An innovative Solar Production Simulator to better teach the foundations of photovoltaic energy to students

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Abstract: This paper deals with a new approach to science and education regarding photovoltaic energy and applications. This teaching method is based on a Solar Production Simulator (SPS). This apparatus is able to reproduce the sun's path on a small scale at all times of the year. The energy production is then estimated with different orientation and/or inclination of a solar sensor. The SPS provides students with the unique opportunity to learn, in a playful manner, the fundamental principles of photovoltaic energy. Several examples of practical work are detailed to give an accurate appreciation of many applications in the photovoltaic sector. A lot of applications could be studied such as implementation of solar position calculations, electrical characterization of solar cells with various technologies or tracking system programming.

Key-Words: Solar energy, Photovoltaic, Solar Production Simulator, Attractiveness of education.

1 Introduction

The energy supply, the diversification of energy sources for domestic consumption and the development of renewable energy sources are crucial issues to the future of Europe, the global equilibrium and tackling climate change [1], [2], [3].

The national energy agency networks have also raised the fundamental question of the global energy consumption which is dramatically increasing due to our quest for a better standard of living and the ever increasing world population [4], [5], [6]. The European Union (EU) has recently given many strong commitments to address these complex issues. In particular, the EU wants to meet the following targets set for 2020: reducing greenhouse gas emissions by 20%, increasing the proportion of renewable energies to 20% and making energy savings of 20% [7].

The need to protect the environment, by limiting our use of fossil fuels, is particularly seen in domestic houses. For example, solar energy is widely used typically where framework legislation is in place in most countries [8].

The educational programs in the areas of electrical engineering and renewable energies must be adapted with international priorities and strategies in the field of energy efficiency in buildings and climate change [9], [10]. New teaching methods must be set up to get a better understanding of renewable energy sources for sustainable development and to promote awareness to long-term behavioral change.

Regarding the education of photovoltaic applications, recent researches have shown that it is crucial to invest in students to give them the tools, the skills, and the understanding since they could potentially be involved in the design, sizing, and installation of solar systems [11].

An innovative Solar Production Simulator (SPS) has recently been invented by a French society named as Freevolt Concept located in the greater Paris area. This apparatus has been developed in collaboration with the University of Tours in France and particularly, Polytech Tours (Electronics and Energy Department) which is an Engineering School. The SPS is used to provide students with first-hand experience and knowledge of solar energy and particularly, photovoltaic applications. This simulator has recently been awarded with 2 gold medals at the 2012 International Invention Exhibition Concours Lépine in Paris. It has also received the Best Product Innovation Award of the Ile-de-France region.

The SPS is a pedagogical tool that reproduces, on a small scale, the sun's path at any time of day. It estimates the energy production of a solar sensor in various inclinations and orientations. Existing solar simulator solutions are not well-appropriated to the characterization of solar sensors in real operating conditions, particularly in case of partial shading or solar radiation non-perpendicular to the sensor surface. In the meantime, the impact of partial shading on the energy production has been widely discussed [12]. The SPS takes into consideration these issues and promises to bring about new opportunities for solar energy and photovoltaic applications for teaching and learning, making the courses more attractive to students.

In this paper, many detailed information about the functioning of the SPS are given. Several examples of practical work to perform within the same equipment are described. These learning exercises are intended for students in their final year of high school, University Institute of Technology or Engineering School. The students completed a satisfaction survey at the end of these practical works. The results are depicted at the end of this article.

2 Story of the SPS and motivations

The Solar Production Simulator (SPS) has been patented in 2010 by a French society, located in the Paris region, named as Freevolt Concept, which is an engineering and consulting firm. The interdisciplinary cooperation is an important aspect of this company. Freevolt Concept develops its own expertise in research, simulation, prototyping activities and pedagogical product manufacturing intended for schools and training centers.

Basic thought behind this invention was to provide both playful and pedagogical tool capable at the same time of characterizing the performances of solar cells, predicting the electrical energy production of a PV plant, and quantifying the impact of weather conditions and solar cell position (orientation, tilt angle). The SPS is the result of almost 3 years of research in collaboration with Freevolt Concept and the University of Tours in France, and especially the Engineering School named as Polytech Tours (Electronics and Energy Department). The school's mission is to train engineering students who are capable of designing, developing and following the manufacturing of electronic devices, circuits and systems with the ability to minimize and make the best use of electrical energy. The training focuses on a project-oriented pedagogy which includes learning about through research and innovation. The drive for innovation is also supported by many industrial partners in the areas of electrical energy management and the GREMAN laboratory (CNRS-UMR 7347) which is a joint research laboratory of the University of Tours specialized in materials, components and systems for electrical energy efficiency.

