Electrical Characterization of CIGSSe Photovoltaic Modules

M. Caruso*, R. Miceli*, S. Guarino*, F. Ricco Galluzzo**, M. Roscia*** and F. Viola*
*Dipartimento di Energia, ingegneria dell'Informazione, e modelli Matematici
Università degli Studi di Palermo
Viale delle Scienze, Ed. 9, Palermo, Italy
**Istituto per la Microelettronica e Microsistemi - Consiglio Nazionale delle Ricerche, Zona Industriale, Ottava Strada n. 5, 95121 Catania, Italy; Dipartimento di Fisica e Astronomia, Università di Catania, Via S. Sofia, 64, 95123 Catania, Italy
***Dipartimento di Ingegneria e scienze applicate
Università degli studi di Bergamo
via Pasubio 7b, 24044 Dalmine (BG), Italy

***Abstract*—This work describes the electrical characterization of CIG(S,Se)$_2$ sub-modules in order to compare the related performances with those obtained from traditional silicon photovoltaic modules. This characterization has been performed through means of a test bench, mainly composed by a solar simulator equipment, allowing the determination of the parameters of the prototypes under test at different irradiances and temperatures.**

***Index Terms*-- CIGSSe modules, PV devices, electrical characterization Introduction**

I. Introduction

Nowadays, a massive use of renewable energy resources, especially for the solar energy, could be a favorable option towards a sustainable development of the human community. An important class of thin film solar cells consists of the CuInGa(S,Se)$_2$ (CIGSSe) type, composed by Copper, Indium, Gallium, Sulfur and Selenide [1-8]. This low-power PV technology could be a significant alternative towards the traditional silicon photovoltaic modules, obtaining performances almost comparable to each other [9-18]. Indeed, because of their relatively good electro-optical properties, the thin film integrated PV have achieved adequate efficiencies. Furthermore, this technology is cost-effective if compared to solar cells based on bulk absorbers. In this context, the aim of this work is to present the experimental electrical characterization of CIG(S,Se)$_2$ sub-modules in order to compare the related performances with those obtained from traditional silicon photovoltaic modules. This characterization has been performed through means of a test bench, mainly composed by a solar simulator equipment, allowing the determination of the parameters of the prototypes under test at different irradiances and temperatures. The procedures applied in the present article are the result of previous applications [19-30]. This work is composed by the following Sections: Section II describes the test bench set-up for the PV modules characterization, Sections III reports the experimental

tests obtained for different values of irradiance, whereas the measurements at different values of temperature are discussed in Section IV.

II. Test Bench Description

In order to electrically characterize the PV modules at different values of both irradiance and temperature, an experimental test bench has been set-up at the DEIM Department and its schematic representation is shown in fig. 1. The test bench is mainly composed by:

- An Oriel Solar Simulator (Class AAA), equipped with an inner 450 W arc lamp, which allows to light in a uniform and stable manner a 2''x 2'' square area with a spectrum that simulates the solar spectrum.
- A 2440 Source-meter (Keithley Instruments), which allows to measure the voltage applied to the test samples and the related current.
- A GPIB-USB data acquisition board (National Instruments), for the acquisition of the main electrical quantities involved during the tests.
- A PC integrated with the source-meter and equipped with the Oriel IV Test Station, for the real-time control and supervision of the tests.
- A reference crystalline silicon PV cell, used for the irradiance regulation.
- A Reference cell meter, which is connected to the reference cell, in order to detect both the irradiance and the temperature of the reference cell.
- A temperature detection system, which is used for the real-time temperature measurement of both the environment and the module under test. This system is composed by a Data Logger (Delta OHM Inc., model DO 9847), equipped with two temperature probes with Pt100 sensors.
- An adequate cooling system, which is used to locally cool down the samples under test.

- A silicone-coated heating mat, equipped with a DC power supply (Kenwood Inc.), which is used for the electrical characterization of the samples at different values of their temperature.
- A Nortech Reflex fiber optic thermometer, which is equipped with two fiber optic temperature probes.
- Ten CIG(s,se)$_2$ PV modules samples, whose main characteristics are reported in Table I.

