

Space engineering - Photovoltaic assemblies and components

EESTI STANDARDI EESSÕNA

NATIONAL FOREWORD

See Eesti standard EVS-EN 16603-20-08:2023 sisaldab Euroopa standardi EN 16603-20-08:2023 ingliskeelset teksti. Standard on jõustunud sellekohase teate avaldamisega EVS Teatajas Euroopa standardimisorganisatsioonid on teinud Euroopa standardi rahvuslikele liikmetele kättesaadavaks 13.09.2023. Standard on kättesaadav Eesti Standardimis-ja Akrediteerimiskeskusest.	This Estonian standard EVS-EN 16603-20-08:2023 consists of the English text of the European standard EN 16603-20-08:2023. This standard has been endorsed with a notification published in the official bulletin of the Estonian Centre for Standardisation and Accreditation. Date of Availability of the European standard is 13.09.2023. The standard is available from the Estonian Centre for Standardisation and Accreditation.
--	---

Tagasisidet standardi sisu kohta on võimalik edastada, kasutades EVS-i veebilehel asuvat tagasiside vormi või saates e-kirja meiliaadressile standardiosakond@evs.ee.

ICS 49.140

Standardite reprodutseerimise ja levitamise õigus kuulub Eesti Standardimis- ja Akrediteerimiskeskusele. Andmete paljundamine, taastekitamine, kopeerimine, salvestamine elektroonsesse süsteemi või edastamine ükskõik millises vormis või millisel teel ilma Eesti Standardimis-ja Akrediteerimiskeskuse kirjaliku loata on keelatud.

Kui Teil on küsimusi standardite autorikaitse kohta, võtke palun ühendust Eesti Standardimis-ja Akrediteerimiskeskusega: Koduleht www.evs.ee; telefon 605 5050; e-post info@evs.ee

The right to reproduce and distribute standards belongs to the Estonian Centre for Standardisation and Accreditation. No part of this publication may be reproduced or utilized in any form or by any means, electronic or mechanical, including photocopying, without a written permission from the Estonian Centre for Standardisation and Accreditation.

If you have any questions about copyright, please contact Estonian Centre for Standardisation and Accreditation: Homepage www.evs.ee; phone +372 605 5050; e-mail info@evs.ee

English version

Space engineering - Photovoltaic assemblies and components

Ingénierie spatiale - Ensembles et composants
photovoltaïques

Raumfahrttechnik - Fotovoltaische Baugruppen und
Komponenten

This European Standard was approved by CEN on 23 July 2023.

CEN and CENELEC members are bound to comply with the CEN/CENELEC Internal Regulations which stipulate the conditions for giving this European Standard the status of a national standard without any alteration. Up-to-date lists and bibliographical references concerning such national standards may be obtained on application to the CEN-CENELEC Management Centre or to any CEN and CENELEC member.

This European Standard exists in three official versions (English, French, German). A version in any other language made by translation under the responsibility of a CEN and CENELEC member into its own language and notified to the CEN-CENELEC Management Centre has the same status as the official versions.

CEN and CENELEC members are the national standards bodies and national electrotechnical committees of Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Republic of North Macedonia, Romania, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Türkiye and United Kingdom.



CEN-CENELEC Management Centre:
Rue de la Science 23, B-1040 Brussels

Table of contents

European foreword	12
Introduction	13
1 Scope	14
2 Normative references	15
3 Terms, definitions and abbreviated terms	17
3.1 Terms from other standards	17
3.2 Terms specific to the present standard	17
3.3 Abbreviated terms	22
3.4 Nomenclature	25
4 General	26
4.1 Overview	26
4.1.1 Objective and organization	26
4.1.2 Interfaces with other areas	28
4.2 Physical properties	29
4.3 Test and storage	29
4.3.1 Test environment	29
4.3.2 Test tolerances and accuracies	30
4.3.3 <<deleted>>	31
4.4 Critical materials	31
5 Photovoltaic assemblies	32
5.1 Overview	32
5.1.1 Description	32
5.1.2 Purpose and objective	32
5.2 Conditions and method of test	33
5.3 Photovoltaic assembly design	34
5.3.1 Overview	34
5.3.2 Parameters related to parts, materials and processes (PMP)	34
5.3.3 Parameters related to design	35

