Thermoelectric conversion in tandem thermoelectric-photovoltaic applications

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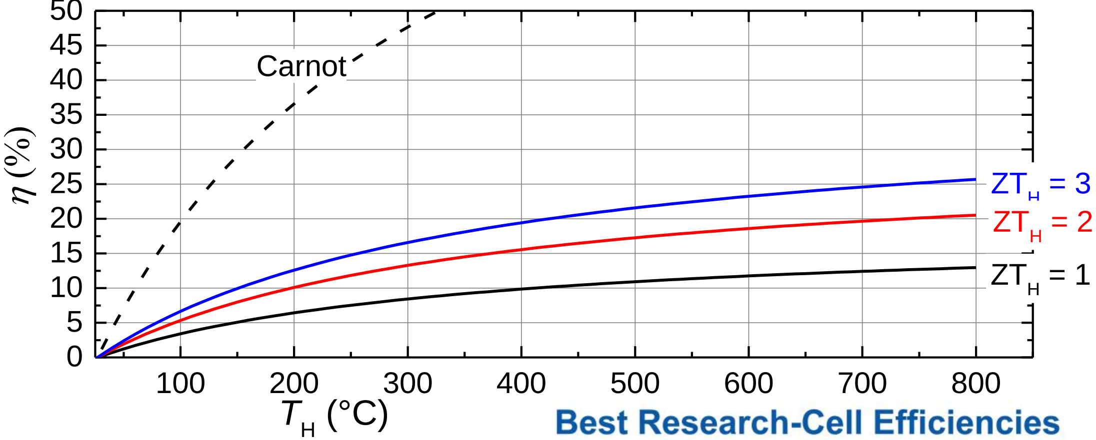
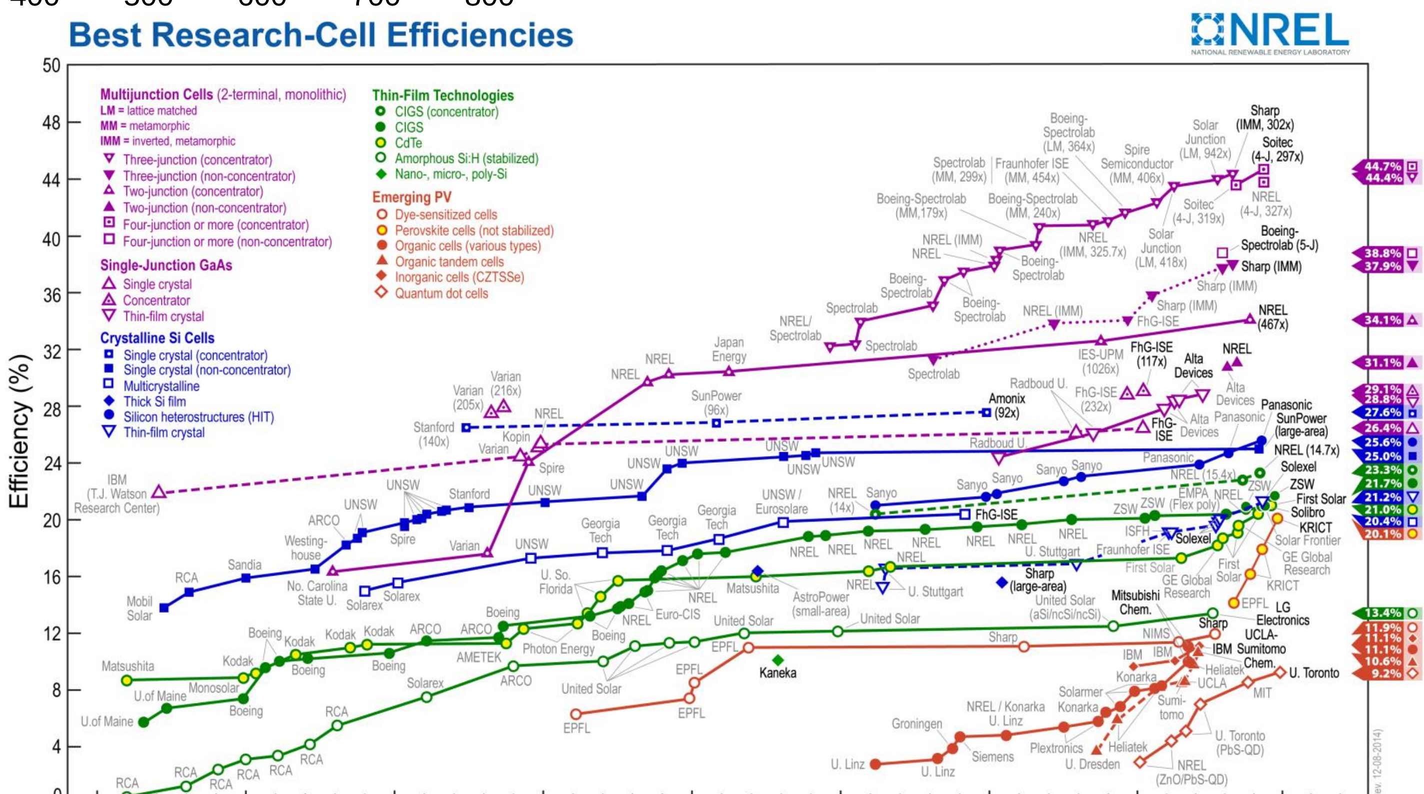
Outline

- A short history of TE solar converters:
  - Pure solar thermoelectric generators (STEGs)
  - Hybrid co-generative STEGs (HCG-STEGs)
  - Hybrid thermoelectric-photovoltaic generators (HTEPVGs)
- Why (and when) we may need STEGs
- HTEPVs: working out the power balance in a single-junction device
  - The *T*-dependent Shockley-Queisser limit
  - HTEPVGs recovering PV hot carrier energy
  - HTEPVGs also recovering low-energy photons
  - Shaping the TEGs
- Opportunities and challenges:
  - PV old goodies redux
  - TEG geometry and TE materials
- Some conclusions

Why we may need TEs for solar conversion



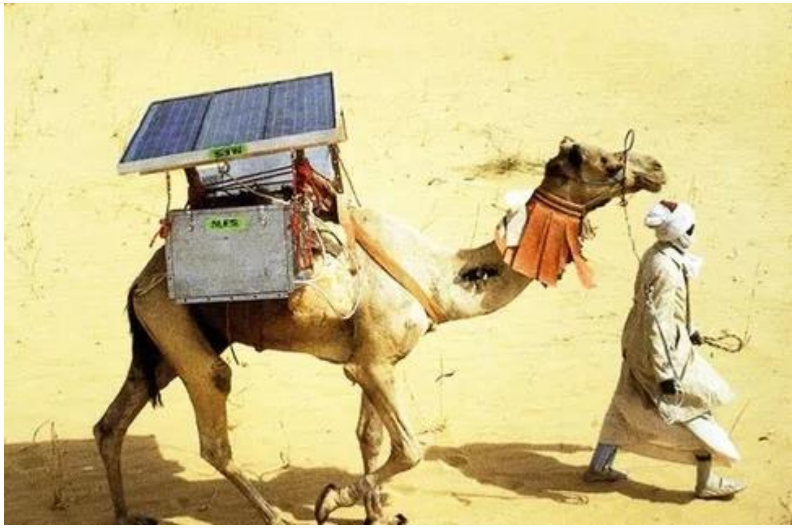


Why we may need TEs for solar conversion

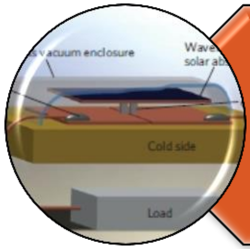
- TE efficiency lags far behind PVs
- It is unrealistic to expect short-term dramatic improvements of TE figures of merit

However:

- TEs allows for thermal concentration, a space-saver
- TEs may operate in harsh environments

