Batteries thermophotovoltaïques : principes et application à la décarbonation de l’industrie

Rodolphe Vaillon

LAAS-CNRS, Université de Toulouse, CNRS, Toulouse, France

GDR CNRS 2198 TREE

Note: the texts underlined in blue are internet links

June 2, 2026 version

Outline

1. Introduction to thermophotovoltaics

Photovoltaics → solar photovoltaics → thermophotovoltaics (**TPV**)
Definitions & notations → performance metrics

2. TPV conversion efficiencies > 40%

Optimizing radiative transfer → spectral selectivity
Implementation → current record efficiency → 50% and more

Remarkable fact

3. The thermophotovoltaic battery

Delivering decarbonized heat (>1200°C) and power to the industry
Key features: VRE share → LDES → HT-TES → low CPE → …
Leading start-ups and their achievements

Remarkable fact

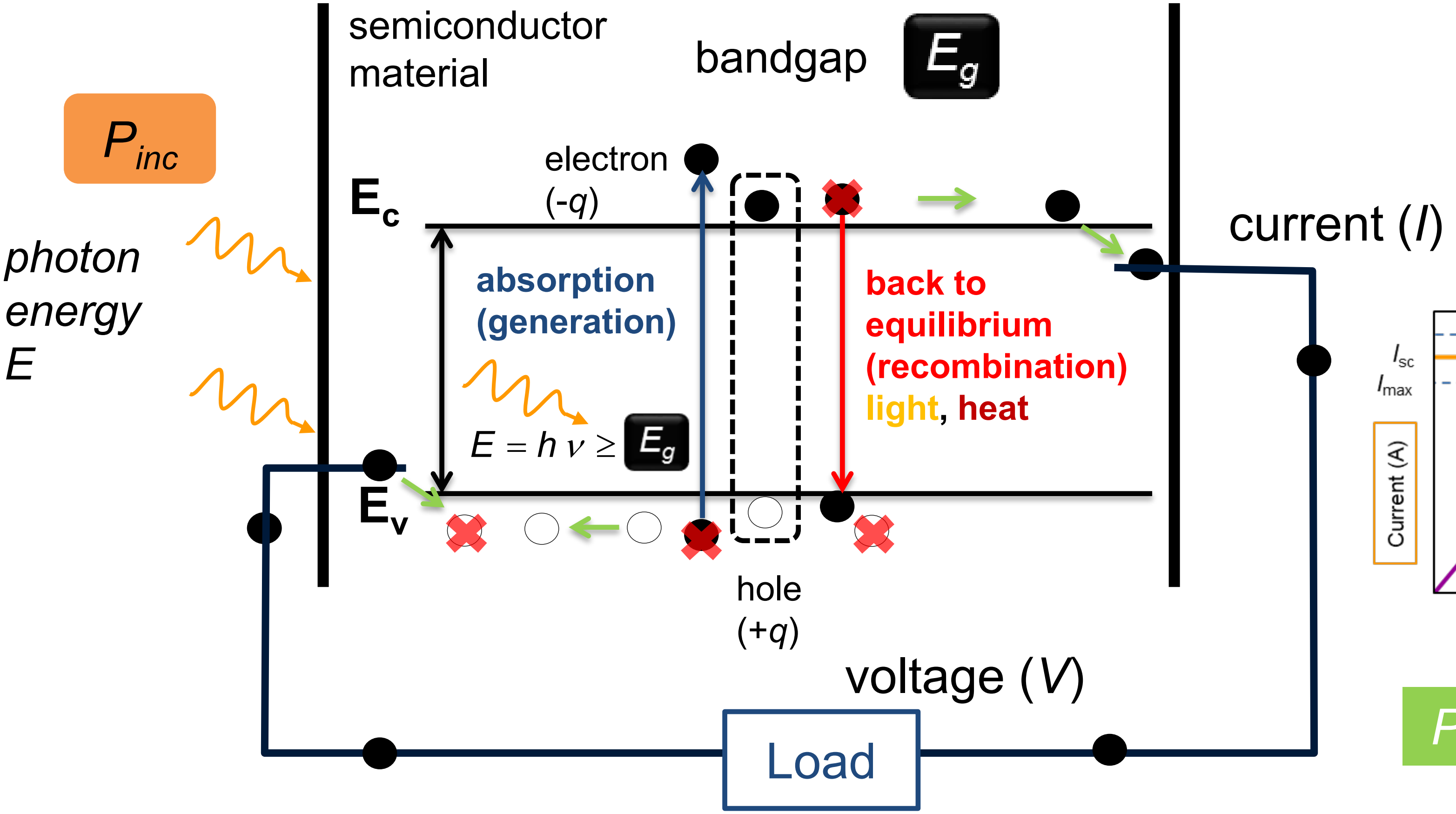
4. A French thermophotovoltaic battery?

Some thermal science challenges
The CNRS network TREE

5. Key messages

1. Introduction to thermophotovoltaics

Photovoltaics in a nutshell



semiconductor
material

bandgap E_g

P_{inc}

photon energy E

E_c

electron
(-*q*)

absorption
(generation)

$E = h\nu \geq E_g$

E_v

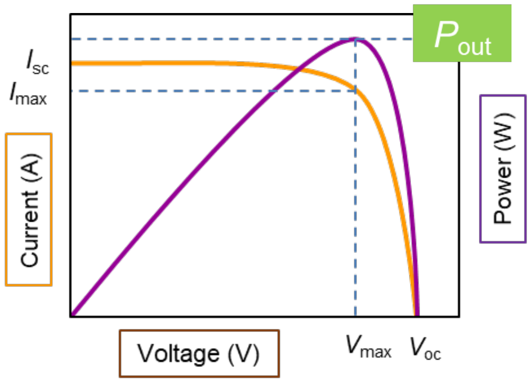
hole
(+*q*)

back to equilibrium (recombination)
light, heat

current (*I*)

voltage (*V*)

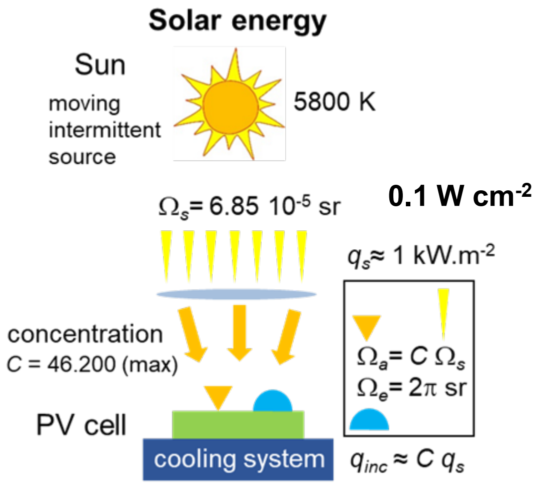
Load



$P_{out} = I_{max} V_{max}$

[generation → separation → collection] of charges → work in an external load

Solar photovoltaics → thermophotovoltaics



Solar energy

Sun

moving
intermittent
source

5800 K

Ω_s= 6.85 10^{-5} sr

0.1 W cm^{-2}

$q_s \approx$ 1 kW.m^{-2}

concentration
C = 46.200 (max)

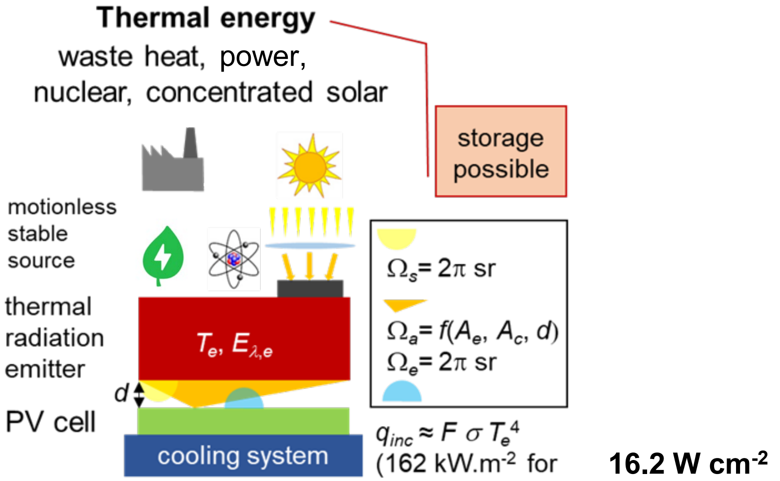
$\Omega_a = C\,\Omega_s$

$\Omega_e = 2\pi$ sr

PV cell

cooling system

$q_{inc} \approx C\, q_s$



Thermal energy

waste heat, power,
nuclear, concentrated solar

storage
possible

motionless
stable
source

thermal
radiation
emitter

T_e, $E_{\lambda,e}$

d

PV cell

cooling system

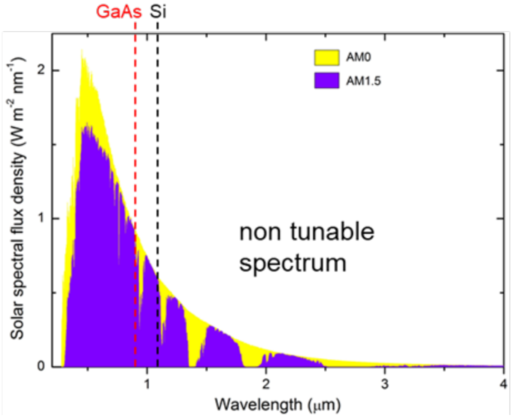
$\Omega_s = 2\pi$ sr

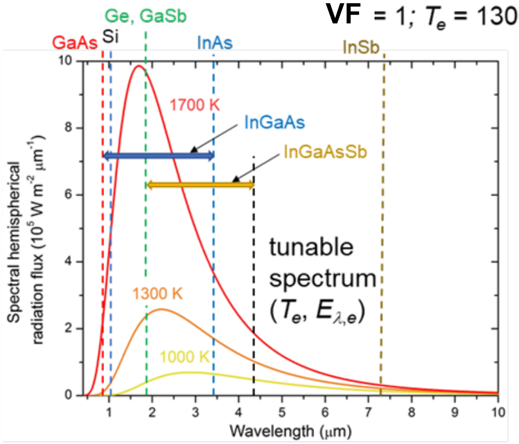
$\Omega_a = f(A_e, A_c, d)$

$\Omega_e = 2\pi$ sr

$q_{inc} \approx F\,\sigma\, T_e^4$
(162 kW.m^{-2} for **VF** = 1; T_e = 1300 K)

