Thermophotovoltaics for solar/power-to-heat-to-power energy conversion

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Note: the texts underlined in blue are internet links

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Outline

Basics of thermophotovoltaics (TPV)
TPV vs. solar PV
Performance metrics

Applications
X-to-heat-to-power conversion
TPV batteries

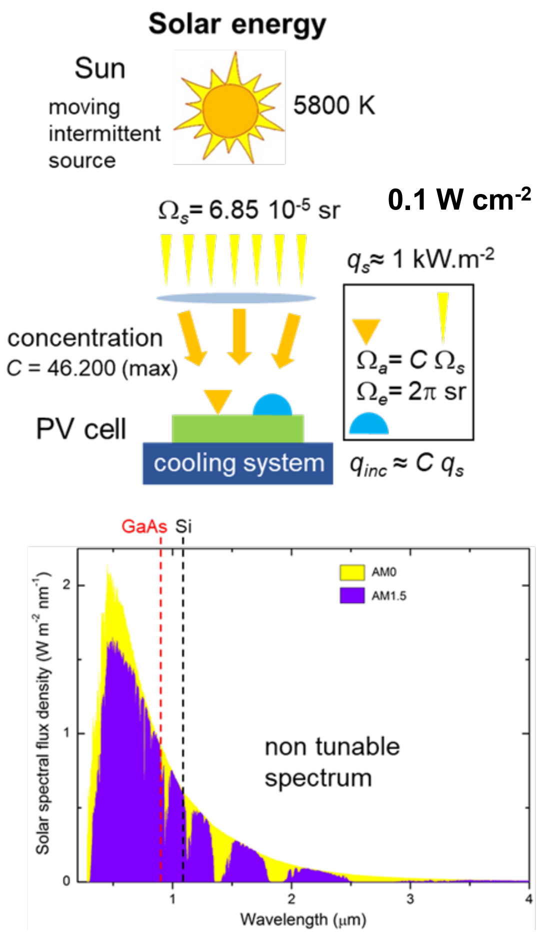
Very recent advances in thermophotovoltaics

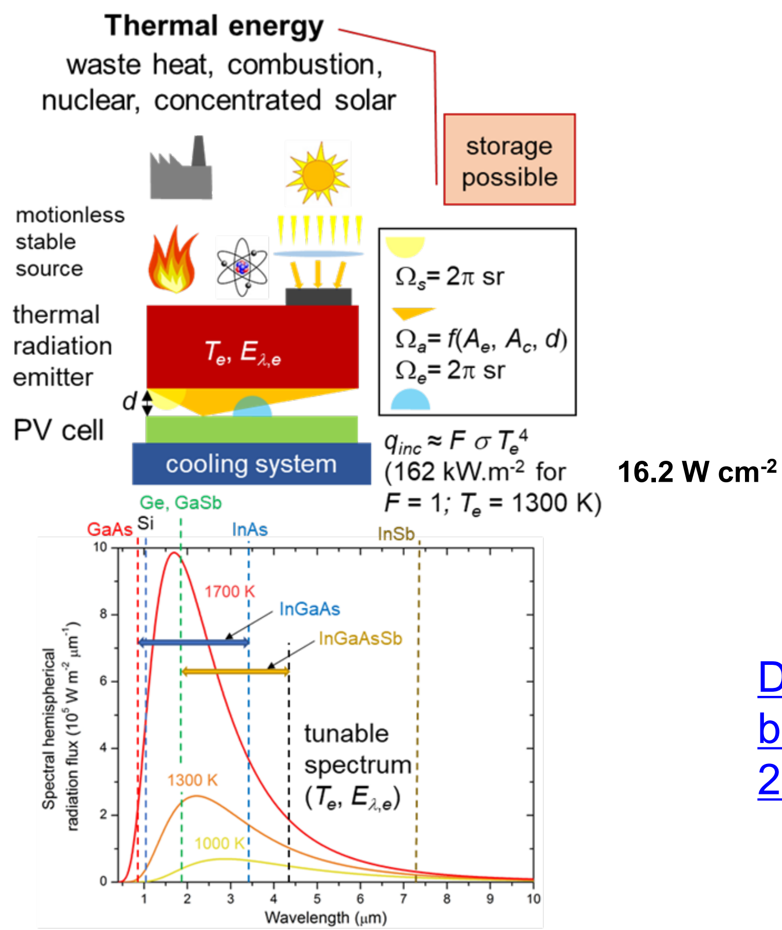
The project-team TREE
The team
Topics, collaborating & networking

Key messages

Basics of thermophotovoltaics

Photovoltaics vs. thermophotovoltaics



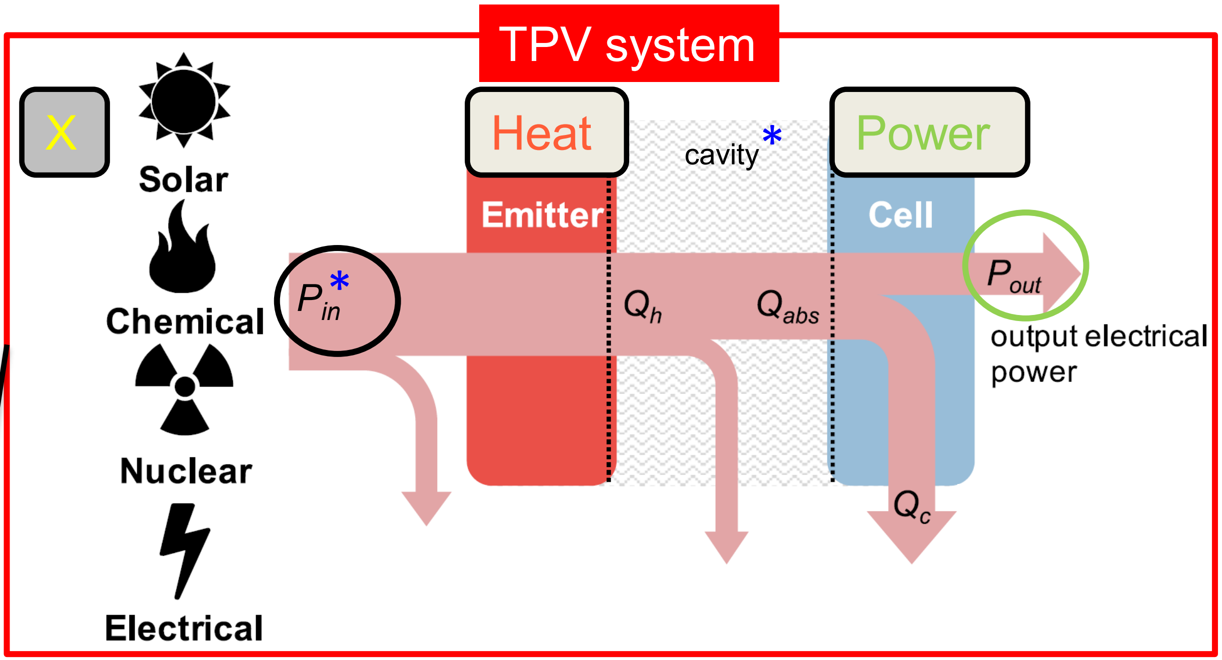


Datas & Vaillon, book chapter, 2020

TPV: PV conversion of (infrared) thermal radiation

Conversion efficiencies

Primary source



[Burger et al., Joule, 2020]

