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Smart light collecting system for the efficiency enhancement of solar cells

Rendicontazione

Informazioni relative al progetto

EPHOCELL

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Final Report Summary - EPHOCELL (Smart light collecting system for the efficiency enhancement of solar cells)

Executive summary:

The EPHOCELL project addresses a novel concept for solar cell enhancement by combining solar energy modulation, combining both up-conversion (UC) and down-shifting (DS). The UC is a process that converts low energy light in higher energy light e.g. infrared to visible light conversion. In the opposite, DS process converts high energy light into low energy light, e.g. ultraviolet (UV) to visible conversion. While DS phenomena is certainly explored, the UC is an 'abnormal' process whose quantum efficiency is notably lower and their practical application in energy devices still remains a great challenge. The solar spectrum received at the Earth surface covers a wide range of wavelengths from 290 to 3 790 nm. In an ideal situation, the absorption spectrum of photovoltaic (PV) materials should perfectly match the entire solar spectrum in order to convert the maximum photons from solar radiation to electricity. However, there is a large mismatch between the solar emission spectrum and the absorption properties of the present PV materials, especially in the infrared region due to limited absorption spectrum of the solar cells. Indeed, the absorption band of the best PV materials can be found between 400 and 1 200 nm depending on the case. The luminescent solar concentrators developed within EPHOCELL permit the conversion of the whole UV light (290 - 400 nm) and a part of deep-red and near-infrared (NIR) light (700 - 860 nm) of solar spectrum to an appropriate radiation. This radiation is mainly in the absorption range for commercial PV modules (and those under development as organic solar cells). The general objective of the EPHOCELL project was to define and develop a robust easy-to-implement wavelength modulator device with new advanced UC and DS materials, to radically improve the efficiency of PV panels.

EPHOCELL project has been based on DS and UC processes, targeting a quantum yield (QY) conversion of least 85 and 12 %, respectively. During the project several strategies have been studied in order to obtain the highest QY for both processes. EPHOCELL compounds were characterised into different host media in terms of QY and stability. In terms of UC important advances were achieved: worldwide record of 13 % QY at moderate Suns equivalents (usually most studied rare earth doped inorganic phosphors need laser power excitation). NIR-to-visible systems were developed and dedicated molecules were designed in order to absorb a wide range of NIR spectral region. Different kinds of material have been used as host material: solvents, low molecular weight polymers, and polymeric gels. UC process in aqueous media has been developed for the first time and high stable systems have been found (overcoming strong accelerated ageing test). In terms of Down Shifting, maximum QY was close to the target, 76 % for large Stokes shift DS (LSS-DS) compounds. The LSS-DS let to obtain high transparent DS sample, suitable for PV application. Solvents, polymers and polymeric gels have been evaluated as DS media, which samples presents long term stability, which permit the study DS in PV cell in outdoor conditions. UC and DS converter devices have been developed independently in order to couple with solar cells. The several configurations have been planned with one or both converter devices. Due to the complexity of these systems, a ray trace model with Monte Carlo have been developed and experimentally validated, in order to discern possible configurations outperforming potential solar cell efficiency enhancement. A set of multiple configurations have been modelled including relative converter-PV positioning, coupling with different optical elements for light concentration in UC / DS processes. The design of the devices has also been supported with a thermal model using COMSOL. Precisely, 9 proof-of-principle devices have been finally selected, constructed and tested (i.e. 6 coupling DS systems and 3 coupling UC systems). Target PV cells for these proof-of-principle devices have been wafer-based crystalline silicon, a-Si and dye-sensitised solar cells. Initially, the enhancement of these proof-of-principle devices has been characterised by means of efficiency (I-V curves) cross-checked with spectral response (EQE). Down-shifter plus PV cell devices have evidenced efficiency enhancement ranging 3 - 10 % in face-to-face configuration, depending on down shifting compound and PV cell. Additionally, 'two-dye' luminescent solar concentrator configuration have shown performance enhancement ranging 45 % using EPHOCELL compounds. UC plus PV cell devices have been evidenced improvements of 0.2 % (semi-transparent a-Si) and 2 % (semi-transparent dye-sensitised solar cells (DSSCs)), with low concentrated light. In parallel, the predictions concerning the future 'ideal' UC systems for coupling with PVs have been modelled through inverse engineering approach. Most promising devices have also been evaluated under real outdoor conditions, presenting similar laboratory characterised performance, after several days of testing. On the other hand, the project has addressed a first insight in a possible cost-benefit estimation of EPHOCELL technology, with respect to other strategies under development for the efficiency enhancement of solar cells. Summarising, the EPHOCELL project evidenced significant step further for light modulation systems for PVs, showing that UC and DS have opportunities in PV technology applications. All the EPHOCELL developments are in line with targets set-up by the Strategic Research Agenda (SRA) of the European PV platform: multiple advances in molecular systems, device design and engineering, robustness evaluation, indoor / outdoor characterisation and first cost-benefit analysis.

