ENHANCED PERFORMANCE OF PV MODULES USING HIERARCHICALLY STRUCTURED GLASS IN DIFFERENT CLIMATIC CONDITIONS

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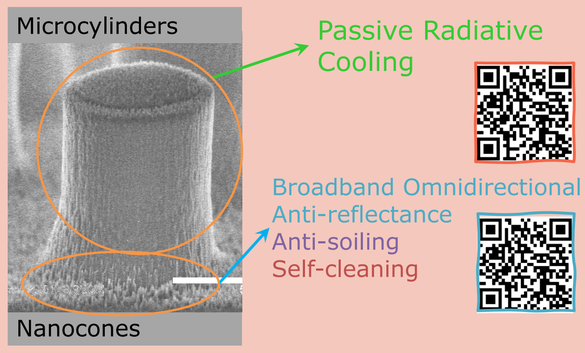
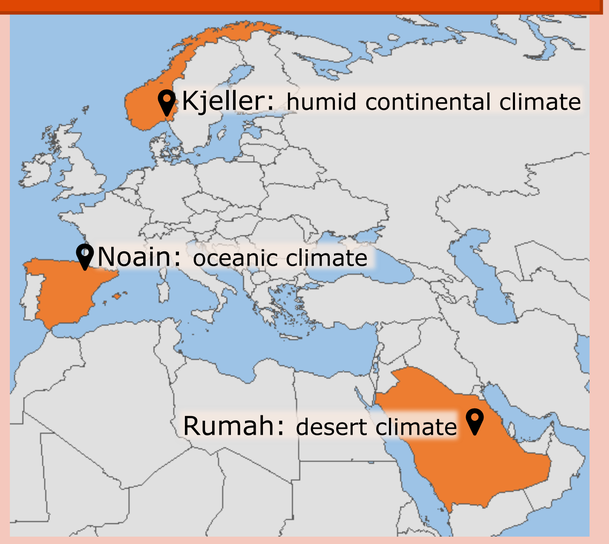
ABSTRACT:
PV modules laminated with hierarchically structured glasses exhibit enhanced performance due to their multifunctional properties. Studies have shown that random nanocones enhance PV module energy production through various mechanisms: they create a broadband omnidirectional anti-reflective (AR) surface, reduce soiling rates by over 50% through anti-soiling (AS) behaviour, and offer extreme abrasion resistance. On the other hand, microcylinders on the glass surface increase glass emissivity, reducing the solar cell's operating temperature through passive radiative cooling (RC). Adding these features to the glass, PV modules can sustain higher power output over time. In this study, all properties associated with structured glasses' PV modules are integrated into PVSyst to assess the increase in energy yield compared to commercial PV modules. Three different locations, representative of various environmental conditions (irradiance, angle of incidence, soiling rate, temperature), are selected for the study: Spain with a moderate climate and low soiling rates, Norway with a colder climate and high diffuse light, and Saudi Arabia with elevated temperatures and higher irradiance and soiling rates.

Keywords: PVSyst, Subwavelength Structures, Anti-Reflectance, Soiling, Radiative Cooling

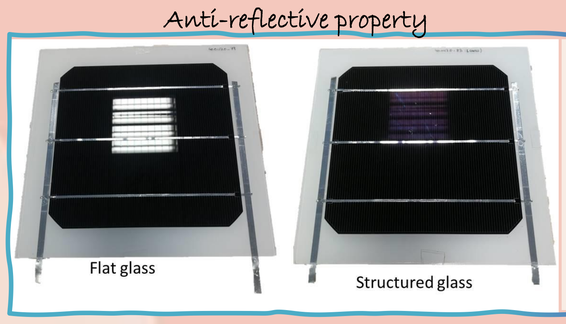
1. MOTIVATION

Study the energy gain of nano/micro-structured glass PV modules installed in different locations

