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Instituto de Energía Solar

AMADEUS project: ultra high temperature energy storage and conversion

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Instituto de Energía Solar

Universidad Politécnica de Madrid

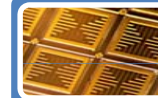
Solar Energy Institute of UPM



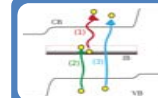
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Silicon technology



Multijunction solar cells, III-V semiconductors



Novel materials and concepts



Photovoltaic plants, BIPV, and smart grids



Concentrator Photovoltaics (CPV)



Thermo-photovoltaics (TPV) & Thermal Energy Storage

Documentary in TVE “Revolución Solar”

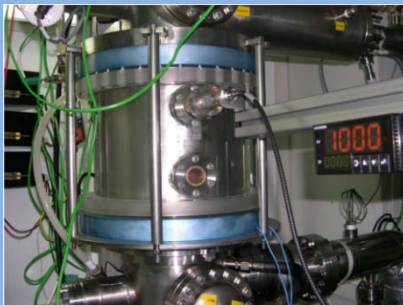
<http://www.rtve.es/alacarta/videos/la-aventura-del-saber/aventurarevsolar/4235638/>

Main equipment



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Silicon production



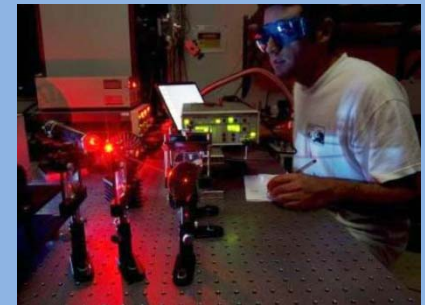
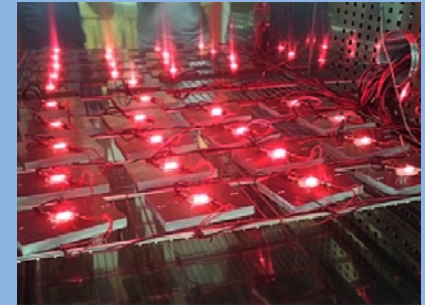
Epitaxial growth



Solar Cell fabrication



Characterization



Contents



1. State of the art of TES
2. Ultra-high temperature TES
3. Ultra-high temperature Energy Conversion: Thermo-PV
4. AMADEUS Project

- 1. State of the art of TES**
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Thermal Energy Storage (TES): State of the art



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Concentrated Solar Power represents 75% of global TES

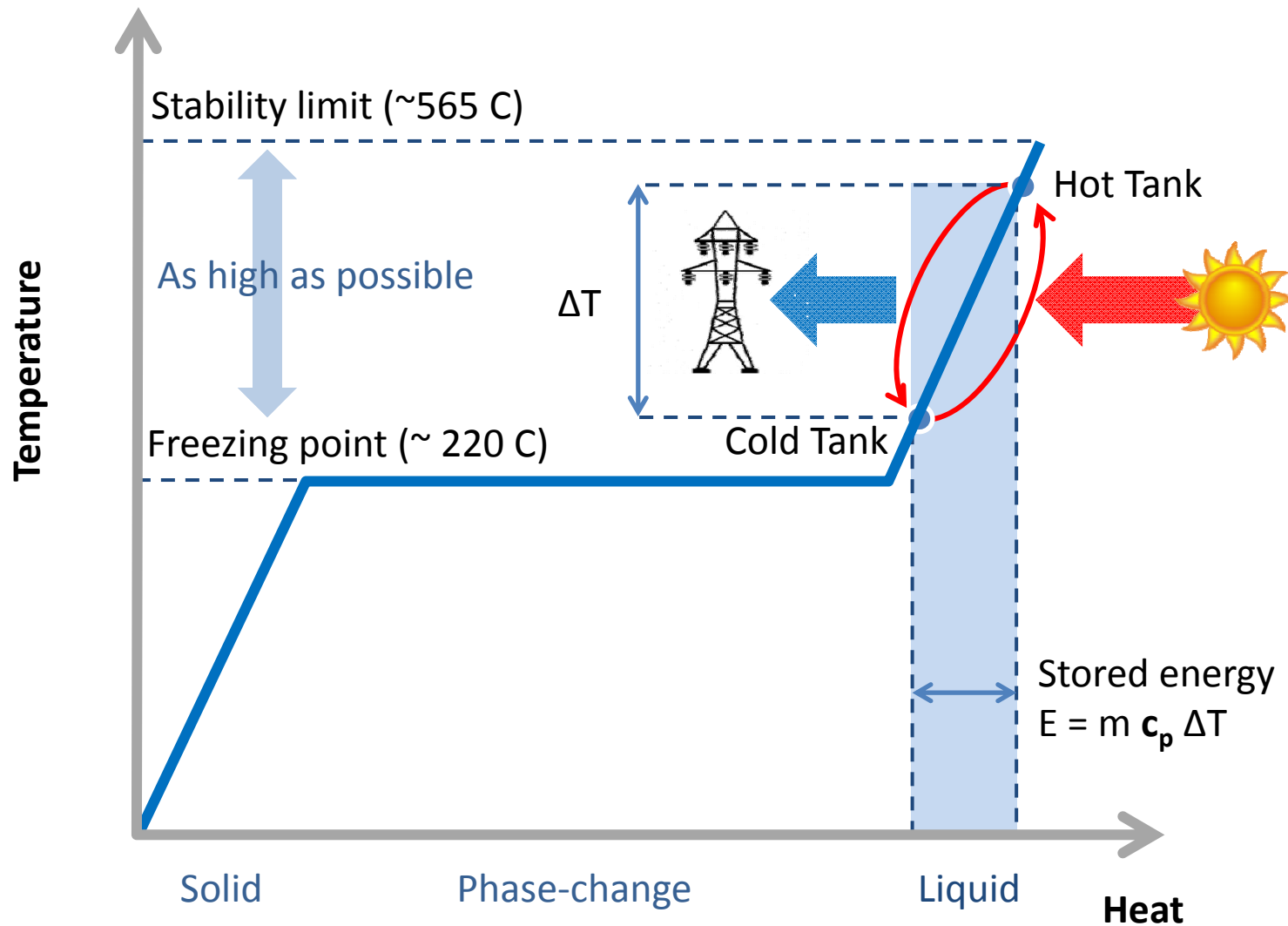


Central Tower
Gemasolar (Sevilla, Spain)

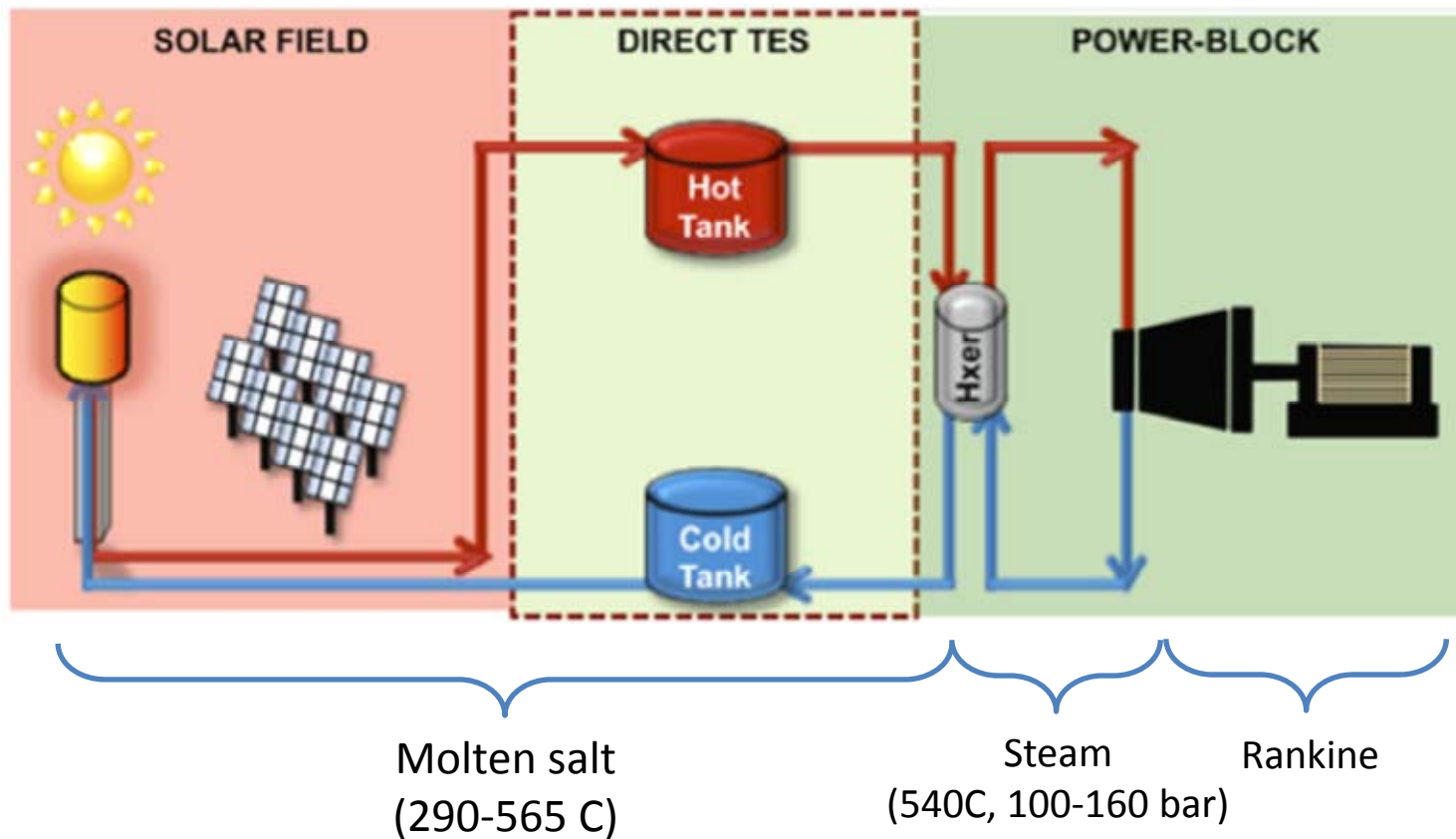


Parabolic-trough
Andasol 3 (Granada, Spain)

Sensible heat storage in molten salts



An example: direct systems (typical of central tower)



M. Liu et al. Renewable and Sustainable Energy Reviews 53 (2016) 1411–1432

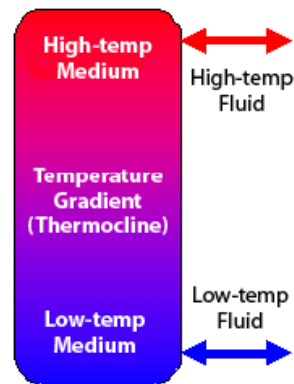
Direct systems (typical of central tower)



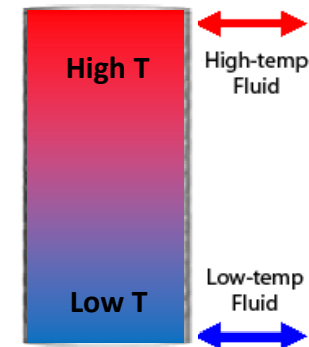
R&D directions on TES



Thermocline



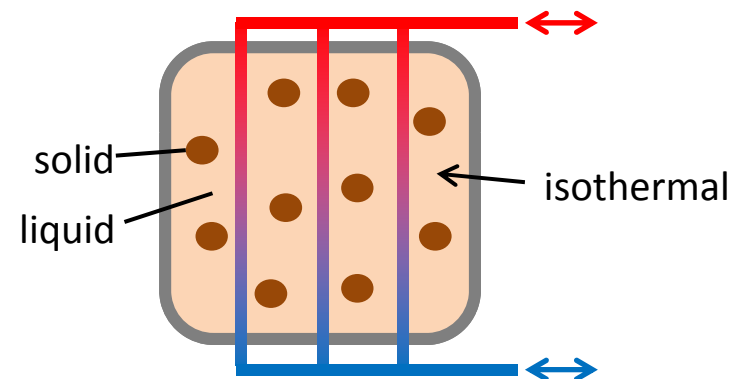
Packed Bed



Solids

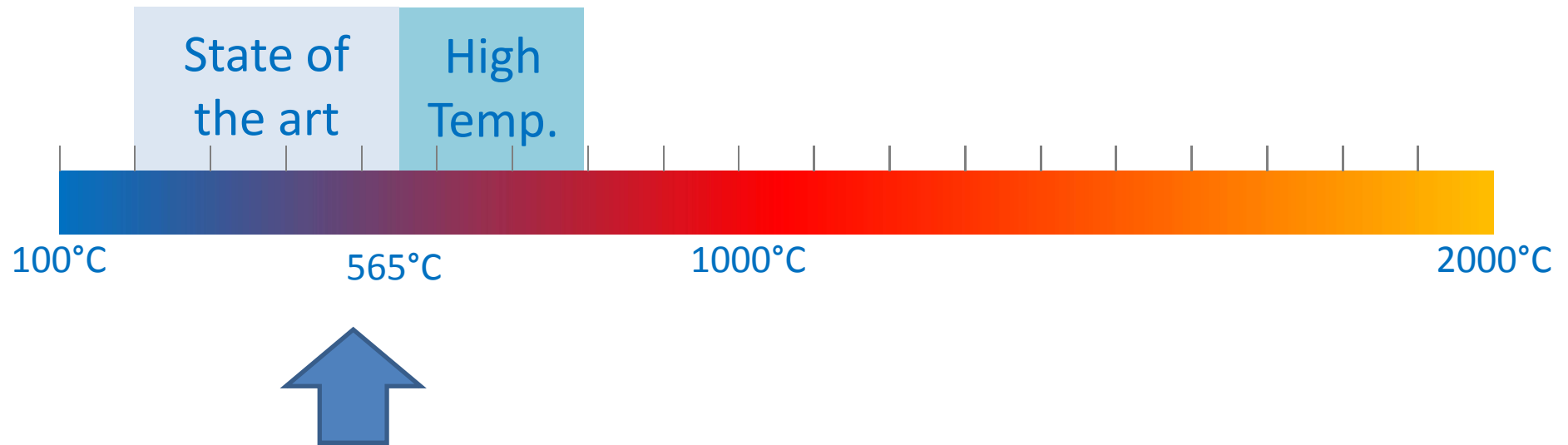


Latent heat



1. State of the art of TES
- 2. Ultra-high temperature TES**
3. Ultra-high temperature Energy Conversion: Thermo-PV
4. AMADEUS Project

Thermal Energy Storage: Temperature Ranges

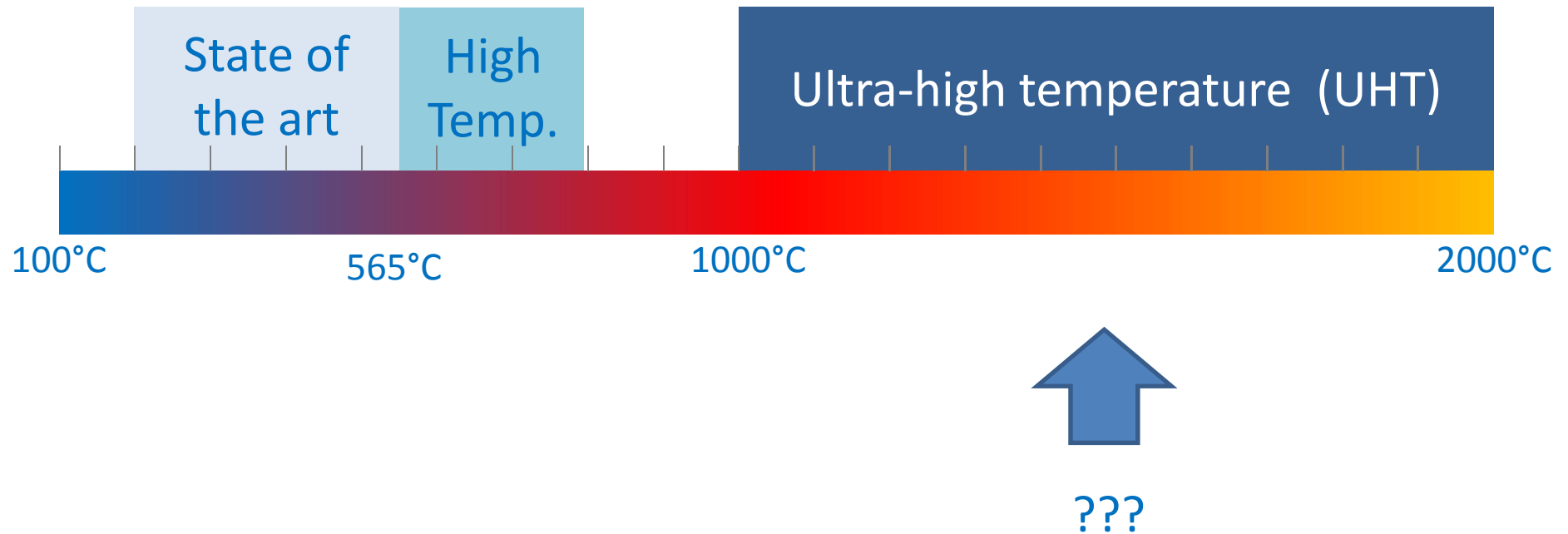


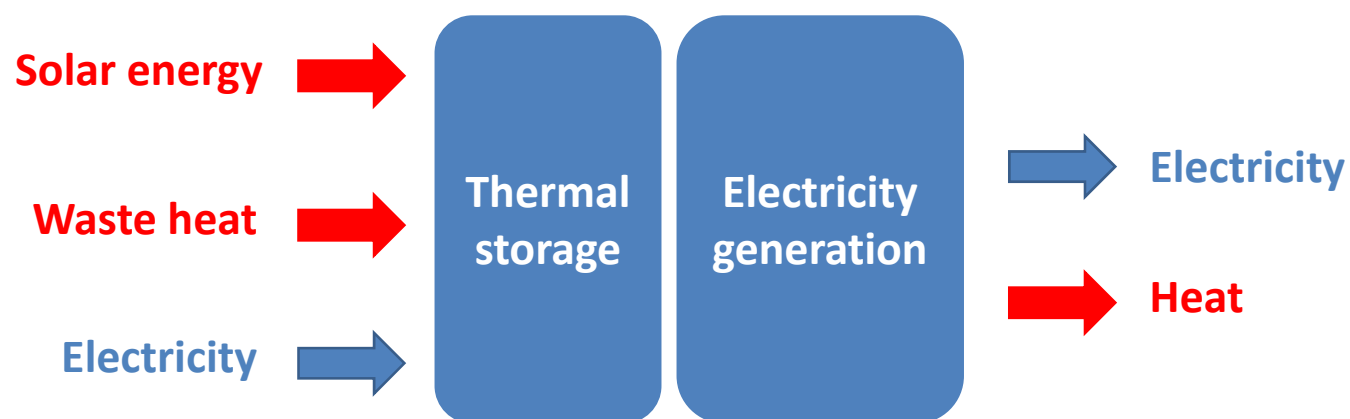
- ✓ Storage: Sensible heat (molten salts)
- ✓ Conversion: Dynamic engines (turbines)

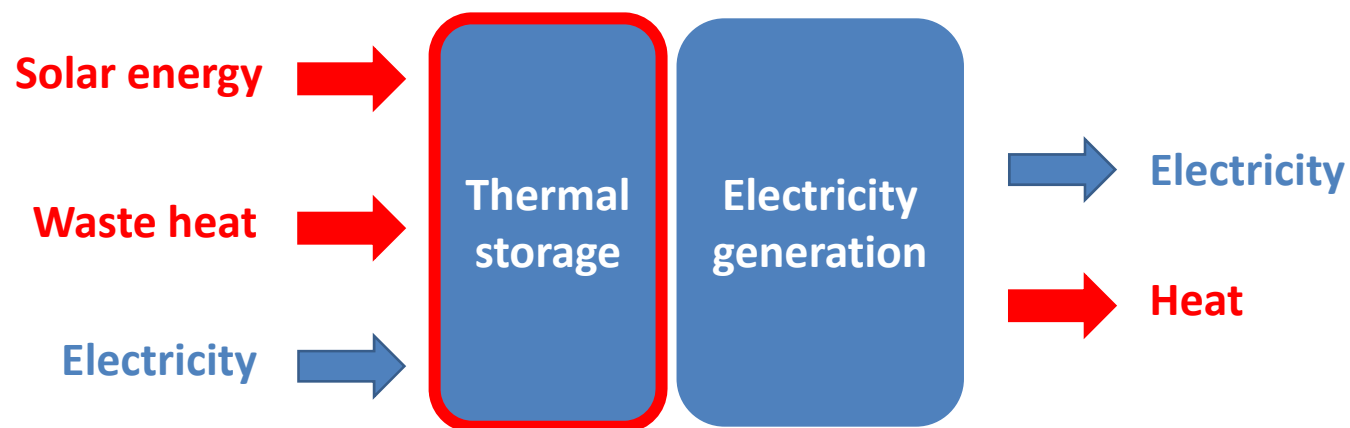
Thermal Energy Storage: Temperature Ranges