Polytech Tours provided a technical support for the SPS. A dozen students, supervised by 3 associate professors, contributed to the development of this innovative tool. Then, the aim of Freevolt Concept was to absorb the know-how. Now the SPS is marketed and some 30 educational institutions (*i.e.* Technological High Schools, University Institutes of Technology and Engineering Schools) are already equipped with this tool.

It is important to highlight the motivations of the SPS in comparison with many solar simulators which are commercially available. For instance, this includes, Newport Oriel, Sciencetech, Spectrolab, and others. These simulators are vital tools in the photovoltaic (PV) industry for effectively measuring PV cell and module performances under known test conditions [13]. IEC and ASTM international documents typically describe various standardized parameters to characterize the electrical performances of PV cells [14]. One of these parameters that can be most difficult both to achieve and to accurately measure is the spectral match of the light source compared to a standardized solar spectrum. Existing solar simulators use various lamp technologies as the light sources. Xenon arc lamp is the most common type of lamp implemented within solar simulators because they offer high intensities and a spectrum that matches well enough to sunlight. Many recent research activities show that light emitting diodes may be used to build solar simulators, and offer good solutions for energy-efficient production of spectrally tailored artificial sunlight [15].

These kinds of equipment are very interesting to characterize photovoltaic cell technologies under standardized test conditions. Despite these positive attributes, these types of simulator may be very expensive and must be handled carefully. Moreover, key technical photovoltaic backgrounds cannot possibly be achieved, such as the impact of partial shading, the influence of the sun's path etc. As a consequence, it could be difficult to use commercial solar simulators for educational purposes.

The SPS helps resolve these issues by giving students an easy and low-cost solution to get a better understanding of the fundamental aspects of photovoltaic applications.

3 Key elements of the SPS

3.1 Hardware part features

The simulator is 55 cm long and 46 cm wide. Its mechanical structure was completely designed, manufactured and assembled by Freevolt Concept.

As can be seen in Fig. 1, the sun's path is materialized using a 50 W halogen lamp which is connected to a 12 V DC low voltage input. Its light intensity, specified by the manufacturer, is equal to 1,100 candelas with a 60° angle of half-intensity cone. This lamp has been calibrated previously. Specifically, the light flux must cover the whole surface of the 10 cm × 10 cm solar cell. As a consequence, the "lamp – solar cell" pairing has been done by testing more than 40 lamps. Using this method, the spectral data are not necessary to size the lamp since it is dedicated to the solar cell dimensions. However, it could be interesting to use Xenon lamps since their spectral characteristics are close to the Sun ones (standard solar spectrum like AMG1.5).

Two servomotors allow controlling the azimuth amplitude and height level of the sun. The maximum azimuth amplitude and elevation of the sun are equal to 42.7 cm and 45.4 cm respectively. Thus, the values of the azimuth angle are in the range of -90° to 90°. Regarding the elevation of the sun, its maximum value is equal to 90°. The circuit controlling the movement of the SPS uses a microcontroller board (Arduino Duemilanove) based on the ATMEGA 328.

The kit is composed of a turret on which a 10 cm long and 10 cm wide solar cell (0.15 Wp) could be magnetized. Amorphous, mono-crystalline and polycrystalline solar cell technologies can be used. A sample holder that incorporates a graph of the sun's path in any geographic location helps to define solar masks. It requires putting obstacles on the sample holder such as trees that could reproduce shady areas on the solar system.

