdot$$

W. Shockley and H. J. Queisser, *J. Appl. Phys.*, **32**, 510 (1961)

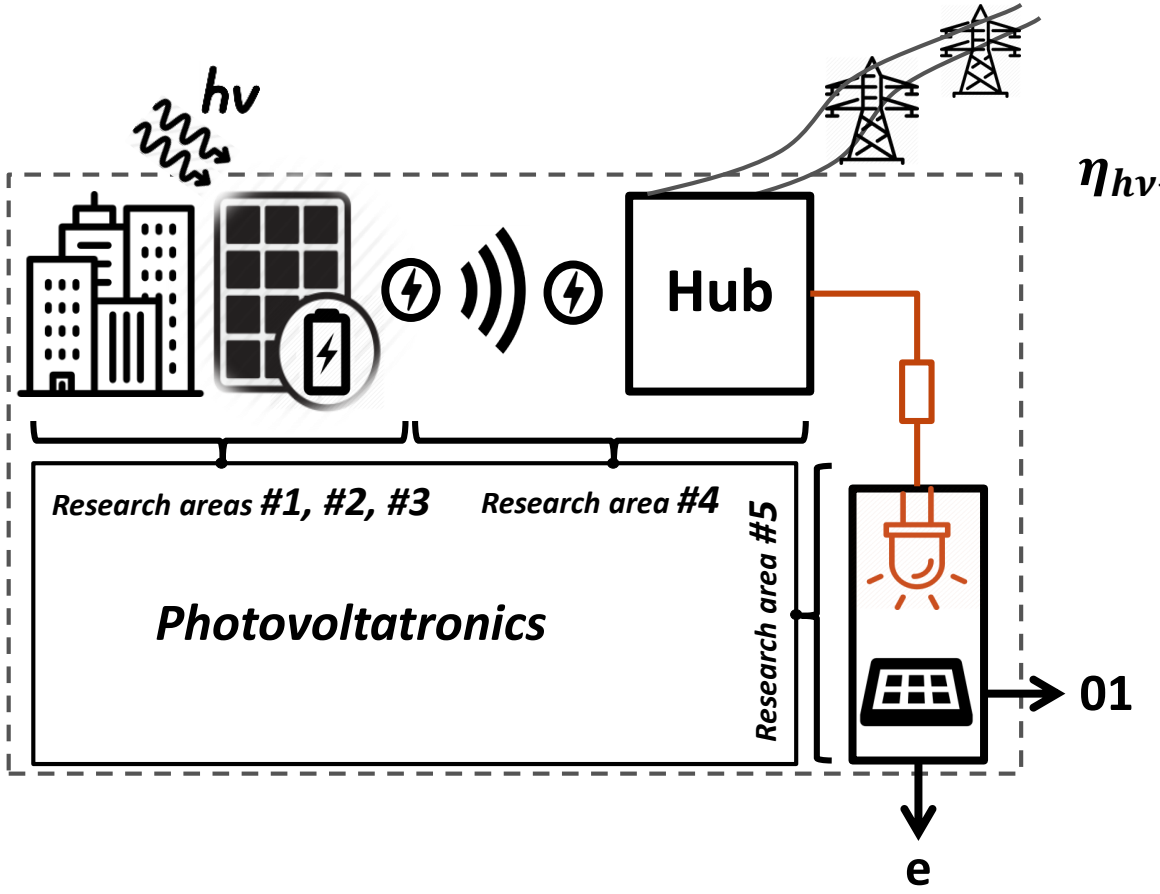
Photovoltatronics energy-information efficiency chain



$$\eta_{h\nu \to e} = \eta_{PV} \cdot \eta_{WPT} \cdot$$

N. Shinohara, *IEEE Microw. Mag.*, **12**, S64 (2011)
W. Shockley and H. J. Queisser, *J. Appl. Phys.*, **32**, 510 (1961)

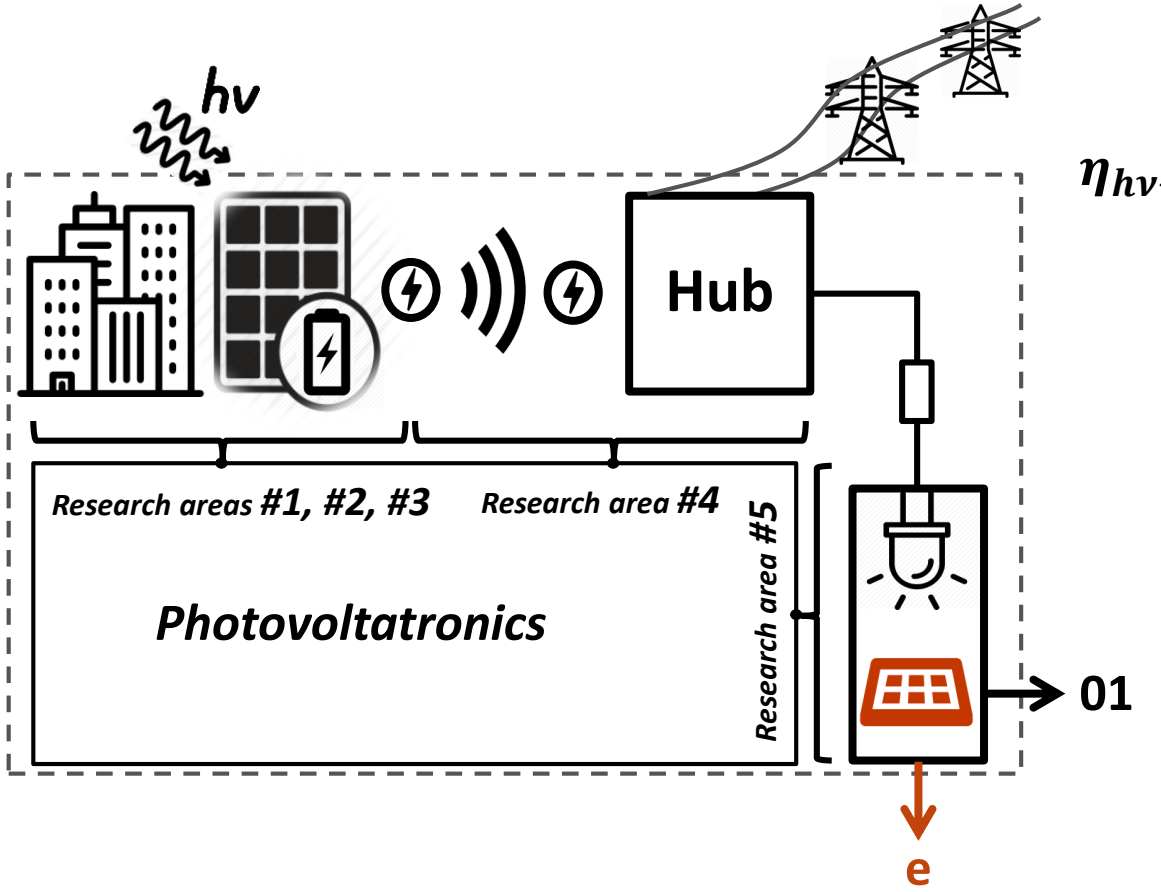
Photovoltatronics energy-information efficiency chain



$$\eta_{h\nu \to e} = \eta_{PV} \cdot \eta_{WPT} \cdot \eta_{WPE} \cdot$$

J. Xue, et al., *Phys. Rev. Appl.*, **8**, 014017 (2017)
N. Shinohara, *IEEE Microw. Mag.*, **12**, S64 (2011)
W. Shockley and H. J. Queisser, *J. Appl. Phys.*, **32**, 510 (1961)