5.4	PVA manufacturing	39
5.4.1	Process validation.....	39
5.4.2	Defect acceptability.....	39
5.4.3	In-process testing	39
5.4.4	Identification and traceability.....	41
5.4.5	Recording	41
5.5	PVA tests	41
5.5.1	Qualification tests	41
5.5.2	Acceptance tests for qualification coupons	50
5.5.3	Definition of tests and checks	51
5.6	Failure definition	62
5.6.1	Failure criteria.....	62
5.6.2	Failed qualification coupons.....	63
5.7	Data documentation	63
5.8	Delivery	63
5.9	Packaging, packing, handling and storage	63
6	Solar cell assemblies	64
6.1	General	64
6.1.1	Testing.....	64
6.1.2	Conditions and methods of test.....	64
6.1.3	Deliverable components	64
6.1.4	Identification and traceability.....	64
6.2	Production control (process identification document).....	65
6.3	Acceptance tests	65
6.3.1	General.....	65
6.3.2	Test methods and conditions	65
6.3.3	Electrical performance acceptance test (EPA).....	66
6.4	Qualification tests	66
6.4.1	General.....	66
6.4.2	Qualification.....	68
6.4.3	Test methods, conditions and measurements.....	69
6.5	Failure definition.....	85
6.5.1	Failure criteria.....	85
6.5.2	Failed SCAs.....	85
6.6	Data documentation	85
6.7	Delivery	85
6.8	Packing, dispatching, handling and storage.....	86

6.8.1	Overview	86
6.8.2	ESD Sensitivity	86
7	Bare solar cells.....	87
7.1	Testing, deliverable components and marking.....	87
7.1.1	Testing.....	87
7.1.2	Deliverable components	88
7.1.3	Marking.....	88
7.2	Production control (process identification document).....	88
7.3	Acceptance tests	89
7.3.1	General.....	89
7.3.2	Test methods and conditions	89
7.3.3	Documentation	90
7.4	Qualification tests	90
7.4.1	General.....	90
7.4.2	Qualification.....	92
7.5	Test methods, conditions and measurements	93
7.5.1	Visual inspection including ELM (VI).....	93
7.5.2	Dimensions and weight (DW).....	95
7.5.3	Electrical performance (EP)	96
7.5.4	Temperature coefficients (TC)	96
7.5.5	Spectral response (SR).....	97
7.5.6	Optical properties (OP)	98
7.5.7	Humidity and temperature (HT).....	98
7.5.8	Coating adherence (CA)	100
7.5.9	Contact uniformity (CU)	100
7.5.10	Contact thickness (CT)	101
7.5.11	Surface finish (SF).....	101
7.5.12	Pull test (PT).....	101
7.5.13	Electron irradiation (EI)	102
7.5.14	Proton irradiation (PI).....	103
7.5.15	Photon irradiation and temperature annealing (PH)	105
7.5.16	Solar cell reverse bias test (RB).....	105
7.5.17	Thermal cycling (CY)	106
7.5.18	Active-passive interface evaluation test (IF).....	106
7.5.19	Flatness test (FT).....	106
7.6	Failure definition	107
7.6.1	Failure criteria.....	107

7.6.2	Failed components	107
7.7	Data documentation	107
7.8	Delivery	108
7.9	Packing, dispatching, handling and storage.....	108
7.9.1	Overview	108
7.9.2	ESD Sensitivity	108
8	Coverglasses.....	109
8.1	Overview	109
8.1.1	Purpose	109
8.1.2	Description.....	109
8.2	Interfaces	109
8.3	Testing, deliverable components and marking.....	109
8.3.1	Testing.....	109
8.3.2	Deliverable components	110
8.3.3	Marking (coating orientation)	110
8.4	Production control (Process identification document)	111
8.5	Acceptance test.....	111
8.5.1	Acceptance test samples	111
8.5.2	Acceptance test sequence.....	111
8.5.3	Test methods and conditions	112
8.5.4	Documentation	112
8.6	Qualification tests.....	112
8.6.1	General.....	112
8.6.2	Qualification.....	113
8.7	Test methods, conditions and measurements	115
8.7.1	Visual inspection (VI)	115
8.7.2	Transmission into air (TA).....	116
8.7.3	Electro-optical properties (EO).....	117
8.7.4	Mechanical properties (MP)	117
8.7.5	Reflectance properties (OP)	118
8.7.6	Normal emittance (NE)	119
8.7.7	Surface resistivity (SC)	119
8.7.8	Flatness or bow (FT).....	120
8.7.9	Transmission into adhesive (TH)	120
8.7.10	Boiling water test (BW)	121
8.7.11	Humidity and temperature.....	121
8.7.12	UV exposure (UV).....	122