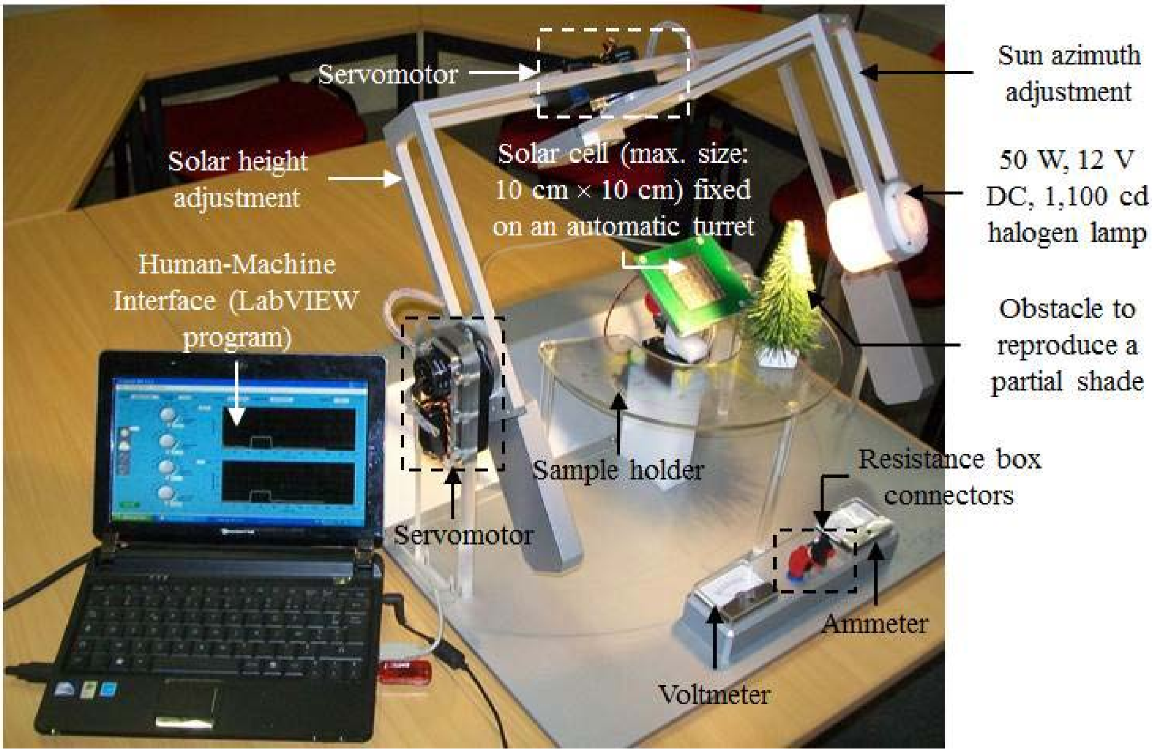


Fig. 1 – Main components of the SPS.

3.2 Human-Machine interface system

The SPS is entirely driven by a PC using an USB port. A fully automated system, built using the LabVIEW programming environment from National Instruments, is implemented in the apparatus. It is important to notice that the human-machine interface is available free of charge (as an executable file). Thus, it is license-free and can be installed on various computers.

The LIFA (LabVIEW Interface For Arduino) toolkit allows the ATMEGA 328 microcontroller to be directly interfaced using LabVIEW. It is possible to control and acquire the transmitted data from the microcontroller.

As can be seen in Fig. 2, the simulation interface is composed of five main parameters that have to be filled out. Firstly, it is necessary to select the city in which the simulation has to be performed. An array of location in Europe (GPS coordinates) is included in the programming environment. Then, it is possible to choose the technology of the solar cell from amorphous, mono-crystalline and polycrystalline silicon. The software includes weather databases. Thus, the solar energy production simulation can be estimated by weighting the weather conditions (*i.e.* full sunshine, cloudy, rainy conditions). The light intensity of the lamp is adjusted in relation to the weather conditions. The solar sensor surface of the building (such as a house) that we wish to predict its energy production is also an input. The system theoretically calculates its peak output solar power. Finally, the azimuth angle and height level of the sun can be set up to take into consideration the orientation and inclination of the building.

The software interface allows the SPS to have three main modes of operation: “day” mode, “month” mode, “year” mode. The “day” mode simulation lasts 1 minute. It only takes 12 minutes to have a simulation result using the “year” mode. Each mode allows displaying the solar energy production directly in the simulation interface. A report containing any relevant information (input and output data) concerning the simulation could be created automatically. The output data such as the voltage and current of the solar cell could be exported to a spreadsheet to be analyzed.

It is important to notice that it is possible to minimize the effect of the ambient light by performing a calibration cycle to better calculate the solar energy production. For this, the simulator measures the ambient light when the lamp is turned-off, then takes the value into account in the simulation results.

