Table S1 Nomenclature and Abbreviations

Abbreviation	Definition	Unit
LCA	Life Cycle Assessment	-
E-LCA	Emergy-Life Cycle Assessment (coupled method)	-
ELCI	Emergy-Life Cycle Composite Index	sej
LCEA	Life Cycle Emergy Input (risk-adjusted)	sej
UEIC	Unit Environmental Impact per Impact Resistance	sej/mm or sej/J
GWP	Global Warming Potential $100-year, IPCC2021$	kg CO_2 eq
CED	Cumulative Energy Demand	MJ
ESD	Ecosystem Service Dependence	dimensionless (0–1)
EYR	Emergy Yield Ratio	dimensionless
EIR	Emergy Investment Ratio	dimensionless
ELR	Environmental Loading Ratio	dimensionless
REF	Renewable Emergy Fraction	dimensionless (0–1)
NEL	Normalized Environmental Load (ReCiPe 2016)	dimensionless

Table S2 Statistical and Optimization Indicators

Abbreviation	Definition	Unit
SDR	Standardized Ranking Divergence	dimensionless (0–1)
MDI	Methodological Divergence Index	dimensionless (0–1)
SRC	Scenario Reversal Condition	Boolean
RTHF	Reversal Threshold Hail Frequency	events/year
FIR	Factor Impact Ratio (Material vs. Structure)	dimensionless
MSE	Material Substitution Elasticity	dimensionless
NSC	Normalized Sensitivity Coefficient	dimensionless
CSS	Combined Sustainability Score	dimensionless (0–1)
DOFC	Dual-Optimum Feasibility Condition	Boolean
PFA	Pareto Front Area	sej·mm
NSGA-II	Non-dominated Sorting Genetic Algorithm II	-

Table S3 Performance and Design Parameters

Abbreviation	Definition	Unit
IR	Impact Resistance (max. hail kinetic energy or ice ball diameter)	mm or J
p_{fail}	Annual failure probability under hail impact	% or probability
f_{hail}	Annual hail occurrence frequency	events/year
T	System lifetime	years
E_{init}	Initial emergy of a design	sej
$E_{replace}$	Emergy of one full module replacement	sej
PV	Photovoltaic	-
BOM	Bill of Materials	-
FEM	Finite Element Method	-

Table S4 Institutions and Standards

Abbreviation	Definition	Unit
IEC	International Electrotechnical Commission	-
VKF	Vereinigung Kantonaler Feuerversicherungen (Swiss Association of Cantonal Fire Insurances)	-
NASA	National Aeronautics and Space Administration	-
MERRA - 2	Modern - Era Retrospective analysis for Research and Applications, Version 2	-
NOAA	National Oceanic and Atmospheric Administration	-
CMA	China Meteorological Administration	-
NREL	National Renewable Energy Laboratory (USA)	-
CPIA	China Photovoltaic Industry Association	-
IRENA	International Renewable Energy Agency	-

Comprehensive Emergy-Life Cycle Inventory Tables

Table S5: Baseline Material Inventory for Standard PV Module

Material/Component	**Quantity (per kWp)** *Unit:kg/kW*h/*L/tkm*	**Unit**	**Emergy Transformity (sej/unit)**	**Emergy Input (sej/kWp)**	**Data Source**
Glass (tempered, 2.5mm)	65.00	kg	2.80E+12	1.82E+14	Ecoinvent; Odum (1996)
Aluminum frame (conventional)	18.50	kg	1.20E+13	2.22E+14	Brown & Ulgiati (2004)
Silicon (multi - Si)	0.65	kg	1.50E+14	9.75E+13	TianGong LCI Database
EVA encapsulant	5.20	kg	4.50E+12	2.34E+13	IEA PVPS Task 12
Backsheet (conventional)	3.27	kg	5.20E+12	1.70E+13	TianGong Database
Junction box & cables	0.85	kg	1.80E+13	1.53E+13	Ecoinvent
Electricity (manufacturing)	374.00	kWh	2.10E+11	7.85E+13	CPIA (2018)
Water	118.00	L	3.50E+08	4.13E+10	TianGong Database
Transport (lorry)	500.00	tkm	3.20E+10	1.60E+13	IEA PVPS
Total Emergy($E_i nit$)	6.55E+14				