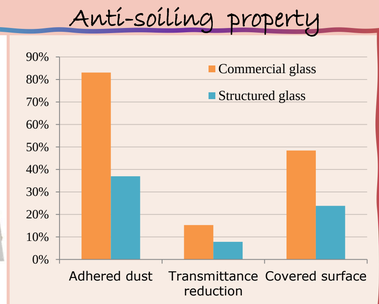




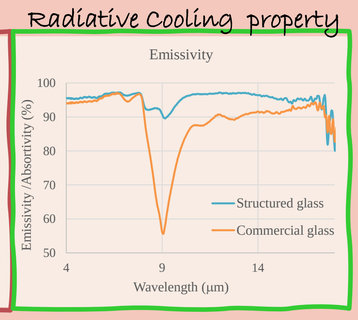
Anti-reflective property



Anti-soiling property



Radiative Cooling property

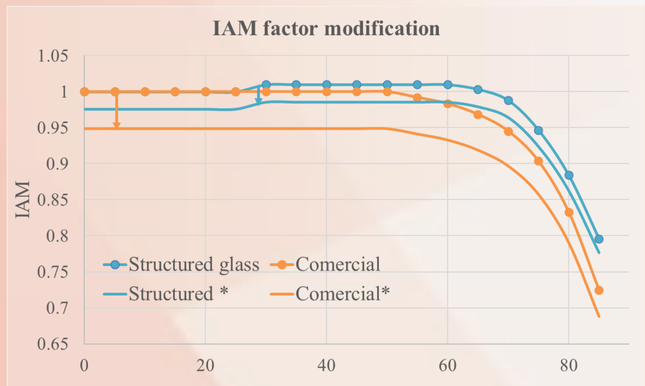


2. METHODOLOGY

Effect of Anti-Reflective property ⇒ IAM factor modification

$$IAM'factor = \frac{I_{sc}(\theta)}{I'_{sc}(\theta = 0) \times cos\,\theta}$$

I'_{sc} ⇒ glass with zero reflectance



Effect of Passive Radiative Cooling

Structured glass emits 14.7% more radiation:

$U_{0,structured} = 29 \Rightarrow 31.6\ W/m^2K$
(empirical recalculation)

Solar farm characteristics

Solar PV farm of 2.2 MWp = 5000 modules (200 modules/string × 25 series) generic Mono 440 Wp Twin 144 half-cells + generic inverter of 2 MWac central inverter

5. RESULTS

Kjeller (Norway)

Commercial PV module

Loss diagram

977 kWh/m²	Global horizontal irradiation
+25.8%	Global incident in coll. plane
-6.05%	IAM factor on global
1155 kWh/m² * 11125 m² coll.	Effective irradiation on collectors
efficiency at STC = 19.80%	PV conversion
2545377 kWh	Array nominal energy (at STC effic.)
-1.23%	PV loss due to irradiance level
-0.32%	PV loss due to temperature

Structured PV module

AR property

Loss diagram

977 kWh/m²	Global horizontal irradiation
+25.8%	Global incident in coll. plane
-2.13%	IAM factor on global
1204 kWh/m² * 11125 m² coll.	Effective irradiation on collectors
efficiency at STC = 19.80%	PV conversion
2651730 kWh	Array nominal energy (at STC effic.)
-1.16%	PV loss due to irradiance level
-0.50%	PV loss due to temperature

energy gain 4.0%

AR + RC properties

Loss diagram

977 kWh/m²	Global horizontal irradiation
+25.8%	Global incident in coll. plane
-2.13%	IAM factor on global
1204 kWh/m² * 11125 m² coll.	Effective irradiation on collectors
efficiency at STC = 19.80%	PV conversion
2651730 kWh	Array nominal energy (at STC effic.)
-1.16%	PV loss due to irradiance level
-0.17%	PV loss due to temperature

energy gain 4.4%

Noain (Spain)

Commercial PV module

Loss diagram

1432 kWh/m²	Global horizontal irradiation
+17.3%	Global incident in coll. plane
-6.01%	IAM factor on global
1579 kWh/m² * 11125 m² coll.	Effective irradiation on collectors
efficiency at STC = 19.80%	PV conversion
3478106 kWh	Array nominal energy (at STC effic.)
-0.86%	PV loss due to irradiance level
-2.51%	PV loss due to temperature

Loss diagram

1432 kWh/m²	Global horizontal irradiation
+17.3%	Global incident in coll. plane
-6.01%	IAM factor on global
-1.39%	Soiling loss factor
1557 kWh/m² * 11125 m² coll.	Effective irradiation on collectors
efficiency at STC = 19.80%	PV conversion
3429675 kWh	Array nominal energy (at STC effic.)
-0.88%	PV loss due to irradiance level
-2.39%	PV loss due to temperature

with soiling losses

Jan.	Feb.	Mar.	Apr.
0.0%	0.0%	0.0%	1.0%
May	**Jun.**	**Jul.**	**Aug.**
2.0%	3.0%	3.0%	3.0%
Sep.	**Oct.**	**Nov.**	**Dec.**
1.0%	0.0%	0.0%	0.0%