TABLE I
CHARACTERISTICS OF THE PV SAMPLES

Overall dimensions [cmxcm]	5.5 x 5.5
Rated current [mA]	80

A photograph of the proposed test bench is shown in fig. 2, whereas fig. 3 shows an image of the samples under test.

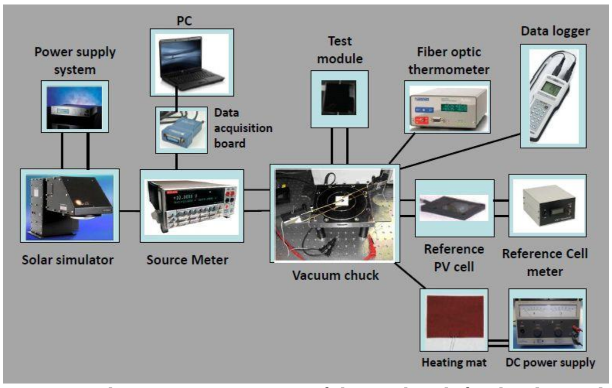

Fig. 1- Schematic representation of the test bench for the electrical characterization of PV cells.

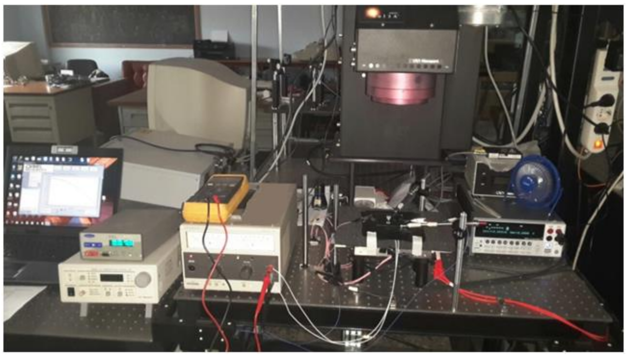

Fig. 2- A photograph of the proposed test bench.

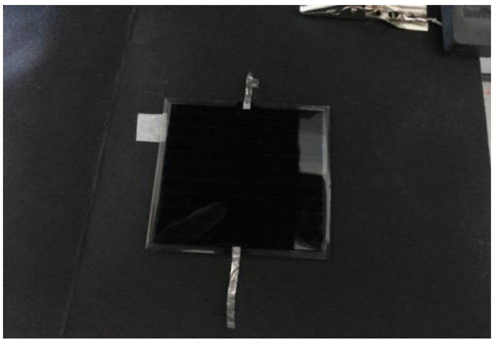

Fig. 3- A photograph of one of the ten CIG(S,Se)$_2$ PV modules samples under test.

III. EXPERIMENTAL TESTS FOR DIFFERENT VALUES OF IRRADIANCE

For the electrical characterization of the proposed samples for different values of applied irradiance, the PV modules under test have been placed on a vacuum chuck platform and their terminals have been electrically connected to the Source Meter 2440. This fact has allowed to detect the *I-V* characteristic of the samples under each of the following irradiance conditions (exposure time - i.e. the time interval in which the samples have been exposed to the Solar Simulator at fixed temperature - 13 s, measuring 100 points of each *I-V* characteristic): 1 SUN, 0.8 SUN, 0.6 SUN, 0.4 SUN, 0.2 SUN, 0.1 SUN and dark condition. In addition, during the previously mentioned tests, the trends as function of the irradiance of the main electrical parameters as efficiency and generated power have been determined. Thus, for each of the ten samples under test, the following electrical parameters have been determined:

- V_{OC} [V], open-circuit voltage;
- I_{SC} [A], short-circuit current;
- $P_{max}= V_m I_m$ [mW], maximum generated power (where V_m and I_m are the voltage and current corresponding to the point of maximum power);
- $ff = V_m I_m / V_{OC} I_{SC}$ [%], fill factor;
- R_V_{OC} [Ω], series resistance;
- R_I_{SC} [Ω], shunt resistance;
- $\eta = P_{max}/P_s$ [%], efficiency (where P_{max} is the maximum electric output power of PV device and P_s is the incident solar power).

For instance, fig. 4 shows the *I-V* characteristics of all the ten samples under test at 1 SUN. It is possible to notice that, even though the modules are referred to the same sample lot, the values of V_{OC} and I_{SC} and the trend gradients are relatively different from each other.