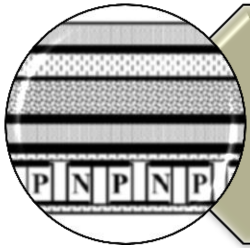


How TEGs may help



STEG: full thermal conversion

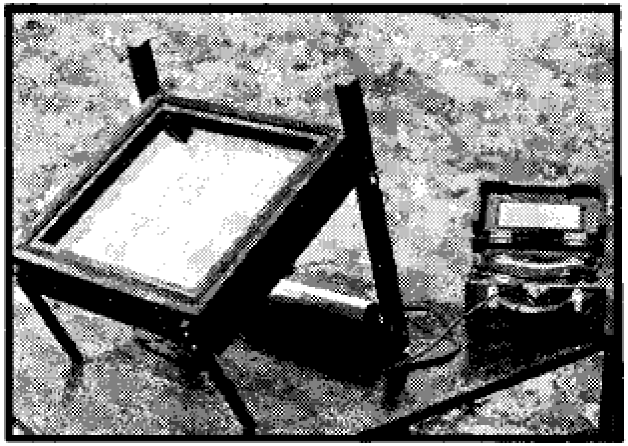
HCG-STEG: TEGs + thermal cogeneration



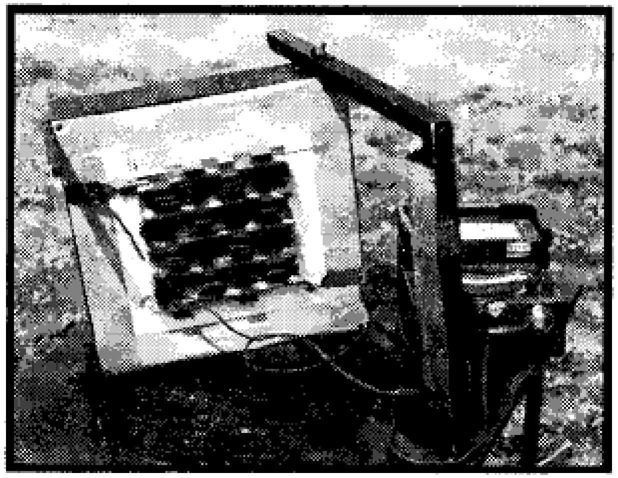
HTEPV: two-stage PV + TEGs

STEGs: Pure solar TEGs

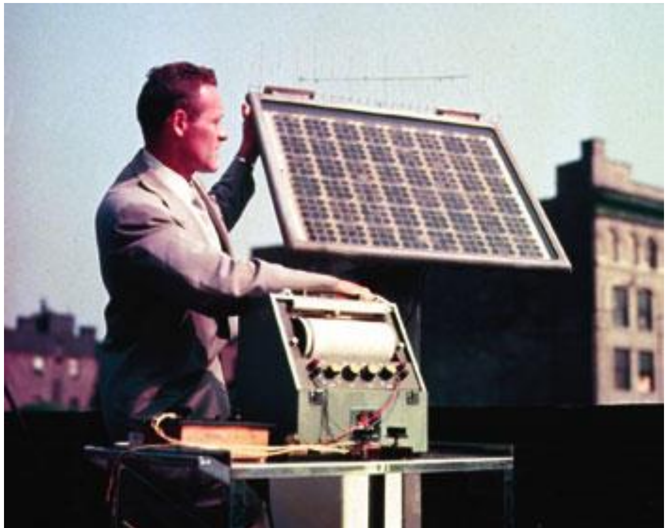
M. Telkes, J. Appl. Phys., 25 (1954) 765



- Convert solar energy into heat and then into electric energy by TEGs
- Operate with T_H= 300 – 1000 °C using from PbTe/PbSe to SiGe alloys

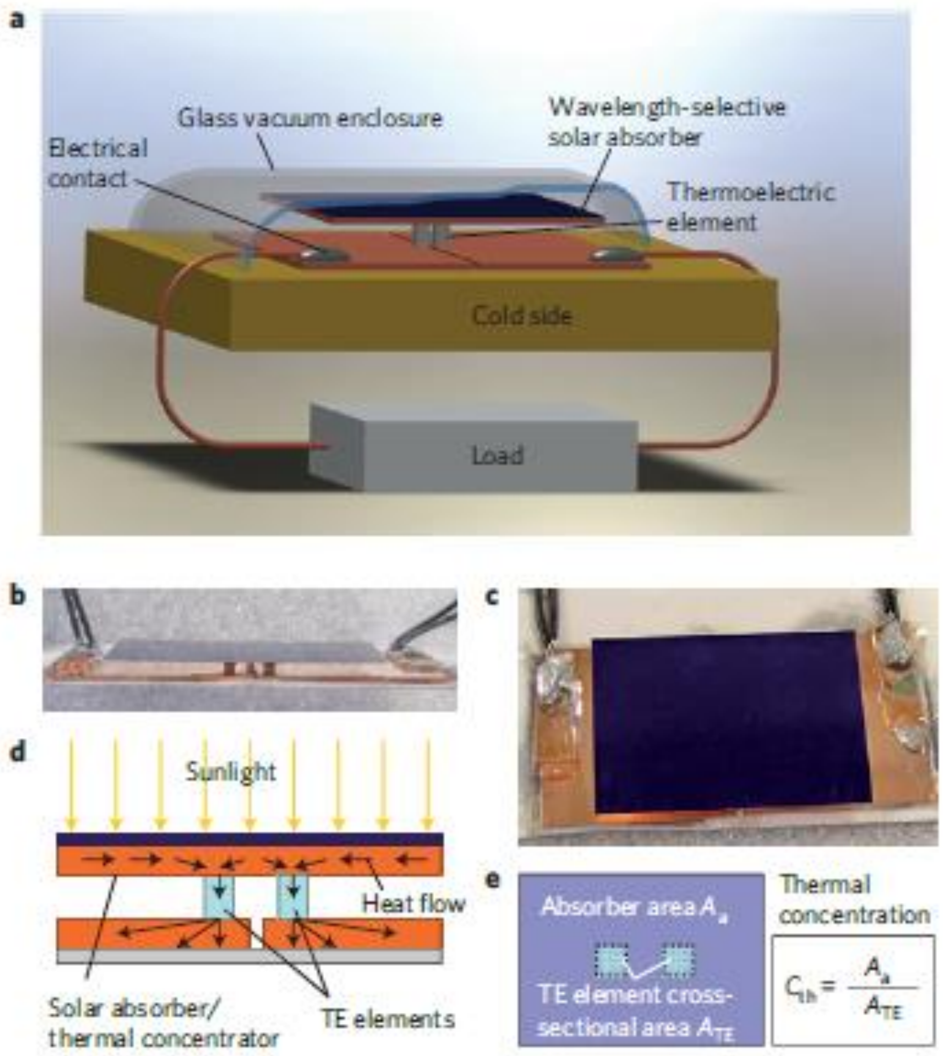


- Telkes' prototype based upon ZnSb and $Bi_{0.91}Sb_{0.09}$ (ZT=0.4)
- η = 0.63 % @ 70°C; η = 3.35 % @ 247°C



Bell labs, 1954 – efficiency of 4%

STEGs: Pure solar TEGs



Non-optically concentrated STEGs now reach ΔT = 100 K with η = 4.6 % using ns-Bi_2Te_3

- thermal concentrators
- quasi-ideal thermal insulation
- selective solar absorber (absorptivity ≈ 0.95, emissivity ≈ 0.2)

Cost ≈ 0.17 $/W (compared to 1.6 $/W for optically concentrated)

D. Kraemer et al., Nat. Mater., 10 (2011) 532

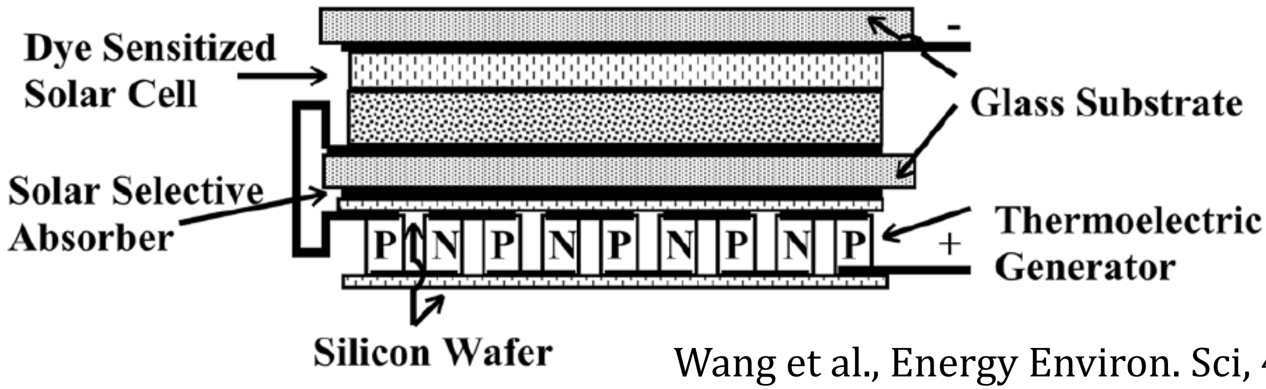
Hybrid co-generative TEGs

- STEGs using output heat flow to heat water or likely
- Electrical efficiency of <5 %
- Typical plant may cogenerate 0.12 $kW_e h$ + 1.2 $kW_{th} h$