Project context and objectives:

a) General objectives

The solar spectrum received at the Earth surface covers a wide range of wavelengths from 290 to 3790 nm. In an ideal situation, the absorption spectrum of PV materials should perfectly match the entire solar spectrum in order to convert the maximum photons from solar radiation to electricity. However, there is a large mismatch between the solar emission spectrum and the absorption properties of the present PV materials, especially in the infrared region. Indeed, the absorption band of the best PV materials can be found between 400 and 1 200 nm depending on the case.

Much of the solar energy available is not used because of the limited absorption spectrum of the solar cells. The luminescent solar concentrators within EPHOCELL will permit the conversion of the whole UV light (290 - 400 nm) and a part of deep-red and NIR light (700 - 860 nm) of solar spectrum to an appropriate radiation. This radiation is mainly in the visible range for commercial PV modules (silicon (Si), amorphous-Si (a-Si) and indium gallium phosphide (GaInP)) and those under development (organic solar cells). The general objective of the EPHOCELL project was to define and develop an easy-to-implement wavelength modulator device with new advanced materials to radically improve the efficiency of PV panels.

The project is based on two mechanisms to modulate the wavelength of the high and low energy non used photons of the solar spectrum:

(i) the DS that allows the absorption of a high-energy photon and the emission of a photon of lower energy; and
(ii) the UC that allows a convert photons with lower energy to higher energy photons.

EPHOCELL focuses on developing DS and UC solar concentrator. Target objective in conversion efficiency is 12 % from NIR to visible UC and 85 % from UV to visible DS. QY is understood as the ratio of number of photon converted vs. number of absorbed photons. The EPHOCELL project pursues robust and easy-to-implement solutions for these novel luminescent solar concentrators including UC molecular mixtures in combination with LSS-DS compounds in functional devices. Suitable solutions and design are under development, with the final goal of achieving a technology that could be transferred to an industrial scale and adapted to already commercial solar cells as well as emerging future technologies.

b) Description of the work performed since the beginning of the project

The main research and development (R&D) activities of EPHOCELL during the period of time from 1 February 2009 (month 1) to 31 January 2013 (month 48) have been focused on the following:

(i) design, synthesis and optimisation of molecular mixtures emitter / sensitiser giving rise to NIR to visible UC with high QY and photo-chemical stability;
(ii) design, synthesis and optimisation of LSS-DS capable of transform UV light onto visible with high QY and photo-chemical stability;
(iii) identification, preparation and optimisation of suitable hosts for EPHOCELL purposes: volatile and non-volatile solvents, polymers, oligomers, liquid oligomers, polymeric gels;
(iv) water-dispersed up-converting nanocapsules with aqueous antioxidants, towards proper and long-term sealing of UC devices;
(v) design, development and optimisation of processing methods and mechanical solutions suitable for taking UC systems out of the glove box and transferring into the technical world (development of functional UC devices);
(vi) establishment and validation of a ray trace modelling tool for rational design of different device configurations in order to couple photo-active devices and PV cells;
(vii) design, development and fabrication of solar cells with appropriate spectral response and transparency for EPHOCELL concept validation (spectral match of solar cells with available photoactive systems);
(viii) design, development and fabrication of different proof of principle including DS and / or UC device

with the developed solar cells (selected from the outputs of ray trace modelling);
(ix) indoor and outdoor PV characterisation of the selected proofs of principle;
(x) establishment and validation of the first thermal modelling tool for guiding final device configurations;
(xi) first approximation to a cost-benefit analysis for determining present and future viability of EPHOCELL concept for PV efficiency enhancement (benchmarking with selected technological alternatives under development outside the consortium).

c) Main results achieved so far:

This section explains the major findings achieved in EPHOCELL so far, which go beyond the state of the art.