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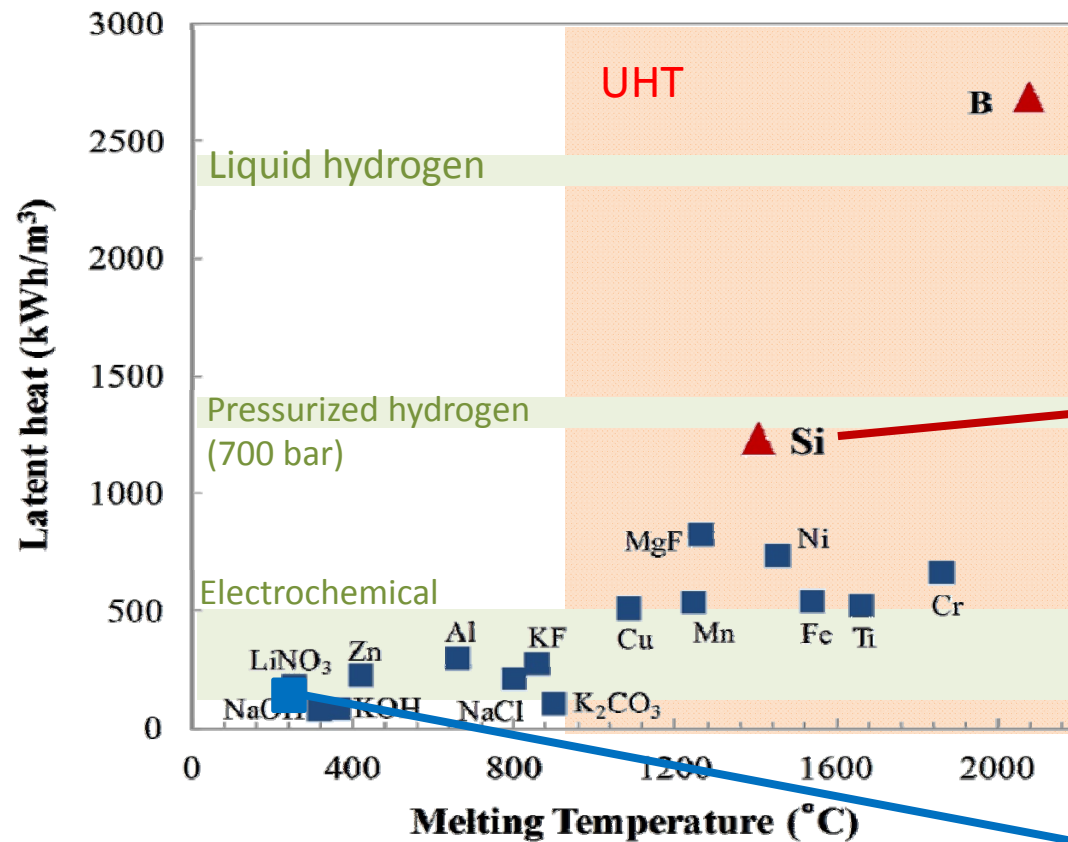




Phase Change Materials: Latent Heat



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Silicon

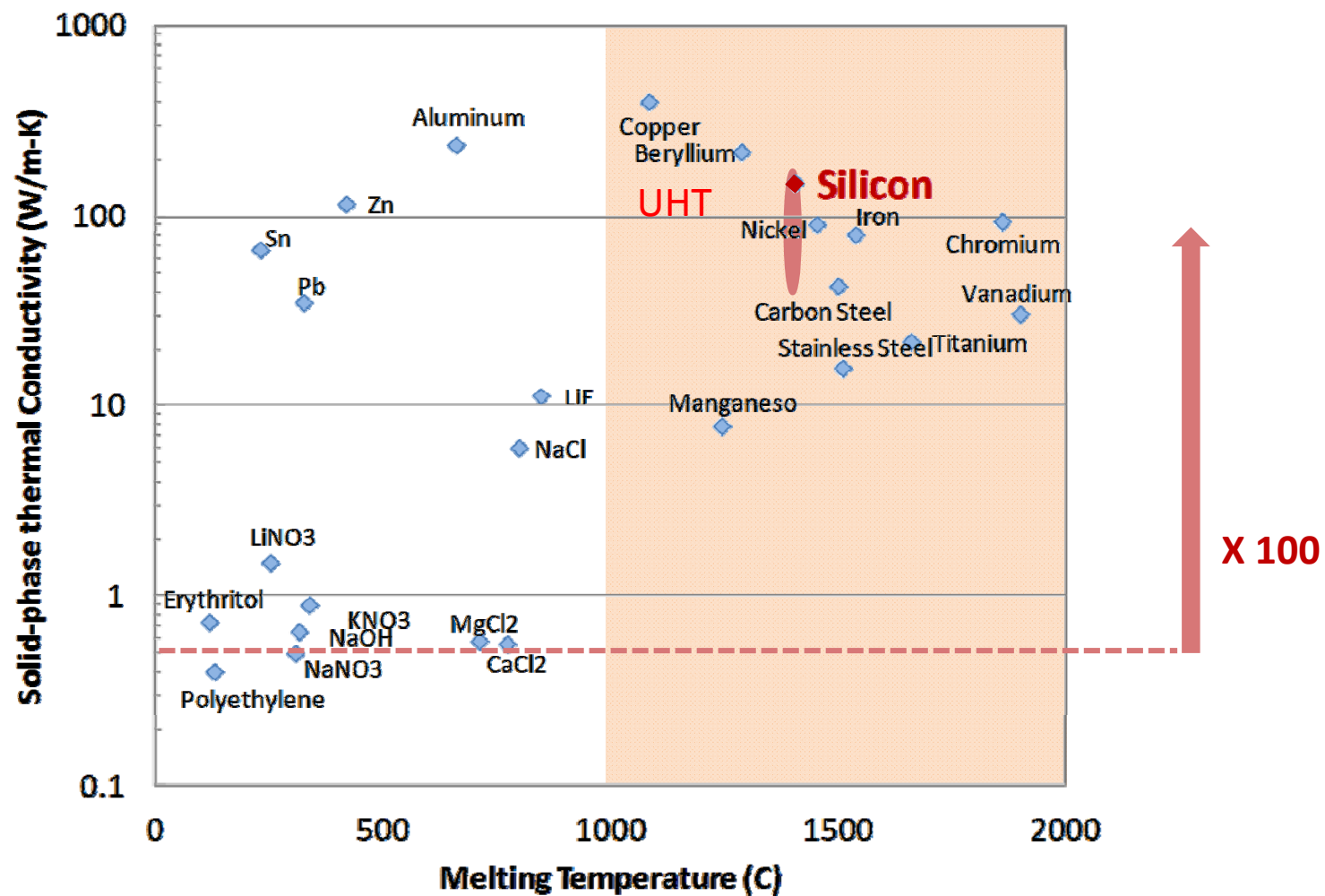
- ✓ 1200 kWh/m³
- ✓ 2 \$/kg => 4 \$/kWh

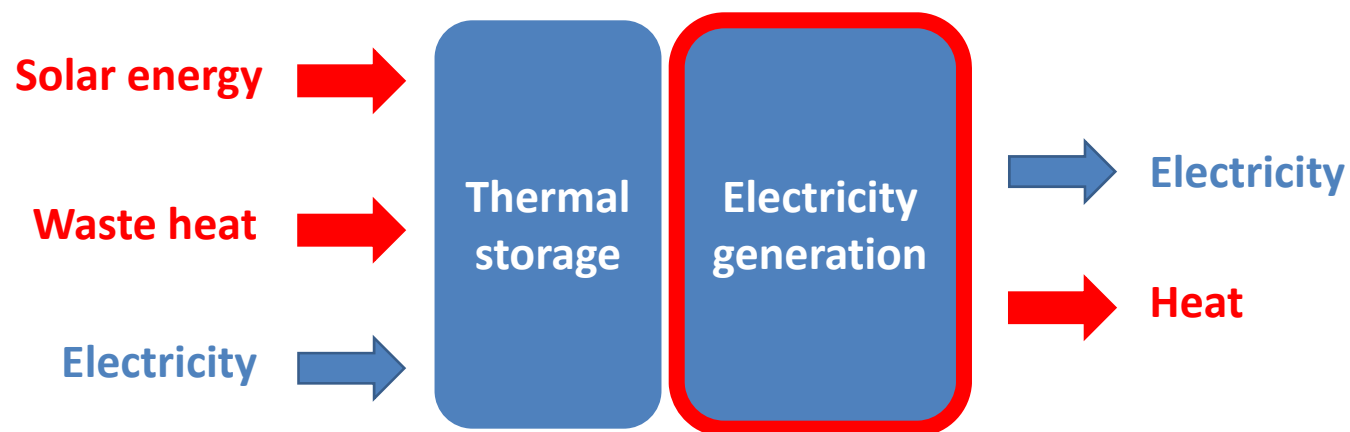
5 times cheaper
12 times smaller

NaNO₃

- ✓ 96 kWh/m³
- ✓ 1 \$/kg => 20 \$/kWh

Phase Change Materials: Thermal Conductivity

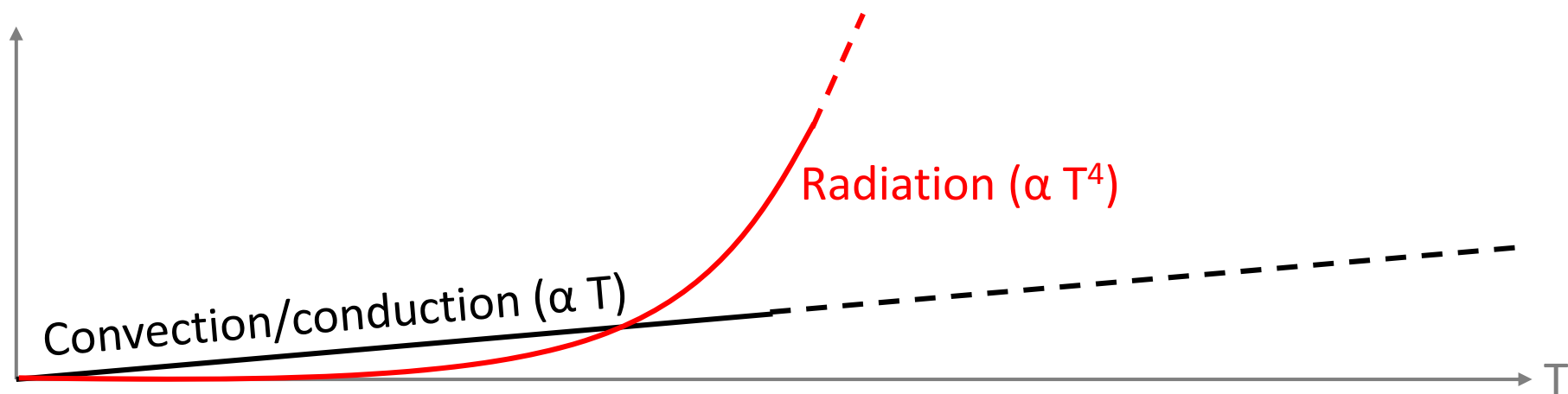
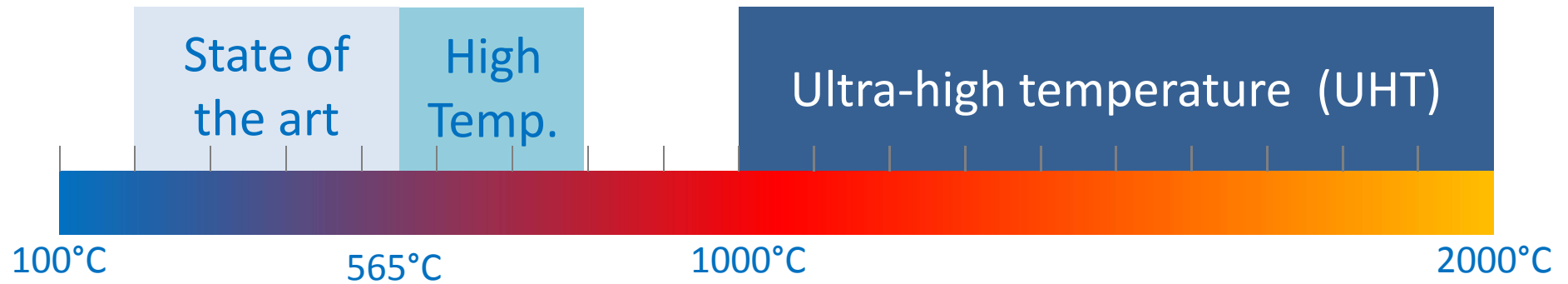




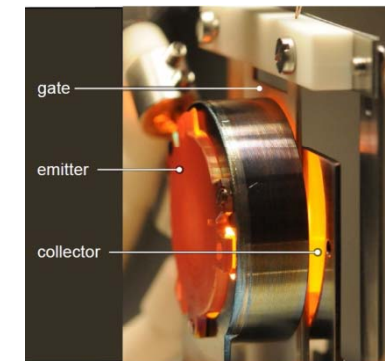
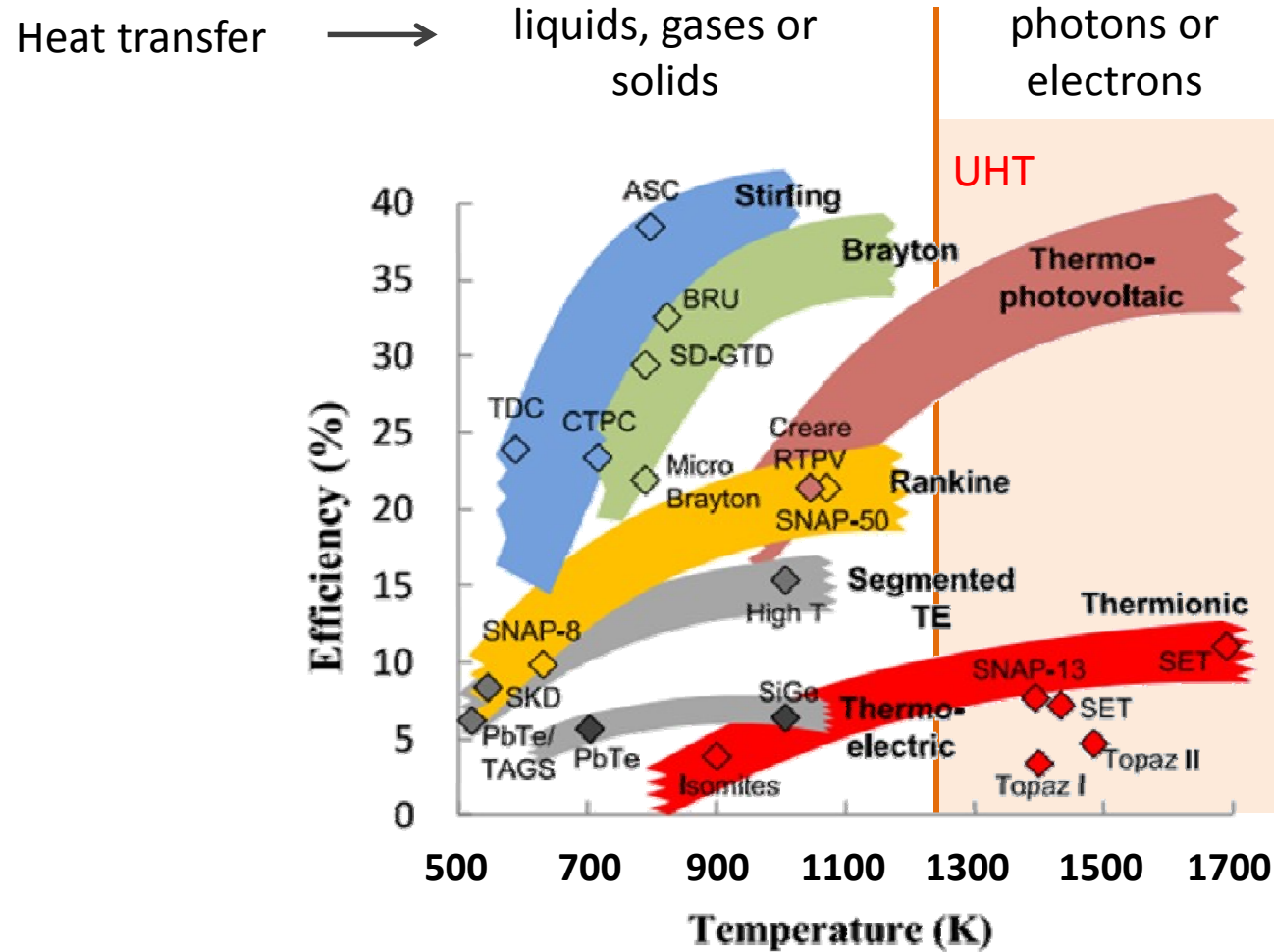
Thermal Energy Storage: Energy Conversion



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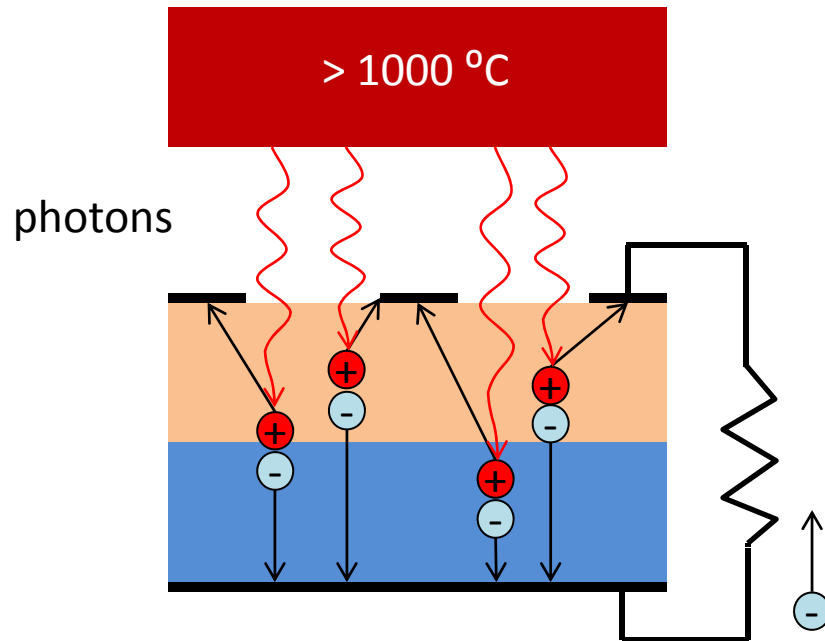


Energy Conversion



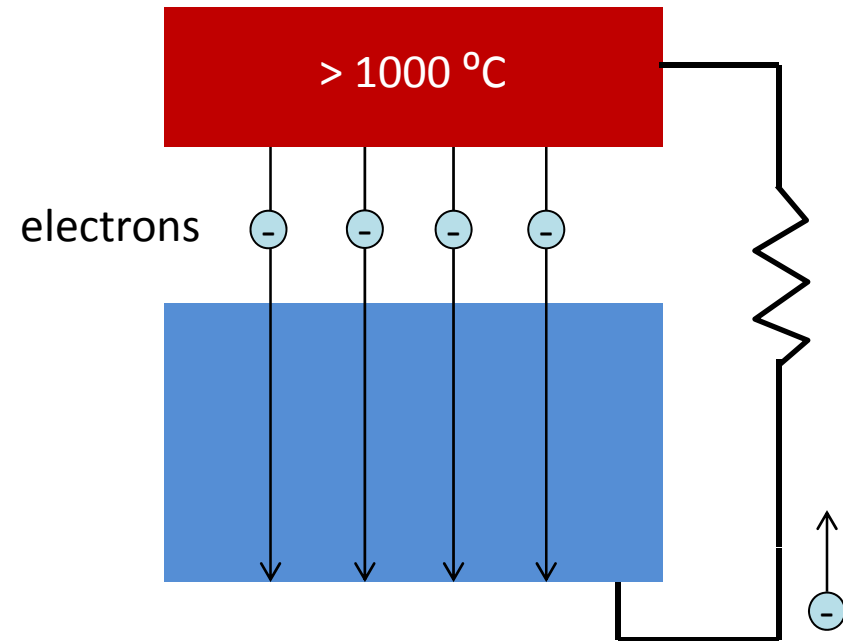
A. Datas, A. Martí, Thermophotovoltaic energy in space applications: Review and future potential, Solar Energy Materials and Solar Cells, Volume 161, March 2017, Pages 285-296

Thermo-Photovoltaic



- ✓ Based on Semiconductors
- ✓ Cold side at $\sim 50\text{ }^{\circ}\text{C}$
- ✓ State of art efficiency 20-25%

