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Project No: 306622

Project Acronym: CA2PVM

Project Full Name: Multi-field and multi-scale Computational Approach to design and durability of PhotoVoltaic Modules

ERC-SG

Mid-Term Activity Report

Period covered: from 01/12/2012 **to** 31/05/2015

Start date of project: 01/12/2012

Duration: 60

Principal Investigator name:
Prof. Marco Paggi

Date of preparation: 05/06/2015

Date of submission (SESAM): 20/07/2015

Report submitted by:
SCUOLA IMT (ISTITUZIONI, MERCATI, TECNOLOGIE) ALTI STUDI DI LUCCA

Mid-Term Activity Report

GENERAL INFORMATION

Project No.:	306622
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Project starting date:	01/12/2012
Project duration [months]:	60
Principal Investigator name:	Prof. Marco Paggi
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Date of submission:	20/07/2015

Mid-Term Activity Report

Summary of the major achievements since the start of the project

The information provided in this section will be available to ERC staff, to members of the ERC panels, and to the Scientific Council

Briefly describe the work performed during the entire lifetime of the project, and in particular towards the objectives foreseen for the final reporting period.

Please specify the outcome in terms of:

- research and technological achievements and the impact and use of them

The main objective of the ERC StG CA2PVM project is to develop an innovative unconventional computational framework complemented by multi-scale experimental testing for the design, characterization, quality control, and lifetime assessment of conventional and innovative photovoltaic (PV) modules. Fundamental research was deemed to be necessary towards the experimental characterization and modelling, for the very first time, of the intrinsic multi-field (multi-physics) and multi-scale features of the problem of fracture in PV modules. The following major achievements and the related impact and usefulness are synthetically summarized in the sequel in reference to the published journal articles.

Achievements in destructive and non-destructive experimental methods

In order to document and characterize the phenomenon of fracture in silicon solar cells and the coupling between elastic, thermal, humidity and electric fields, an extensive experimental campaign on semi-flexible PV modules (provided by Solbian Energie Alternative S.r.l., an Italian industry of the PV sector that has endorsed the project) and on PV modules with glass cover has been carried out during the first half of the project. Cracks have been monitored via electroluminescence (EL) imaging, a non-destructive technique to quantify the effect of the crack pattern in solar cells on the electric field and monitor its evolution. Tests performed so far, relevant for the durability of PV modules, regarded: (i) hail impacts on PV modules; (ii) bending tests; (iii) cyclic thermal and humidity tests. Although similar qualification tests are promoted by the standards of the International Electrotechnical Commission and are adopted by most of the PV industries, the monitoring of cracking and of the connected degradation processes are time consuming activities not feasible at the industrial level. On the other hand, acquiring this information is a crucial step towards the realization of a benchmark database to develop and validate novel computational methods with predictive capabilities, as well as for comparing the durability performance of new PV modules that will be put on the market.

So far, results of monotonic and cyclic bending tests on semi-flexible PV modules have been reported in [1] and have shown, for the very first time, the fundamental interplay between elastic deformation and electric response in the case of cracked solar cells. Unconventional phenomena of partial electric insulation at cracks, electric recovery, and fatigue crack propagation, impossible in the case of stand-alone silicon cells, have been highlighted. The physical interpretation of these phenomena was made via the analysis of the residual compressive stress state in the laminate promoting crack closure effects, pinpointing the need of simulating the mechanics of the PV module laminate as a whole. A careful inspection of the EL images has also been proven to be very useful in distinguishing the various sources of cracking and electric defects taking place during production, installation, or service. This methodology has been included in a novel testing procedure proposed for solar plants [2], whose effectiveness has been validated based on a wide experimental campaign on-site and in the lab.

In parallel to experimental testing at the module scale, unconventional experimental methods at the micro-scale have been developed by exploiting the features of the scanning electron microscope quipped with a tensile stage, and the confocal profilometer for surface roughness characterization available in the MUSAM-Lab at IMT Lucca. These facilities are employed to characterize fracture events in the critical components of the module, as well as to investigate crack propagation in silicon thin films. The latter activity, still ongoing and in collaboration with the Institute for Solar Energy

Research Hamelin (Germany), led to preliminary results on thermally-induced spalling (accepted and soon in press in Energy Procedia) that are very promising to move this solar cell production technology from the research level to the industry. Moreover, advanced statistical and spectral methods for the multi-scale characterization of texturing and roughness of solar cell surfaces have been published in [3]. Results have shown that the statistical and fractal approaches to characterize and simulate random rough surfaces are not accurate to simulate these textured surfaces due to the appearance of bi-fractal properties and cut-offs to the single power-law spectral density function not present in classical self-affine fractals. These important conclusions open a frontier of research on the realization of new spectral generation methods to consistently reproduce the unique morphological features of textured surfaces, an essential task for subsequent ray-tracing simulations to minimize reflectance, and for virtual testing of the sealing performance of the silicon cell-polymer interface to minimize moisture degradation.