(i) Design, synthesis and optimisation of molecular mixtures emitter / sensitiser giving rise to NIR to visible UC with high QY and robustness: Worldwide record of the TTA-UC process (determined in classical terms): 13 % (higher that the planned target, 12 %) from red to blue UC system. Two UC systems with long lifetime exposed to extreme conditions test and UC in aqueous media were developed.
(ii) Design, synthesis and optimisation of LSS-DS capable to transform UV light onto Vis with high QY and robustness: europium and terbium LSS-DS compound with high QY, approximately 76 %.
(iii) Identification, preparation and optimisation of suitable hosts for EPHOCELL purposes: solvents (volatile, non-volatile), low molecular weight polymer, polymers, polymeric gels.
(iv) Design, development and optimisation of processing methods and mechanical solutions suitable for taking UC systems out of the glove box and into the technical world. UC under sunlight in optimal mechanically closed container.
(v) Design and modelling different device configurations for coupling luminescent-active systems and PV cells. Inverse engineering results for ideal UC and DS systems. First ray trace model capable to design device with UC and DS for several photoactive molecules and PV components. Empirical validation of the model and useful for predictive device performance.
(vi) Design, development and fabrication of suitable solar cell for suitable adjustment with available UC system into EPHOCELL. Semi-transparent solar cell of a-Si and dye sensitised solar cell suitable for the best UC systems available.
(vii) Design, development and fabrication of different DEMOs including Down Shifter or Up Converter device with developed solar cells. At least 9 proof of principle with 3 DEMOs have been done. DS and UC characterised under outdoor conditions. Monitoring of proof of principle.
(viii) First thermal model of those proofs of principle. Modelling of thermal behaviour of UC device under concentrated light. Modelling of thermal behaviour of solar cell under concentrated light.
(ix) Report on the viability of EPHOCELL technology against other technologies applied in PV for efficiency enhancement approach. Benchmarking study between EPHOCELL technology and other current technologies with the same technological target: improvement of PV efficiency. First estimation of UC and DS cost.

Project results:

In the following paragraphs, more details of previous achievements are presented.

(1) Design, synthesis and optimisation of molecular mixtures emitter / sensitiser giving rise to NIR to Vis UC with high QY and robustness

Great efforts have been centred in this direction in order to reach the 'ideal' UC molecular system for a certain PV cell. As major requirement, the UC systems should absorb unused fraction of sunlight and blue-shift the reemission in a central wavelength, where the quantum efficiency of target solar cells present a maximum. Extensive work has been carried out by chemical tuning of sensitiser and emitter molecules, in order to maximise the overall conversion efficiency covering a broad and complementary spectral range. Significant advances have been found on novel molecular UC systems (chemical tuning), evaluation of conversion efficiency and stability as well as modelling for the understanding of the energy transfer mechanisms of UC and related experimental studies.

Reference systems at the beginning of the project were red-to-blue UC with QY in the range of 3 %, while project objective are systems with QY of 12 % with high blue-shift and high photo-chemical stability. The target of QY of 12 % in even exceeded in conjunction with relative small blue-shift, but QY still remains low for high-blue shift systems. Worldwide record value for the UC QY has been achieved. Good emitter molecules for the combination with tetraanthroporphyrin systems are needed. In all cases the value of QY correspond to per centage, for light intensity of 36 Suns equivalents (AM1.5) where QY values correspond to the up conversion of absorbed photons. EPHOCELL introduces a new concept in term of practicable UC devices: UC efficiency, which corresponds to the yield of up converter photons due to incident photon. In terms of robustness, different host media are studied for UC systems. UC model, Perylene / PdOEP, is used to select the best host in terms of QY and stability (presented in next paragraph). Toluene results the best option in terms of QY. UC model in non-volatile solvent presents higher stability than toluene in short term in presence of oxygen. Accelerated ageing test (Xenotest) under controlled atmosphere is used to evaluate the longtime stability of the different UC samples. Although UC is very sensitive organic systems, EPHOCELL finds two solvents where UC system is huge robust, one of them is standard toluene.

As UC QY depend, among other parameters, on molar concentration of emitter and sensitiser then fine tuning is done in order to maximise UC efficiency in UC devices. All the UC system has been characterised with an experimental setup, based on supercontinuous quasi-continuous-wave (CW) laser up to 2 W of power allows excitation of any Q-band needed without restriction. In addition, light intensities in order of 1 to 100 suns can be emulated.

(2) Design, synthesis and optimisation of LSS-DS capable of transform UV light onto Vis with high QY and robustness

Rare Earth compounds, of europium and terbium, for LSS-DS strategy are selected as down-shifters in EPHOCELL. The studied organolanthanide complexes are based on europium and terbium Rare Earth, which have evidenced QY up 76 and 72 % in solution, respectively. The europium compounds has been identified as suitable candidate with excitation spectrum well located 300 - 400 nm and emission centred at 610 nm. Meanwhile terbium based compound were identified as good candidate for emission centred at 550 nm with excitation spectrum located 300 - 375 nm. DS compound have been synthesised in gram scale in order to provide samples for luminescent device fabrication. DS compounds are studied in several different media: solvent, polymeric matrix, polymeric gels and ink / paste for printed techniques. Complete physical, chemical and photochemical characterisation has been done in all DS samples. Robust down shifting samples are obtained in solution, for long-time stability under controlled ambient conditions. DS molecules in solid polymeric samples are selected for DS-PV proof of principle. The DS films have enough stability in order to implement indoor and outdoor measurements for several weeks.