8.7.13	Electron irradiation (EI)	122
8.7.14	Proton irradiation (PI).....	123
8.7.15	Breaking strength (BS).....	123
8.7.16	Thermal cycling (CY)	123
8.7.17	Abrasion resistance (coated surface) (AE).....	124
8.7.18	Coating adhesion (TD).....	124
8.8	Failure definition	124
8.8.1	Failure criteria	124
8.8.2	Failed components	124
8.9	Data documentation	125
8.10	Delivery	125
8.11	Packing, dispatching, handling and storage.....	125
9	Solar cell protection diodes	126
9.1	Overview	126
9.2	Testing, deliverable components and marking.....	126
9.2.1	Testing.....	126
9.2.2	Deliverable components	127
9.2.3	Marking.....	128
9.3	Production control (process identification document).....	128
9.3.1	Integral protection diodes.....	128
9.3.2	External protection diodes	128
9.4	Acceptance tests	128
9.4.1	General.....	128
9.4.2	Integral protection diodes.....	129
9.4.3	External protection diodes	129
9.4.4	External and integral diodes	129
9.4.5	Test methods and conditions	130
9.4.6	Documentation	130
9.5	Qualification tests	131
9.5.1	General.....	131
9.5.2	Integral protection diodes.....	131
9.5.3	External protection diodes	132
9.5.4	Integral and external protection diodes	134
9.6	Test methods, conditions and measurements	135
9.6.1	General.....	135
9.6.2	Visual inspection (VI)	135
9.6.3	Dimensions and weight (DW).....	136

9.6.4	Thermal cycling (CY)	137
9.6.5	Burn in (BI)	137
9.6.6	Humidity and temperature.....	138
9.6.7	Contact uniformity (CU)	139
9.6.8	Contact thickness (CT)	139
9.6.9	Surface Finish (SF).....	139
9.6.10	Contact adherence (CA)	140
9.6.11	Pull test (PT).....	141
9.6.12	Electron irradiation (EI)	142
9.6.13	Temperature annealing (TA).....	142
9.6.14	Temperature behaviour (TB).....	143
9.6.15	Diode characterization (DC).....	143
9.6.16	Human body ESD (DE).....	144
9.6.17	Switching test (DS)	145
9.6.18	Long Duration – Life test (LT)	147
9.7	Failure definition	149
9.7.1	Failure criteria	149
9.7.2	Failed components	150
9.8	Data documentation	150
9.9	Delivery	150
9.10	Packing, despatching, handling and storage	150
9.10.1	Overview	150
9.10.2	ESD sensitivity.....	150
10	Solar simulators and calibration procedures	151
10.1	Solar simulators.....	151
10.1.1	Spectral distribution	151
10.1.2	Irradiance uniformity	153
10.1.3	Irradiance stability.....	154
10.2	Standard cell and Solar simulator calibration.....	155
10.2.1	Primary standards.....	155
10.2.2	Secondary working standards (SWS)	155
10.2.3	Standards cells documentation	157
10.2.4	Maintenance of standards.....	157
10.2.5	Recalibration and intercomparison.....	157
10.2.6	Solar simulator calibration and maintenance.....	157
11	Capacitance measurement methods	159