Achievements in physical modelling and computational methods

Physical modelling and computational research have focused on three aspects of high complexity: (i) proposal of a global-local computational approach to simulate the structural response of PV modules (composed of up to 60 cells) and fracture events at each solar cell level, as well as model order reduction techniques to reduce the computation time; (ii) multi-physics description of fracture in solar cells in the presence of elastic, thermal, and electric fields, along with a fully-consistent derivation of the novel constitutive crack models for implicit solution schemes; (iii) modelling of the thermo-visco-elastic and moisture diffusion constitutive response of the polymer encapsulating solar cells; micromechanical characterization of the fibrillar behaviour of the polymer during peeling and finite element implementation of the proposed constitutive laws within 2D and 3D interface finite elements for implicit large deformation simulations in statics and dynamics.

Regarding (i), an innovative multi-physics and multi-scale computational approach has been developed [4] by integrating laminate structural models, multi-physics modelling, and cohesive fracture in solar cells. This pioneering work establishes the general computational framework for the characterization of PV modules' durability and opens a new frontier of research for renewable solar energy systems. Ongoing research regards the use of different structural models for the laminate (3D brick elements vs. solid shell finite elements), as well as the simulation of 3D fracture in solar cells discretized by solid shell finite elements. Towards the simulation of large-scale PV modules, the computational cost is a problem at stake and will be subject of intensive research in the second half of the project. Suitable model order reduction techniques can be invoked and preliminary results have concerned the solution of the problem of heat conduction in the laminate in the presence of realistic environmental conditions [5].

As far as the sub-topic (ii) is concerned, research results regard a new image analysis software [6] developed to identify grain boundaries in polycrystalline solar cells from real images and realize finite element models for fracture mechanics simulations. Based on this input, the competition between intergranular and transgranular cohesive fracture has been investigated in [6] by adopting a novel intrinsic cohesive zone model approach to minimize the unphysical compliance due to the inserted interfaces. Results have shown the prevalence of transgranular fracture over the intergranular one.
From the point of view of the constitutive behaviour of cohesive cracks subject to cyclic thermo-mechanical deformation, a new thermo-elastic cohesive zone model has been proposed in [7,8] for the simulation of transient heat conduction at partially bonded interfaces and cracks. The novelty of the approach relies in the incorporation of roughness of cracks in silicon, generalizing the Kapitza model of thermal conductance at bi-material interfaces. The Kapitza model has been enhanced by allowing for a partial transfer of heat via the spots in contact along the rough crack, to depict a phenomenon of partial thermal insulation observed in experiments [7]. A rigorous fully consistent formulation allows for the simulation of the transient thermo-elastic and heat transfer coupled problems via a fully implicit solution scheme [8]. Moreover, in order to simulate the effect of the thermo-mechanical field on the electric field, a generalized electric model accounting for elastic deformation effects for mono- and poly-crystalline solar cells in the presence of cracks has been developed [9] and validated with experiments. Regarding rough cracks in contact (due to residual compressive stresses in the laminate), modelling results have established universal scaling laws in the tangential contact response in the presence of partial slip [10], and advancements in

modelling their fatigue crack propagation by considering the topological features of roughness [11].

