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Dielectric solar concentrators for building integration of hybrid photovoltaic-thermal systems

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Acknowledgments

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CNRS France

Imperial College London

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Outline

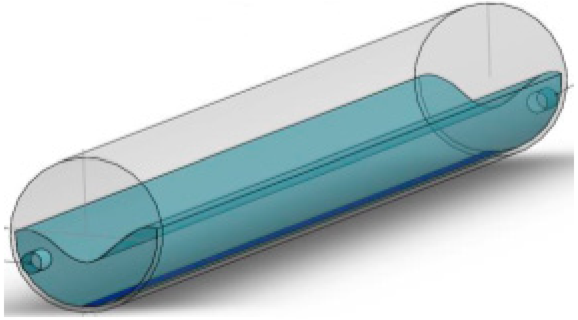
- Motivation
- Dielectric liquids analysis

  D. Chemisana, E.F. Fernandez, A. Riverola and A. Moreno, Fluid-based spectrally selective filters for direct immersed PVT solar systems in building applications, Renewable Energy, 123, 263-272, 2018
- Mid-infrared emissivity modelling

  A. Riverola, A. Mellor, D. Alonso Alvarez, L. Ferre Llin, I. Guarracino, C.N. Markides, D.J. Paul, D. Chemisana and N. Ekins-Daukes, Mid-infrared emissivity of crystalline silicon solar cells, Solar Energy Materials and Solar Cells, 174, 607-615, 2018
- Optical design

  A. Riverola, A. Moreno and D. Chemisana, Performance of a dielectric PVT concentrator for building-façade integration, Optics Express, Accepted Manuscript, 2018
- Energetic dynamic modelling and simulation

  A. Moreno, A. Riverola and D. Chemisana, Energetic simulation of a dielectric photovoltaic-thermal concentrator, Solar Energy, 169, 374-385, 2018
- Future work



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Motivation

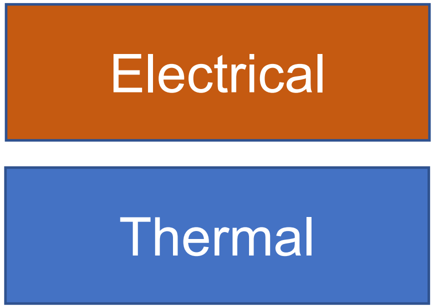
Buildings account for 40% of total energy consumption & 36% of total CO_2 emissions in the EU

Energy Performance of Buildings Directive, 20-20-20 objectives

http:// houseplans.pro /
EPBD, European Commission, 2018

→

-Energy demands



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-Limited space

-Architectural integration

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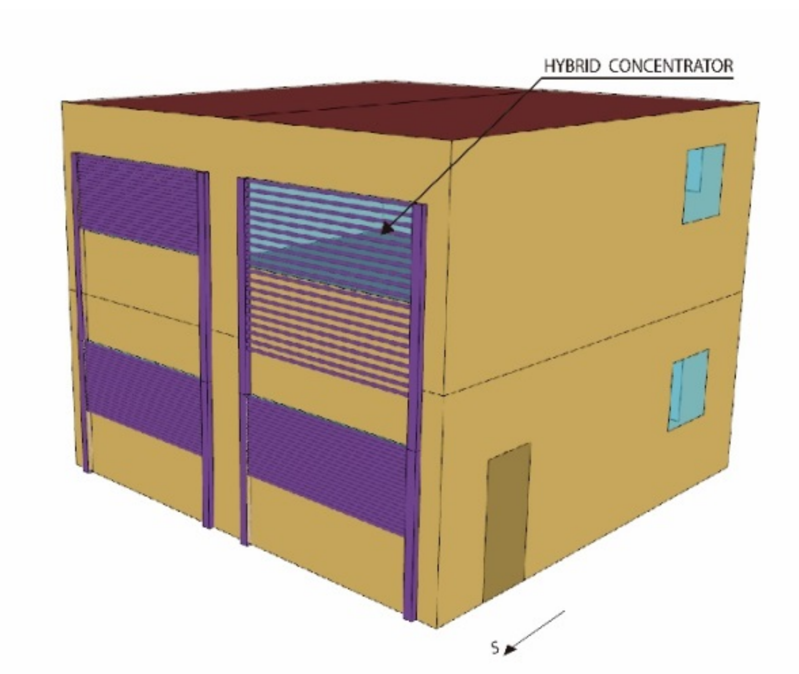
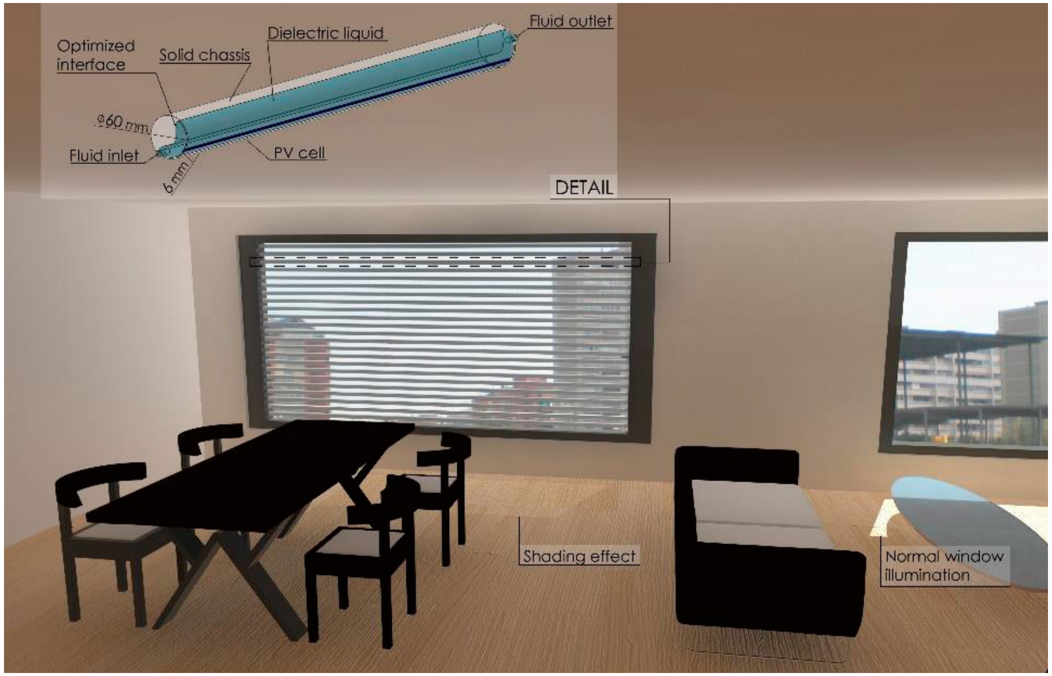
Motivation

Nearly Zero-Energy Buildings (NZEB)

Total energy used by building ≈ renewable energy created on-site





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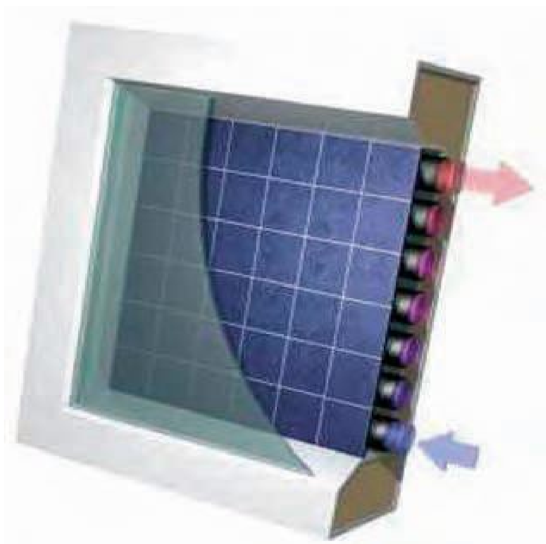
Motivation

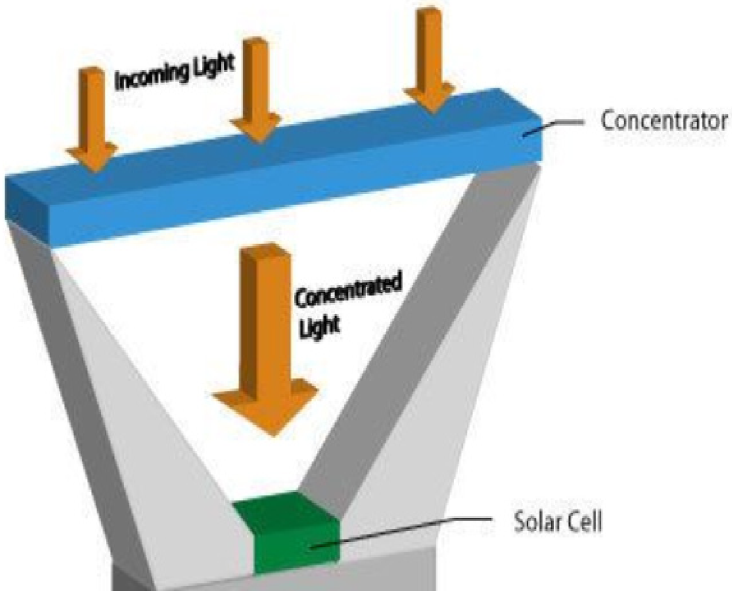
Photovoltaic-thermal (PVT)



- -High combined efficiency ~ 70%
- -60% less area than separated
- -Reduce cells temperature

Da Silva, R.M., Solar Energy, 84 (2010) 1985-1996
Affolter et al. PVT Roadmap (2006)

Low-concentration (LCPVT)

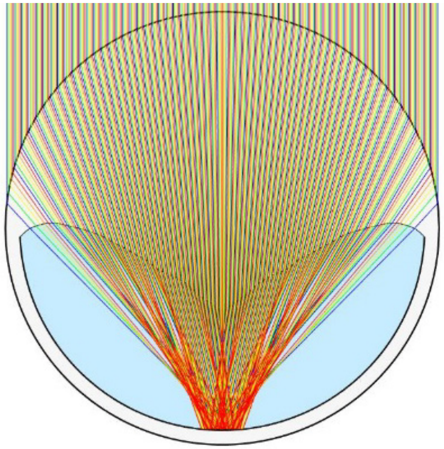


- -Lighting control for windows
- -Low tracking requirements
- -Standard c-Si cells

https://alchetron.com/Concentrator-photovoltaics

Motivation

Direct-immersed LCPVT



-Better temperature control
-Optical filters

Chemisana, D., et al., Renewable Energy 85 (2016) 564–572

First, direct-immersed CPVTs reported in late 70's based on a reflective concentrator

↓

Not suitable for building integration (BI)

Vivar and Everett, Prog. Photovolt. Res. Appl, 22, 2014, 612-633

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Dielectric liquids analysis

Chemisana, D., et al., Renewable Energy 123 (2018) 263-272

Candidate fluids for direct immersion?

Liquid	ε_r	C_e ($J\ g^{-1}\ K^{-1}$)	ρ ($kg\ m^{-3}$)	μ ($mPa\ s^{-1}$)	[$T_{melting}$-$T_{boiling}$] (ºC)
DIW	80.2	4.18	1000	1.0	[0 - 100]
IPA	18.6	2.60	785	2.4	[-89 - 82.6]
IBA	15.8	2.30	802.5	3.9	[-108 - 107.9]
GLY	42.5	2.20	1100	1553	[17.8 - 290]
DMSO	48.9	1.96	1260	2.7	[19 - 189]

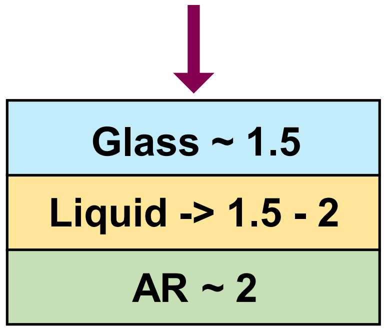
- Spectral properties not affected operating at temperatures < 80ºC.
- GLY becomes yellowish with time.
- DIW may oxidize metallic components.
- Alcohols (IPA, IBA) may degrade polymeric materials and sealants.
- Non-alcohols liquids melting points at temperatures >= 0ºC.

Dielectric liquids analysis

Chemisana, D., et al., Renewable Energy 123 (2018) 263-272

Optical Properties

Minimise Fresnel losses.