By applying the same procedure above described, the

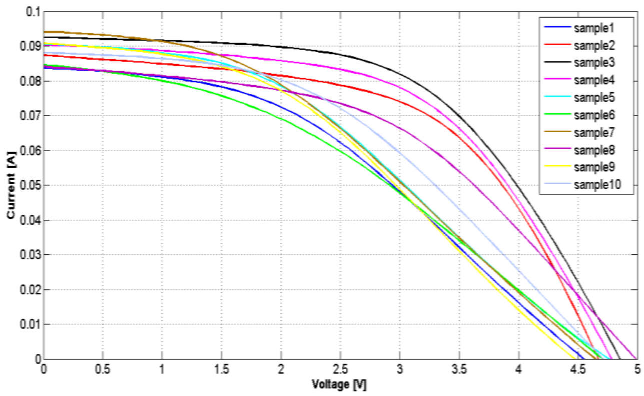

Fig. 4 – *I-V* characteristics of the samples under test at 1 SUN.

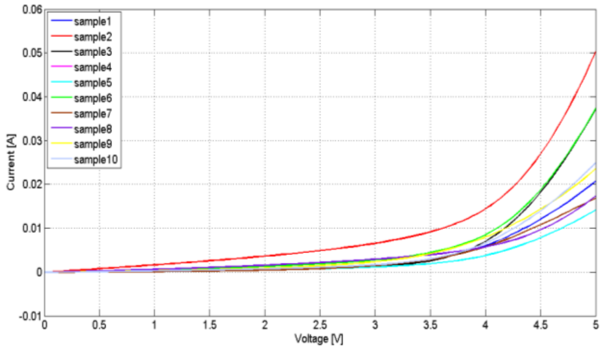

Fig. 5 – *I-V* characteristics of the samples under test in dark condition.

I-V characteristics for all the imposed irradiance conditions have been determined and, as example, fig. 5 shows the *I-V* characteristics in dark condition.

Other interesting results can be observed in figures 6 and 7, where the *I-V* characteristics of samples nr. 3 and 4 are plotted and parametrized as function of the irradiance. From these graphs it appears evident that the values of the series resistance are relatively high for each sample under test.

Other experimental results are plotted in the graph of fig. 8, which shows the I_{sc} vs irradiance trend for the ten proposed test samples. It can be observed that I_{sc} increases almost linearly for increased valued of the applied irradiance. This is due to the increasing photoelectric effect, which is proportional to the irradiance.

Moreover, fig. 9 shows the V_{oc} vs irradiance trend for all the ten proposed test samples. V_{oc} increases for increased values of the irradiance, even though the dependence is not linear.

The overall efficiencies as function of the irradiance for samples 3 and 4 are reported in the same graph of fig. 10. It can be noticed that, in the range between 0.4 and 1 SUN, the efficiency maintains almost a constant value equal to 8.5% and 8%, respectively.

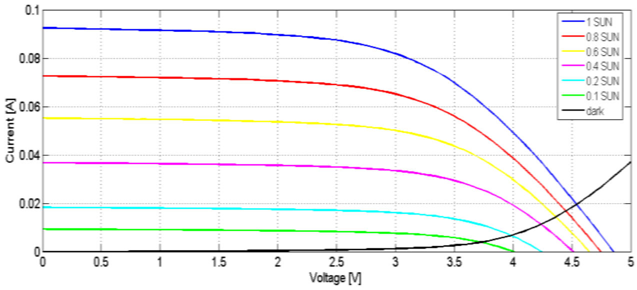

Fig. 6 – *I-V* characteristics of sample nr. 3, parametrized for different values of irradiance.

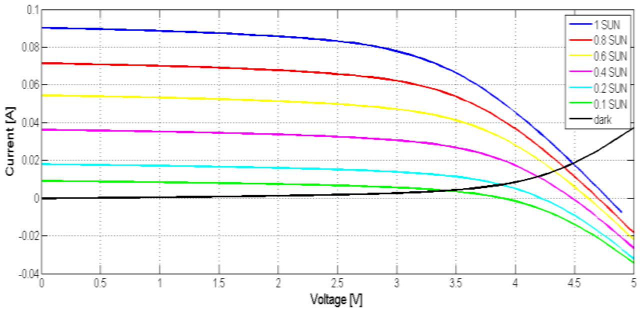

Fig. 7 – *I-V* characteristics of sample nr. 4, parametrized for different values of irradiance.