Structured PV module

AR property

Loss diagram

1432 kWh/m²	Global horizontal irradiation
+17.3%	Global incident in coll. plane
-2.07%	IAM factor on global
1645 kWh/m² * 11125 m² coll.	Effective irradiation on collectors
efficiency at STC = 19.80%	PV conversion
3623694 kWh	Array nominal energy (at STC effic.)
-0.82%	PV loss due to irradiance level
-2.72%	PV loss due to temperature

energy gain 3.9%

AR + AS properties

Loss diagram

1432 kWh/m²	Global horizontal irradiation
+17.3%	Global incident in coll. plane
-2.07%	IAM factor on global
-0.75%	Soiling loss factor
1632 kWh/m² * 11125 m² coll.	Effective irradiation on collectors
efficiency at STC = 19.80%	PV conversion
3596523 kWh	Array nominal energy (at STC effic.)
-0.82%	PV loss due to irradiance level
-2.66%	PV loss due to temperature

energy gain 4.6%

AR + AS + RC properties

Loss diagram

1432 kWh/m²	Global horizontal irradiation
+17.3%	Global incident in coll. plane
-2.07%	IAM factor on global
-0.75%	Soiling loss factor
1632 kWh/m² * 11125 m² coll.	Effective irradiation on collectors
efficiency at STC = 19.80%	PV conversion
3596523 kWh	Array nominal energy (at STC effic.
-0.82%	PV loss due to irradiance level
-2.15%	PV loss due to temperature

energy gain 5.1%

Rumah (Saudi Arabia)

Commercial PV module

Loss diagram

2173 kWh/m²	Global horizontal irradiation
+9.6%	Global incident in coll. plane
-5.84%	IAM factor on global
2242 kWh/m² * 11125 m² coll.	Effective irradiation on collectors
efficiency at STC = 19.80%	PV conversion
4939877 kWh	Array nominal energy (at STC effic.)
-0.37%	PV loss due to irradiance level
-9.14%	PV loss due to temperature

Loss diagram

2173 kWh/m²	Global horizontal irradiation
+9.6%	Global incident in coll. plane
-5.84%	IAM factor on global
-6.37%	Soiling loss factor
2099 kWh/m² * 11125 m² coll.	Effective irradiation on collectors
efficiency at STC = 19.80%	PV conversion
4625405 kWh	Array nominal energy (at STC effic.)
-0.43%	PV loss due to irradiance level
-8.74%	PV loss due to temperature

with soiling losses

Jan.	Feb.	Mar.	Apr.
5.8%	5.8%	4.9%	1.0%
May	**Jun.**	**Jul.**	**Aug.**
2.0%	3.0%	3.0%	3.0%
Sep.	**Oct.**	**Nov.**	**Dec.**
1.0%	0.0%	0.0%	0.0%

Structured PV module

AR property

Loss diagram

2173 kWh/m²	Global horizontal irradiation
+9.6%	Global incident in coll. plane
-1.94%	IAM factor on global
2335 kWh/m² * 11125 m² coll.	Effective irradiation on collectors
efficiency at STC = 19.80%	PV conversion
5144319 kWh	Array nominal energy (at STC effic.)
-0.34%	PV loss due to irradiance level
-9.39%	PV loss due to temperature

energy gain 3.8%

AR + AS properties

energy gain 7.1%

Loss diagram

2173 kWh/m²	Global horizontal irradiation
+9.6%	Global incident in coll. plane
-1.94%	IAM factor on global
-3.21%	Soiling loss factor
2260 kWh/m² * 11125 m² coll.	Effective irradiation on collectors
efficiency at STC = 19.80%	PV conversion
4979016 kWh	Array nominal energy (at STC effic.)
-0.36%	PV loss due to irradiance level
-9.17%	PV loss due to temperature

AR + AS + RC properties

energy gain 7.7%

Loss diagram

2173 kWh/m²	Global horizontal irradiation
+9.6%	Global incident in coll. plane
-1.94%	IAM factor on global
-3.21%	Soiling loss factor
2260 kWh/m² * 11125 m² coll.	Effective irradiation on collectors
efficiency at STC = 19.80%	PV conversion
4979016 kWh	Array nominal energy (at STC effic.)
-0.36%	PV loss due to irradiance level
-8.72%	PV loss due to temperature

CONCLUSIONS

Features of the enhanced PV modules:
Hierarchically structured glass with several key functionalities:

- Enhanced broadband omnidirectional anti-reflective properties.
- 50% reduction in soiling rate due to anti-soiling characteristics.
- Reduced operating temperature through passive radiative cooling, attributed to higher emissivity.
- Improved abrasion resistance.

The combination of AR, AS, and RC properties in structured glass shows potential for improving PV module performance across different climates, with the greatest impact in regions with higher temperatures and soiling rates.

	Anti-reflective	+ Anti-soiling	+ Radiative Cooling
Norway	4.0%		4.4%
Spain	3.9%	4.6%	5.1%
Arabia Saudi	3.8%	7.1%	7.7%

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