11.1	Single junction solar cell capacitance measurement.....	159
11.1.1	Overview	159
11.1.2	Signal measurement method	159
11.1.3	Measurement procedure.....	160
11.1.4	Measurement analysis	163
11.1.5	Measurement of the capacitance of a multi-junction cell	166
11.2	Time domain capacitance measurement	167
11.2.1	Overview	167
11.2.2	Measurement procedure.....	168
12	Planar Blocking Diodes	170
12.1	Overview	170
12.2	Testing, deliverable components and Marking.....	170
12.2.1	Testing.....	170
12.2.2	Deliverable components	171
12.2.3	Marking.....	171
12.3	Production control (process identification document).....	172
12.4	Acceptance test.....	172
12.4.1	General.....	172
12.4.2	Planar blocking diodes.....	172
12.5	Qualification tests	173
12.5.1	General.....	173
12.5.2	Blocking diodes	173
12.5.3	Production and test schedule.....	173
12.5.4	Qualification test samples	173
12.5.5	Qualification testing	174
12.6	Test methods, conditions and measurements	177
12.6.1	Visual inspection (VI)	177
12.6.2	Dimensions and weight (DW).....	177
12.6.3	Diode characterization (DC).....	178
12.6.4	Humidity and Temperature	178
12.6.5	Temperature Cycling (CY)	180
12.6.6	Contact Adherence (CA).....	180
12.6.7	Burn-in (BI)	181
12.6.8	Long duration-Life Test (LT)	182
12.6.9	Temperature behaviour test (TB)	182
12.6.10	Temperature robustness test (TR)	183
12.6.11	Total Dose Radiation Testing (RT).....	183

12.6.12 Temperature Annealing (TA)	185
12.6.13 Contact uniformity test (CU).....	185
12.6.14 Surface Finish test (SF)	186
12.6.15 Human Body ESD test (ESD)	186
12.6.16 Pull test (PT) / Interconnector adherence test (IA)	187
12.6.17 Surge test (ST)	187
12.6.18 Thermo-optical data (TO).....	188
12.7 Failure definition	188
12.7.1 Failure criteria.....	188
12.7.2 Failed Blocking Diodes	188
12.8 Data documentation	189
12.9 Delivery	189
12.10 Packing, despatching, handling and storage	189
12.10.1 Overview	189
12.10.2 ESD sensitivity.....	189
Annex A (normative) Source control drawing for photovoltaic assembly (SCD-PVA) - DRD.....	190
Annex B (normative) Source control drawing for solar cell assembly (SCD-SCA) - DRD	196
Annex C (normative) Source control drawing for bare solar cell (SCD-BSC) - DRD	201
Annex D (normative) Source control drawing for coverglass (SCD-CVG) - DRD	209
Annex E (normative) Source control drawing for External Protection Diodes (SCD-EPD) - DRD.....	215
Annex F (normative) Process identification document (PID) - DRD	219
Annex G (normative) Data documentation package (DDP) - DRD.....	221
Annex H (normative) Source control drawing for Planar Blocking Diodes (SCD-PBD) - DRD	224
Bibliography	229
 Figures	
Figure 4-1: Specification hierarchy	28
Figure 6-1: Definition of cell defects	70
Figure 6-2: Test points for electrical performance measurement.....	72

Figure 7-1: Definition of bare solar cell defects.....	94
Figure 8-1: Methods of defining coverglass orientation	111
Figure 8-2: Edge chip parameters	116
Figure 8-3: Corner chip parameters	116
Figure 8-4: Coverglass manufacturing tolerance limits	117
Figure 8-5: Schematic for calculating surface resistivity	120
Figure 8-6: Definition of coverglass flatness.....	120
Figure 9-1: Diode forward and reverse test profile.....	147
Figure 9-2: Diode switching test profile	147
Figure 11-1: Solar cell impedance measurement equipment.....	161
Figure 11-2: Channel balancing and reduction of the parasitic inductances	162
Figure 11-3: Measurement of the resistance value of the shunt in the measuring conditions (shunt in parallel with the input of the network analyser)	162
Figure 11-4: Small signal electrical schema biased with a DC voltage associated impedance	165
Figure C-1 : BSC front side	203
Figure C-2 : BSC rear side	203
Figure C-3 : BSC contact	203

