

New Software Package for Teaching and Learning the Basics of Photovoltaic System Sizing

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Abstract: This paper describes an innovative and highly modular software tool named PVLab and developed by the GREMAN laboratory in collaboration with Polytech Tours from the University of Tours (France). This simulation package assists the designer in the sizing of PV (photovoltaic) installations. PVLab has a high level of flexibility, allowing its physical models and databases (e.g., meteorological data) to be modified according to the user's needs. This is made possible through the use of expertise applied to all of the computing steps, and to the MATLAB development environment. The user's ability to control the source code itself will allow much greater progress to be made in the field of renewable energy applications than with PVsyst, which is currently the commercial reference. All of these features come together to make PVLab the perfect tool for modernizing higher education, in particular with regard to students' competencies.

Key-Words: Solar energy, Photovoltaic, Powerful software package, Attractiveness of education.

1 Introduction

Since recent years, the higher education landscape has been undergoing considerable change as a result of technological innovations and new pedagogical approaches [1], [2], [3]. The Bologna Declaration and Lisbon Strategy in Europe are the clearest examples of international commitment to reform and modernization of university education [4], [5].

The degree and qualifications obtained, in terms of workload, level and learning outcomes are major pillars of the Bologna Process [6]. The competency-based management has been developed to increase the readability and comparability of European higher education degrees worldwide [7], [8]. This approach also supports the employability of higher education graduates [9]. Indeed, they are expected to be fully operational in an international context upon completion of their studies.

About 100 Engineering Schools in France have already started the process at the moment. This movement should speed up with the Engineering Education Commission (CTI) guidelines. The Polytechnic Engineering School of the University of Tours (Polytech Tours, France) has just initiated the continuous skills development. The Electronics

and Energy Department, which trains future engineers to design and to have an in-depth understanding of electronic systems, has recently set up new pedagogical tools to achieve the education system modernization target.

With regard to the education of photovoltaic (PV) applications in particular, recent researches have focused attention on students' investment to give them the methods, tools, skills, and understanding since they could potentially be involved in the design, sizing, and installation of PV systems within an efficient industrial context [10], [11].

As the use of photovoltaics expands, with more and more commercial and residential users investing on solar energy systems around the globe, there is a growing demand for software that can be used for the design, simulation, data analysis, and troubleshooting of PV systems, from the preliminary assessment of energy efficiency and cost-effectiveness to the development of the project documentation. For many years, PVsyst has been accepted as a reference by architects, engineers, teachers and researchers, especially as a result of its easy-to-use, and accuracy of electrical energy production estimation thanks to its extensive PV-

component, and meteorological databases [12]. However, using this kind of software package, it is not possible to modify the electrical, optical and thermal models, nor the internal databases (*i.e.*, PV modules, inverters, and meteorological databases) [13]. A major question is whether existing commercial PV software, such as PVsyst, are sufficient to accurately forecast the efficiency of a PV plant taking into consideration all technical and environmental requirements.

In this context, the GREMAN laboratory, a favored partner of Polytech Tours, and a research unit funded jointly by the University of Tours (France) and CNRS (French National Center for Scientific Research), has developed its own PV simulation package, and named "PVLab". PVLab, based on the MATLAB development environment (also developed with the Scilab open source software), is a powerful, innovative and highly flexible tool that allows users to personalize various models (*i.e.*, electrical, optical, and thermal models) and databases (*i.e.*, PV components such as inverters, solar models and above all, meteorological databases), in order to gain a better understanding of their impact on the production of electricity and the efficiency of PV power plants [14], [15].

PVLab has been originally dedicated to research activities to get a better understanding of the factors (for instance, from the following non exhaustive list: ambient temperature, wind speed, wind direction) that affect the electricity production of a PV power plant. Nonetheless, PVLab has many degrees of freedom by using an open architecture such as the MATLAB environment. That is the reason why this PV software package has become an increasingly popular tool for education. The engineering students of the Electronics and Energy Department of Polytech Tours (France) get the chance to use PVLab to improve their knowledge and technical skills in the field of photovoltaics, while recognizing the benefits of a competence-based approach.