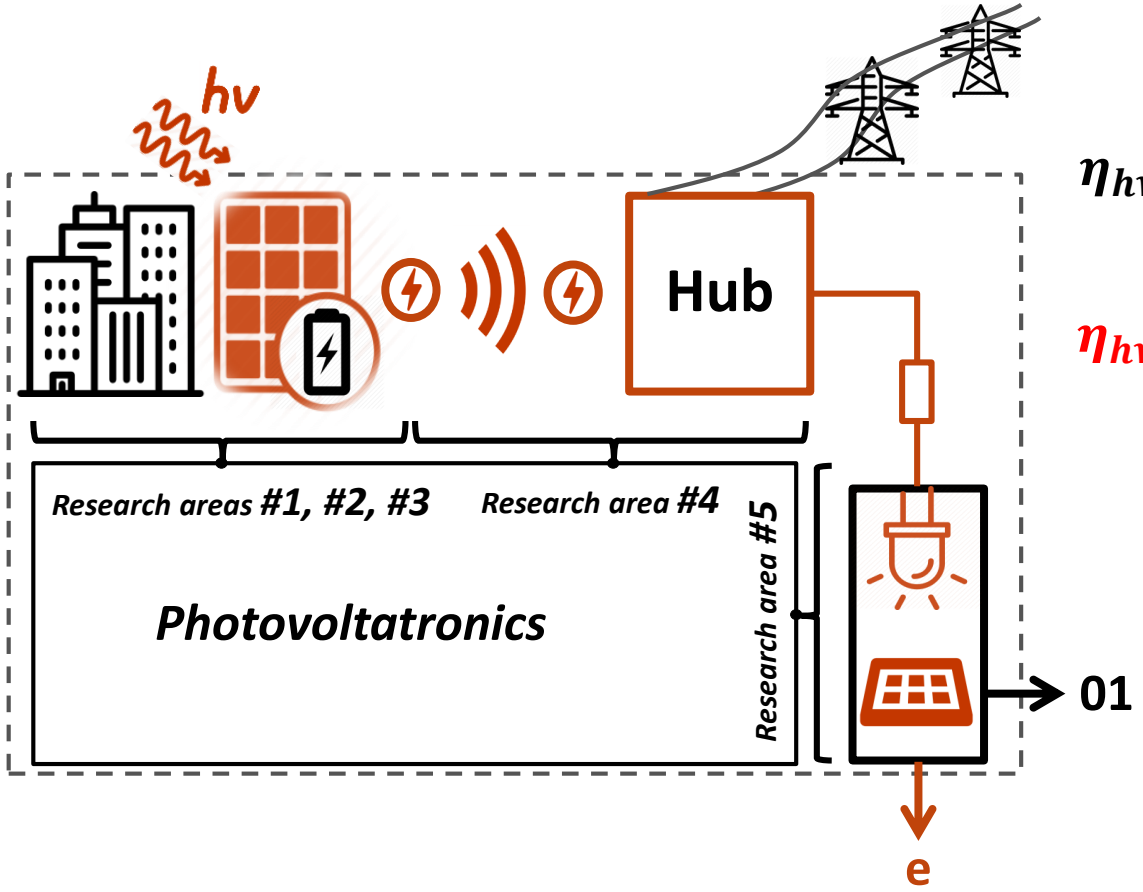
Photovoltatronics energy-information efficiency chain



$$\eta_{h\nu \to e} = \eta_{PV} \cdot \eta_{WPT} \cdot \eta_{WPE} \cdot \eta_{IPV}$$

M. Freunek, et al., *IEEE J. Photovolt.*, **3**, 59 (2012)
J. Xue, et al., *Phys. Rev. Appl.*, **8**, 014017 (2017)
N. Shinohara, *IEEE Microw. Mag.*, **12**, S64 (2011)
W. Shockley and H. J. Queisser, *J. Appl. Phys.*, **32**, 510 (1961)

Photovoltatronics energy-information efficiency chain

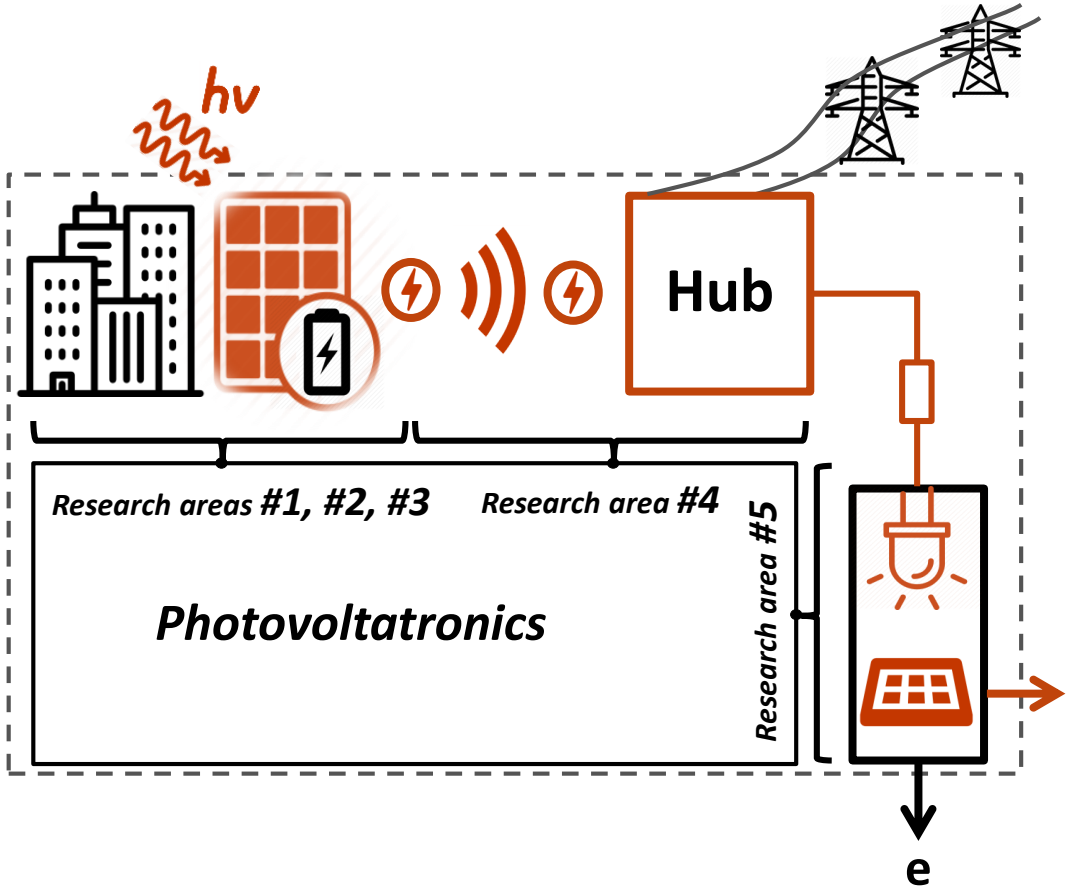


$$\eta_{h\nu \to e} = \eta_{PV} \cdot \eta_{WPT} \cdot \eta_{WPE} \cdot \eta_{IPV}$$