Tables

Table 4-1: Test tolerances on temperature.....	30
Table 5-1: Qualification test plan for PVA.....	42
Table 5-2: Acceptance test plan	51
Table 6-1: Qualification test plan for SCA.....	67
Table 6-2: Maximum dimensions of corner chips, edge chips and surface nicks	70
Table 7-1: Acceptance test matrix	89
Table 7-2: Qualification test plan for bare solar cells	91
Table 7-3: Maximum dimensions of corner chips, edge chips and surface nicks	94
Table 8-1: Qualification test plan for coverglasses	114
Table 9-1: Acceptance test matrix IPD	129
Table 9-2: Acceptance test matrix EPD.....	129
Table 9-3: Qualification test plan for integral protection diode	132
Table 9-4: Qualification test plan for bare protection diodes	133
Table 9-5: Diode long duration-life test parameters.....	149
Table 10-1: <<deleted>>	152
Table 10-2: Classes of single and multi-source solar simulators (informative).....	152
Table 10-3: Classes of solar simulators with respect to nonconformity of irradiance uniformity (informative)	154

Table 10-4: Classes of solar simulators with respect to temporal instability of irradiance	155
Table 12-1: Acceptance test matrix planar blocking diodes	172
Table 12-2: Qualification test plan for bare blocking diodes	175
Table 12-3: Qualification test plan for connector integrated blocking diodes	176
Table 12-4: Diode Irradiation and bias conditions.....	184
Table B-1 : Minimum current requirement for solar assemblies (25 °C or operating temperature)	198
Table C-1 : Electrical performance pass-fail criteria	205
Table D-1 : Average transmission into air before test (%)	211
Table D-2 : Maximum average deviation of transmission into air after test (%).....	212

European foreword

This document (EN 16603-20-08:2023) has been prepared by Technical Committee CEN-CENELEC/TC 5 "Space", the secretariat of which is held by DIN.

This standard (EN 16603-20-08:2023) originates from ECSS-E-ST-20-08C Rev.2.

This European Standard shall be given the status of a national standard, either by publication of an identical text or by endorsement, at the latest by March 2024, and conflicting national standards shall be withdrawn at the latest by March 2024.

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. CEN [and/or CENELEC] shall not be held responsible for identifying any or all such patent rights.

This document supersedes EN 16603-20-08:2014.

The main changes with respect to EN 16603-20-08:2014 are listed below:

- Implementation of change requests
- Addition of new clause 12 "Planar Blocking Diodes"
- Check and update of the use of the verb "define" in the document

This document has been prepared under a standardization request given to CEN by the European Commission and the European Free Trade Association.

This document has been developed to cover specifically space systems and has therefore precedence over any EN covering the same scope but with a wider domain of applicability (e.g. : aerospace).

According to the CEN-CENELEC Internal Regulations, the national standards organizations of the following countries are bound to implement this European Standard: Austria, Belgium, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, Former Yugoslav Republic of Macedonia, France, Germany, Greece, Hungary, Iceland, Ireland, Italy, Latvia, Lithuania, Luxembourg, Malta, Netherlands, Norway, Poland, Portugal, Romania, Serbia, Slovakia, Slovenia, Spain, Sweden, Switzerland, Turkey and the United Kingdom.

Introduction

The qualification, procurement, storage and delivery of space solar arrays are specified in the dedicated solar array specification, where requirements for the solar array electrical layout, structure and mechanism are specified.

This Standard outlines the requirements for the qualification, procurement, storage and delivery of the main assemblies and components of the space solar array electrical layout: photovoltaic assemblies, solar cell assemblies, bare solar cells, coverglass and protection diodes. This Standard does not outline the requirements for the qualification, procurement, storage and delivery of the solar array subsystem, comprising the solar panels, structural parts and mechanisms.

The general requirements are covered in the main part of this Standard (clauses 5 to 11). Annex A to Annex E specify the contents of the source control drawing of photovoltaic and solar cell assemblies, bare solar cells coverglasses and protection diodes and include the inspection data, physical and electrical characteristics, other ratings and acceptance and qualification specific requirements, which can be different for each space project.

This Standard is divided into five specific subjects, each one corresponding to each assembly or component:

- Clause 5 for photovoltaic assemblies,
- Clause 6 for solar cell assemblies,
- Clause 7 for bare solar cells,
- Clause 8 for coverglasses,
- Clause 9 for protection diodes,
- Clause 12 for planar blocking diodes.

Two additional clauses are dedicated to Sun simulators and calibration procedures (clause 10) and capacitance measurement methods (clause 11).

NOTE At the time of the publication of this Standard the handbook ECSS-E-HB-20-08A, that is called in this document, has not yet been published.