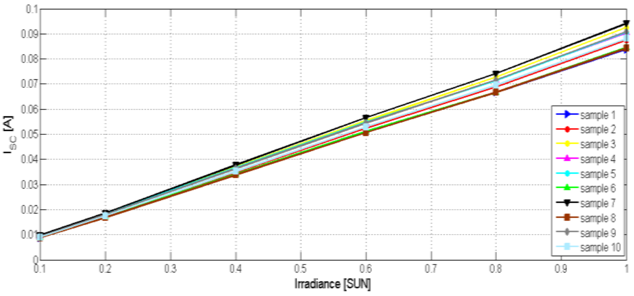

Fig. 8 - I_{sc} vs irradiance trends for all the ten samples under test.

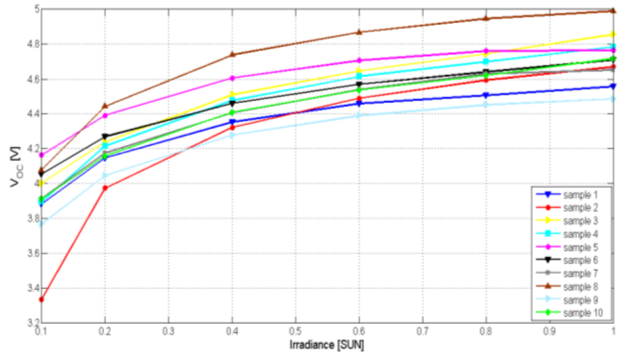

Fig. 9 - V_{oc} vs irradiance trends for all the ten samples under test.

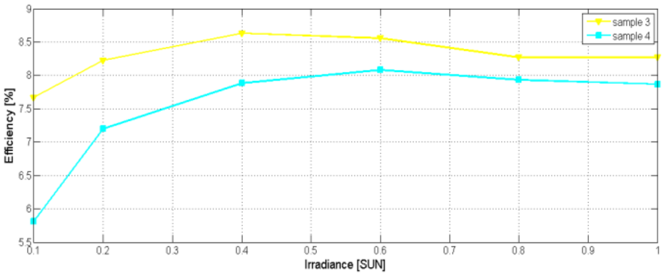

Fig. 10 - Overall efficiencies as function of the irradiance for samples 3 and 4.

IV. Experimental Tests for Different Values of the Samples Temperature

The samples under test have been electrically characterized also for different values of their temperature by using the same test bench described in section 1. More in particular, the samples have been tested under the following working conditions:

- Temperature range of the samples: 25° C- 70° C with steps of 5°C;
- constant value of the applied irradiance, equal at 1 SUN (1000 W/m^2)
- solar spectrum equal to AM 1,5 G
- exposure time: 11 s for the measurement of 50 points of each *I-V* characteristic.

The irradiance has been regulated under the previously mentioned value by using the reference silicon cell. Furthermore, the temperature of each sample has been controlled by finely regulating the voltage applied to the heating mat. It has been experimentally observed that, during the exposure time, the temperature of the samples was increased of 1°C.

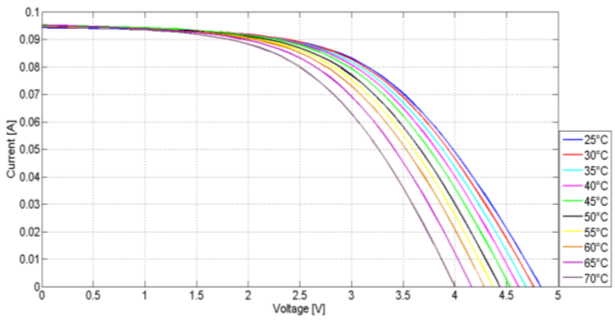

Fig. 11 - Electrical current – voltage (V-I) characteristics, related to the sample n. 3 for different values of its temperature.

