TwinSolar workshop

BIPV

Appearance of BIPV

Agenda

What is a colour?

- Physics of light and colour
- Human colour vision

How can we quantify colours?

- Colour matching functions
- Colour spaces
- Colour parameters

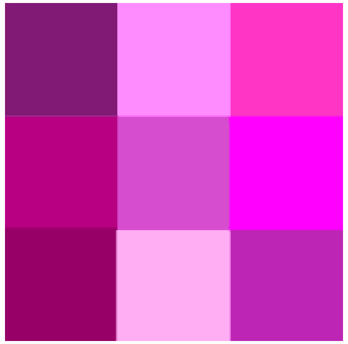
How does BIPV achieve colouration?

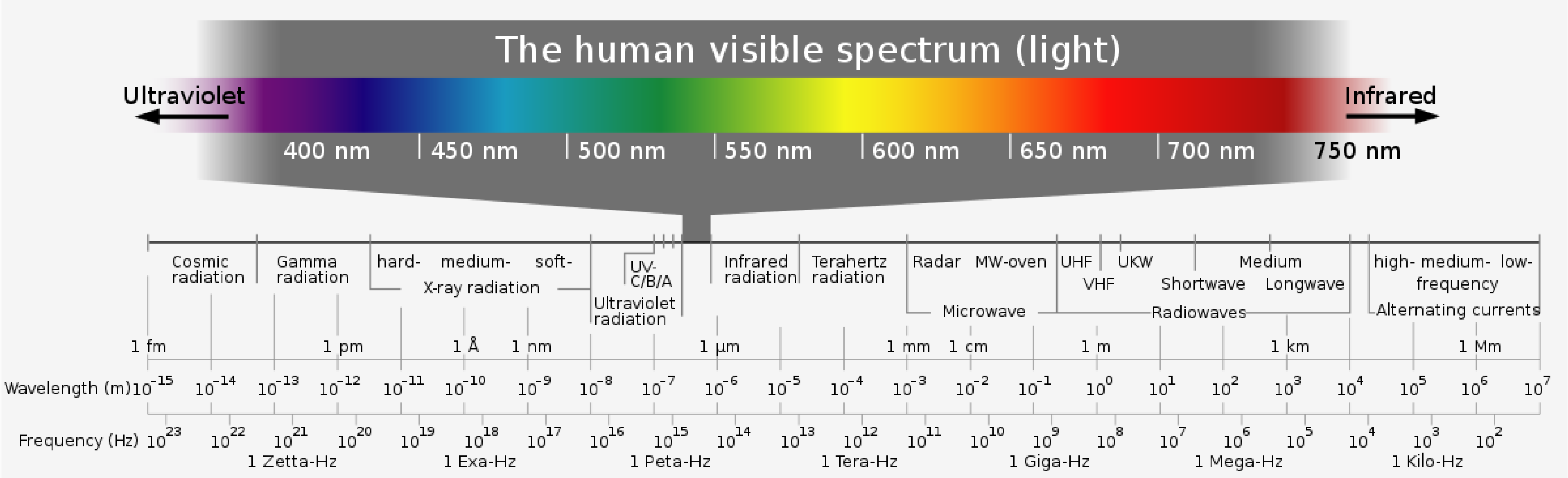
- Absorptive vs structural colours
- Associated power losses

What are colours?

“Spectral colours” (monochromatic)
- Spectral property of light
- Visible range: ~380 – 750 nm

“Non-spectral colours”
- Grayscale colours, shades





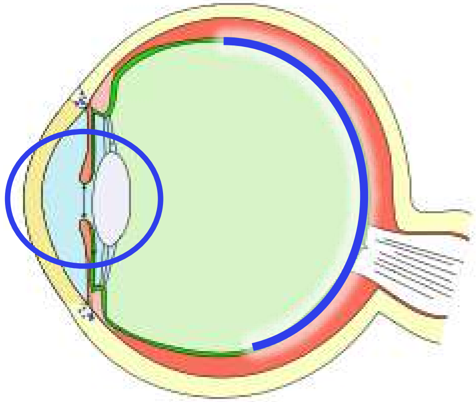
Human colour vision

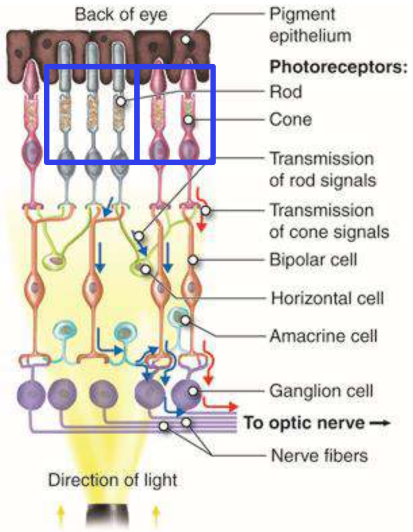
Visual system in the eye:

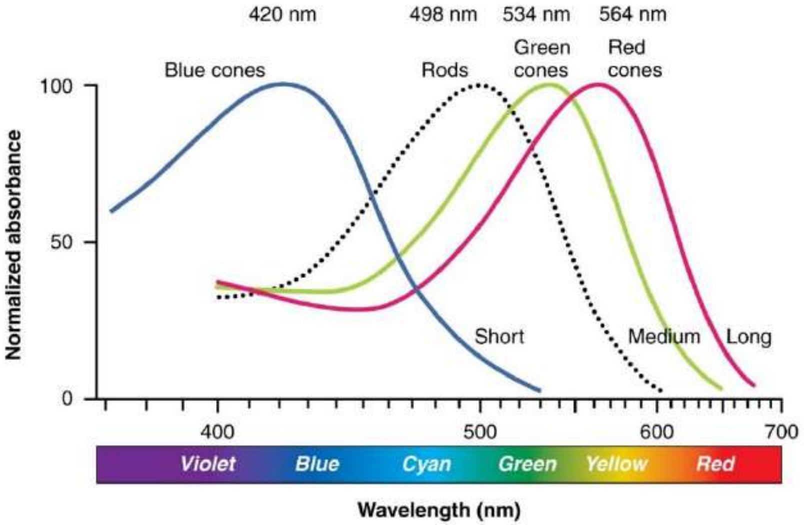
- Focusing system (lenses)
- Receptive system (retina)

Two main kinds of photoreceptors:

- Rods: Low-light (“scotopic”) vision
- Cones: Daylight (“photopic”) vision
  – 3 types: red, green and blue







Colour matching functions

Correlate spectra to colour coordinates

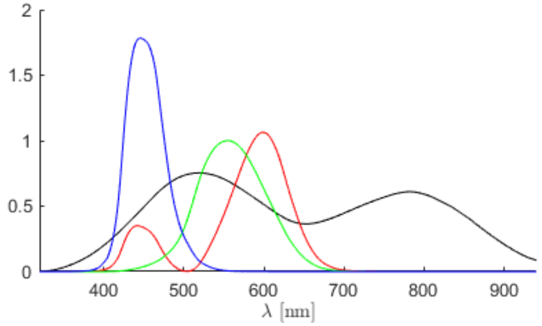
Experiments by W.D. Wright and J. Guild in 1920s

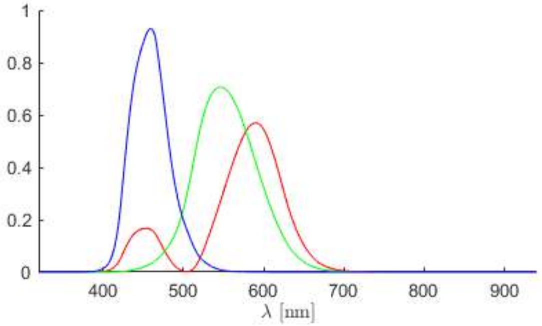
- Follow human colour vision

$$X = \int_\lambda L_{e,\Omega,\lambda}(\lambda)\bar{x}(\lambda)d\lambda$$

$$Y = \int_\lambda L_{e,\Omega,\lambda}(\lambda)\bar{y}(\lambda)d\lambda$$

$$Z = \int_\lambda L_{e,\Omega,\lambda}(\lambda)\bar{z}(\lambda)d\lambda$$



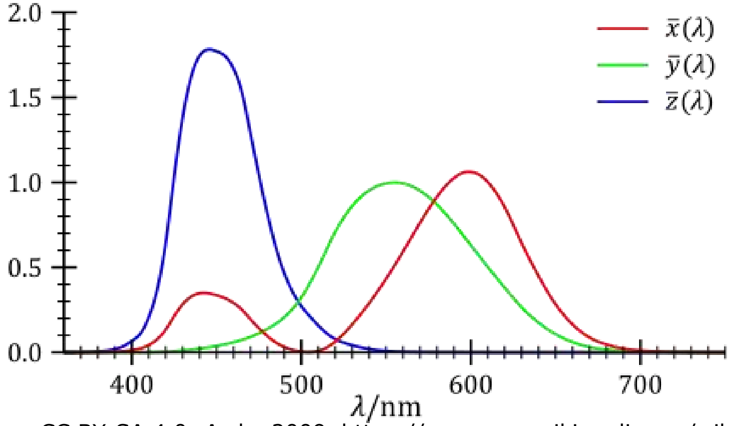


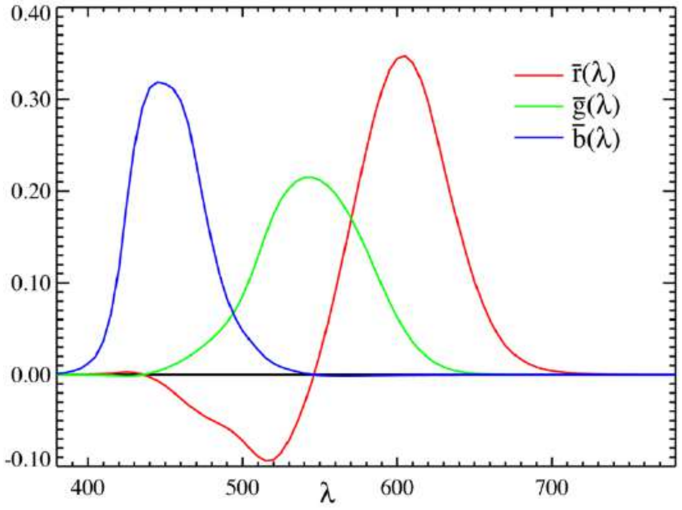
XYZ = [56, 67, 54]

Different colour spaces

- CIE 1931 XYZ
- CIE 1931 RGB

CIE 1931 colour matching functions



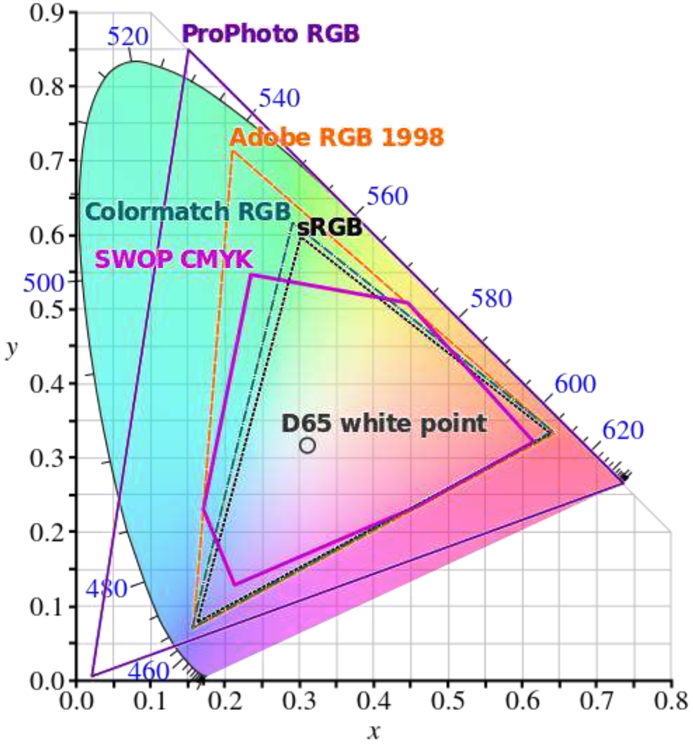


Technical colour spaces

RGB – “red – green – blue”
- In digital displays
- Variety of proprietary colour spaces
- Cover only parts of the visible gamut