16.2 W cm^{-2}

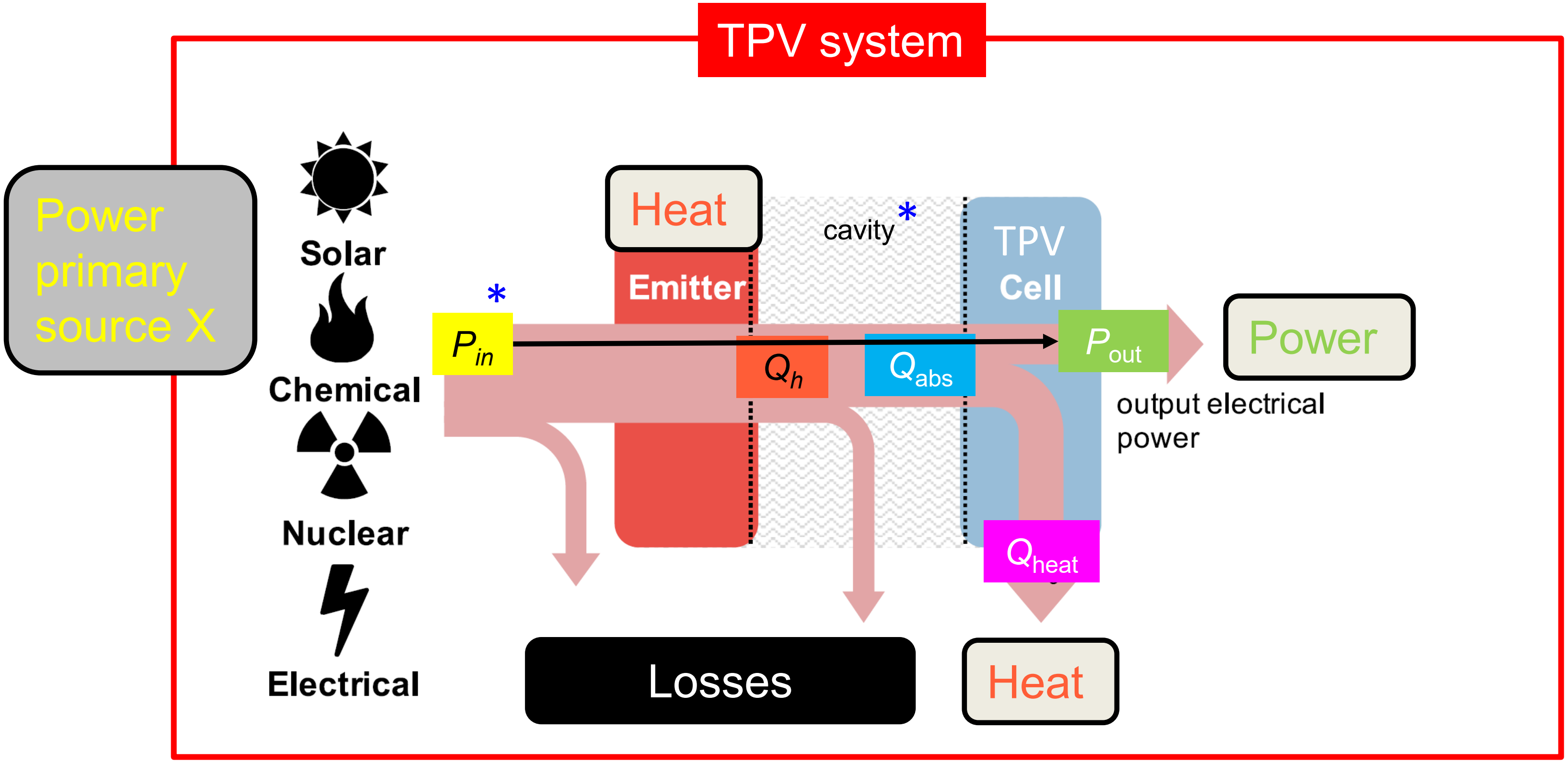




Datas & Vaillon, book chapter, 2020

TPV: PV conversion of (infrared) thermal radiation

Thermophotovoltaic conversion system



TPV system

Power primary source X

Solar

Chemical

Nuclear

Electrical

* P_{in}

Heat

Emitter

cavity *

TPV Cell

Q_h

Q_{abs}

P_{out}

Power

output electrical power

Q_{heat}

Losses

Heat

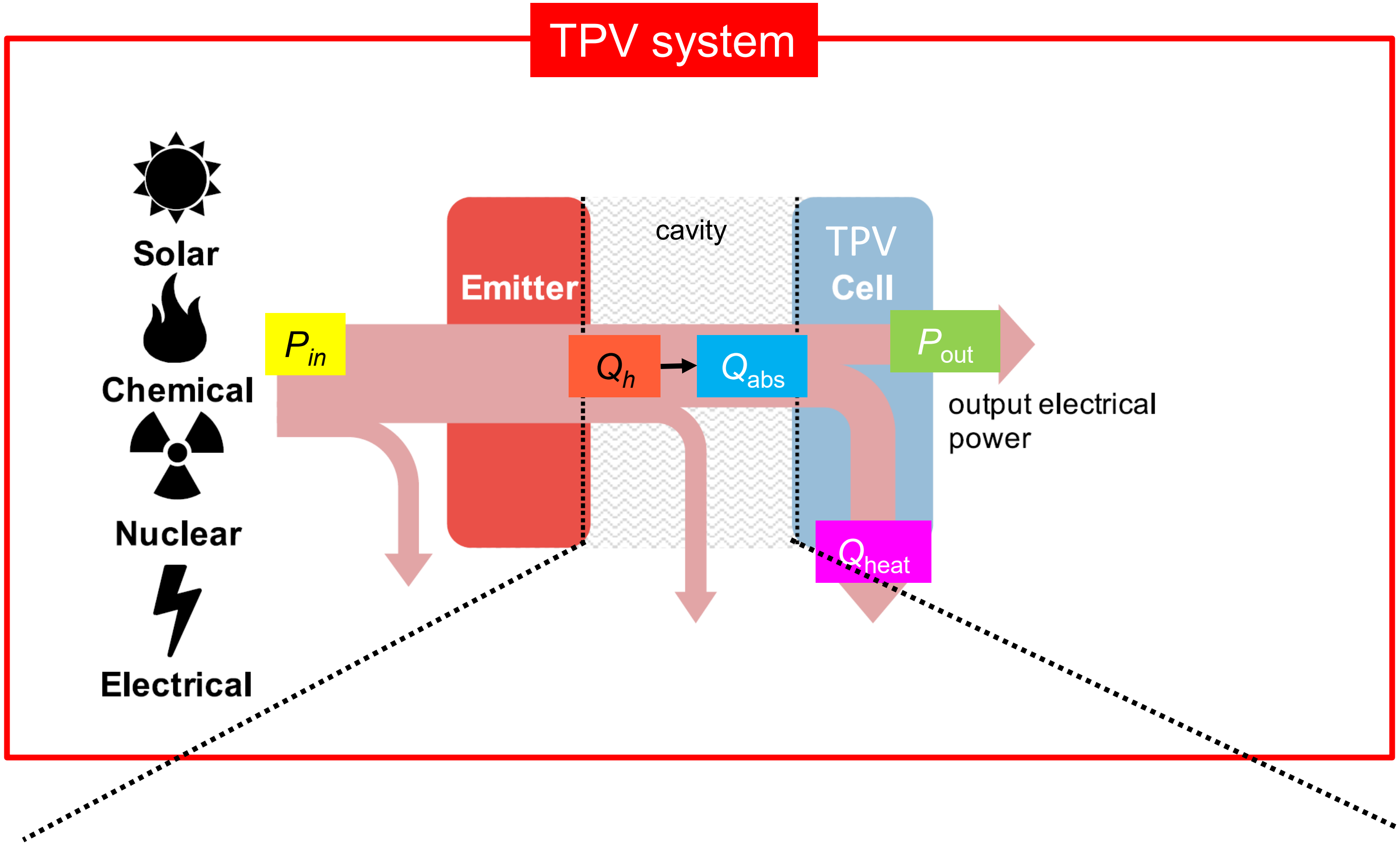
[Burger et al., Joule, 2020](#)

* Added to the original figure

P_{in} power in → P_{out} electrical power

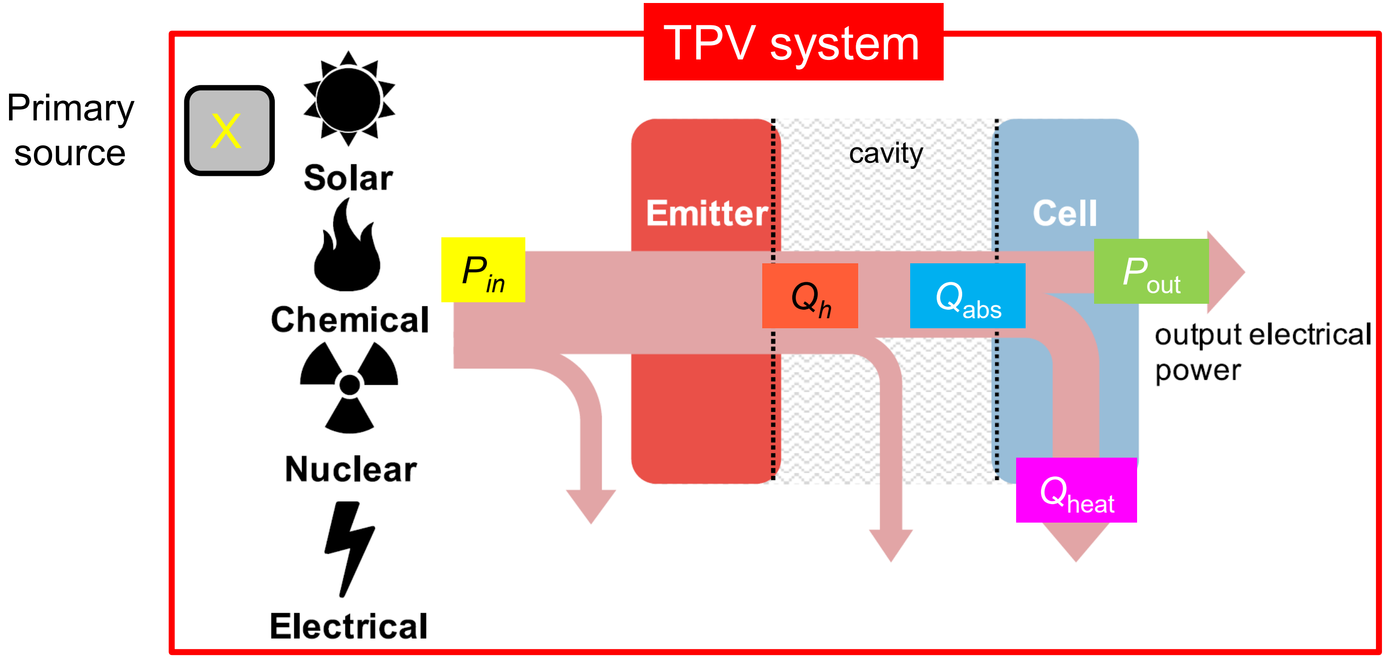
\+ Q_{heat} heat

Thermophotovoltaic conversion system



Q_h **net thermal power** out of the emitter → Q_{abs} **net thermal radiation** power absorbed by the cell