$$\eta_{h\nu \to e} \leq 33.4\%$$

M. Freunek, et al., *IEEE J. Photovolt.*, **3**, 59 (2012)
J. Xue, et al., *Phys. Rev. Appl.*, **8**, 014017 (2017)
N. Shinohara, *IEEE Microw. Mag.*, **12**, S64 (2011)
W. Shockley and H. J. Queisser, *J. Appl. Phys.*, **32**, 510 (1961)

Photovoltatronics energy-information efficiency chain



$$\eta_{h\nu\to e} = \eta_{PV} \cdot \eta_{WPT} \cdot \eta_{WPE} \cdot \eta_{IPV}$$

$$\eta_{h\nu\to e} \leq 33.4\%$$

$$EE_{h\nu\to 01} \leq 619\ Tbit/Joule$$

At least $10\ keV\ per\ bit$ is needed

E. Bjornson and E. G. Larsson, *IEEE ACSSC*, 1252 - 1256 (2018)
M. Freunek, et al., *IEEE J. Photovolt.*, **3**, 59 (2012)
J. Xue, et al., *Phys. Rev. Appl.*, **8**, 014017 (2017)
N. Shinohara, *IEEE Microw. Mag.*, **12**, S64 (2011)
W. Shockley and H. J. Queisser, *J. Appl. Phys.*, **32**, 510 (1961)

Research **Area 1**

Modeling and multi-layer mapping for optimum energy harvesting from ambient energy sources

Why?

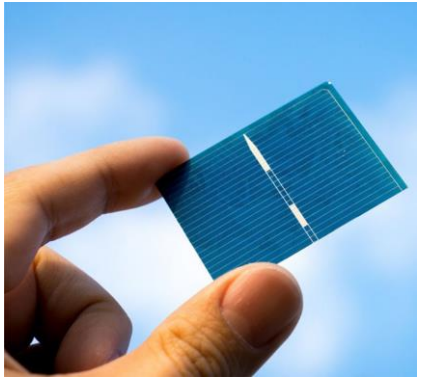
At each instant of time

Power produced =

Source

×

Converter



×

Area

Not in our control

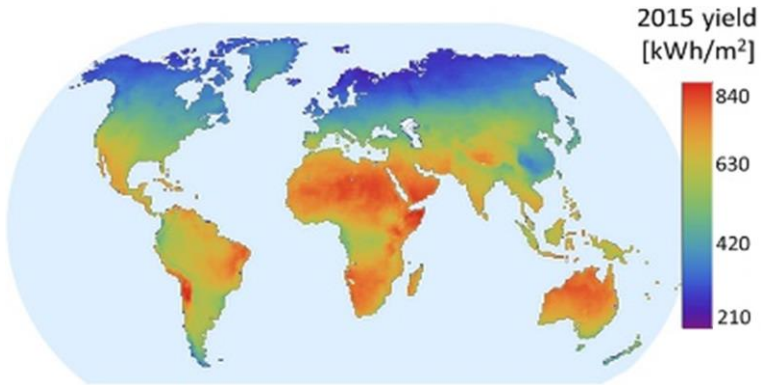
Reaching η limit

Photovoltatronics

Area 1

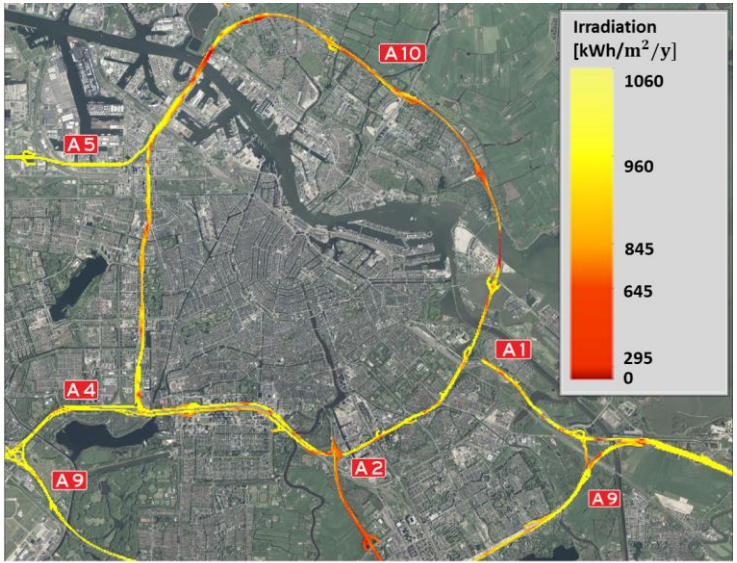
Current status >>> single layer map

From efficiency limit to PV yield limits



Spectrum Weather Geometry

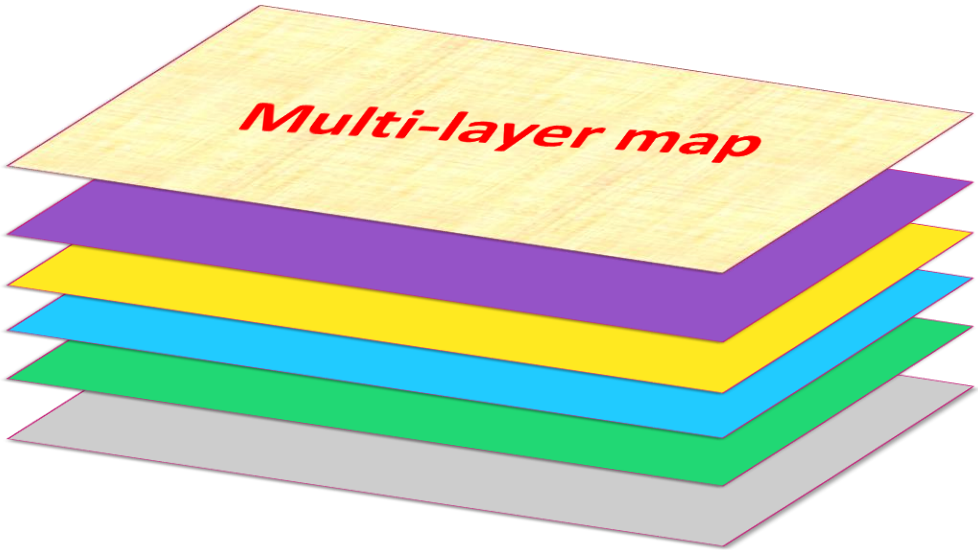
Current PV technologies



M. Zeman, et al., *PVSEC-30 & GPVC* (2020)
C. Ferri, et al., *EUPVSEC-37* (2020)
I. M. Peters and T. Buonassisi, *Joule*, **2**, 1160 (2018)

Future perspective >>> multi-layer map

From efficiency limit to realistic PV yield limits **Spectrum** **Weather** **Geometry**



+

Future PV technology
Energy consumption
Infrastructures (e.g. Grid)
Societal regulations
Etc.