(3) Identification, preparation and optimisation of suitable hosts for EPHOCELL purposes

During this final period, the search of new suitable host for UC continued. The progress in that sense indicated that the performance and the stability of UC systems comprised of emitter and sensitiser molecules is critically dependent on the presence of the atmospheric dioxygen. Additionally, high local molecular mobility is needed in order to ensure efficient energy transfer. For this reason low Tg media as polymers, alternative non-volatile solvent, liquid oligomers and polymeric gels, are studied as UC hosts. Non-volatile solvents and low molecular weight polymers present UC QY lower than standard volatile case: toluene. This behaviour is repeatable observed for various non-volatile solvent or low molecular weight polymers (or oligomers). But, as main outcome, the short-term UC-efficiency stability is significantly increased regarding the stability in volatile organic solvents. The accelerated ageing test, selected for EPHOCELL samples, destroys the UC process in all low molecular weight protein (LMWP) samples, except in the case of UC model in toluene and particular eutectic mixture. In general, the non-volatile organic solvents and LMWP ensures increase UC-stability. Additional, the exchange of the volatile organic solvent (toluene) with LMWP (oligomers) or non-volatile organic solvents satisfies all requirements for efficient sealing. Polymeric gels are also studied as UC host. UC model Perylene / PdOEP present UC photoluminescence in developed polymeric gel. Non-volatile and volatile solvent based gels are developed. Also gelificated low molecular weight polymer is studied as UC host. Only toluene based gels accomplish optical requirements, with high transparency aspect. UC QY in the gel is lower than in toluene, but new applications can be possible in this type of innovative hosts.

An important step done onto UC system towards more realistic application is the demonstration of TTA - UC process in an aqueous environment with UC hydrophobic dyes system in micellar structures. UC standard system presents UC photoluminescence into micelles of non-ionic surfactants. The transfer of the hydrophobic UC-molecular system from an organic solvent to the aqueous environment, keeping the efficiency of the UC - process not changed, could solve the sealing problem for the UC devices completely. Additionally, solvent induced ageing of the sealing material will be drastically reduced. QY of red-to blue UC system in micelles is approximately 4.4 lower than toluene but with great possibilities from practical application side. In terms of QY and stability, toluene is the best candidate found in EPHOCELL to prepare the UC shifters for proof of principle.

In the case of LSS-DS compounds, solvents, polymers and polymer based gels are the host matrix studied by the consortium for make DS device. Blending technique is one of the routes to design DS device as DS films. Grafting technique strategy to link LSS-DS molecules to polymer host by synthesising ligands including grafting functional groups is also studied. In term of DS polymeric films, blending and grafting techniques are compared. The benchmarking done between both techniques, in terms of QY and stability, indicate that the two strategies are similar. DS QY depends on DS compound concentration in non-liquid host, decreasing in some cases in solid polymeric matrix. Then, in order to have non liquid host with higher QY, polymeric gels also are developed as DS molecules host. Full characterisation of all DS samples has been done, evaluating morphological and optical properties. Characterisation of stability of LSS-DS systems in polymeric films and gel matrix) is done. Long-time stable DS sample have been found, such as europium compound in solution under controlled atmosphere. Short term lifetime is available in the rest of DS samples. The selection of LSS-DS compound with its host media (solution, polymeric film, gel, paste) depends on the DS and PV configuration design. At first stage, QY and process of fabrication will be a priority. In the case of europium compound, higher QY is achieved when the RE complex is blended with a polymeric film. In the case of the terbium compound, polymeric films are relative easy to use as DS lenses, but much higher QY is measured in solution sample.

(4) Design, development and optimisation of processing methods and mechanical solutions suitable for taking UC systems out of the glove box and into the technical world

In order to fulfil proof-of-principle / demo activities with current UC systems, EPHOCELL selected to work under mechanical protection and liquid phase to prove the concept. UC liquid samples present better stability (demonstrated by accelerated ageing studies), technologically more feasible at present, maximum QY efficiency is retained. However, device engineering is needed for real devices. For this reason, EPHOCELL consortium selected to work with glass encapsulation for UC systems. UC systems are prepared into glove box, used as processing methodology. UC filled rectangular cross section glass tubes are selected for UC device. The encapsulation process is checked with laser, with concentrated solar simulator light and concentrated sunlight (see Figure 5). In the last case an optical setup is developed in order to concentrate the light of the solar simulator (also direct sunlight). Two low solar concentrator of ca. 10x and 21x suns equivalent is developed, with final spot of 2 mm.