TPV system efficiency η_{system}



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

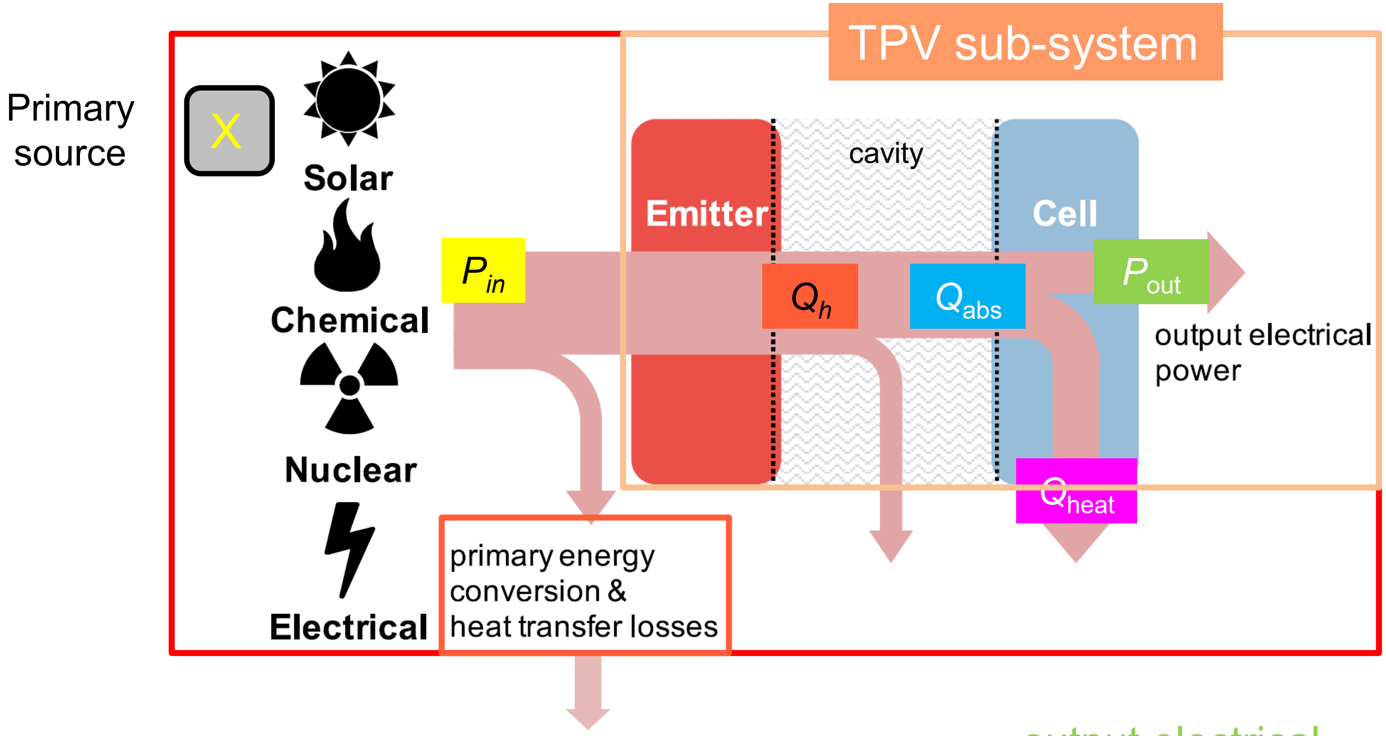
output electrical power

input power

~ solar PV conversion efficiency

TPV sub-system efficiency

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



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

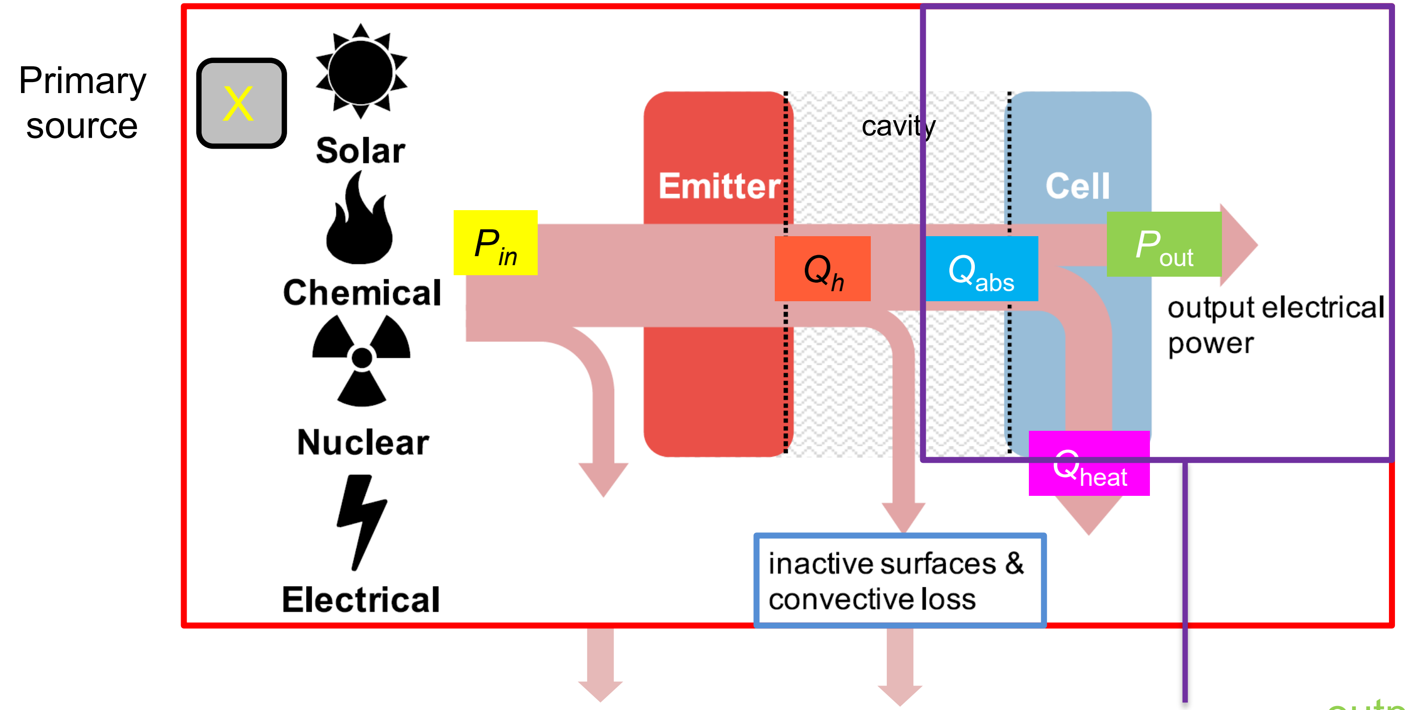
X-to-Heat conversion efficiency

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

output electrical power

net thermal power out of the emitter

Pairwise efficiency $\eta_{pairwise}$



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

X-to-Heat conversion efficiency

cavity efficiency

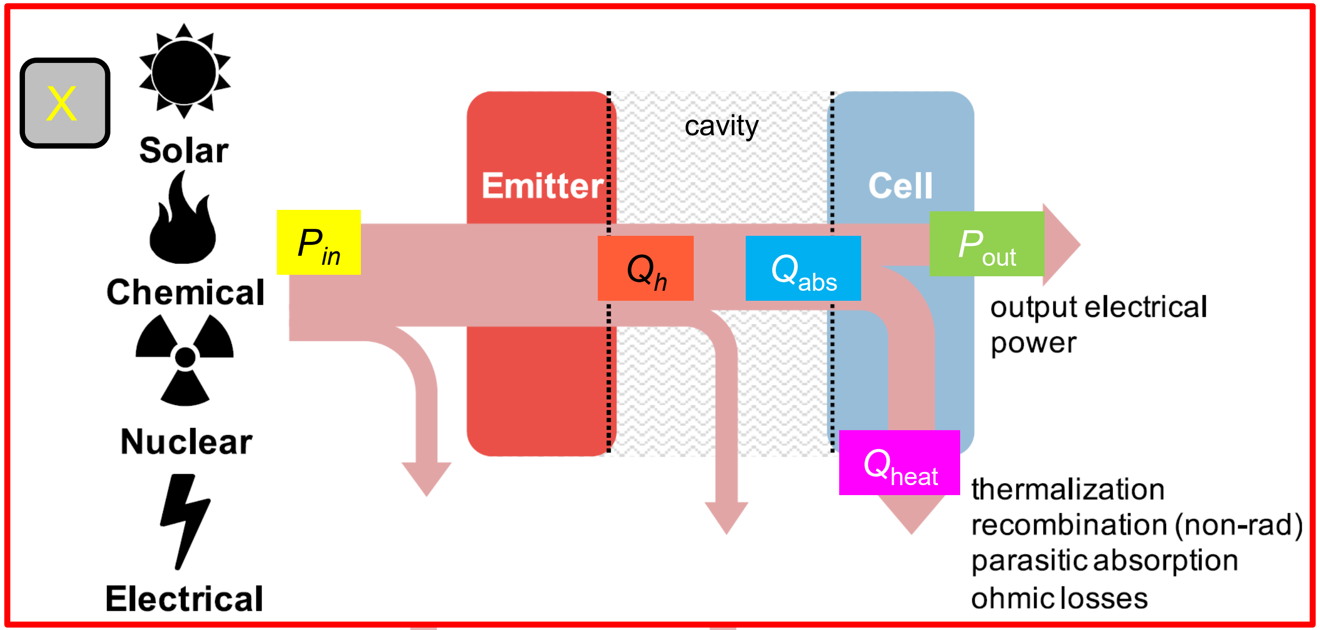
$\eta_{pairwise}$

output electrical power

net thermal radiation power
absorbed by the cell

Pairwise efficiency

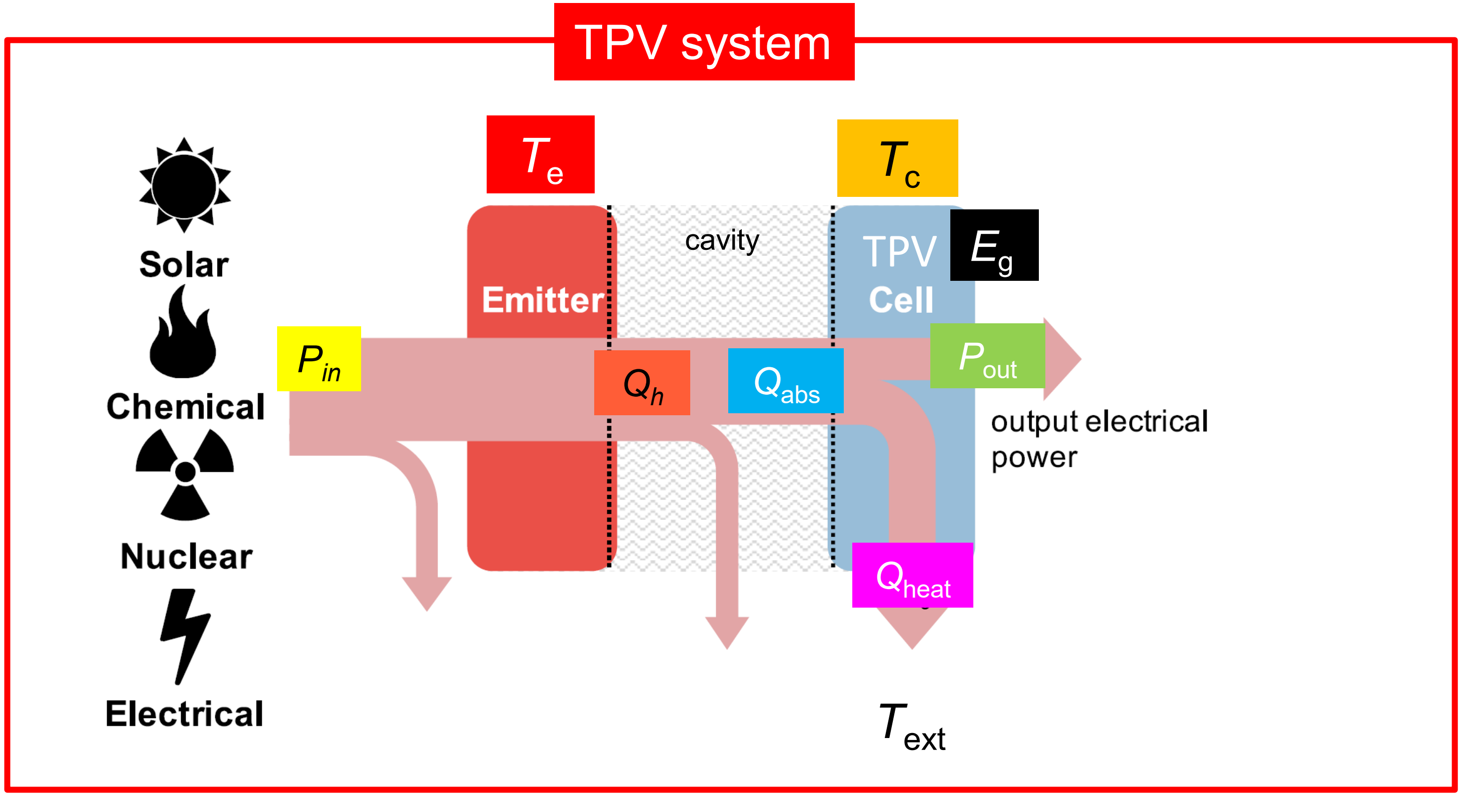
$\eta_{pairwise}$



$$\eta_{system} = \frac{P_{out}}{P_{in}} = \underbrace{\frac{Q_h}{P_{in}}}_{\text{X-to-Heat conversion efficiency}} \times \underbrace{\frac{Q_{abs}}{Q_h}}_{\text{cavity efficiency}} \times \underbrace{\frac{P_{out}}{P_{out} + Q_{heat}}}_{\eta_{pairwise}}$$

convenient for measurements

Definitions and notations



T_e emitter temperature

T_c cell temperature

Q_{heat} dissipated to an external medium at T_{ext} < T_c

E_g cell bandgap (single stage)

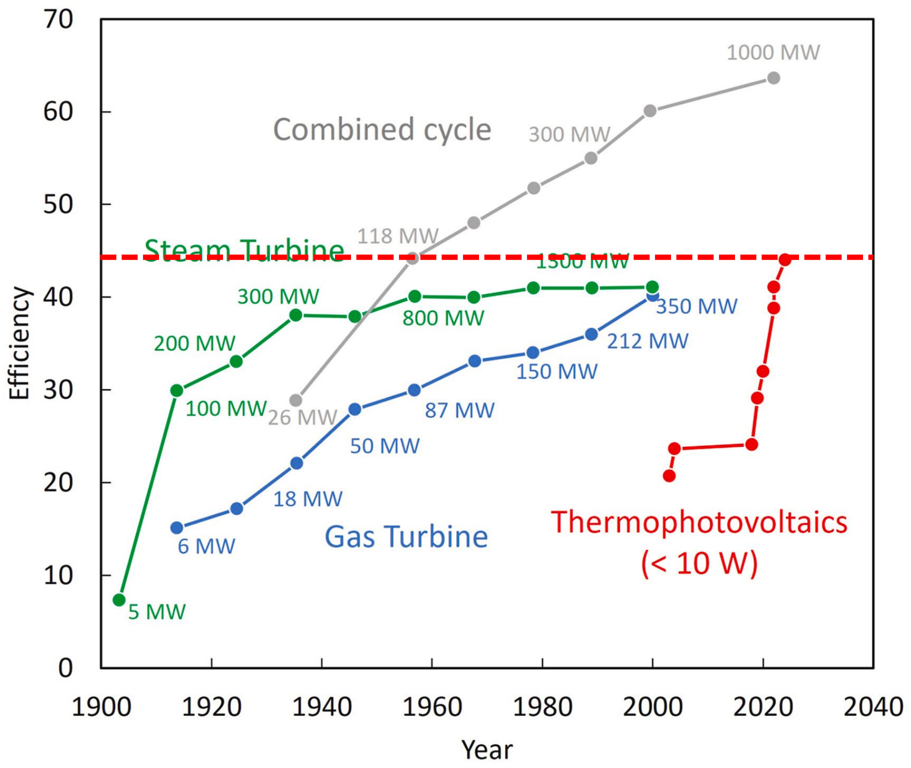
2. TPV conversion efficiencies > 40%

A remarkable fact

Embracing thermophotovoltaic electricity: Pathways to market adoption

Alejandro Datas [a,*], Paolo Bondavalli [b], Antonio Marco Pantaleo [b,c]

[Solar Energy Materials and Solar Cells, 2025]



"TPV has emerged as the most efficient solid-state heat engine, (…) at radiant emitter temperatures spanning from 1000 to 2400◦C".