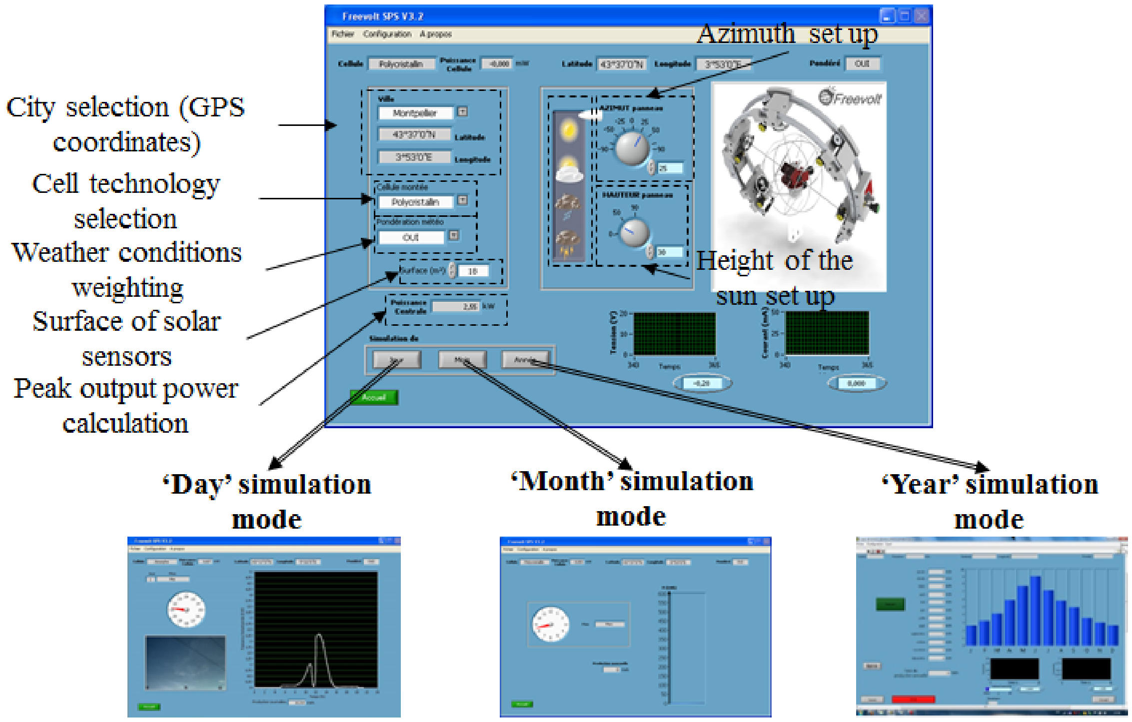


Fig. 2 – Human-machine interface of the SPS.

4 Examples of practical work

4.1 Course learning objectives

The third year students of the Electronic engineering and Energy department at the University of Tours in France, in the context of their training program, receive a course entitled “Management of solar energy and photovoltaic applications”. This course, which is part of the area of electrical energy systems, covers fundamental knowledge of solar energy and reviews the design, installation, operation and evaluation of solar photovoltaic systems intended for use in residential applications.

The course consists of 12 hours of lectures and 12 hours of practical work using the SPS to illustrate the technical concepts explained during the lessons. Topics that are covered include the solar energy fundamentals, photovoltaic market situation, solar cells, modules and areas, photovoltaic plant sizing and analysis of performances. At the end of this training program, the students are expected to identify the main drivers behind solar photovoltaic and make a valued judgment on the suitability of a photovoltaic system for a given situation.

Students are assessed and informed of their progress on an on-going basis throughout the program. They may also be involved in the continuous improvement process of the operation of the SPS. The method of teaching is referred to an approach that is more outcome-based, while being more attractive [16]. In this way, this pattern of learning enables students to increase and improve their skills to respond quickly and flexibly to changing renewable market requirements.

In the next sections, two practical works are particularly described. The first one deals with the electrical characterization of a photovoltaic unit. This exercise is based on the use of a solar matrix (this product is included in the SPS toolkit). The second practical work helps to learn how to use the SPS to get a better understanding of its operating modes. In particular, the students must be able to establish a solar mask and to get a better understanding of the influence of partial shading on electrical energy production

The students completed a satisfaction survey at the end of these practical works. A summary of the results is given at the end of this paper.

4.2 Solar matrix and its applications

A solar matrix (see Fig. 3) has recently been developed to provide opportunity for students to build their own photovoltaic unit. This solar matrix is composed of 12 photovoltaic cells with the same characteristics and technology (*i.e.* amorphous silicon). It may be applied alone or in conjunction with the SPS.

A practical work, using the solar matrix only, is proposed below. The aim of the study is to build a 0.32 mW photovoltaic power plant and establish its I-V curve. It is important to notice that several solar matrixes could be associated to build larger photovoltaic power unit.