Y. Vorobiev, Int. J. Photoen., (2013) 704087
P. Sundarraj et al., RSC Adv., 4 (2014) 46860

Hybrid TE-PV (HTEPV) generators

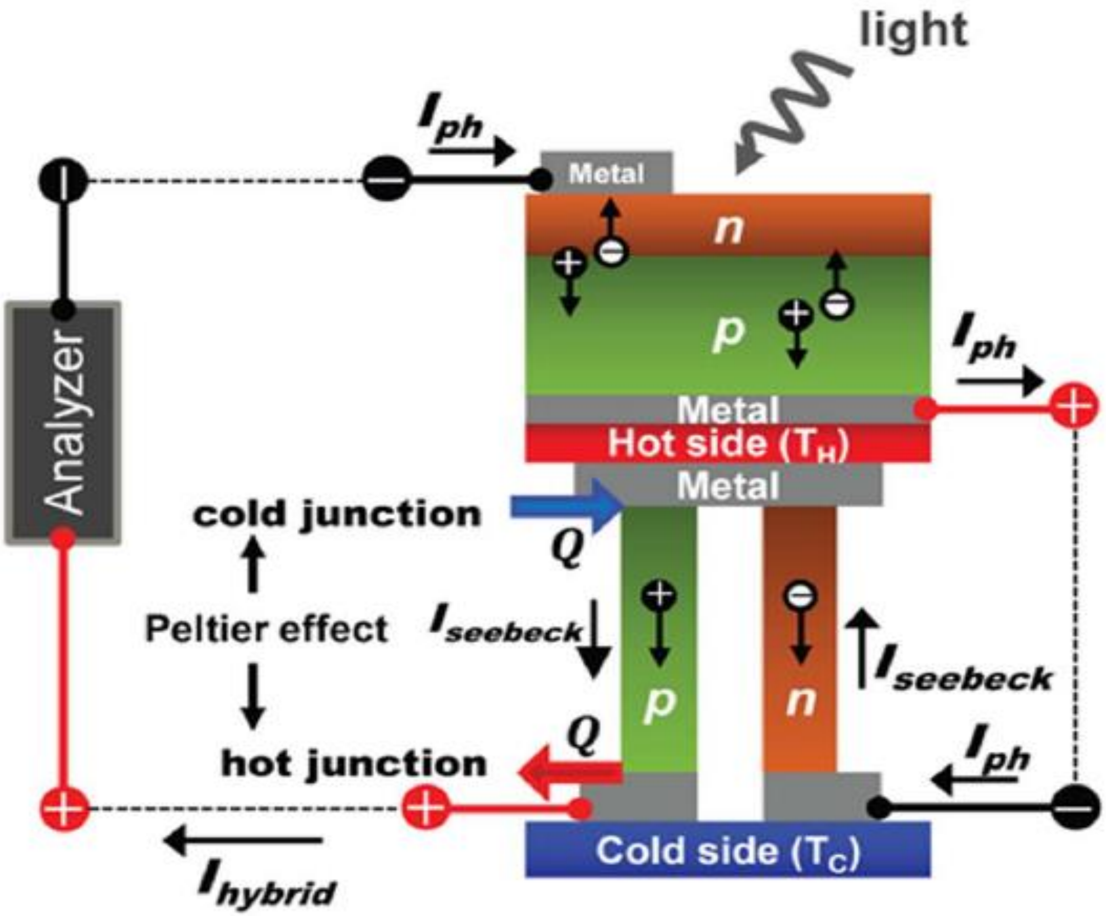
- TEG reuses the heat released by the PV
- Possibly optically concentrated

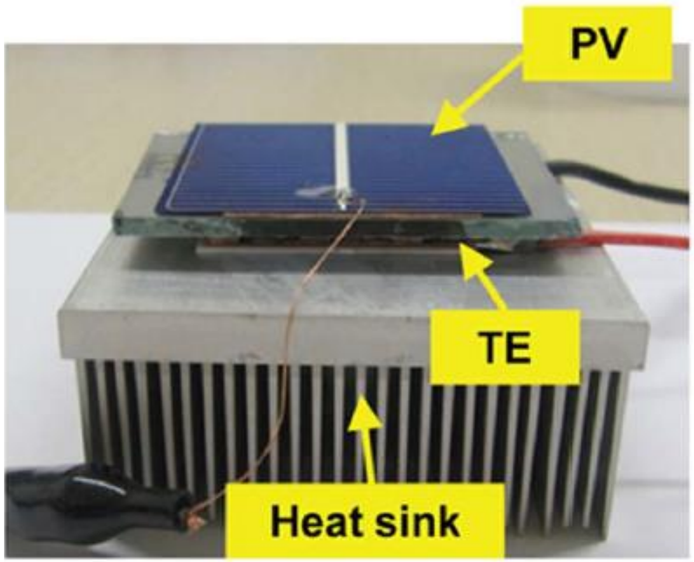


Wang et al., Energy Environ. Sci, 4 (2011) 3676

- DSSC + SSA + TEG(Bi_2Te_3) achieve η_{tot} = 13.8%, 12.8 mW/cm^2

The basic principles of HTEPV design





K.-T. Park et al., Sci. Rep. 3, (2013) 422

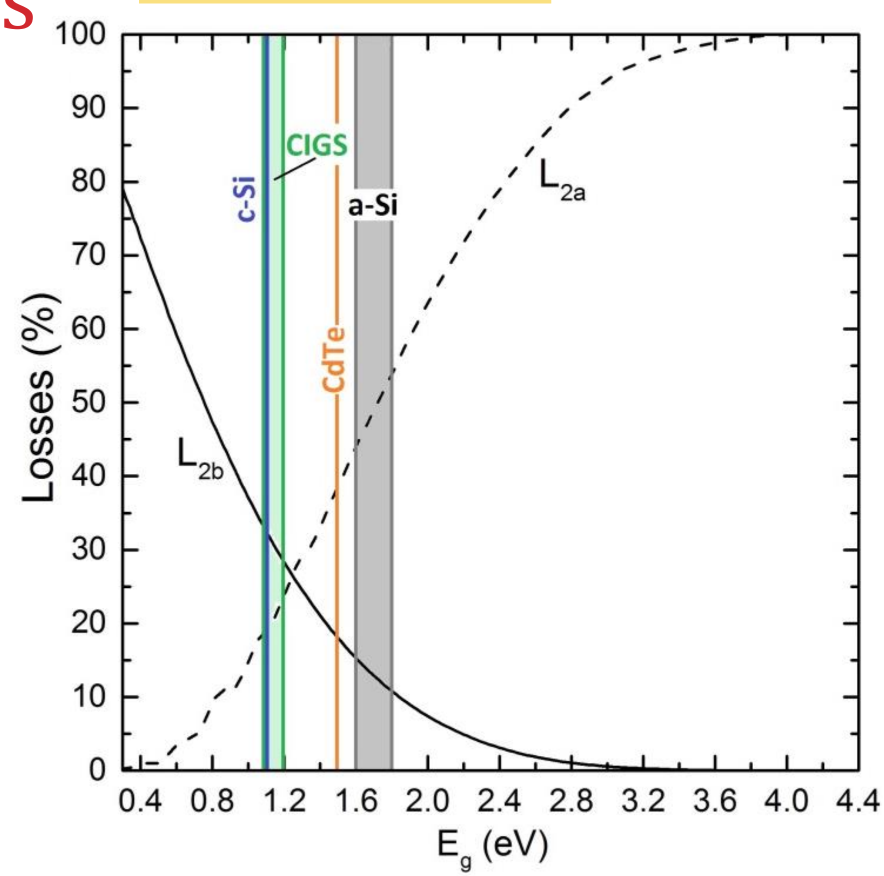
SJ solar cell model: Losses

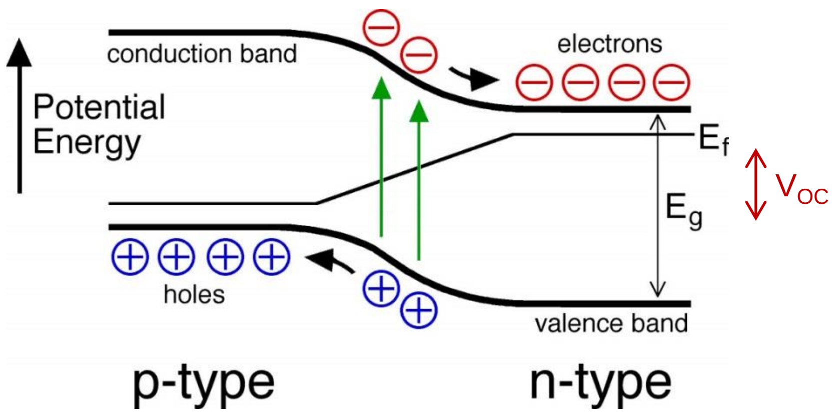
1 - Contact Grid Shadows	4.0%
1 - Reflections	4.0%
3 - Unintended Abs.	1.0%
4 - hν < E_g	29.2%
5 - hν > E_g	18.8%
6 - η_Q=0.9	1.0%
7 - $E_g > qV_{oc}$	19.2%
8 - FF=0.78	4.7%