How is that possible?

↓

Spectral selectivity

Out-of-band and in-band spectral regions

Out-of-band

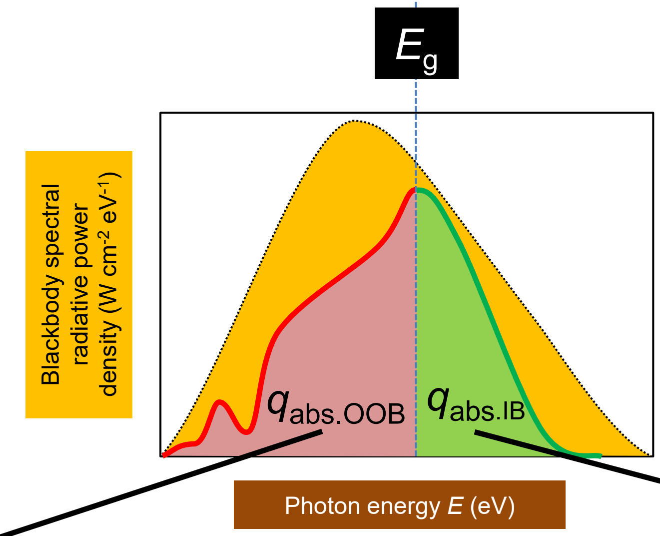
$E < E_g$

Photons are useless to PV conversion

In-band

$E > E_g$

Photons may participate to PV conversion



To be minimized

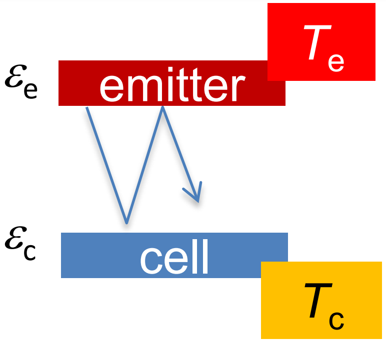
To be maximized*

This is the so-called spectral selectivity

*Optimized (heating issues)

Conditions for achieving spectral selectivity

1D planar configuration



$b(E,T)$ = spectral photon flux density of a blackbody at temperature T

E = photon energy

$T_c << T_e$

Net radiative heat power density absorbed by the cell

$$q_{abs} = \int_0^\infty \frac{E\left(b(E,T_e) - \cancel{b(E,T_c)}\right)}{\frac{1}{\varepsilon_e(E)} + \frac{1}{\varepsilon_c(E)} - 1}\, dE$$

$$= \int_0^\infty \boxed{Tr(E)}\; E\, b(E,T_e)\, dE$$

Burger et al., Joule, 2020

Transmission function

$$\boxed{Tr(E)} = \frac{\varepsilon_e(E)\,\varepsilon_c(E)}{1 - (1 - \varepsilon_e(E))\,(1 - \varepsilon_c(E))}$$

accounting for multi-reflection

Conditions for achieving spectral selectivity

Ideal emitter and cell radiative properties

To be maximized

$$\eta_{\text{pair}} = \frac{p_{\text{out}}}{q_{\text{abs}}} = \frac{\left[q\int_{E_g}^{\infty} Tr_{\text{IB}}(E)\, IQE\; b(E,T_e)\, dE\right]\; V_{oc}\, FF}{\int_0^{E_g} Tr_{\text{OOB}}(E)\, E\; b(E,T_e)\, dE + \int_{E_g}^{\infty} Tr_{\text{IB}}(E)\, E\; b(E,T_e)\, dE}$$

In-band

$$Tr(E) = \frac{\varepsilon_{\text{e}}(E)\,\varepsilon_{\text{c}}(E)}{1-(1-\varepsilon_{\text{e}}(E))\,(1-\varepsilon_{\text{c}}(E))}$$

$E > E_g$ $\quad Tr_{\text{IB}} \rightarrow 1$

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

This contributes to increasing p_{out} and η_{pair}

*Thermal issues not considered

Conditions for achieving spectral selectivity

Ideal emitter and cell radiative properties

$$\eta_{\mathrm{pair}} = \frac{p_{\mathrm{out}}}{q_{\mathrm{abs}}} = \frac{\left[q \int_{E_g}^{\infty} Tr_{\mathrm{IB}}(E)\, IQE\, b(E,T_e)\, dE\right] V_{oc}\, FF}{\int_0^{E_g} Tr_{\mathrm{OOB}}(E)\, E\, b(E,T_e)\, dE + \int_{E_g}^{\infty} Tr_{\mathrm{IB}}(E)\, E\, b(E,T_e)\, dE}$$

To be minimized

Out-of-band

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

$E < E_g$ $Tr_{\mathrm{OOB}} \rightarrow 0$

EITHER the emitter **OR** the cell must be **a perfect reflector**

This contributes to increasing η_{pair} (no impact on p_{out})

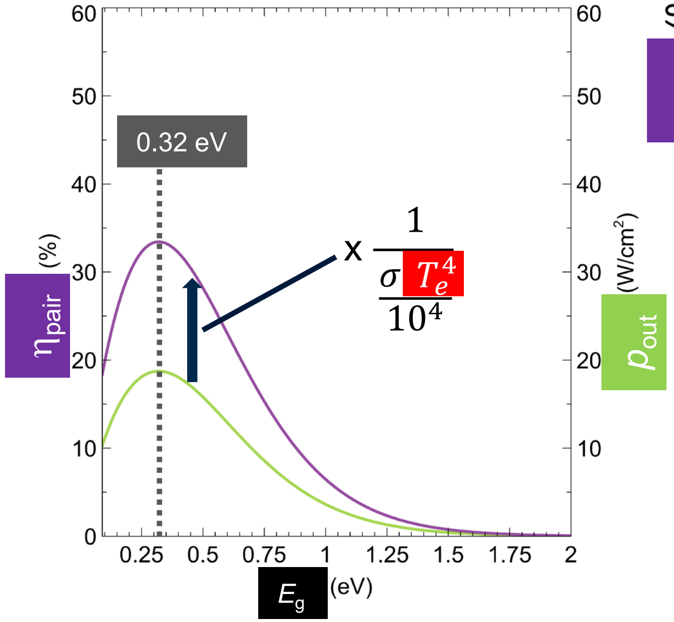
Spectral selectivity and optimum $E_{g,opt}$