See Orals at EUPVSEC
6BO.17.1 & 6DO.6.1
5CO.12.3

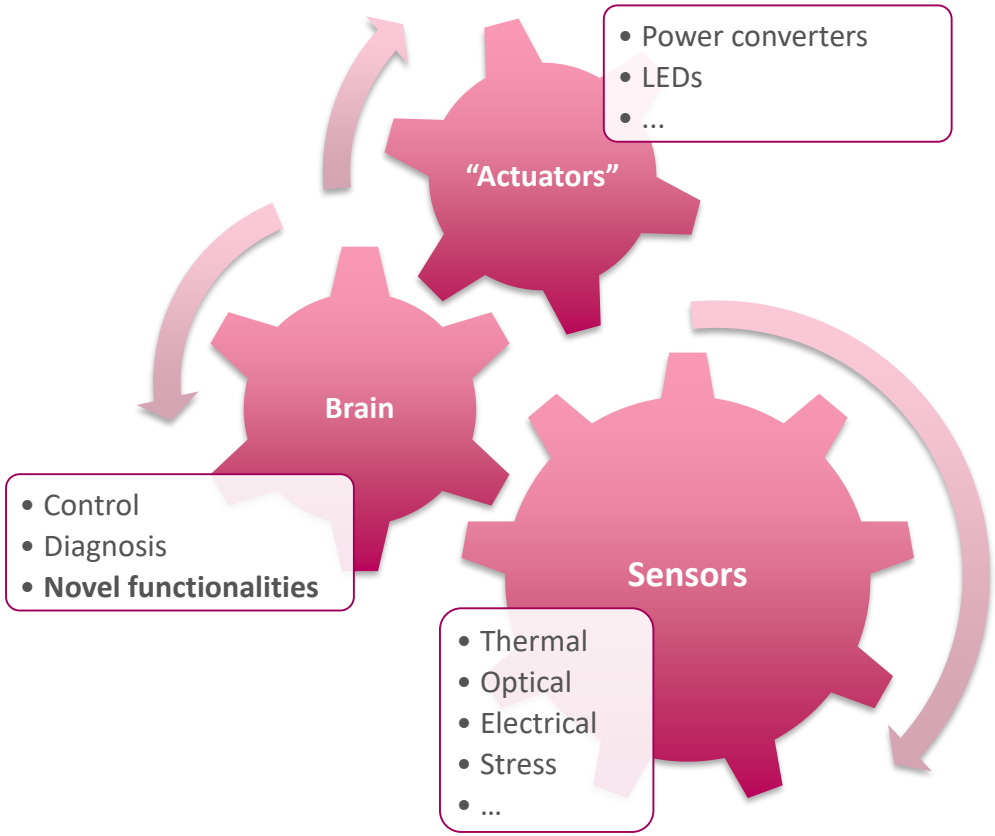
to sketch the *true* horizon and foresee bottlenecks

M. Verkou, et al., *IEEE 48th Photovoltaic Specialists Conference (PVSC)*.2021.

Research Area 2

PV-based intelligent energy agents

PV-based intelligent energy agents

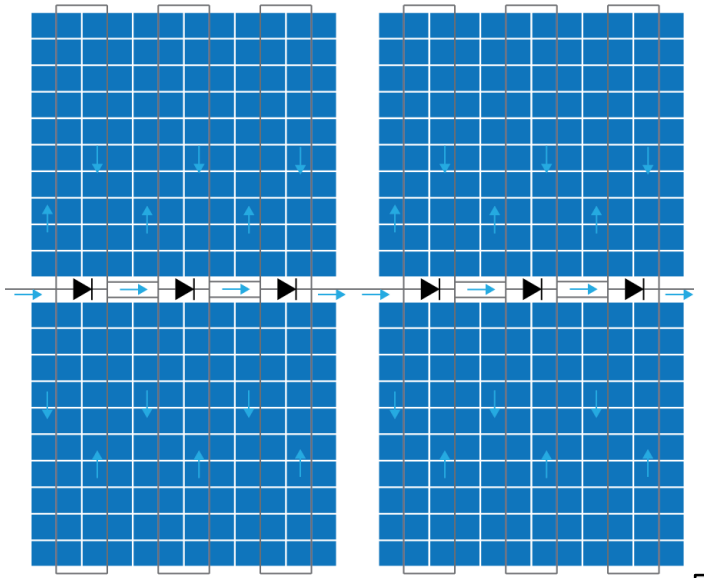


Intelligent energy agents to continuously deliver optimal energy

- **Sensors integrated for:**
  - Identification of operating conditions
  - Early detection of malfunctions
- **Algorithms must be developed to:**
  - Optimize energy production
  - Device diagnosis and prognosis
  - Enable novel functionalities
- **Actuators make the magic real!**

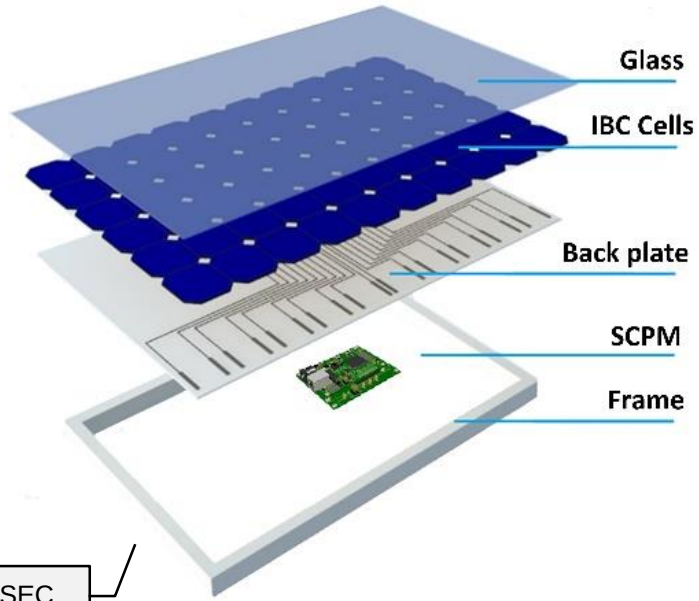
Power management in PV applications

- **Current status**
  - Bypass-diode based solutions



Source: pveasy.com

- **Future**
  - Smart power management



See Oral at EUPVSEC
1AO.3.2

O. Isabella, H. Ziar, M. Zeman. (Patent, 2019)

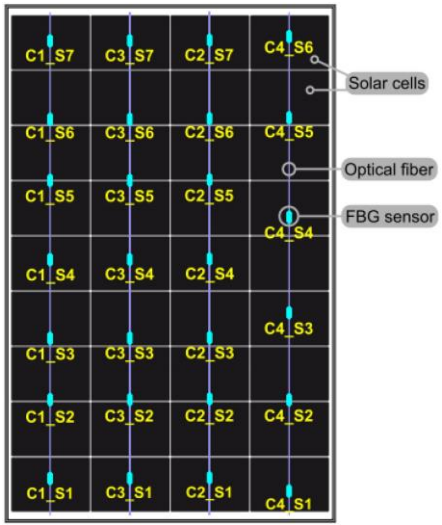
A. Calcabrini, M. Zeman, O. Isabella, V. Stornelli, M. Muttillo, (Patent, 2020)