Dielectric liquid	Power loss (%)
No liquid in the cavity	18.1
DIW	8.22
IPA	7.46
IBA	7.16
GLY	6.20
DMSO	6.17

λ = 589 nm

Dielectric liquids analysis

Chemisana, D., et al., Renewable Energy 123 (2018) 263-272

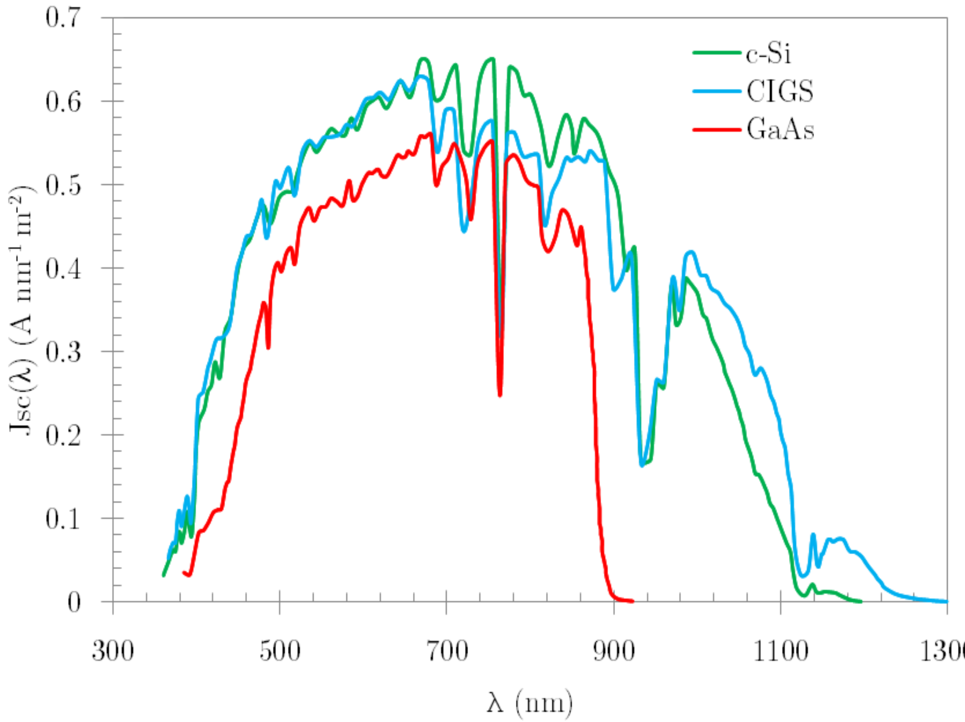
Optical Properties

Optical filters should have:
1) High transparency for PV production
2) High absorptance out of PV response range

<u>Ideal Filter window (IFW)</u>

.

Minimum spectral bandwidth which comprises 75% of spectral current



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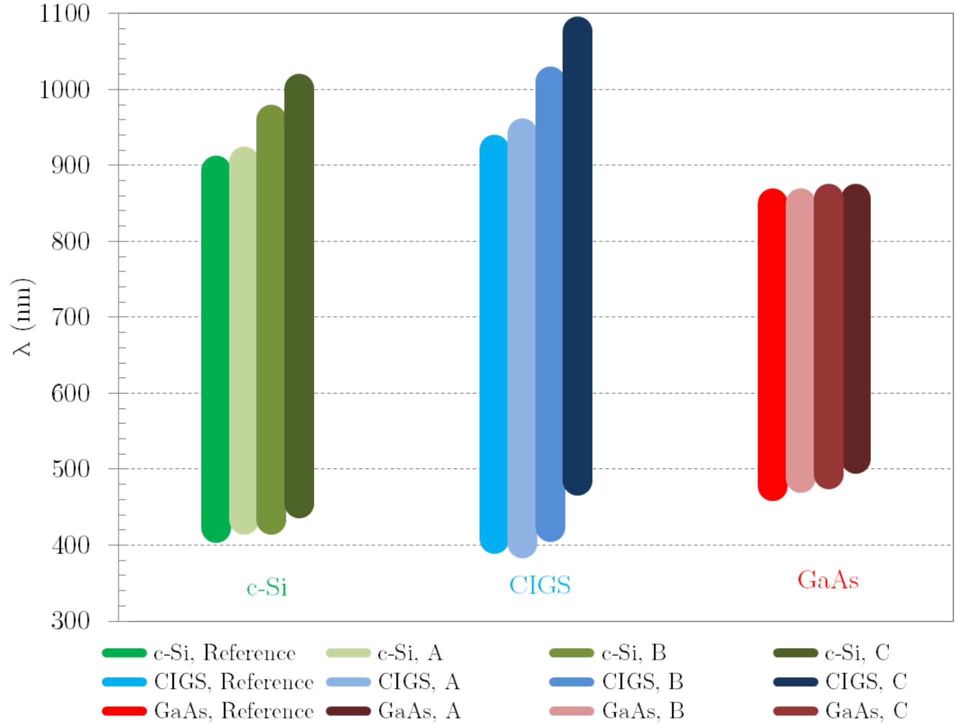
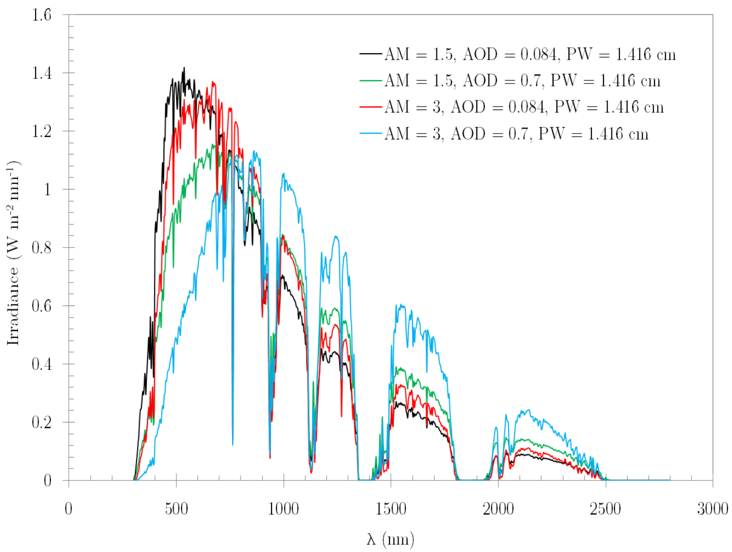
Dielectric liquids analysis

Chemisana, D., et al., Renewable Energy 123 (2018) 263-272

Optical Properties

Ideal filter window (IFW)





Case	AM	AOD	PW (cm)
Ref	1.5	0.084	1.416
A	3	0.084	1.416
B	1.5	0.7	1.416
C	3	0.7	1.416

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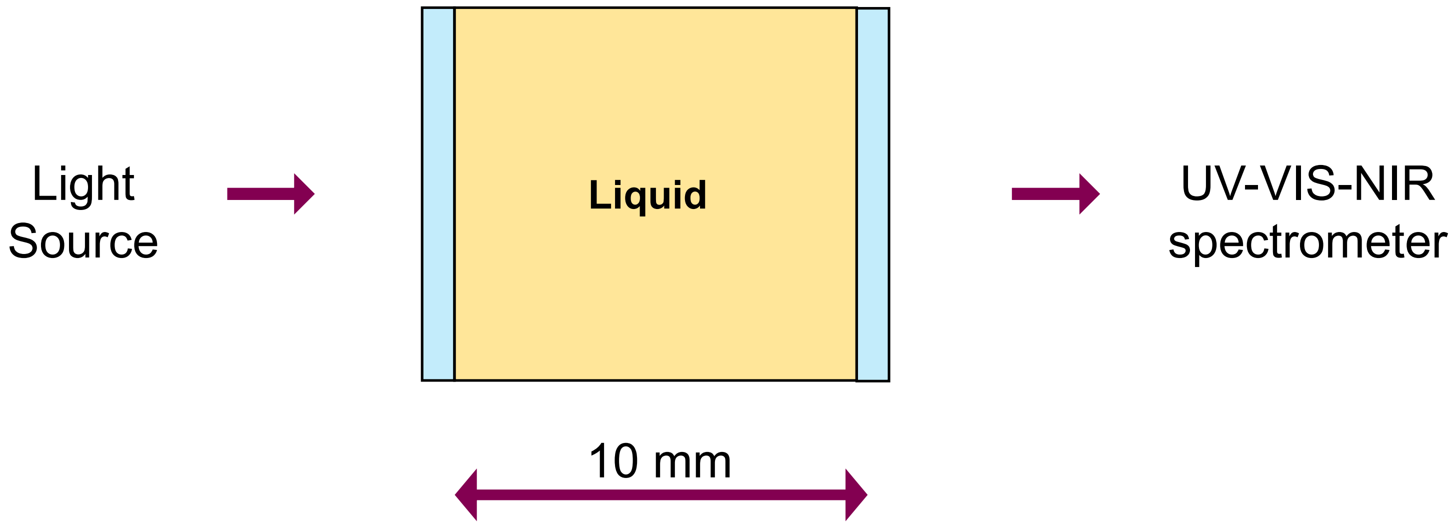
Dielectric liquids analysis