(5) Design and modelling different device configurations for coupling luminescent-active systems and PV cells. Inverse Engineering results

From the final results on DS, terbium(III) and europium(III) rare Earth based complexes are promising candidates for LSS-DS. Maximum emission intensity is found at ca. 610 and 550 nm, for europium and terbium complexes, respectively. In the case of UC, metallated macrocycles sensitisers have band-like absorption spectrum, with two strong absorption bands, namely the Soret-band and the Q-band. Between those two absorption peaks, optical absorbance is relatively low are significantly less absorber. This phenomenon is called 'transparency window'. The spectral width of the transparency window is determined by the range of wavelengths where the absorbance of the sensitiser drops to the value of 10 % of the local absorption maxima. The UC and DS couple systems are selected in order to fit each other with the emission in the same central wavelength inside the transparency window. Ray Trace model is very useful tool established and validated by the consortium. To the best of our knowledge, this is the first time that ray trace modelling is developed for UC and DS photoluminescent layers. The consortium uses it to design different devices coupling DS and UC layers incorporating selected DS and UC couples. Different devices are design and modelling with ray trace model, with one or two of shifters: with DS (DS_PV), with UC (UC_PV) and with both DS and UC (UC_DS_PV) devices.

Ray trace modelling takes into account:

- UC system optical properties: absorbance and emission spectra, Sun equivalents dependence for UC

QY, optimal emitter and sensitiser concentration dependence for UC QY.
- UC container: transmission, refractive index, internal thickness.
- DS shifter: absorbance and emission spectra, DS molecules concentration, thickness.
- Solar cells: semi-transparent, opaque PV cells (crystalline Si (c-Si), a-Si and DSSC), and their external quantum efficiency (EQE) characteristics.
- Photon management: compatibilities between UC and DS spectral ranges with spectral response of solar cell, relative position of the UC / DS shifter and PV (face to face, face to edge, beam splitting) for modelling the UC_PV devices (> 10), DS_PV devices (> 5) and UC_DS_PV devices. The most promising configurations, demonstrating maximum predicted Jsc enhancement, indicate that a semi-transparent solar cell type with EQE lying within the UC transparency window is most suitable for integration of the EPHOCELL UC systems. In the case of DS, no penalisation occurs between DS shifters and selected PV types. The model predicts up to 3 and 1 % of Jsc enhancement in DS_PV and UC_PV device, respectively.

Is possible to attain larger enhancement in PV cell Jsc from UC and DS layers? The EPHOCELL project also answers this question: YES. The empirically validated ray trace model has been used to make estimation on Jsc enhancement using, up to now, undeveloped new ideal UC systems (in an 'inverse engineering' study). The model takes as hypothesis an ideal UC system, with no Soret band absorption and a Q-band with absorption at wavelength between 700 to 1 100 nm, for semitransparent a-Si:H solar cell developed in EPHOCELL. In that case, several parameter are variable: UC QY, the dependence of UC QY on incident light intensity , solar cell transparency at NIR wavelengths, sensitiser absorption within the UC transparency window and sensitiser Qband absorption range (from 700nm onset to a defined upper limit). The results of these studies indicate that: It can be an enhancement in Jsc up to 9 % is predicted if the a-Si cell were 90 % transparent at Qband wavelengths, Qband range can be extended to 1 100nm and UC QY is maintained at > 10 %.

(6) Design, development and fabrication of suitable solar cell for suitable adjustment with available UC system into EPHOCELL

From results on DS and UC spectral coupling, specially due to the presence of Soret band UC sensitiser the consortium have developed new solar cells for EPHOCELL purposes. Soret band wavelength ranges of UC sensitisers and solar cell absorbance spectrum have an overlapping, which shows that the available UC into EPHOCELL penalise the commercial solar cell performance. For this reason the consortium develop new solar cell, which suitable absorbance and external quantum efficiency, accomplish the following requirement: the EQE into UC transparency window. Two semitransparent a.Si:H and DSSC solar cells, with low absorption in Q band sensitiser, with suitable EQE for some of the UC systems are developed. New a-Si solar cell can couple with NIR to yellow UC system meanwhile the new DSSC can couple with most of the 'red to blue' UC systems. For a-Si:H solar cell, a development of new transparent conductive oxide have been done. In the case of the new DSSC, several dyes have been studied for optimal spectral response. Both types of solar cell are fabricated and characterised (JV and EQE measurements). Also these solar cells are fabricated directly onto UC device in order to optimise photon coupling.

(7) Design, development and fabrication of different proof of principle including DS or UC device with

developed solar cells

Previous paragraph shows that the progress in UC is very high; and suitable solar cells are developed for achieved a proof of concept, based on spectral coupling and ray trace modelling recommendations. 'From simple to complicated' strategy is used for fabrication of different proofs of principle. UC_PV_1 configuration is first selected. A simple but careful protocol of UC_PV fabrication are developed.