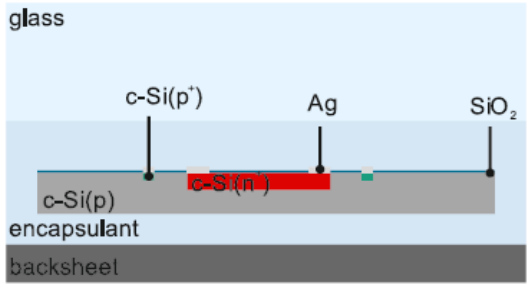
A. Calcabrini, et al. Renewable Energy 179 (2021)

Sensors in PV applications

- **Current status**
  - PV system level sensing

- **Future**
  - Sensors integration in PV cells and modules





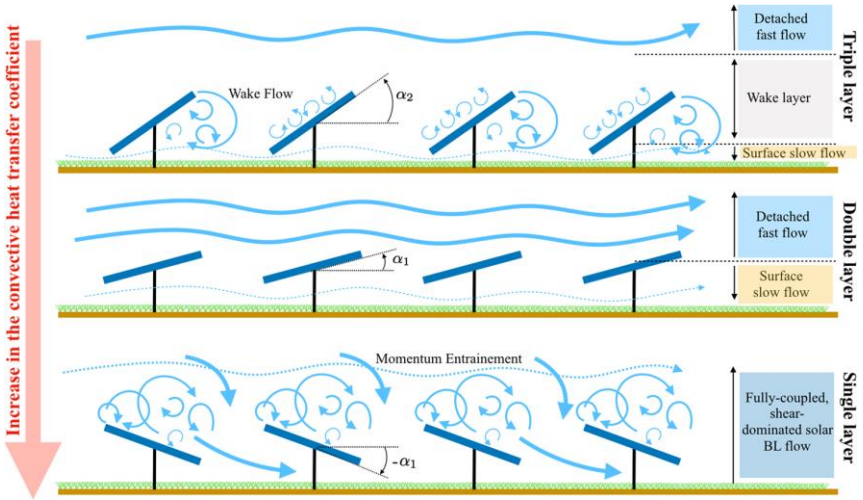
https://www.kintech-engineering.com/catalogue/solar/hukseflux-sr20/

E.A. Santolin, et al., *J. Microw. Optoelectron. Electromagn. Appl.*, **15**, 333 (2016)

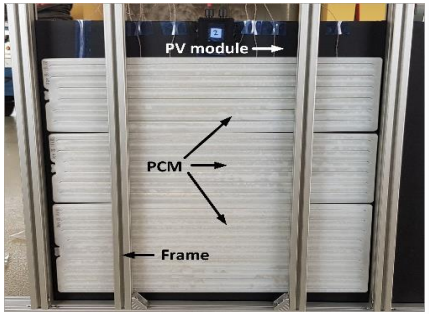
A.J. Beinert, et al., *Prog Photovolt Res Appl*., **28**, 717 (2020)

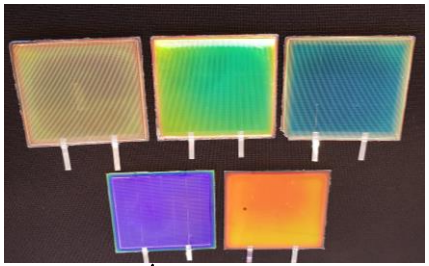
Thermal management in PV applications

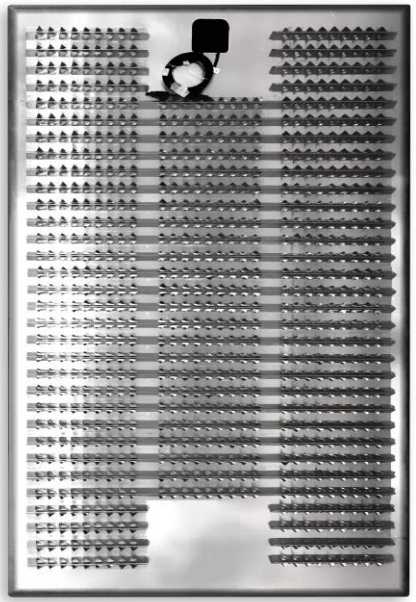
- **Current status**
  - Cooling through convection



- **Future**
  - Integration of module cooling techniques







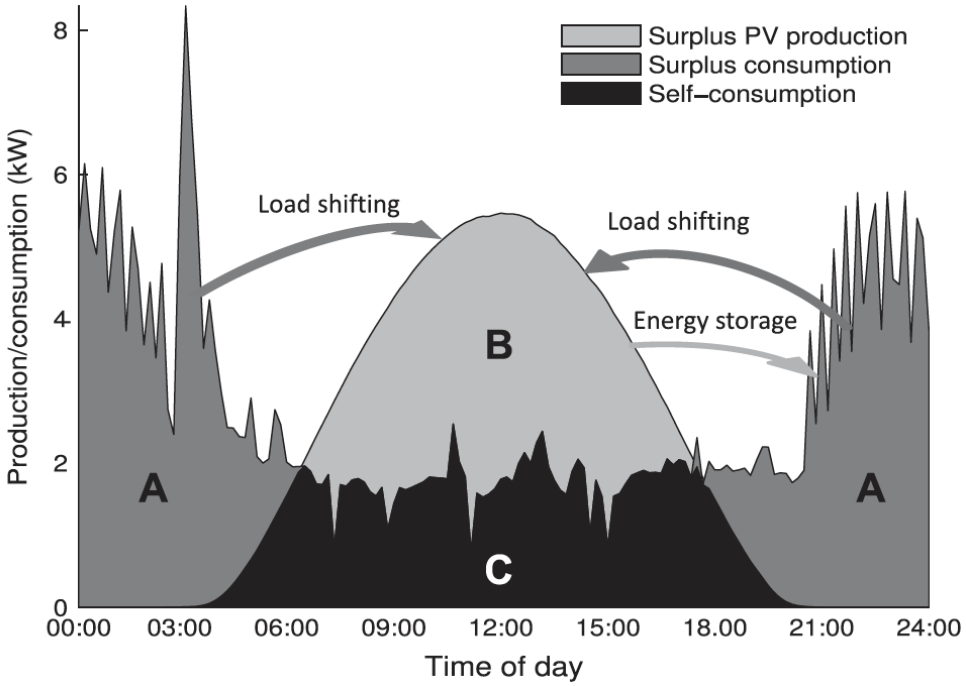
See Oral at EUPVSEC
1BO.16.2

A. Glick, et al., *Sci. Rep.*, **10,** 10505 (2020)
https://www.coolback.com/
J. C. Ortiz Lizcano, et al., EUPVSEC-35 (2018)
J. C. Ortiz Lizcano, et al., EUPVSEC-36 (2019)

Research Area 3

Stabilizing energy output by integrating storage within a PV module

Why should we integrate storage?