* Added to the original figure

η_{system} $= \dfrac{P_{out}}{P_{in}}$

output electrical power

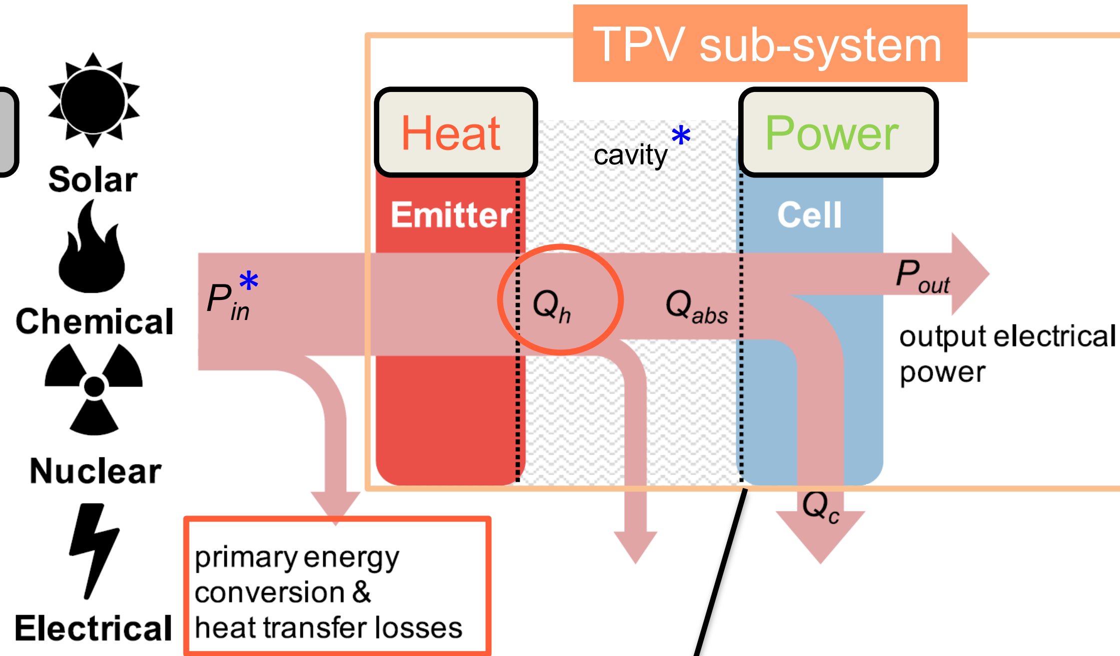
input power

TPV system efficiency

~ solar PV conversion efficiency

Conversion efficiencies

Primary source: X



[Burger et al., Joule, 2020](#)

* Added to the original figure

net heat flow out of the emitter

output electrical power

$$\eta_{system} = \frac{P_{out}}{P_{in}} = \frac{Q_h}{P_{in}} \times \frac{P_{out}}{Q_h}$$

net heat flow out of the emitter

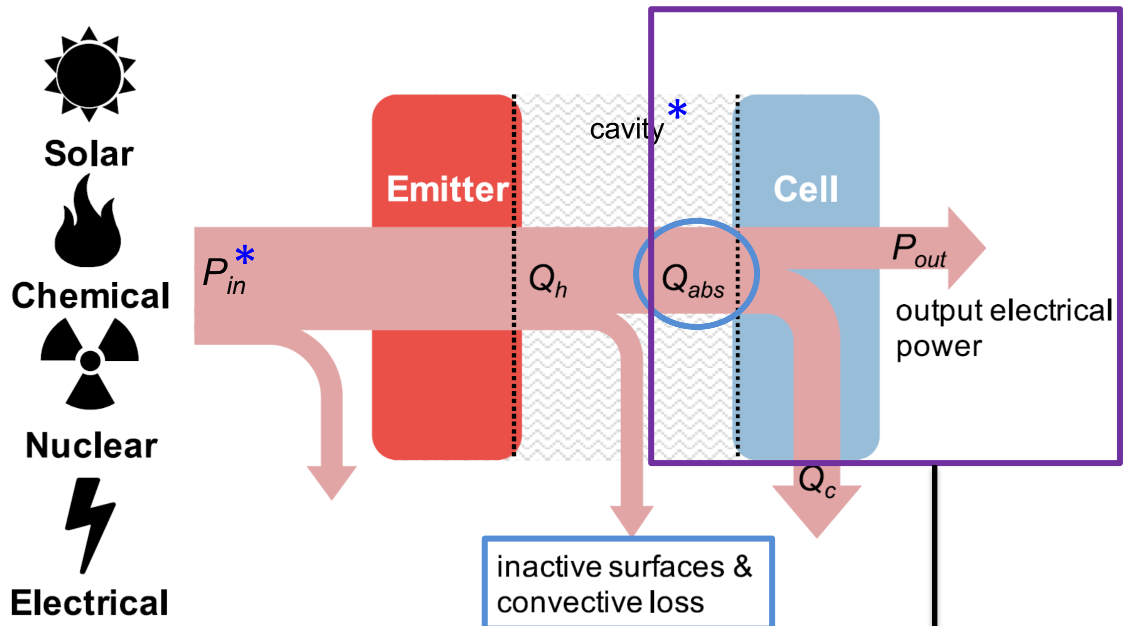
input power

X-to-Heat conversion efficiency

$\eta_{TPV\text{-}sub}$

TPV sub-system efficiency

Conversion efficiencies



Burger et al., Joule, 2020

* Added to the original figure

net heat absorbed by the cell

output electrical power

$$\eta_{system} = \frac{P_{out}}{P_{in}} = \frac{Q_h}{P_{in}} \times \frac{Q_{abs}}{Q_h} \times \frac{P_{out}}{Q_{abs}}$$

net heat flow out of the emitter

net heat absorbed by the cell

ATTENTION

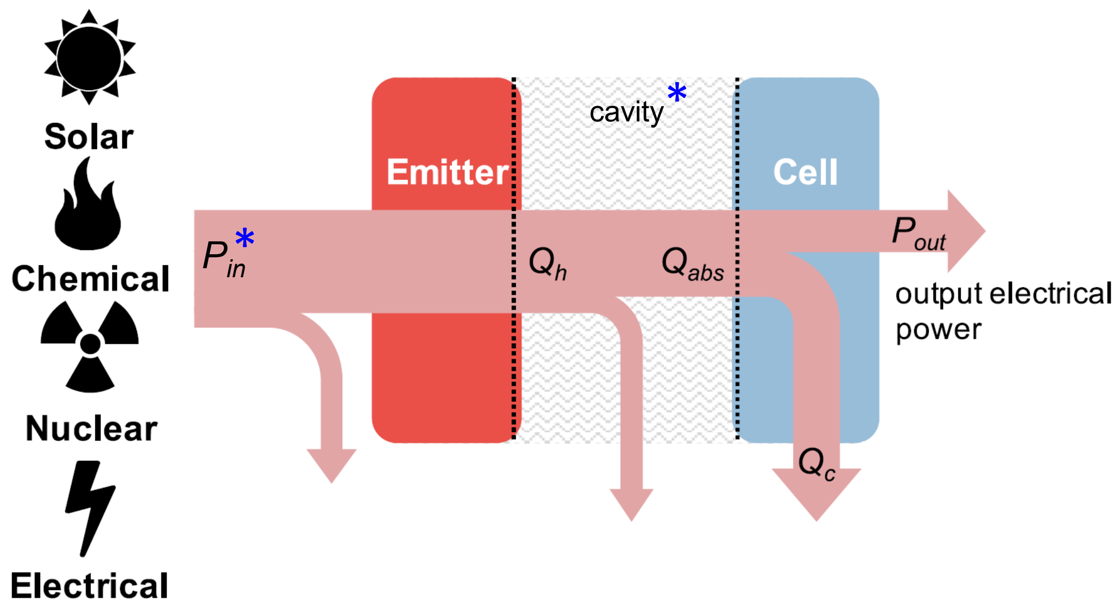
X-to-Heat conversion efficiency

cavity efficiency

$\eta_{pairwise}$

pairwise efficiency

Conversion efficiencies



Burger et al., Joule, 2020

* Added to the original figure

$$p_{out} = \frac{P_{out}}{A_{cell}}$$

electrical power density

$$\eta_{system} = \frac{P_{out}}{P_{in}} = \frac{Q_h}{P_{in}} \times \frac{Q_{abs}}{Q_h} \times \frac{P_{out}}{Q_{abs}}$$