CMYK – “cyan – magenta – yellow – black”
- Used for printing

Actual display and print colours are device dependent

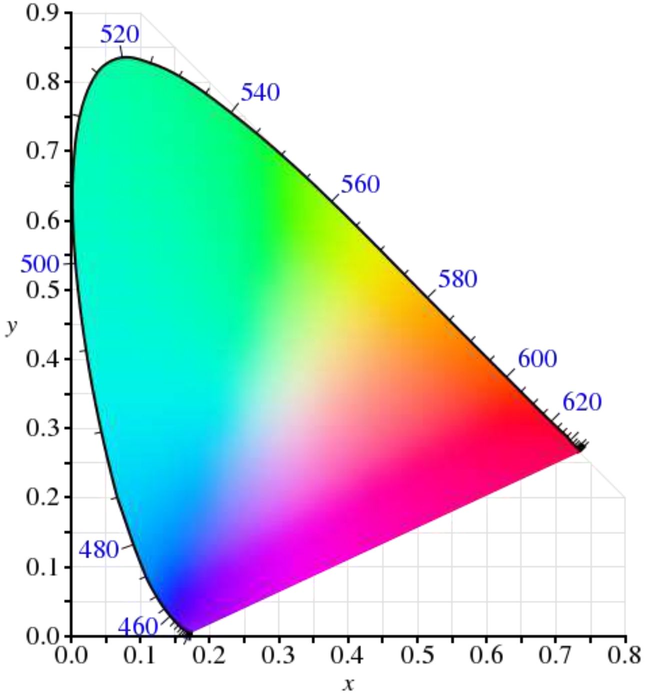


Advanced colourspaces

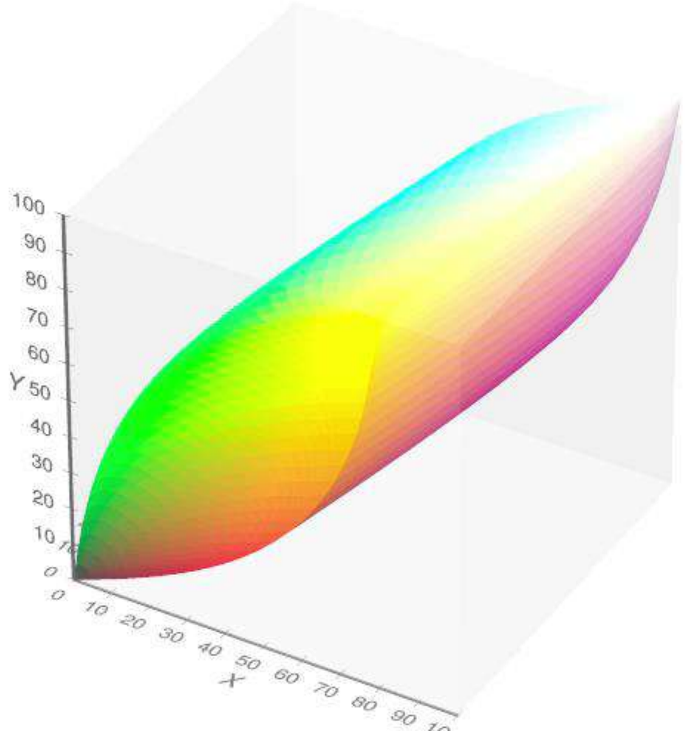
"Commission Internationale de l'Éclairage"
"International Commission on Illumination"

CIE 1931
- XYZ and RGB

xyY derived colorspace
- Chromaticity:
  - $\boldsymbol{x} = \frac{X}{X+Y+Z}$
  - $\boldsymbol{y} = \frac{Y}{X+Y+Z}$
  - $z = \frac{Z}{X+Y+Z}$
- $x + y + z = 1$
- Brightness: **Y**



Public Domain: BenRG, 2009, https://commons.wikimedia.org /wiki/File:CIE1931xy_blank.svg



CC BY-SA 4.0: Michael Horvath (SharkD), Christoph Lipka, 2017, https://en.wikipedia.org/wiki/File:Visible_gamut_within_CIEXYZ_color_space_D65_whitepoint_mesh.webm

Advanced colourspaces

Problem: CIE 1931 is not perceptually uniform

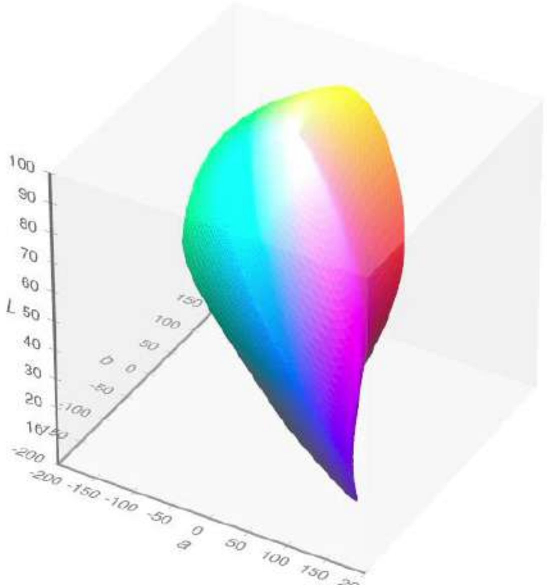
Two new colourspaces developed in 1976:

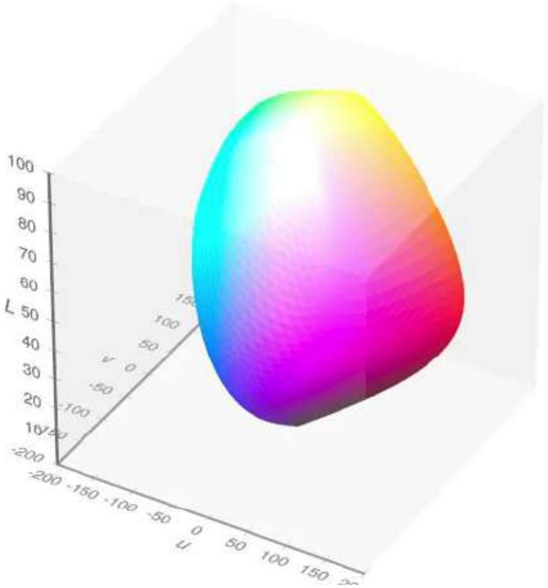
- CIELAB
  - L*a*b*
  - For colourful surfaces and dyes
- CIELUV
  - L*u*v*
  - For colour displays

Lightness: L*

Chromaticity: a*, b*, u*, v*

Better perceptual uniformity but not perfect





Advanced colourspaces

Colour appearance models

- Refinements of CIELAB
- E.g. CIECAM02, CAM16, CIECAM16

Cover additional phenomena:

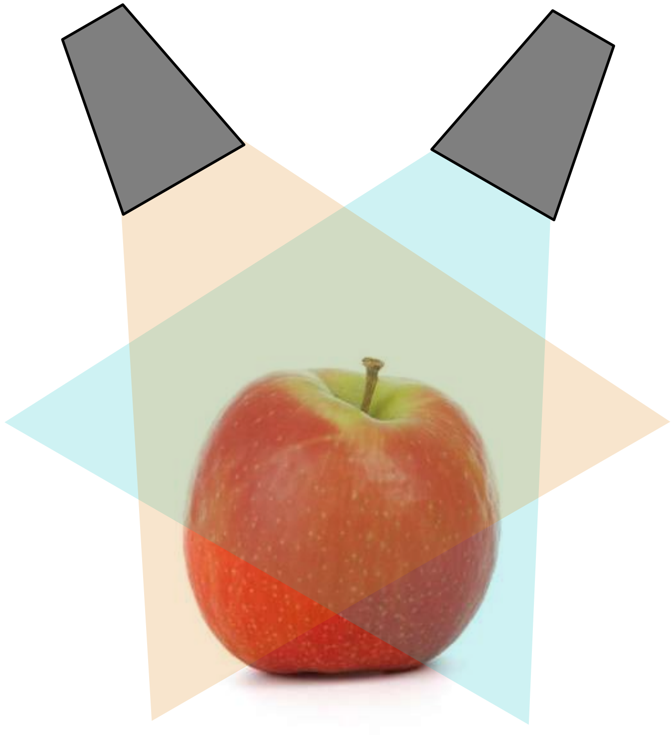
- Compensation of white point (colour temperature) of a light source
  – “Chromatic adaptation”
- Effects of the background colour and brightness
- Influence of brightness on colour and contrast

More complicated

Require more inputs

Accurate descriptions of colour perception is very challenging!

CIELAB is a good, simple baseline for comparison!



The CIELAB colour space

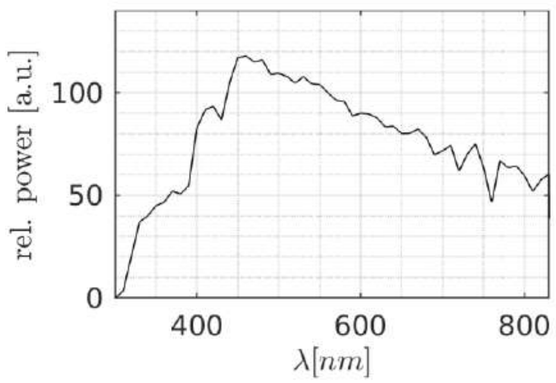
Relies on a “standard observer”

- Device-independant
- Like CIE 1931 XYZ

Relies on a “reference white”

- Compensates for different illumination conditions
- D65 or D50 (printing industry)

D65 standard illuminant



$X_nY_nZ_n$ = [95, 100, 108.9]

CIE 1931 XYZ
colour coordinates of reference white
(3° standard observer, D65 standard illuminant)

XYZ = [56, 67, 54] → L*a*b* = [85.5, -18.3, 16.7]

CIE 1931 XYZ colour coordinates

$$L^* = 116 f\left(\frac{Y}{Y_n}\right) - 16$$

$$a^* = 500\left(f\left(\frac{X}{X_n}\right) - f\left(\frac{Y}{Y_n}\right)\right)$$

$$b^* = 200\left(f\left(\frac{Y}{Y_n}\right) - f\left(\frac{Z}{Z_n}\right)\right)$$

$$f(t) = \begin{cases} \sqrt[3]{t} & \text{if } t > \delta^3 \\ \frac{t}{3\delta^2} + \frac{4}{29} & \text{otherwise} \end{cases}; \ \delta = \frac{6}{29}$$

CIELAB colour coordinates

Colour charts and palettes

Variety of systems

- RAL colour standard (Germany)
- Pantone Colour Matching System (US)
- NCS Colour Palette (Sweden)
- DIC Colour System Guide (Japan)
- (…)

Technically not colourspaces

- Physical or digital representations
- Used for selecting colours

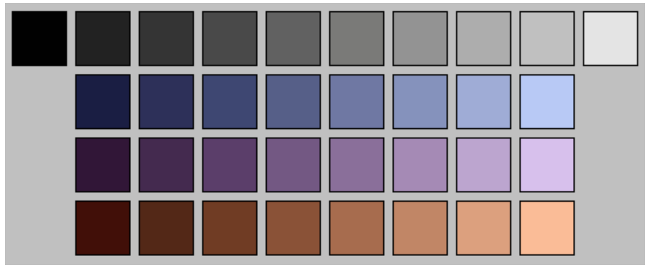
Most have defined colour coordinates

Some are proprietary

Colour metrics

Lightness (L*)

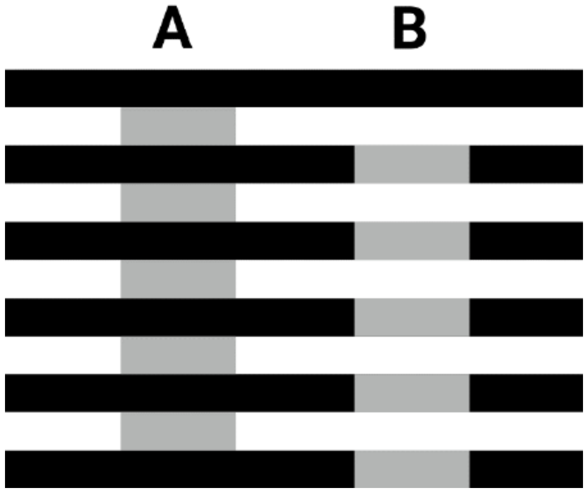
- Ranges from black to white
- Perception of the (total) reflectance of a surface
- Compared to a similarly lit, perfectly white object



Luminance (L_v)

- Photometric quantity
- Luminous intensity
  per unit area in a certain direction
- Unit: [cd/m^2]

White's illusion



Brightness (Q)

- Perception of the luminance of an object
- Depends on the background and context

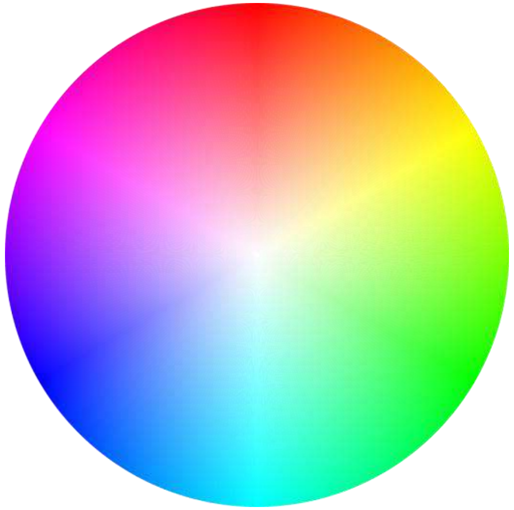
Colour metrics

Colourfulness
- Degree of difference from a colour to gray

Chroma (C*)
- Colourfulness relative to the brightness of a white colour under similar conditions
- $C^*_{ab} = \sqrt{a^{*2} + b^{*2}}$