Chemisana, D., et al., Renewable Energy 123 (2018) 263-272

Optical Properties

Spectral transmittance measurement

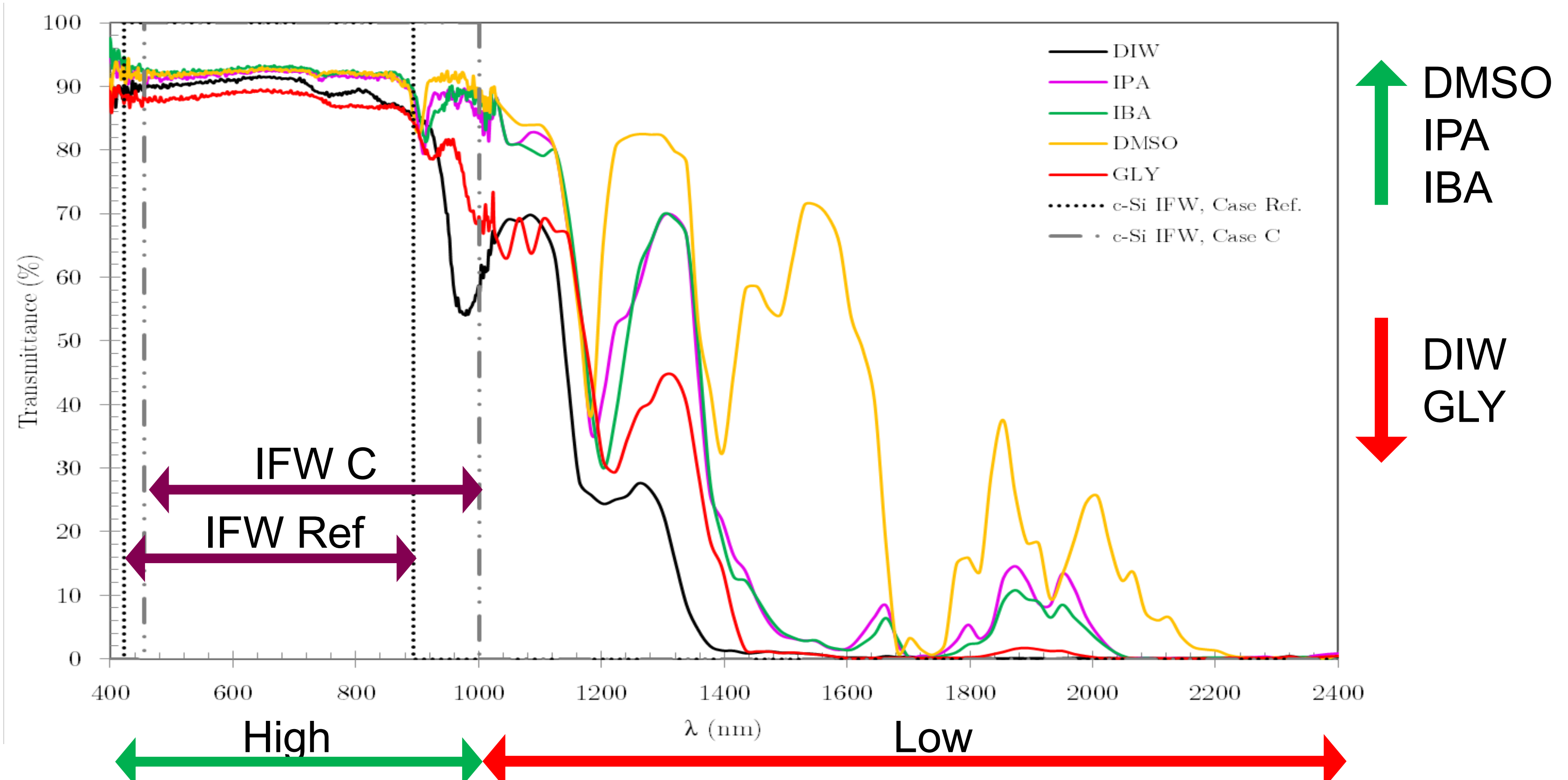


Dielectric liquids analysis

Chemisana, D., et al., Renewable Energy 123 (2018) 263-272

Optical Properties

Spectral transmittances and IFW ranges for c-Si → Pure substances

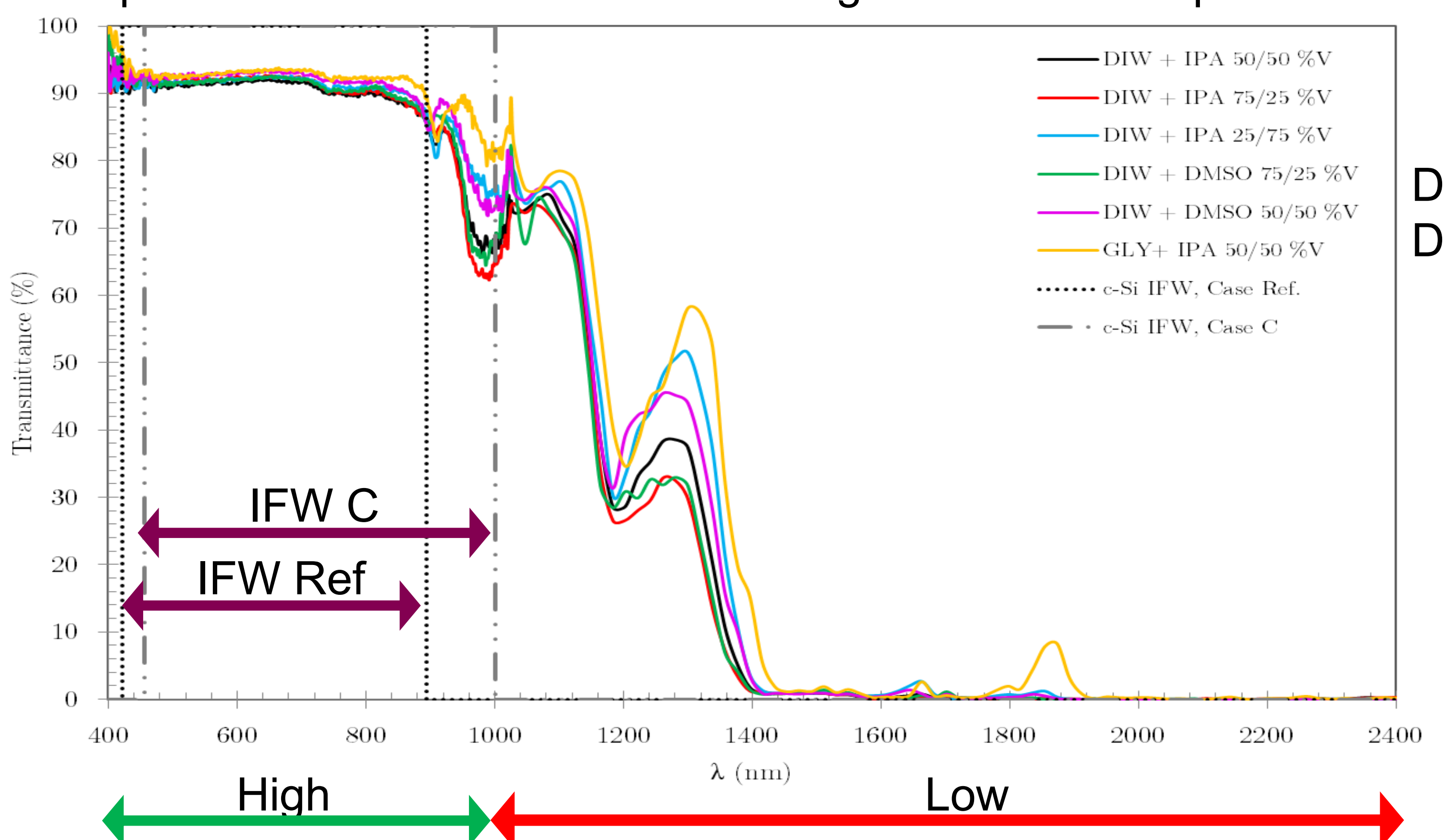


Dielectric liquids analysis

Chemisana, D., et al., Renewable Energy 123 (2018) 263-272

Optical Properties

Spectral transmittances and IFW ranges for c-Si → Liquid mixtures



DIW+IPA
DIW+DMSO
✓

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Dielectric liquids analysis

Chemisana, D., et al., Renewable Energy 123 (2018) 263-272

Thermal Properties

- High specific heat and thermal conductivity to maximise thermal exchange.
- Low coefficient of expansion.
- Appropriate range of temperatures between melting and boiling points.

From the optical analysis:

Dielectric liquid	Irradiance transmitted (%), range (1000-2500) nm
DIW	1.15
IPA	5.01
IBA	4.43
DMSO	25.7
GLY	2.07

Dielectric liquids analysis

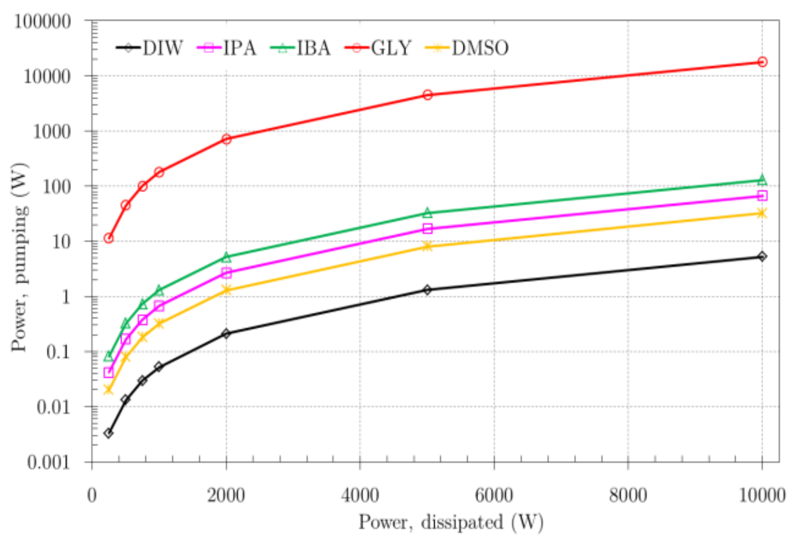
Chemisana, D., et al., Renewable Energy 123 (2018) 263-272

Thermal Properties

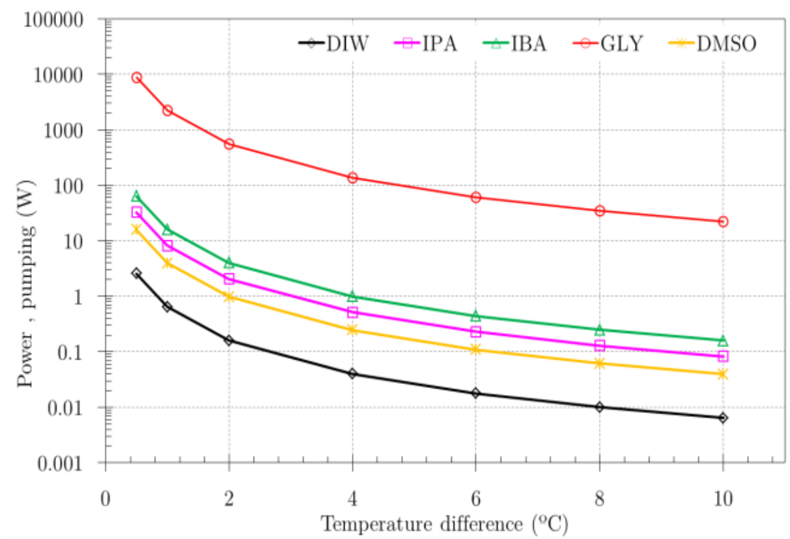
- High liquid density and low viscosity, maximise heat removal with low pressure losses.

Pumping power for 1m^2 flat-plate collector

ΔT = 7ºC



Power dissipated = 500 W/m^2



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Dielectric liquids analysis

Chemisana, D., et al., Renewable Energy 123 (2018) 263-272

- Adequate melting points to avoid freezing
- High transmittance for the bandwidth fixed based on the IFW criteria,
- High absorbance for photons above the upper interval of the IFW
- Good thermal characteristics to remove heat with high efficiency
- Low pumping power

DIW
IPA
DIW+IPA
DIW+DMSO

✓

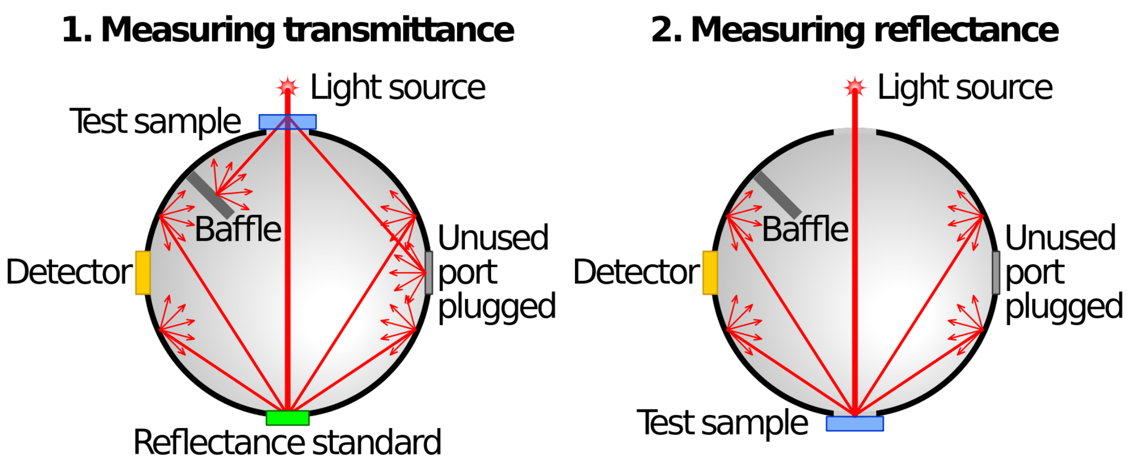
Mid-infrared emissivity modelling

Riverola, et al., Solar Energy Materials and Solar Cells, 174 (2018) 607-615

Why is it important?

- Determining operating temperatures
- Heat transfer calculations
- Radiative cooling
- Enabling PVT systems to operate at higher temperature

Measuring emissivity



https://en.wikipedia.org/wiki/Integrating_sphere

Emissivity (λ) = Absorptivity (λ) = 1 – Reflectivity (λ) – Transmissivity (λ)

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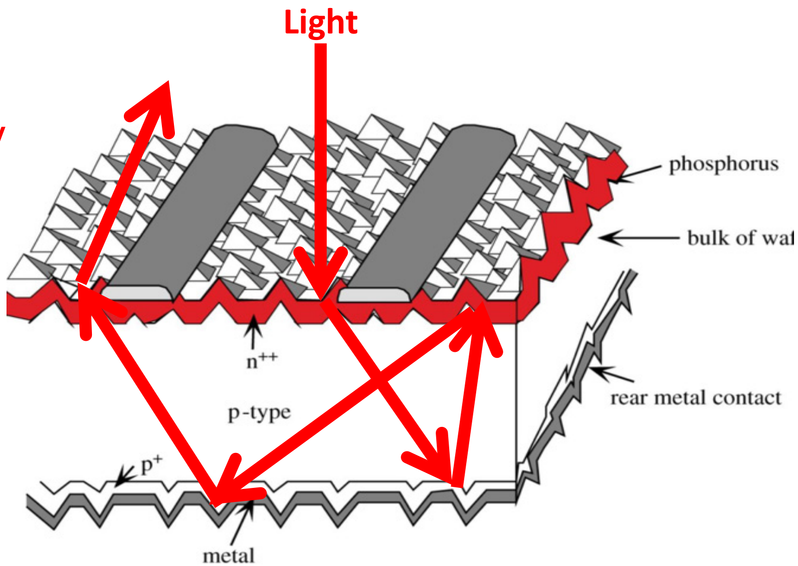
Mid-infrared emissivity modelling

Riverola, et al., Solar Energy Materials and Solar Cells, 174 (2018) 607-615

Simulation Method?