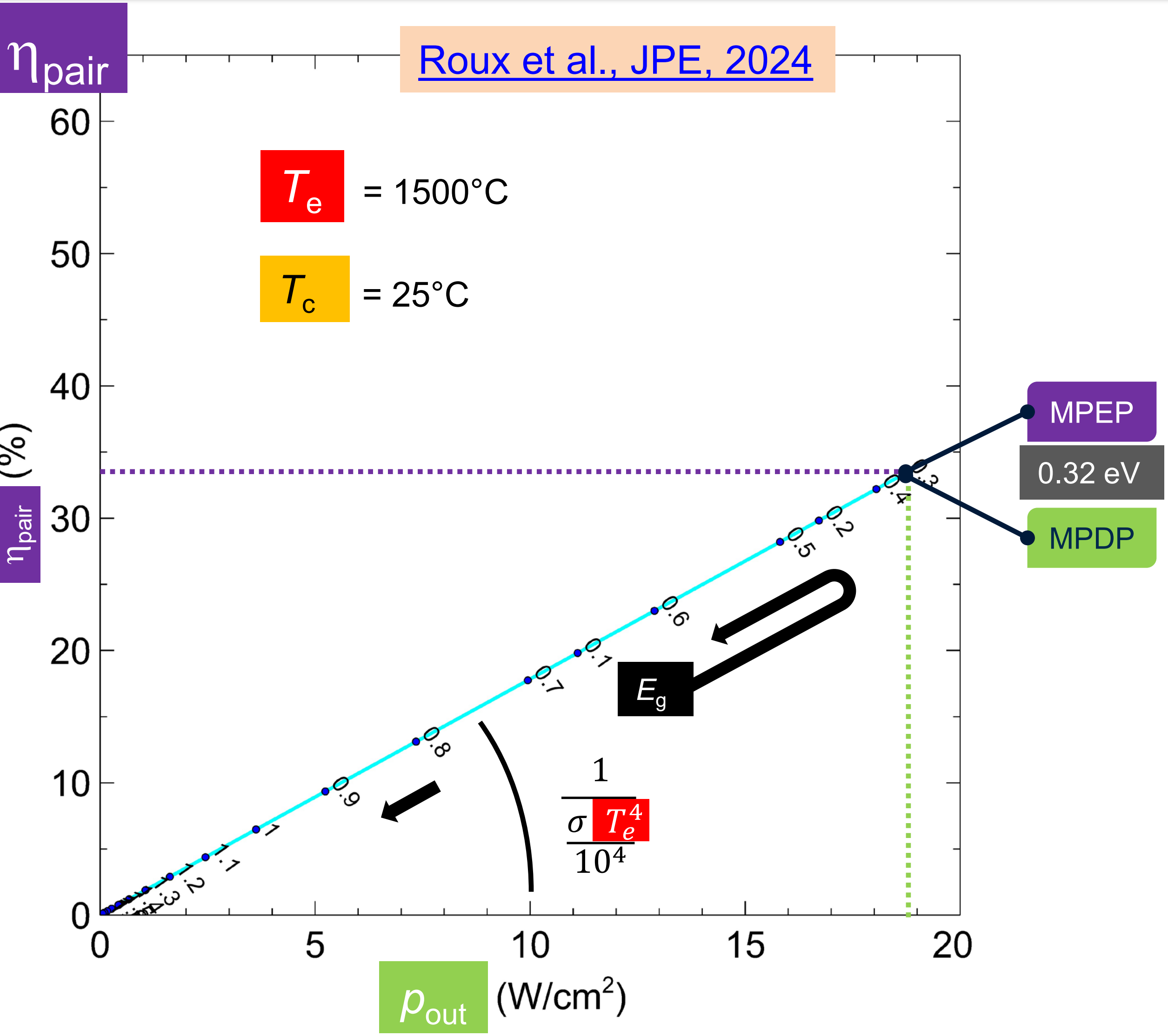
1D planar configuration

Theoretical (detailed balance) limit

Tr_{OOB} = 1

No spectral selectivity





Roux et al., JPE, 2024

T_e = 1500°C

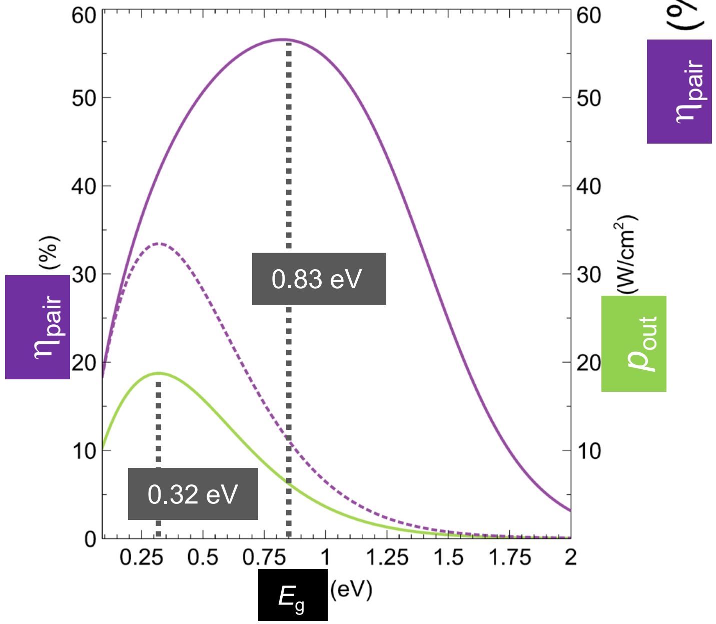
T_c = 25°C

Spectral selectivity and optimum $E_{g,opt}$

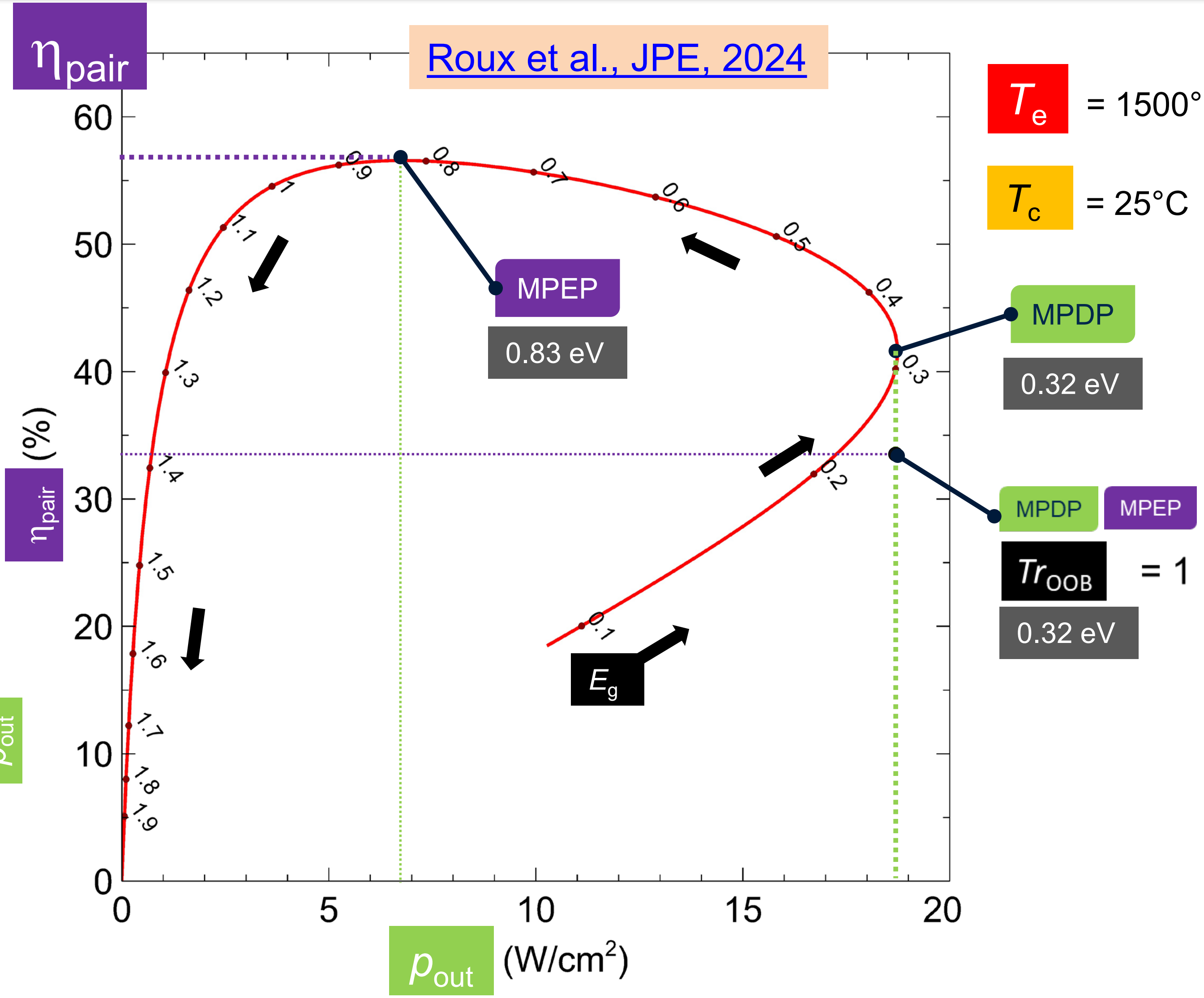
1D planar configuration

Tr_{OOB} = 0.02

Spectral selectivity



[Roux et al., JPE, 2024]()



T_e = 1500°C

T_c = 25°C

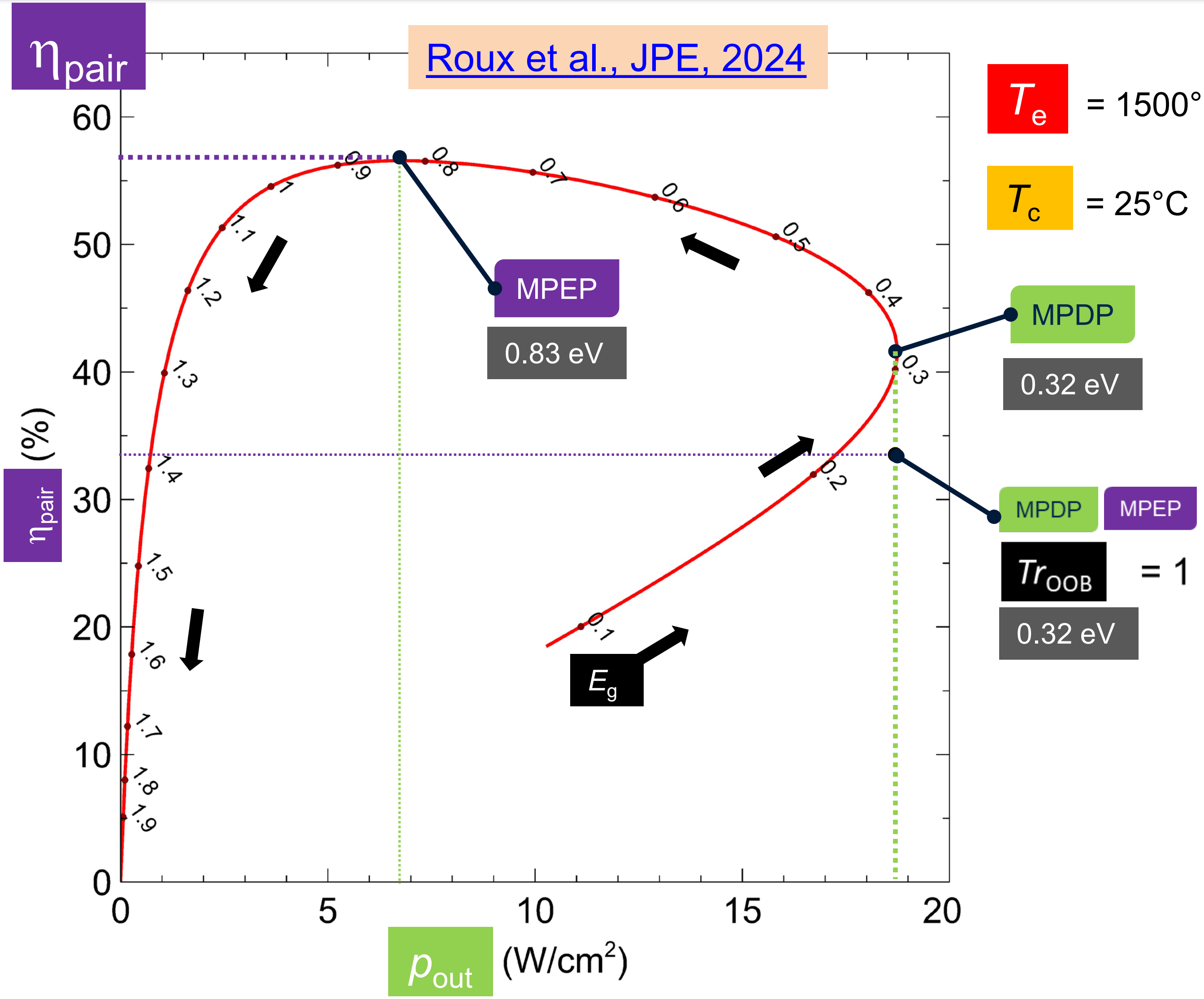
Spectral selectivity and optimum $E_{g,opt}$

1D planar configuration

Tr_{OOB} = 0.02

Spectral selectivity

Allows to enhance efficiency,
but, it is not possible to maximize both electrical power and efficiency



T_e = 1500°C

T_c = 25°C

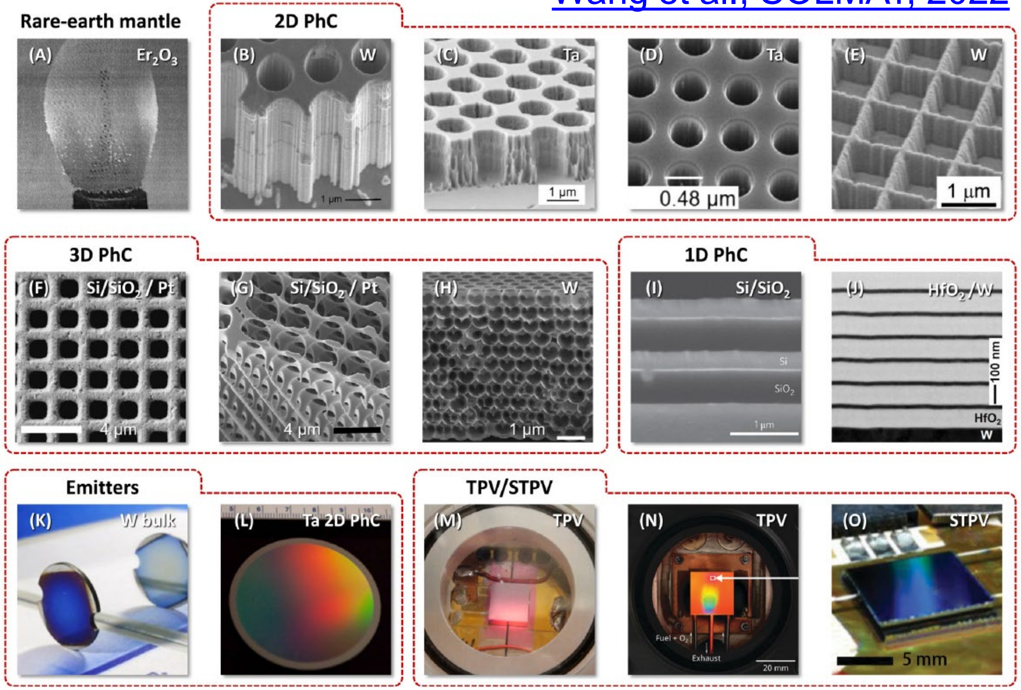
Achieving spectral selectivity: emitter pathway

emitter $\varepsilon_{e,IB}$ $\rightarrow 1$ $\varepsilon_{e,OOB}$ $\rightarrow 0$

cell $\varepsilon_{c,IB}$ $\rightarrow 1$ $\varepsilon_{c,OOB}$ arbitrary

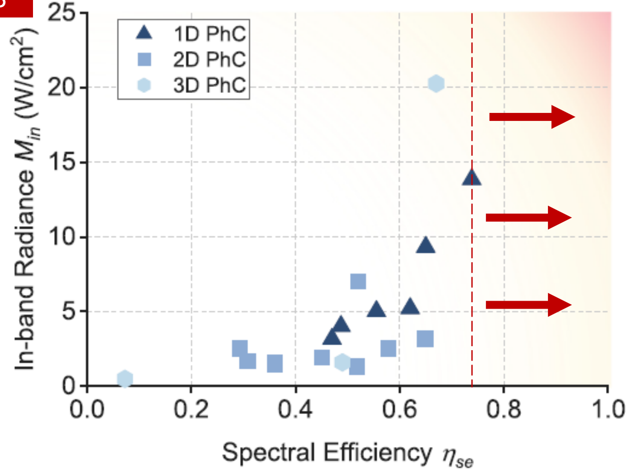
Review article

Wang et al., SOLMAT, 2022



$q_{em,IB}$

Wang et al., SOLMAT, 2022



$q_{em,IB}$ / $q_{em,tot}$

Best performances

$\varepsilon_{e,IB}$ ~ 0.9

$\varepsilon_{e,OOB}$ ~ 0.1

Room for improvements

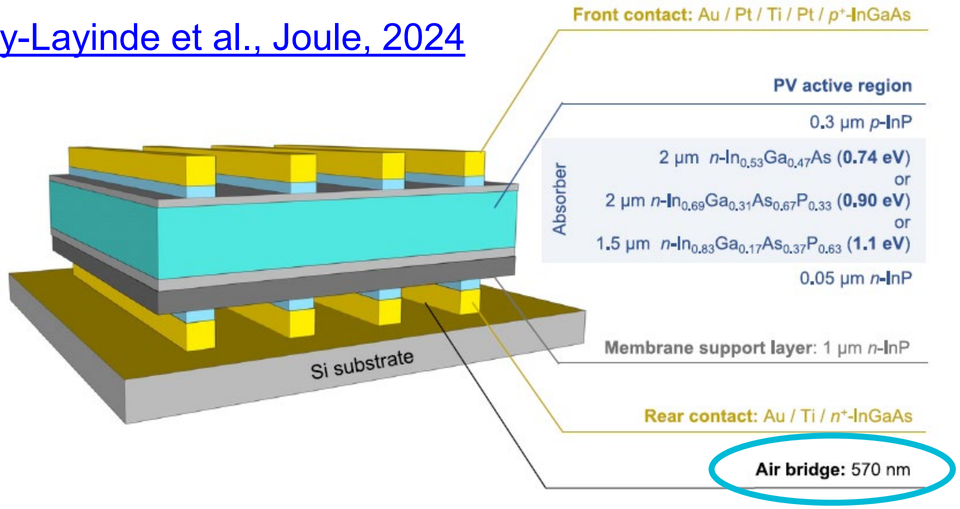
Achieving spectral selectivity: cell pathway