Saturation (s)
- Colourfulness relative to the objects own brightness
- $s_{ab} \approx \frac{C^*_{ab}}{L^*}$

Hue (h)
- Differentiates between individual colours
- Often given as an angular quantity
- $h_{ab} = atan2(b^*, a^*)$



Metamerism

Different spectral power distributions leading to identically perceived colours

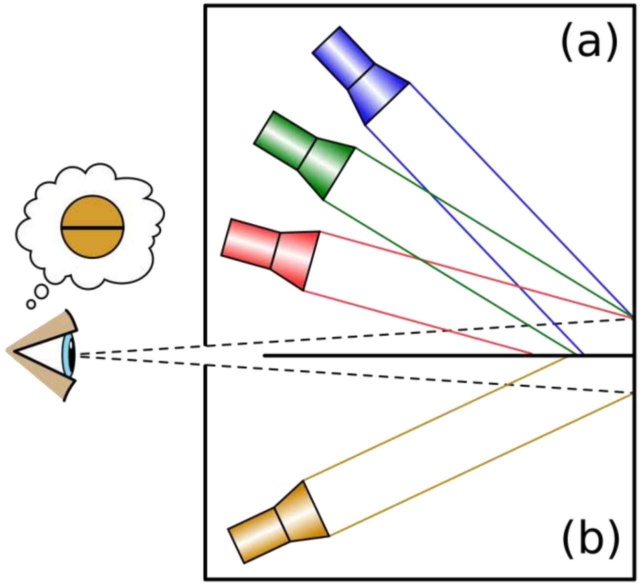
Depends on illumination

- Reflected colour is product of illumination colour and spectra reflectance
- Often fails under different illumination

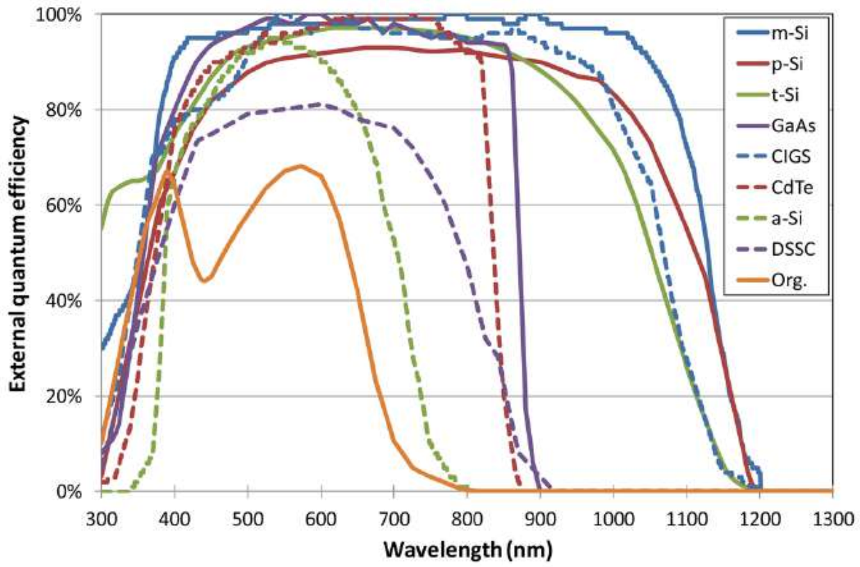
Depends on observer

- Colourblindness increases metamerism

Different spectral distributions result in more or less efficient BIPV



Adapted from CC BY-SA 4.0: MikeRun, 2019, https://commons.wikimedia.org/wiki/File:Metamerism.svg



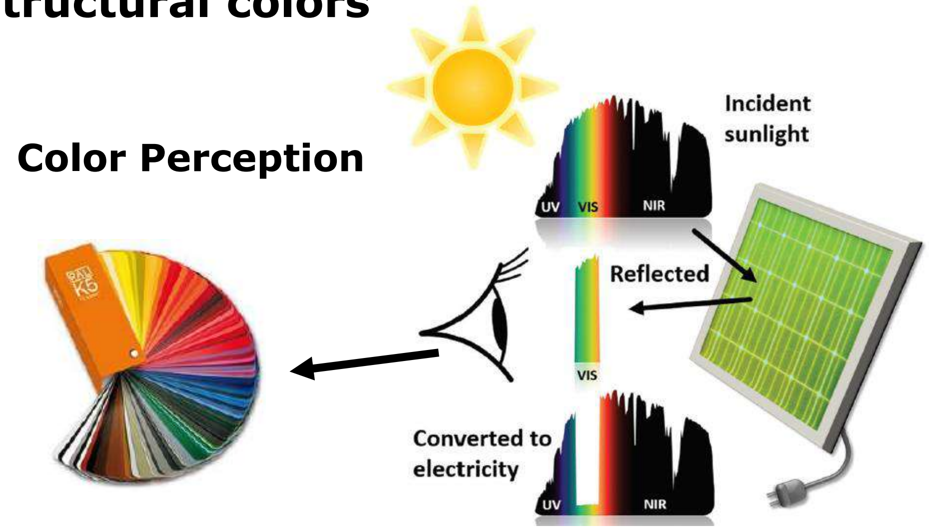
From materials to colours

2 major ways to achieve colours:

- Absorptive colours (pigments)
- Structural colours (thin film stacks)

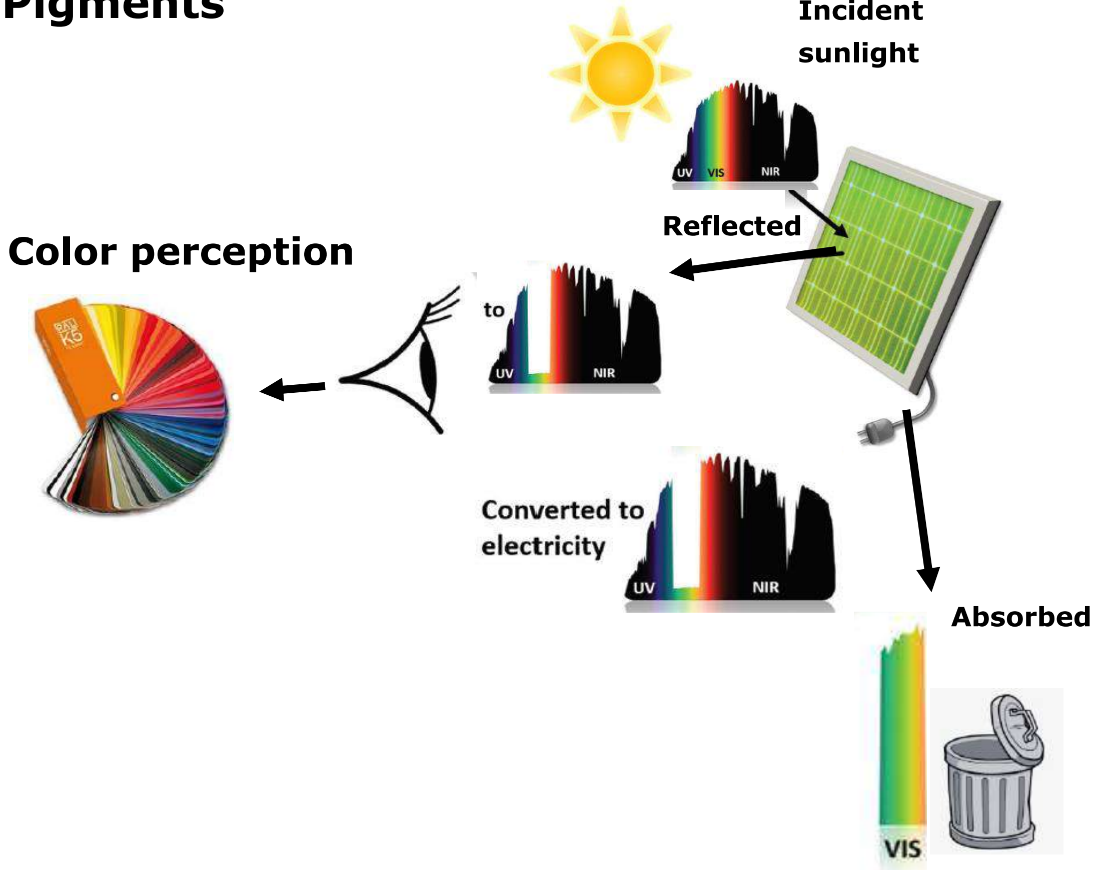
Different impact on performance

Structural colors



https://doi.org/10.1039/c8ee03161d

Pigments



Overall reflections from PV

Affected by the surface glass

- Specular vs diffuse reflections

Fresnel reflections

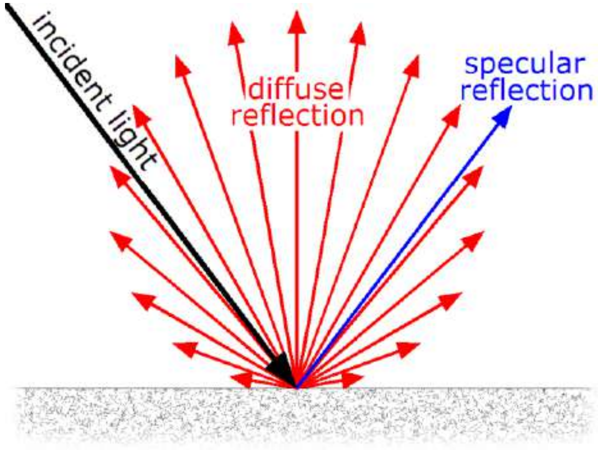
- $R = \left|\frac{n_1 - n_2}{n_1 + n_2}\right|^2$ (single interface at θ=0°)

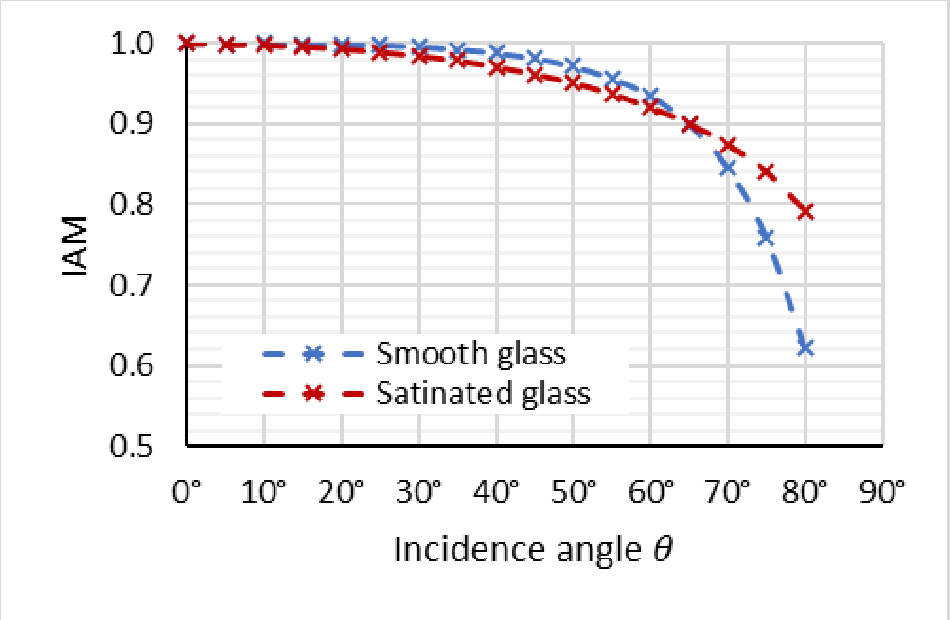
Contained within IAM losses

- Incidence angle modifier
- $IAM(\theta) = \frac{I_{sc}(\theta)}{I_{sc}(0°) \cdot \cos\theta}$

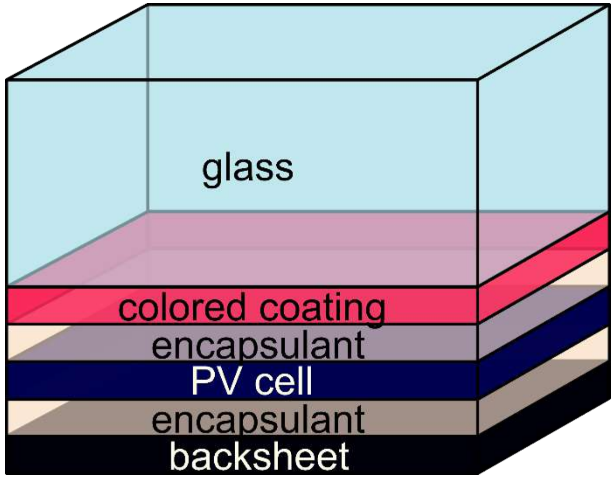
Reflections can lead to glare

- Increased scattering with rough surfaces
- Structured glass, satinated / frosted glass