- Ray tracing / Monte-Carlo – computationally costly
- Full wave optical – computationally prohibitive



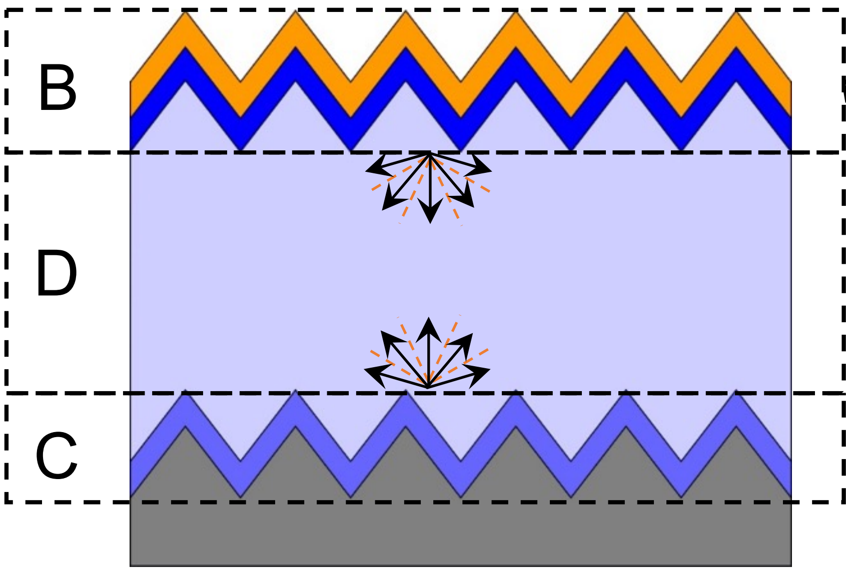
Wafer thickness ~ 200 µm
Texture features ~ 4 µm
Coatings ~ 50 nm

Green MA, 1995, Silicon solar cells: advanced principles and practice

Mid-infrared emissivity modelling

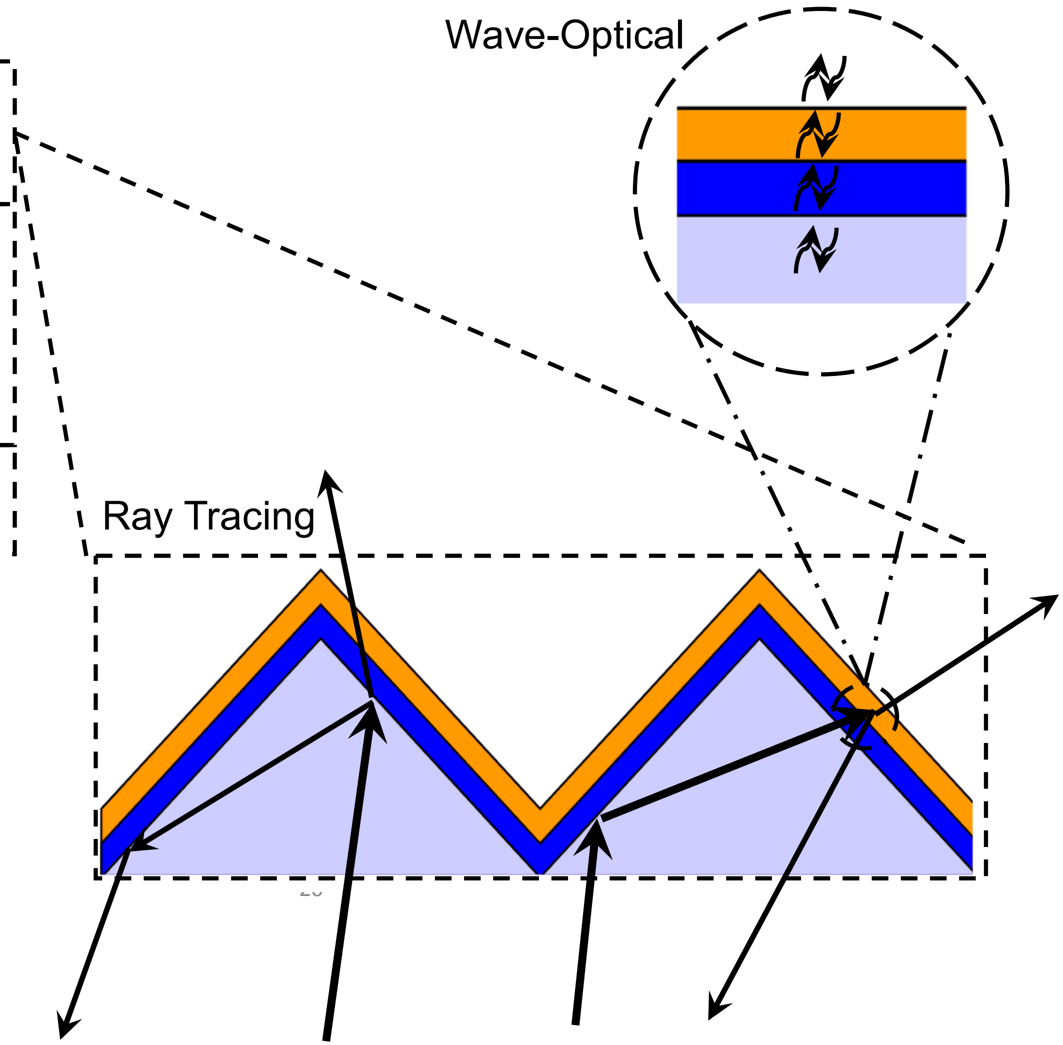
Riverola, et al., Solar Energy Materials and Solar Cells, 174 (2018) 607-615

Matrix Formalism – (OPTOS*)



$$B,C=\begin{pmatrix} \theta_1 \rightarrow \theta_1 & \cdots & \theta_n \rightarrow \theta_1 \\ \theta_1 \rightarrow \theta_2 & \cdots & \theta_n \rightarrow \theta_2 \\ \vdots & \ddots & \vdots \\ \theta_1 \rightarrow \theta_n & \cdots & \theta_n \rightarrow \theta_n \end{pmatrix}$$

$$D=\begin{pmatrix} e^{-\alpha d/\cos\theta_1} & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & e^{-\alpha d/\cos\theta_n} \end{pmatrix}$$



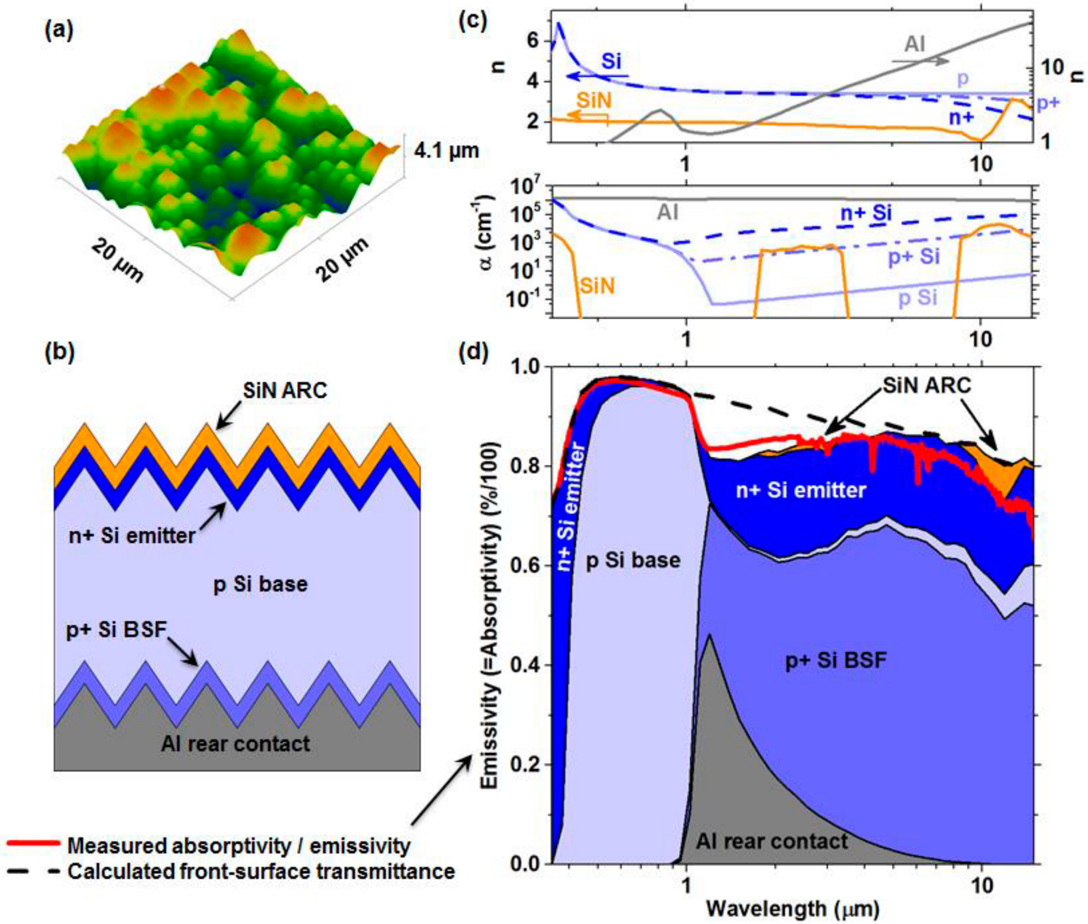
*Tucher, N., et al., Optics Express 23 (2015) A1720-A1734

*Eisenlohr, J., et al., Optics Express 23 (2015) A502-A518

Mid-infrared emissivity modelling

Riverola, et al., Solar Energy Materials and Solar Cells, 174 (2018) 607-615

Unencapsulated c-Si cell



Santbergen, R., et al., Sol. Mat. 92 (2008) 432-444

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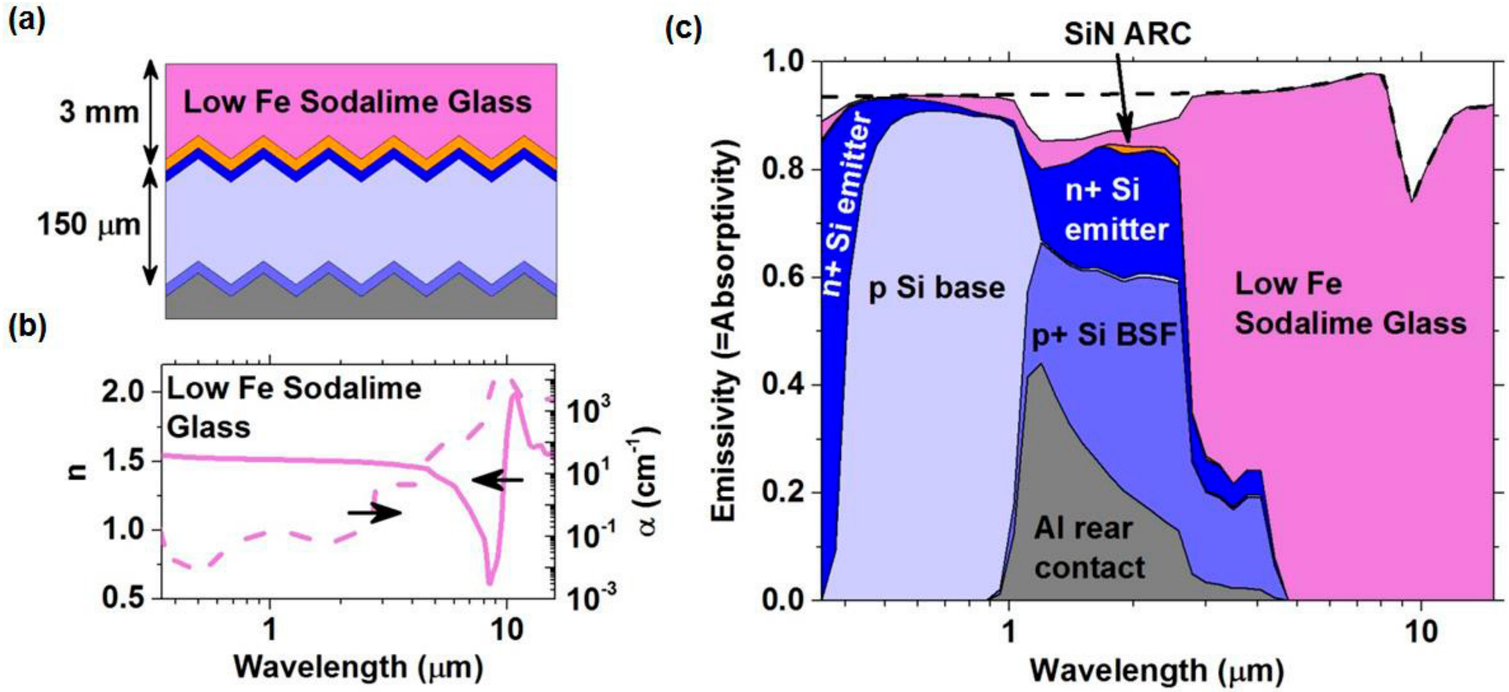
Mid-infrared emissivity modelling

Riverola, et al., Solar Energy Materials and Solar Cells, 174 (2018) 607-615

Encapsulated c-Si cell



Rubin, M., Solar Energy Materials 12 (1985) 275-288

Mid-infrared emissivity modelling

Riverola, et al., Solar Energy Materials and Solar Cells, 174 (2018) 607-615

- Unencapsulated mono-crystalline silicon solar cells have a MIR emissivity of ~80%
- Encapsulated mono-crystalline silicon solar cells have a MIR emissivity of ~90%