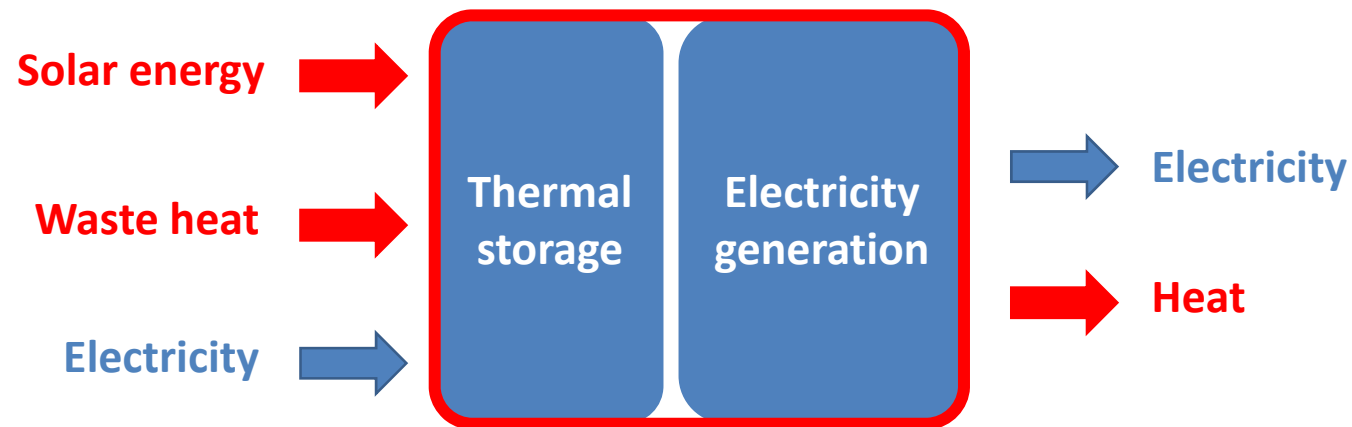
Thermionic



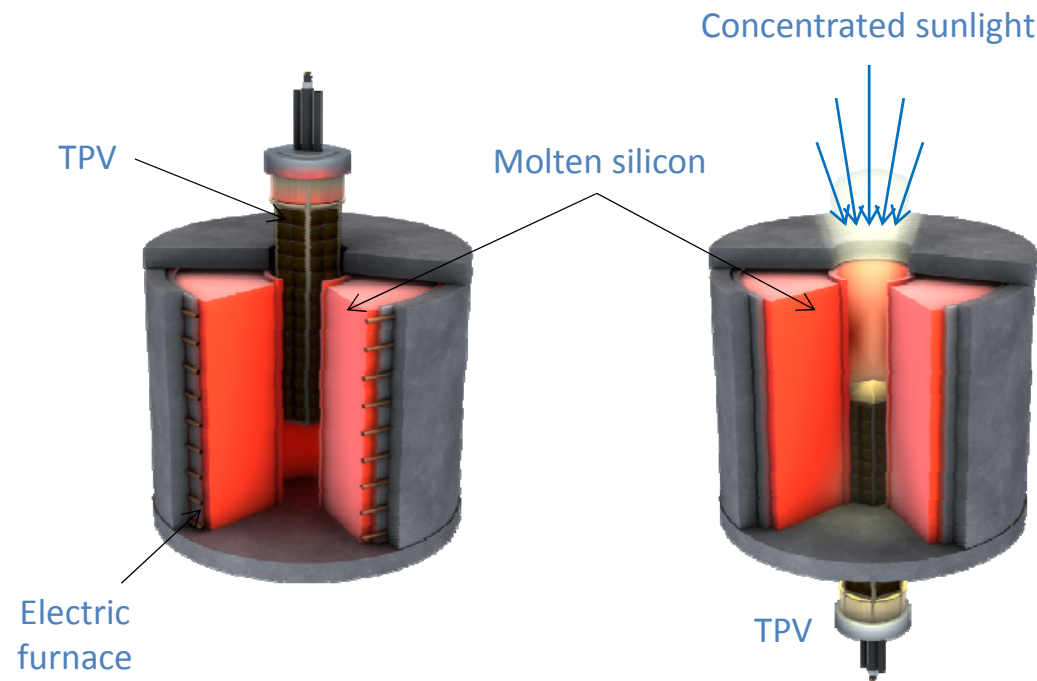
- ✓ Based on refractory metals
- ✓ Cold side at several 100's $^{\circ}\text{C}$
- ✓ State of art efficiency 5-10 %

K. Aizat, et al. Review on Thermionic Energy Converters, IEEE Trans Elect Dev, Vol. 63, NO. 6, JUNE 2016
T. Bauer "Thermophotovoltaics: Basic principles and Critical aspects of System Design", Springer.

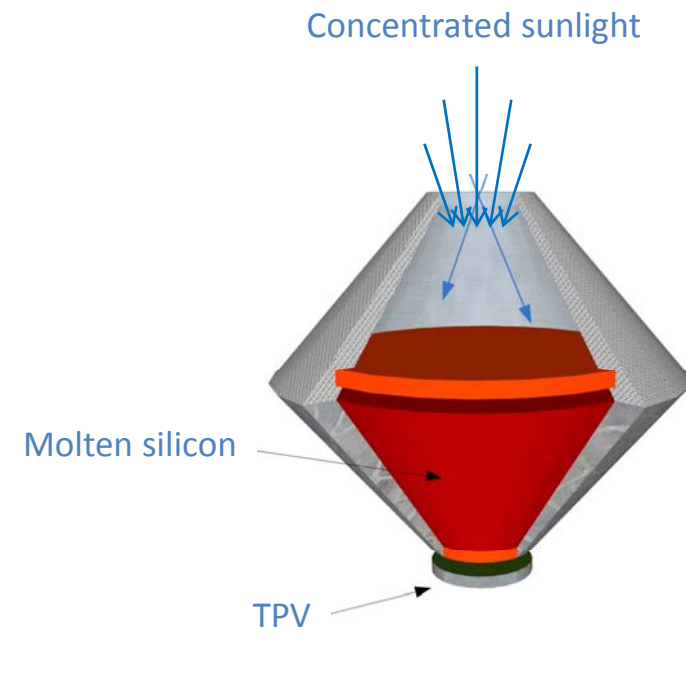
Full system ?



System examples



A. Datas, et. al. Energy, Vol 107, pp 542–549 (2016)



A. Datas, et al. Solar Energy, Vol 96, pp 33–45 (2013)

Patents: ES261062, US2015/0256119A1, WO2015/132305A1

Application in Solar Thermal Power Generation



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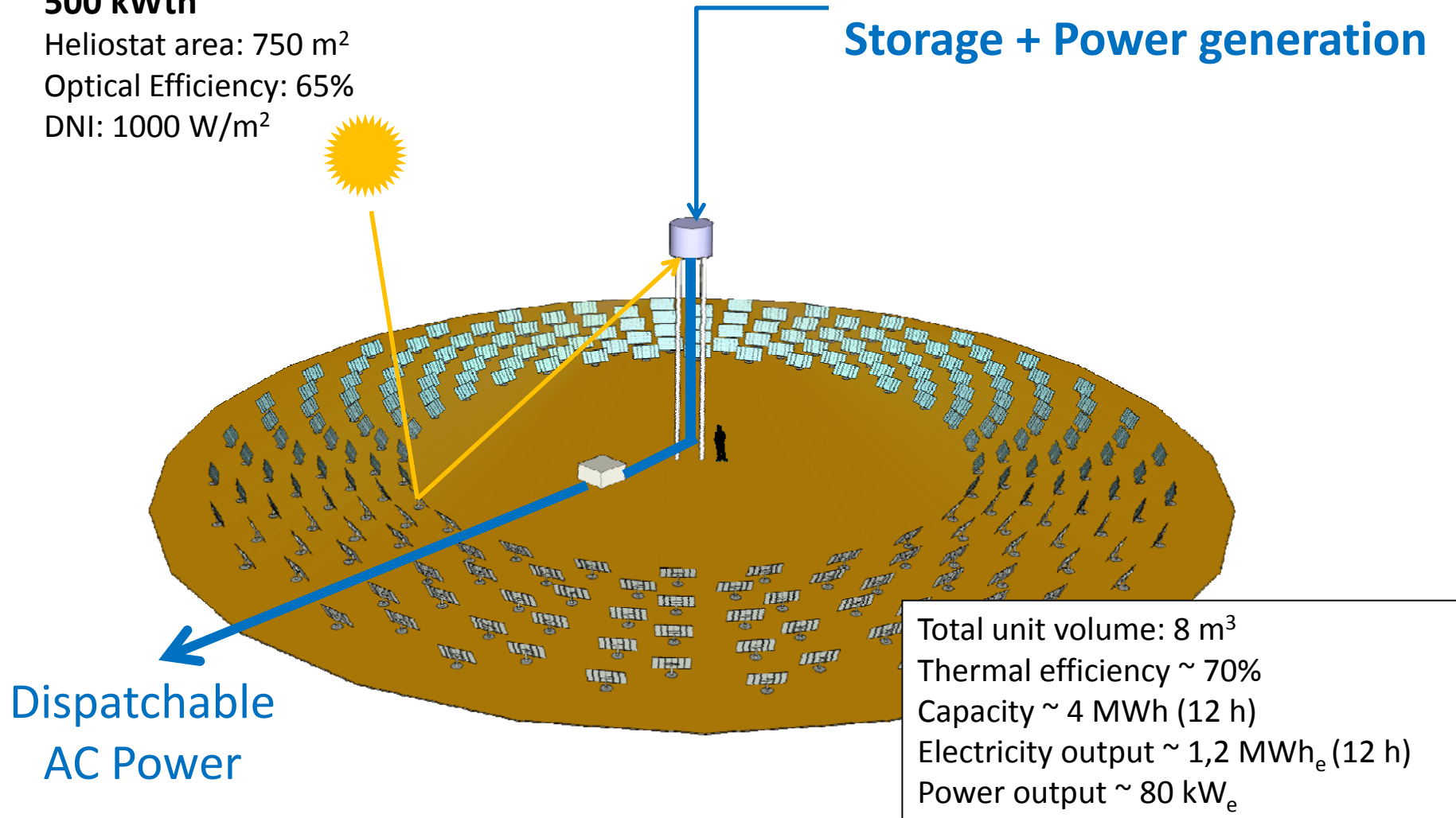
500 kW_{th}

Heliostat area: 750 m²

Optical Efficiency: 65%

DNI: 1000 W/m²

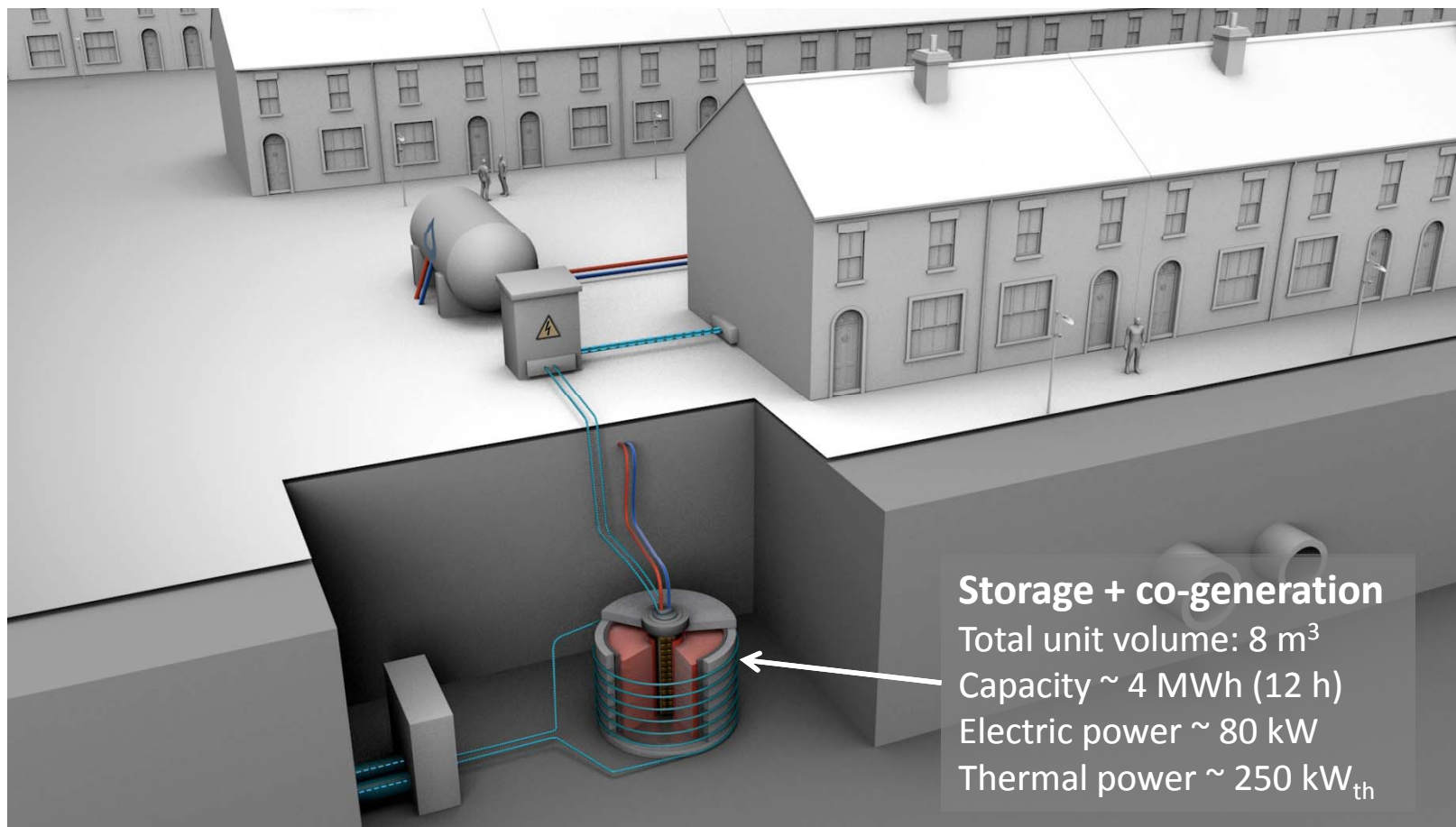
One Small Unit =
Storage + Power generation



Application in Electricity Storage and district heating/cooling

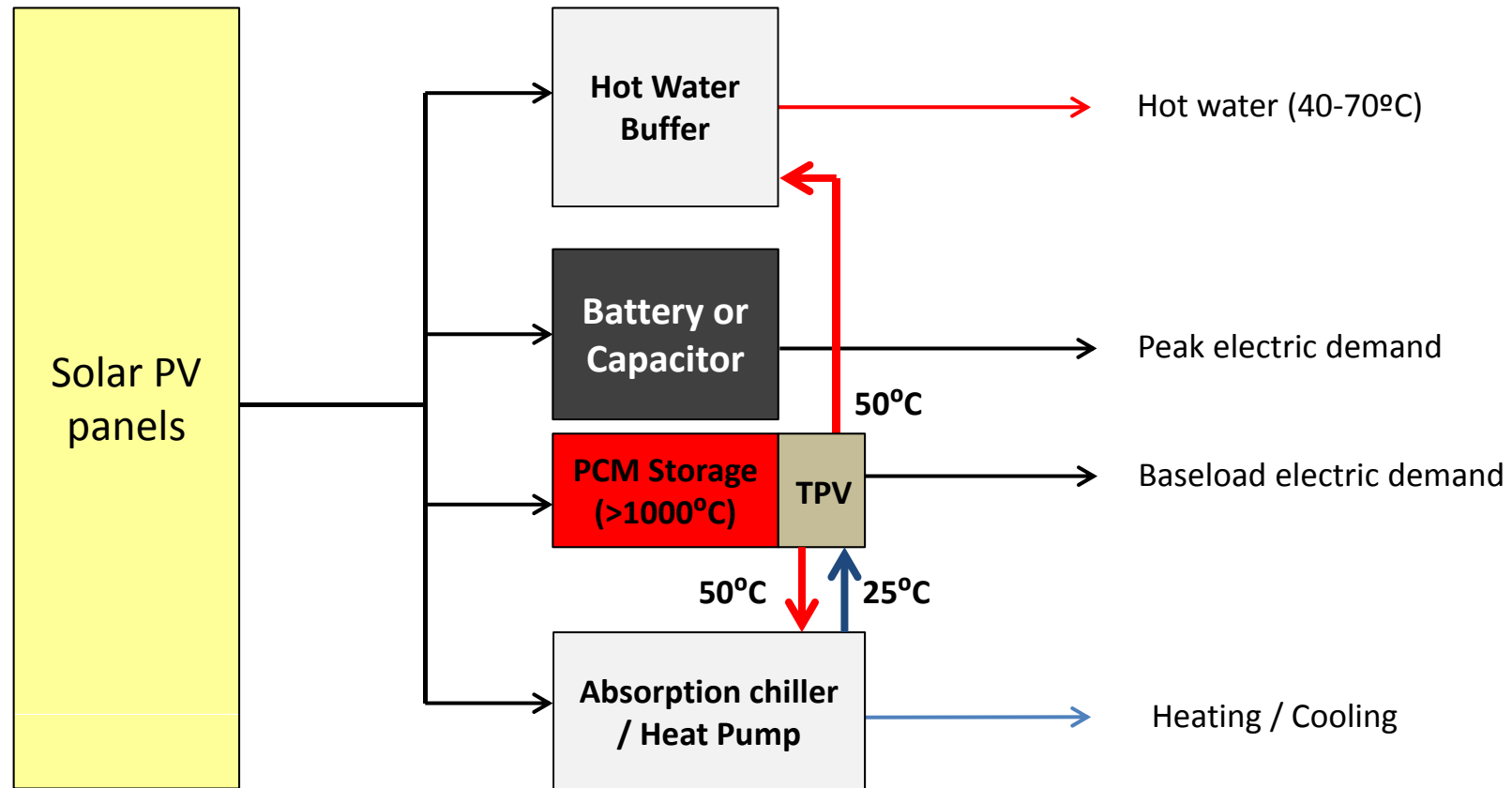


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~ 150 homes

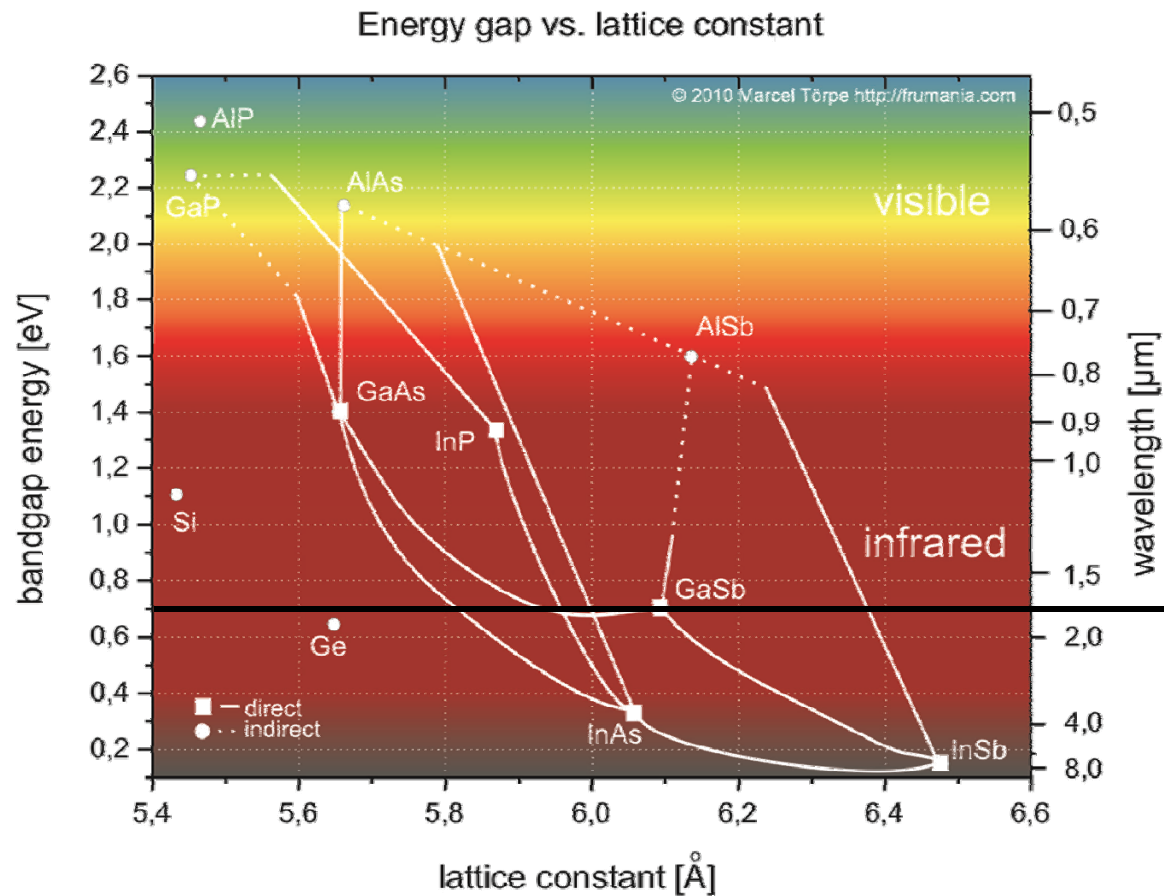
Application in Electricity Storage and district heating/cooling





1. State of the art of TES
2. Ultra-high temperature TES
- 3. Ultra-high temperature Energy Conversion: Thermo-PV**
4. AMADEUS Project

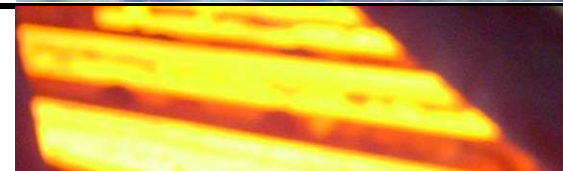
Thermophotovoltaics: Infrared semiconductors