emitter $\varepsilon_{e,IB} \rightarrow 1$ $\varepsilon_{e,OOB}$ arbitrary

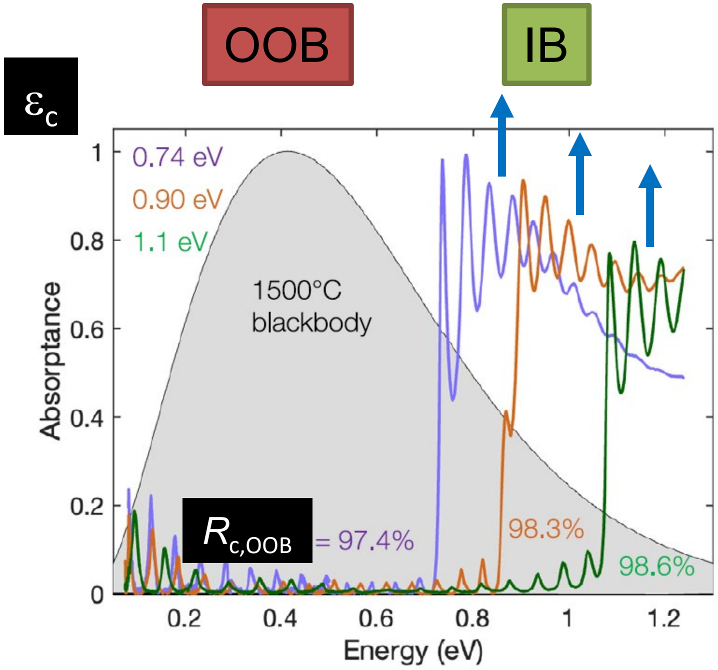
cell $\varepsilon_{c,IB} \rightarrow 1$ $\varepsilon_{c,OOB} \rightarrow 0$

Air-bridge TPV cells

Roy-Layinde et al., Joule, 2024



Back reflector: the cell layer stack above it **must be transparent** in the OOB region



Best performances

$\varepsilon_{c,OOB}$ ~ 0.014 to 0.026 at T_e = 1500 ˚C

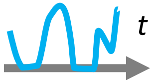
Record η_{pair} ~ 44% → 50%

3. The thermophotovoltaic battery

Basic principles

1

Intermittent low-cost Power



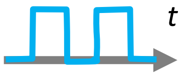
2

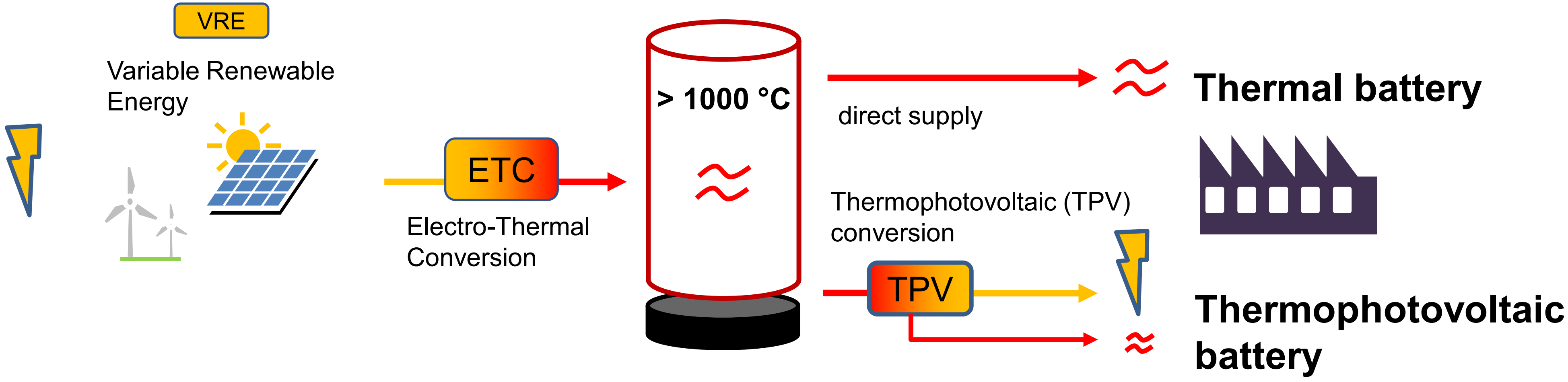
High-Temperature Thermal Energy Storage

HT-TES

3

On-demand decarbonized Heat and Power





VRE

Variable Renewable Energy

ETC

Electro-Thermal Conversion

> 1000 °C

direct supply

Thermophotovoltaic (TPV) conversion

TPV

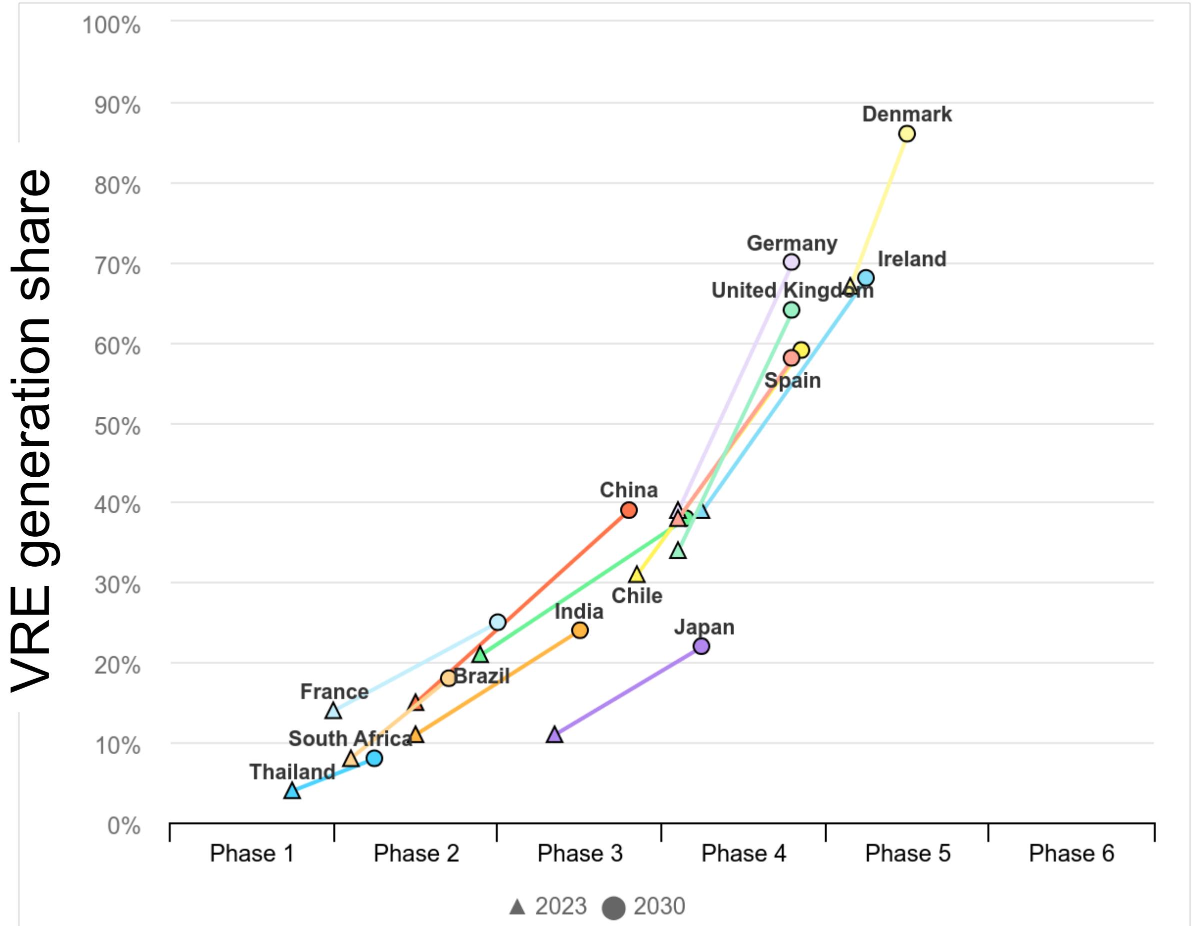
Thermal battery

Thermophotovoltaic battery

Variable Renewable Energy integration

VRE

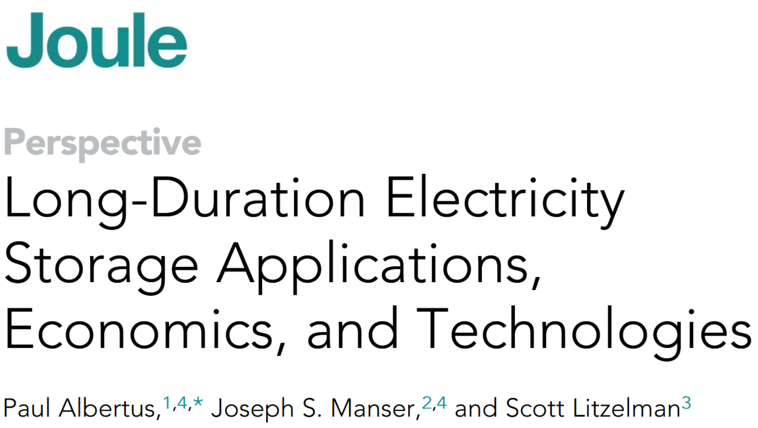
2023 – 2030 trajectory



https://www.iea.org/...

Increasing share of VRE (→ 2050)

Long-Duration Energy Storage



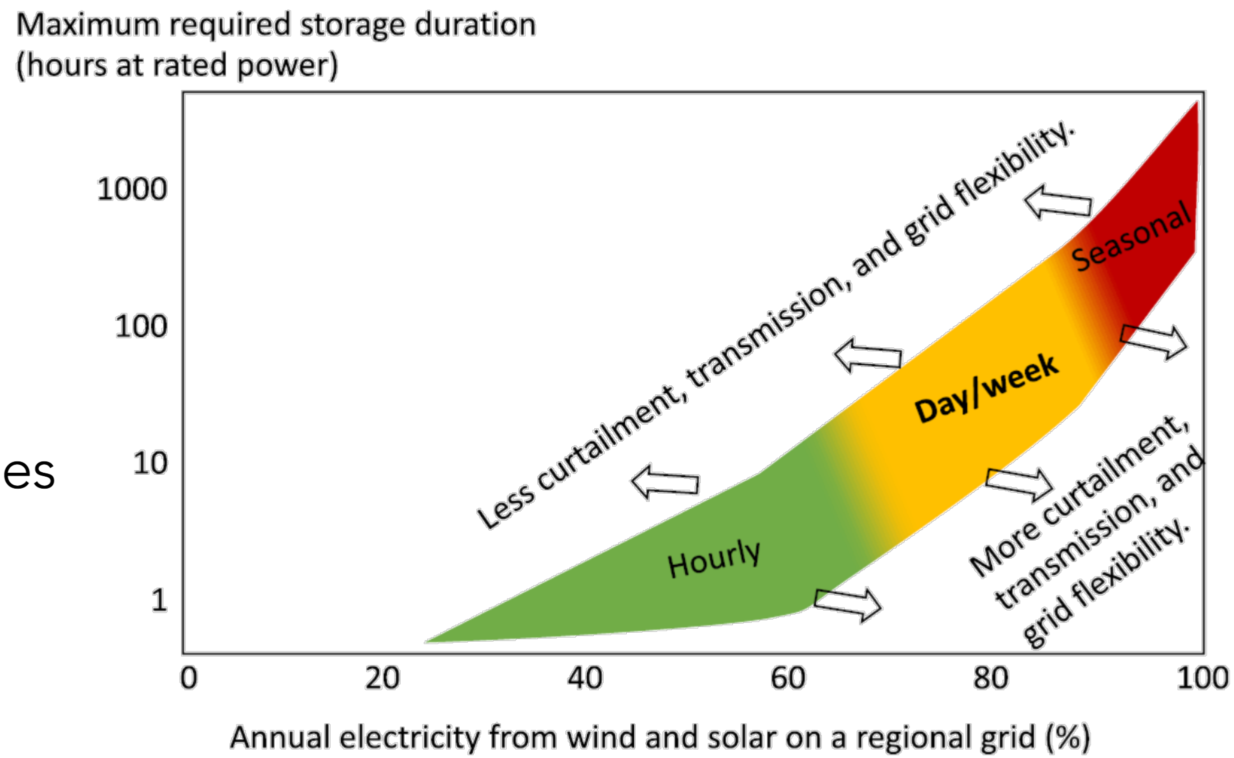
Joule

Perspective

Long-Duration Electricity Storage Applications, Economics, and Technologies

Paul Albertus,[1,4,*] Joseph S. Manser,[2,4] and Scott Litzelman[3]