The physical and structural characterization of the polymer encapsulant layers embedding the solar cells (sub-topic iii) has requested a significant research effort since this component plays a crucial role for the durability and protection of any PV system. A novel thermo-visco-elastic constitutive relation for epoxy vinil acetate (EVA) based on fractional calculus has been proposed [12] and validated with experiments in order to effectively characterize its time-dependent response. The advantage of the proposed model over the classic Prony series with up to 100 arms regards the use of just two free parameters, allowing for a much easier identification and implementation in the finite element method. Coupling with moisture diffusion via a suitable geometrical multi-scale scheme is an ongoing activity.
To reduce the computational complexity in discretizing the thin encapsulant layers, attempts to transform this finite thickness interphase to a mathematically equivalent zero-thickness interface have been made. On this line of research, a new nonlinear fracture mechanics cohesive zone model has been proposed in [13] by accounting for the mass of the interface and its thickness-dependent stiffness. Its fully-consistent implementation within an interface finite element topology has been proven to be very effective to perform implicit finite element simulations of cohesive fracture in statics and dynamics. This computational model has been used to make an insight into the explanation of the fundamental phenomenon of increase in the apparent strength of bonded joints in the dynamic regime, pinpointing for the very first time the effect of the adhesive mass and stiffness. These results are deemed to be very useful to guide the choice of the encapsulant thickness in PV modules.
The degree of adhesion of the encapsulant over solar cells has been further investigated by examining the physical phenomenon of debonding taking place via fibrillation (craze) formation. This phenomenon is very complex due to the lack of mechanistic understanding of the microscopic phenomenon of fibrillation and the inherent large deformation regime during peeling. An unprecedented 3D anisotropic cohesive zone model incorporating the in-plane and out-of-plane statistical distributions of fibrils and their microscopic nonlinear debonding response has been proposed in [14]. To deal with large deformation fracture processes, interface finite element formulations have been generalized to deal with large displacements and moderate rotations [15]. The applicability of the proposed approach, which is the first able to simulate the effect of re-orientation of fibrils during the deformation process, will be exploited towards the design of interfaces in new PV modules to facilitate recycling. Moreover, it is expected to have a huge impact in many other fracture problems involving hyperelastic continua containing fibrils, such as soft biological materials and paper tissue. It also opens new perspectives for the study of coupled nonlinear problems with geometrical instabilities and fracture mechanics (wrinkling of stiff layers bonded onto soft substrates vs. delamination; mechanics of thermal barrier coatings).
Finally, micromechanical characterization of diffusive transport phenomena at the solar cell-glass interface has been investigated due to their relevance for the assessment of sealing of the solar cells via the fluid epoxy material during lamination. Roughness leads to anomalous transport phenomena [16,17] and governs moisture diffusion and the sealing performance. A fundamental insight into the scaling of the free volume and of the topology of the evolving network channels as functions of the applied pressure applied to rough surfaces in contact has been proposed in [18]. The numerical simulation method for rough contact based on the boundary element method (BEM) has also been improved by exploiting novel optimization algorithms for the solution of the Signorini contact problem [19]. This led to computational methods between one and two orders of magnitude faster than the state-of-the-art algorithms for the solution of contact problems with BEM.

Further research is planned in the second half of the project towards the realization of an integrated software for the simulation of PV modules degradation, including all the new models developed so far. The capabilities of solid-shell finite element formulations, particularly powerful from the computational point of view, will be exploited to discretize of the layers of the laminate. Research is also ongoing to generalize the solid shell formulation to handle multi-physics problems and model fracture events in the silicon layer.

- novel and/or unconventional methodologies

(1) Proposal of a novel multi-scale and multi-physics computational approach to simulate the electric response of PV modules with cracked solar cells integrating nonlinear structural mechanics formulations for the laminate, computational fracture mechanics, microstructural information from

materials science, coupled thermo-elasticity, and electric models.

(2) Development of novel interface finite elements for quasi-static and dynamics fracture at bi-material interfaces under the presence of both material and geometric nonlinearities. The novel mathematical formulations have been implemented in the finite element analysis programme FEAP for fully implicit solution schemes.

(3) Unconventional experimental campaign on PV modules with detailed monitoring of the evolution of crack patterns and electric degradation in case of mechanical (monotonic and cyclic tests with up to 600 bending cycles) or thermo-hygrometric (with up to 500 thermo-hygrometric cycles) loading. The obtained database will be used to validate the developed computational models and will also be made freely available to the scientific community at the end of the project, as a fundamental benchmark for future developments in the field.

(4) Novel numerical methods for the characterization of anomalous transport and diffusive phenomena across contact domains with rough boundaries, to characterize the sealing performance of joints. Research is ongoing to integrate computational fluid dynamics with computational contact mechanics software for rough surfaces.

- inter and cross disciplinary developments

Solar energy systems have typically been a subject of investigation by theoretical and applied physicists, focusing on the physics of semiconductors to improve the solar energy conversion efficiency, and by electric engineers, investigating the electric performance of the PV system and its integration in the electric grid. Indeed, durability of PV modules requires considerations proper of structural mechanics. On the other hand, a mono disciplinary structural mechanics approach would be insufficient, since most of the measureable quantities of practical interest are the electric ones.

Contrary to mono-disciplinary approaches, the results obtained so far in the present project pinpoint the need of approaching the problem of durability and design of innovative PV systems by integrating physical and electric models, nondestructive testing, materials science considerations, and computational mechanics methodologies. The original idea to move from the solar cell level to the multi-physics behaviour of the whole laminate containing the solar cells, thus integrating mechanics with physics and materials science research, represents an important cross disciplinary achievement to shed light on the mechanisms inducing crack formation and degradation of the electric performance in PV modules.