✓ Radiative Cooling

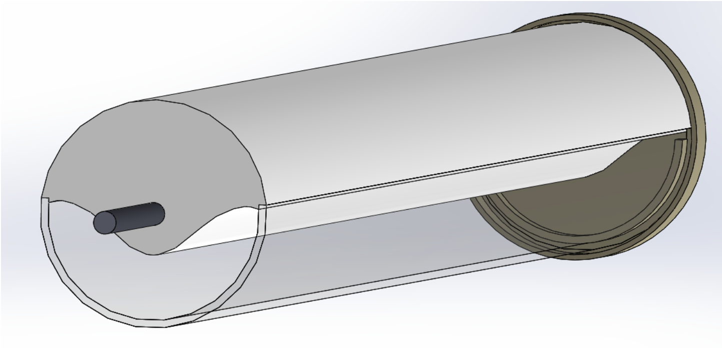
✗ Limited thermal efficiency

Optical design

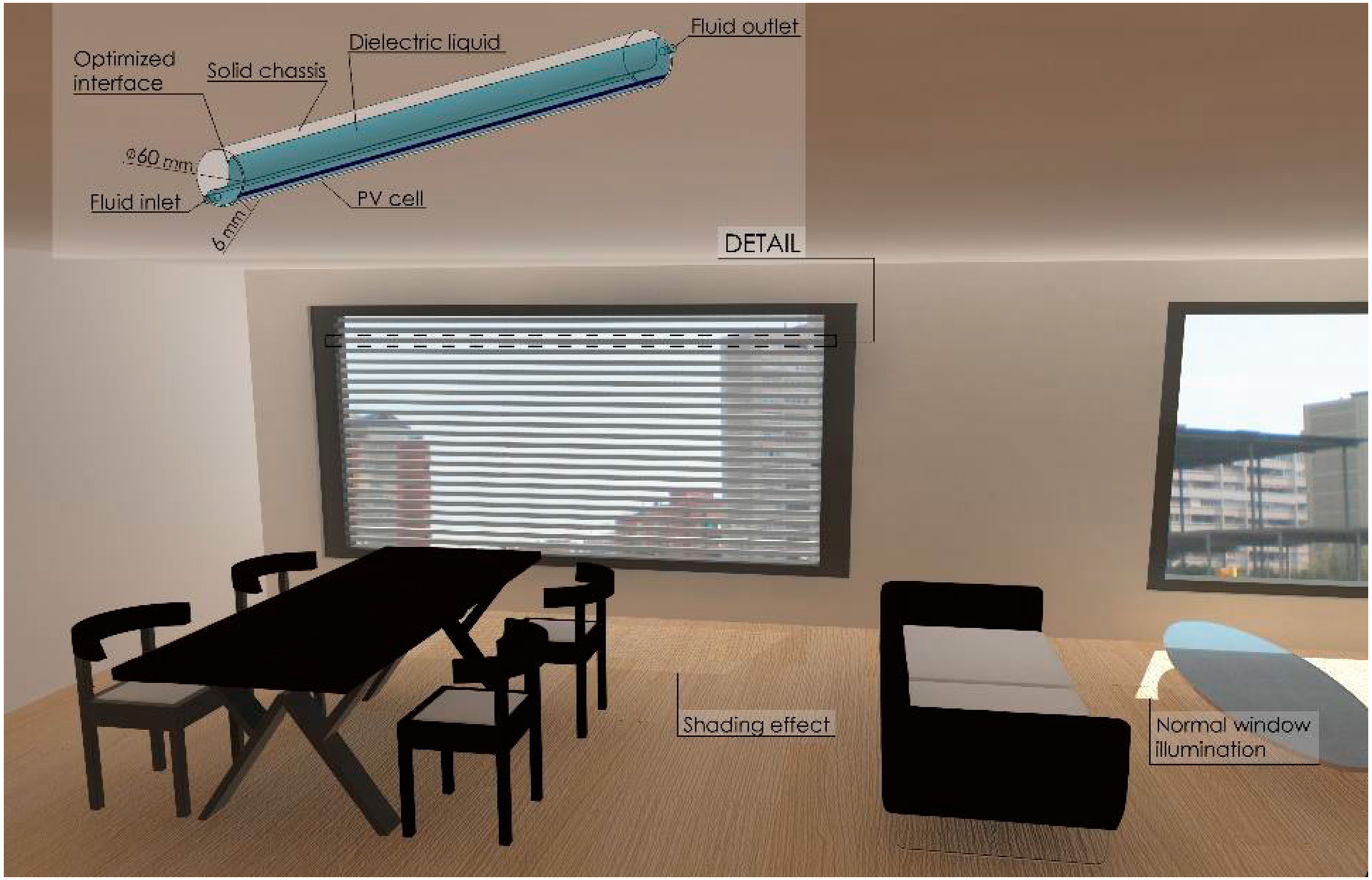
Riverola, et al., Optics Express, 2018, Accepted Manuscript

Requirements and goals

- Building integration potentially over façades and windows
- Low-Medium concentration
- Direct-immersed PVs in dielectric liquids
- Partially cover electricity and heat energy demands of buildings
- Reasonable performance
- Cost-effective



Optical design



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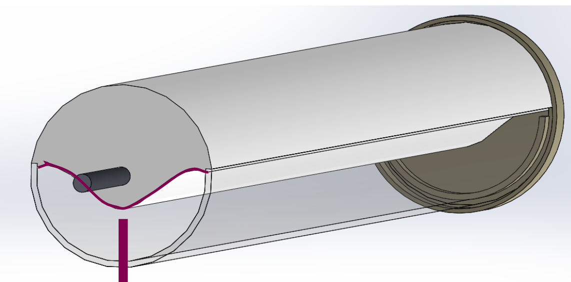
Optical design

Riverola, et al., Optics Express, 2018, Accepted Manuscript

Model

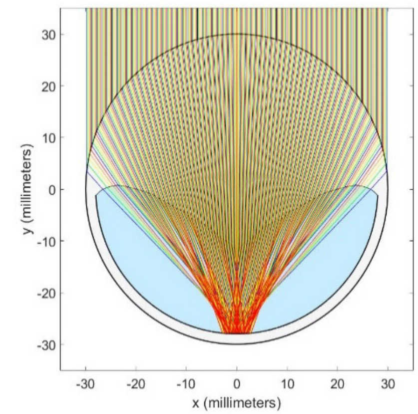


Free-form profile (B-Spline)

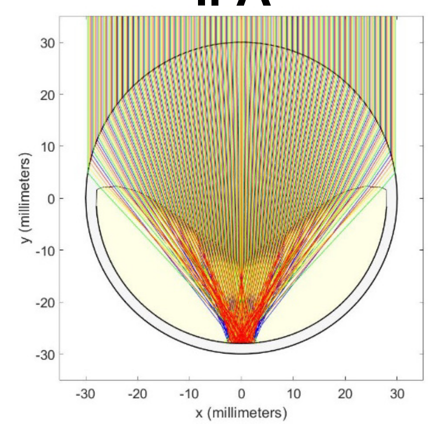
Ray-tracing optimisation

C_g ~ 10-20x
Maximise: Optical efficiency
Irradiance uniformity

DIW



IPA



Optical design

Riverola, et al., Optics Express, 2018, Accepted Manuscript

Ray-tracing characterisation

Magnitude	DIW			IPA		
Geometrical Concentration (-)	10	15	20	10	15	20
Weighted Optical Efficiency (-)	0.76	0.76	0.75	0.81	0.81	0.80
Non-Uniformity (-)	0.14	0.19	0.20	0.13	0.40	0.41
Acceptance Angle ± (º)	1.11	0.71	0.47	1.08	0.53	0.40

Weighted Optical Efficiency is defined for the Si spectral response bandwidth

$$\text{Weighted Optical Efficiency} = \frac{J_{SC}}{J_{SC,\eta=1}}$$

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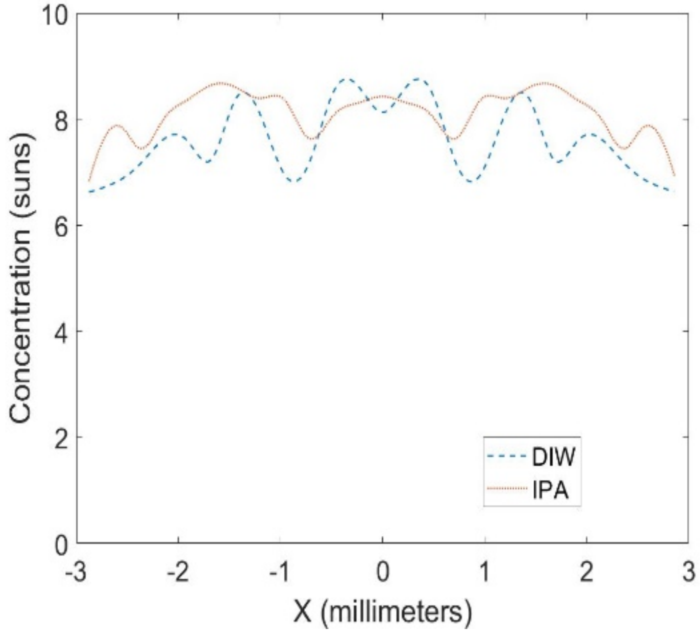
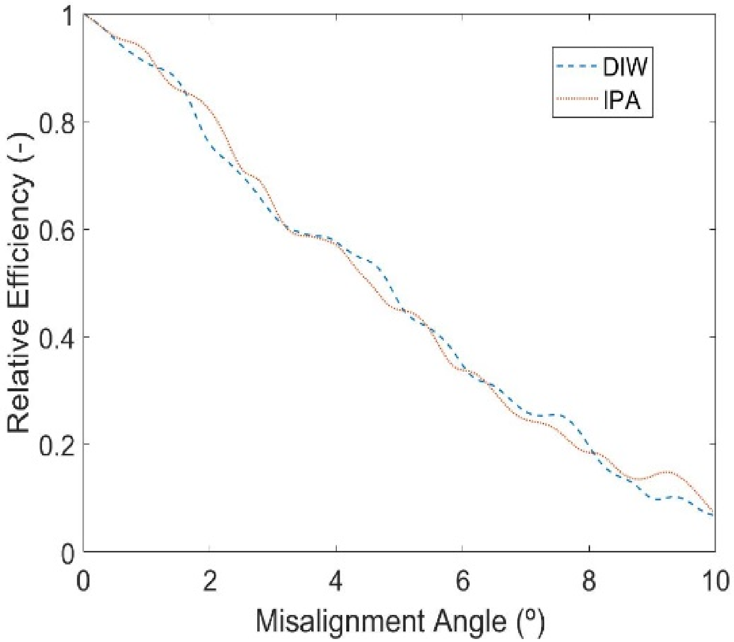
Optical design

Riverola, et al., Optics Express, 2018, Accepted Manuscript

Ray-tracing characterisation

Geometrical concentration = 10x

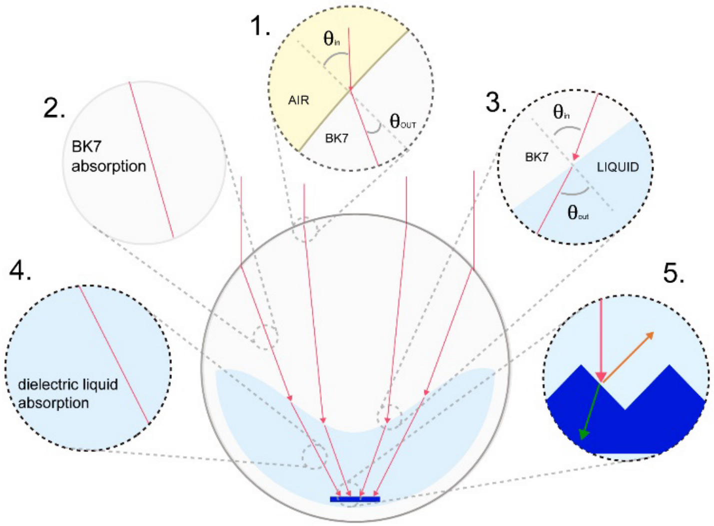




Optical design

Riverola, et al., Optics Express, 2018, Accepted Manuscript

What's the main difference between both systems?