Fig. 4 shows its assembly wiring diagram. In this example, 4 strings are associated in parallel. Each string is composed of 3 series-connected photovoltaic cells. In the practical work, the students must plot the I-V curve of the whole system in the following conditions: a lighting level of 1,000 lux, a room temperature equals to 20 °C. The students can use a lux-meter and a decade resistance box to plot the I-V characteristics of the photovoltaic power unit.

Fig. 3 – Solar matrix used to build a whole photovoltaic power system.

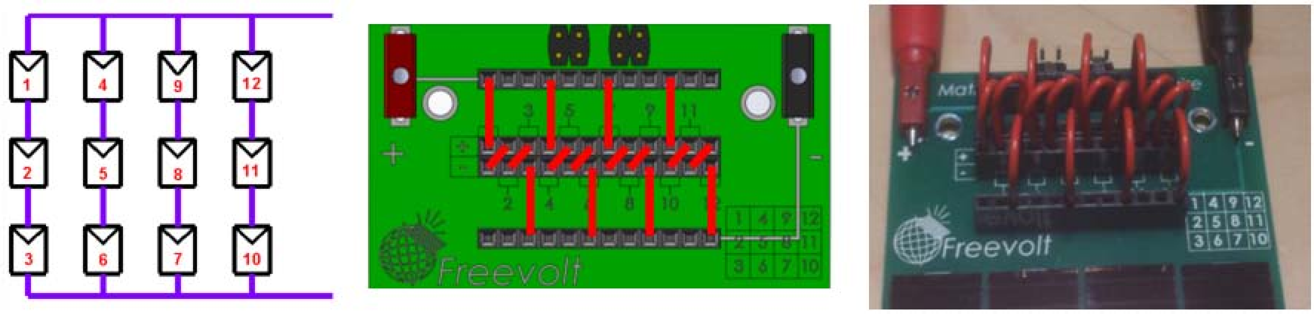


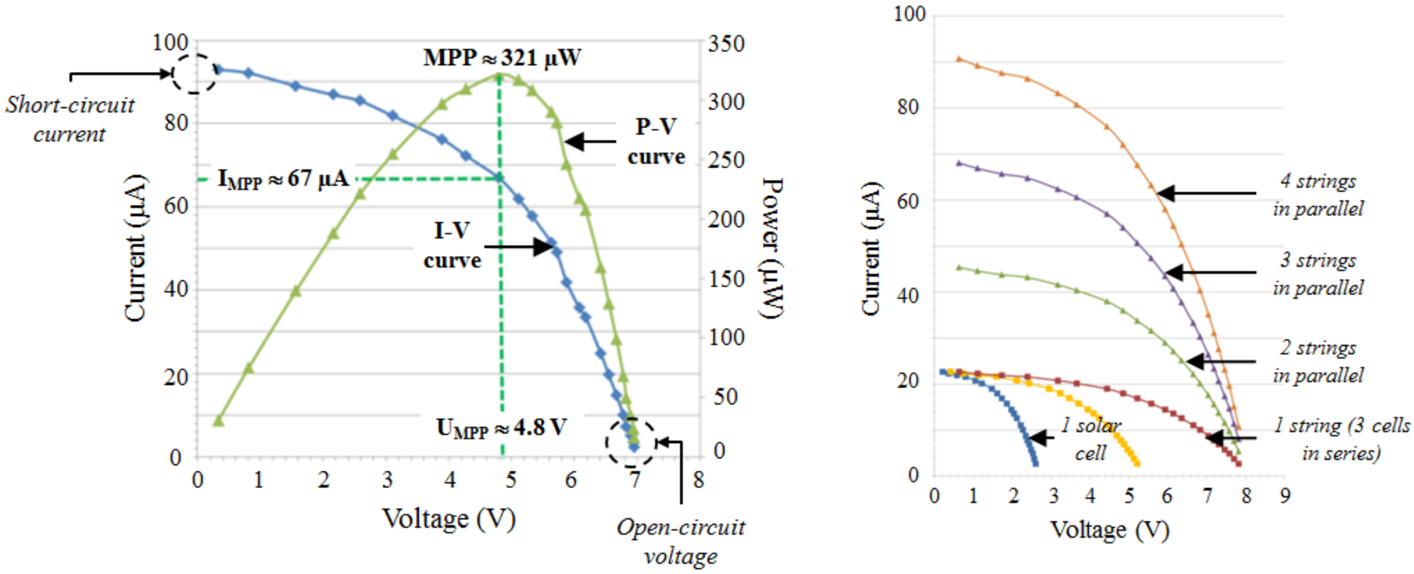
Fig. 4 – First practical work example: conception of a 0.32 mW photovoltaic power system.