$\eta_{pair} = \frac{P_{out}}{Q_{abs}}$

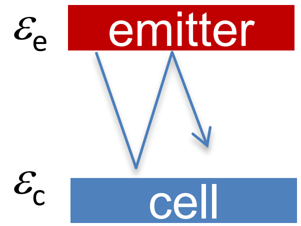
pairwise efficiency

Main performance metrics

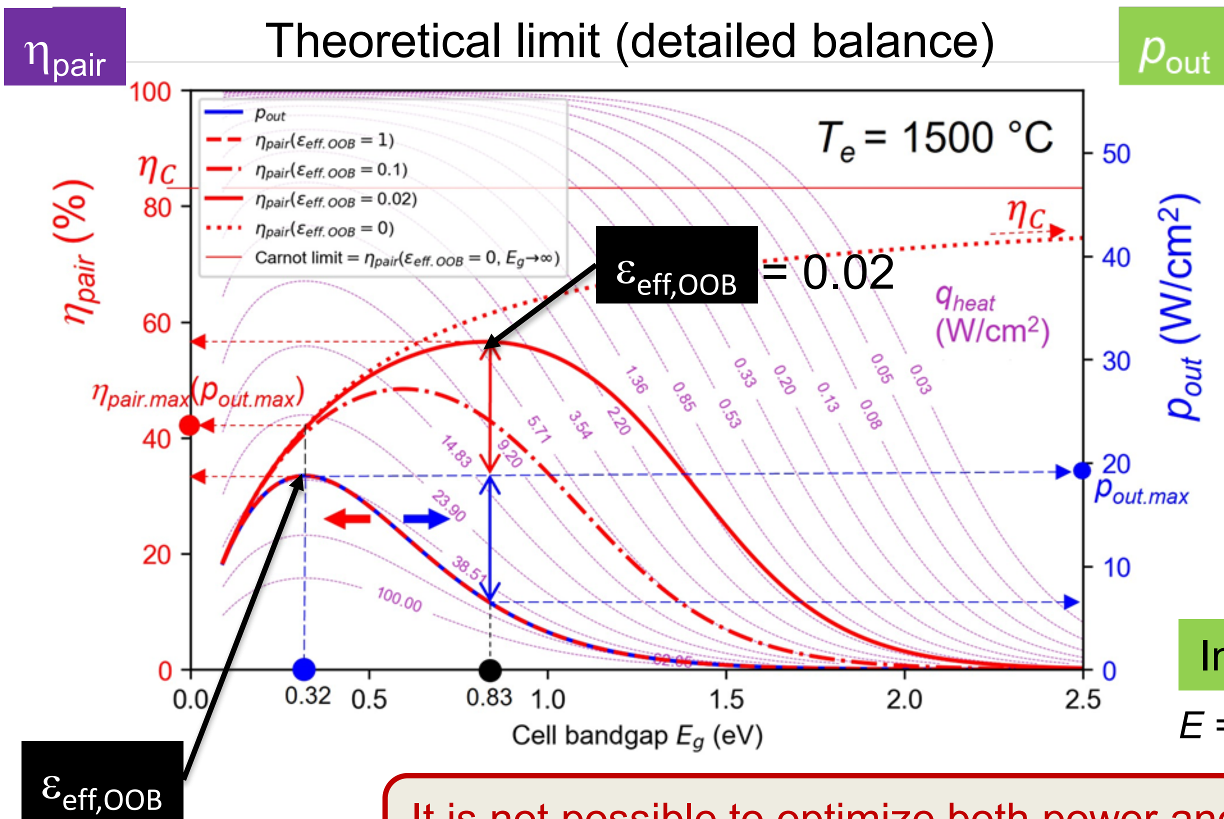
Major differences between TPV and PV

Spectral selectivity

$$\varepsilon_{\mathrm{eff}}(E) = \frac{\varepsilon_{\mathrm{e}}(E)\,\varepsilon_{\mathrm{c}}(E)}{1-(1-\varepsilon_{\mathrm{e}}(E))\,(1-\varepsilon_{\mathrm{c}}(E))}$$



Theoretical limit (detailed balance)



$$\eta_{pair} = \frac{p_{out}}{q_{abs}}$$

$$= \frac{j_{sc}\,V_{oc}\,FF}{\int_0^\infty \varepsilon_{\mathrm{eff}}(E)\,E\,b(E,T_e)\,dE}$$

$$= \frac{\left[q\int_{E_g}^{\infty}\varepsilon_{\mathrm{eff.}IB}(E)\,IQE\,b(E,T_e)\,dE\right]V_{oc}\,FF}{\int_0^{E_g}\varepsilon_{\mathrm{eff.}OOB}(E)\,E\,b(E,T_e)\,dE + \int_{E_g}^{\infty}\varepsilon_{\mathrm{eff.}IB}(E)\,E\,b(E,T_e)\,dE}$$

In-band (IB)

$E = E_{photon} > E_g$

Out-of-band (OOB)

$E = E_{photon} < E_g$

It is not possible to optimize both power and efficiency
Major impact on efficiency of minimizing out-of-band radiation exchange

Major differences between TPV and PV

Spectral selectivity

$$\varepsilon_{eff}(E) = \frac{\varepsilon_e(E)\,\varepsilon_c(E)}{1-(1-\varepsilon_e(E))\,(1-\varepsilon_c(E))}$$

Maximizing p_{out}

In-band (IB)

$\varepsilon_{eff,IB} \rightarrow 1$

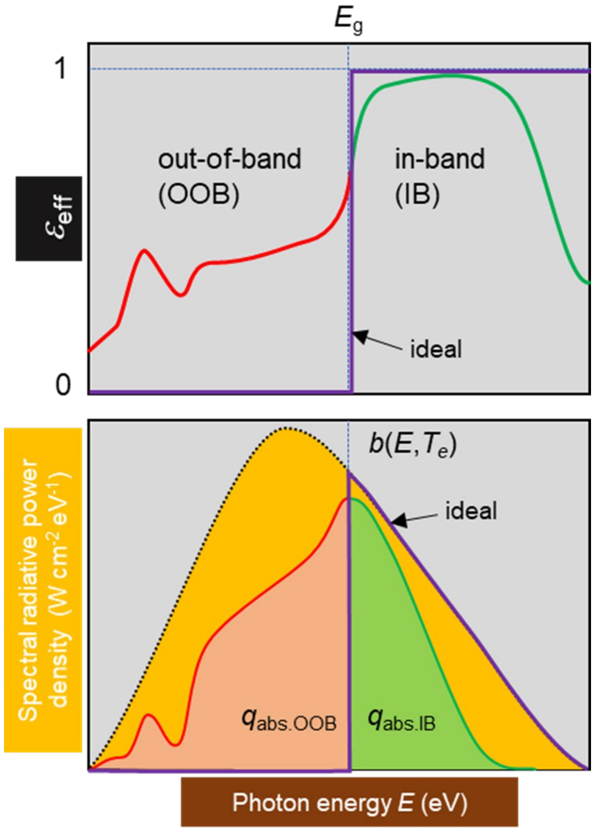
BOTH the emitter and the cell must be **blackbodies**