Printed glass (pigments)

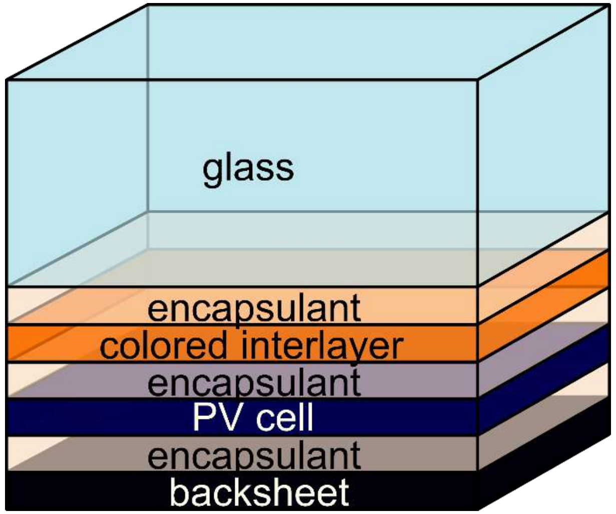


Digital printing on glass:
- Ceramic frit inks used
- Durable enamel through high temperature process

Freedom of design
- Inks not designed for good photon economy
- Variation in pattern / density

Can also be enameled (screen printed)

Coloured interlayers (pigments)



Commercial: based on pigments

- Polymer films, fabrics, …

High flexibility

- Roll-to-roll production
- Independent choice of glass

Lamination on top of glass possible

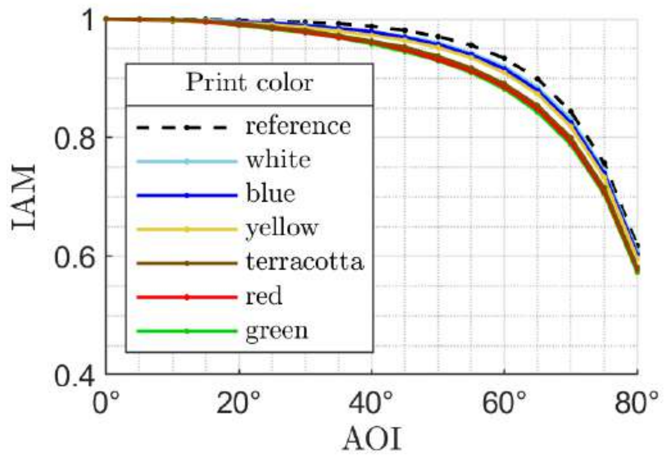
Performance impact (pigments)

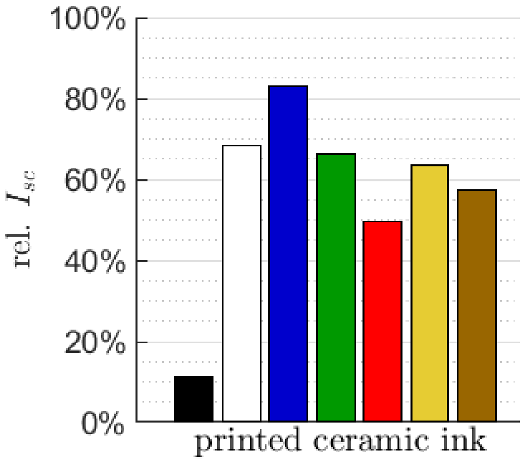
Up to 50% loss

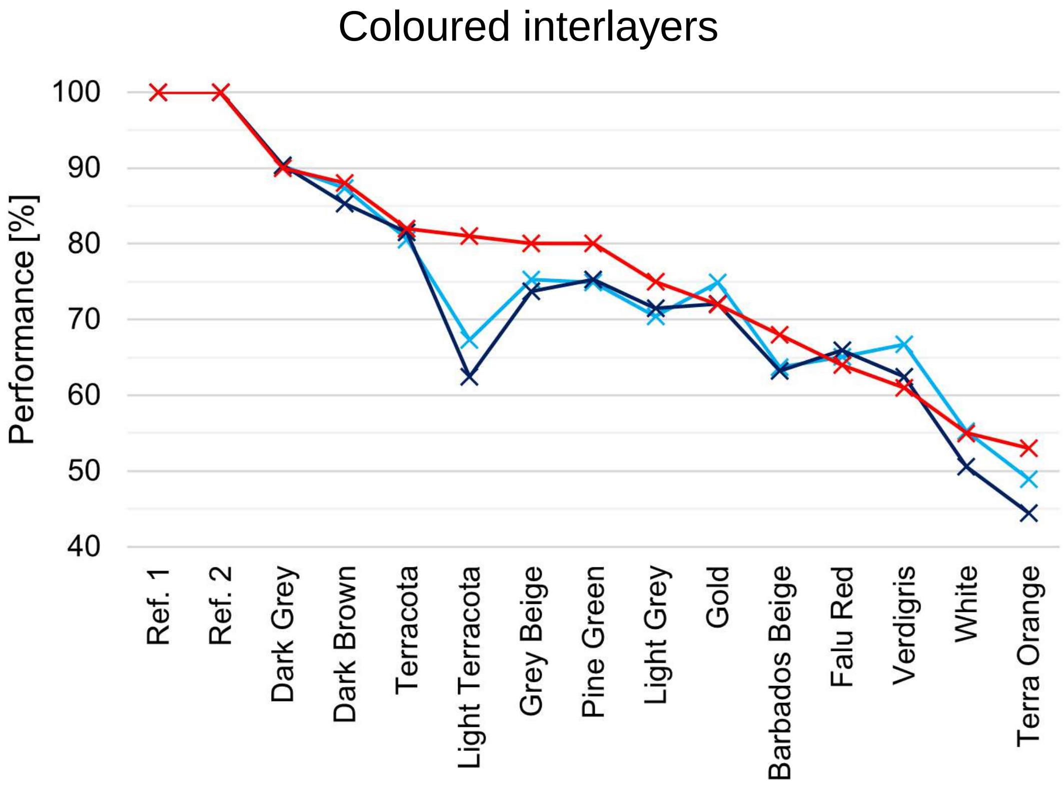
- Depending on colour
- Mostly due to poorly optimized pigments

Increased IAM losses

- Additional material interface

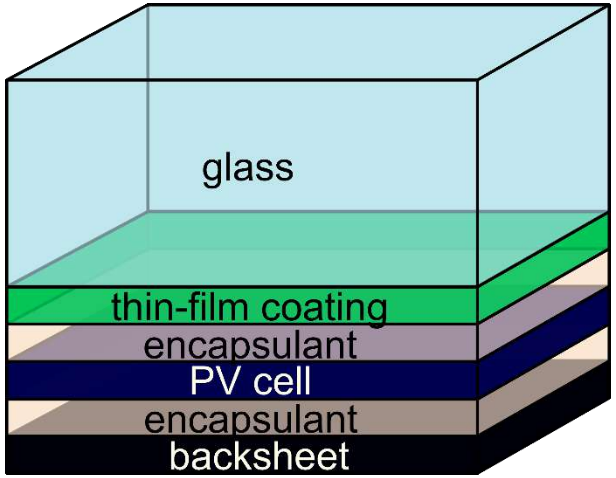






Structural colours

Inspired by nature (Morpho butterfly, etc)

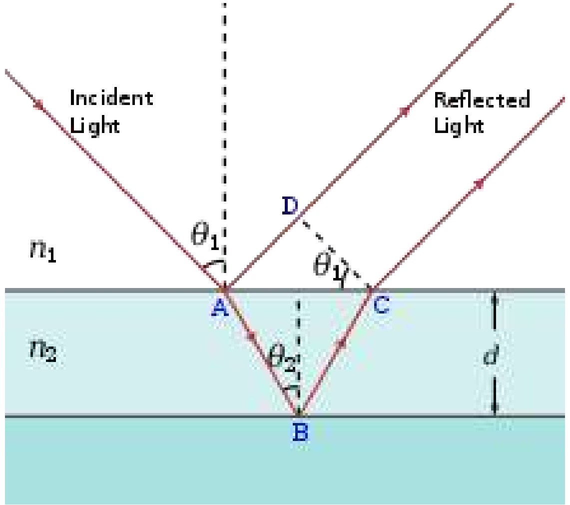


Based on dielectric thin-film stacks

- Applied directly to glass (inflexible)
- Change in refractive index (Fresnel reflections)

High angular dependency

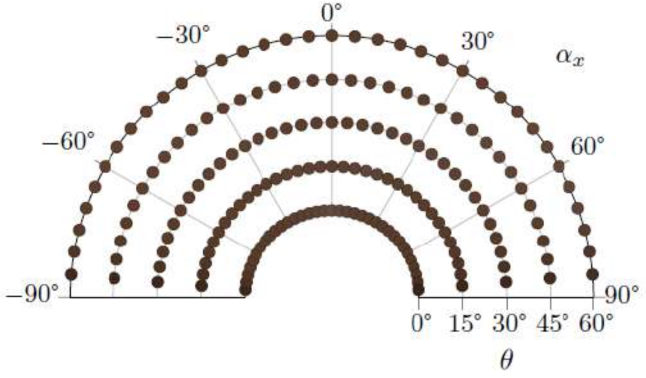
- Hue (iridescence)
- Saturation

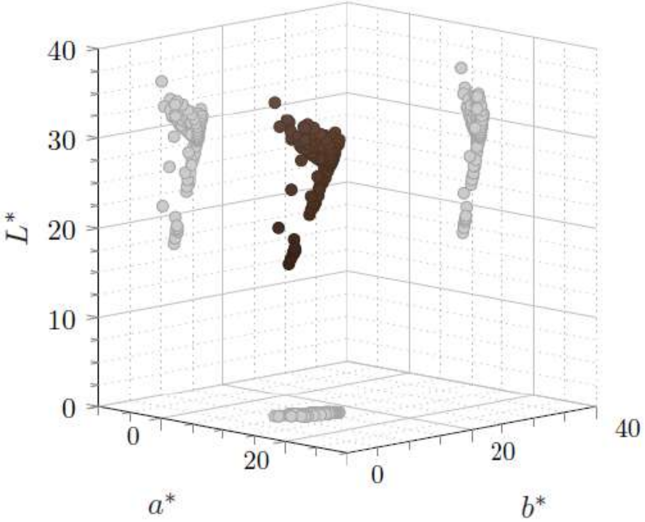


https://solarlab.dk/references-and-inspiration/new-build-cis-campus-covered-with-custom-solar-facade/

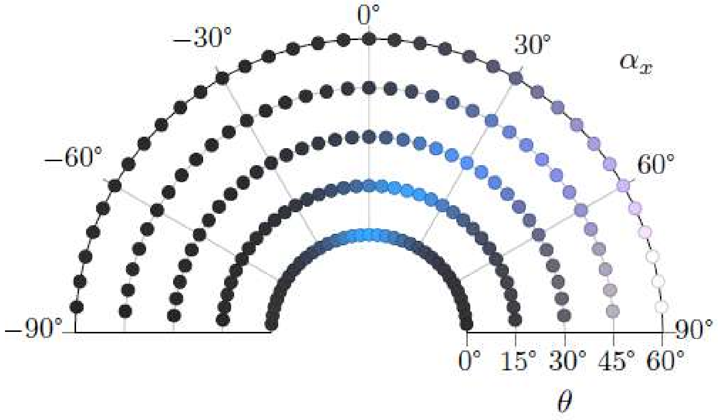
Appearance measurements – angular uniformity

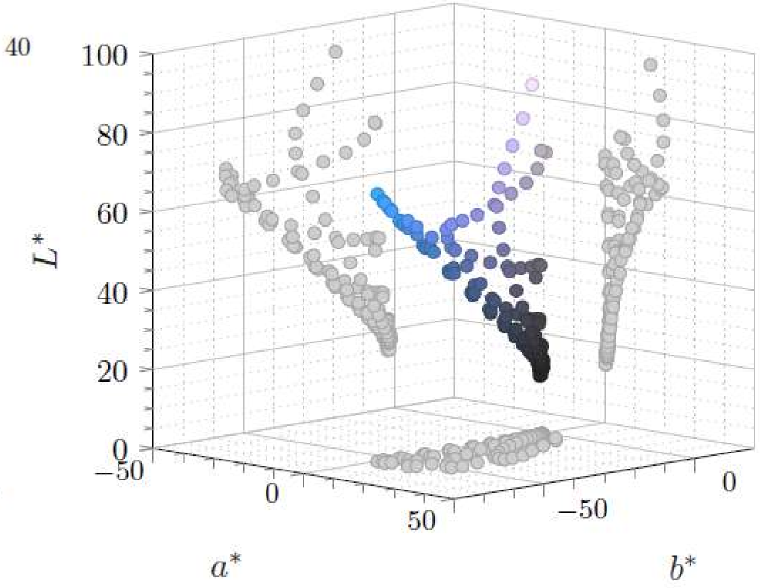
Inkjet printed colour:





Structural colour:





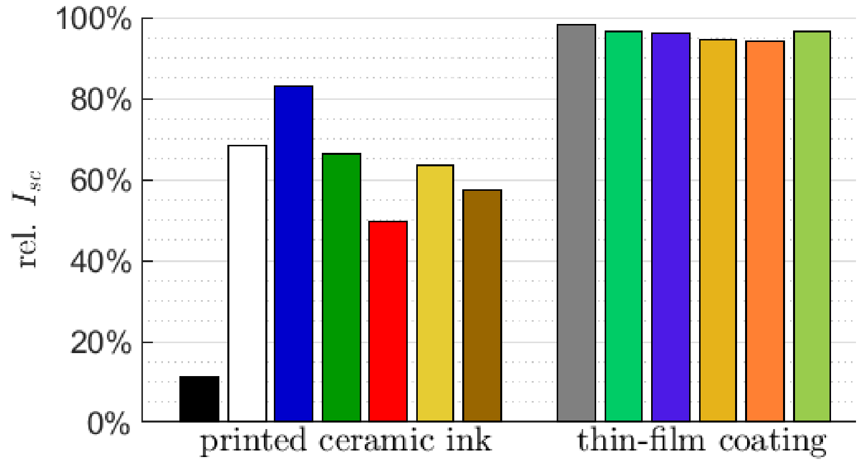
Performance impact (structural colours)

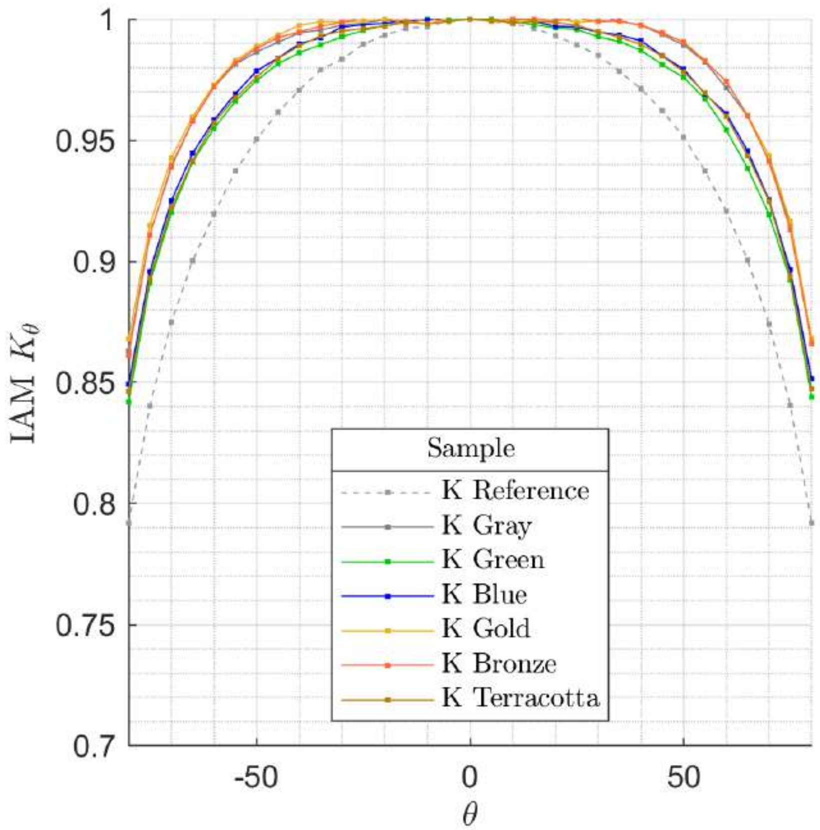
Very low transmission losses

- No absorption losses

Additional IAM losses

- Dominated by Fresnel reflections

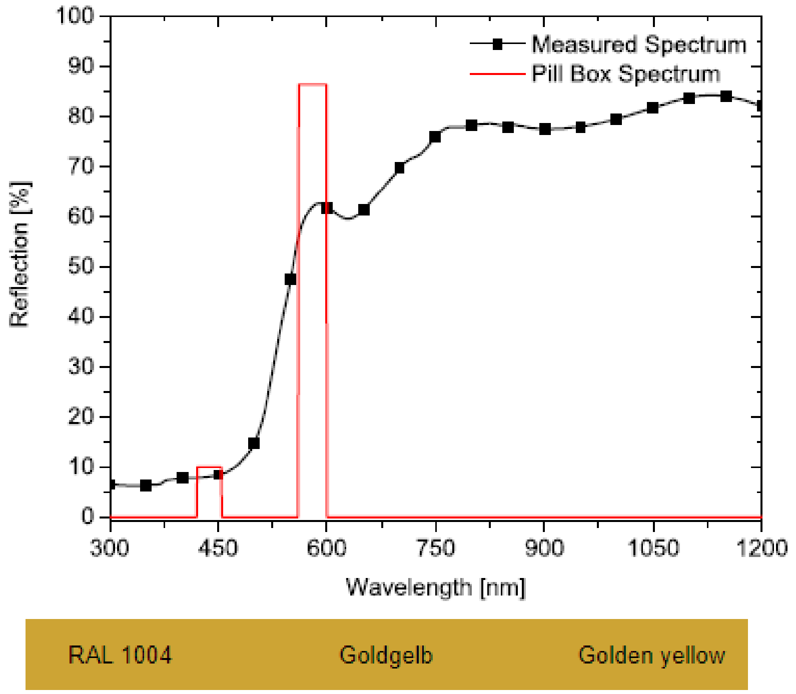




Performance limits

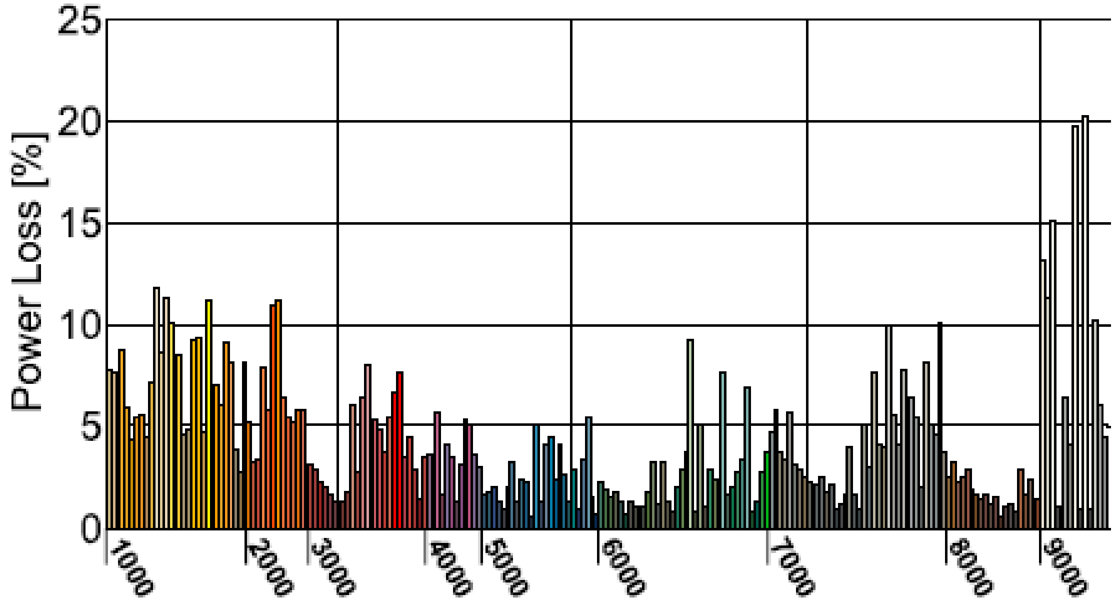
Theoretical pillbox spectra

- Assuming no absorption in colouration materials
- 2 reflection pillboxes match all possible colours



Losses for theoretical spectra:

G. Peharz, A. Ulm / Renewable Energy 129 (2018) 299–308



BREAK

TwinSolar workshop

BIPV

Glare mitigation and associated losses

Why glare?

Low frequency, high impact risk

- Local or regional legislature
- Unclear requirements for assessment

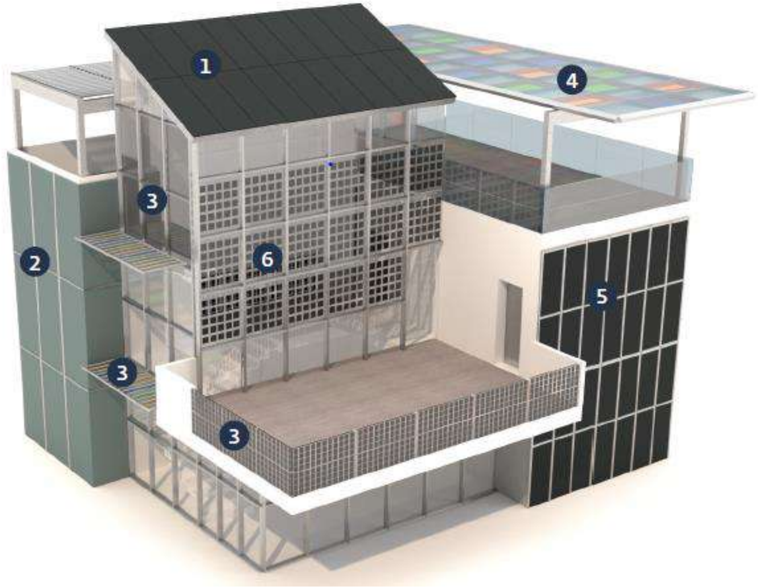
No standardized methods or metrics

- Threshold values
- Modelling constraints

High importance for BIPV

- Atypical orientations
- High variety of products
- Complex glass surfaces

L. Brotas, J. Wienold, “Solar reflected glare,” presentation, Radiance community workshop, 2014



P. Corti, P. Bonomo, F. Frontini, P. Macé, E. Bosch, “Building Integrated Photovoltaics: A practical handbook for solar buildings’ stakeholders – Status Report 2020,” tech. report, 2020

Glare threshold values

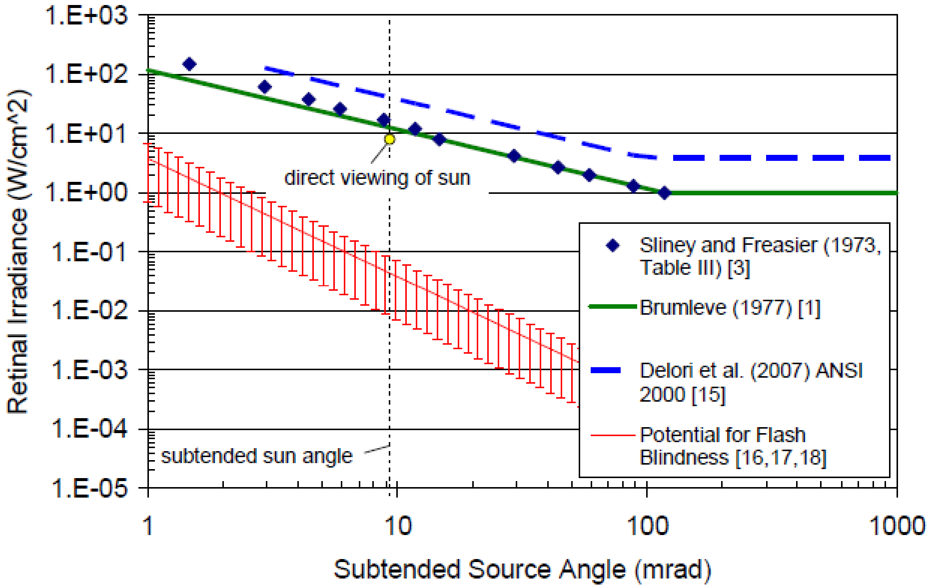
Levels of glare:

- Retinal burn damage (permanent)
- Flash blindness (temporary)
- Discomfort or disability glare

Threshold values:

- Physiological/medical data
- Limits of retinal irradiance
- Can be converted to source radiance through known properties of the human eye in sunny conditions [1]:

$$E_r \approx \frac{\pi}{578} L_s$$



Retinal burn damage and flash blindness thresholds [1]

Glare threshold values

Glare type	Retinal irradiance
Retinal burn damage [1]	100-400 $[\mathrm{kW/m^2}]$
Flash blindness [1]	0.1-1 $[\mathrm{kW/m^2}]$
Discomfort glare [2]	1.5-4.8 $[\mathrm{W/m^2}]$