Fig. 5 *(a)* shows the result of the experimental measurements. The students must be able to give the main characteristics of the whole system: the open-circuit voltage (about 7 V in this exercise), the short-circuit current (about 93 µA in this case study), and the maximum power point (MPP equal to 0.321 mW).

In this case study, the aim is not only to establish the I-V curve of a photovoltaic power unit but also to get a better understanding of the influence of solar cell interconnection (see Fig. 5 *(b)*).

Another interesting experiment to perform consists in studying the impact of partial shading on the electrical energy production of the photovoltaic plant. In particular, the students could add several by-pass diodes (1 A, 20 V, Schottky diode [1N5817]), enabling the solar cells to generate energy even in these conditions.

Finally, it is possible to study various physical phenomena using the solar matrix. In this paper, this solar matrix is implemented in its standalone version. It is possible to couple it with the SPS.



(a) *(b)*

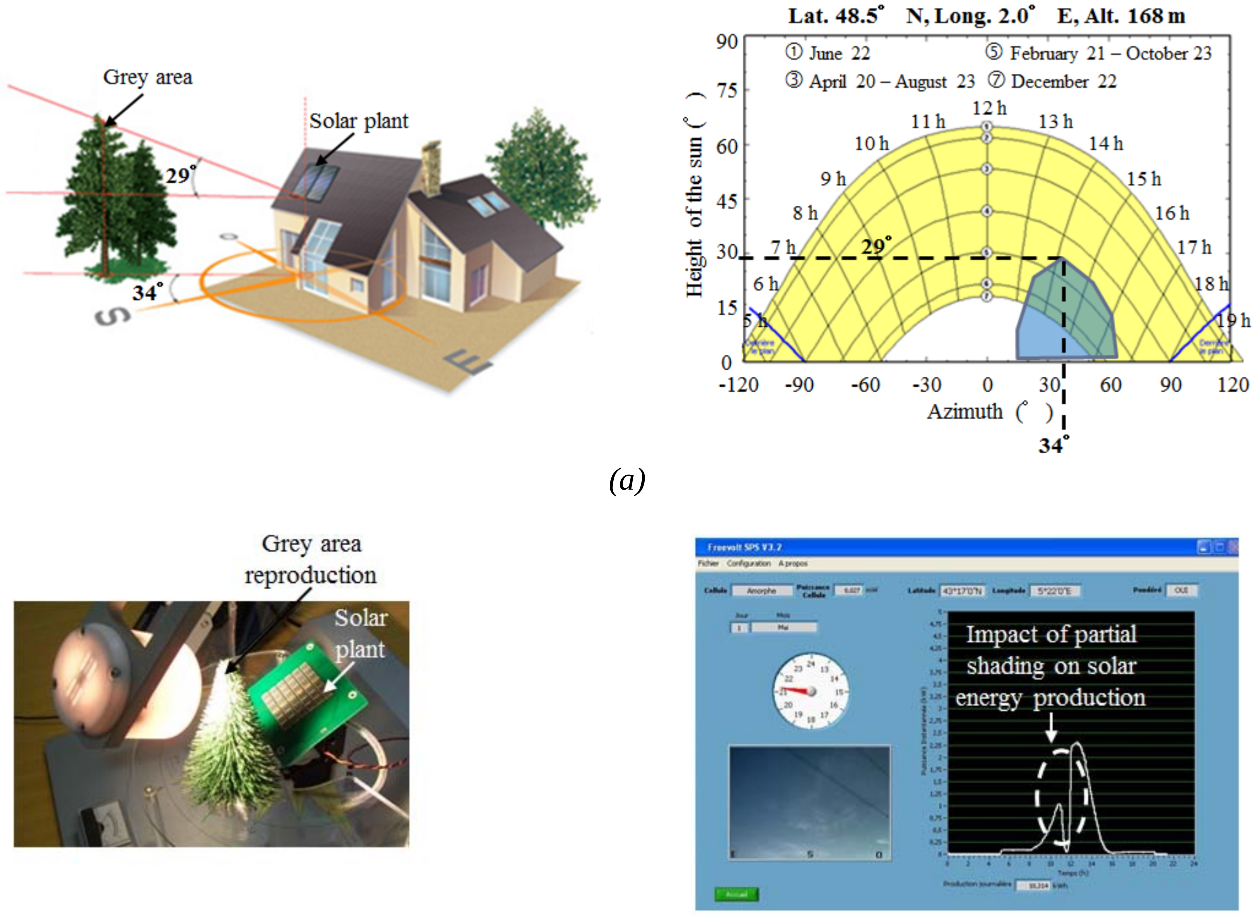
Fig. 5 – First practical work example: *(a)* Electrical characterization result of a 0.32 mW photovoltaic power system. *(b)* Impact of the solar cell interconnection.