Maximizing η_{pair}

Out-of-band (OOB)

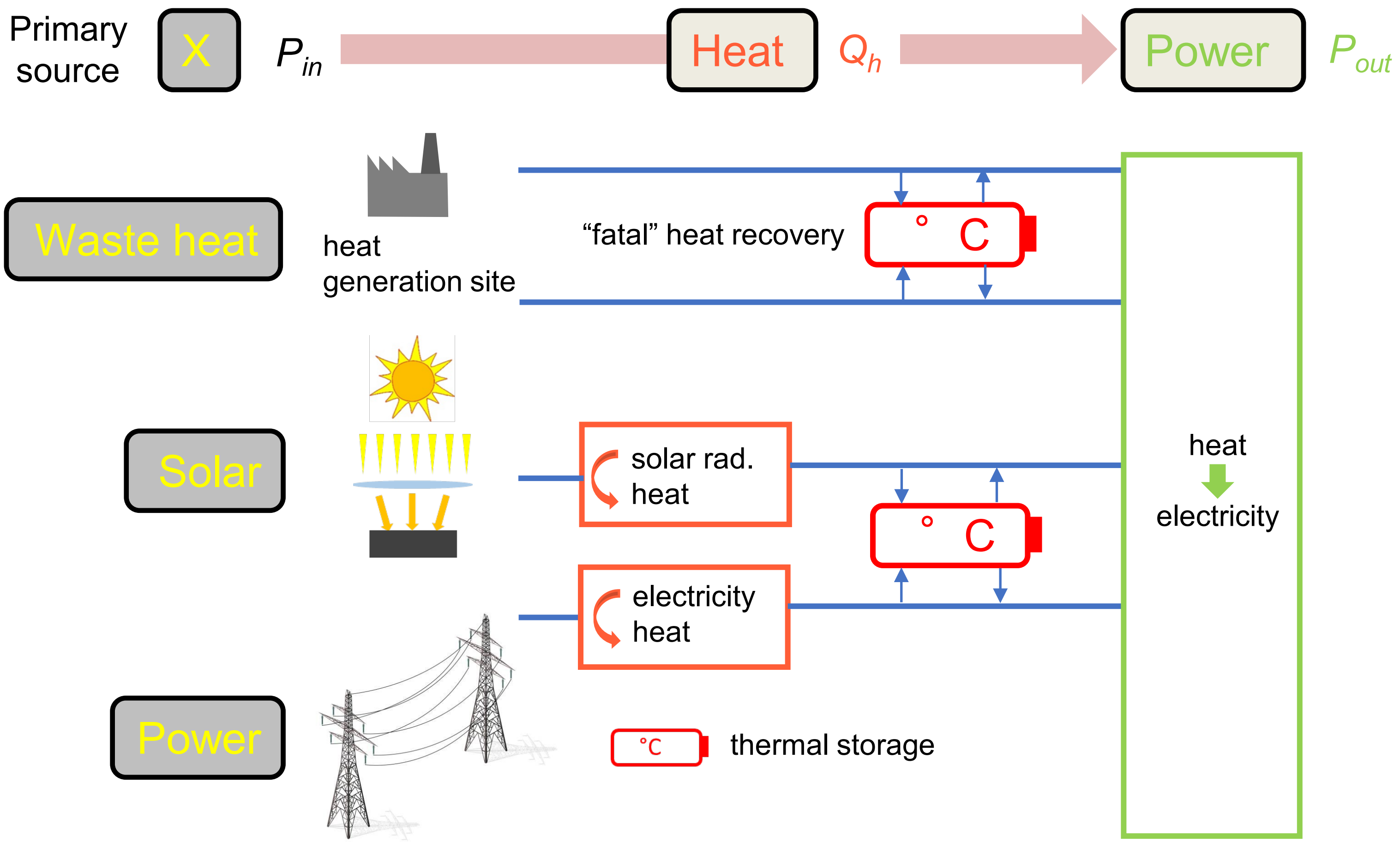
$\varepsilon_{eff,OOB} \rightarrow 0$

EITHER the emitter OR the cell must be **perfect reflectors**



Applications

X-to-Heat-to-Power conversion



Heat coming from various primary sources + Heat storage

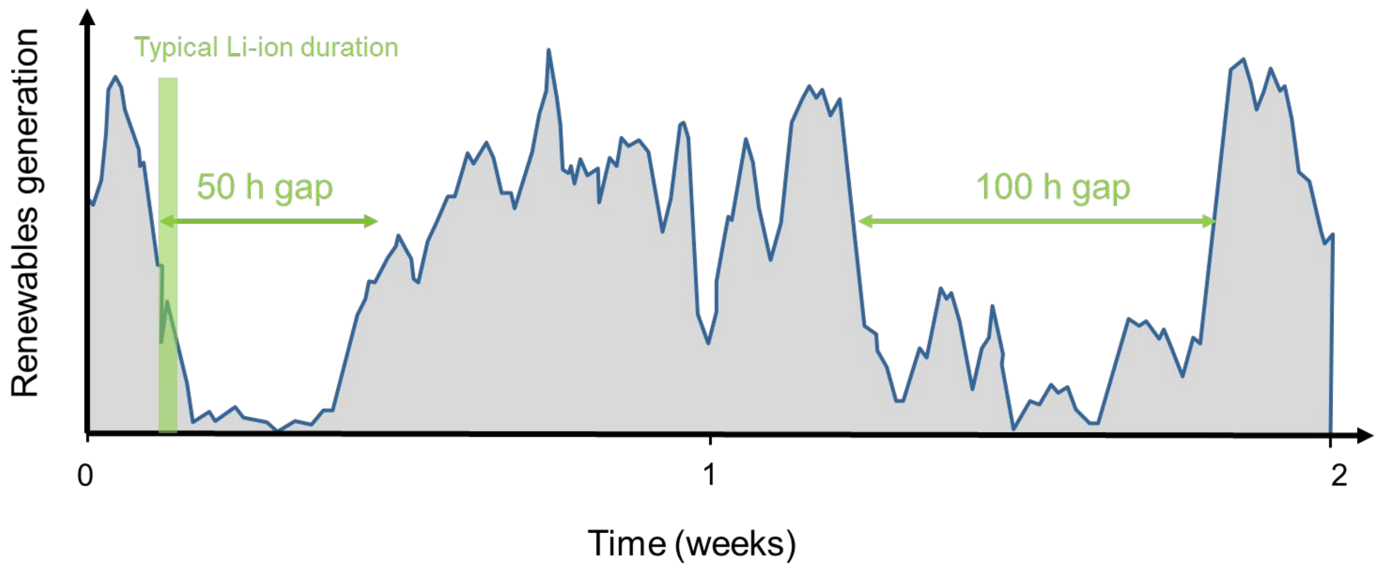
TPV batteries

Power-to-Heat-to-Power conversion

Fluctuating power generation from solar and wind

Solar

Wind