L_{2a}

L_{2b}

η=16.6%





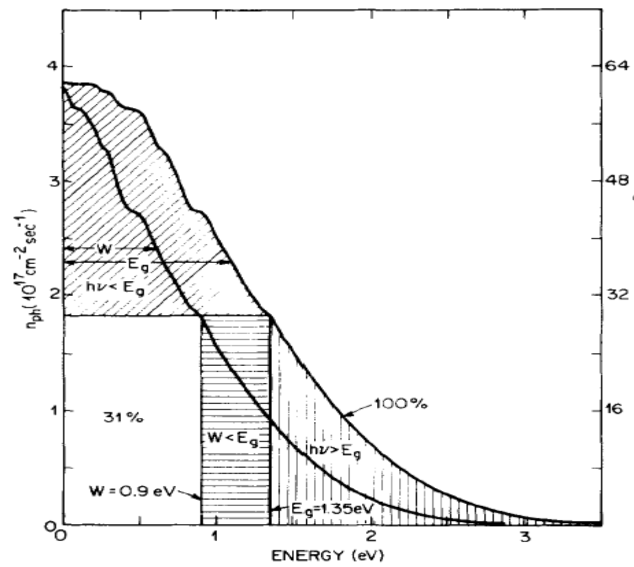
SJ solar cell model: the SQ limit

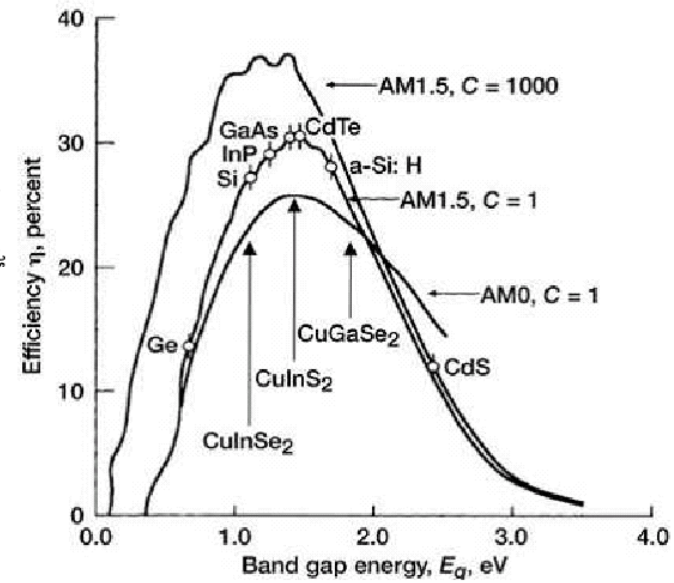
Thermodynamic Limit

≈ 95%

Shockley & Queisser Limit ≈ 31%

at $E_g \approx 1.35$ eV



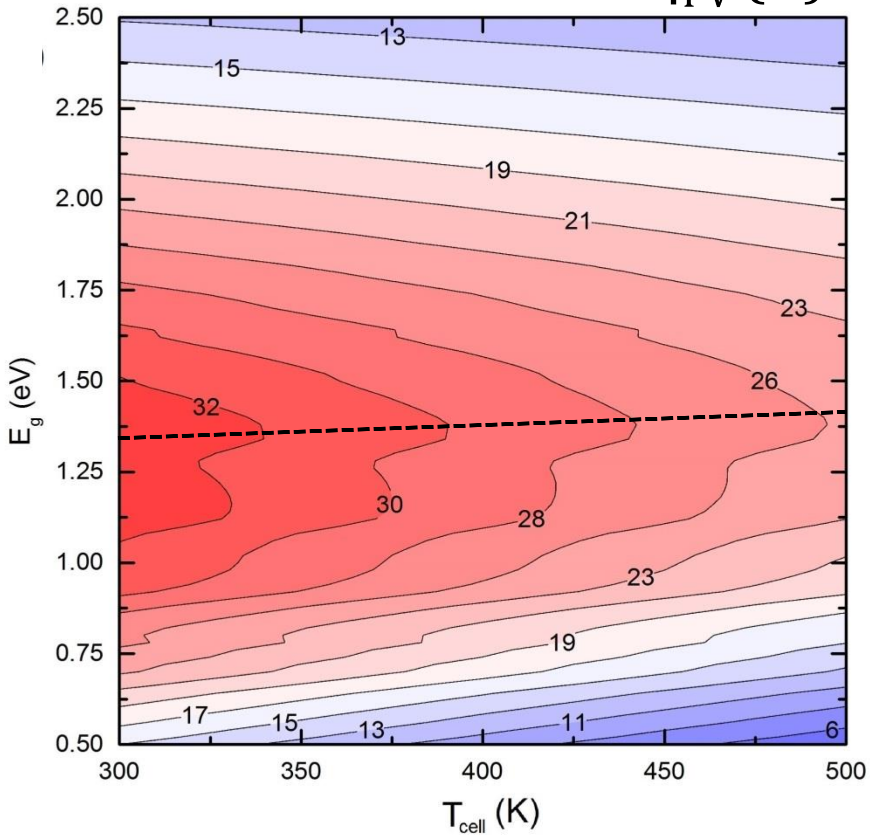


i. all photons with $E_\gamma > E_g$ are absorbed, while photons with $E_\gamma < E_g$ produce no effect
ii. unitary quantum efficiency
iii. $T_{\mathrm{cell}} = T_{\mathrm{a}}$
iv. the only mechanism of electron-hole recombination is radiative

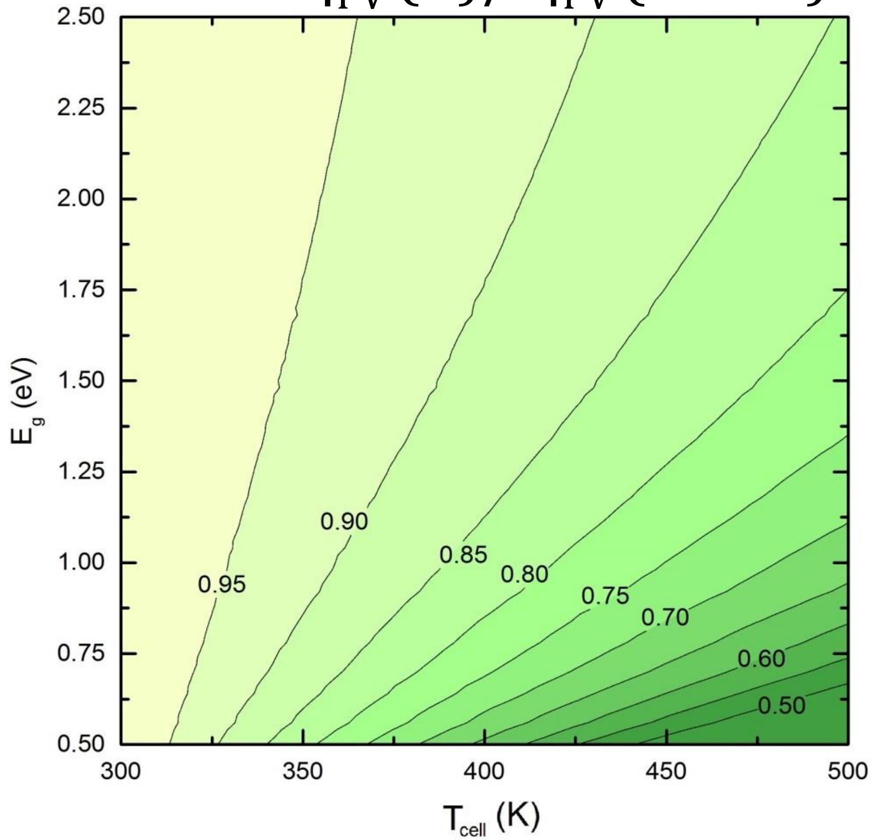
W. Shockley, H. J. Queisser, J. Appl. Phys. 32 (1961) 510