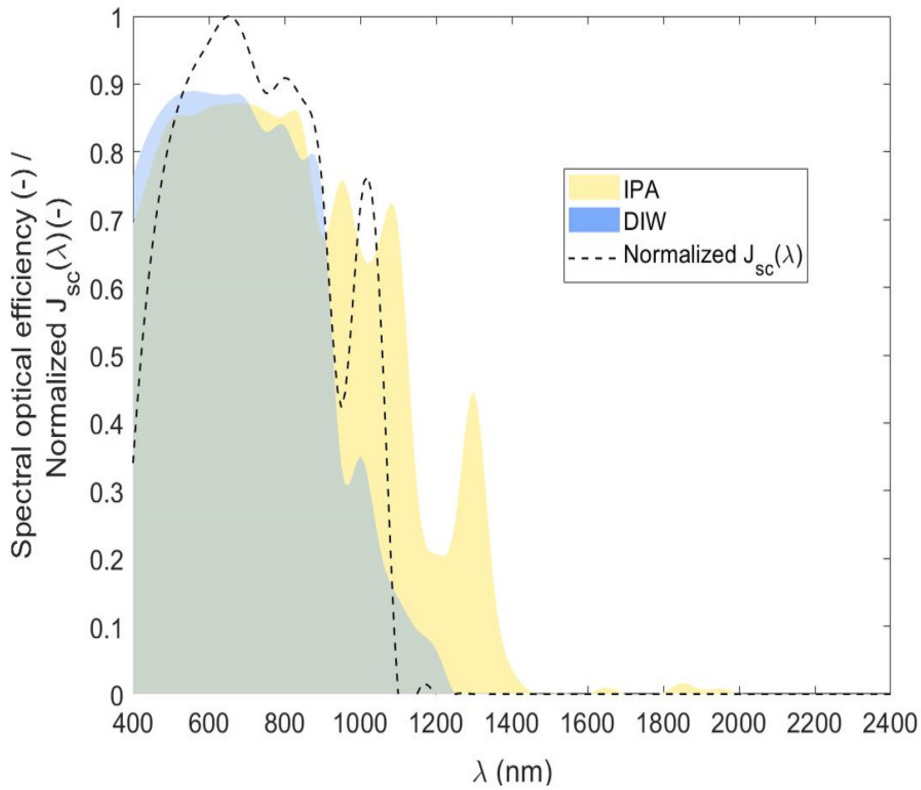


	DIW	IPA
Optical Loss	**Optical Efficiency (%)**	
Fresnel 1	92.9	92.9
BK7 abs.	99.5	99.5
Fresnel 2	98.7	99.0
Liquid abs.	86.5	92.0
Reflected cell	96.0	95.9

Optical design

Riverola, et al., Optics Express, 2018, Accepted Manuscript

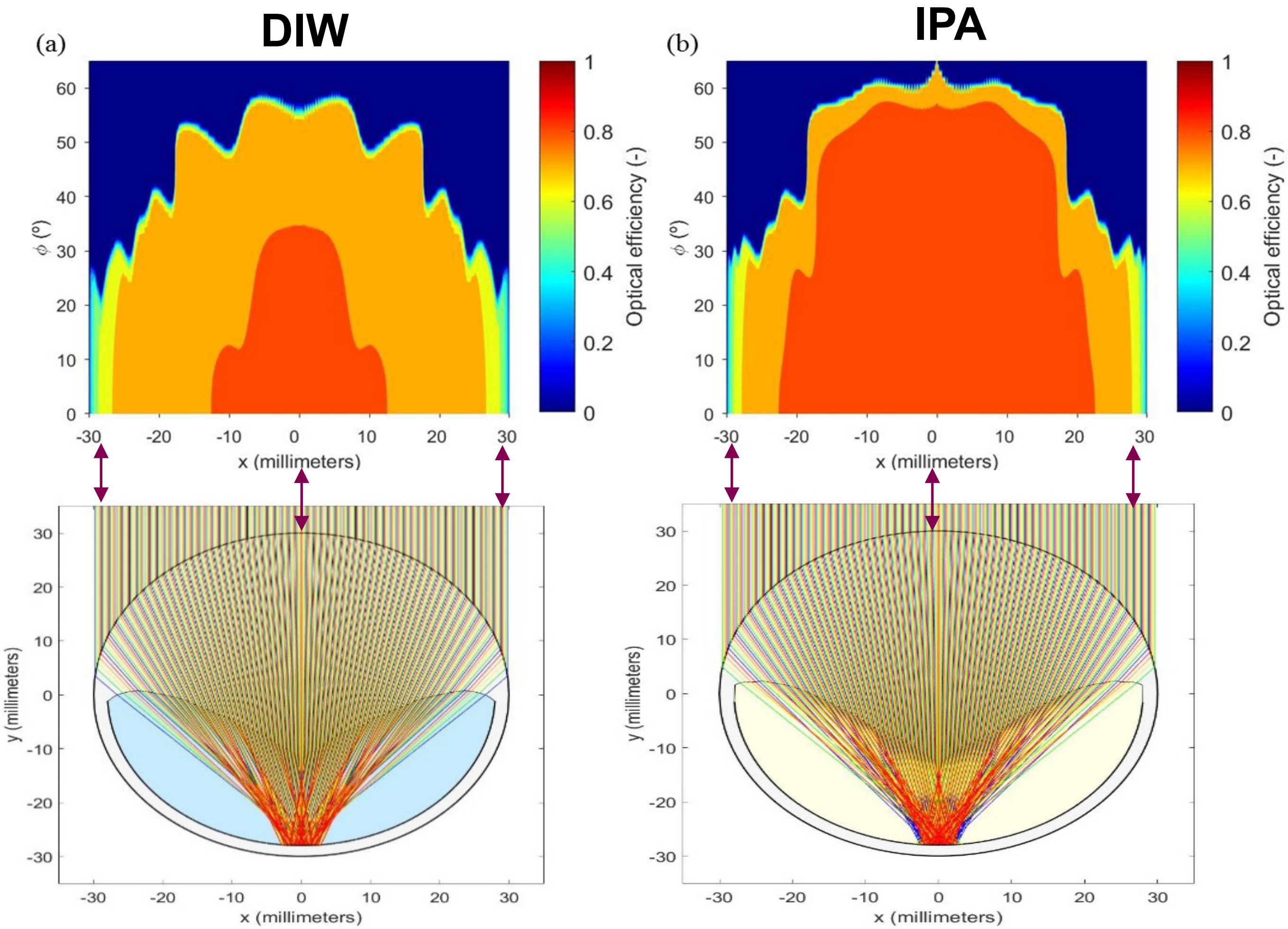
What's the main difference between both systems?



Optical design

Riverola, et al., Optics Express, 2018, Accepted Manuscript

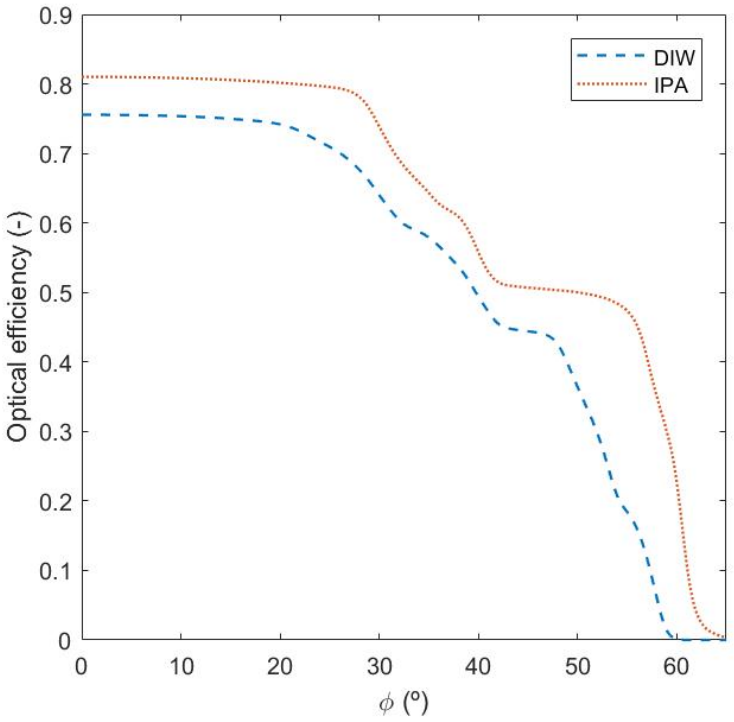
What about the azimuth?



Optical design

Riverola, et al., Optics Express, 2018, Accepted Manuscript

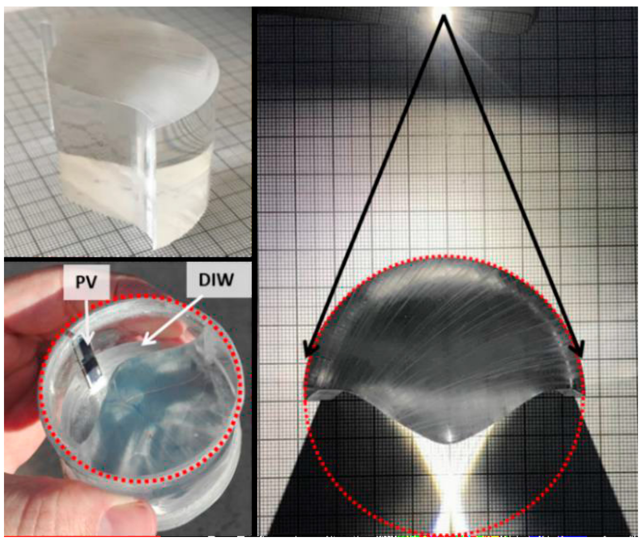
What about the azimuth?



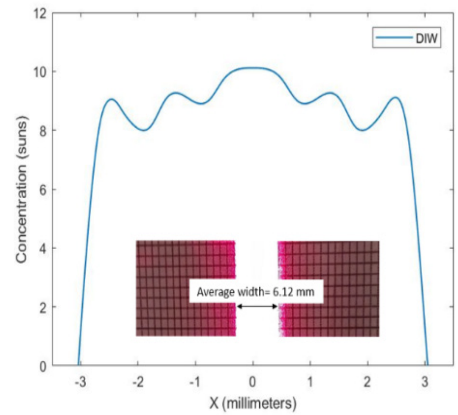
Optical design

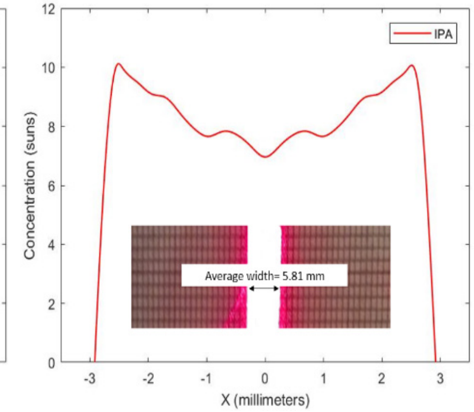
Riverola, et al., Optics Express, 2018, Accepted Manuscript

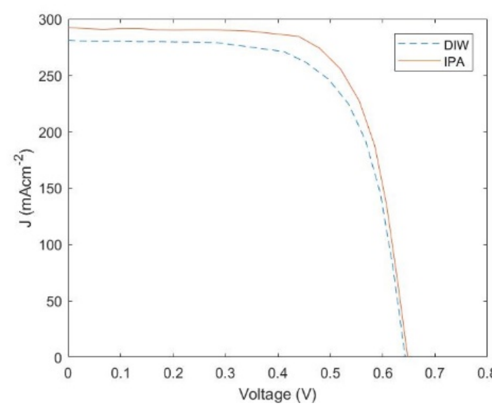
Fabrication and experimental optical performance



$\lambda = 640.1$ nm







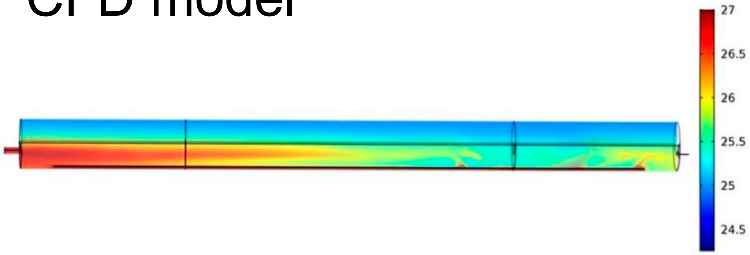
experimental optical efficiency for DIW is 73.5% and for IPA 76.5%.

Moreno, A., et al., Solar Energy, 169 (2018) 374-385

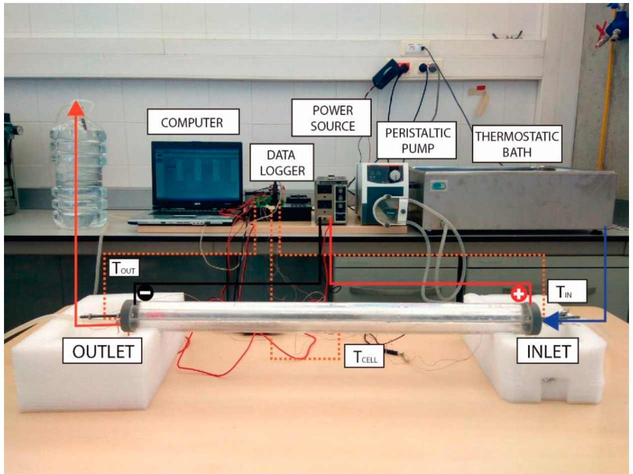
Energetic dynamic modelling and simulation

Thermal characterisation

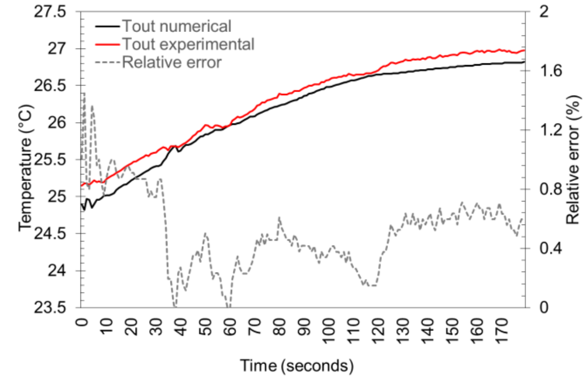
CFD model

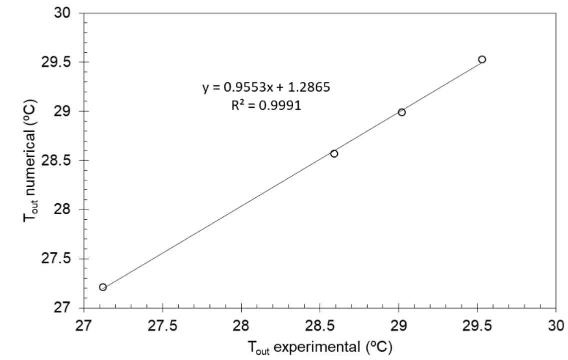


Experimental validation



Great agreement!