Solar-PV



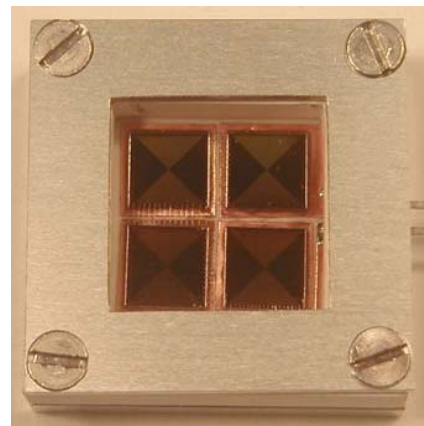
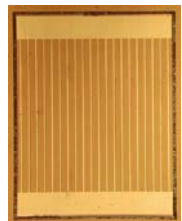
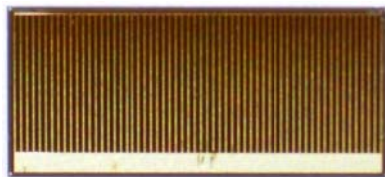
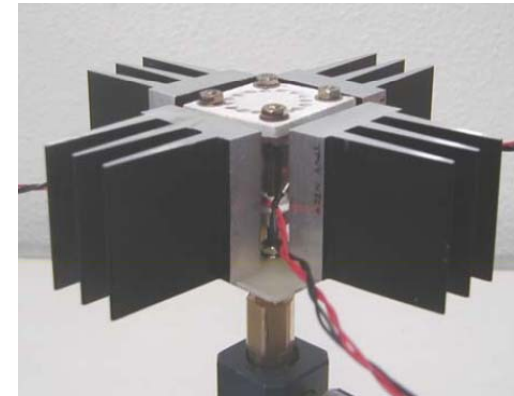
Thermo-PV



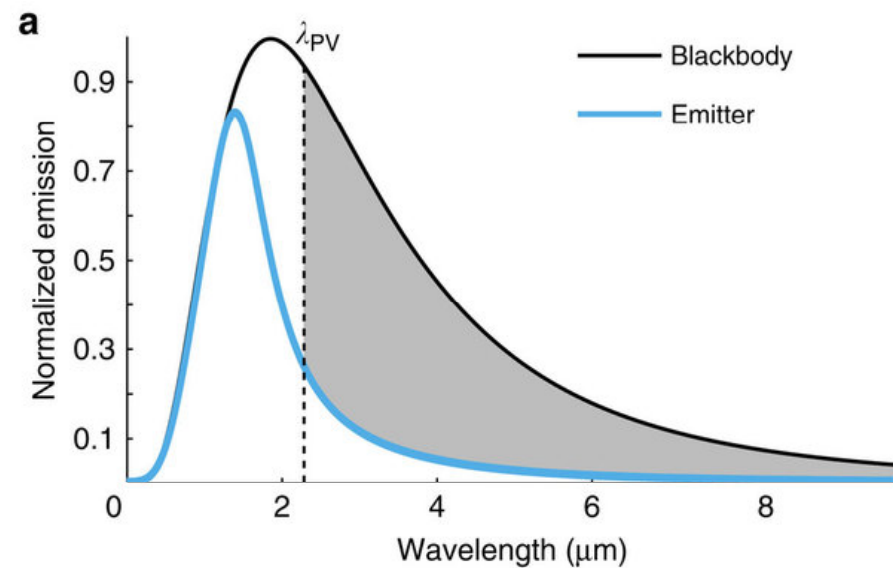
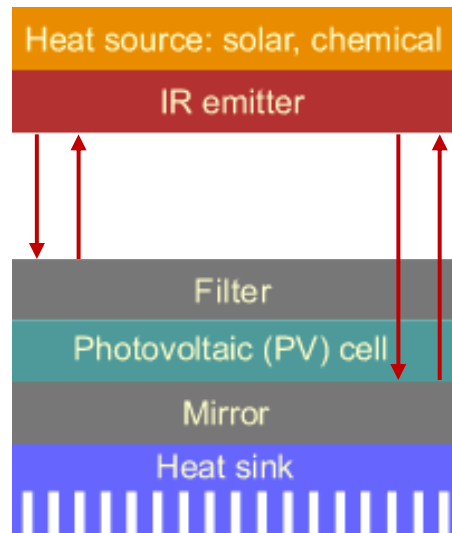
Thermophotovoltaics: Infrared semiconductors



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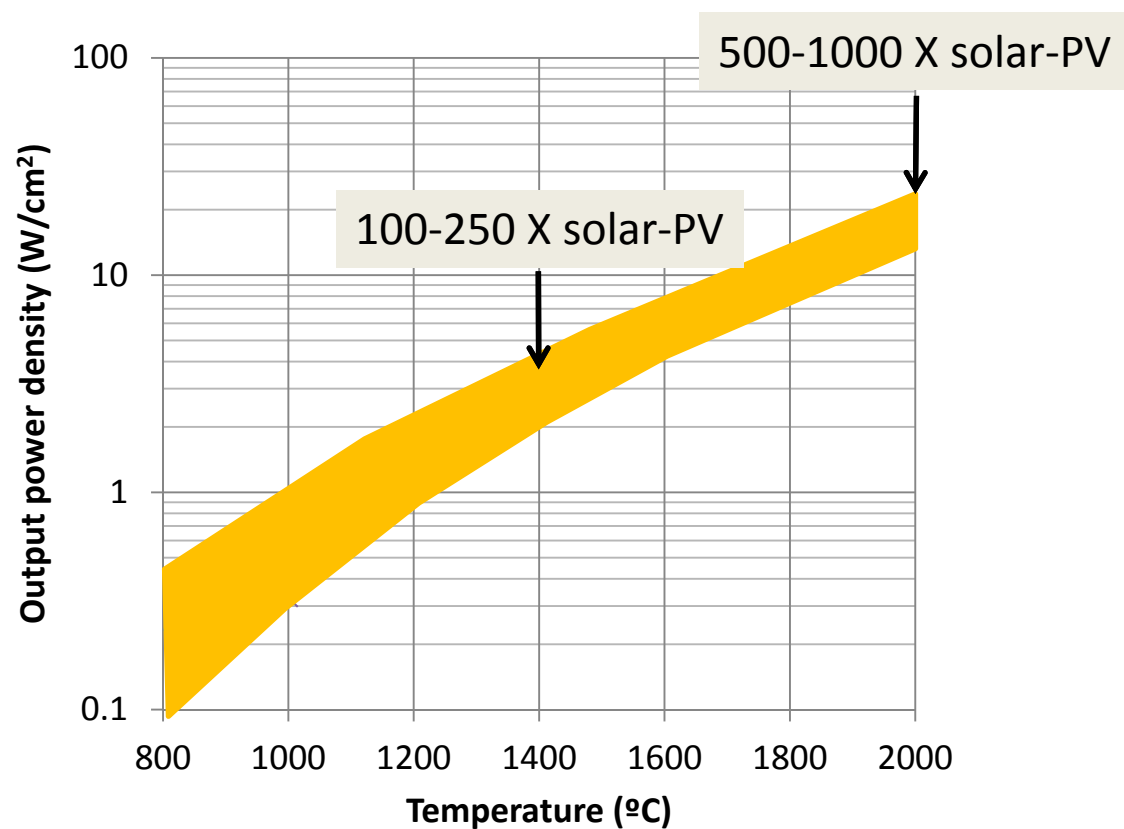
Thermophotovoltaics: Conversion efficiency



State of the art $\sim 25\%$ (@1100 °C)

B. Wernsman, et al. Greater Than 20% Radiant Heat Conversion Efficiency of a Thermophotovoltaic Radiator/Module System Using Reflective Spectral Control, IEEE TRANSACTIONS ON ELECTRON DEVICES, VOL. 51, NO. 3, MARCH 2004

Thermophotovoltaics: Power density



Thermo-photovoltaics research at IES-UPM



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- Started in 1999
- Historical motivation: Capability of manufacturing GaSb TPV cells
- First projects: micro-power generation in domestic furnaces (power conditioning)



Diffusion furnace
(GaSb cell fabrication)

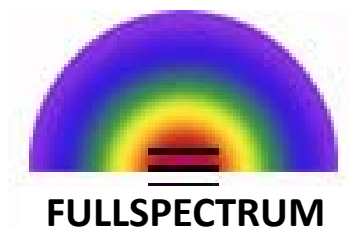


GaSb TPV cell



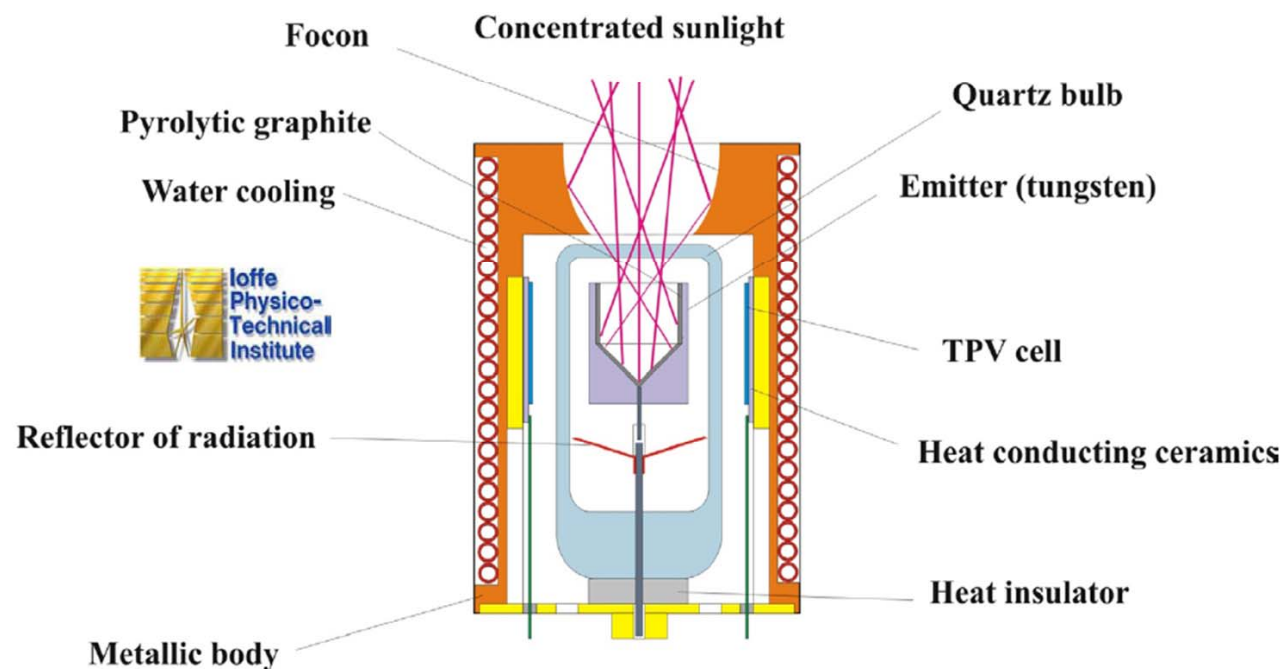
First TPV applications





Solar Thermo-Photovoltaics (STPV)

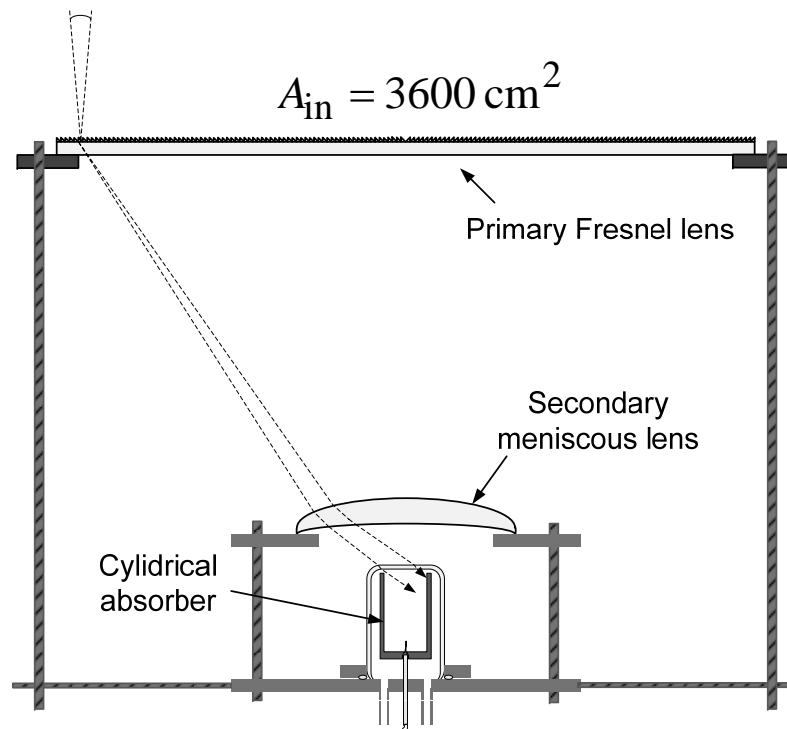
Theoretical efficiency limit $\sim 85.4\%$



FULLSPECTRUM project results



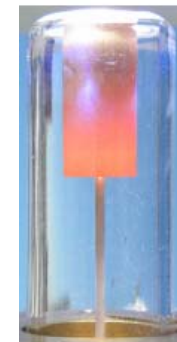
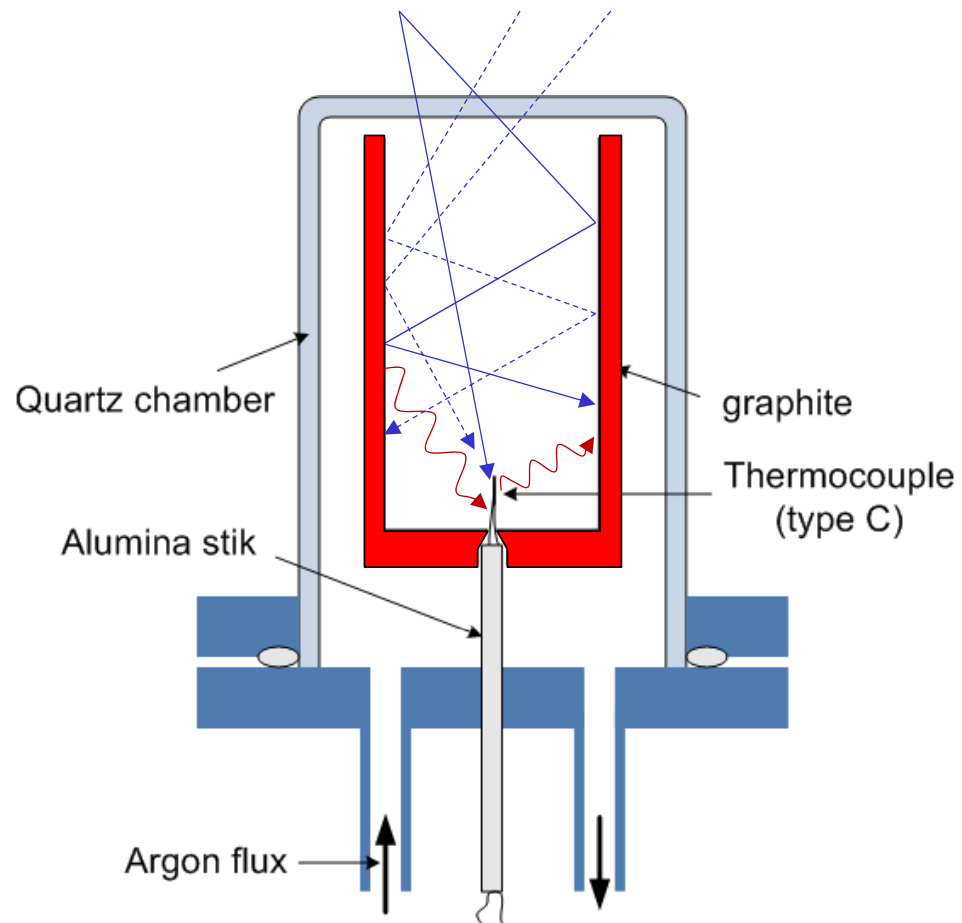
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FULLSPECTRUM project results



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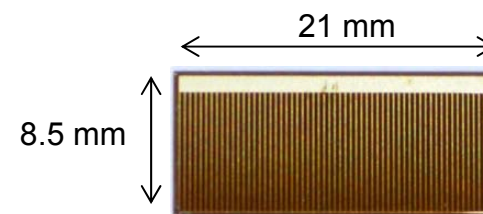


800-1400 degC

FULLSPECTRUM project results

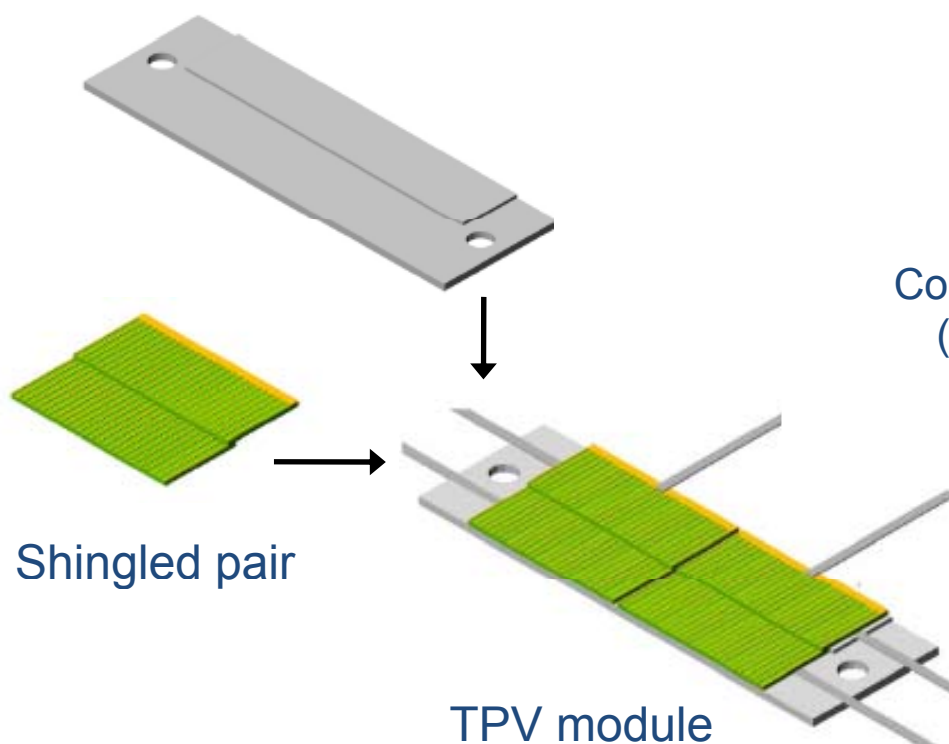


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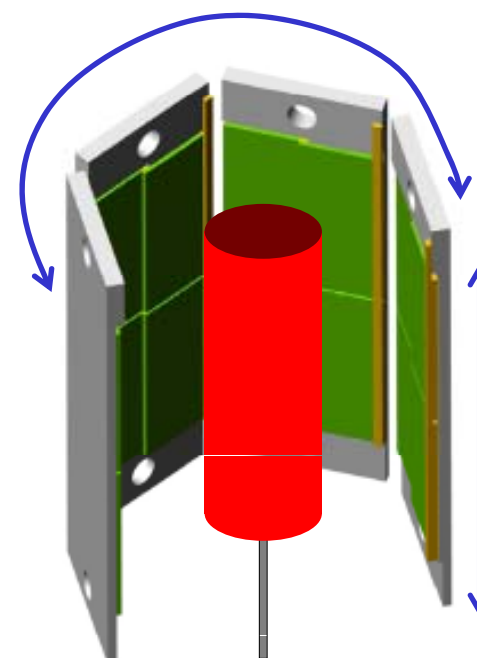


Fraunhofer
ISE

Terraced Substrate



Series
Connection
(12 cells)



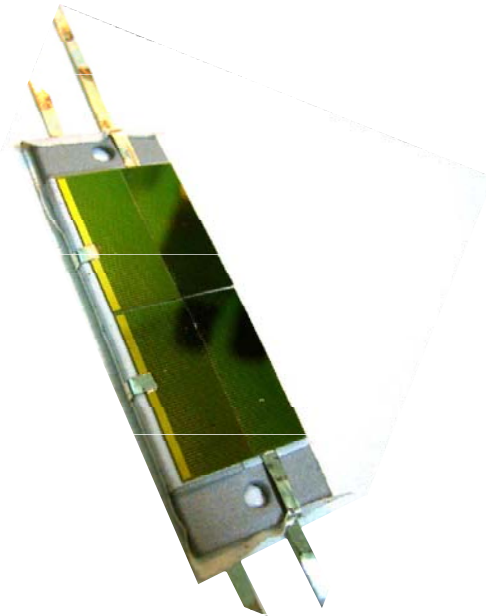
Parallel
Connection
(2 cells)

FULLSPECTRUM project results



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TPV module



Full TPV generator



FULLSPECTRUM project results

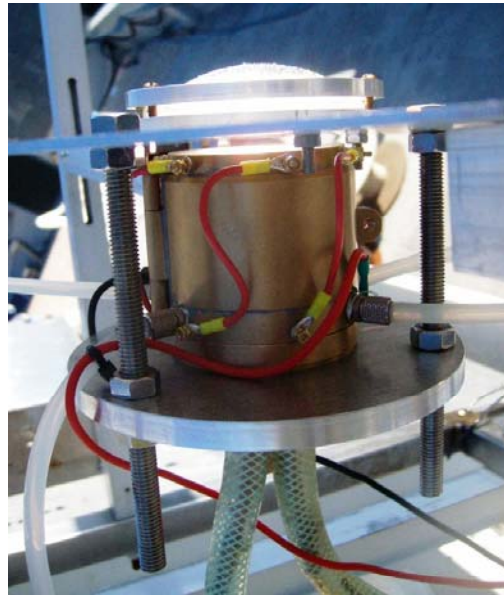


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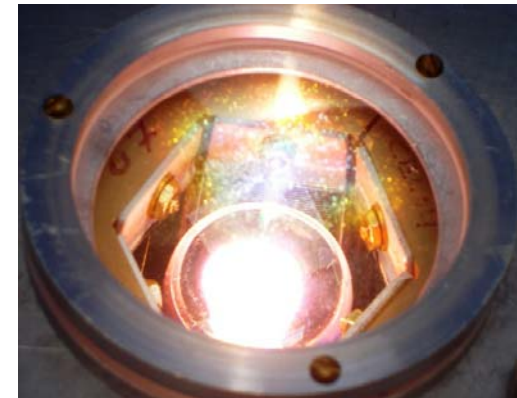