3000 TWh

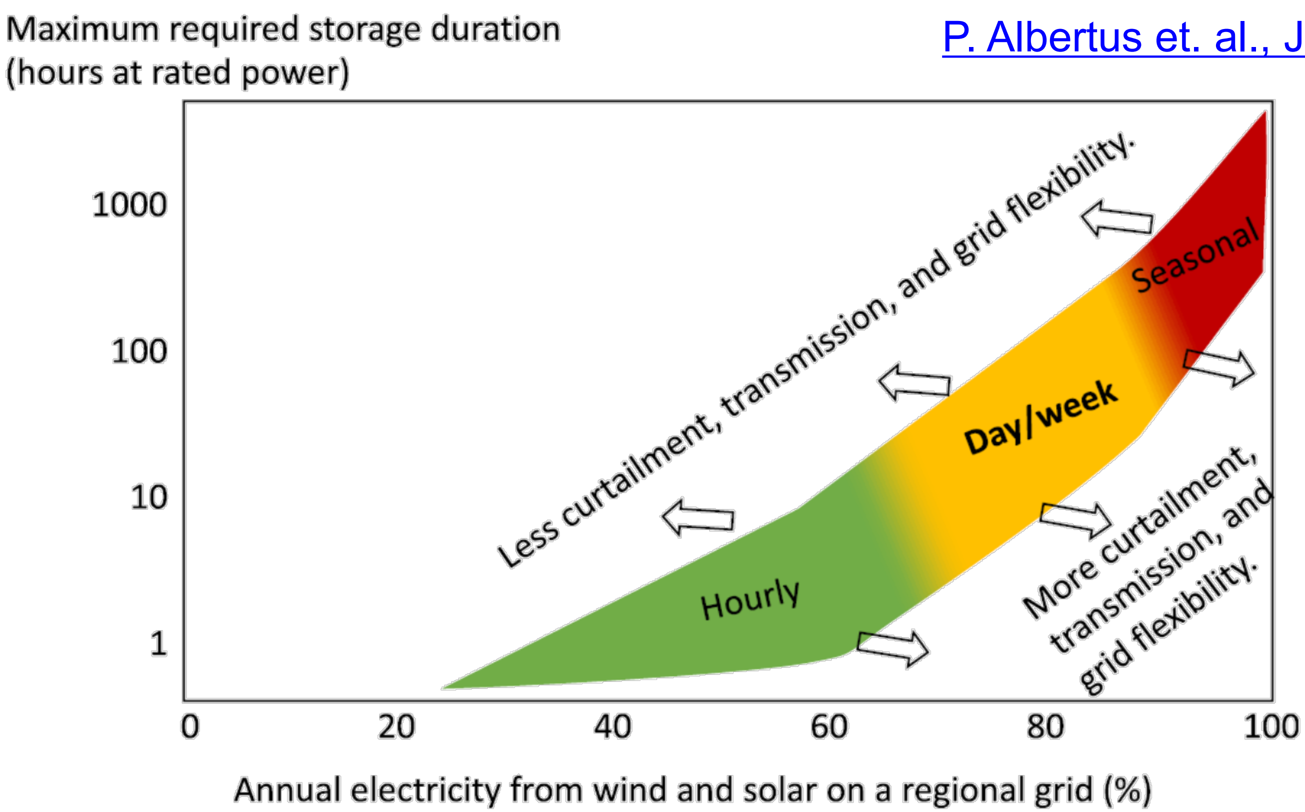
EU electricity consumption 2021

TPV batteries

Power-to-Heat-to-Power conversion

Need of long duration energy storage

P. Albertus et. al., Joule, 2020



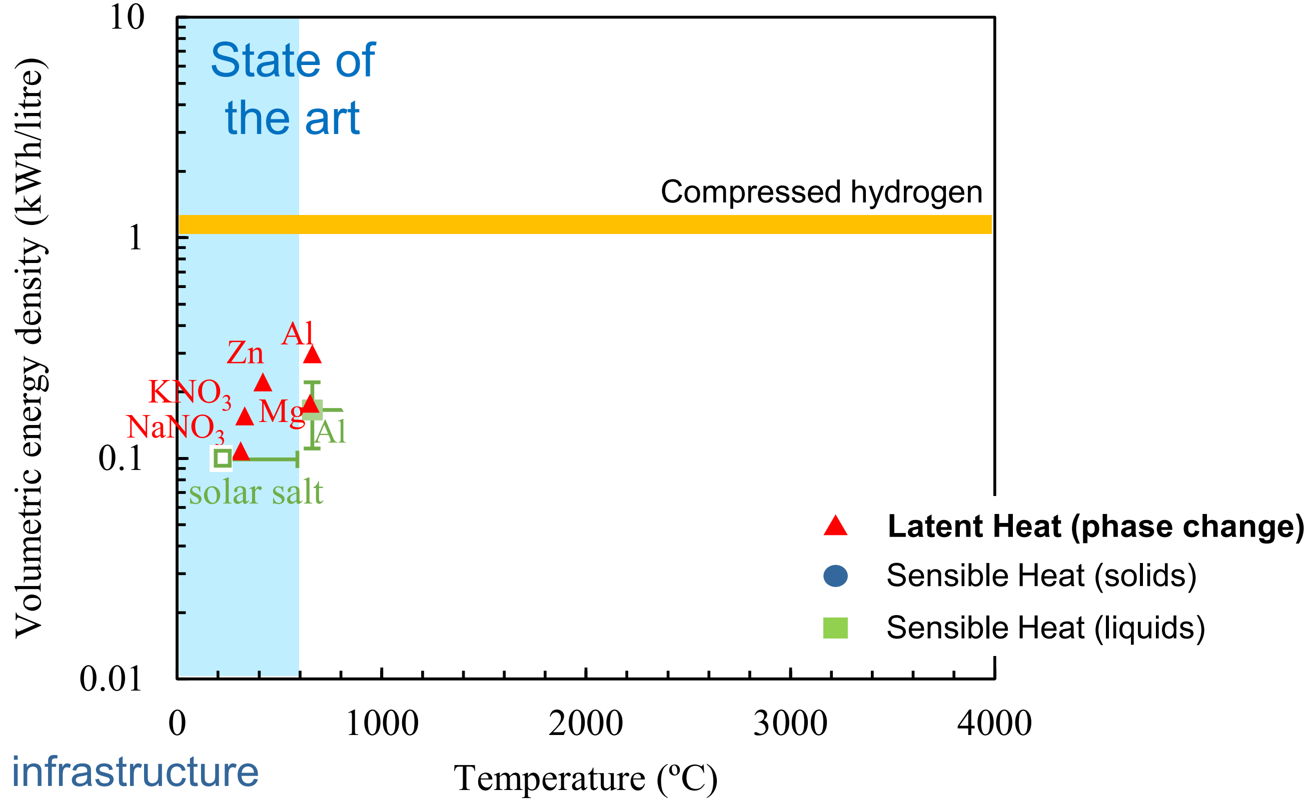
Power-to-Heat-to-Power conversion

Searching for a cheap and dense energy storage

Mechanical (compr. air, gravity, …)

- Low energy density (< 0,01 kWh/litre)

Thermal (sensible, latent,…)