[P. Albertus et. al., Joule, 2020]

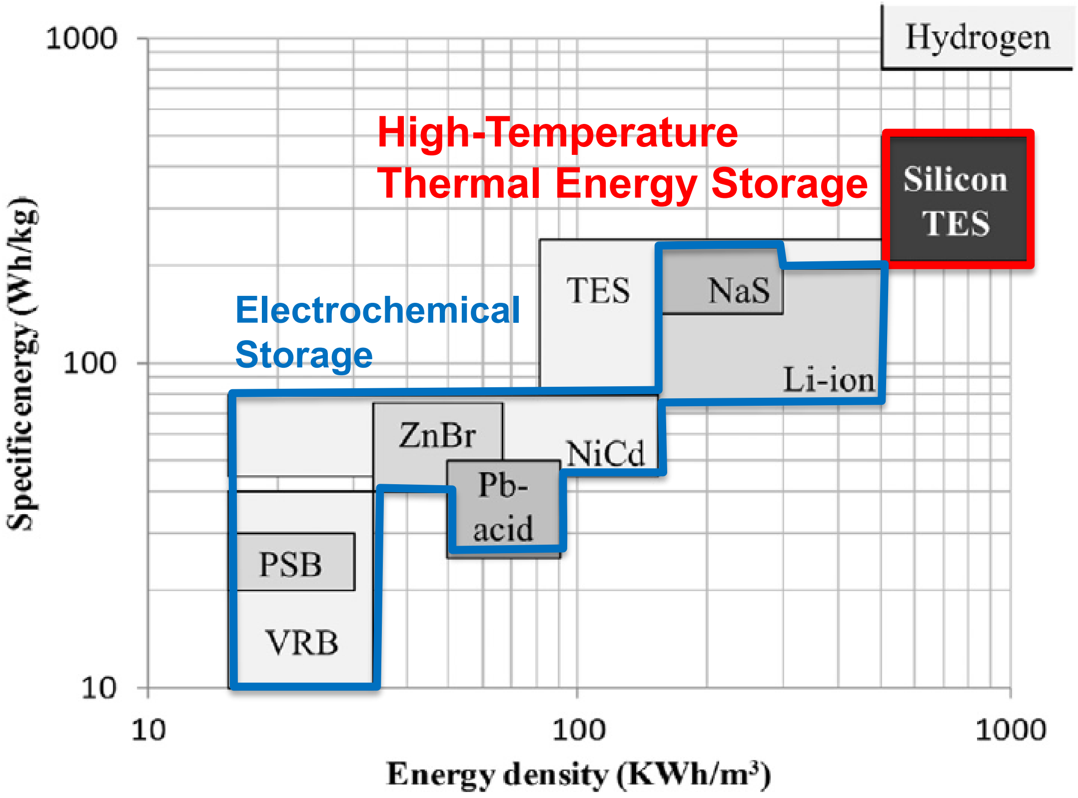


Increasing VRE share → need for Long-Duration* Energy Storage (LDES)

(* > 12 h)

Key features: energy / volume unit

HT-TES



Datas et al., Energy, 2016

High-temperature Thermal Energy Storage (TES) allows for **very-high energy densities**

Key features: low cost energy storage

HT-TES

Joule

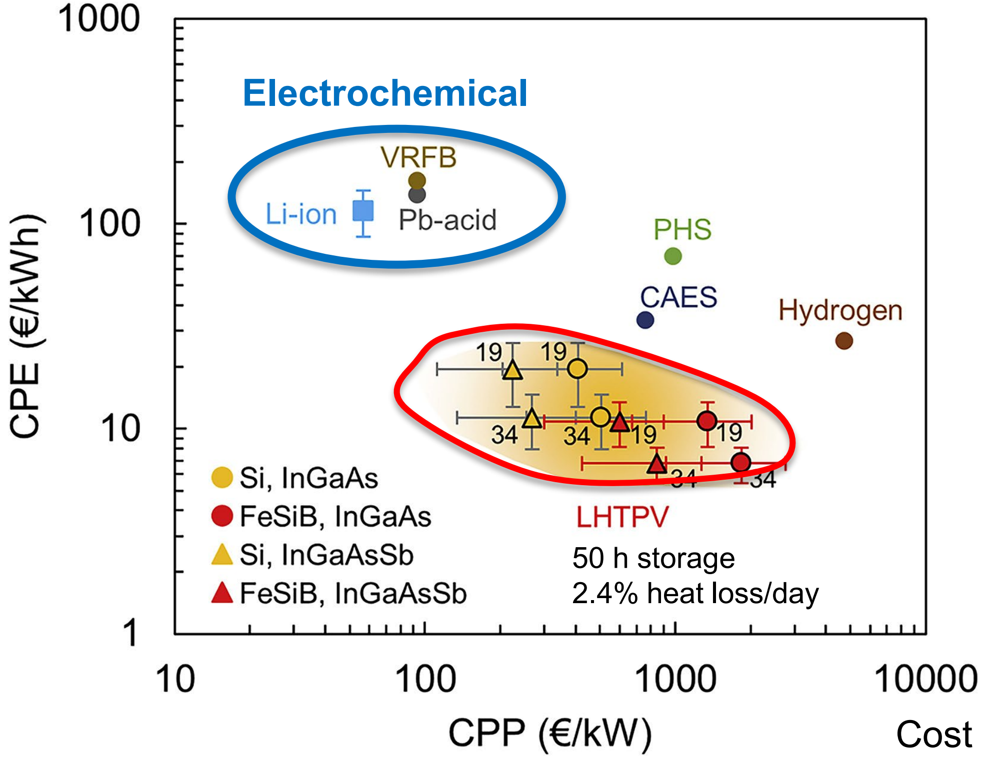
Article

Latent heat thermophotovoltaic batteries

Alejandro Datas,[1,3,*] Alicia López-Ceballos,[1] Esther López,[1] Alba Ramos,[1,2] and Carlos del Cañizo[1]

Datas et al., Joule, 2022

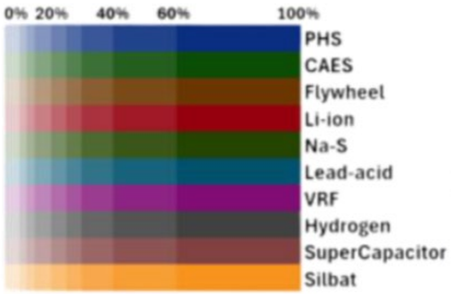
Cost Per Energy



Cost Per Power

Electro-Thermal Energy Storage (long duration) **is cheap**

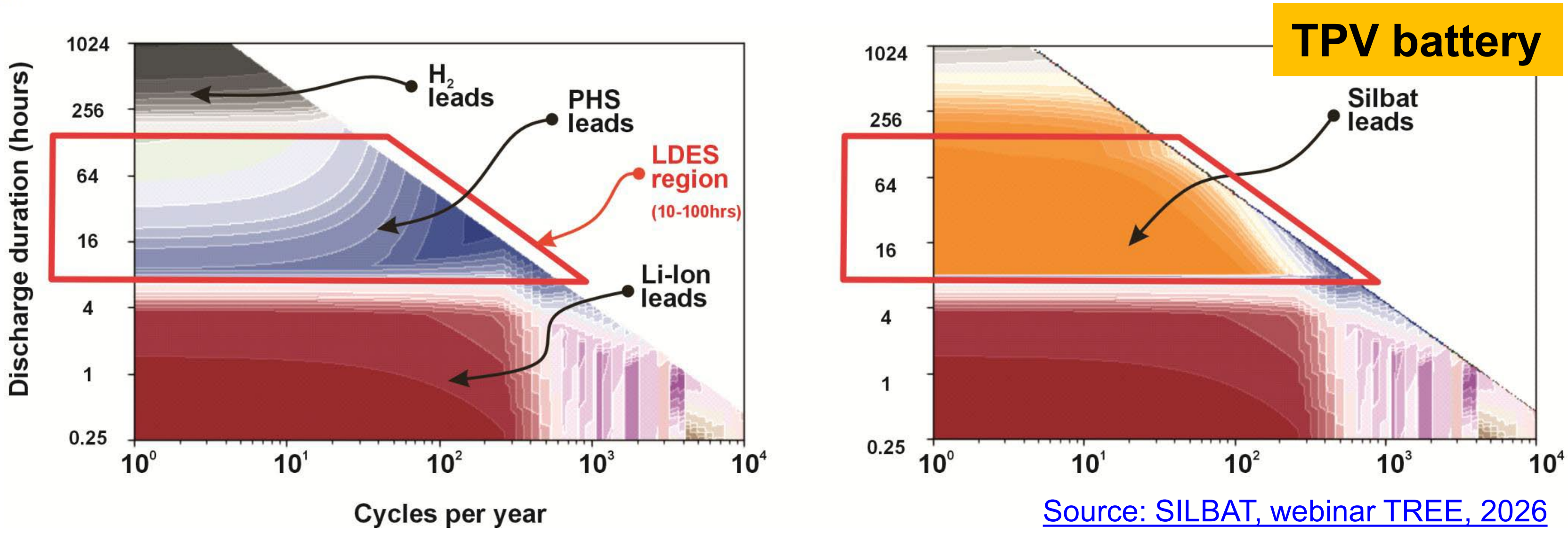
Key features: lowest LCOS (long discharge duration)



LCOS increase for second cheapest technology

LCOS: Levelized Cost Of Storage. It divides the total cost of an electricity storage technology across its lifetime by its cumulative delivered electricity ($/MWh).

Color indicates the technology with lowest LCOS



[Source: SILBAT, webinar TREE, 2026](#)

Methodology described in [Schmidt & Staffel, Monetizing energy storage, 2023](#)

TPV batteries are advantageous for LDES (> dozens of h)

See also [Datas et al., Joule, 2022](#) [Qu et al., ECM, 2026](#)

Key features: decarbonizing industry

Driving to net zero industry through Long Duration Energy Storage, 2023

"Long duration energy storage technologies paired with renewables could reduce global industrial greenhouse gas emissions by 65%.

'Hard-to-electrify' heat (> 1,000°C): LDES offers game-changing longer-term opportunities".

Kauko et al., EERA, 2022

> Industrial process heat above 500°C

- Potential of **929 TWh fossil fuel replacement** with renewable energy and/or surplus heat
- GHG reduction of **277 MtCO2e/year**

Maddedu et al., 2020

> Industrial process heat above 1000°C

- Mostly steel, cement, ceramic and glass industries
- ~ **277 TWh** for Europe

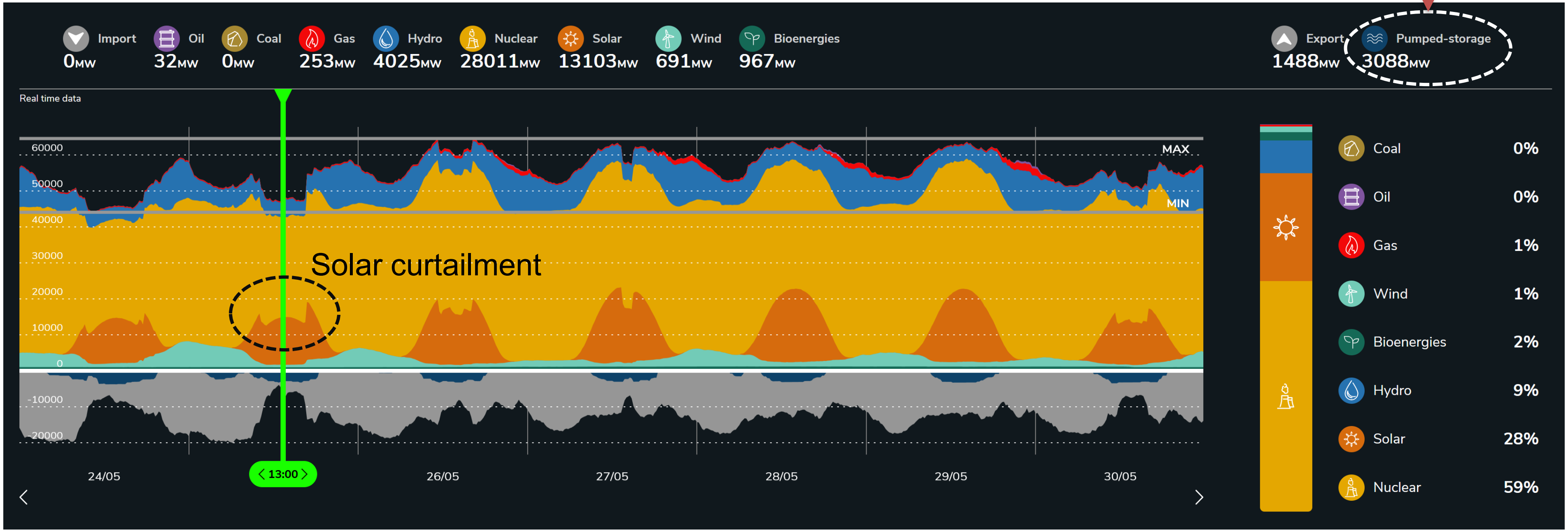
Key features: reducing VRE curtailment

Le réseau
de transport
d'électricité

Power generation by energy source

Week of May 24 to May 30 2026

Not enough



https://www.rte-france.com/...