4.3 Example of practical work linked to the operating mode of the SPS

In this section of the article, a practical work linked to the operating mode of the SPS is proposed.

This exercise consists in analyzing the influence of partial shading on the energy production of a solar cell. It could be performed using the three operating modes of the SPS (i.e. “day”, “month”, “year” modes). First of all, the students have to establish a solar mask. It means that they identify shadows cast by several objects such as trees, street lamps, neighboring buildings etc. They typically analyze the school building and its surroundings. As can be seen in Fig. 6 *(a)*, a solar mask is drawn from the grey areas. The next step consists in putting the solar mask on the sample holder of the SPS. The students can use many objects (e.g. trees) on a smaller scale to reproduce the grey areas. Various miniature objects are included in the SPS toolkit.

Finally, it is possible to calculate the electrical energy production of a solar cell using the simulator. Fig. 6 *(b)* shows the results from the "day" mode of the apparatus. From this kind of graph, the students must be able to quantify the energy loss due to the partial shadings.



Cellule: Amorphe

Latitude: 43°17'0"N

Longitude: 5°22'0"E

Pondéré: OUI

Jour: 1

Mois: Mai

(a)

(b)

Fig. 6 – Practical work example linked to the operating of the SPS: *(a)* **Example of solar mask chart.** *(b)* **Impact of a partial shading on the solar energy production ("day" mode simulation result).**

5 Use of the SPS to predict the electrical energy production of a PV plant

In addition to those practical works, it could be interesting to use the SPS to predict the electrical energy production of a PV plant. The real energy production of 2,475 Wp solar power plant located in Paris is compared to the one simulated using the SPS.

The photovoltaic plant is composed of 11 monocrystalline modules (SPR-225-WHT from SunPower). The overall surface of solar collectors installed is about 14 m². The tilt and orientation angles of these modules are equal to 30° and -30° respectively.

All the characteristics of the PV plant were implemented into the simulator. Fig. 7 shows the comparison of annual energy production results between the SPS and the solar power plant. The annual plant output is equal to 2,627 kWh. The SPS predicted an annual solar energy production equal to 2,540 kWh.

These results exhibit a gap between the real measurements and the SPS results lower than 5%. However, it is interesting to note that this gap is higher than 15% in several months. The need to take into consideration weather conditions could explain this difference. Indeed, the SPS uses the 2010 data from France’s national meteorological service to estimate the solar energy production while the real data (from the solar power plant) were measured in 2011. A long-term average of weather is being implemented in a future release of the SPS software to overcome this problem.