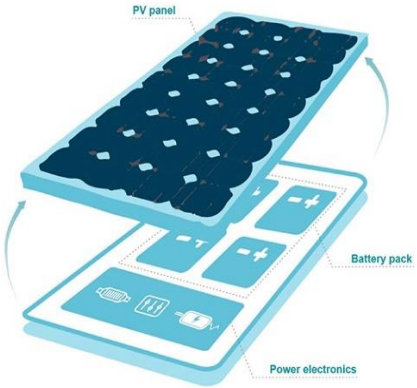


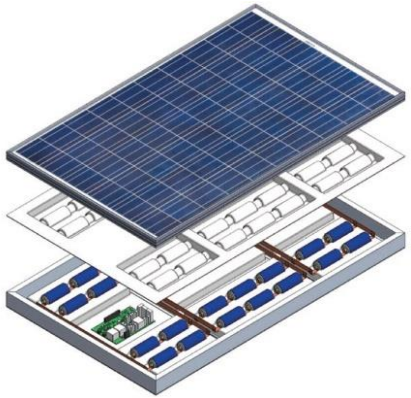
PV power is fluctuating and intermittent

Generation-demand balance with storage

R. Luthander, et al., *Applied Energy,* **142**, 80(2015)

Advantages of module-level storage integration





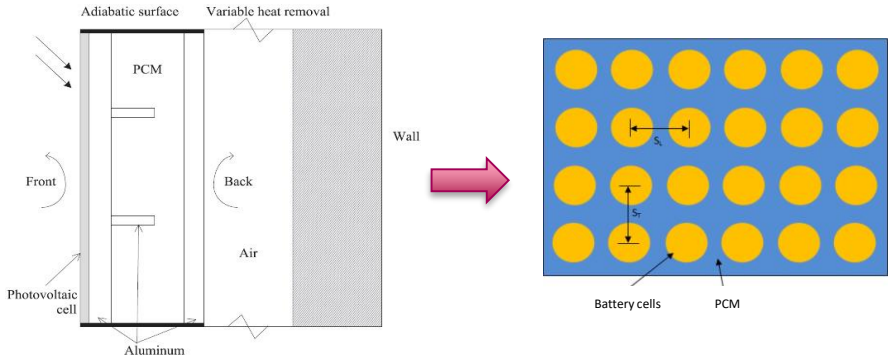
- **Higher volumetric and gravimetric density**
  - Less wiring
  - Common encapsulation and electrodes
- **Quicker and cheaper manufacturing**
  - Fewer materials and lower energy compared to separate fabrication of individual components
- **Self-sustaining portable solutions**
  - Ideal for remote areas or medical/rescue equipment
- **User-friendly (easy installation)**
  - All-in-one solution

V. Vega-Garita, et al., *Progr. Photovolt: Res. Appl.*, **27**, 346 (2019)
A. Dedé, et al., *IEEE SPEEDAM*, 895 (2016)

Major challenges and future research

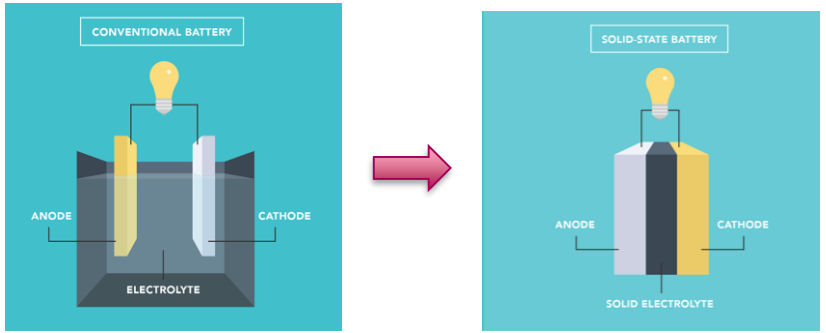
- **Thermal management**
  - Reduced lifetime due to high temperature

Combining cooling techniques with battery integration



- **Safety**
  - Accidents (fire) with liquid-state batteries

From liquid-state to solid-state storage



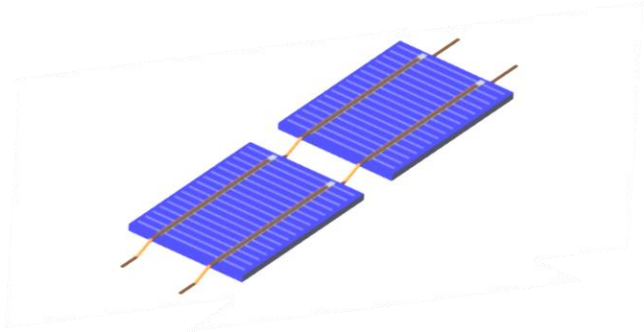
T. Ma, et al., *Renewable and Sustainable Energy Reviews,* **43**, 1273 (2015)
R. D. Jilte, et al., *Applied Thermal Engineering,* **161** (2019)
https://chargedevs.com/features/solid-state-battery-tech-whats-close-to-commercialization-and-whats-still-years-away/
https://www.quantumscape.com/

Research **Area 4**

Wireless transmission of electricity through novel electrode design of PV modules

Why wireless transmission in PV devices?

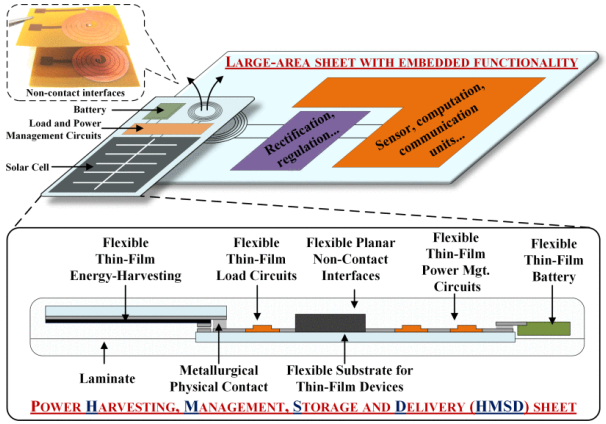
- **Conventional interconnection lead to 2.27-2.76% relative cell-to-module efficiency losses for conventional modules [1,2]**
  - Series resistance
  - Shadowing losses