Full STPV system

TPV generator



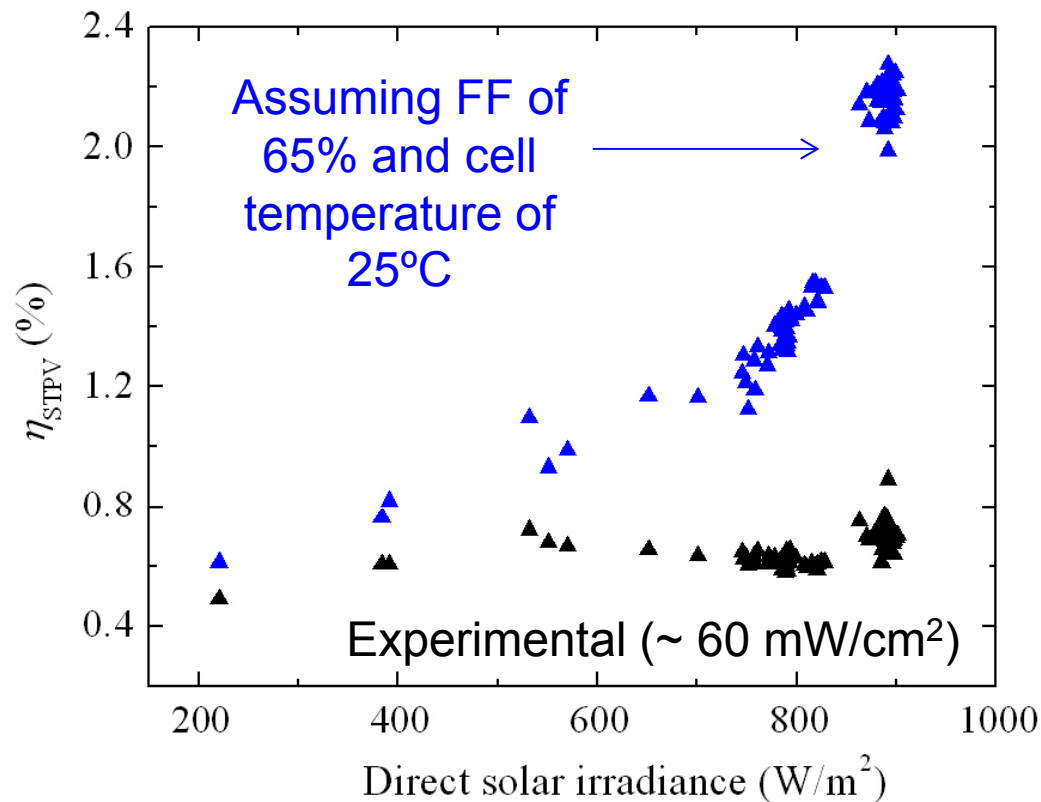
Sunlight input view



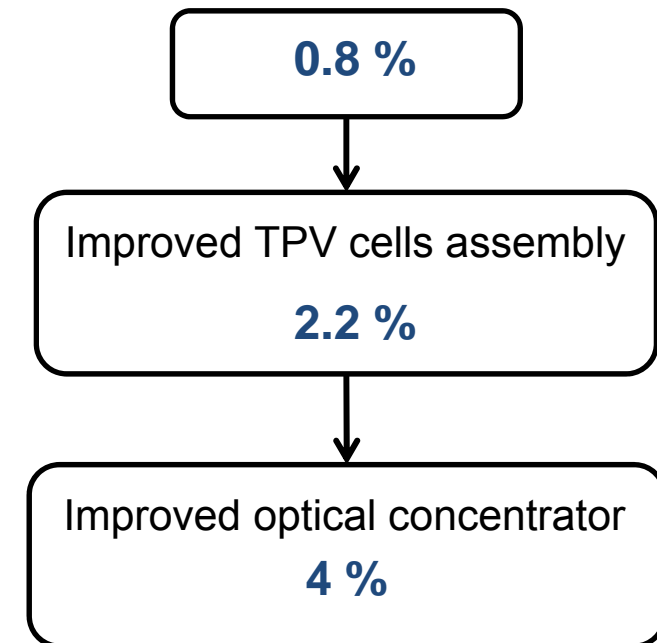
FULLSPECTRUM project results



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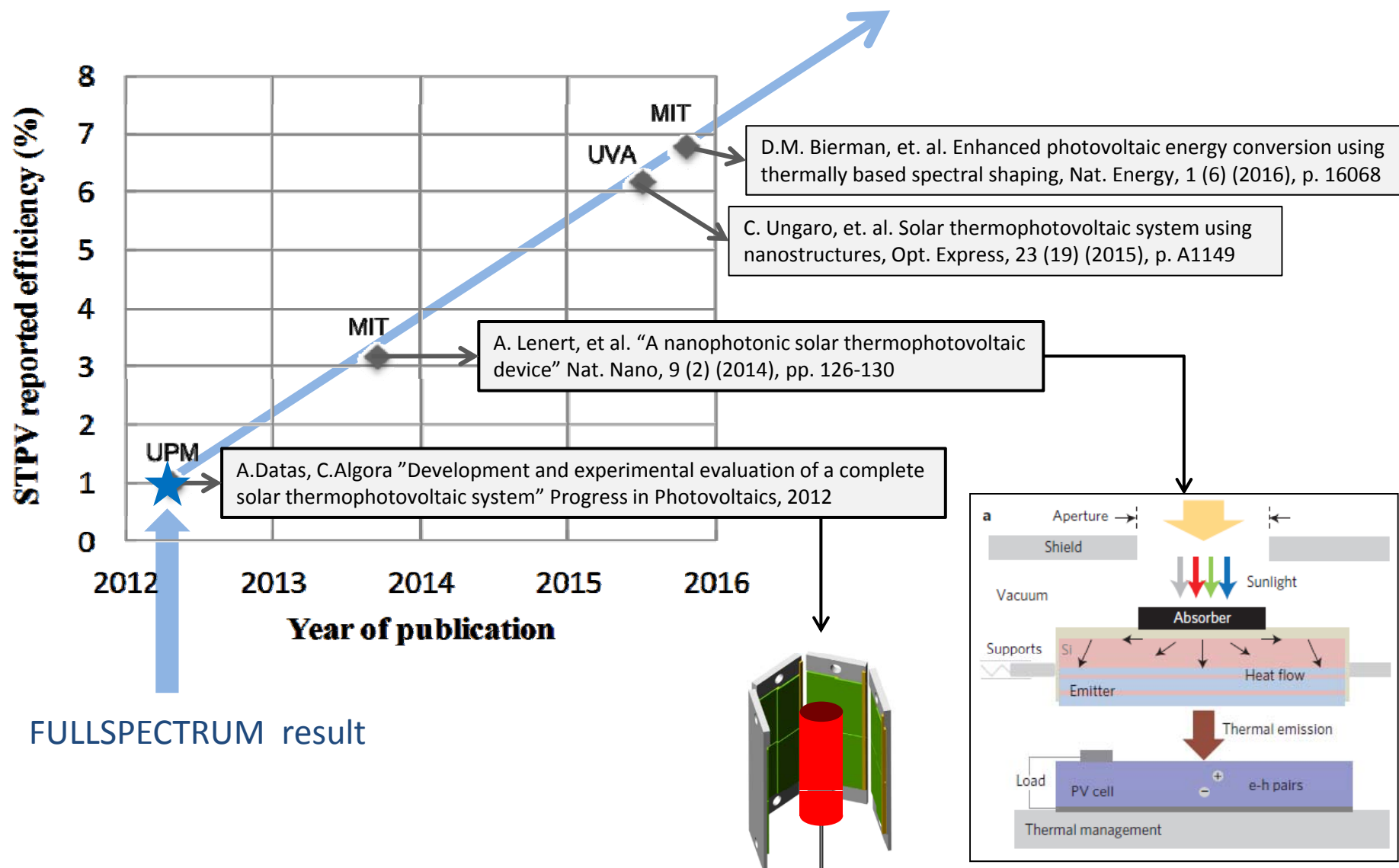


The first reported
solar-to-electricity
conversion efficiency
for STPV (*)



(*) A.Datas, C.Algora "Development and experimental evaluation of a complete solar thermophotovoltaic system" Progress in Photovoltaics, 2012

Recent developments on Solar-TPV

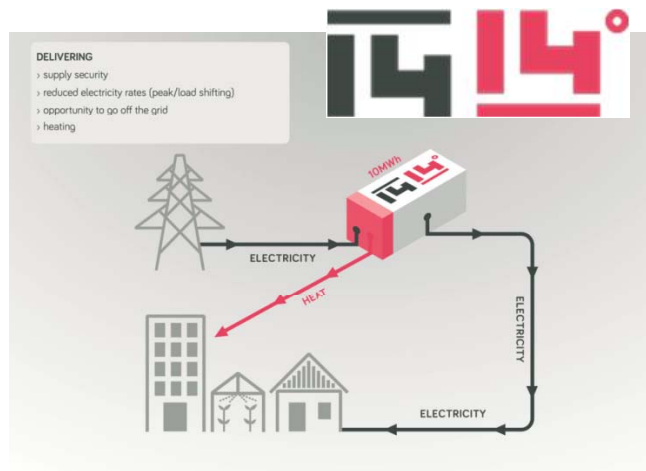


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Ongoing Projects



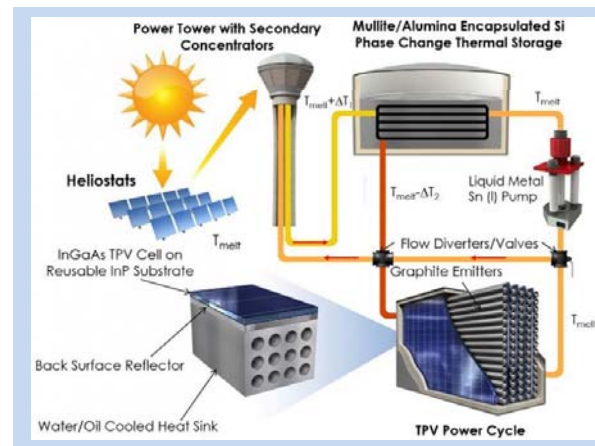
1414 Degrees (Australia)



Molten silicon
+
Brayton engine

www.1414degrees.com.au

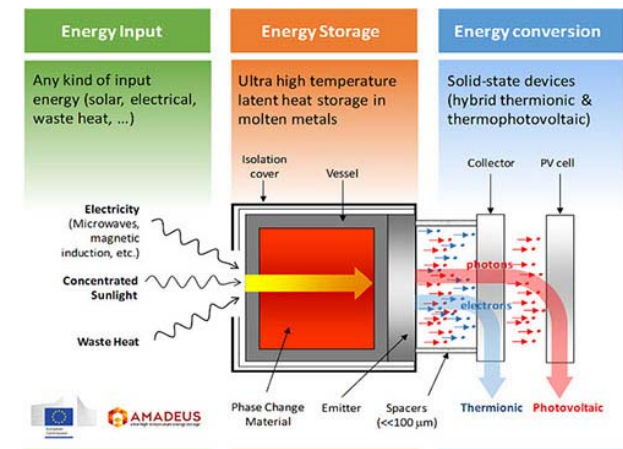
ARPA-E Project (USA)



Molten silicon
+
pumped liquid metal + TPV

(*)

AMADEUS Project (EU)



Molten silicon alloys
+
TPV & thermionics

(*)Pumping liquid metal at high temperatures up to 1,673 kelvin, Nature 550, 199–203 (Oct 2017)

AMADEUS Project (2017-2019)



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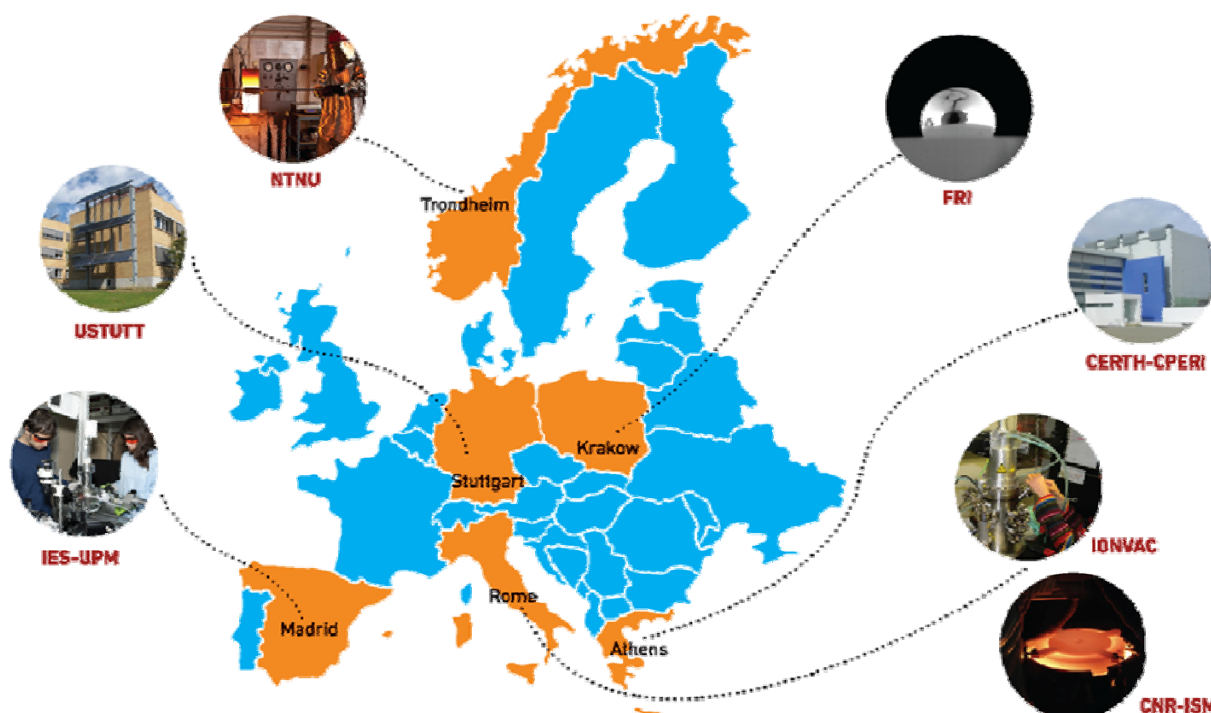
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FET-OPEN
HORIZON 2020

- ✓ Grant Number: 737054
- ✓ 7 partners
 - 3 Universities
 - 3 R&D Centers
 - 1 SME
- ✓ Budget: 3.270.496,25 €
- ✓ Jan 2017 – Dec 2019
- ✓ Coordinator: UPM (Spain)

www.amadeus-project.eu



AMADEUS Project (2017-2019)



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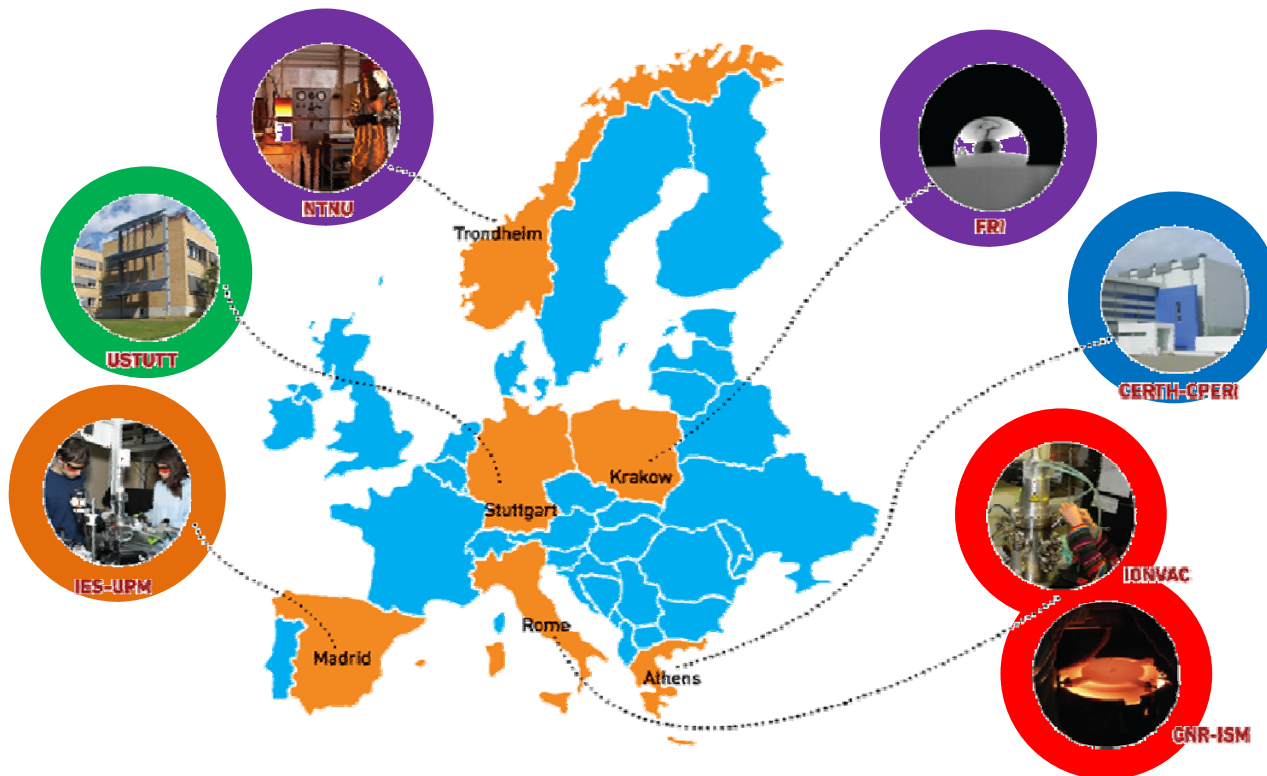
Instituto de Energía Solar



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- ✓ Coordinator: UPM (Spain)

www.amadeus-project.eu



Metallurgy, Thermal insulation, CFD simulation, Thermionics, Thermo-Photovoltaics

First Project Meeting in Krakow (Poland, June 2017)



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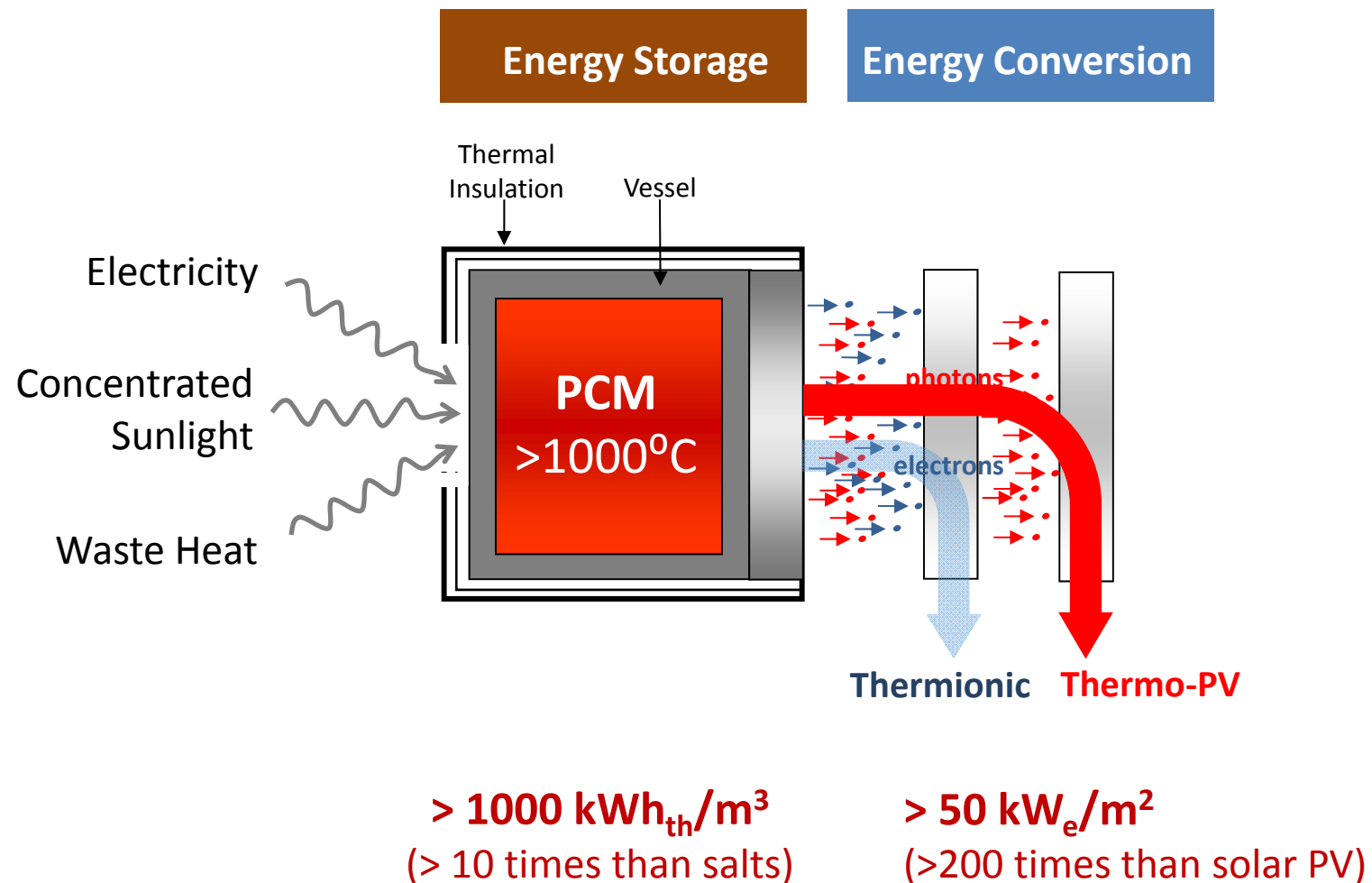