As Figure 6 indicates, a coordinate protocol between the partners (MPIP, DIT, LEITAT, UPC) was implemented. The shown UC_PV devices correspond to a-Si:H solar cell with 'near-red-to-yellow' UC systems, with three solar cell deposited onto the same UC container. High transparent electrode and optimal layer thickness make this solar cell higher transparent than commercial a-Si:H solar cells. UC_PV with DSSC is filled with 'red to blue' UC system. The performance of these proofs of principle devices are studied under simulated indoor conditions, acquiring JV and EQE measurements, before and after UC solution is filled into the UC container. The enhancement in Jsc is correlated with spectral response of UC_PV device, where the EQE with UC must show an increment in generated photons in the Q band wavelength range.

Analogously for DS_PV proof of principle, a protocol is developed in order to evaluate high quality device with enhanced efficiency. DS polymeric films (fabricated by DLAB) are used in different DS_PV devices. In these proofs of principle, opaque commercial and fabricated c-Si cells and opaque DSSC are used.

The final characterisation, of the designed and fabricated proofs of principle, indicates:

- DS_PV_1 with europium compound doped polymeric film in face to-face configuration onto opaque DSSC produce an enhancement of 3 % in Jsc
- DS_PV_2 with europium compound doped polymeric slab in face to edge configuration with opaque DSSC produce and enhancement of 250 % in Jsc
- DS_PV_3 with Lumogen Red frame spacer (new DSSC architecture) does not present significant enhancement. Further optimisation must been done
- UC_PV_1 with semitransparent a-Si:H solar cell with IR to yellow UC system with a-Si:H solar cell, presents an enhancement in EQE measurements due to UC (Rubrene / TAP ensemble). EQE with UC is non-null for Q band sensitiser wavelengths, when no signal is present without UC. Considering the EQE of the device and the reference solar spectrum (AM1.5) this improvement can be quantified around a 0.2 % increase in the Jsc value
- UC_PV_1 with semi-transparent DSSC with red to blue UC (mixed sensitisers). The EQE evidenced an increase when the solution was pumped laterally by an intense bias light. The increase in the Jsc value can be estimated around a 2.7 %. Anyhow, notice that illuminating through the vitrotube implicitly penalise the performance of the solar cell due to the Soret band absorption of the solution.

(7) Design, development and fabrication of different DEMOs including DS or UC device with developed solar cells

Most of the proofs of principle are also evaluated and working in outdoor conditions for certain periods of time (day scale). Only DS_PV devices showing positive results under simulated indoor conditions are considered for DEMO activities (due to the project timeline). For quantitative measurements, a platform composed by two sets of equipment, is used. The first is for measurements of the ambient outdoor solar irradiance data, and the second one is for measurement of the solar cell device performance characteristics. The global radiation on the horizontal surface (Gh) is measured using pyranometers, and spectroradiometer is used to record the solar spectrum from 337 to 1 100 nm. The second set of core components are used to measure power, current and voltage output, from the solar device. This permitted to measure different solar cell devices, facilitates a large number of I-V measurements to be taken on up to 16 test devices (using 4-wire tests) within a relatively short timeframe. The performance of proofs of principle is in correlation with the solar cell used and the stability of DS shifter in each DS_PV proof of principle. As an example, first results indicate that europium doped polymeric film and UV blocking layer maintain similar performance in DSSC under outdoor conditions.

(8) First thermal model of those proofs of principle

The thermal model was developed to study the thermal behaviour of UC_PV device, because UC needs concentrated light and this can increase the temperature of the solar cell. For empirical validation of this model, two devices were used: UC container filled with toluene and UC container filled with UC system in solution. UC container with under 20 suns equivalent concentrated light, presented an increment in temperature of 11 degrees of Celsius. Meanwhile UC container with UC system in solution, showed an increment of 9 degrees of Celsius in the illuminated face. The increment in temperature corresponded to exposed UC container face, directly under concentrated light, with and without light Then, lower temperature was achieved (2 degrees of Celsius lower) with UC system. Well match between measured and predicted temperature difference was achieved with the thermal model. Then, the thermal model is used to predict the thermal behaviour of UC_PV system. The model predicts low temperature increment in UC_PV system (semi-transparent DSSC with red to blue UC system) respect to the same system with plane toluene filled UC container. Although, more improvements in the thermal model are needed, (for example, including variation in PV cell performance due to temperature and concentrated light) a first output indicates that UC system reduces the increment of temperature for UC_CPV systems.

(9) Report on the viability of EPHOCELL technology against other technologies applied in PV for efficiency enhancement approach

Previous paragraph show that spectral converter can be used in PV technologies and more research should be done. But is EPHOCELL technology economically viable? A report with an inverse cost-benefit analysis of EPHOCELL technology in order to determine 'What do the costs need to be for EPHOCELL to be viable in the market' is done. The study makes the comparison between the cost-benefit (EUR / Wp) ratio of EPHOCELL with the current modules market price (EUR / Wp) making a benchmarking of EPHOCELL against other technologies that share the goal of increasing the electric generation. The study takes into account the same PV technologies used in EPHOCELL devices: c-Si, a-Si:H and DSSC. As no real cost are currently available then a reasonable hypothesis is done: the increment on the cost is proportional to the enhancement in the efficiency. The results of the study indicate that in order to have a viable product in all the market segments, its price must be the lowest price calculated within these three PV technologies. In this way, it is the a-Si:H semi-transparent technology that defines the current prices for UC and DS systems as the following ones: Cost UC = 0.096 EUR / Wp and Cost DS = 0.011 EUR / Wp.