Results of interdisciplinary nature were stemming from the collaboration with the Department of Energy of Politecnico di Torino (Italy), leading to a novel integrated diagnostic method where electric measurements of a PV park are complemented by the electroluminescence inspection of the crack pattern in damaged PV modules [2].

Interaction with applied physicists on the production of thin film solar cells via thermally-controlled spalling led to an ongoing collaboration with the Institute for Solar Energy Research Hamelin (Germany). In this case, mechanics plays an essential role for the understanding and control of the phenomenon of thermally-induced crack propagation to effectively produce silicon thin films (results are in progress).

Another cross disciplinary development achieved in the project regarded the significant speedup from 1 to 2 orders of magnitudes in the solution of contact problems between rough surfaces. This was achieved by developing novel optimization algorithms stemming from the research on quadratic programming in the area of convex optimization and control [19], in cooperation with Prof. Alberto Bemporad at IMT Lucca.

- knowledge and technology transfer

So far, the project has received endorsement by Solbian Energie Alternative SrL (Italy), an Italian producer of unconventional semi-flexible PV modules engaged in the research to increase the quality of their products and minimize safety issues. Jabil Circuit Inc. (St. Petersburg, Florida, USA) with its 1 GW PV production facilities in Poland has also expressed interest in collaborating on the

development of a real time software for the simulation of the degradation of cracks in PV modules to improve the over-conservative rejection criteria of cracked PV modules after manufacturing. Applied Materials Inc. (Italy), a company focusing on solutions to improve PV factory productivity and reduce operating costs, endorsed the ERC research and is collaborating with the PI on the realization of a software for the electric characterization of cracked solar cells, to be used in their laboratories. Letters of endorsement are enclosed.

As an outcome of the ideas resulting from the project, the PI applied for an ERC Proof of Concept grant aiming at developing patentable technical solutions to produce PV modules with crack-insensitive silicon solar cells. The ERC PoC proposal passed all the criteria for excellence but, based on its ranking, it has been included in a reserve list for possible funding. If not granted, it will be improved and re-submitted for the next call.

Further activities of knowledge transfer to the PV industry sector and to policy-makers are undertaken by the PI via his participation in the works of the Technical Committee of the Task 13 of the International Energy Agency on "Performance and Reliability of Photovoltaic Systems". The technical reports resulting from the Task 13 activities will have a great visibility and will further disseminate the key results of the present ERC project beyond the university research environment.

- establishment and/or consolidation of the research group and team composition

IMT Institute for Advanced Studied Lucca, the current host institution for the ERC StG CA2PVM project, has promoted the independence of the PI according to the ERC recommendations, giving him the required freedom in the choice of the personnel, in the independency in the scientific enquiry, and providing administrative support in the administration of the grant.

At IMT Lucca the PI is currently director of the research unit MUSAM on “Multi-Scale Analysis of Materials” (http://musam.imtlucca.it). From November 2014 to November 2016 the PI has the role of director of a PhD curriculum on Computational Mechanics within the multidisciplinary PhD programme at IMT Lucca. In the same institute, he is directing the MUSAM-Lab, the first experimental laboratory of IMT Lucca fully supported by the ERC StG CA2PVM.

His research group is currently composed of 7 PhD students (3 enrolled at Politecnico di Torino: I. Berardone, A. Infuso, O.S. Ojo; and 4 at IMT Lucca: P. Lenarda, P. Cinat, V. Carollo, V. Govindarajan), 1 research collaborator at IMT Lucca (C. Borri), 1 post-doctoral researcher at IMT Lucca (P. Budarapu), and 1 Assistant Professor at IMT Lucca (A. Bacigalupo). Moreover, Dr. José Reinoso, Assistant Professor at the University of Seville (Spain), and Dr. Mauro Corrado, Assistant Professor at Politecnico di Torino and currently Marie Curie Fellow at the Ecole Polytechnique Federale de Lausanne (Switzerland), are also collaborating with the PI on the ERC research as visiting professors at IMT Lucca. All the publications enclosed in the mid-term report have been the result of independent research carried out by the PI with his collaborators.