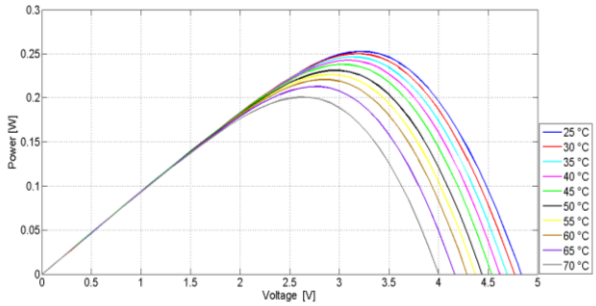

Fig. 12 - *P-V* characteristics, related to the sample n. 3 for different values of the temperature.

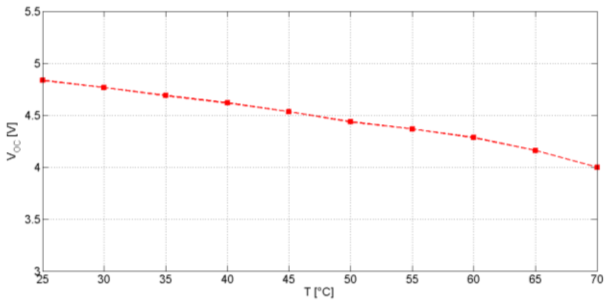

Fig. 13 – V_{OC} of sample n. 3, as function of its temperature.

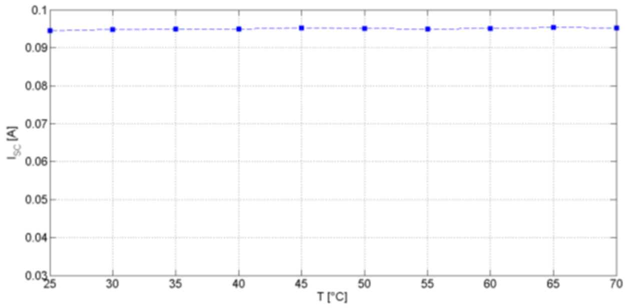

Fig. 14– I_{sc} of sample n. 3 as function of its temperature.

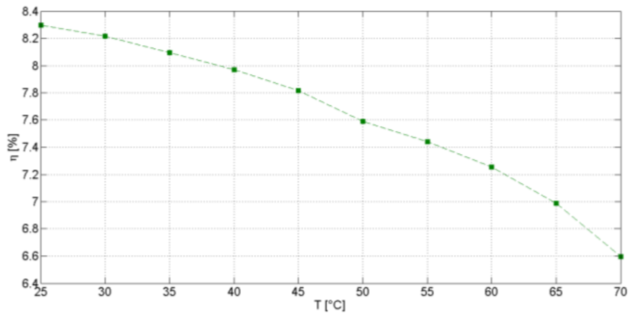

Fig. 15– Global efficiency of sample n. 3 as function of its temperature.

Based on these assumptions, the I-V characteristics of the ten samples have been detected and the main electrical parameters reported in section 2 have been determined and parameterized for the imposed temperature range. As example, figure 11 shows the I-V characteristic of sample nr.3, parameterized for the imposed values of the surface temperature. It can be noticed that, for increased values of the temperature, a relevant decrease of V_{oc} is detected, while I_{sc} maintains almost a constant value. The power/voltage characteristic, parameterized as function of the temperature, is plotted in fig. 12. From this graph it can be observed that, for increased values of the temperature, a significant reduction of the generated power is detected.

The trends over temperature of V_{oc}, I_{sc} and η are reported in figs. 13, 14 and 15, respectively. From their analysis, it can be stated that increased values of the temperature determine a decay on its performances. As a matter of fact, I_{sc} maintains almost a constant value when the sample temperature is increased, while V_{oc} decreases with an almost linear trend. Therefore, the global efficiency decreases for increased values of temperature, as shown in fig. 15.

V. Conclusions

In this work, the electrical characterization of CIGSSe modules has been described and discussed. An adequate test bench has been set-up and the experimental results have shown that the CIGSSe technology could be promising, but it has still to be improved.

ACKNOWLEDGMENT

The Authors wish to thank all the LOOX and the SDESLab staff.

REFERENCES

[1] U. Gangopadhyay, S. Jana, and S. Das, “State of Art of Solar Photovoltaic Technology,” in Conference Papers in Science, 2013, vol. 2013.