The last value can increase up to 0.023 EUR / Wp if we only consider the case of the c-Si modules, which currently represent 90 % of the market. EPHOCELL project is the first European project that works on both UC and DS in PV field. These technologies are considered as novel technology by the European PV platform. In its last SRA, it is stated ( ) 'that a novel technology relates to the maturity of different approaches. It is used here for developments and ideas that can lead to potentially disruptive technologies, but where there is not yet clarity on practically achievements conversion efficiencies or future costs'. At the end of the project, EPHOCELL consortium demonstrates that UC and DS systems should remain under research to confirm their viability, technical and economical, in PV field. The proofs of principle with DS show a variety of application in c-Si and DSSC technologies. Ray Trace model, empirical validated, also predict an enhancement with UC with continued development of UC spectral properties. Taking into account the roadmap of SRA, the EPHOCELL project has achieved several objectives during the execution period. Finally, EPHOCELL consortium suggests increasing research effort on:

- Finding UC system with maximum absorption beyond IR and lower (or no) absorption in visible region (to achieve power conversion efficiency enhancement in commercial PV types).
- More studies should be done in order to have high stable UC and DS system during, at least, the PV cell lifetime.
- The DS and UC system synthesis must be scalable in order to achieve low cost production.

Potential impact:

- The EPHOCELL project contributes to realise the expected impact by focusing on the development of highly innovative materials that will increase the efficiency of PV devices. The efficiency enhancement of these devices is presently limited by the intrinsic conversion yield of the material and the small portion of the solar spectrum that the current technologies are able to exploit. The new methods and materials developed for the UC and DS systems (in different devices) demonstrate to substantially increase the efficiency of the PV cells in different configuration. The proposed solution goes well beyond the state-of-the-art with notable innovations in materials and sustainable energy as well as an industrial solution of a medium / long term nature.
- First ray trace model for design UC and DS in PV technologies. The ray trace model studies show not also the viability of design and developed such type of devices but also give a response to the future research activities about the possible enhancement onto PV cell due to UC systems.
- The values of UC QY are even exceeding the target of 12 % in EPHOCELL DOW. Worldwide record in UC QY is achieved, with high red-blue shift under low solar concentration (less than 100 suns, typically in inorganic rare earth up conversion systems).
- All these achievements are close to SRA of European PV platform, which considerer UC and DS as novel technologies in the PV field. Latest SRA document proposes several requirements for these technologies and EPHOCELL is close to them.
- Polymeric sheet with UC and DS molecules: EPHOCELL shows that DS molecules can be introduce in polymeric matrix, but UC molecules need some freedom of movement.
- Increment in efficiency between 10 - 20 %, EPHOCELL show an enhancement of Jsc up to 3 % in existing DSSC PV with the developed DS layers and 2.7 % in UC_PV with red to blue UC systems. It is also shown that Jsc can be increased by up to 9 % from UC if the solar cell is 90 % transparent in Q band absorption range.

- Incident light at 1 sun or low concentration. EPHOCELL shows low solar concentrator. Also ray trace model, empirically validated, show that enhancement of Jsc can be achieved at 1 sun incidence for ideal UC systems.
- UC and DS cost < 0.05 EUR / Wp. No cost of UC and DS are currently available, but EPHOCELL technology can be viable if the cost of Cost UC = 0.096 EUR / Wp and Cost DS = 0.011 EUR / Wp in the case of a-Si. UC plus DS plus PV cost < 0.3 EUR / W when both converters are take into account.
- Lifetime > 10 years. Stability test done in EPHOCELL, show high stability in DS and UC system if they are well sealed against oxygen presence.
- Suitability: All PV technologies EPHOCELL results in DS can be applied onto several PV systems: c-Si, DSSC, a-Si, OPV. Limitation exists in UC application, which up to now can be fit with semi-transparent solar cells which EQE are in the transparency window of the selected UC system.

In addition to the huge progress beyond the state of art achieved, new developments have also been accomplished due to EPHOCELL progress:

- UC in water environment,
- DS as UV blocking layer for organic PV as DSSCs,
- UC and DS in polymeric gels,
- ray trace model: photon management with UC and DS for PV technologies, for design and predictions,
- first cost-benefit study for UC and DS technologies in PV field.