AMADEUS Project: The Concept



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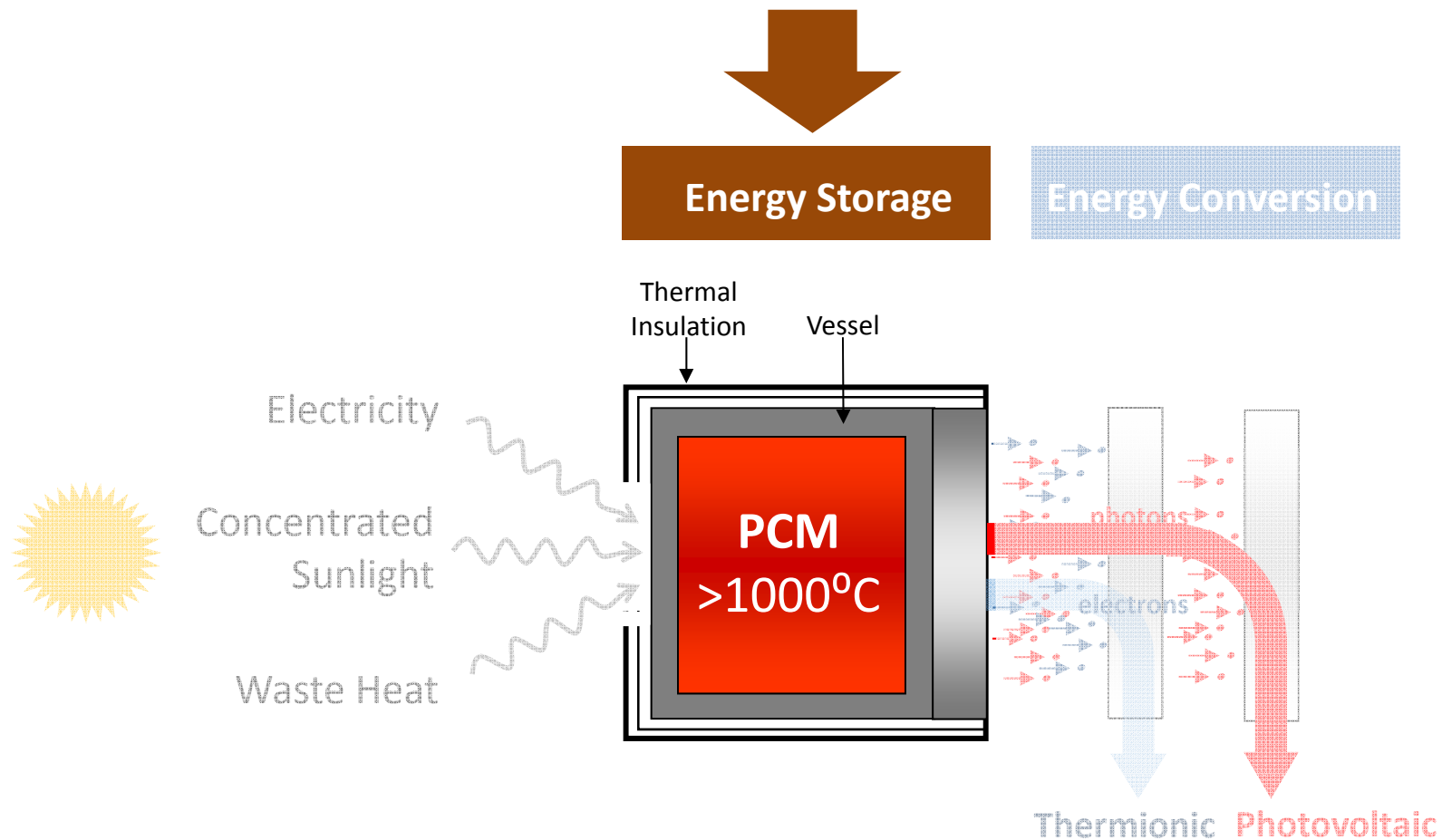
A.Datas, et. al. "AMADEUS: Next Generation of Materials and Solid State Devices for Ultra High Temperature Energy Storage and Conversion" at SolarPACES Conference (2017)



AMADEUS Project: The Concept

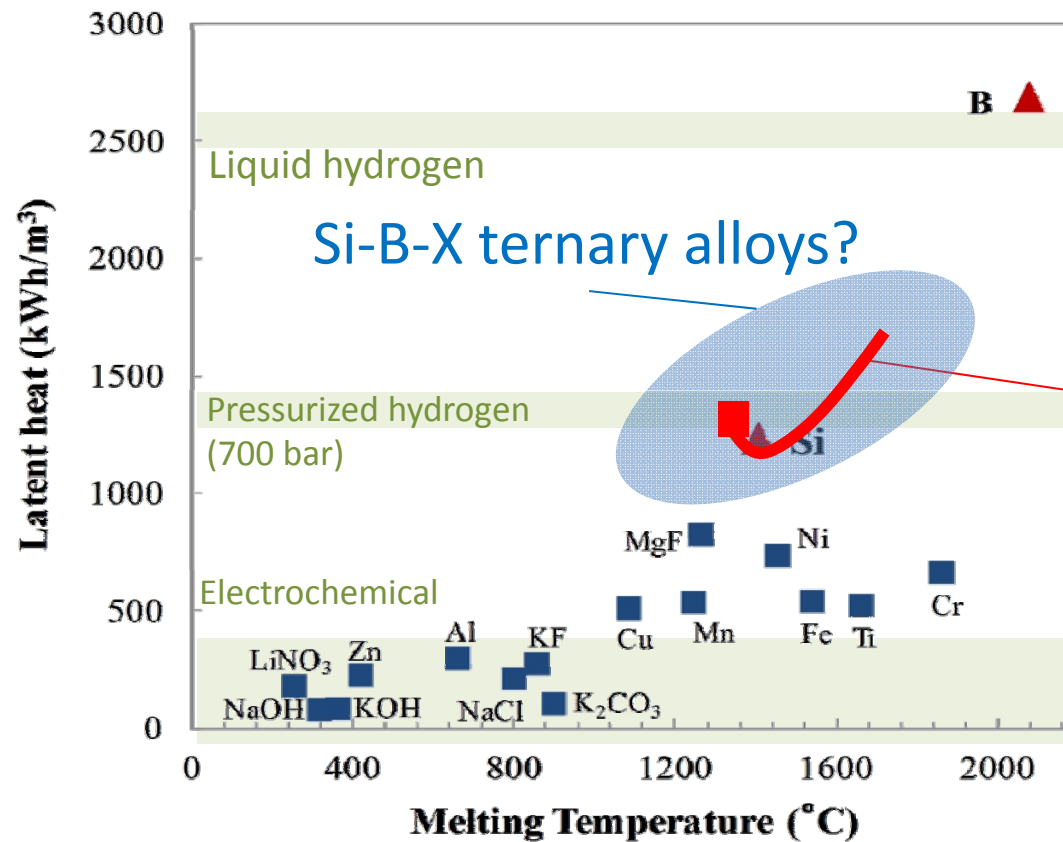


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$> 1000 \text{ kWh}_{\text{th}}/\text{m}^3$
(> 10 times than salts)

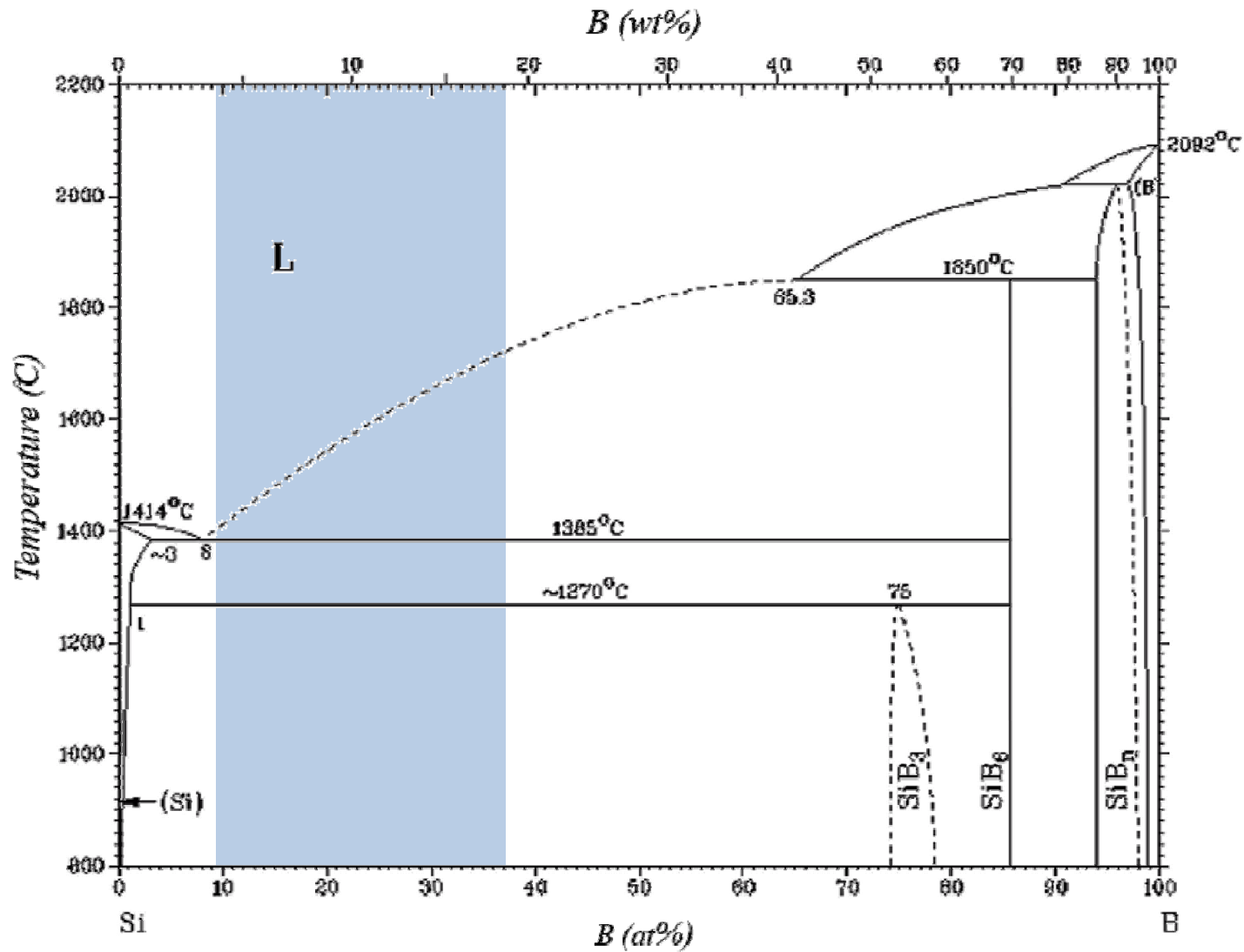
Silicon-Boron-X alloys for latent heat storage



Si-B binary alloys

- ✓ Increase latent heat?
- ✓ Tune melting point?
- ✓ Reduce **freezing expansion**?

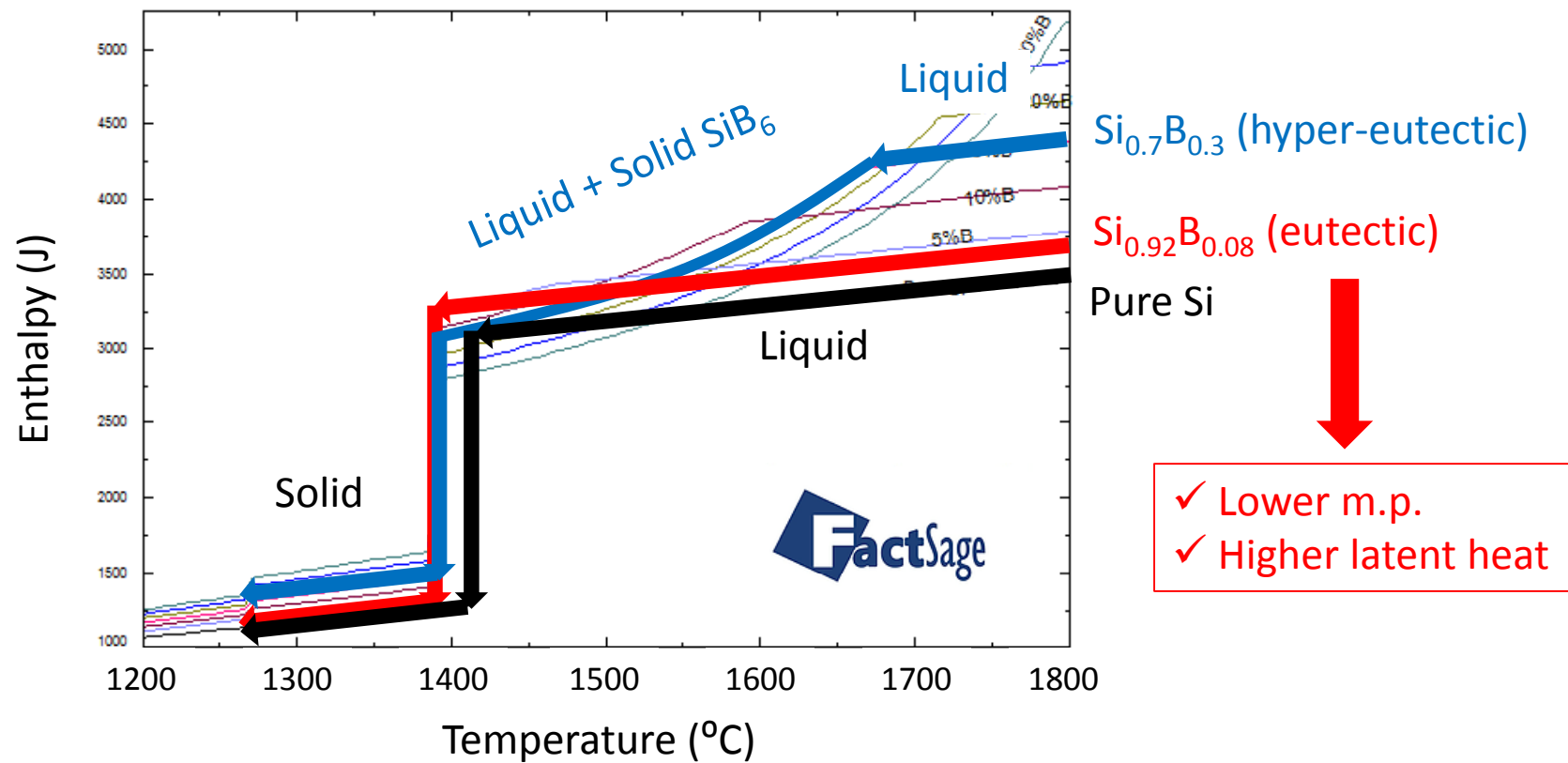
The Silicon-Boron system



Silicon-Boron cooling curves (simulated)

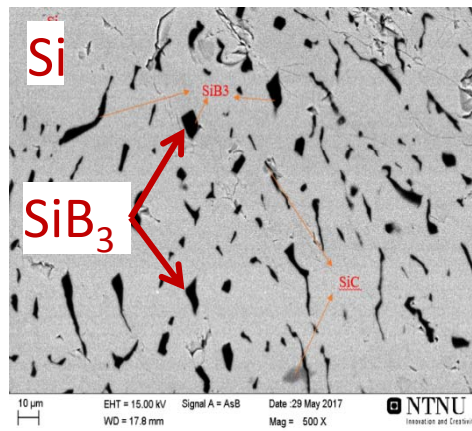


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Material development

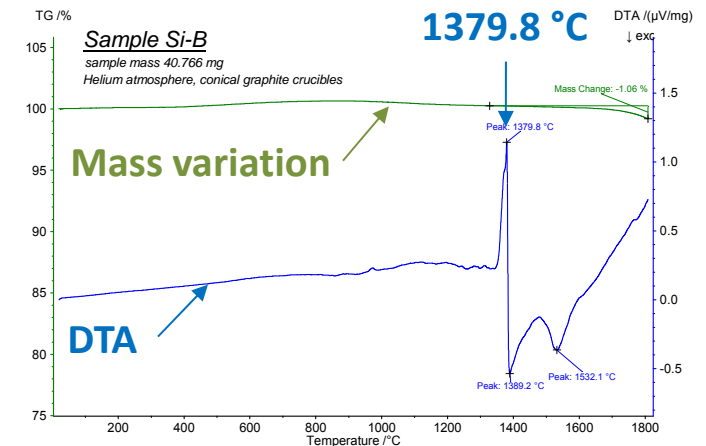
Si - 5 wt%B



Si - 15 wt%B



Thermo-physical characterization (TG-DTA*)



*TG-DTA: Thermogravimetry – Differential Thermal Analysis

Vessel reactivity at high temperatures

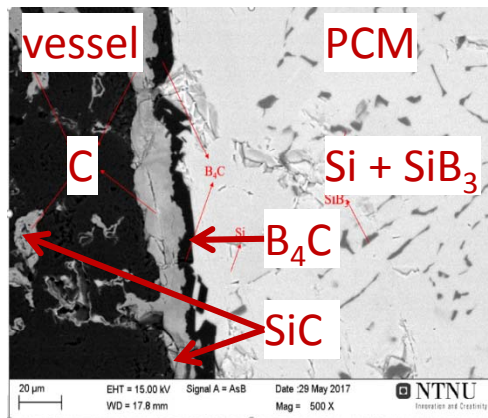


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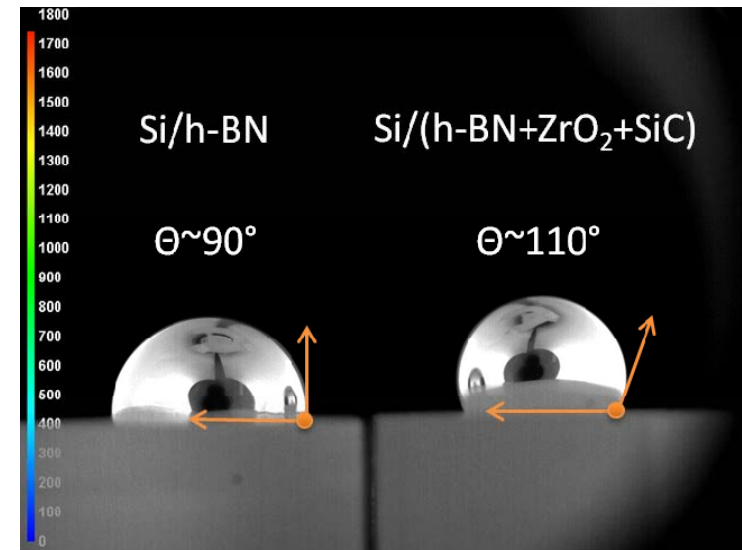
Instytut Odlewnictwa
Foundry Research Institute

NTNU

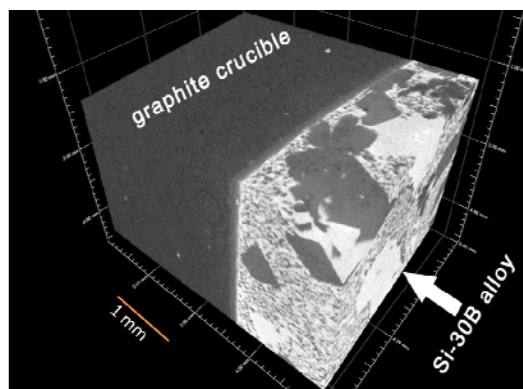
SEM



Wetability tests
(Sessile drop method)



Computed tomography (CT)