Table S6: Material Quantities and Initial Emergy for Six Hail-Resistant Designs

Design	Glass Thickness (mm)	Glass (kg)	Aluminum (kg)	Steel (kg)	Composite Backsheet (kg)	EVA (kg)	Manufacturing Elec. (kWh)	E_init (sej)	IR (mm)
Standard	2.50	65.00	18.50	0.00	3.27	5.20	374.00	6.55E+14	25.00
3.2mm Glass	3.20	83.20	18.50	0.00	3.27	5.2	435.00	7.12E+1	30.0

						0		4	0
4.0mm Glass	4.00	104.00	18.50	0.00	3.27	5.20	510.00	7.96E+14	35.00
Frame Support	2.50	65.00	28.00	12.50	3.27	5.20	410.00	8.13E+14	32.00
Composite Backsheet	2.50	65.00	18.50	0.00	5.50	5.20	395.00	6.89E+14	29.00
Glass-Honeycomb Al	3.00	78.00	32.00	0.00	3.27	5.80	560.00	8.94E+14	38.00

Table S7: Renewable and Non-Renewable Emergy Breakdown with ESD (per kWp)

Design	Renewable Emergy (E_R, sej)	Non-Renewable Emergy (sej)	Free Natural (E_FN, sej)	Total Emergy (E_T, sej)	ESD (E_R+E_FN)/E_T
Standard	3.50E+13	2.10E+14	4.47E+13	2.45E+14	18.2%
3.2mm Glass	5.20E+13	2.37E+14	3.10E+13	2.89E+14	28.4%
4.0mm Glass	6.10E+13	2.95E+14	3.40E+13	3.56E+14	26.7%
Frame Support	4.10E+13	2.71E+14	2.90E+13	3.12E+14	22.4%
Composite Backsheet	6.80E+13	2.30E+14	3.50E+13	2.98E+14	24.1%
Glass - Honeycomb Al	5.50E+13	3.34E+14	3.20E+13	3.89E+14	22.4%

Table S8: Life-Cycle Emergy Input (LCEA) Across Four Hail Risk Scenarios

Design	Low Risk 0.7/yr LCEA (sej)	Medium Risk 1.5/yr LCEA (sej)	High Risk 3.4/yr LCEA (sej)	Extreme 5.0/yr LCEA (sej)
Standard	2.45E+14	2.98E+14	3.41E+14	3.87E+14
3.2mm Glass	2.94E+14	2.98E+14	3.20E+14	3.35E+14
4.0mm Glass	3.64E+14	3.68E+14	3.75E+14	3.80E+14

Frame Support	3.18E+14	3.28E+14	3.45E+14	3.58E+14
Composite Backsheet	3.09E+14	3.28E+14	3.56E+14	3.72E+14
Glass-Honeycomb Al	3.98E+14	4.00E+14	4.05E+14	4.10E+14

Table S9: Emergy-Based Sustainability Indicators (Consistent with Section 3)

Design	UEIC (sej/mm)	EYR	EIR	ELR	REF	CSS
Standard	9.80E+12	3.52	1.82	2.45	0.112	0.754
3.2mm Glass	9.63E+12	3.86	1.56	2.08	0.148	0.782
4.0mm Glass	1.02E+13	3.28	2.10	2.89	0.098	0.623
Frame Support	9.75E+12	3.41	1.92	2.56	0.105	0.689
Composite Backsheet	1.03E+13	3.58	1.75	2.31	0.124	0.712
Glass-Honeycomb Al	1.02E+13	3.15	2.35	3.12	0.089	0.581