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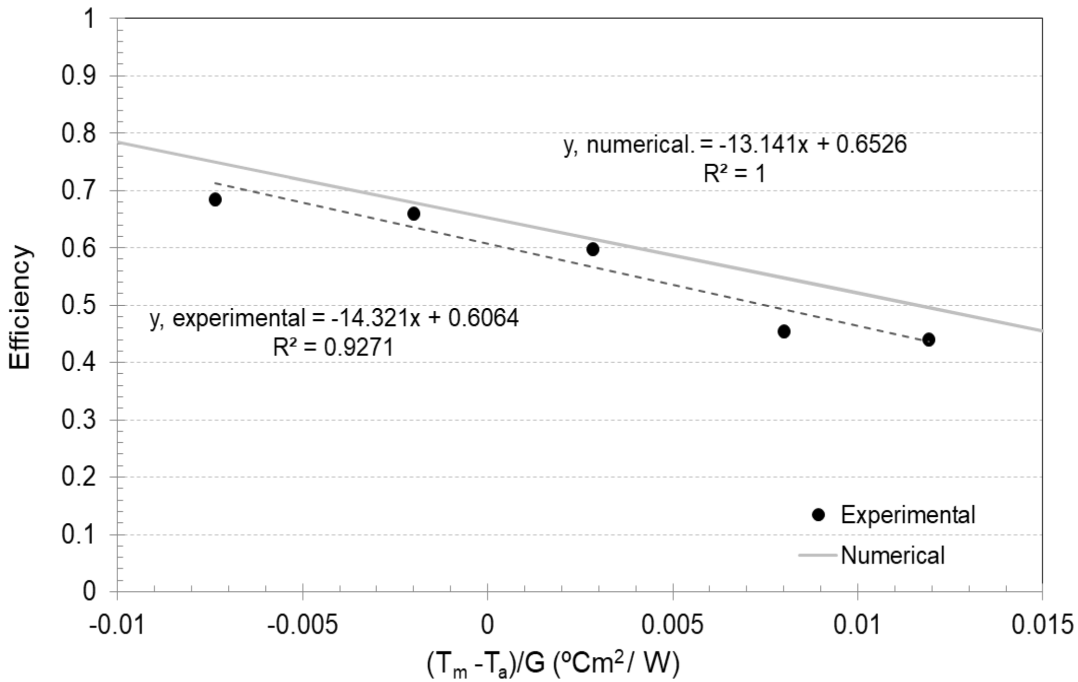
Energetic dynamic modelling and simulation

Thermal characteristic curve under wind velocity of 2 m/s



Churchill, S. W., and Bernstein, M., J. Heat Transfer 99 (1977), 300

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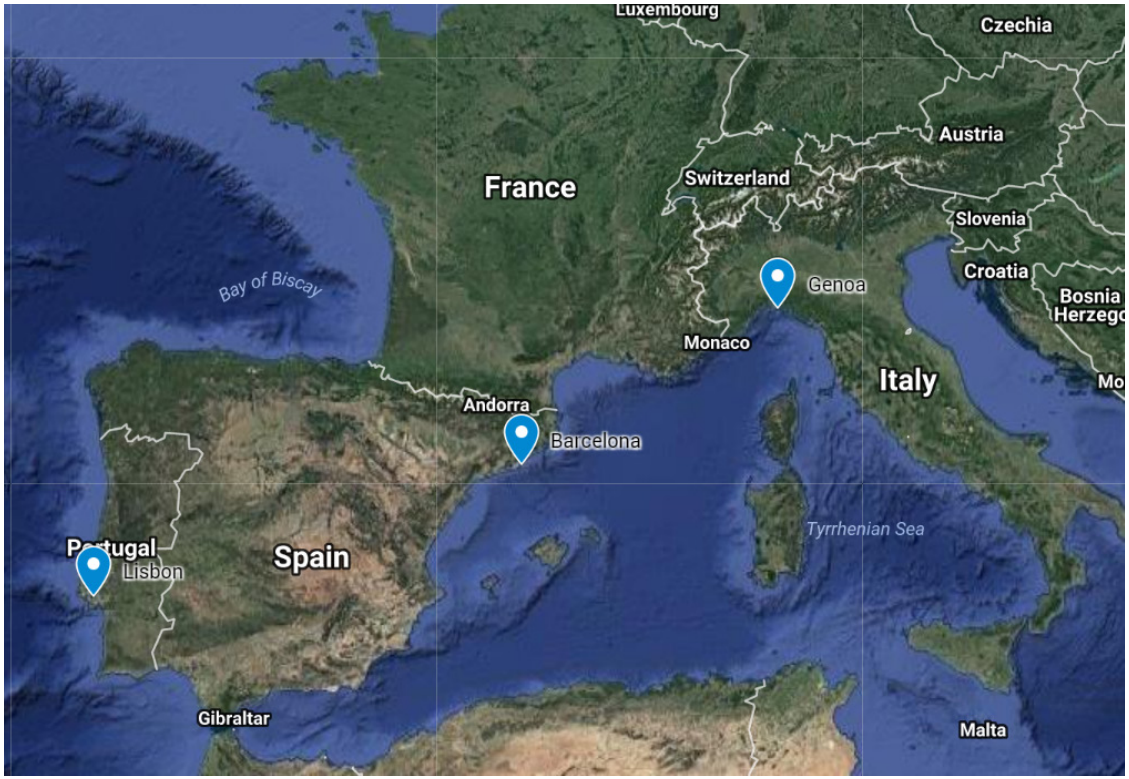
Moreno, A., et al., Solar Energy, 169 (2018) 374-385

Energetic dynamic modelling and simulation

Simulation – Selected locations?



- Avoid shading between modules

↓

Latitudes > 35º

- High heat loss coefficient

↓

Mild winters & hot summers

↓

Csa climate

Köppen-Geiger climate classification

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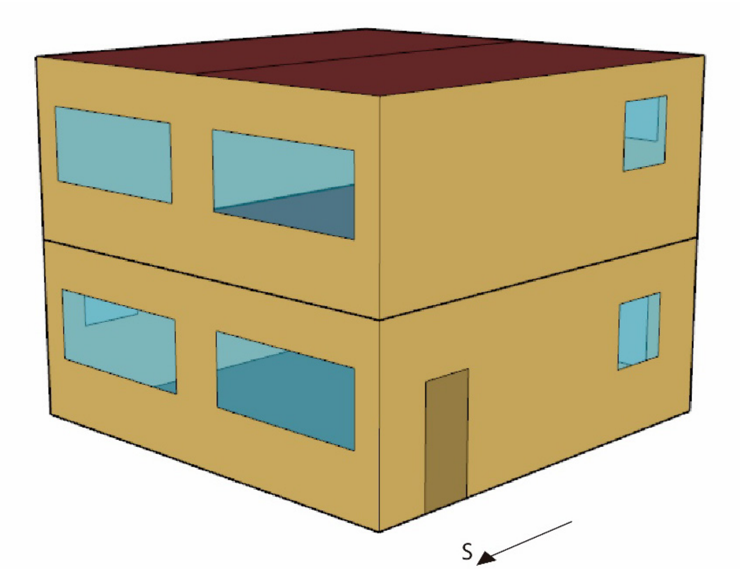
Energetic dynamic modelling and simulation

Building description and demands



- 2-story single family house
- Habitable area = 144.5 m^2

Energy demands

- Domestic Hot Water (DHW)
  → Gas boiler
- Space Heating & Cooling (SH&C)
  → Reversible Heat Pump

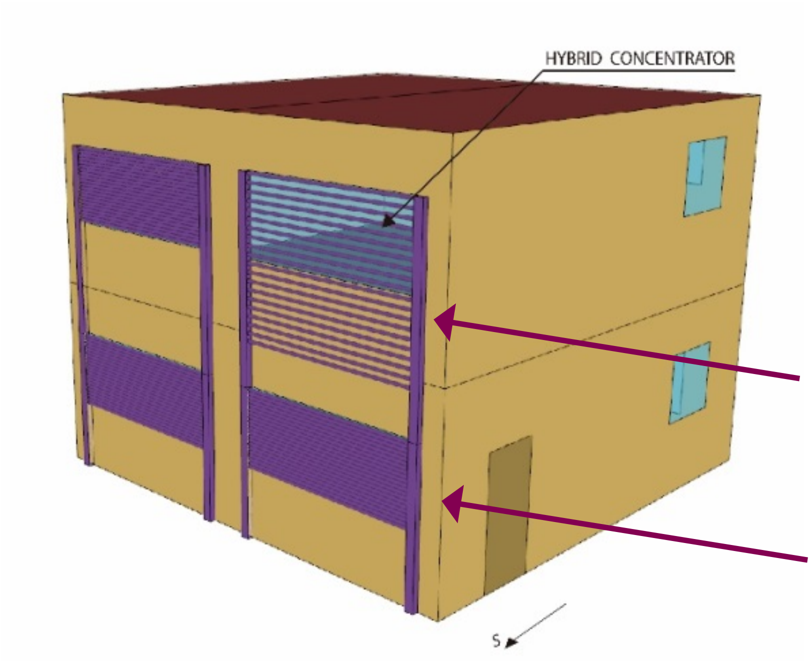
Location	DHW (kWh/m^2)	SH (kWh/m^2)	SC (kWh/m^2)	Electricity (kWh/m^2)
Lisbon	16.3	53.3	12.6	31.7
Barcelona	16.9	74.4	11.1	37.5
Genoa	16.7	80.2	15.5	40.2

TRNbuild tool

DHWcalc

Energetic dynamic modelling and simulation

Building description with CPTV collectors



- 21 rows per window
- Collectors total area = 16.7 m^2

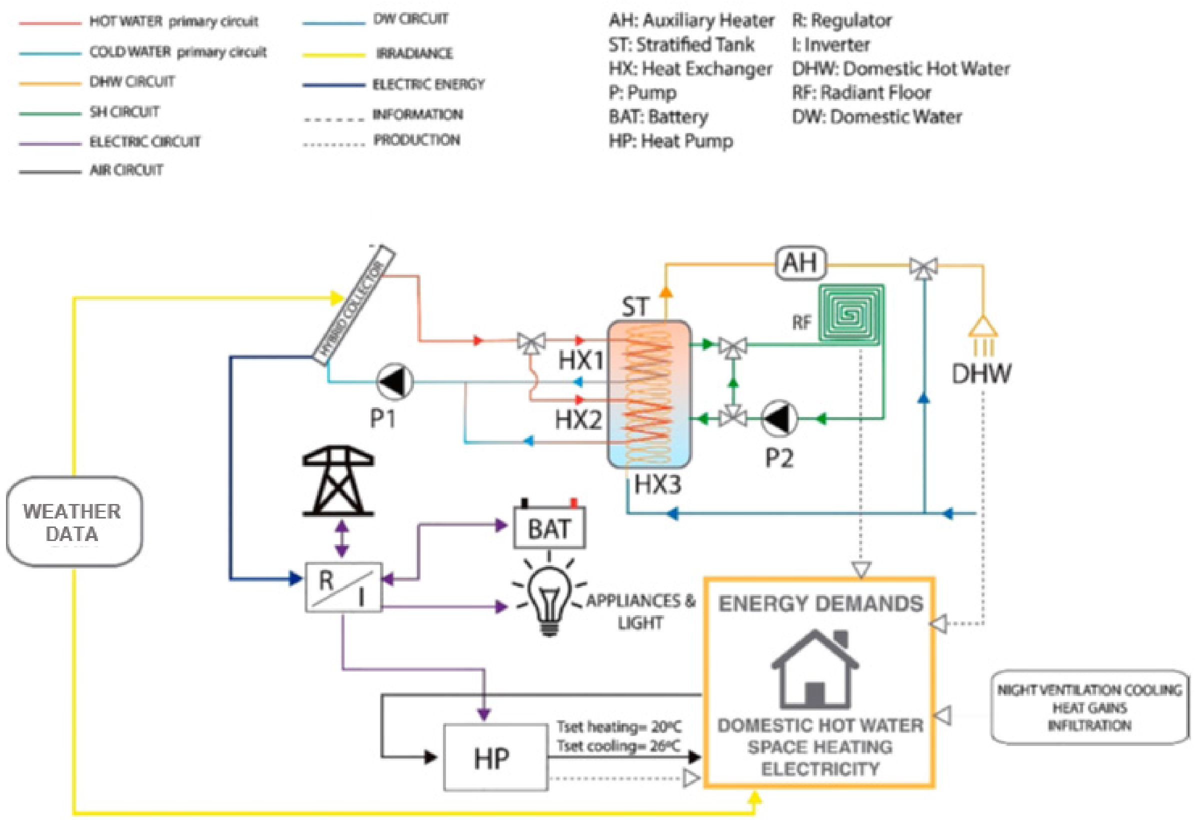
Maximum interspace

Minimum interspace

Moreno, A., et al., Solar Energy, 169 (2018) 374-385

Energetic dynamic modelling and simulation

Simulated system topology



CPVT Thermal prod.