The future
of European
competitiveness
Part B | In-depth analysis and recommendations
SEPTEMBER 2024

"The Draghi report"

"Up to 310 TWh of renewable generation could be curtailed due to these limitations in the grid by 2040".

https://commission.europa.eu/...

Leading startups

ANTORA

Estimated cumulated funding > 230 M$

www.antora.com

1

INTERMITTENT,
LOW-COST ENERGY

2

ENERGY STORED AS
HEAT IN CARBON
BLOCKS

3

ALWAYS-ON HEAT AND
POWER AT INDUSTRIAL
SCALE

ANDREW PONEC

CEO
B.S. Stanford U.

DAVID BIERMAN, Ph.D.

CCO
Ph.D. MIT

JUSTIN BRIGGS, Ph.D.

COO
Ph.D. Stanford U.

ANTORA A remarkable fact

Energy Storage NEWS

US startup Antora deploys 5GWh thermal energy storage system at biofuels facility in South Dakota

By Andy Colthorpe

May 20, 2026

CBS NEWS

Business

South Dakota ethanol plant to run on stored wind energy in first-of-its-kind thermal storage project

May 20, 2026 / 8:33 AM CDT / AP

Antora commissions one of the world's largest battery storage systems to power South Dakota industrial facility with affordable energy →

POWERING SOUTH DAKOTA INDUSTRY WITH AFFORDABLE ENERGY

https://www.antora.com/

Leading startups

TPV

FOURTH POWER

Estimated cumulated funding > 50 M$

gofourth.com

Amy et al., Appl. Energy, 2022

Heat-to-Power: TPV conversion

Founder
& Chief
Technologist

Prof. Asegun Henry

Massachusetts Institute of Technology

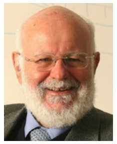
"Power at Scale
with this
Sun in a Box"

https://www.youtube.com/watch?v=t98-LwO_0tE#t=2m03s

Leading startups

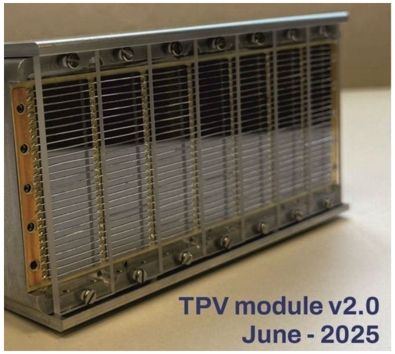
silbat.com/

Estimated cumulated funding > 7 M€



Prof. Antonio Luque
Co-founder CSO

Ignacio Luque, PhD.
Co-founder CEO



Webinar TREE, 2026

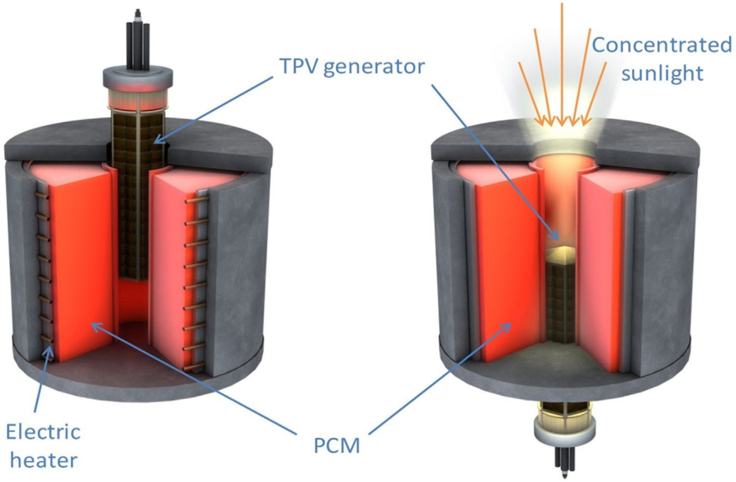
Latent heat storage
(Si alloys)

Ge TPV cells
and modules

thermophoton.com

Estimated cumulated funding > 1 M€

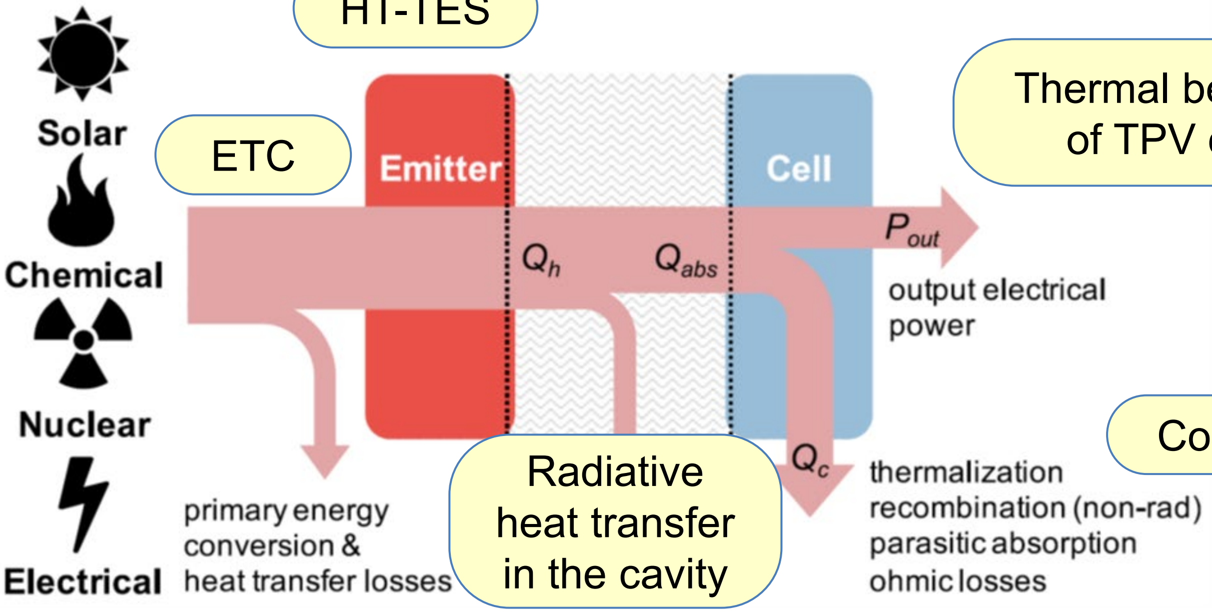
Alejandro Datas, Ph.D.
CTO



Datas et al., Energy, 2016

4. A French TPV battery?

Some thermal science challenges



HT spectrally selective emitters

HT-TES

ETC

Thermal behavior of TPV cells

Radiative heat transfer in the cavity

Cooling

Multi-scale multi-physics modelling

The SFT community has a strong expertise to offer for tackling these challenges

GDR Thermal Radiation to Electrical Energy conversion

Members: 21 French academic laboratories

C2N
Cemhti
CETHIL UMR 5008
Laboratoire ESYCOM
Institut Européen des Membranes UMR 5635

iemn
ies INSTITUT D'ÉLECTRONIQUE ET DES SYSTÈMES
imanp
inl
INSTITUT P'

IPVF Joint Research Unit
INSTITUT PASCAL sciences de l'ingénierie et des systèmes
iTheMM Institut de Thermique, Mécanique, Matériaux
IUSTI LABORATOIRE AIX MARSEILLE UNIVERSITÉ CNRS
LABORATOIRE CHARLES COULOMB MONTPELLIER

LAAS CNRS
lemta Laboratoire Énergies & Mécanique Théorique et Appliquée
LTEN
PROMES
RAPSODEE UMR CNRS 5302 IMT Mines Albi-Carmaux
Laplace

TREE

(2025-2029)

Partners

Schlumberger slb

ETC ECO-TECH CERAM

cea Le Ripault

GDR 2198 TREE – tree.cnrs.fr

Research axes

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

2- Heat transfer

3- Photovoltaics

4- Materials: fabrication & characterization

5- Advanced concepts

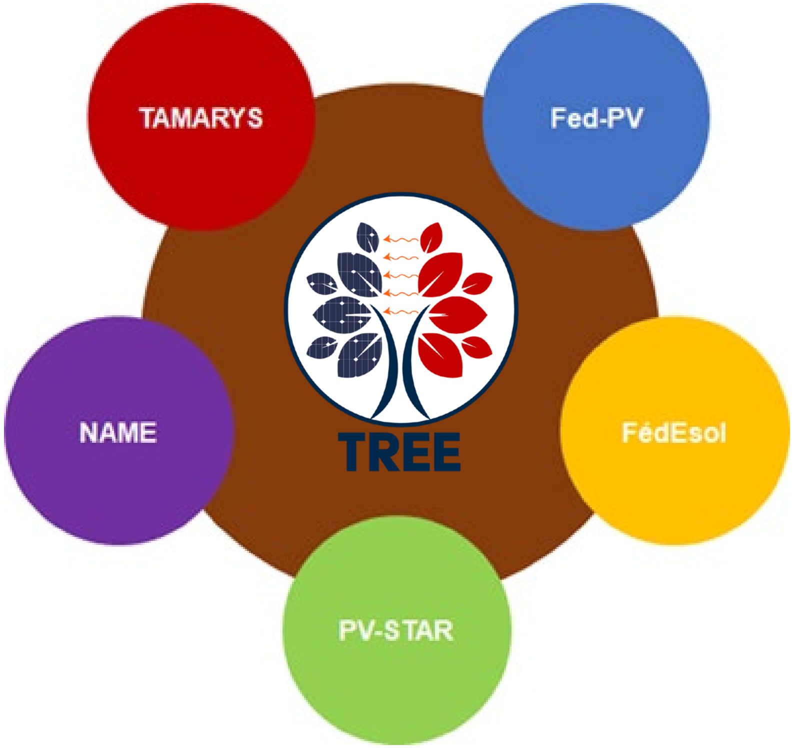
T1- Multi-scale/physics modelling

T2- Environmental aspects (LCA,…)

T3- Development of a TPV battery

T4- Collaborations with private and foreign institutions

Connections with other organizations



5. Key messages

Key messages

- Similarities and differences between TPV and solar PV conversions
- TPV batteries are currently emerging
- They contribute to decarbonizing industry and to better integrating VRE into the power grid
- Possible thanks to high-temperature thermal energy storage and recent record TPV conversion efficiencies (> 40%)
- At least four start-ups develop TPV batteries
- Opportunity for the French thermal science community to contribute to the science around TPV batteries
- GDR CNRS TREE ("Thermal Radiation to Electrical Energy conversion", 2025-2029)

For further information

- Burger, T., Sempere, C., Roy-Layinde, B., & Lenert, A. (2020). Present efficiencies and future opportunities in thermophotovoltaics. *Joule*, *4*(8), 1660-1680.
- Datas, A., & Vaillon, R. (2021). Thermophotovoltaic energy conversion. In Ultra-high temperature thermal energy storage, transfer and conversion (pp. 285-308). Woodhead Publishing.
- Vaillon, R., & Chapuis, P.-O. (2025). Conversion thermophotovoltaïque: des principes aux applications. Techniques de l'Ingénieur.

TPV
16th World Conference
on Thermophotovoltaic Generation of Electricity

7-9 July 2026
Nantes, France

Défis Clés OCCITANIE
La Région Occitanie Pyrénées · Méditerranée
PVSTAr. LE PHOTOVOLTAÏQUE EN OCCITANIE

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ANR-16-CE05-0013
ANR-21-CE50-0018
ANR-25-CE05-1640

Thank you!

rodolphe.vaillon@cnrs.fr