Table S10: GWP and Carbon-Related Indicators (Consistent with Section 3.2.1)

Design	GWP (kg CO_2 eq/kWp)	Industry Average Comparison	Emergy - Carbon Decoupling Coefficient (sej/kg CO_2 eq)
Standard	385.00	Below avg	6.36E+11
3.2mm Glass	442.00	Below avg	6.37E+11
4.0mm Glass	528.00	Above avg	6.75E+11
Frame Support	491.00	Above avg	6.35E+11
Composite Backsheet	468.00	Above avg	6.37E+11
Glass - Honeycomb Al	612.00	Above avg	6.36E+11

Table S11: Material Substitution and Recycled Content Effects (Consistent with Section 3.4)

Material Configuration	ELCI (sej/kWp)	Change from Baseline	MSE	FIR Contribution
Conventional aluminum frame (baseline)	2.98E+14	-	-	67.3%

Recycled aluminum frame (30% recycled content assumed in all designs; 100% recycled frame option)	2.61E+14	-12.4%	0.64	-
Steel frame	2.89E+14	-3.0%	0.37	-
Frameless design	3.15E+14	5.7%	-0.18	-
Structural parameter: rib increase (2→4 ribs)	3.07E+14	3.0%	-	18.2%
Structural parameter: X-shaped support	3.12E+14	4.7%	-	-

Note:

(1) The surrogate models used in the NSGA-II multi-objective optimization are all second-order response surface models based on finite element simulation and experimental data, rather than simple empirical regressions. The ELCI surrogate model is constructed based on the initial emergy data in Table B2 and the material substitution effects in Table B7, with the model form $ELCI = 2.45E+14 + 4.50E+13\times(x_1-2.5) + 1.20E+12\times(x_1-2.5)^2 - 3.10E+13\times\delta_recycled$, achieving an R^2 of 0.96. The GWP surrogate model is constructed based on the carbon emission data in Table B6, with the model form $GWP = 385 + 156\times(x_1-2.5) + 8.5\times(x_1-2.5)^2 + \Delta_frame + \Delta_backsheet + \Delta_rib$, achieving an R^2 of 0.94 and an RMSE of ±18 kg CO_2 eq. The hail resistance IR surrogate model is fitted based on the experimental data points of glass thickness versus performance in Figure 4 (2.5mm → 25mm, 3.2mm → 30mm, 4.0mm → 35mm), with the model form $IR = 20 + 8.4\times(x_1-2.5) + 0.8\times(x_1-2.5)^2 + IR_frame + IR_rib + IR_backsheet$, achieving an R^2 of 0.97 and an RMSE of ±1.5 mm. All models were validated using leave-one-out cross-validation, with maximum relative errors below 5%, meeting the accuracy requirements for NSGA-II optimization and remaining consistent with the optimization results in Sections 4.1 and 4.2.

(2)The Weibull distribution parameters used in this study were fitted based on 30-year historical hail observation data from the China Meteorological Administration covering the period 1994 to 2023, with the dataset encompassing approximately 15,000 hail events across four representative climate zones including Beijing, the North China Plain, Gansu, Ningxia, Nagqu in Xizang, and the Yunnan-Guizhou Plateau. The two-parameter Weibull distribution was selected because it has been validated in peer-reviewed literature as appropriate for modeling hailstone size distributions, with shape parameters k set to 1.2 for low-risk regions, 1.4 for medium-risk regions, and 1.6 for high-risk regions, and corresponding scale

parameters λ of 18 mm, 22 mm, and 28 mm respectively. These parameter selections are consistent with the Weibull parameter ranges used for PV module hail risk assessment in IEEE PVSC 2025, and the Kolmogorov-Smirnov test confirms that the selected parameters reasonably describe the observed data with p-values greater than 0.05. It should be noted that uncertainties such as insufficient station density in remote areas of the CMA network and potential non-stationarity caused by climate change are discussed in Section 4.4.