[2] A. Bosio, D. Menossi, G. Rosa, and N. Romeo, “Key developments in CIGS thin film solar cells on ceramic substrates,” Crystal Research and Technology, vol. 49, pp. 620–627, 2014.

[3] F. C. Krebs, Stability and degradation of organic and polymer solar cells. Wiley Online Library, 2012.

[4] E. Lee, S. J. Park, J. W. Cho, J. Gwak, M.-K. Oh, and B. K. Min, “Nearly carbon-free printable {CIGS} thin films for solar cell applications ,” Solar Energy Materials and Solar Cells , vol. 95, pp. 2928–2932, 2011.

[5] K. Matsunaga, T. Komaru, Y. Nakayama, T. Kume, Y. Suzuki, “Mass-production technology for CIGS modules,” Solar Energy Materials and Solar Cells, vol. 93, pp. 1134–1138, 2009.

[6] F. Biccari, C. Malerba, M. Valentini, C. Azanza, R. Chierchia, P. Mangiapane, E. Salza, G. Arabito, A. Mittiga, L. Mannarino, and others, “Realizzazione e caratterizzazione di dispositivi fotovoltaici in film sottili di Cu2ZnSnS4,” tech. rep., ENEA, 2011.

[7] G. Adamo, and A. Busacca, “Time Of Flight measurements via two LiDAR systems with SiPM and APD,” AEIT 2016 - International Annual Conference, 5 – 7 Oct. 2016, Capri, Italy.

[8] A. Parisi, F. R. Galluzzo, M. Caruso, G. Adamo, R. Pernice, R. L. Oliveri, G. Ferrara, R. Inguanta, S. Guarino, S. Stivala, A. C. Cino, R. Miceli, C. Sunseri, and A. C. Busacca, “Characterization of Thin Film $Cig(S,Se)_2$ Submodules Using Solar Simulator and Laser Beam Induced Current Techniques,” 2015 Fotonica AEIT Italian Conference on Photonics Technologies, 6 - 8 maggio 2015, Torino, Italia-

[9] Stivala, S., Busacca, A.C., Curcio, L., Oliveri, R.L., Riva-Sanseverino, S., Assanto, G., ”Continuous-wave backward frequency doubling in periodically poled lithium niobate”, (2010) Applied Physics Letters, 96 (11), art. no. 111110

[10] C. Dispenza, M. A. Sabatino, S. Alessi, G. Spadaro, L. D’Acquisto, R. Pernice, G. Adamo, S. Stivala, A. Parisi, P. Livreri, and A. C. Busacca, “Hydrogel films engineered in a mesoscopically ordered structure and responsive to ethanol vapors”, Reactive & Functional Polymers, vol. 79, 2014.

[11] R. Pernice, A. Andò, D. Musso, A. Parisi, S. Mangione, L. Curcio, S. Stivala, and A.C. Busacca, "Packet loss recovery in an indoor Free space optics link using rateless codes", Proc. 2014 16th International Conference on Transparent Optical Networks (ICTON), Graz, Austria, , pp. 1-4, Jul. 2014.

[12] R. Pernice, A. Andò, D. Musso, F. Lionti, A. Parisi, S. Mangione, G. Adamo, L. Curcio, S. Stivala, and A. C. Busacca, "Rateless codes mitigation technique in a turbulent indoor Free Space Optics link", Proc. 2014 Third Mediterranean Photonics Conference, Trani, Italy, pp. 1-3, May 2014.

[13] A. Parisi, R. Pernice, V. Rocca, L. Curcio, S. Stivala, A. C. Cino, G. Cipriani, V. Di Dio, G. Ricco Galluzzo, R. Miceli, and A. C. Busacca, "Graded carrier concentration absorber profile for high efficiency CIGS solar cells", Int. J. Photoenergy, vol. 2015, Article number 410549, 2015.

[14] A. Parisi, R. Pernice, A. Andò, A.C. Cino, V. Franzitta, and A.C. Busacca, “Electro-optical characterization of ruthenium-based dye sensitized solar cells: A study of light soaking, ageing and temperature effects”, Optik, vol. 135, pp. 227-237, Apr. 2017.