Hydrogen

- Complex infrastructure
- Very high power cost

TPV batteries

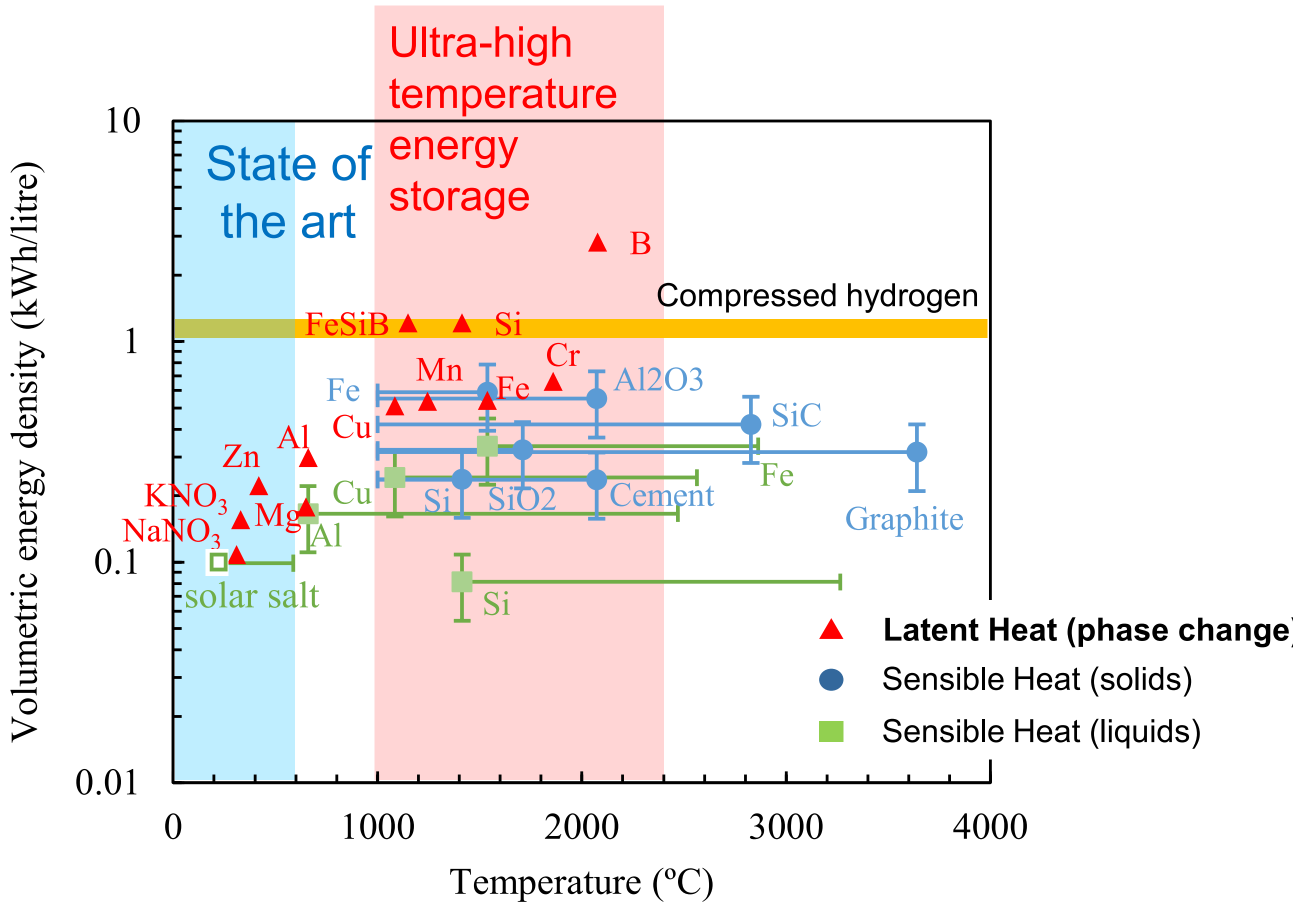
Power-to-Heat-to-Power conversion

Searching for a cheap and dense energy storage

Mechanical (compr.air, gravity, …)

Thermal (sensible, latent,…)

Hydrogen



Power-to-Heat-to-Power conversion

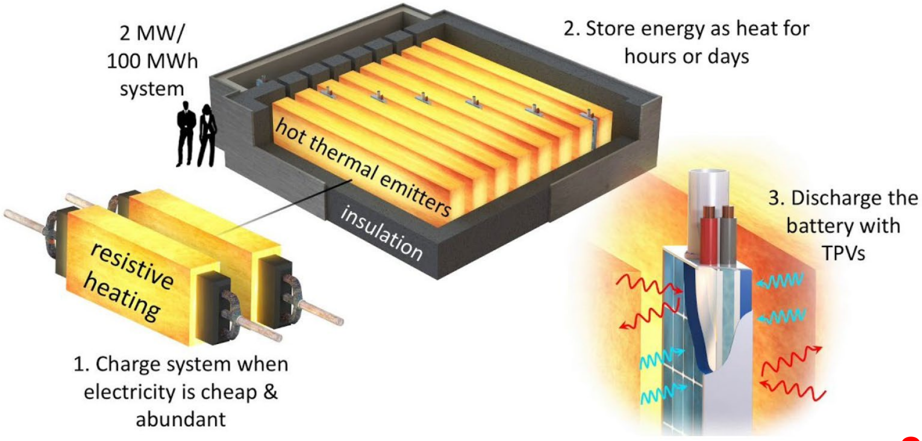
Academic projects and private companies (1)

ANTORA

Company

- **Sensible heat** (solid graphite at 1800 ºC)

cells developed by NREL



150 M$ recent fundraising

2 MW (/year) TPV cell manufacturing facility

TPV batteries

Power-to-Heat-to-Power conversion

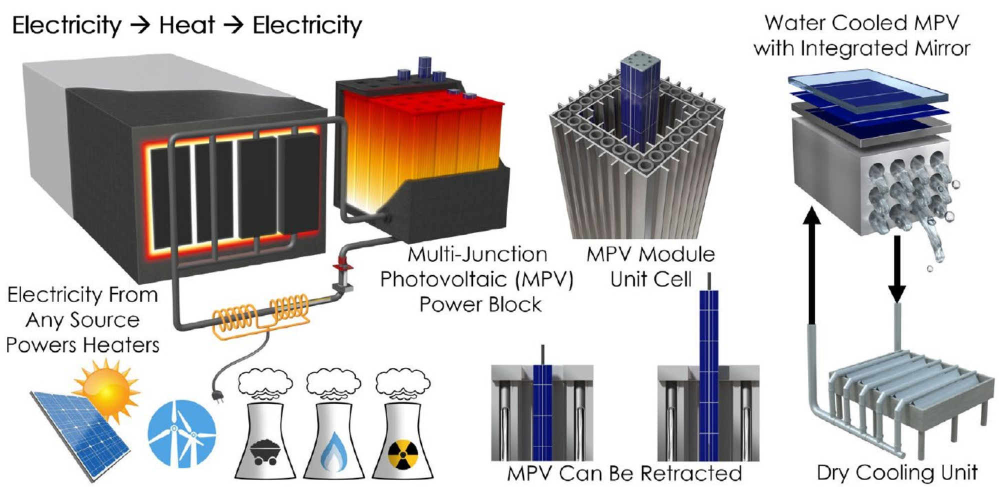
Academic projects and private companies (2)

FOURTH POWER

Company

Massachusetts Institute of Technology

Amy et al., Appl. Energy, 2022



Sensible heat
(liquid silicon at 2400 ºC)

cells by NREL Transforming ENERGY

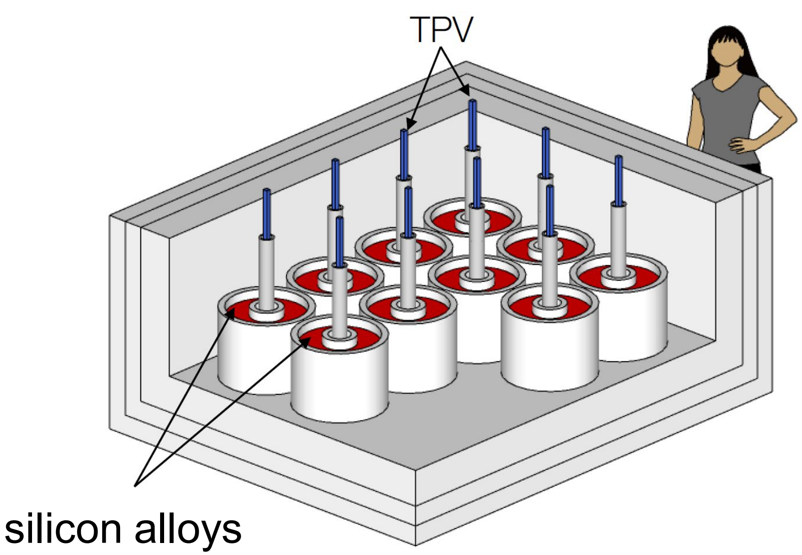
Power-to-Heat-to-Power conversion

Academic projects and private companies (3)