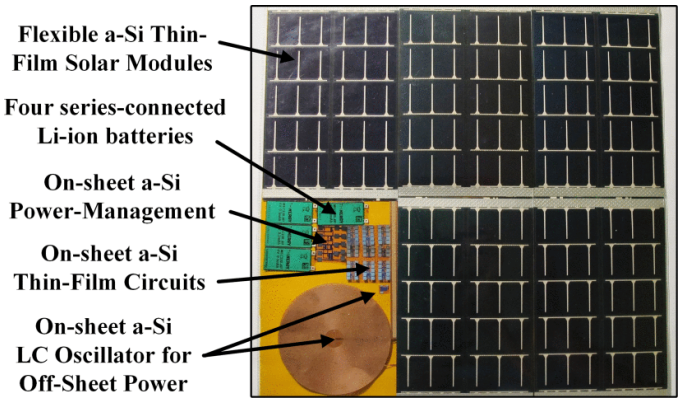


- **Conventional cabling and interconnection of PV modules**
  - Huge amount of material
  - High installation cost

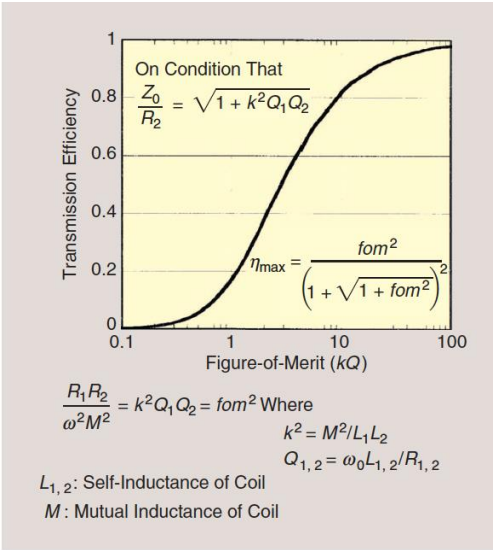
[1] M. Mittag et al., *IEEE PVSC*, 1531 (2017)
[2] I. Haedrich, et al., *Solar energy materials and solar cells*, **131**, 14 (2014)

Example of wireless transmission of PV electricity





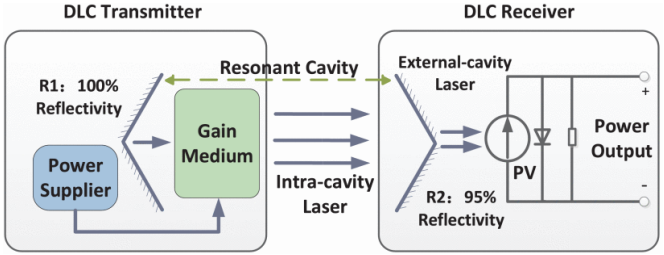
- **Enabling Wireless Power Transfer (WPT) on PV modules:**
  - Primary transmission coil on PV module side
  - MPPT and DC/AC conversion on PV module side
  - System optimized for ~100% transfer efficiency



N. Shinohara, *IEEE Microwave magazine*, **12**, S64 (2011)
W. Rieutort-Louis, et al., *IEEE Journal of Photovoltaics*, **4**, 432 (2014)

PV with integrated WPT: future prospective

- **WPT integrated in junction box**
  - Planar coil + DC/AC + MPPT
- **Novel cell architecture for cell-level integration of**:
  - Primary coil (inductive WPT)
  - Primary plate (capacitive WPT)
- **WPT from every (sub-)module to a shared energy exchange hub:**
  - Improved shade tolerance
  - Primary-to-secondary voltage boost through secondary coil (hub) design
- **Optical transmission of energy as laser beams**



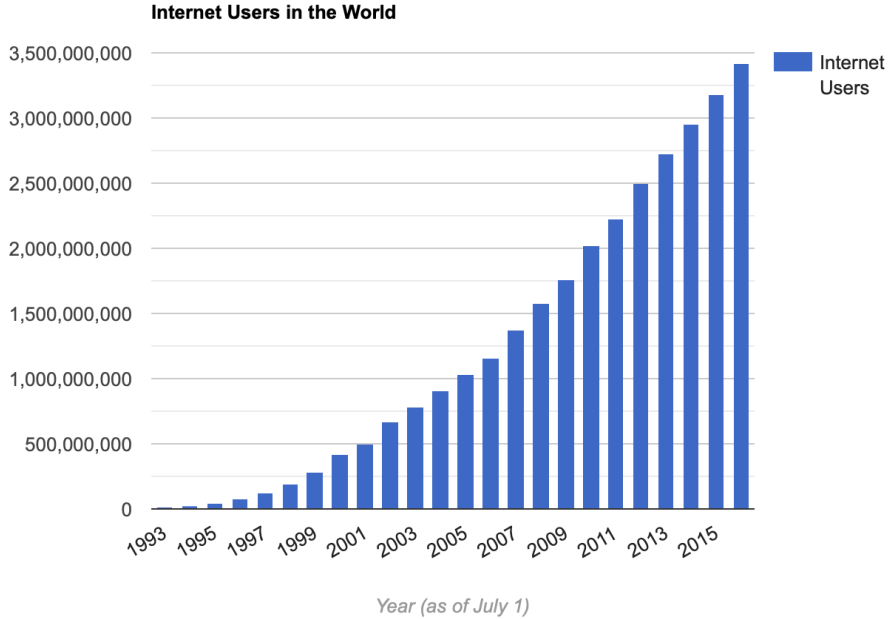
  - Projects in space

Q. Zhang, et al., *IEEE Internet of Things Journal*, **5**, 3853 (2018)
ESA projects: https://tinyurl.com/yy2pfcna

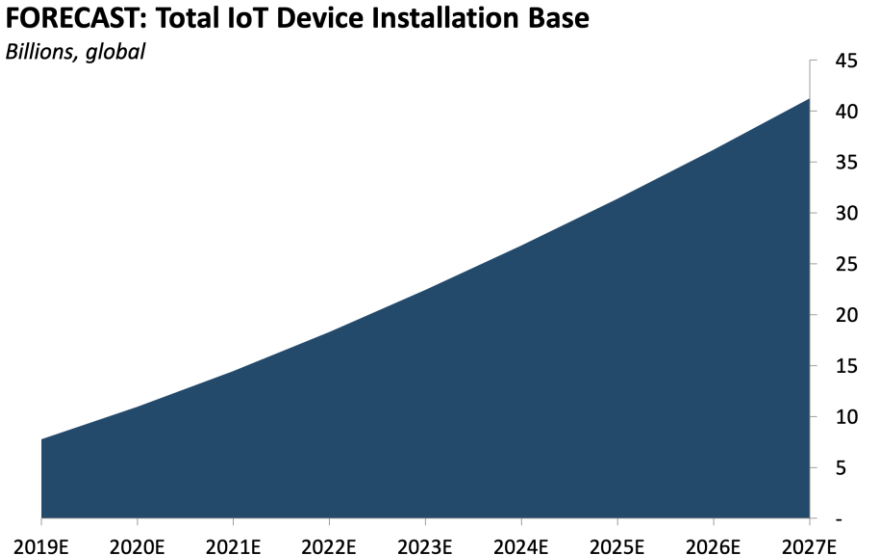
Research Area 5

Integration and control of light generating elements for light communication, lighting and infotainment

Why should we integrate light communication?