[15] E. Cantelar, G. Lifante, F. Cussó, M. Domenech, A. Busacca, A. Cino, and S. Riva Sanseverino, “Dual-polarization-pump CW laser operation in Nd3+:LiNbO3 channel waveguides fabricated by reverse proton exchange”, Opt. Mater., vol. 30, no. 7, pp. 1039-1043, Mar. 2008.

[16] A. Parisi, L. Curcio, V. Rocca, S. Stivala, A. C. Cino, A. C. Busacca, G. Cipriani, D. La Cascia, V. Di Dio, R. Miceli, and G. R. Galluzzo, “Thin film CIGS solar cells, photovoltaic modules, and the problems of modeling", Int. J. Photoenergy, vol. 2013, Article number 817424, 2013.

[17] Lu, Y., Stegmaier, M., Nukala, P., Giambra, M.A., Ferrari, S., Busacca, A., Pernice, W.H.P., Agarwal, R., “Mixed-mode operation of hybrid phase-change nanophotonic circuits”, (2017) Nano Letters, 17 (1), pp. 150-155.

[18] V. Franzitta, S. Culotta, D. Milone, G. M. Lo Giudice, “Small wind technology diffusion in suburban areas of sicily”, *Sustainability* Volume 7, Issue 9, Pages 12693-12708, 2015.

[19] V. Franzitta, A. Orioli, A. Di Gangi, F. Foresta, “The recent change in the italian policies for photovoltaics: Effects on the energy demand coverage of grid-connected pv systems installed in urban contexts”, *Energies*, 9, 944; doi:10.3390/en9110944, 2016.

[20] G. Sorentino., G. Scaccanoce, M. Mrale, V. Franzitta, “The importance of reliable climatic data in the energy evaluation”, *ENERGY*, Volume 48, Issue 1, pp 74-79, Dec. 2012.

[21] V. Franzitta, M. Lagenndusa, G. Peiri, G. Rzzo, G. Scaccanoce, “Toward a European Eco-label brand for residential buildings: Holistic or by-components approaches?” *Energy*, Volume 36, Issue 4, pp 1884-1892, Apr. 2011.

[22] V. Franzitta, M. Beccali, F. Butera, R.S. Adhikari, “Update on desiccant wheel model” *Int. Jour. of Energy Res.*, Volume 28, Issue 12, pp 1043-1049, Oct. 2004.

[23] V. Franzitta, A. Orioli, A. Di Gangi, “Assessment of the Usability and Accuracy of Two-Diode Models for Photovoltaic Modules”, *Energies*, 10, 564; doi:10.3390/en10040564, 2017.

[24] V. Franzitta, D. Curto, A. Viola, D. Milone, “The Desalination Process Driven by Wave Energy: A Challenge for the Future”, *Energies*, 9, 1032; doi:10.3390/en9121032, 2016.

[25] V. Franzitta, D. Curto, D. Milone, D. Rao, “Assessment of Renewable Sources for the Energy Consumption in Malta in the Mediterranean Sea”, *Energies*, 9, 1034; doi:10.3390/en9121034, 2016.

[26] V. Franzitta, A. Orioli, A. Di Gangi, “Assessment of the Usability and Accuracy of the Simplified One-Diode Models for Photovoltaic Modules”, *Energies*, 9, 1019; doi:10.3390/en9121019, 2016

[27] V. Franzitta, D. Curto, “Sustainability of the Renewable Energy Extraction Close to the Mediterranean Islands”, *Energies*, 10, 283; doi:10.3390/en10030283, 2017.

[28] V. Franzitta, D. Curto, P. Catrini, “Wave Energy Assessment along Sicilian Coastline, Based on DEIM Point Absorber”, *Energies*, 10, 376; doi:10.3390/en10030376, 2017.

[29] E. Chiodo, A. Del Pizzo, L.P. Di Noia, D. Lauria, “Modeling and bayes estimation of battery lifetime for smart grids under an Inverse Gaussian model.” *International Review of Electrical Engineering*, vol. 8, n. 4, pp. 1253-1266, 2013.

[30] G. Brando, A. Dannier, A. Del Pizzo, R. Rizzo, “A generalized modulation technique for multilevel converters.” *In Proc. International Conference on Power Engineering - Energy and Electrical Drives POWERENG 2007*, Portugal, 2007.