INSTITUTO DE ENERGÍA SOLAR

POLITÉCNICA

Datas et al., Joule, 2022



Latent heat

(silicon alloys at ~1400 ºC)

THERMOPHOTON

Spin-off

Very recent advances in thermophotovoltaics

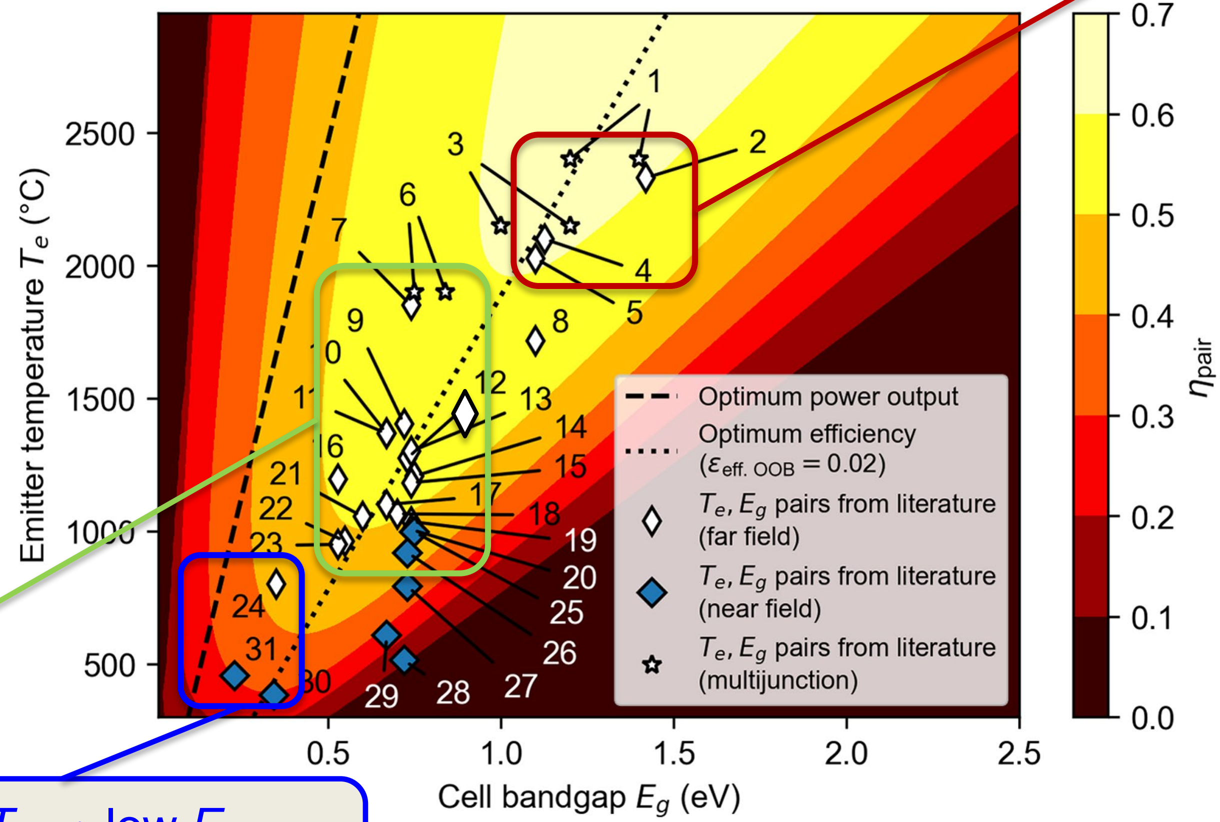
Semiconductor materials

Dependence on T_e and E_g

(datapoints from 32 experiments)

$\varepsilon_{\mathrm{eff,OOB}} = 0.02$

p_{out} η



High $T_e \rightarrow$ high E_g (solar cells)

Mainstream (InGaAs, GaSb)

Low $T_e \rightarrow$ low E_g (photodetectors)

Roux et al., JPE, 2024

Very recent advances

Record η_{pair}

Single junction cells

η_{pair}

< 1 W/cm^2

p_{out}

Wernsman et al., IEEE TED, **2004** **23.6%**

0.6 eV InGaAs TPV cell T_e = 1039 ˚C

Woolf et al., Optica, 2018 24.1%

0.6 eV InGaAs TPV cell T_e = 1055 ˚C

(E. Yablonovitch)

Omair et al., PNAS, 2019 29.1%

0.75 eV InGaAs TPV cell T_e = 1207 ˚C

Fan et al., Nature, 2020 32%

0.74 eV InGaAs TPV cell T_e ~ 1200 ˚C

Lenert et al., PNAS, 2022 32.5%

0.74 eV InGaAs-InP HJ TPV cell T_e ~ 1036 ˚C

Tervo et al., Joule, 2022 38.8%

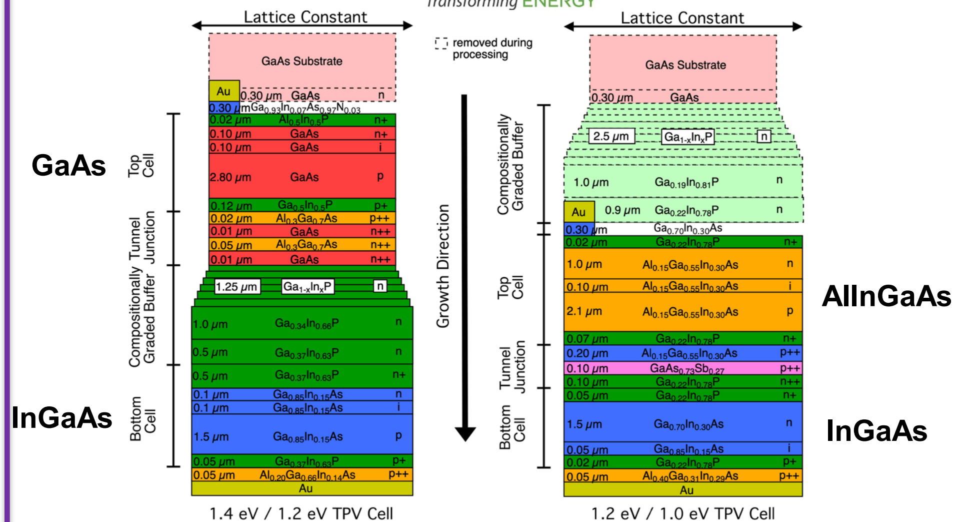
0.74 eV InGaAs TPV cell T_e ~ 1850 ˚C

Roy-Layinde et al., Joule, **2024** **43.8%**

0.90 eV InGaAs TPV cell T_e ~ 1435 ˚C

Tandem junction cells

NREL Transforming ENERGY (M. Steiner)



p_{out} ~ **2.39 W/cm^2** (T_e = 2400 ºC)