[1] C.K. Ho, C.M. Ghanbari, R.B. Diver, “Hazard analysis of glint and glare from concentrating solar power plants”, SolarPACES 2009, September 2009

[2] G. Bargary, Y. Jia, and J. L. Barbur, “Mechanisms for discomfort glare in central vision,” Investig. Ophthalmol. Vis. Sci., vol. 56, no. 1, pp. 464–471, January 2015

BRDF and glare

Bi-directional reflectance distribution function:

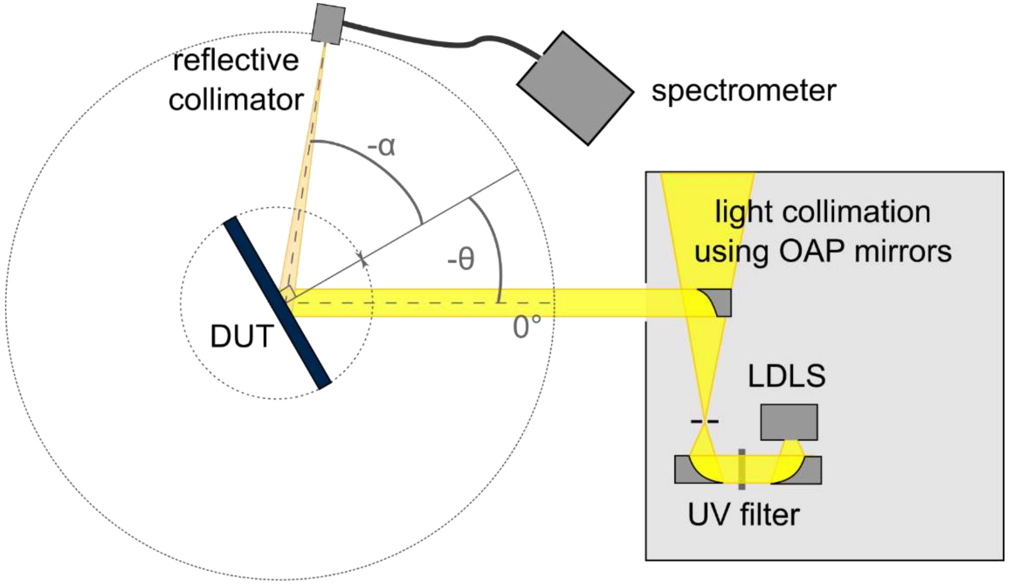
- $B(\theta, \alpha) = \frac{dL_r(\alpha)}{dE_s(\theta)}$
- $E_r \approx \frac{\pi}{578} B(\theta, \alpha) E_s$

BRDF threshold values:

- Assuming $E_s = 1000\ \mathrm{W/m^2}$

BRDF measurements

- PV mini-modules with 8 different glass surfaces
- Single-plane gonioreflectometer
- Integrated reflectance 300-980 nm

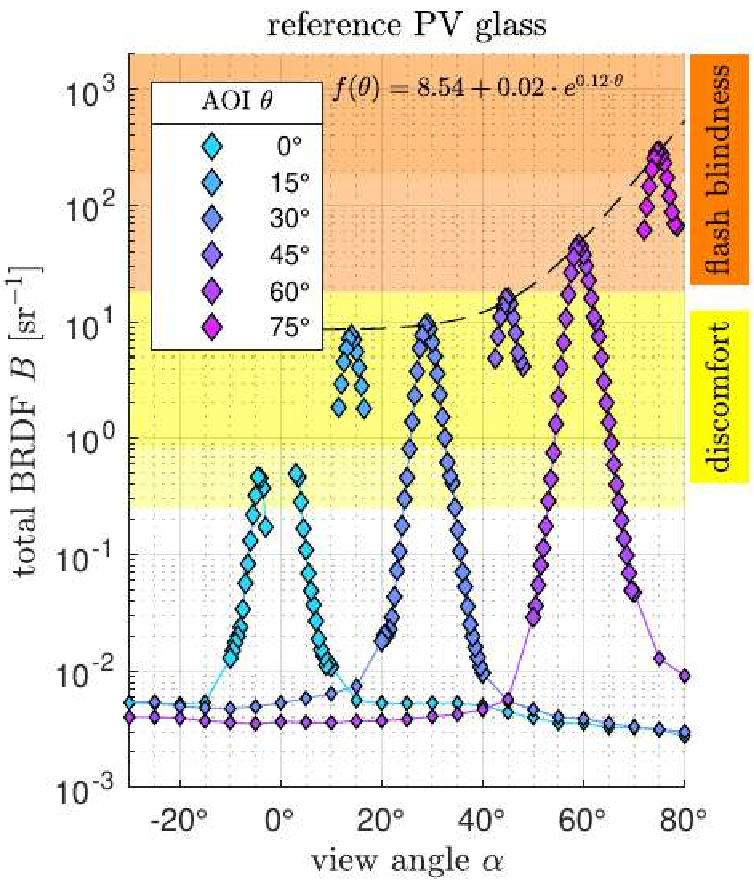


Single-plane gonioreflectometer

Glare threshold values (assuming $E_s = 1000\ W/m^2$ for BRDF)

Glare type	Retinal irradiance	BRDF
Retinal burn damage	100-400 $[\mathrm{kW/m^2}]$	1.8-7.4 $[10^4 \mathrm{sr^{-1}}]$
Flash blindness	0.1-1 $[\mathrm{kW/m^2}]$	18-184 $[\mathrm{sr^{-1}}]$
Discomfort glare	1.5-4.8 $[\mathrm{W/m^2}]$	0.25-0.85 $[\mathrm{sr^{-1}}]$

Results: PV reference glass

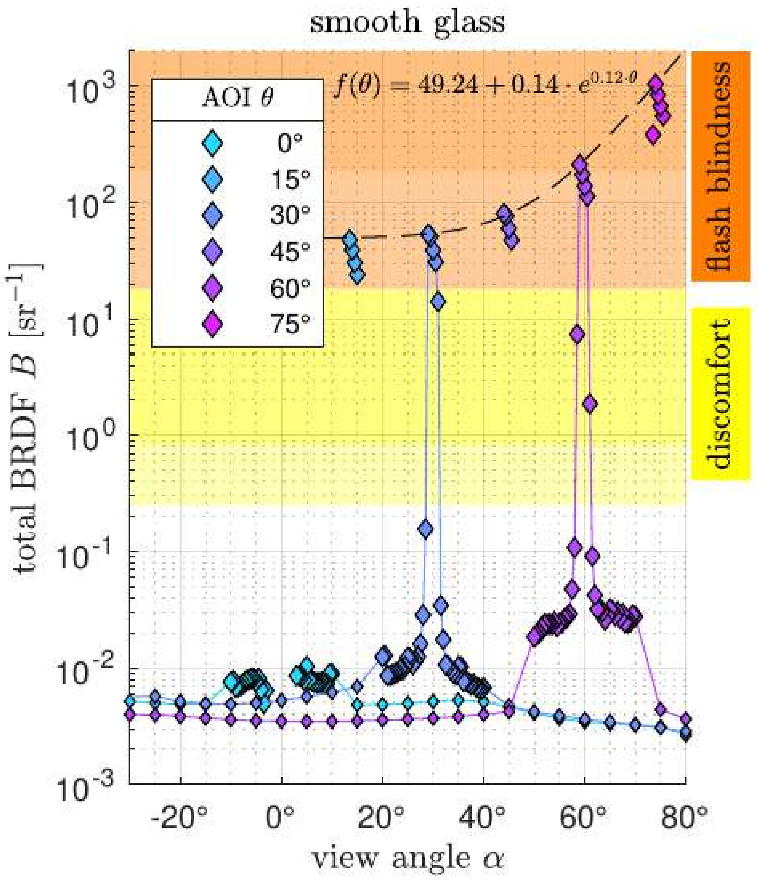


- Slightly uneven surface structure
- Diffusion around specular reflection angles (α=θ)

For specular reflections:

- Discomfort glare regardless of AOI
- Flash blindness risk at high AOI
- Peak BRDF follows $f(\theta) = a + b \cdot e^{c \cdot \theta}$

Results: Anti-reflective coating

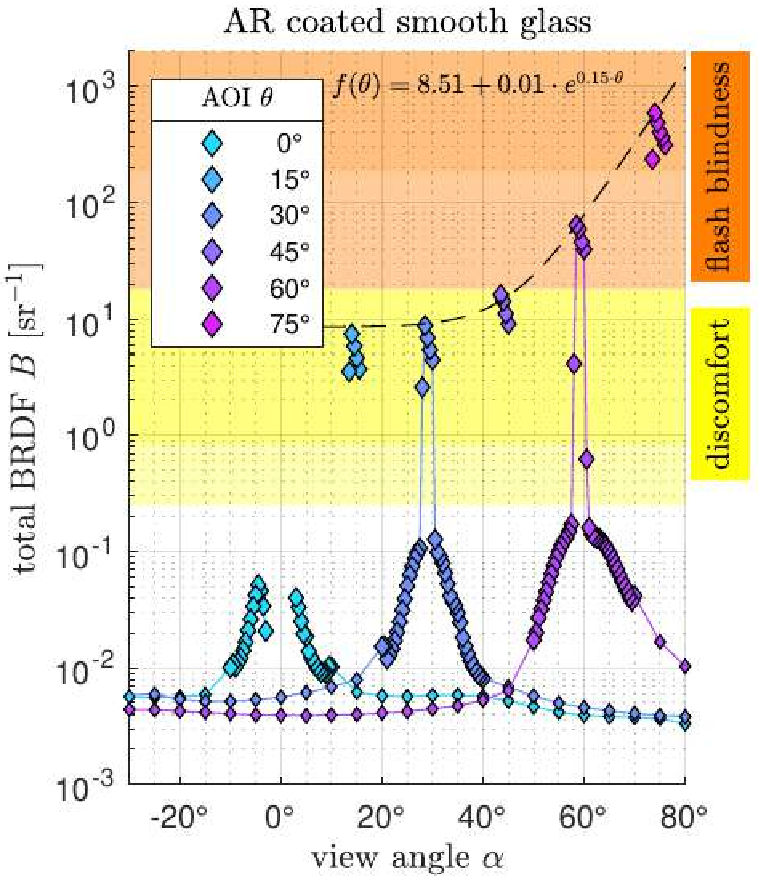


Flat, smooth glass surface

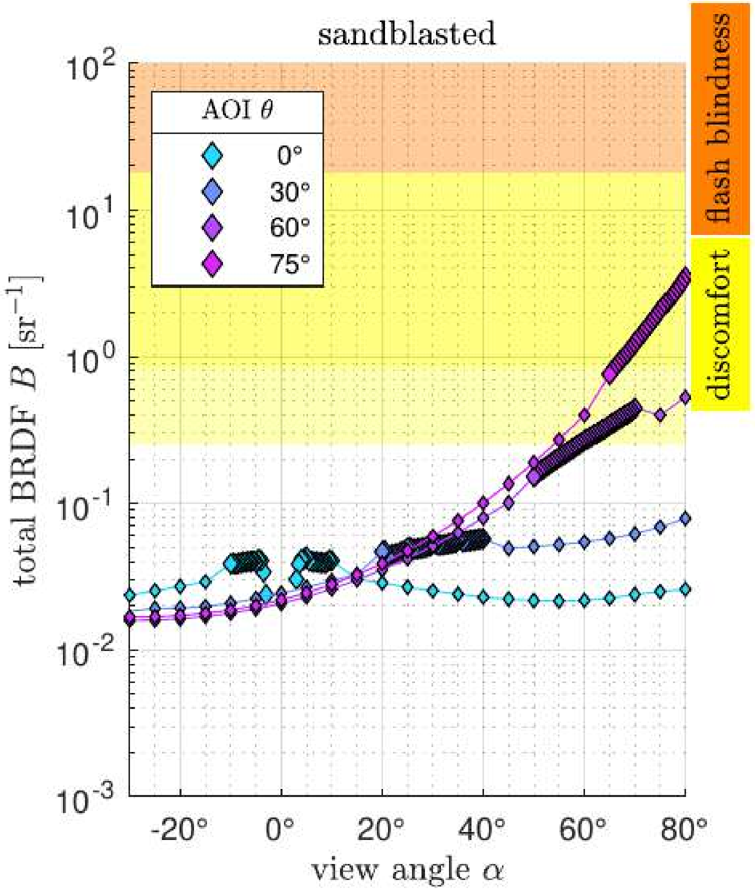
- Increased specular reflections
- No observable diffusion
- Flash blindness risk at all AOIs

AR coated glass surface

- Reduces glare potential to approx. reference sample values
- Increases diffusion
- Insufficient to prevent glare