Owing to previous successes, EPHOCELL can significantly contribute to the Lisbon strategy goals by increasing the efficiency of solar panels, the possibilities of European energetic production based on renewable energies and enlarging the PV market together with its associated labour force.

EPHOCELL has achieved to develop four prototypes that will concentrate the focus for exploitation of results:

- PV cells with UC with applications not only in photonics for processing of infrared light to visible but also in security (detection of fake currency, banknote, passport etc.), biology (for oxygenic photosynthesis via photon UC) and ongoing research (such as plasmonic solar cells).
- Thin polymeric layer with DS fixed over a solar cell with a foreseen enhancement of the energy output > 4 %. It is expected to exploit this new technology in different markets such as security sector.
- Luminescent solar concentrator configuration on DS, it is an alternative approach to lower the costs of PV.
- Photoluminescent inks with DS, that could be commercialise in the growing market of printed electronic, especially for organic light-emitting diode (OLED) displays, e-paper materials, conductive colours and PV.

It is expected a stable positive trend in income evolution during projected years (2016 to 2020) with aggregated revenues of nearly EUR 3.05 million in 2020.

As of 31 January 2013, the dissemination activities conducted are:

- 9 published journal papers and 3 further papers submitted,

- 7 published proceedings papers and 1 published extended abstract and 4 proceedings paper accepted,
- 21 conferences / workshops attended, at which 32 presentations were given (11 oral, 21 poster presentations). 2 further conference presentations accepted for 2013,
- 3 invited lectures given,
- 1 published book article and 1 published magazine article,
- 1 workshop hosted and organised by LEITAT Technologies, Terrassa, Spain, 2012,
- 1 EPHOCELL information brochure leaflet,
- 7 - 9 planned journal publications,
- 1 preliminary patent application (see D7.3 'Exploitation plan').

The detail of all dissemination activities can be consulted in EPHOCELL website (see http://www.leitat.org/EPHOCELL/ online).

The main conferences / workshops attended have been:

- International Renewable Energy Conference and Exhibition (Eilat, Israel) 16 - 15 February 2010,
- Hybrid and Organic PVs 2010 (Assisi, Italy) the 23 - 27 May 2010,
- 25th European PV Solar Energy Conference and Exhibition (Valencia, Spain) the 6 - 9 September 2010,
- Workshop on PVs and Nanotechnology: from innovation to industry (Aix-les-Bains, France) the 29 September - 1 October 2010,
- Hybrid and Organic PVs 2011 (Capri, Italy) 29 May - 1 June 2011,
- International Exhibition and Conferences on Nanotechnologies and Organic Electronic - Nanotex 2011 (Thessaloni-ki, Greece) 9 - 16 July 2011,
- III International Symposium Topical Problems of Biophotonics 2011 (St. Petersburg, Russia) 16 - 22 July 2011,
- International Discussion Meeting on Polymer Crystallisation (Beijing, China) 1 - 5 August 2011,
- 26th European PV Solar Energy Conference and Exhibition (Hamburg, Germany) 5 - 9 September 2011,
- X Brazilian MRS Meeting 2011 (Gramado, Brazil), 25 - 29 September 2011,
- 8th PV Science Application and Technology (PVSAT-8) Conference and Exhibition (Newcastle upon Tyne, UK), 2 - 4 April 2012,
- Materials Research Spring Meeting (San Francisco, USA), 09th-13th April 2012,
- Hybrid and Organic PV (HOPV) congress 2012 (Uppsala, Sweden), 6 - 9 May 2012,
- LOPE_C 5th international Conference and Exhibition for the Organic and Printed Electronics Industry (Munich, Germany), 11 - 13 June 2012,
- 6th International Conference on Times of Polymers (TOP) and Composites (Ischia, Italy), 10 - 14 June 2012,
- 40th Annual NATAS Conference (Orlando, USA), 12 - 15 August 2012,
- SPIE, Optics and Photonics (San Diego, USA), 25 - 29 August 2012,
- 27th European PV Solar Energy Conference and Exhibition (Frankfurt, Germany), 24 - 28 September 2012,
- Thin Film and 3rd Generation PV: New Processes and technologies for advanced cost efficient devices (I) (Barcelona, Spain), 14 December 2012.

Furthermore, a final Workshop 'Luminescent Solar Concentrator Workshop' was organised by the

Coordinator and was held in LEITAT 's headquarters in Terrassa (Spain) together with the 3rd Generation PV cells Cluster meeting on 2 - 3 October 2012.

List of websites: http://www.leitat.org/ephocell/

Documenti correlati

Final Report - EPHOCELL (Smart light collecting system for the efficiency enhancement of solar cells)

Ultimo aggiornamento: 1 Settembre 2013

Permalink: https://cordis.europa.eu/project/id/227127/reporting/it