The SQ radiative limit

$\eta_{PV}(T)$



$\eta_{PV}(T) / \eta_{PV}(300\ K)$

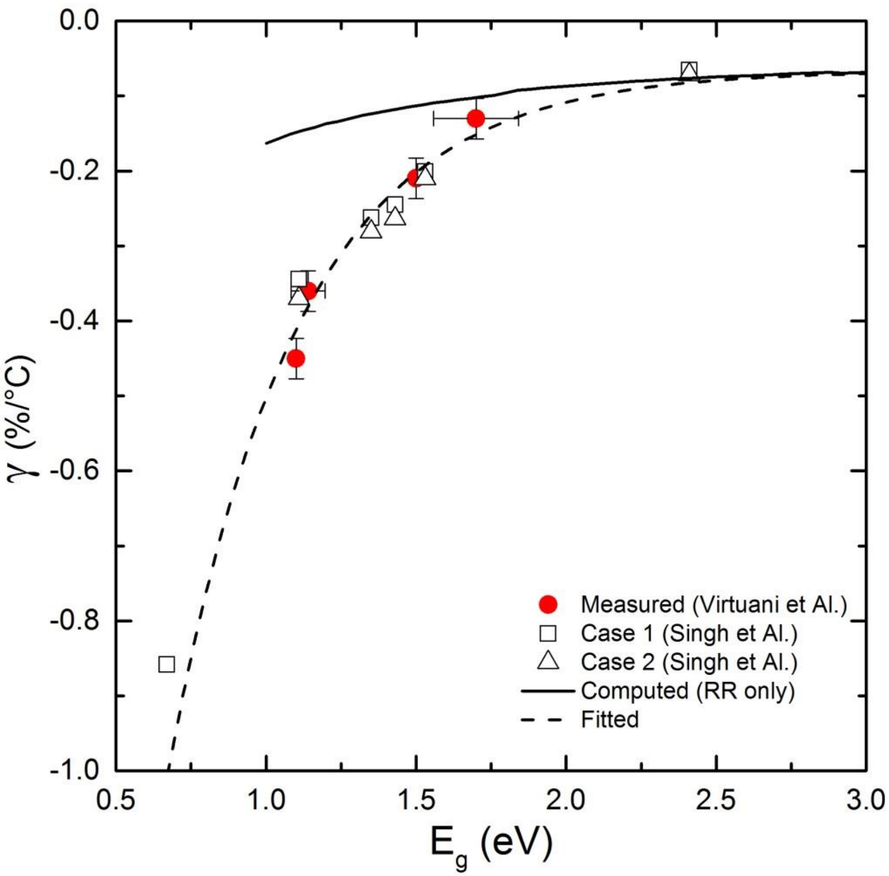


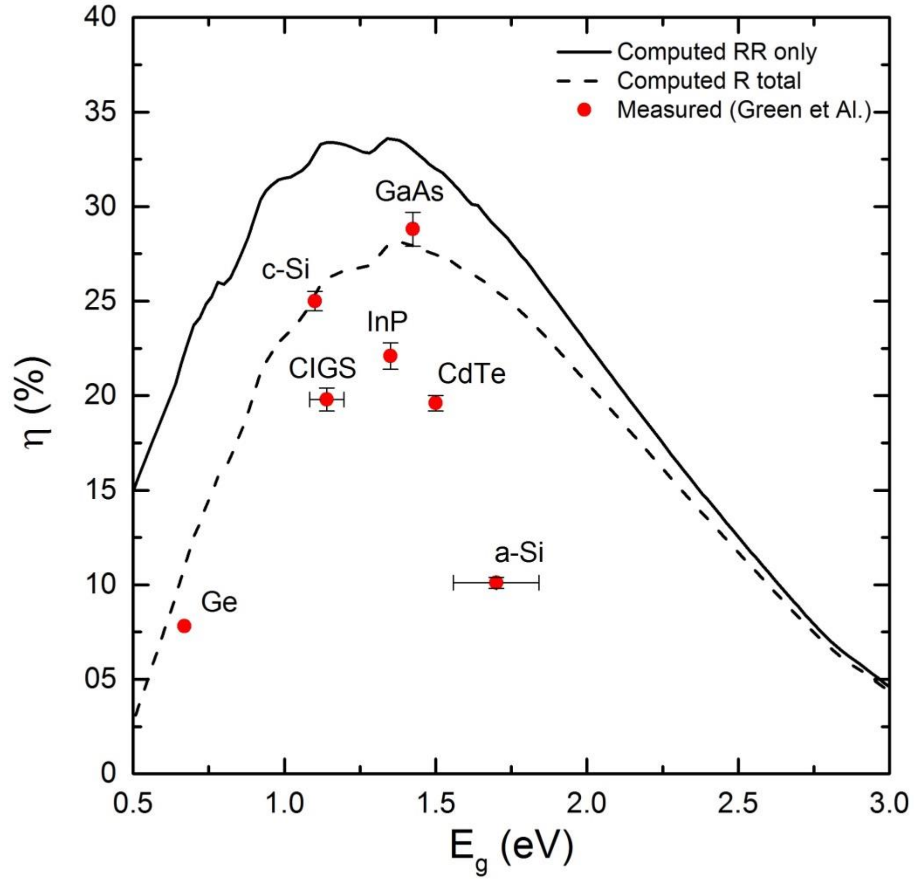
max η_{PV} (300 K) = 33.6 % at 1.36 eV

E_g effect on η_{PV} decreases

B. Lorenzi et al., J. Mater. Res., DOI: 10.1557/jmr.2015.174

Accounting also for recombination

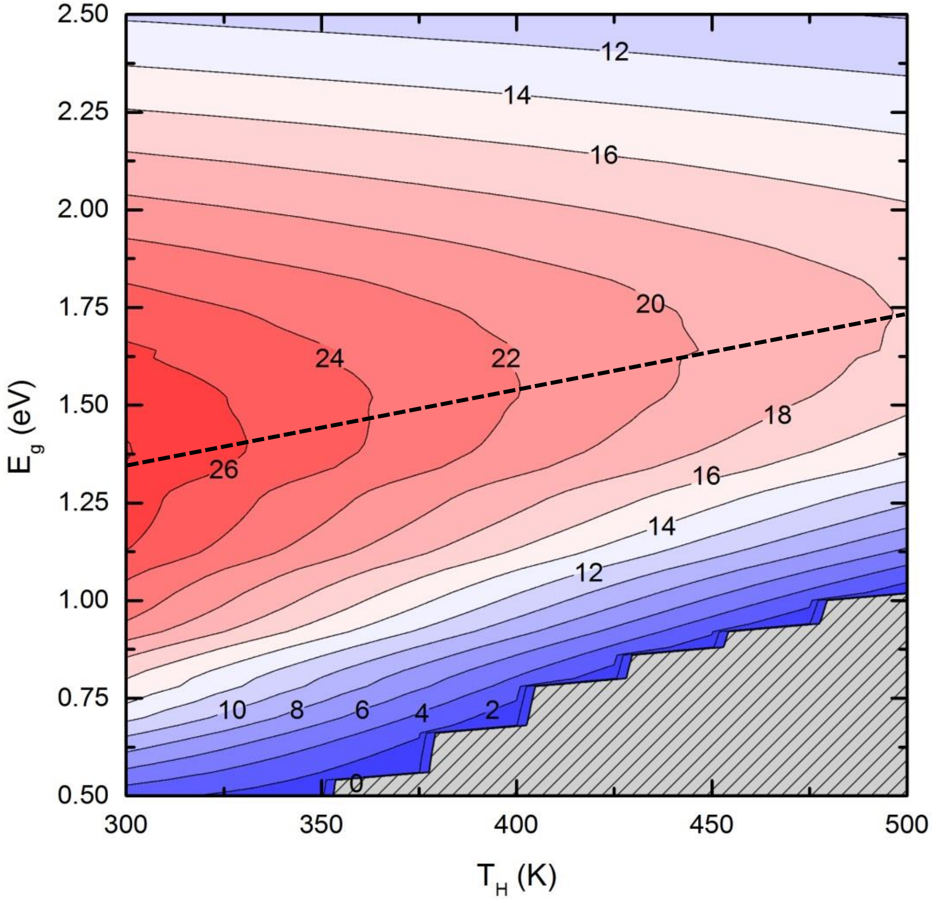




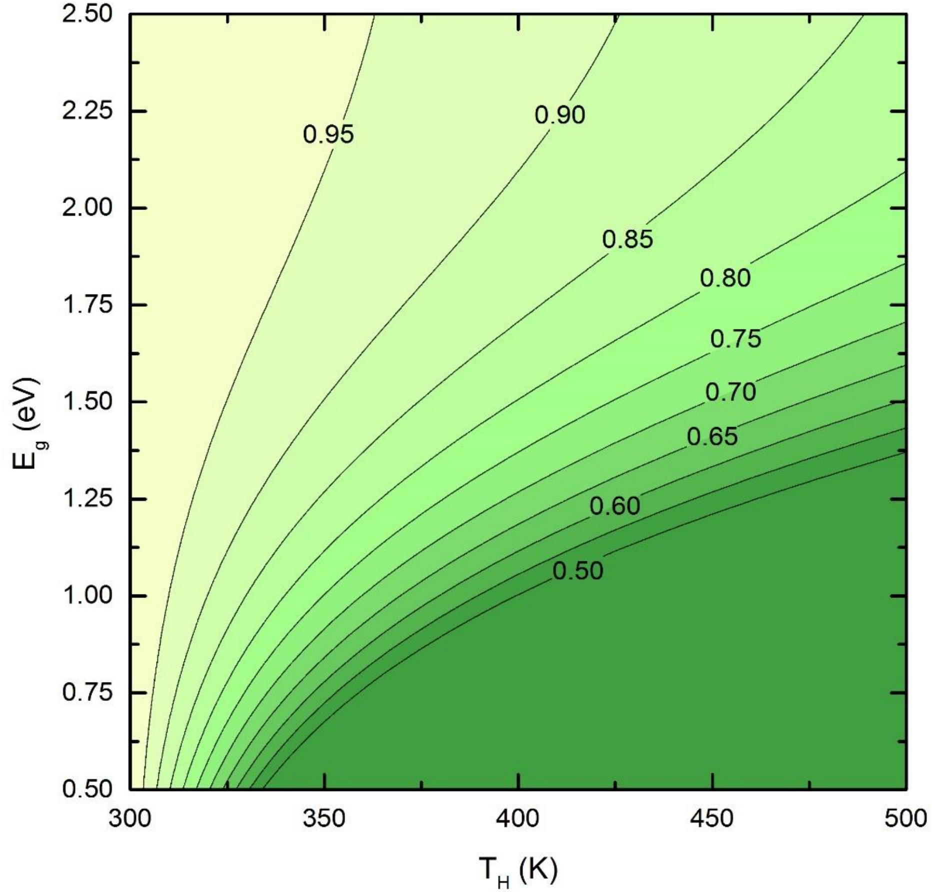
A. Virtuani, et al.; Proc. 25th UE-PVSEC, Sept. 2010, Valencia, Spain
M. Green, et al.; Prog. Photovolt. Res. Appl., 22, 1–9 (2014)
P. Singh, et al.; Sol. En. Mat. & Sol. Cells, 101 (2012) 36-45