Results: Satinated glass

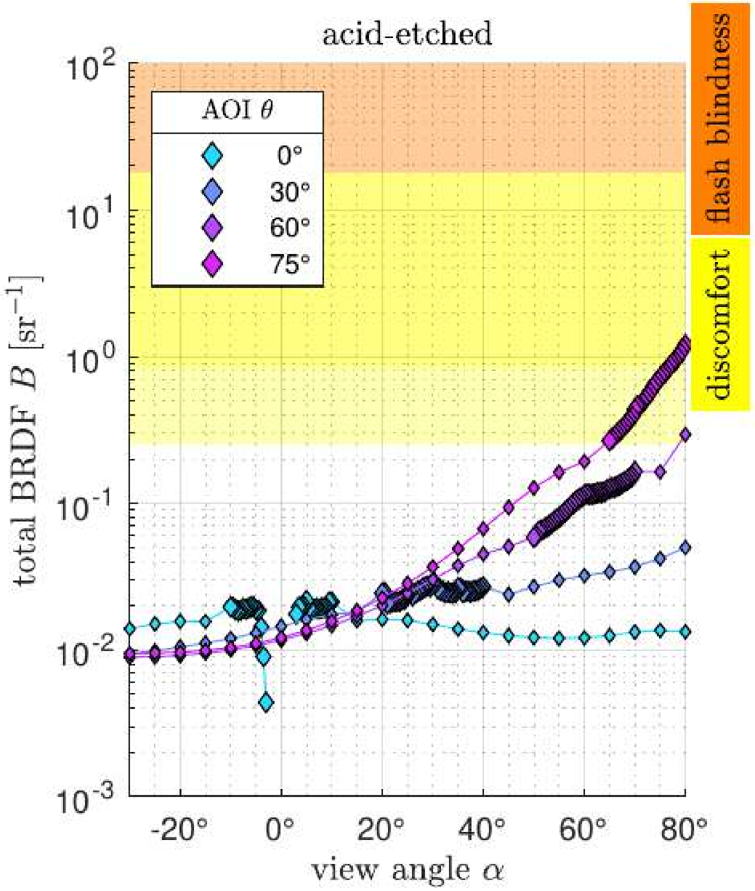


Microstructured glass surface

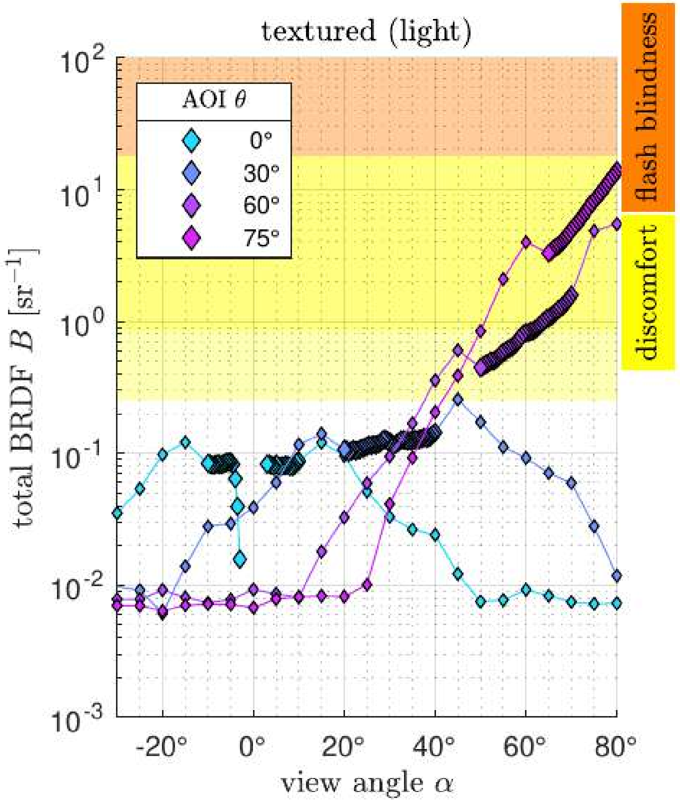
- Sandblasted reference glass
- Acid-etched PV glass

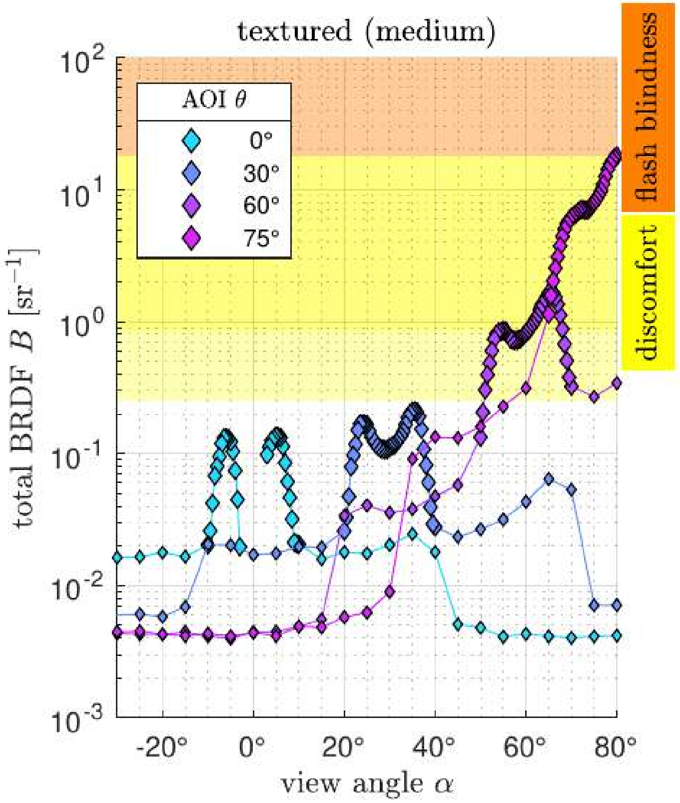
Diffuse reflections

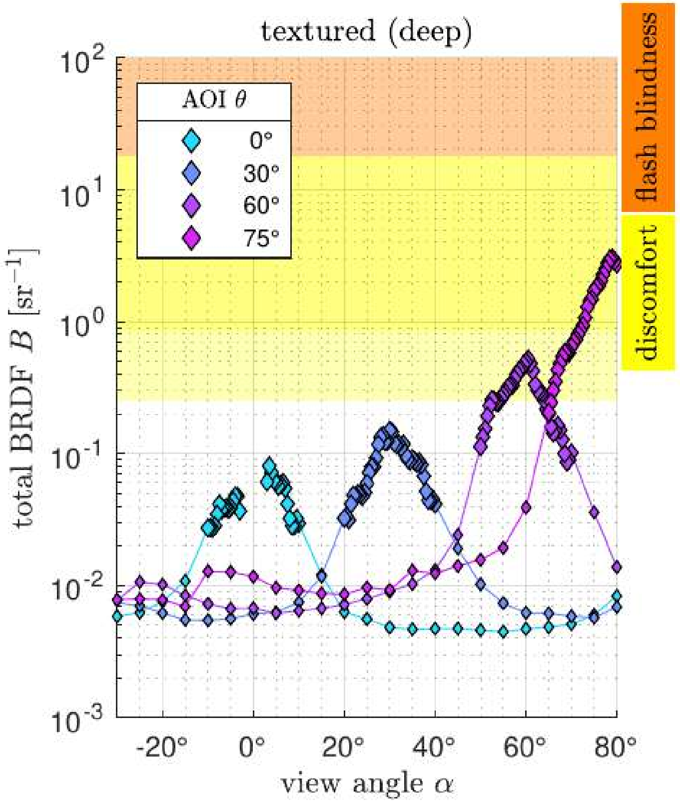
- Increased reflectance at high AOIs
- Forward scattering along glass surface at high AOIs



Results: Textured glass







Albarino S

Albarino G

What is the performance impact?

Satinated PV glass is great…

- Reduced glare risk
- Reduced angular-dependent transmission losses (increased IAM at high incidence angles)
- More uniform appearance with some coloration technologies

… but…

- How does it affect transmittance at normal incidence?
- Is there a difference between different satination technologies?
  - Can we explain the differences?
  - Acid-etching of glass uses HF-acid, can it be replaced?

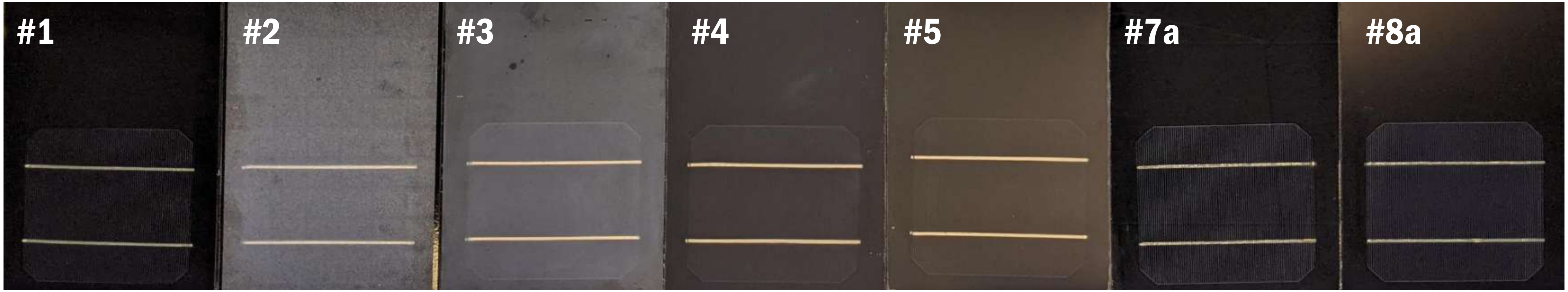
Samples

- References
- Acid-etched glass
- Sandblasted glass
- Laser-satinated glass

Acid-etched glass:

- Different satination degrees
- Low-iron and “normal” float glass

#	Description	Samples
1	Lightly structured low-iron float glass	4
2	#1 sandblasted	3
3	#1 laser-satinated	3
4	Acid-etched low-iron float glass	3
5	Acid-etched low-iron float glass	3
6	Acid-etched float glass	3
7a	Flat low-iron float glass	1
7b	Flat float glass	1
8a	#7a lightly acid-etched	1
8b	#7b lightly acid-etched	1
9a	#7a acid-etched variant 1	1
9b	#7b acid-etched variant 1	1
10a	#7a acid-etched variant 2	1
10b	#7b acid-etched variant 2	1



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6	Acid-etched float glass	3
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8b	#7b lightly acid-etched	1
9a	#7a acid-etched variant 1	1
9b	#7b acid-etched variant 1	1
10a	#7a acid-etched variant 2	1
10b	#7b acid-etched variant 2	1

Transmittance loss in coupons

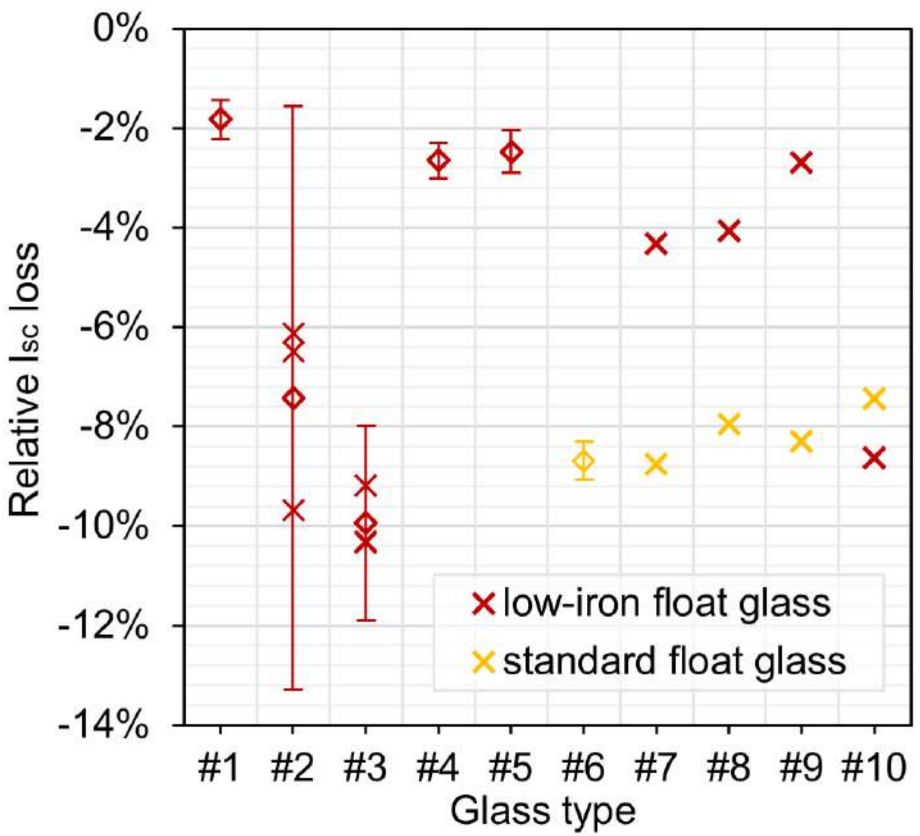
Coupon samples:

- 2-BB mono-Si cells (efficiency ~19%)
- EVA, black BS

IV-measurements before and after encapsulation with Pasan cell tester

Results:

- Acid etched glass < 1 p.p. additional loss
- High losses for sandblasted and laser-satinated glasses
- Not enough samples (#7-10)



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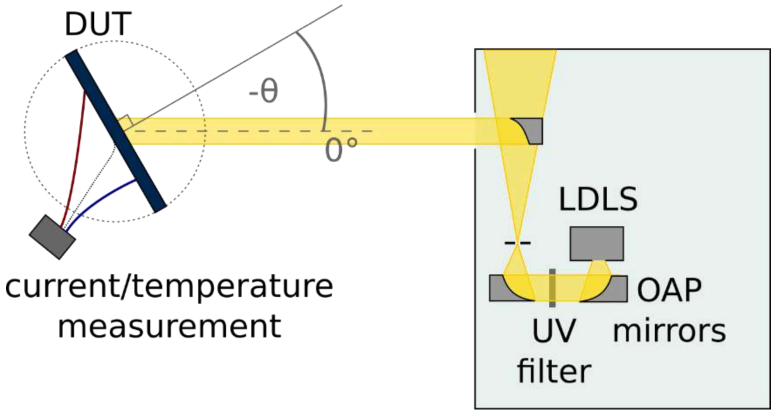
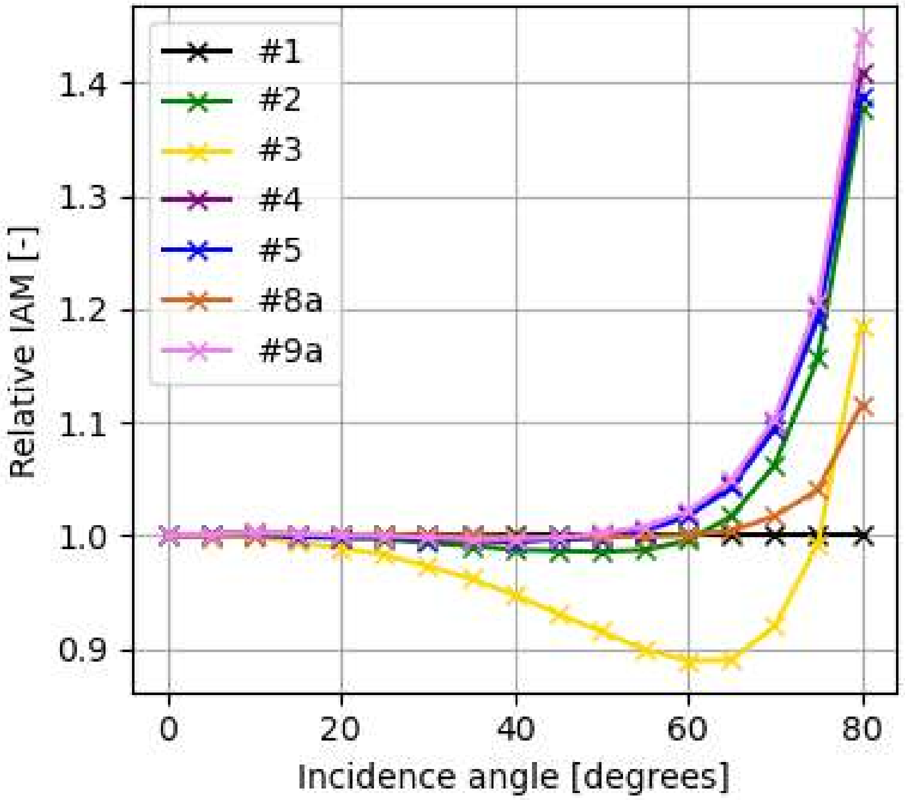
IAM losses





Results:

- IAM significantly higher at AOI > 55° for acid-etched glasses
- Minor reductions at low angles

- Further losses for sandblasted and laser-satinated glasses

#	Description	Samples
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10b	#7b acid-etched variant 2	1

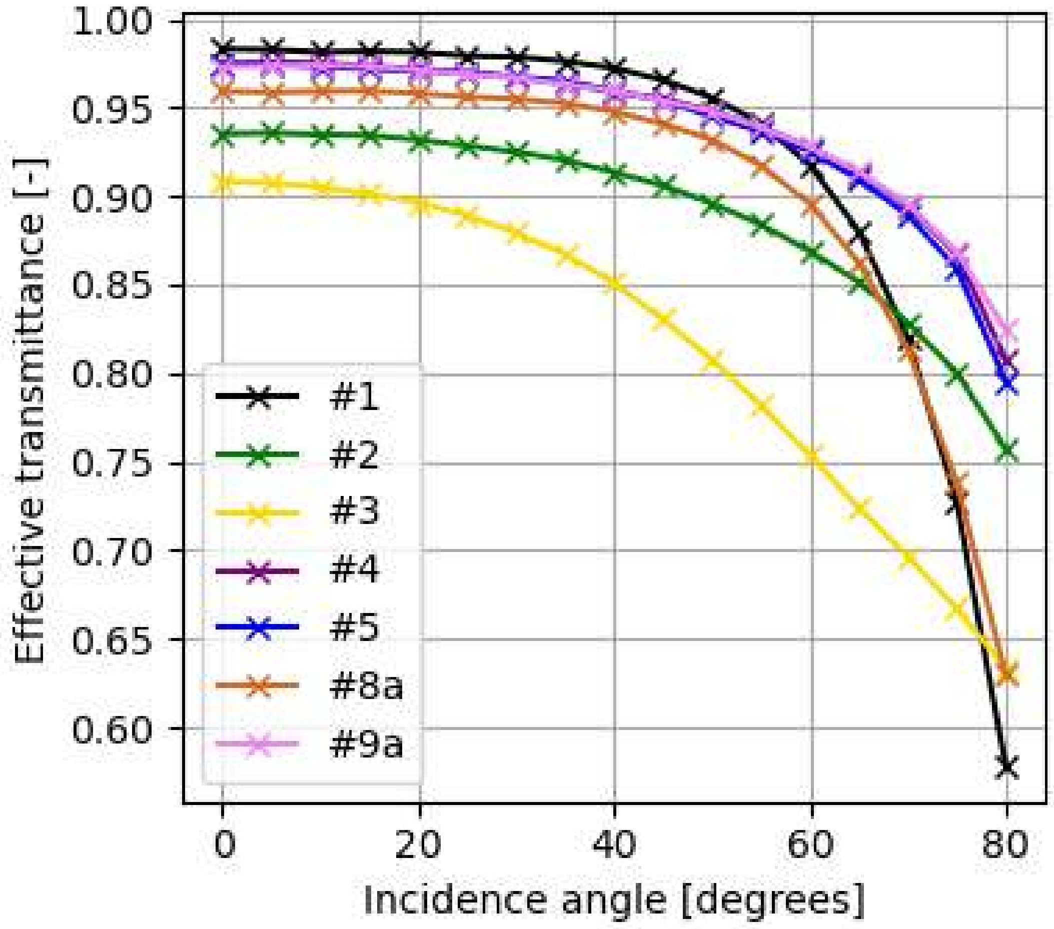
Combined losses

Acid-etched samples:

- Perform better at AOI > 55°
- Negligible losses at low incidence angles
- Higher satination is favourable

Other samples perform much worse

- What could be the reason?



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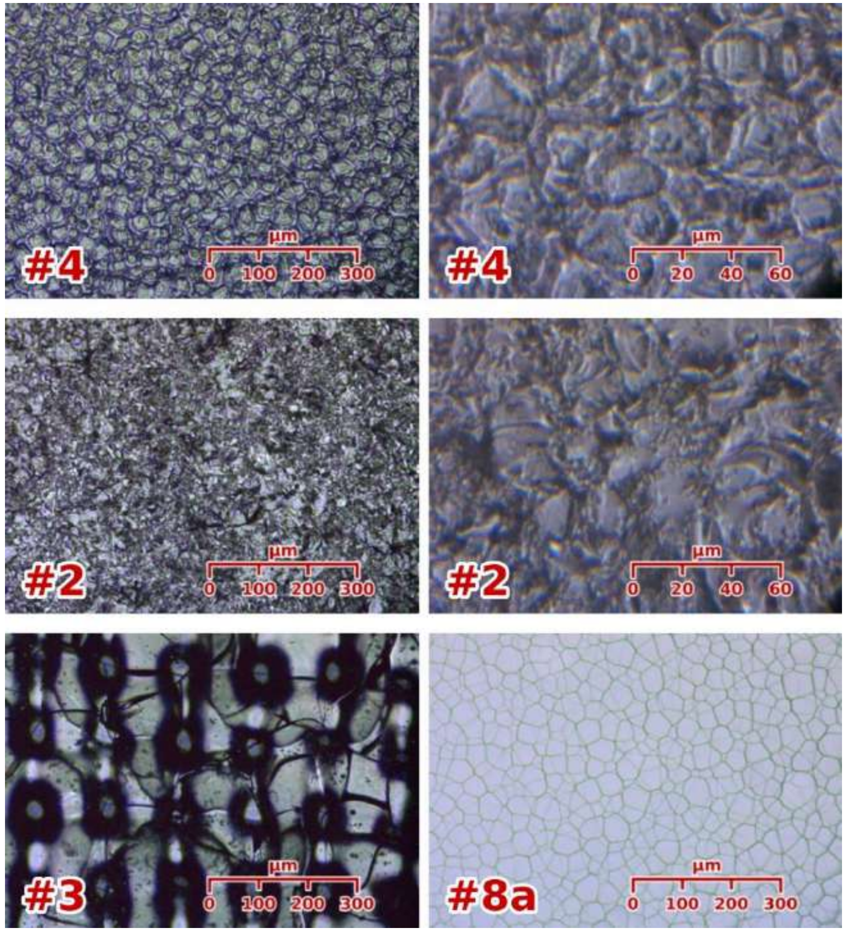
Surface structure

Through-light visual microscopy

Satinated glasses:
- Irregular, quasi-circular depressions
- Smooth surface appearance

Sandblasted glass:
- Sharp surface edges
- Dirty-white appearance
- Continuous abrasion

Laser satinated glass:
- Regular, deep wells
- Glittery appearance



Summary & Conclusions

Measured 8 different satinated surfaces

- Acid-etched
- Sandblasted
- Laser-satinated

Transmittance and IAM measurements on coupons

- At AOI > 55°, satinated glass outperforms flat glass
- Especially useful for non-optimal orientations and tilts
  – e.g. building-integrated PV, product-integrated PV

- Sandblasted and laser-etched glasses are not viable alternatives

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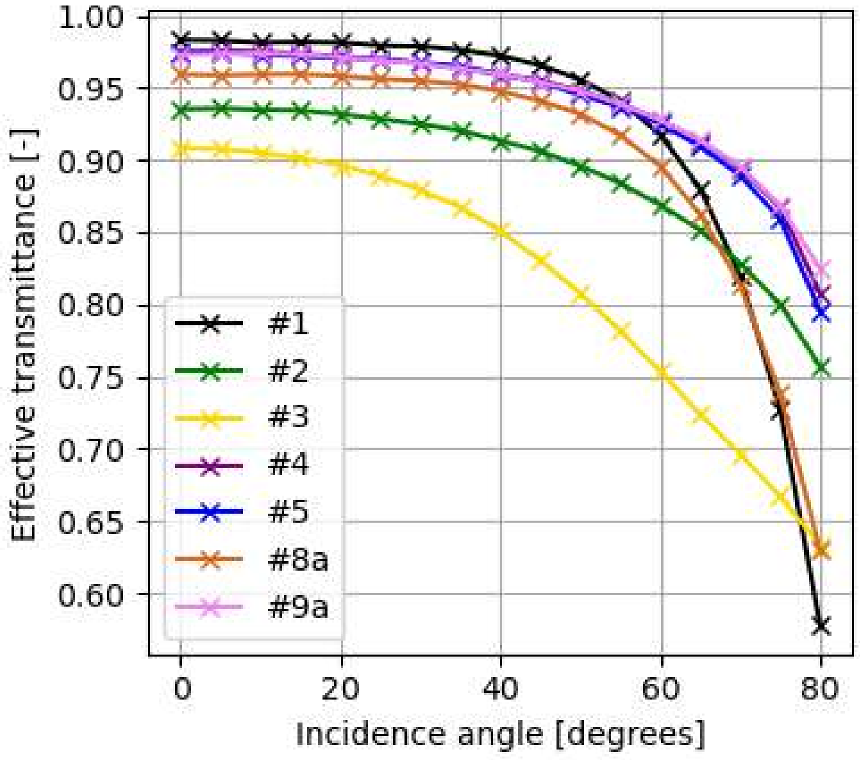

Time for questions!

DTU