- others

Invited lectures and invited seminars on the ERC StG research delivered by the PI

(1) "Multi-physics Modelling of Photovoltaic Laminates", Seminar at the MUSIC Graduate School on Multiscale Methods for Interface Coupling, Institute of Continuum Mechanics, Leibniz University of Hannover, Hannover, Germany, May 18, 2015.
(2) "New trends in computational modelling of interfaces", Seminar at the Laboratorio di Fisica Non Lineare e Modelli Matematici, Università Campus Bio-Medico di Roma, Roma, May 15, 2015.
(3) "A geometrical multiscale numerical method for coupled hygro-thermo-elastic problems in layered materials" (authors: P. Lenarda and M. Paggi), Invited talk at the Workshop State of the art and challenges in thermal and mechanical modelling of ceramic materials, Trento, March 20, 2015.
(4) "Modelling and simulation of fracture in classical and hierarchical polycrystalline materials towards the design of super-resistant cutting tools", Invited lecture at the Special Interest Seminar on Simulation and Modelling in Hard Materials, Euro PM2014 Congress & Exhibition, Salzburg, Austria, 21-24/09/2014.
(5) "Flaw tolerance of continuum and discrete mechanical systems: the roles of heterogeneity and nonlocality" (M. Paggi, A. Infuso), Opening lecture at the ECT* Workshop on New Frontiers in

Multiscale Modelling of Advanced Materials, Trento, Italy, 17-20/06/2014.
(6) "Nonlinear fracture dynamics of laminates with finite thickness adhesives", Seminar at the University of Seville, Seville, Spain, 27/6/2014.
(7) "Multi-physics modelling of cracking in quasi-brittle materials for energy applications", Seminar at the University of Trento, Trento, Italy, 18/6/2014.
(8) "Experimental evidence of electro-thermo-elastic coupling in quasi-brittle materials for energy applications", Seminar at the University of Trento, Trento, Italy, 18/6/2014.
(9) "Quantitative analysis of cracking in in photovoltaic modules using a multi-physics approach", Seminar at the Institute for Solar Energy Research, Hamelin, Germany, 3/6/2014.
(10) "An overview on contact and fracture mechanics for interface problems", Seminar at the University of Evry, Evry, France, 23/05/2014.
(11) "Multi-scale and multi-physics models applied to interface problems", Seminar at the University of Paris-EST, Marne-La-Valléee, France, 16/5/2014.
(12) "Mechanical challenges in the durability of photovoltaic modules", Seminar at the Institute for Mechanics, Technische Universität Berlin, Berlin, 17/12/2013.
(13) "Modelling of cracking in PV modules: Physical aspects and Computational Methods", Opening lecture of the Workshop "Measurements and Models for PV-Module analysis", Institute of Solar Energy Research, Hamelin, Germany, 5/11/2013.
(14) "Recent advances of interface constitutive laws for Fracture Mechanics", Seminar at the Institute of Structural Mechanics of the Leibniz University of Hannover, Hannover, Germany, 19-23/08/2013.
(15) "Emergent properties in interface mechanical problems: A paradigm of organized complexity", Seminar at the IMT Institute for Advanced Studies, Lucca, Italy, 5/3/2013.
(16) "Physical modelling and computational strategies for 2D and 3D cohesive fracture and recent progresses towards multi-physics", Seminar at the University of Paris-EST, Marne-La-Vallée, France, 21-25/01/2013.

Publishable brief summary of the achievement of the project

This section should normally not exceed 1 page.

Stand alone description of the project and its outcomes

Photovoltaics (PV) is one the most growing technology in the World for renewable, sustainable, non-polluting, widely available clean energy sources. To make it further sustainable and durable, the present project aims at developing unconventional simulation tools and experimental methods to effectively characterize and optimize the performance and the durability of photovoltaic systems subject to mechanical and environmental loadings. Research results regard the development of a novel multi-physics simulation method of PV modules integrating: (i) advanced structural mechanics models to compute the stress and deformation fields in PV laminates; (ii) geometrical multi-scale numerical schemes to solve thermal and moisture diffusion problems; (iii) nonlinear fracture mechanics formulations to simulate crack propagation in the solar cells; (iv) electric models to quantify the electric output of the device, also in the presence of moisture degradation and cracks in silicon.
Target applications concern not only traditional ground-mounted PV modules, but also novel building-integrated PV solutions. Both traditional technologies based on mono- and poly-crystalline silicon semiconductors and innovative semi-flexible PV modules and thin film solar cells are investigated. Knowledge and technology transfer regard the development of simulation tools for industrial quality control to avoid over-conservative rejection of partially cracked PV modules, monitoring criteria for operating PV-plants to quantify the energy losses according to the causes, methods to improve PV production technologies, as well as new solutions to facilitate recycling of PV modules at the end of their lifetime.

Major problems / Difficulties

The information provided in this section will be available to ERC staff, to members of the ERC panels, and to the Scientific Council

Please specify any major problems/difficulties you may have encountered until now or may anticipate in the near future. Please suggest possible corrective actions.