Accounting also for recombination

$\eta_{PV}(T)$



$\eta_{PV}(T)/\eta_{PV}(300\ K)$



Sub-Gap Absorber

Case 1 (non SGA)

$$L_{2b}(E_g)\Phi_{sun} = \frac{1}{R_T}(T_{cell} - T_a)$$

$$P_{TEG}^{out} = \eta_{TEG} L_{2b}(E_g)\Phi_{sun}$$

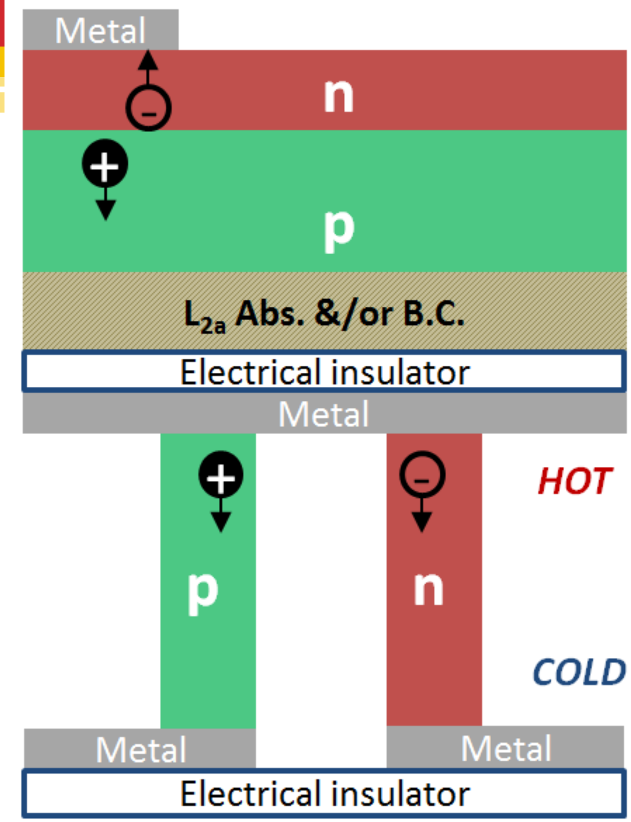
Case 2 (SGA)

$$(L_{2a}(E_g) + L_{2b}(E_g))\Phi_{sun} = \frac{1}{R_T}(T_{cell} - T_a)$$

$$P_{TEG}^{out} = \eta_{TEG}\left[L_{2a}(E_g) + L_{2b}(E_g)\right]\Phi_{sun}$$

$T_H = T_{cell}$

$T_C = T_a$



$$\eta_{TEG}^{out} = \frac{P_{TEG}^{out}}{\Phi_{sun}} = \begin{cases} \eta_{TEG} L_{2b}(E_g) \\ \eta_{TEG}\left[L_{2a}(E_g) + L_{2b}(E_g)\right] \end{cases}$$

$$\eta_{TEG} = \left(1 - \frac{T_a}{T_{cell}}\right)\frac{\sqrt{1+Z\bar{T}} - 1}{\sqrt{1+Z\bar{T}} + T_a/T_{cell}}$$

ZT = 1

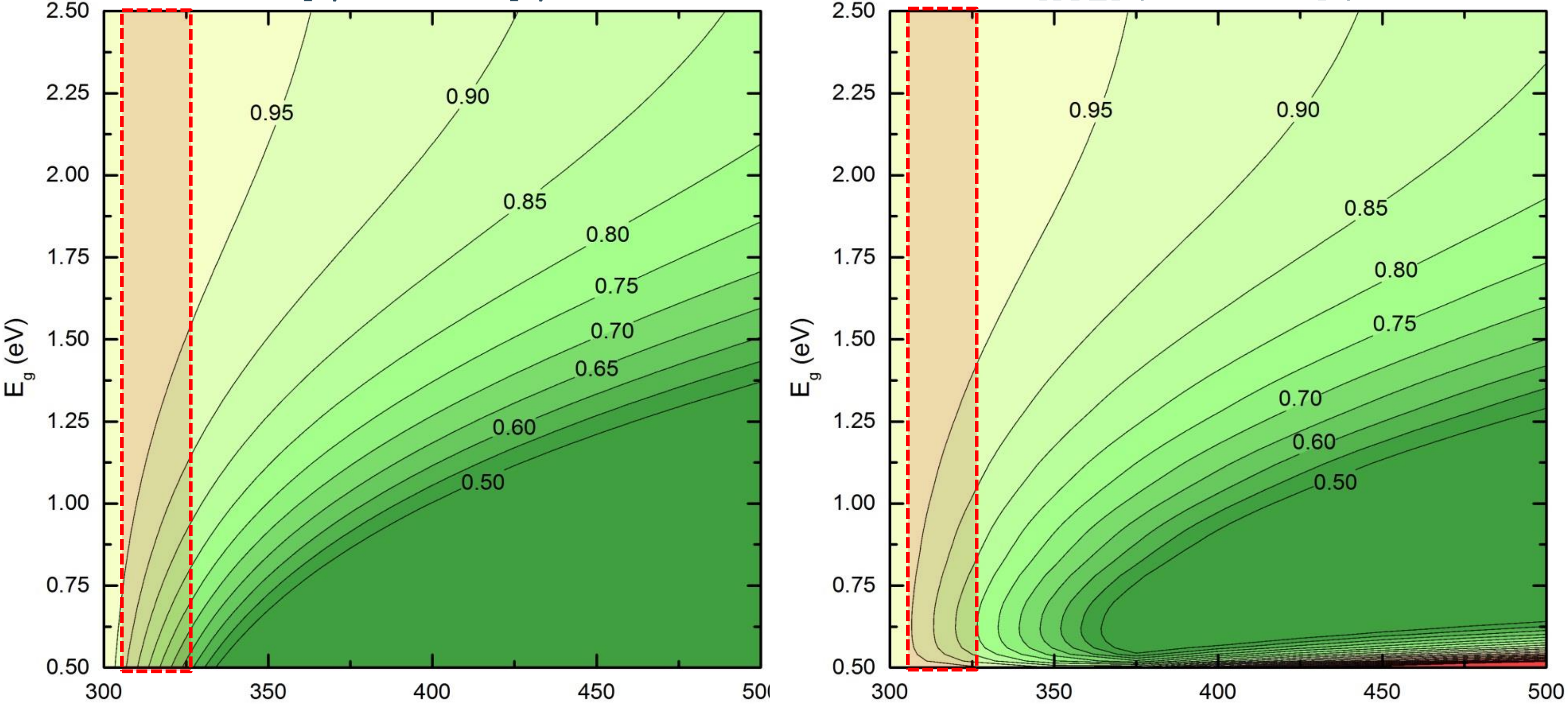
$$\eta_{HTEPV} = \frac{P_{PV}^{out} + P_{TEG}^{out}}{\Phi_{sun}} = \begin{cases} \eta_{PV} + \eta_{TEG} L_{2b}(E_g) \\ \eta_{PV} + \eta_{TEG}\left[L_{2a}(E_g) + L_{2b}(E_g)\right] \end{cases}$$

Lossless Electric Hybridization

K.-T. Park et al. Sci. Rep.; 3, (2013) 422

Non-SGA

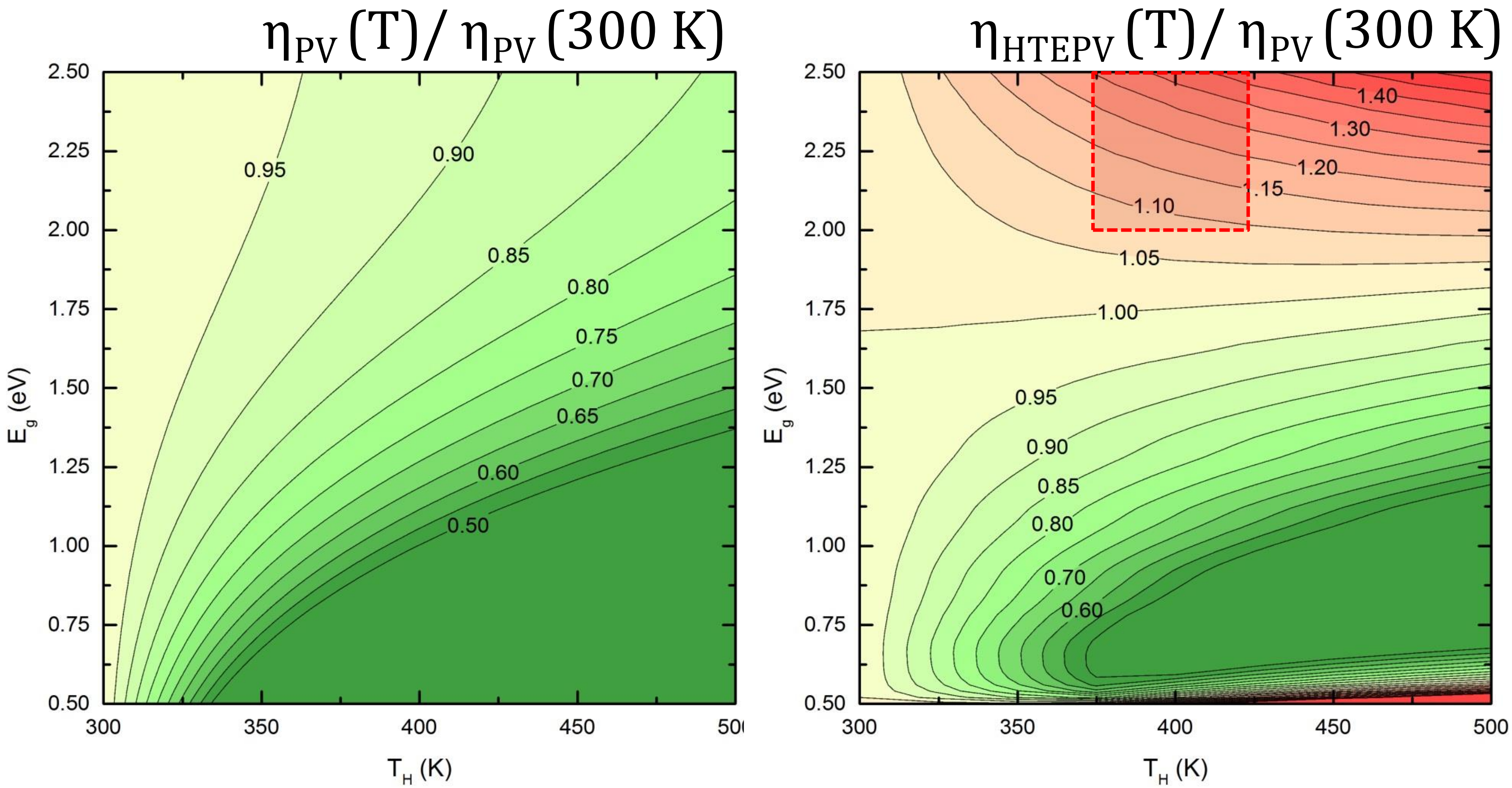
$\eta_{PV}(T)/\eta_{PV}(300\ K)$ $\eta_{HTEPV}(T)/\eta_{PV}(300\ K)$