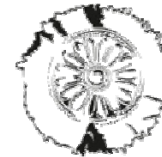


After 5 minutes at 1750 °C

2-phase CFD simulation

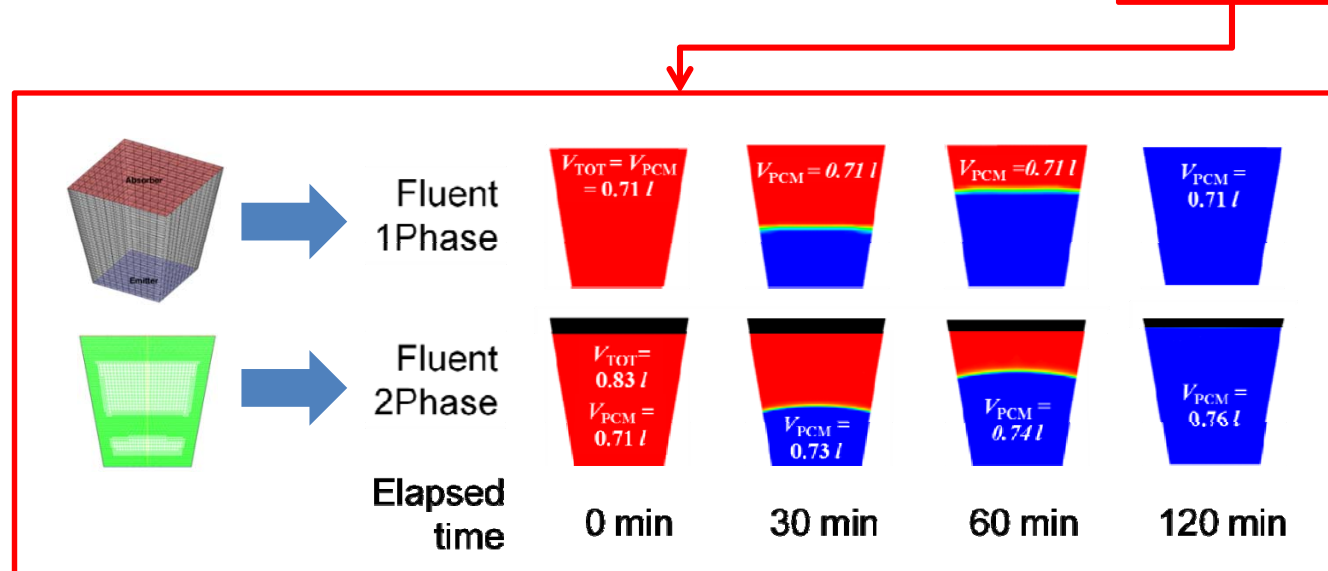
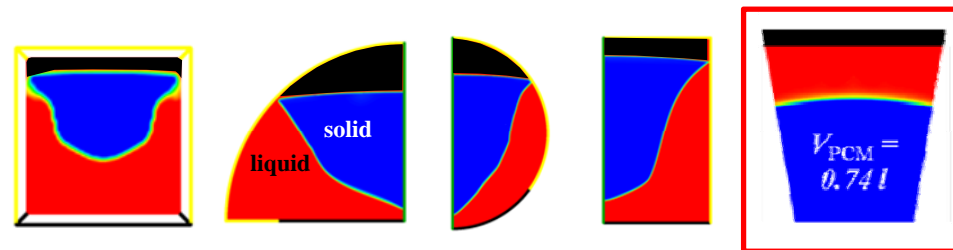


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CERTH
CENTRE FOR
RESEARCH & TECHNOLOGY
HELLAS

Container
geometrical
optimization



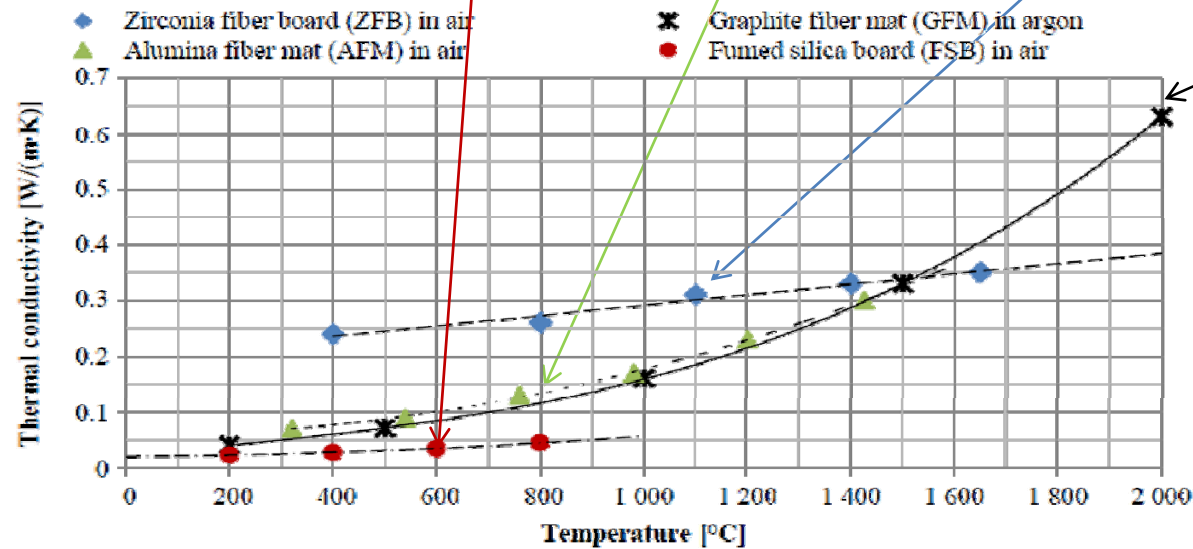
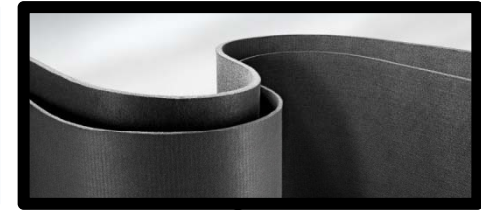
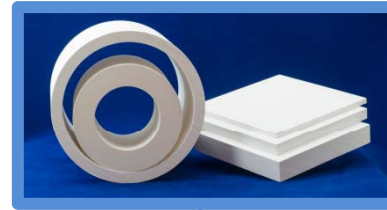
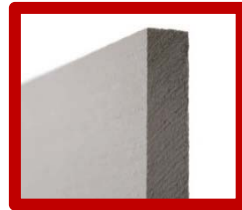
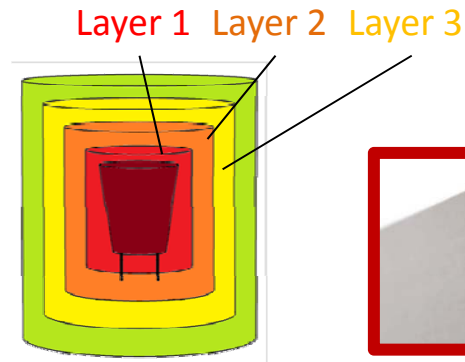
A.Datas, et. al. "Molten Silicon Storage of Concentrated Solar Power with Integrated Thermophotovoltaic Energy Conversion" at SolarPACES Conference (2017)

Thermal Insulation

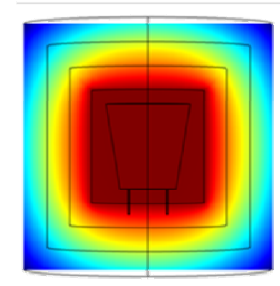


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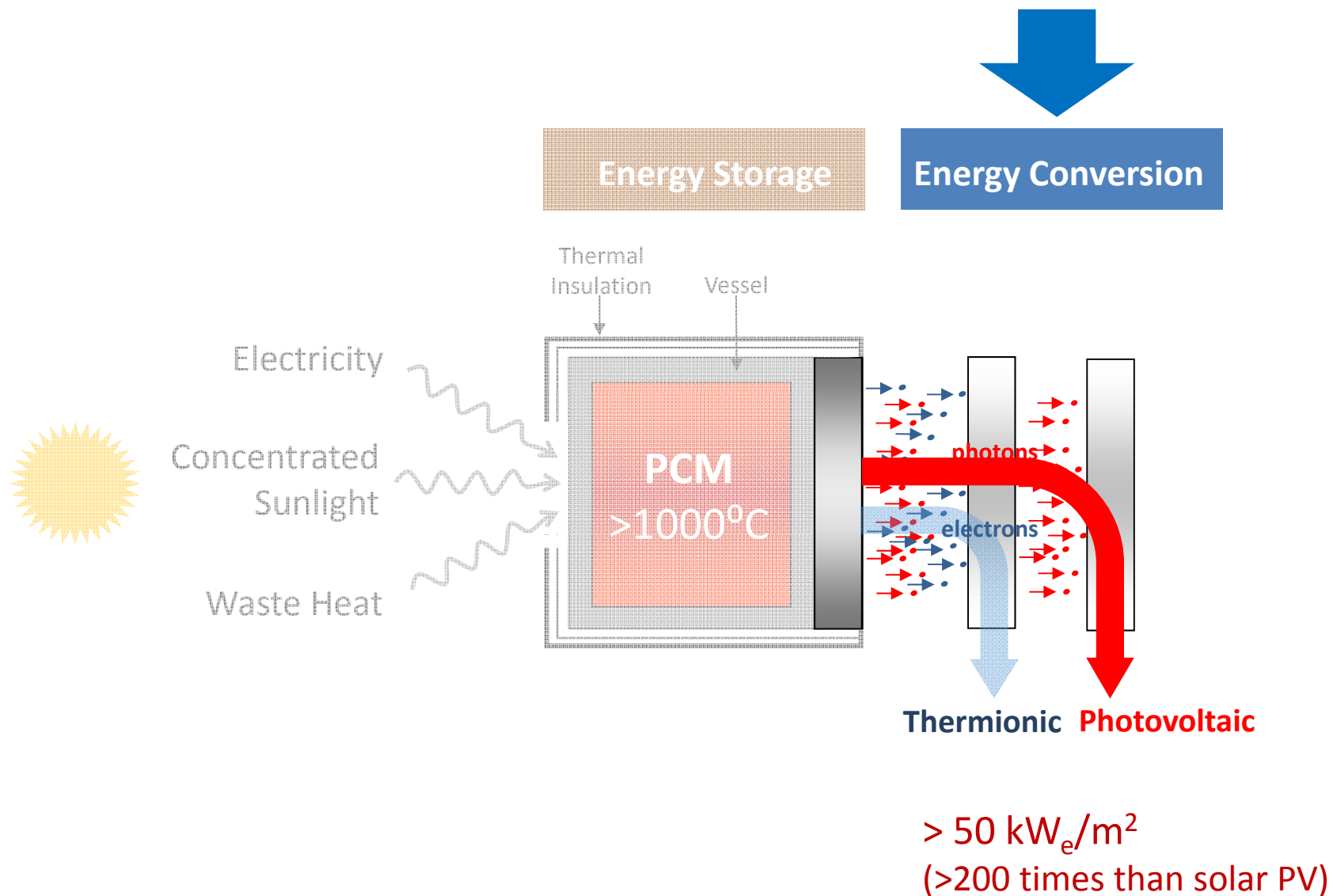
University of Stuttgart
Institute of
Thermodynamics and
Thermal Engineering



COMSOL®
simulations



S.Lang, et. al. "Thermal Insulation of an Ultra-High Temperature Thermal Energy Store for Concentrated Solar Power" at SolarPACES Conference (2017)

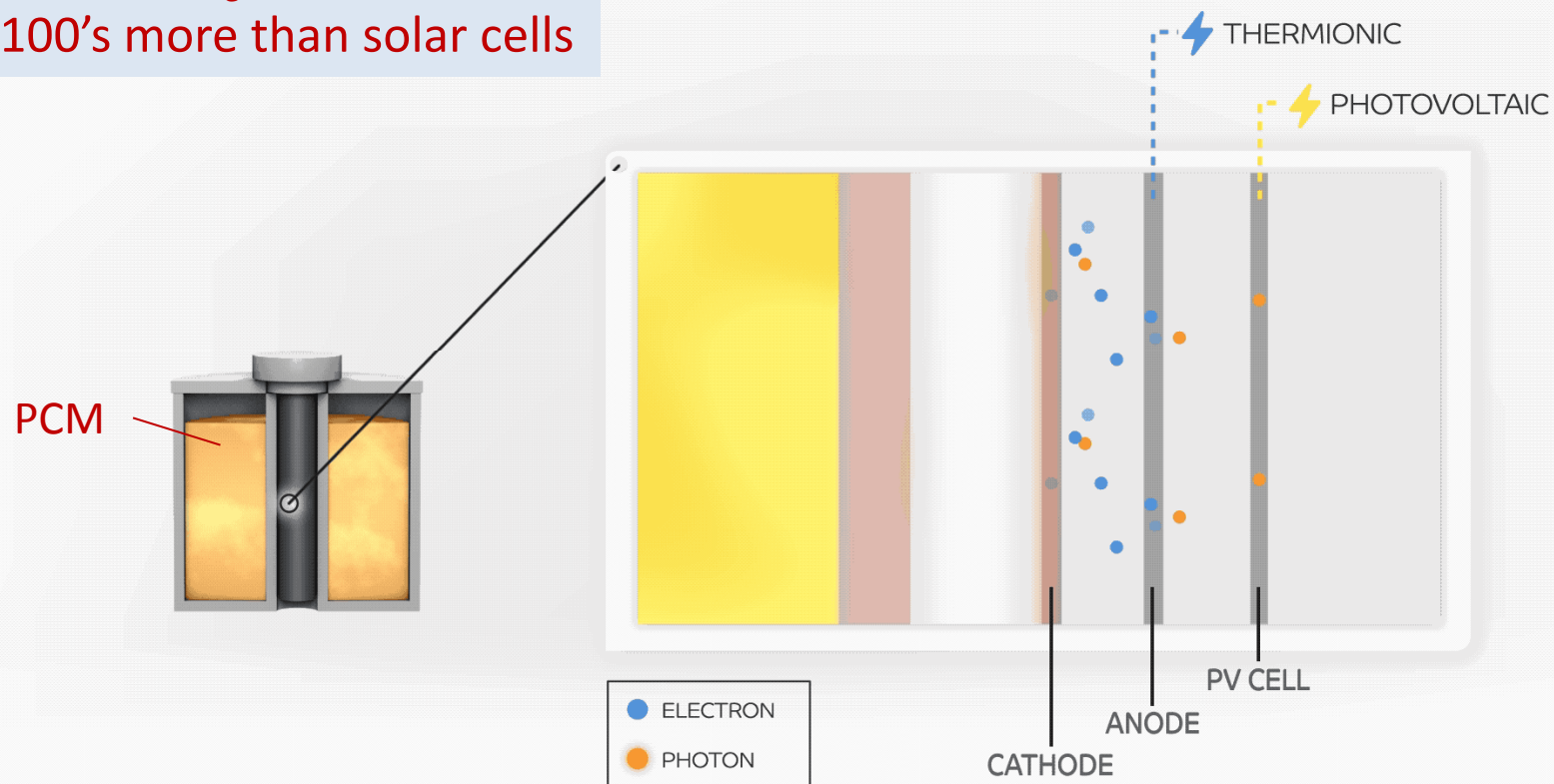


Hybrid Thermionic-Photovoltaic (TiPV) Converter



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10's of kW_e/m^2
100's more than solar cells



A. Datas, Hybrid Thermionic-Photovoltaic Converter, Applied Physics Letters (2016)

Patent: ES2584105, WO 2017/134321 A

Hybrid Thermionic-Photovoltaic (TiPV) Converter



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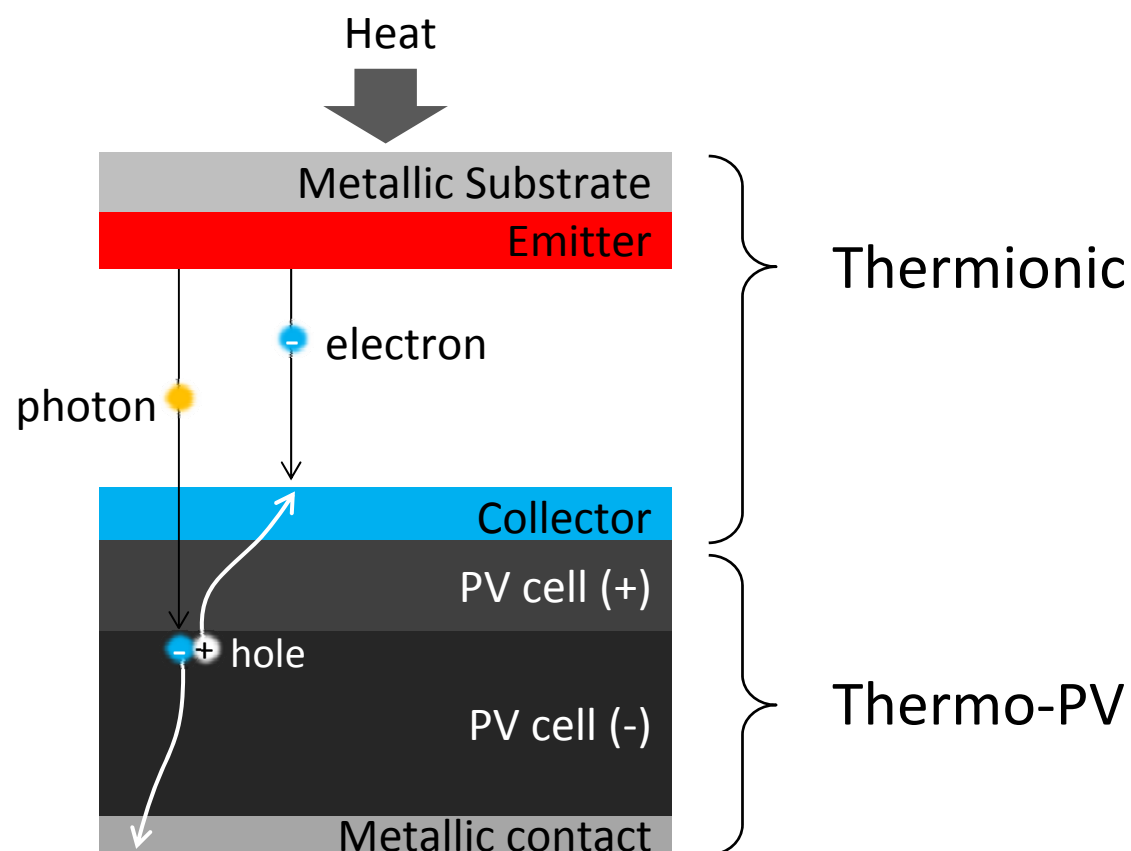


National Research Council of Italy

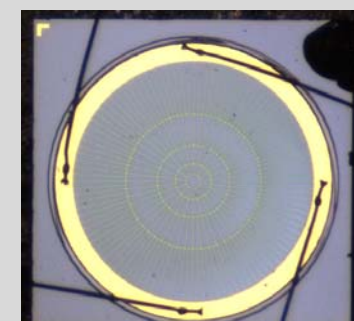


**LaB₆ on W by Pulsed Laser
Deposition (10-20 nm)**

**BaF₂ on PV cell by Magnetron
Sputtering (<1 nm)**



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InGaAs TPV cell

TiPV device characterization

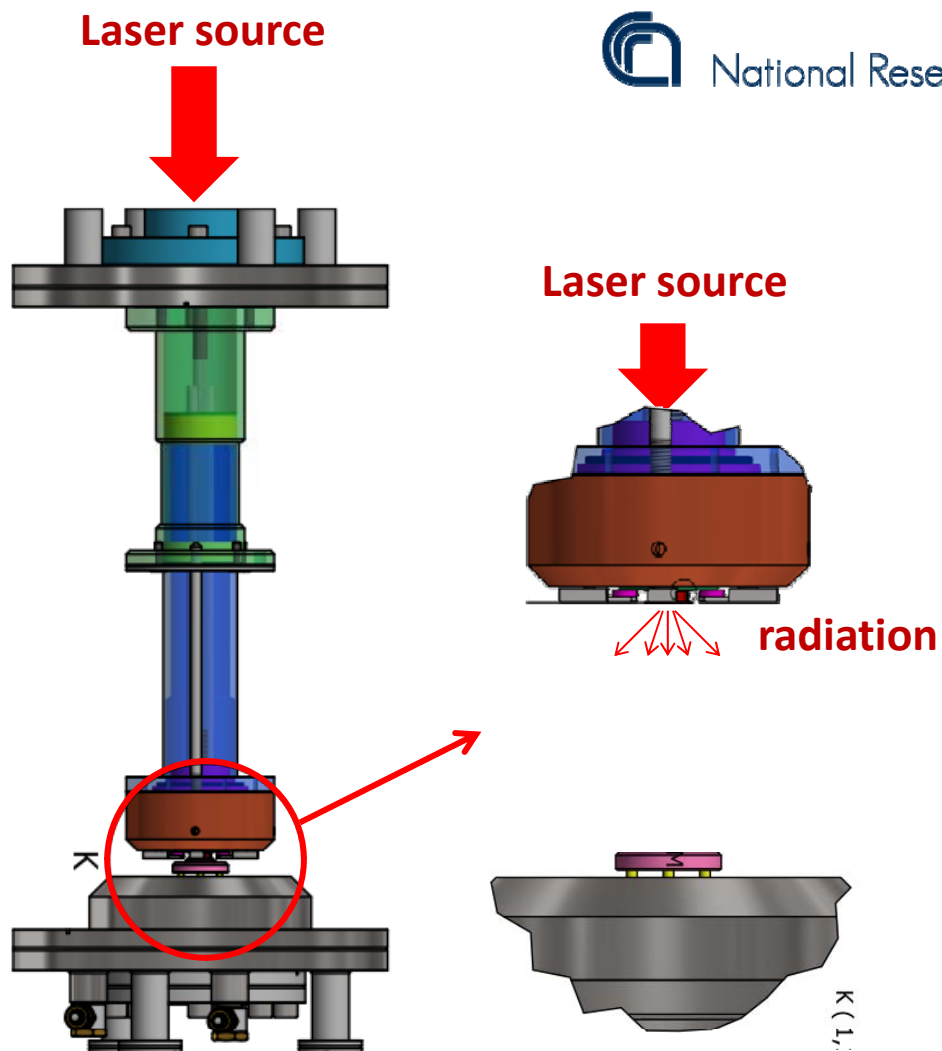


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National Research Council of Italy

IONVAC Process



Full System Prototype



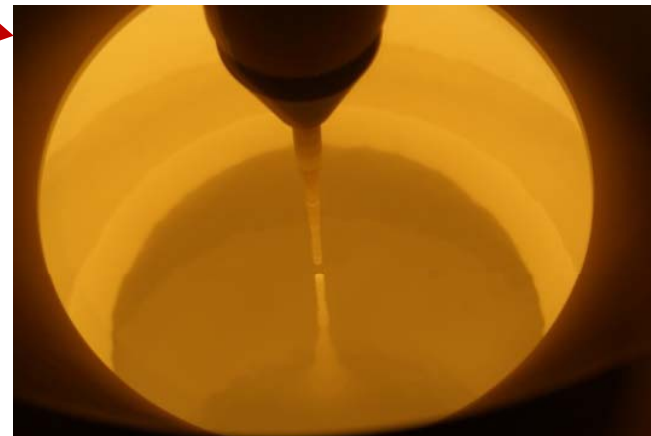
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Experiments starting soon...