Scientific problems

No major scientific problems have been encountered or are anticipated.

Technical problems

No major technical problems have been encountered or are anticipated.

Support provided by the Host Institution (Start-up facilities, working space, access to labs, equipments, resources, etc)

Support provided by the Host Institution was adequate. No problems have been encountered or are anticipated.

Others

N/A

Information you would only want to share with ERCEA

N/A

List of free Keywords

Photovoltaics, durability, coupled problems, nonlinear fracture mechanics, multi-physics simulations, multi-scale computational methods, multi-scale material testing

Annex: Project output records

A1. Publications partly or wholly resulting from the project

LIST OF SCIENTIFIC PUBLICATIONS, STARTING WITH THE MOST IMPORTANT ONES										
No.	Title / DOI	Main author	Title of the periodical or the series	Number, date or frequency	Publisher	Place of publication	Date of publication	Relevant pages	Is open access provided to this publication ?	Type
1	Fatigue degradation and electric recovery in Silicon solar cells embedded in photovoltaic modules 10.1038/srep0 4506	Marco Paggi , Irene Berardon e , Andrea Infuso , Mauro Corrado	Scientific Reports	Vol. 4	Nature Publishing Group	United Kingdom	28/03/2014	1-7	Yes	Peer reviewed
2	A power and energy procedure in operating photovoltaic systems to quantify the losses according to the causes 10.1016/j.sol ener.2015.05.033	F. Spertino , A. Ciocia , P. Di Leo , R. Tommasini , I. Berardone , M. Corrado , A. Infuso , M. Paggi	Solar Energy	Vol. 118	Elsevier Limited	United Kingdom	01/08/2015	313-326	Yes	Peer reviewed
3	Topological characterizat ion of antirefl ectiv e and hydrophobic rough surfaces: are random process theory and fractal mod eling applicable? 10.1088/0022- 3727/48/4/045301	Claudia Borri , Marco Paggi	Journal of Physics D - Applied Physics	Vol. 48/Issue 4	Institute of Physics Publishing	United Kingdom	04/02/2015	045301	Yes	Peer reviewed
4	A multi-physics and multi-scale numerical approach to microcrackin g and power-loss in photovoltaic modules 10.1016/j.com pstruct.2012.08.014	Marco Paggi , Mauro Corrado , Maria Alejandra Rodriguez	Composite Structures	Vol. 95	Elsevier BV	Netherlands	01/01/2013	630-638	Yes	Peer reviewed
5	Model order reduction applied to heat co nduction in photovoltaic modules	S.O. Ojo , S. Grivet-T alo	Composite Structures	Vol. 119	Elsevier BV	Netherlands	01/01/2015	477-486	Yes	Peer reviewed

	10.1016/j.com pstruct.2014.09.008	cia , M. Paggi								
6	Image analysis of polycrystalline solar cells and modelling of intergranular and tran sgranular cracking 10.1016/j.jeu rceramsoc.2013.12.051	Andrea Infuso , Mauro Cor rado , Marco Paggi	Journal of the European Ceramic Society	Vol. 34/Is sue 11	Elsevier BV	Netherlands	01/09/2014	2713-2722	Yes	Peer revie wed
7	Numerical Modelling of Microcracking in PV Modules Induced by Thermo-mechan ical Loads 10.1016/j.egy pro.2013.07.310	Marco Paggi , Alberto Sap ora	Energy Procedia	Vol. 38	Elsevier BV	Netherlands	01/01/2013	506-515	Yes	Peer revie wed
8	A coupled cohesive zone model for transi ent analysis of thermoelastic interface debonding 10.1007/s0046 6-013-0934-8	Alberto Sa pora , Marco Paggi	Computational Mechanics	Vol. 53/Is sue 4	Springer Verlag	Germany	01/04/2014	845-857	Yes	Peer revie wed
9	A Generalized Electric Model for Mono an d Polycrystalli ne Silicon in the Presence of Cracks and Random Defects 10.1016/j.egy pro.2014.08.005	Irene Bera rdone , Mauro Corrado , M arco Paggi	Energy Procedia	Vol. 55	Elsevier BV	Netherlands	01/01/2014	22-29	Yes	Peer revie wed
10	Partial-slip frictional response of rough sur faces 10.1038/srep0 5178	Marco Paggi , Roman Pohrt , Valentin L. Popov	Scientific Reports	Vol. 4	Nature Publishing Gr oup	United Kingdom	05/06/2014	1-6	Yes	Peer revie wed
11	On the dependency of the parameters of f atigue crack growth from the fractal dim ension of rough crack profiles 10.1177/09544 06213515643	M. Paggi , O. Plekhov	Proceedings of the Institution of Mechan ical Engineers, Part C: Journal of Mecha nical Engineering Science	Vol. 228/I ssu e 12	SAGE Publications Lt d	United Kingdom	01/08/2014	2059-2067	Yes	Peer revie wed
12	An Accurate Thermoviscoel astic Rheo logical Model for Ethylene Vinyl Acetate Based on Fractional Calculus 10.1155/2015/ 252740	Marco Paggi , Alberto Sap ora	International Journal of Photoenergy	Vol. 2015	Hindawi Publishing C orporation	United States	01/01/2015	1-7	Yes	Peer revie wed
13	Nonlinear fracture dynamics of laminates with finite thickness adhesives 10.1016/j.mec hmat.2014.07.012	M. Corrado , M. Paggi	Mechanics of Materials	Vol. 80	Elsevier	Netherlands	01/01/2015	183-192	Yes	Peer revie wed
14	An anisotropic large displacement cohesive zone model for fibrillar and crazing inter faces 10.1016/j.ijs olstr.2015.04.042	M. Paggi , J. Reinoso	International Journal of Solids and Stru ctures	Vol. 69-70	Elsevier Limited	United Kingdom	01/06/2015	106-120	Yes	Peer revie wed