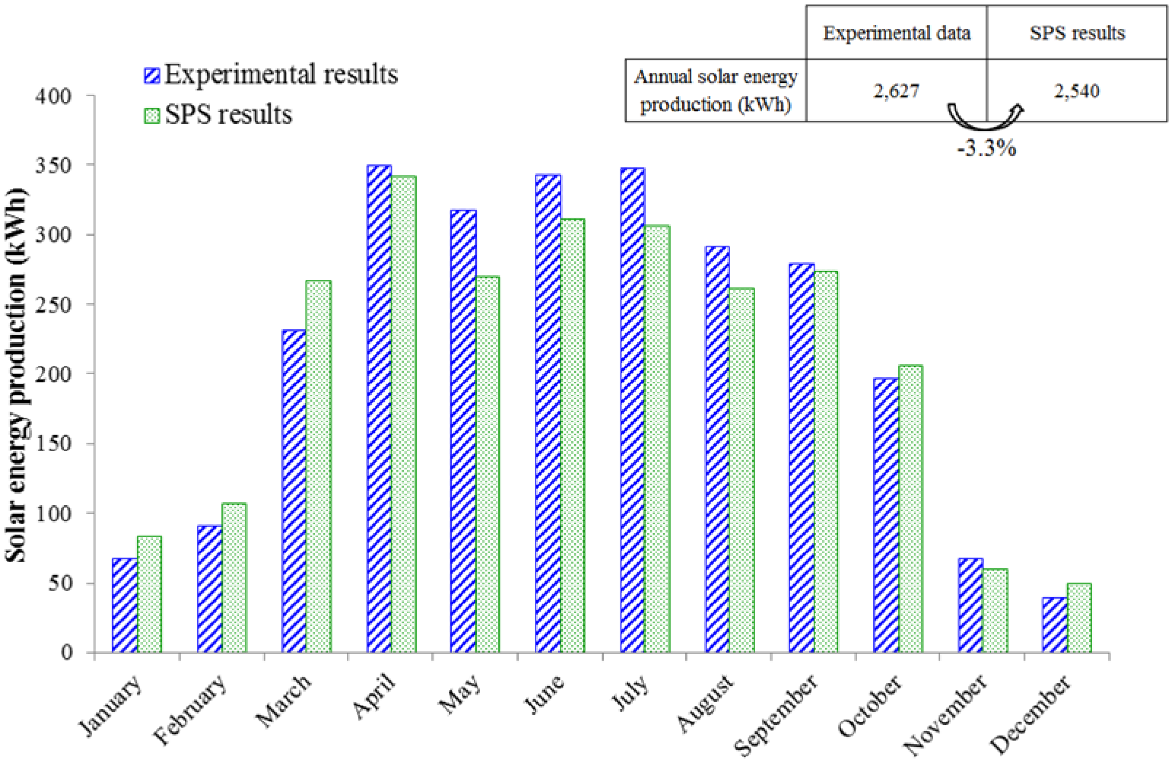


Fig. 7 – Use of the SPS to predict the electrical energy production of 2,475 Wp PV plant.

6 Students’ feedback

The thirty third year engineering students of the Electronic engineering and Energy department had the opportunity to use the SPS during the exercises so as to motivate to apply themselves practically.

Each student filed a questionnaire at the end of the practical. The aim of this questionnaire is to give an overall satisfaction score of the simulator, and its utility in the learning process. In particular, four questions were highlighted and scored on a scale of ‘1’ to ‘4’. The ‘1’ and ‘4’ marks are the lowest and highest evaluations of each question respectively [17]. Table 1 summarizes the results. A total satisfaction score of 83.5% was obtained for the SPS.

By means of this innovative teaching method, it is possible to achieve significantly better results taking into consideration students’ knowledge in active learning. What have they considered to be positive about this form of education? The students tell us that the SPS helps them to have quick explanation of the backgrounds of photovoltaic applications with a clear understanding of the studied problems. An individual professor’s approach to each student is also reported. This innovative approach helps in developing individual self-reliance.

Table 1 – Satisfaction survey summary.

Question	Poor = 1	Good = 2	Very good = 3	Excellent = 4	Average score	Satisfaction score
1. Did you benefit from this teaching approach to learn basics of photovoltaic?	2.1%	12.3%	41.2%	44.4%	3.28	82.0%
2. Did you improve your skills in solar energy applications?	2.5%	11.2%	39.7%	46.6%	3.30	82.5%
3. Score the easy way to use the SPS.	1.3%	4.9%	51.2%	42.6%	3.35	83.8%
4. Score the specific use of the SPS.	1.2%	7.9%	37.3%	53.6%	3.43	85.8%
Total score						83.5%

7 Conclusion

The Solar Production Simulator (SPS) described in this paper is an innovative educational tool to give, in a playful way, technical background and basics knowledge of solar energy and photovoltaic applications.

The operating modes of the SPS have widely been described. This tool has many applications. Two examples of practical work have particularly been detailed. The first one deals with the electrical characterization of a 0.32 mW photovoltaic power system using a solar matrix. This product is included in the SPS toolkit. The second practical work described in this paper consists in studying the influence of partial shading on the electrical energy production of a solar cell.

While the interest of this simulator is before all pedagogical, another exercise could be done using the apparatus. Indeed, it is possible to predict the energy efficiency of a photovoltaic power plant, when it is put into a situation in habitat applications. It could look forward to helping designers develop the best layout for a solar plant. Finally, this simulator could also act as a demonstrator dedicated to Agencies for Environment and Energy Management.

The students could participate in an interactive learning process using the SPS. The satisfaction survey summary can highlight the relevance of the simulator in the study of solar energy foundations.

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