The TEG stage leads to truly minor improvements.
Extra cost is hard to justify

E. Skoplaki; Sol. En., 83, 422 – 427 (2009)
T. Nordmann and L. Clavadetscher, in Proc. 3rd WCPEC 3, 2–5 (2003)

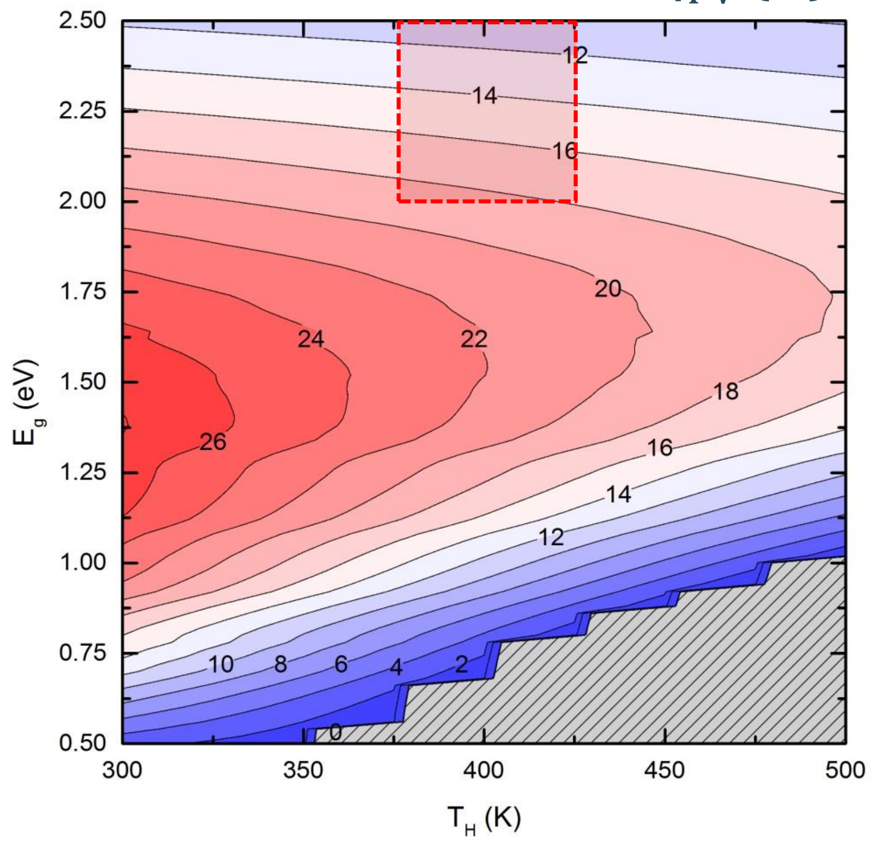
SGA



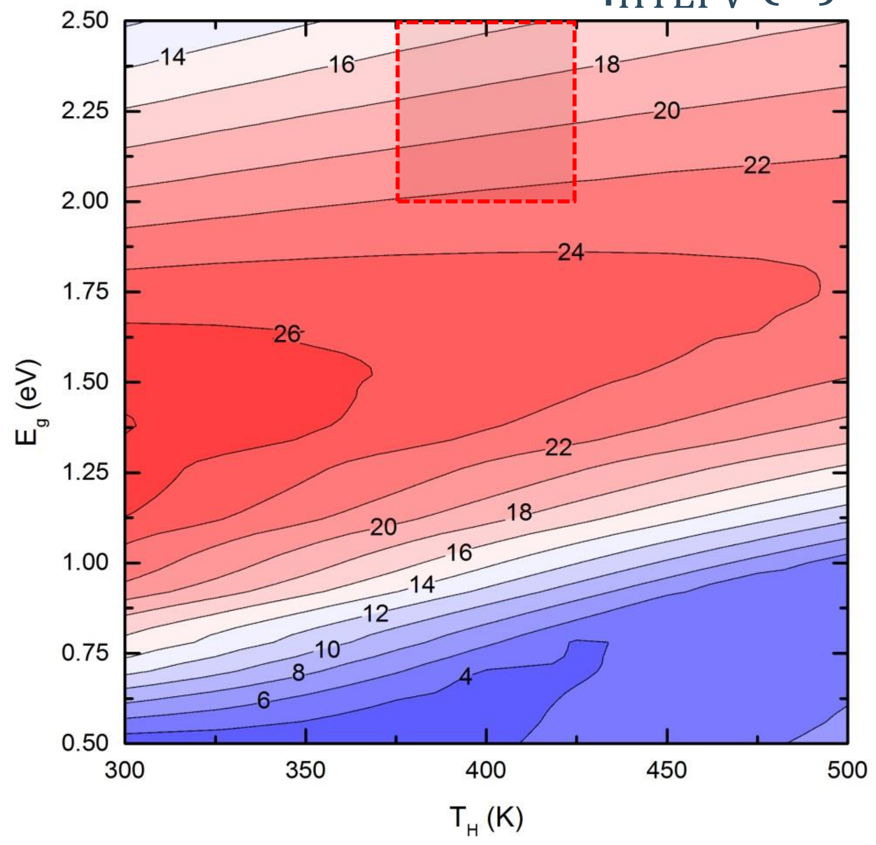
- Higher efficiencies for standard SJ solar cells with E_g > 1.75 eV
- Use of wide-bandgap PV materials, normally not considered