15	A consistent interface element formulation for geometrical and material nonlinearitie s 10.1007/s0046 6-014-1077-2	J. Reinoso , M. Paggi	Computational Mechanics	Vol. 54/Issue 6	Springer Verlag	Germany	01/12/2014	1569-1581	Yes	Peer revie wed
16	Diffusion phenomenon in the hyperbolic a nd parabolic regimes 10.1016/j.phy sleta.2013.07.009	A. Sapora , M. Codegone , G. Barbero	Physics Letters, Section A: General, Ato mic and Solid State Physics	Vol. 377/Issu e 37	Elsevier	Netherlands	01/11/2013	2416-2421	Yes	Peer revie wed
17	Adsorption–de sorption phenomena and diffusion of neutral particles in the hyperb olic regime 10.1088/1751- 8113/47/1/015002	A Sapora , M Codegone , G Barbero , L R Evangeli sta	Journal of Physics A: Mathematical and T heoretical	Vol. 47/Issue 1	Institute of Physics Publishing	United Kingdom	10/01/2014	015002	Yes	Peer revie wed
18	Evolution of the free volume between rou gh surfaces in contact 10.1016/j.wea r.2015.04.021	M. Paggi , Q.-C. He	Wear	Vol. 336-337	Elsevier BV	Netherlands	01/08/2015	86-95	Yes	Peer revie wed
19	Optimization algorithms for the solution of the frictionless normal contact between r ough surfaces 10.1016/j.ijs olstr.2015.06.005	A. Bemporad , M. Paggi	International Journal of Solids and Stru ctures	Vol. 69-70	Elsevier Limited	United Kingdom	01/06/2015	94-105	Yes	Peer revie wed
20	Computational Modeling of Discrete Mechanical Systems and Complex Netw orks: Where We are and Where We are Going 10.3389/fmats .2015.00018	Andrea Infuso , Marco Paggi	Frontiers in Materials	Vol. 2	Frontiers	Switzerland	09/03/2015	1-3	Yes	Peer revie wed
	Integrity and durability of photovoltaic modules:an overview of mechanical failure modes	M. Paggi	Acta Fracturae CONVEGNO IGF XXII ROMA 2013		Italian Group of Fra cture	Cassino, Italy	01/07/2013	16-22	Yes	Conference
	A coupled thermo-elect ro-mechanical model for fracture in solar cells	M. Paggi, I. Berardon e, M . Corrado	ECCM16 - 16 TH EUROPEAN CONFER ENCE ON COMPOSITE MATERIALS, S eville, Spain, 22-26 June 2014		University of Seville	Seville, Spain	22/06/2014		Yes	Conference
	Electrical recovery and fatigue degradation phenomena in cracked silicon cells	M. Paggi, I. Berardon e, A . Infuso, M. Corrado	Journal of Energy Challenges and Mechani cs, Proceedings of the 1st International Symposium on Energy Challenges and Mechanics		North Sea Conference & Journal	Aberdeen, United Kin gdom	08/07/2014	1-5	Yes	Conference
	Emergent properties in interface mechani cal problems	M. Paggi	XXI Congresso Associazione Italiana di M eccanica Teorica e Applicata		Edizioni Libreria Co rtina	Torino, Italy	17/09/2013	1-7	Yes	Conference