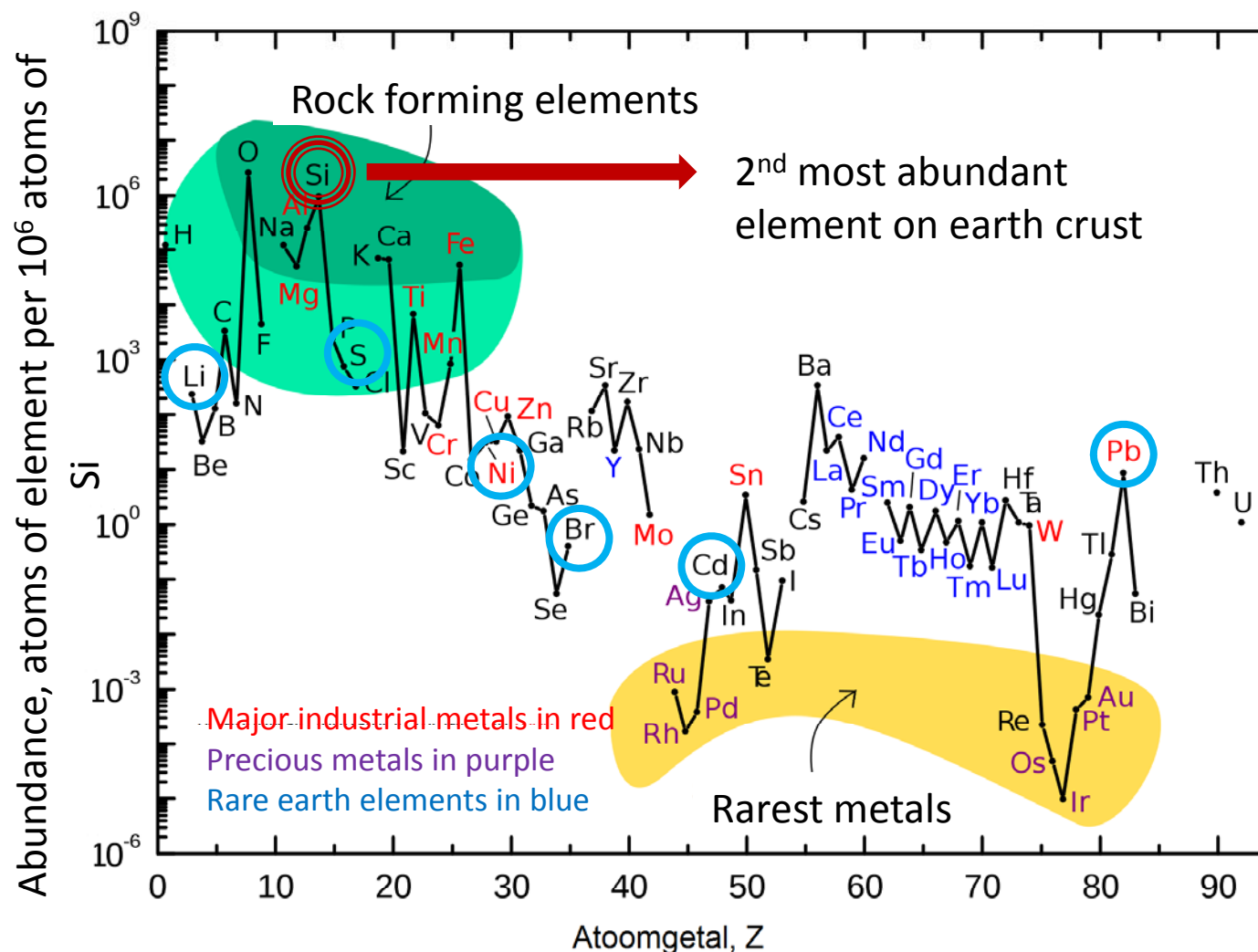
Alejandro Datas
a.datas@ies-def.upm.es

<https://youtu.be/D7huVnCnK8s>

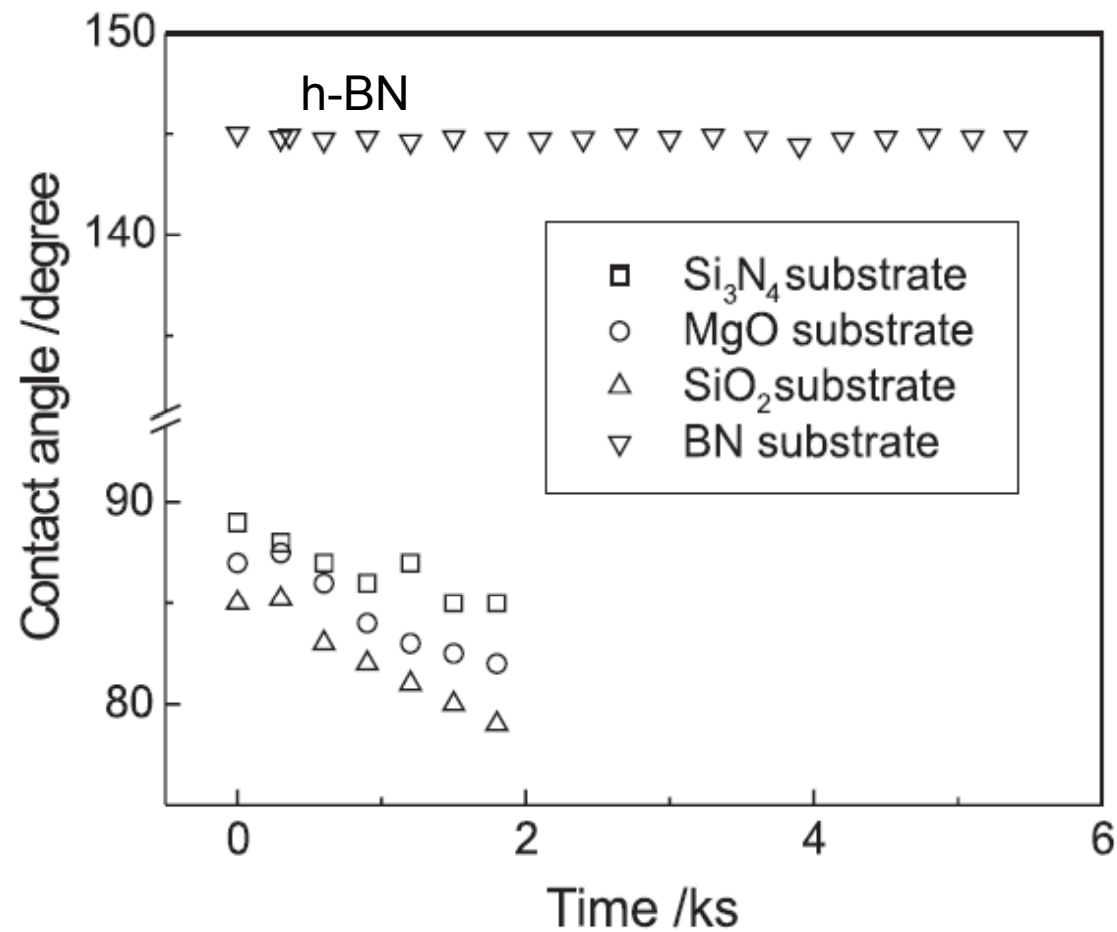


Backup slides

Elements abundance

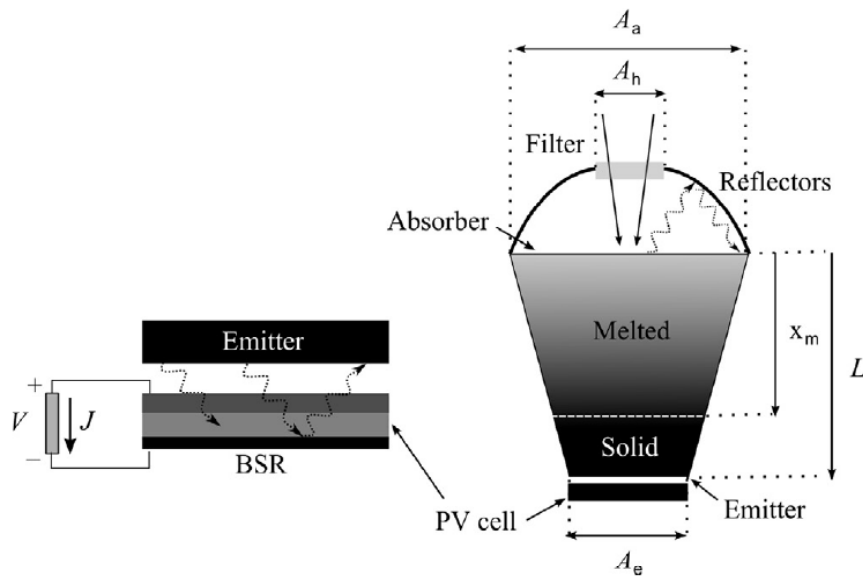


Contact angles of liquid silicon

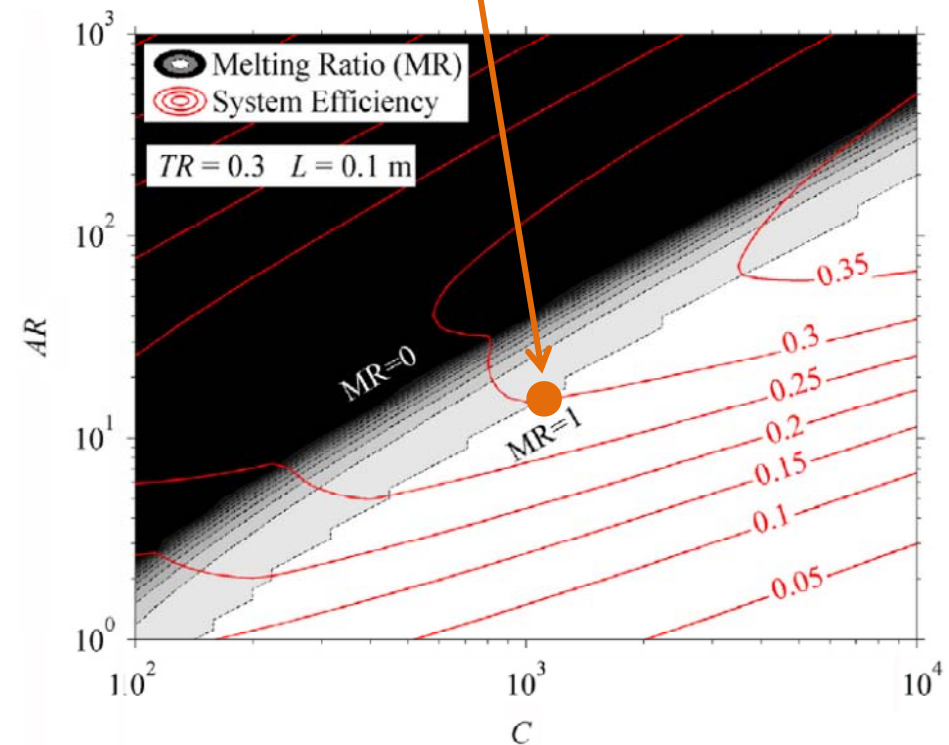


Z. Yuan et al.. Wettability and reactivity of molten silicon with various substrates. Appl. Phys. A 78 (2004) 617–622

Storage Integrated STPV (SISTPV)

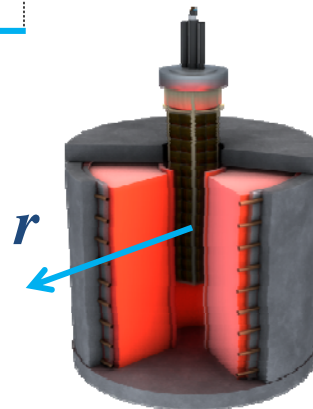
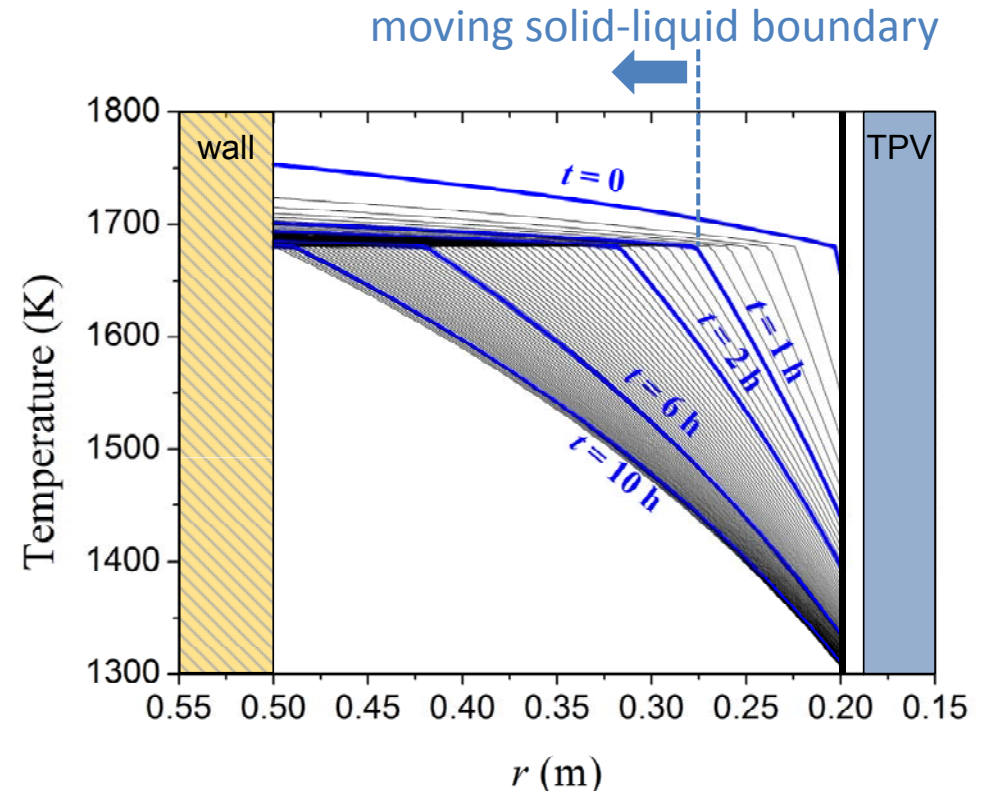
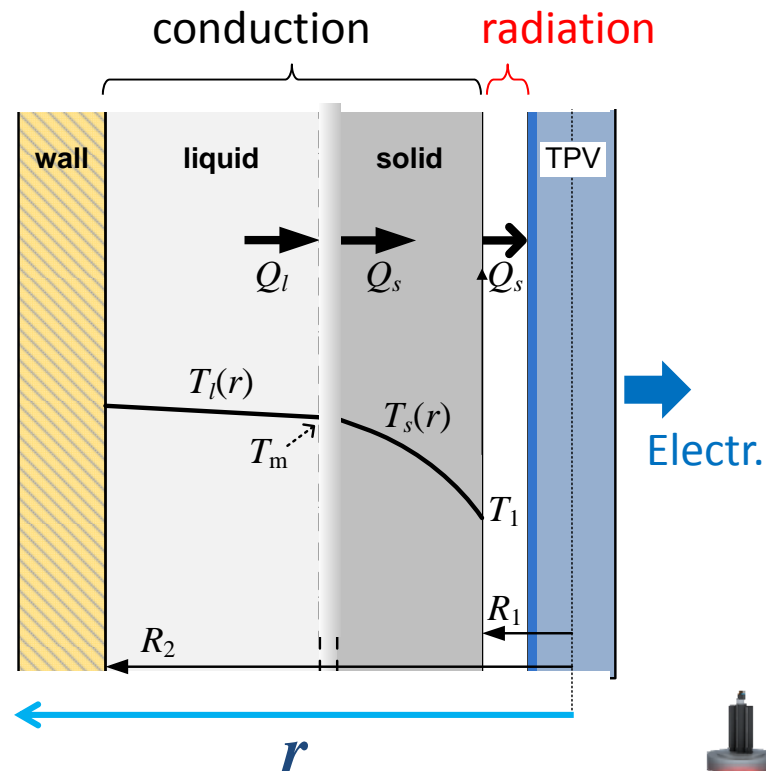


30% @ 1000 suns



A.Datas, et al. Solar Energy, Vol 96, pp 33–45 (2013)

UHT-TES with integrated TPV energy conversion



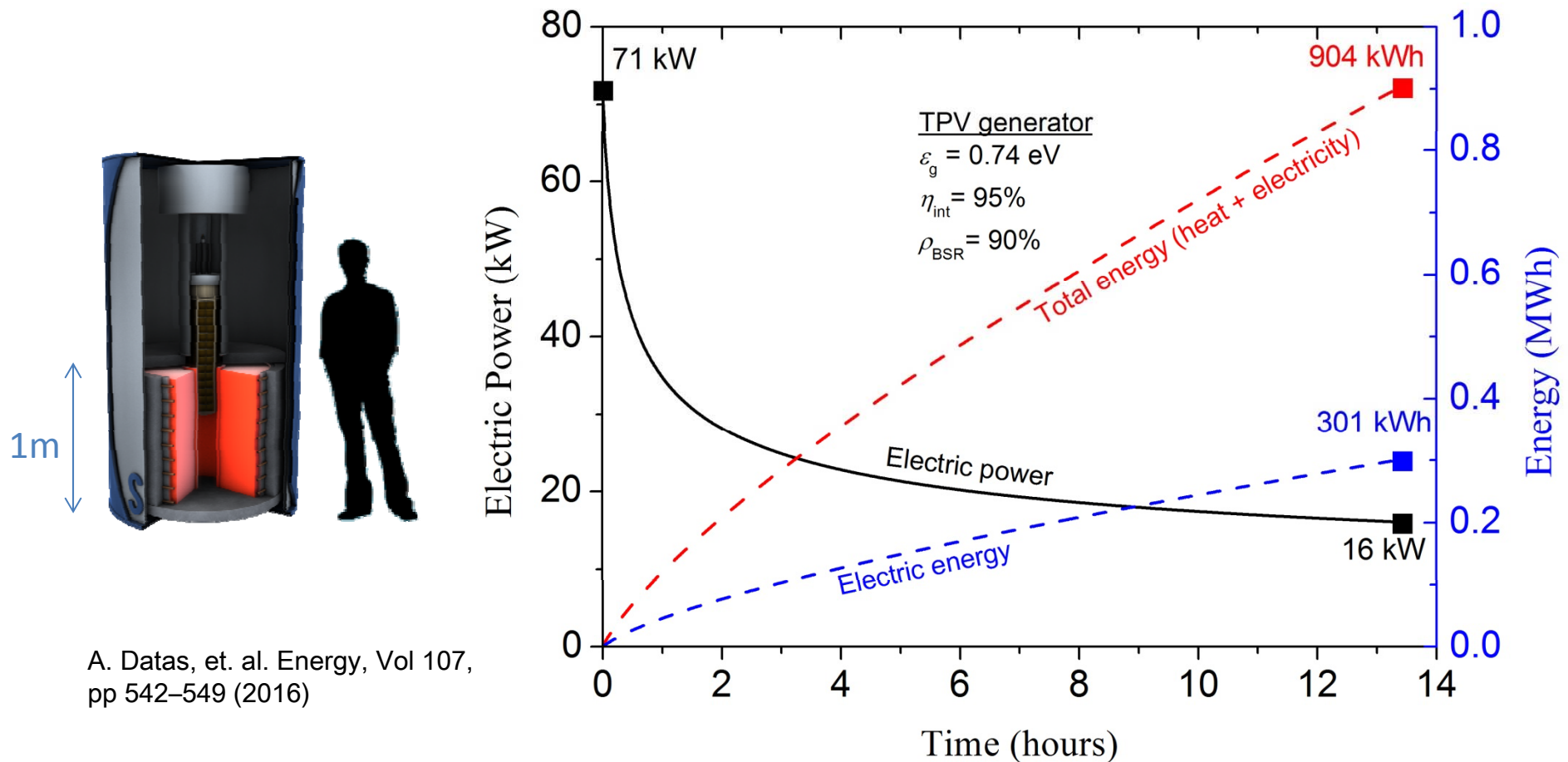
A. Datas, et. al. Energy, Vol 107, pp 542–549 (2016)

UHT-TES with integrated TPV energy conversion



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1 m³ → ~ 1MWh → power 30 homes



A. Datas, et. al. Energy, Vol 107, pp 542–549 (2016)

(*) Average Spanish home consumption (heat + electricity): 10,500 kWh/year (36% electricity, 64% heat)