Source: internetlivestats.com



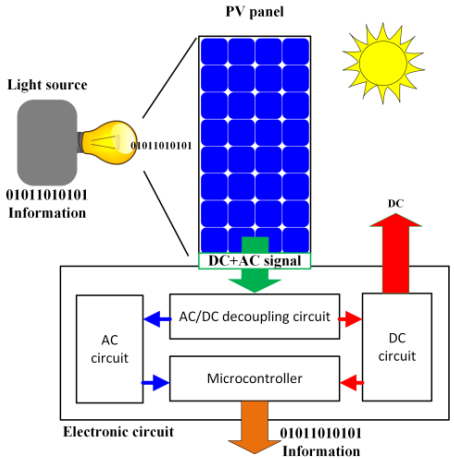
Source: Business Insider Intelligence estimates, 2020

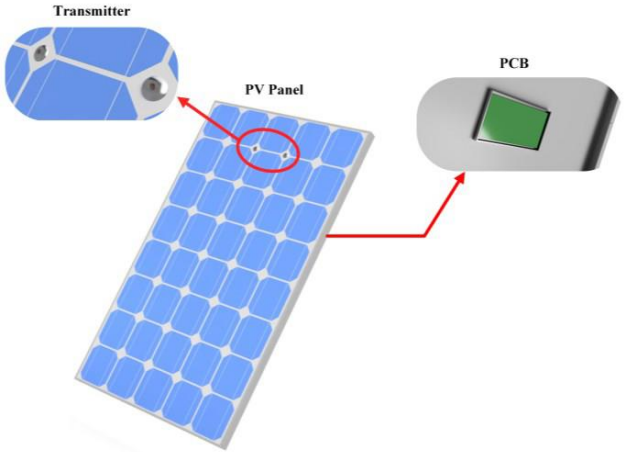
Radio-frequency spectrum is becoming insufficient!

LiFi

Haas, Harald, et al. *Journal of lightwave technology* 34.6 (2016)

Major advantages and challenges





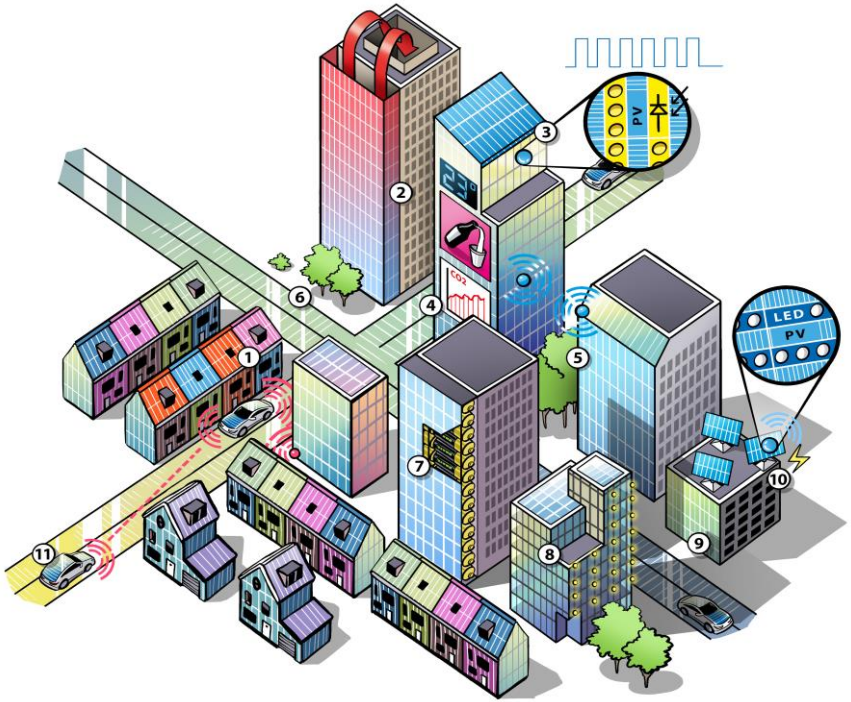
Advantages

- Higher capacity thanks to light frequencies
- Gbps data rates possible
- Multipurpose integrated devices
- Re-use of available infrastructure

Challenges

- **Bi-directionality**
  - Integration of light sources on PV module
- **Light pollution**
- **Joint MPPT and data exchange**
  - Multifunctionality

Application in the city of the future

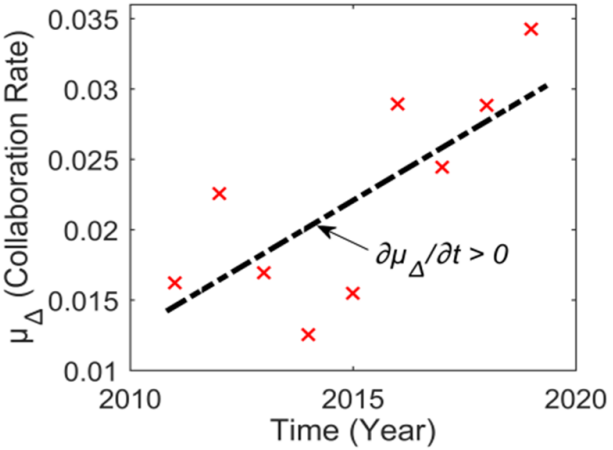


- **Building-to-building communication**
  - District-level energy management
  - Safety information (also shared with occupants using indoor Li-Fi)
- **Vehicle-to-vehicle communication**
  - Self-driving and improved safety
- **City-to-vehicle communication**
  - City traffic control
- **PV-based media facades**
  - Sharing of visual information and/or advertisement

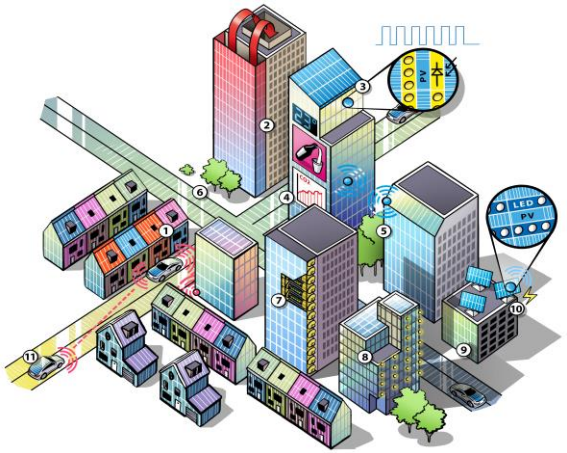
Conclusions

Conclusion

- Number of publications and the **collaboration rate** for research areas related to photovoltatronics **is increasing**, which is a sign its emergence.



- **Photovoltatronics** combine and steer electrification and digitization through the development of multi-functional PV-based intelligent energy agents.



Thank you for your attention!

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