A2. Research fieldwork

List of fieldworks		
Period (start-end)	Place	Purpose

A3. Awards and recognitions

List of awards and recognitions					
Award type	Title of the award	Person to whom the award was made	Year	Short description of the reason the award was made (if applicable)	Any further information / clarification
Fellowship / membership of learned society	Nominated member of the Young Academy of Europe	Marco Paggi	2014		
Membership of editorial boards	Associate Editor of the Journal of Mechanical Engineering Science (Proc. IMechE Part C)	Marco Paggi	2014		Associate Editor for the Materials, Stress Analysis & Structures section of the journal
Membership of editorial boards	Member of the Editorial Board of The Journal of Strain Analysis for Engineering Design	Marco Paggi	2014		
Membership of editorial boards	Member of the Editorial Review Board of the journal Frontiers in Mechanics of Materials	Marco Paggi	2014		
Membership of editorial boards	Member of the Editorial Board of the American Journal of Engineering and Applied Sciences	Marco Paggi	2015		
Membership of editorial boards	Member of the Editorial Board of Scientific Reports, Nature Publishing Group	Marco Paggi	2015		Member of the Editorial Board for the category Chemical Physics

A4. Patents, licensing, intellectual property

List of patents, licensing, intellectual property

Type of IP Rights	Confidential	Foreseen embargo date dd/mm/yyyy	Application reference(s) (e.g. EP123456)	Subject or title of application	Applicant(s) (as on the application)

A5. Dissemination to non-academic audience

List of disseminations								
No.	Type of activities	Main Leader	Title	Date	Place	Type of audience	Size of audience	Countries addressed
1	Presentations	SCUOLA IMT (IST ITUZIONI, MERCATI, TECNOLOGIE) ALTI STUDI DI LUCCA	Research on photovol taics - Poster presented at the ERC Information Day http://erc.europa.eu/erc-information-day-citta-della-scienza	29/10/2013	Napoli, Italy	Scientific community (higher education, Research) - Civil society - Policy makers - Medias		Italy
2	Presentations	SCUOLA IMT (IST ITUZIONI, MERCATI, TECNOLOGIE) ALTI STUDI DI LUCCA	Research on Photovol taics - Stand at the at SHINE! Night of Researchers in Tuscany, an event promoted by Marie Curie Actions and Tuscany Region	27/09/2013	Lucca, Italy	Scientific community (higher education, Research) - Industry - Civil society - Policy makers - Medias		Italy
3	Other forms of dissemination	POLITECNICO DI TORINO	Rendimento pannelli fotovoltaici: Il progetto di studio al Politecnico di Torino http://www.zwickitaliablog.it/rendimento-pannelli-fotovoltaici-il-progetto-di-studio-al-politecnico-di-torino/	03/09/2013	Torino, Italy	Scientific community (higher education, Research) - Industry - Civil society		Italy
4	Presentations	SCUOLA IMT (IST ITUZIONI, MERCATI, TECNOLOGIE) ALTI STUDI DI LUCCA	EUROMECH Colloquium 575 "Contact Mechanics and Coupled Problems in Surface Phenomena", http://575.euromech.org/	30/03/2015	Lucca, Italy	Scientific community (higher education, Research) - Industry - Policy makers - Medias		Italy, Russia, USA, France, Germany, Switzerland, UK, Czech Republic, Denmark, Spain, Sweden
5	Other forms of dissemination	SCUOLA IMT (IST ITUZIONI, MERCATI,	Presentation of the project activities at a meeting	10/03/2014	Lucca, Italy	Scientific community (higher education,		Italy, EU

		TECNOLOGIE) ALTI STUDI DI LUCCA	with the Director of the Institute for Energy and Transport of the Joint Research Centre (Eur opean Commission)			Research) - Policy m akers		

A6. Other significant outputs / information

Information on other important outputs which have arisen - wholly or partly - from this project.

N/A

(Only for ERC projects selected from the 2012 and 2013 calls for proposals)

This grant agreement includes special clause 39, requiring you to make best efforts towards open access to publications resulting from this project. Should, despite your best efforts, not all publications be available in open access, please give reasons why this is the case.

All the publications have been made open access.

Attachments	endorsement_letters.pdf
Project No.:	306622
Project acronym:	CA2PVM
Project title:	Multi-field and multi-scale Computational Approach to design and durability of PhotoVoltaic Modules
Project starting date:	01/12/2012
Project duration:	60
Principal Investigator name:	Prof. Marco Paggi
Report submitted by:	SCUOLA IMT (ISTITUZIONI, MERCATI, TECNOLOGIE) ALTI STUDI DI LUCCA
Date:	20/07/2015