SGA

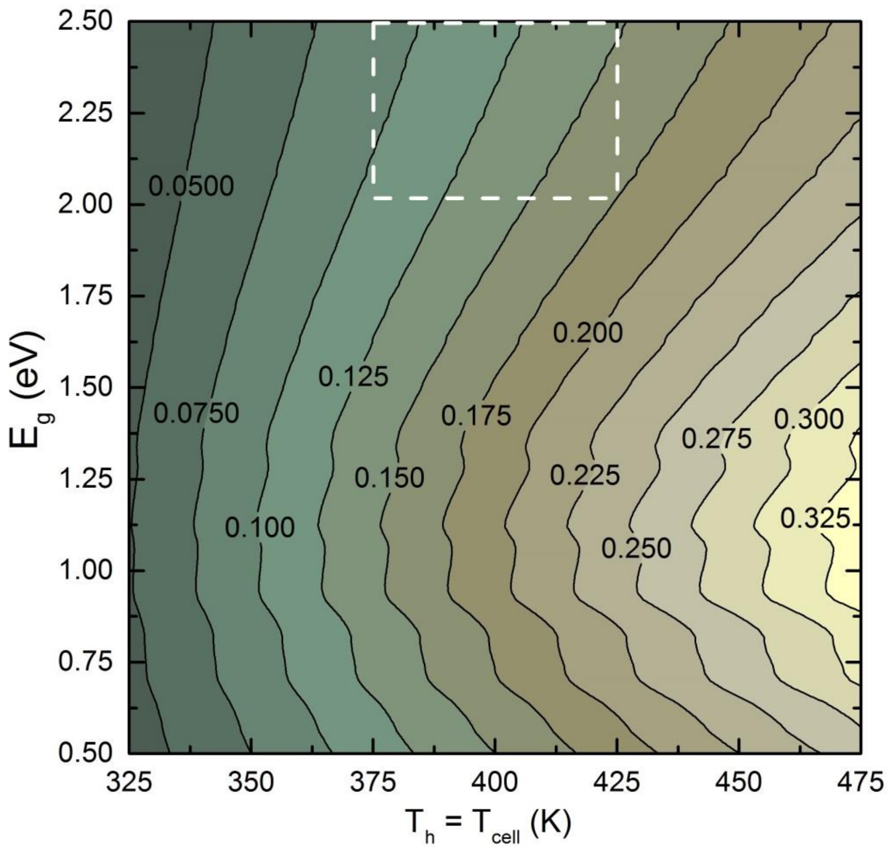
$\eta_{PV}(T)$



$\eta_{HTEPV}(T)$



Heat exchange to the ambient



HTEPV – SGA Case

$$(L_{2a}(E_g) + L_{2b}(E_g))\Phi_{sun} = \frac{1}{R_T}(T_{cell} - T_a)$$

R_T^{opt} = 0.1 – 0.175 m²K/W

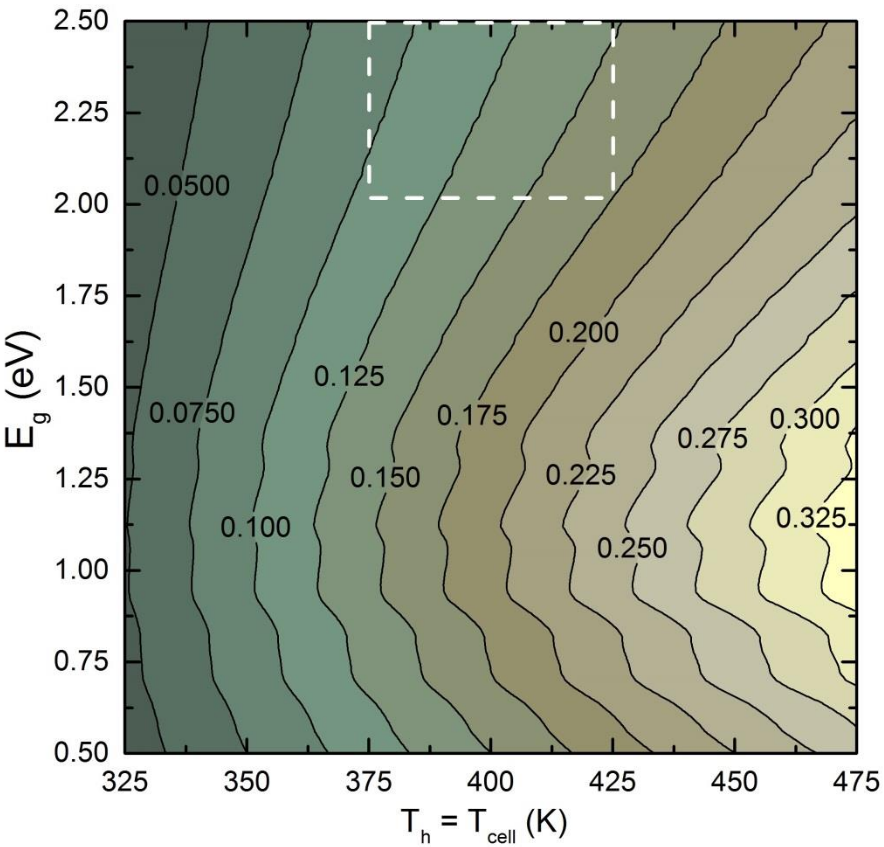
PV only

PV array type	R_T (m^{2}K/W)
Well cooled	0.02
Free standing	0.0208
Flat on roof	0.026
Not so well cooled	0.0342
Transparent PV	0.0455
Façade integrated	0.0538
On sloped roof	0.0563

x 50

E. Skoplaki, Solar Energy, 83, 422 – 427 (2009)

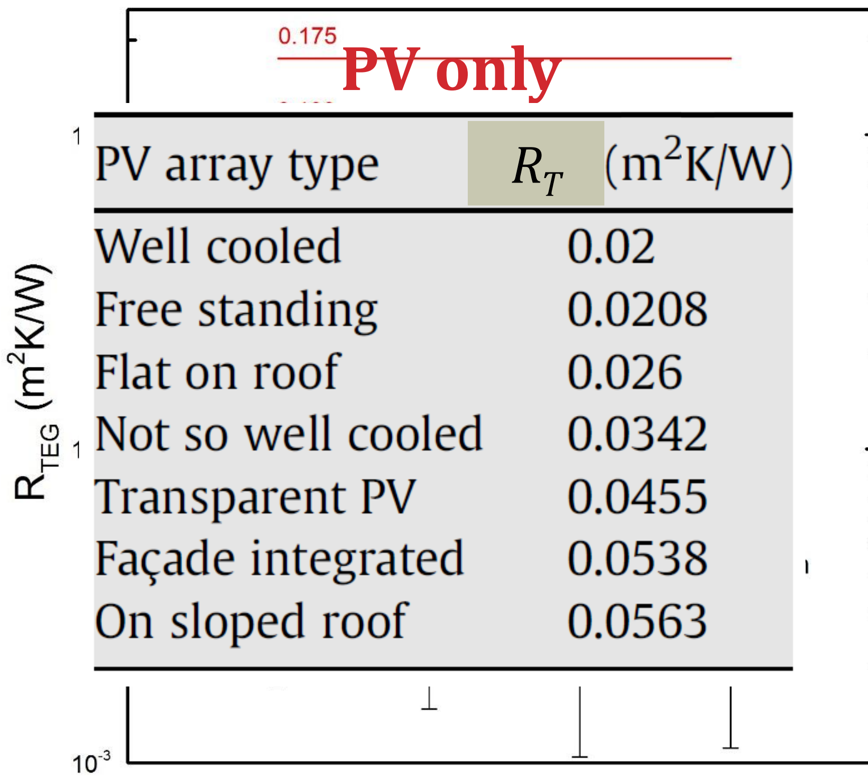
Heat exchange to the ambient



R_T^{opt} = 0.1 – 0.175 m²K/W

HTEPV – SSA Case

$$(L_{2a}(E_g) + L_{2b}(E_g))\Phi_{sun} = \frac{1}{R_T}(T_{cell} - T_a)$$



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E. Skoplaki, Solar Energy, 83, 422 – 427 (2009)

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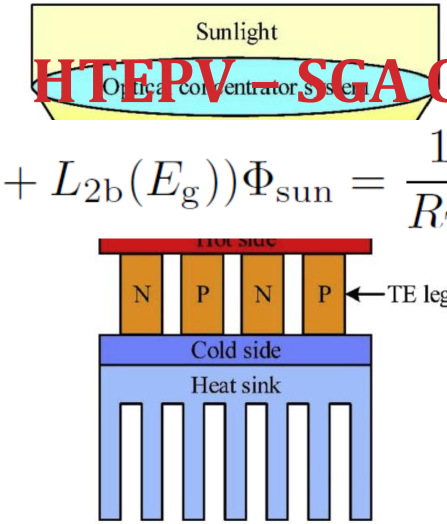
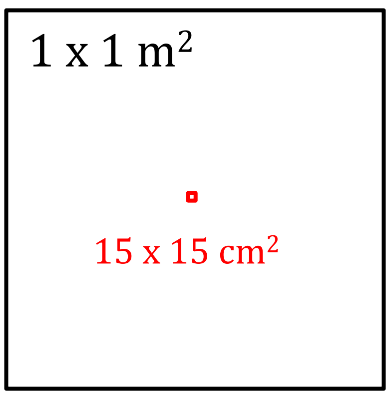
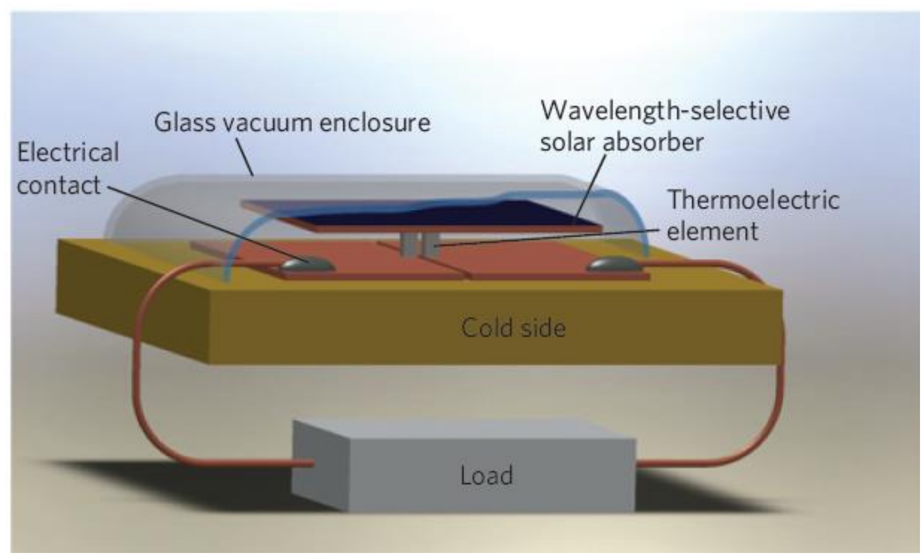


Optical concentration enables standard TEGs

Thermal concentration >> reduced TEGs





J. Zhang et al.; Energy 78, 895 – 903 (2014)
D. Kraemer et al.; Nat. Mater. 10, 422 – 427 (2011)

Summary

- STEGs are effective test benches to implement thermal concentration strategies
- STEGs will compete with PVs only for ZT > 2

- SGA-HTEPV proves hybridization advantages:
  - Higher efficiencies for PVs with E_g > 1.75 eV
  - New possibilities for wide-bandgap PV materials
  - Need for optical or thermal concentration due to thermal matching

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sinergy-project.eu

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