- DHW
- SH
  → Radiant floor (RF)

CPVT Electrical prod.

- A&L
- SH&C
  → Heat Pump (HP)

self-consuming
connected
to power grid with
backup batteries

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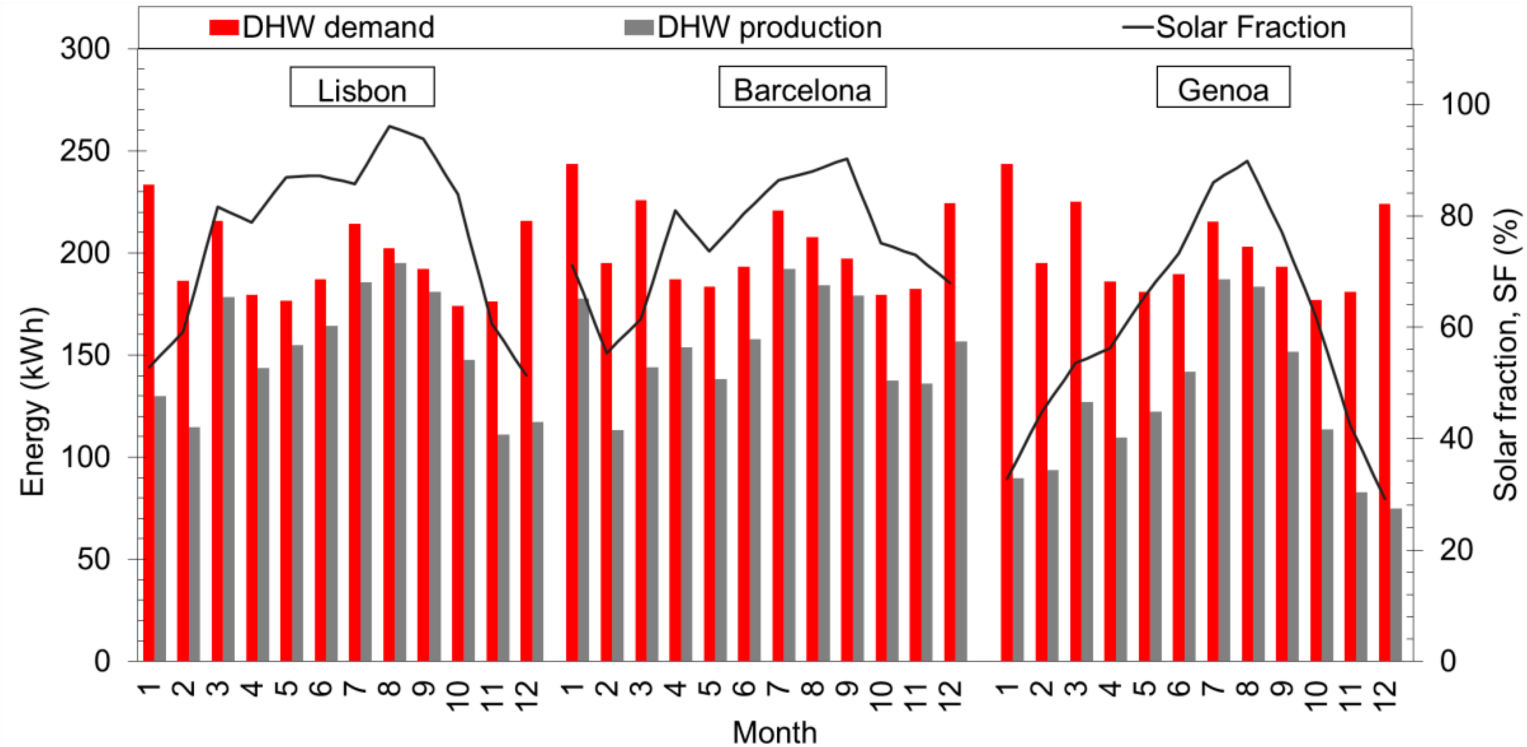
Moreno, A., et al., Solar Energy, 169 (2018) 374-385

Energetic dynamic modelling and simulation

Domestic Hot Water (DHW)

$$SF_{DHW} = 100\left(1 - \frac{Energy\ \ DHW,auxiliary}{Energy\ \ demand\ \ DHW}\right)$$

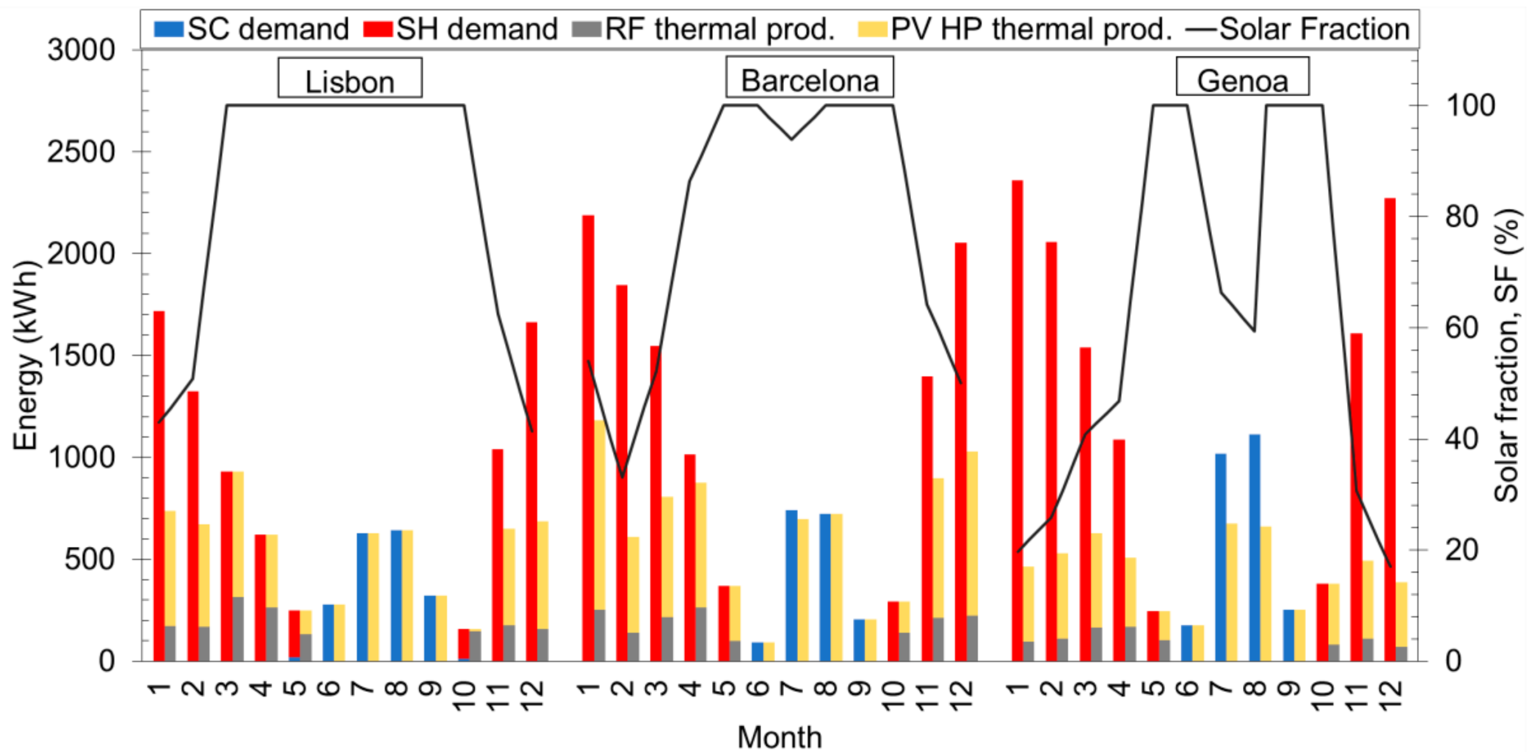


Annual SF: 77.5% 76.6% 61.2%

Energetic dynamic modelling and simulation

Space Heating (SH) and Cooling (SC)

$$SF_{SH\&C} = 100\left(1 - \frac{Energy\ \ SH\ \&\ C\ \ from\ \ grid}{Energy\ \ demand\ \ SH\ \&\ C}\right)$$

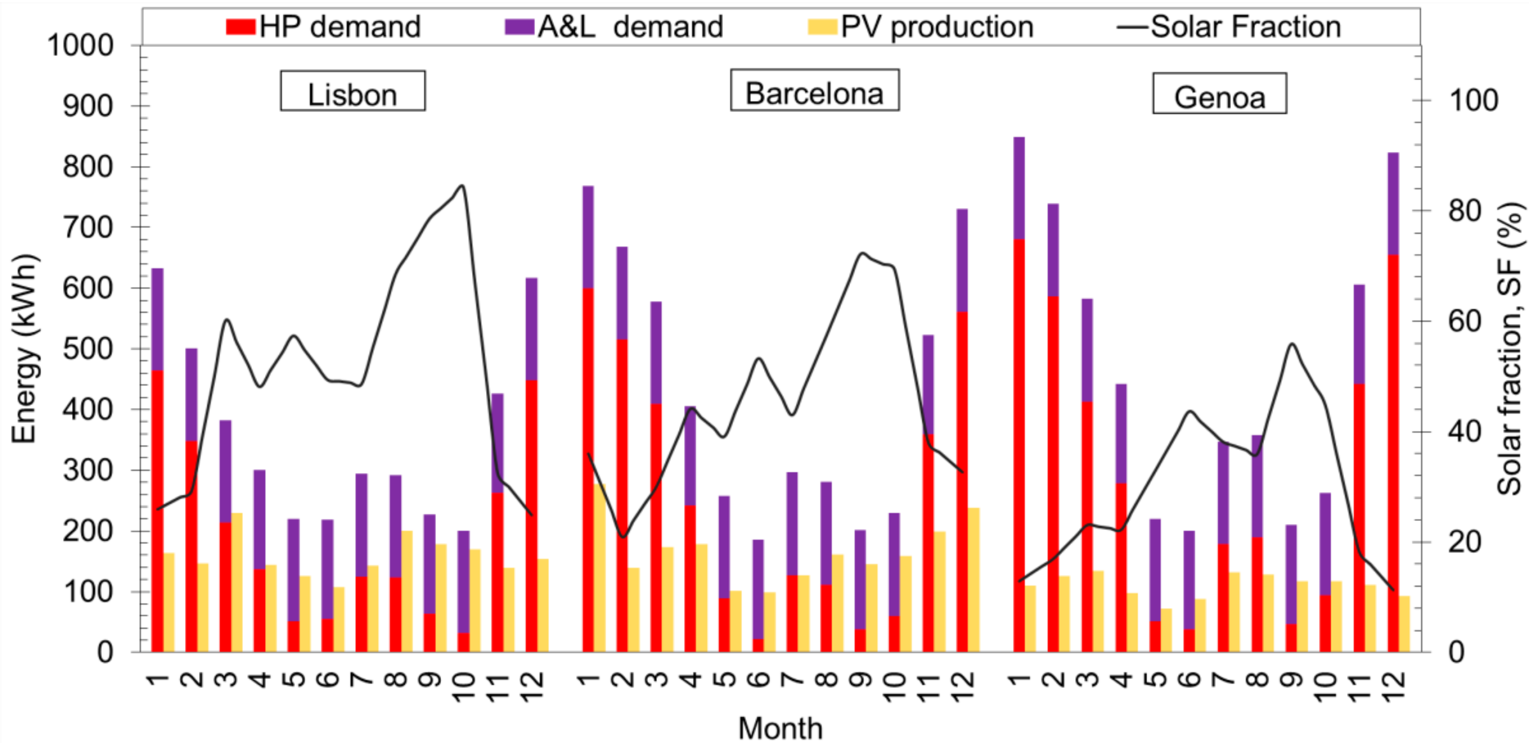


Annual SF: 68.7% 62.4% 38.3%

Energetic dynamic modelling and simulation

Electricity demands

$$SF_{ELECTRICAL} = 100\left(\frac{Electrical\ energy\ from\ CPVT}{Electrical\ energy\ demand}\right)$$



Annual SF: 44.1% 38.9% 23.5%

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Future work

- Improve the thermal efficiency, reducing convective and radiative losses.
- Test for a long time period and over a real building or a full-scale testing unit.
- The energy output could be enhanced by solar cells with lower temperature coefficients and higher cell efficiencies.

Q&A

Thanks for your attention!

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