LaPotin et al., Nature, 2022

40%

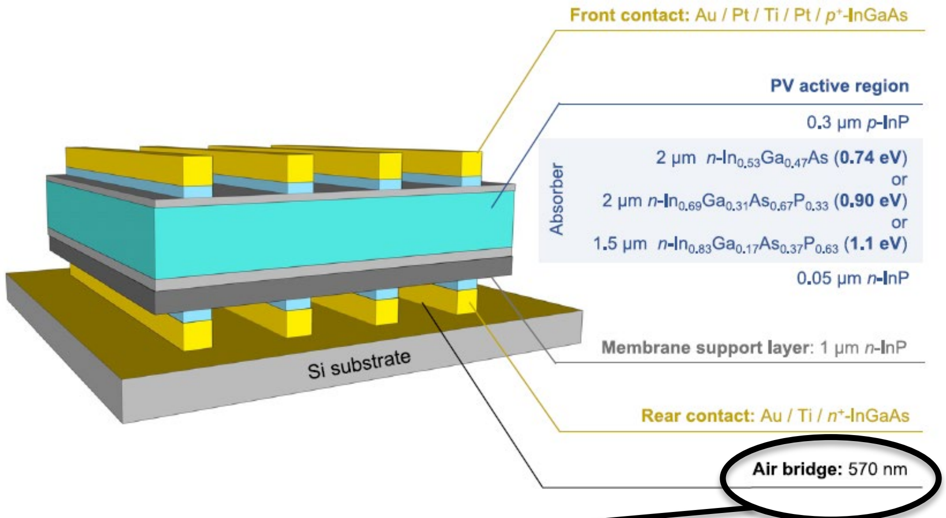
All from the

…Towards 50% pairwise efficiency

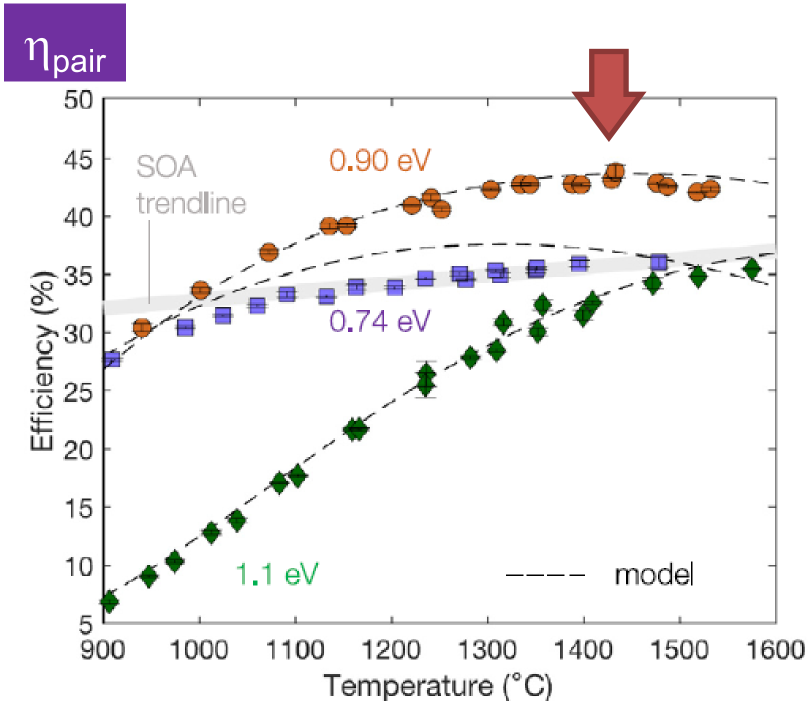
Record η_{pair}

Record efficiency
single junction TPV cell

Roy-Layinde et al., Joule, **2024**



$\varepsilon_{c,OOB}$ ~ 1.4 to 2.6% at T_e = 1500 ˚C



maximum p_{out} = **1.2 W/cm²** for which E_g?

Very impressive, **but** experiments with a view factor < 0.4%

The project-team TREE

Supported by cnrs ingénierie

The team

20 French laboratories

Activities and events

- **Research roadmap** → new projects: online collaborative work sessions (open)
- **Workshop TREE** 1 (2022) & 2 (2023)
- **TREE-SCHOOL** 2024

Topics, collaborating and networking

Research topics

1- Primary energy-to-heat conversion and heat storage

2- Heat transfer

3- Photovoltaics

4- Materials: fabrication & characterization

5- Advanced concepts

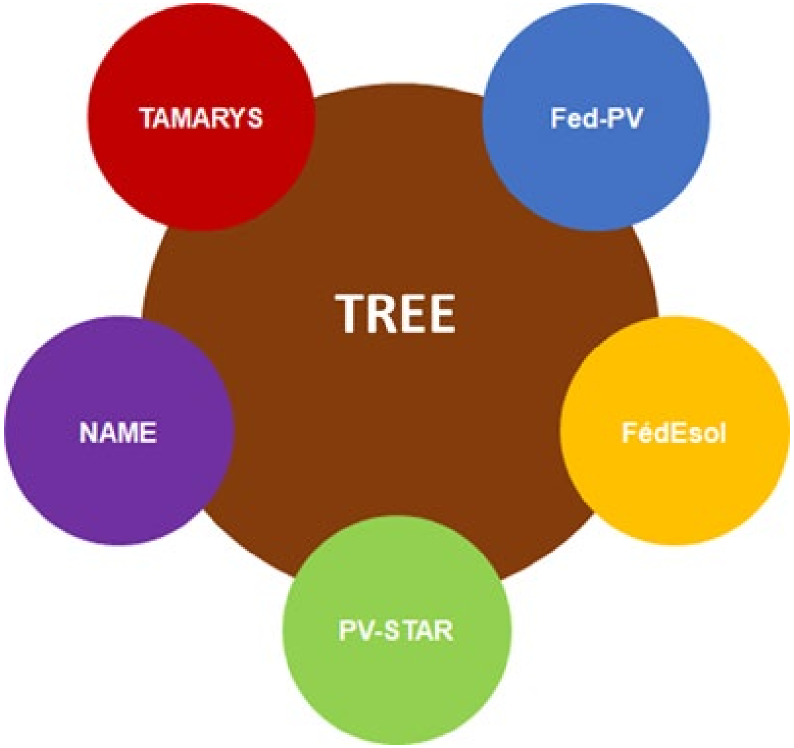
T1- Multi-scale/physics modelling

T2- Environmental aspects (LCA,…)

T3- Development of a TPV battery

T4- Collaborations with private and foreign institutions

Connexions with other organizations



Key messages

- Similarities and differences between TPV and solar PV conversions
- Solar/Power-to-Heat-to-Power conversion ("TPV batteries") is currently boosting R&D on TPV
- Possible thanks to ultra-high temperature energy storage
- At least three ongoing projects develop TPV batteries
- Record-breaking pairwise efficiencies evolve **very rapidly**
- Opportunities to extend existing Concentrated Solar + Thermal Energy Storage technologies to TPV batteries
- French project-team (thematic network [GDR] in 2025?) TREE

TREE-SCHOOL 2024

Thermal radiation to electrical energy conversion: from basic principles to advanced systems

October 13-18, 2024
Fréjus, France

Supported by cnrs ingénierie, physique et chimie

	morning	morning	afternoon	afternoon	evening
Sunday, Oct. 13					Introduction
Monday, Oct.14	1- Basics of thermal radiation	2- Basics of PV conversion	3-Introduction to TPV	4- TPV batteries	Poster session
Tuesday, Oct. 15	5- Heat sources and generation	6- Detailed balance for TPV	7- Heat storage	8- Environmental aspects	Panel discussion (TPV batteries)
Wednesday, Oct. 16	9- Properties at high temperature	10- Selective emitters			Panel discussion (heat sources)
Thursday, Oct. 17	11- Fabricating PV cells	12- Photonics in PV cells	13- Near-field TPV	14 – Characterization of TPV devices	Gala dinner
Friday, Oct. 18	15- Multi-scale/ physics modelling	16- Advanced concepts	Conclusion		

Thank you!

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