1

Scope

This Standard specifies the general requirements for the qualification, procurement, storage and delivery of photovoltaic assemblies, solar cell assemblies, bare solar cells, coverglasses, protection diodes and planar blocking diodes suitable for space applications.

This standard does not cover the particular qualification requirements for a specific mission.

This Standard is primarily applicable for qualification approval for photovoltaic assemblies, solar cell assemblies, bare solar cells, coverglasses, protection diodes and planar blocking diodes, and to the procurement of these items.

This standard is limited to crystalline Silicon and single and multi-junction GaAs solar cells with a thickness of more than 50 μm and does not include thin film solar cell technologies and poly-crystalline solar cells.

This Standard does not cover the concentration technology, and especially the requirements related to the optical components of a concentrator (e.g. reflector and lens) and their verification (e.g. collimated light source).

This Standard is not applicable for qualification of the solar array subsystem, solar panels, structure and solar array mechanisms.

This standard may be tailored for the specific characteristic and constraints of a space project in conformance with ECSS-S-ST-00.

Qualification is a process to confirm compliance with requirements that have been established with reference to foregoing characterization and engineering test programs. Guidelines for characterization and engineering tests and for relaxation of qualification tests due to similarity with earlier performed qualification are described in the handbook ECSS-E-HB-20-08. Those clauses in this standard, for which the Handbook gives additional information, will refer to the Handbook.

Normative references

The following normative documents contain provisions which, through reference in this text, constitute provisions of this ECSS Standard. For dated references, subsequent amendments to, or revision of any of these publications do not apply. However, parties to agreements based on this ECSS Standard are encouraged to investigate the possibility of applying the more recent editions of the normative documents indicated below. For undated references, the latest edition of the publication referred to applies.

EN reference	Reference in text	Title
EN 16601-00-01	ECSS-S-ST-00-01	ECSS system – Glossary of terms
EN 16603-10-03	ECSS-E-ST-10-03	Space engineering – Testing
EN 16603-20	ECSS-E-ST-20	Space engineering –Electrical and electronic
EN 16603-20-06	ECSS-E-ST-20-06	Space engineering – Spacecraft charging
EN 16602-60	ECSS-Q-ST-60	Space product assurance — Electrical, electronic and electromechanical (EEE) components
EN 16602-70-01	ECSS-Q-ST-70-01	Space product assurance – Cleanliness and contamination control
EN 16602-70-06	ECSS-Q-ST-70-06	Space product assurance – Particle and UV radiation testing for space materials
EN 16602-70-09	ECSS-Q-ST-70-09	Space product assurance – Measurements of thermo-optical properties of thermal control materials
	ISO 15387	Space Systems – Single junction space solar cells – Measurement and calibration procedures
	ISO 14644-1:1999	Cleanrooms and associated controlled environments – Part 1: Classification of air cleanliness
	MIL-E-12397B	Eraser, rubber pumice for testing coated optical elements
	MIL-STD-750	Test methods for semiconductor devices
	IEC 60749-26:2006	Semiconductor devices – Mechanical and climatic test methods - Part 26: Electrostatic discharge (ESD) sensitivity testing – Human body model (HBM)
	IEC 60904-7	Photovoltaic devices – Part 7: Computation of the spectral mismatch correction for measurements of photovoltaic devices
	IEC 60904-10	Photovoltaic devices – Part 10: Methods of linearity measurement

EN reference	Reference in text	Title
	ASTM D1193-99	Standard specification for reagent water
	ESCC 23800 Issue 1	Electrostatic Discharge Sensitivity Test Method; ESCC Basic Specification
	ESCC 24900 Issue 2	Minimum Requirements for Controlling Environmental Contamination of Components; ESCC Basic Specification
	ESCC 2265000	Evaluation test programme for discrete Non- microwave semiconductors; ESCC Basic Specification
	EN 1464:2010	Adhesives - Determination of peel resistance of adhesive bonds - Floating roller method
	Gueymard, C., 2018	Gueymard, C., Revised composite extraterrestrial spectrum based on recent solar irradiance observations Solar Energy, Volume 169, 2018, Pages 434-440, ISSN 0038-092X, https://doi.org/10.1016/j.solener.2018.04.067 . (https://www.sciencedirect.com/science/article/pii/S0038092X1830433X)