In this paper, many detailed information about the functioning of PVLab are given. An example of practical work is described. This learning exercise is 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 Use of PVLab: motivations and general architecture

2.1 Strengths and challenges of PVLab in comparison with existing software

The detailed sizing of a PV power plant consists in laying down the procedures for construction, taking into account technical requirements, economical criteria and energy efficiency.

PV simulation tools are here to estimate the yearly electricity production of a whole system but also to quantify the perturbing effects in order to analyze the shortcomings and optimize the PV installation [16]. Many commercially available PV software packages can be found on the market. At the moment, PVsyst is the ultimate benchmark for architects, engineers, installers and researchers. Moreover, this software tool is very popular for teaching purposes [17].

Fig. 1 (a) shows the PVsyst simulation block diagram. The software package includes extensive meteorological and PV components' databases (in particular, PV modules and inverters).

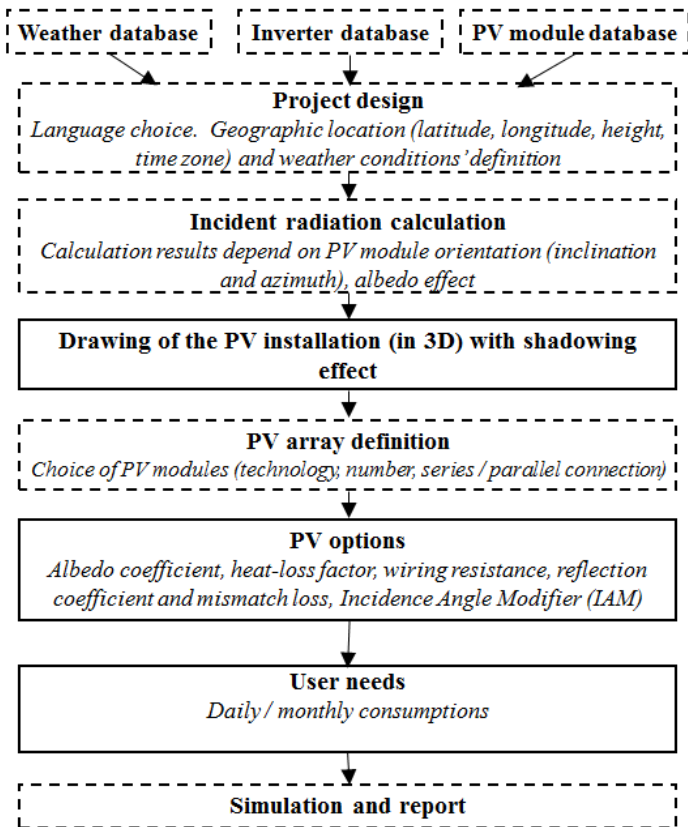
The simulation procedure is based on a project strategy that aims to build a thorough system design using detailed hourly simulations. This mode gives the user the possibility of performing different system simulation runs and compares them. The plane orientation must be defined (with the possibility of tracking planes or shed mounting). The user can choose the specific system components. He is assisted in designing the PV installation (*i.e.*, solar panel technology, number of PV modules connected in series and parallel, and inverter type). In a second phase, the user can specify more detailed parameters and analyse fine effects like thermal behaviour, wiring, PV module quality, mismatch and incidence angle losses, horizon (far shading), or partial shadings of near objects on the PV array. Results include many simulation variables, which may be displayed in monthly, daily or hourly values, and even transferred to other software. The "Loss Diagram" is particularly useful for identifying the weaknesses of the system design. A complete report may be printed for each simulation run, including all parameters used for the simulation, and the main results. It is also worth noting that an economic evaluation of the PV system may be established on the basis of both defined parameters simulation results.

The PVsyst simulation tool is distributed in the form of executable programs. Thus, it is impossible

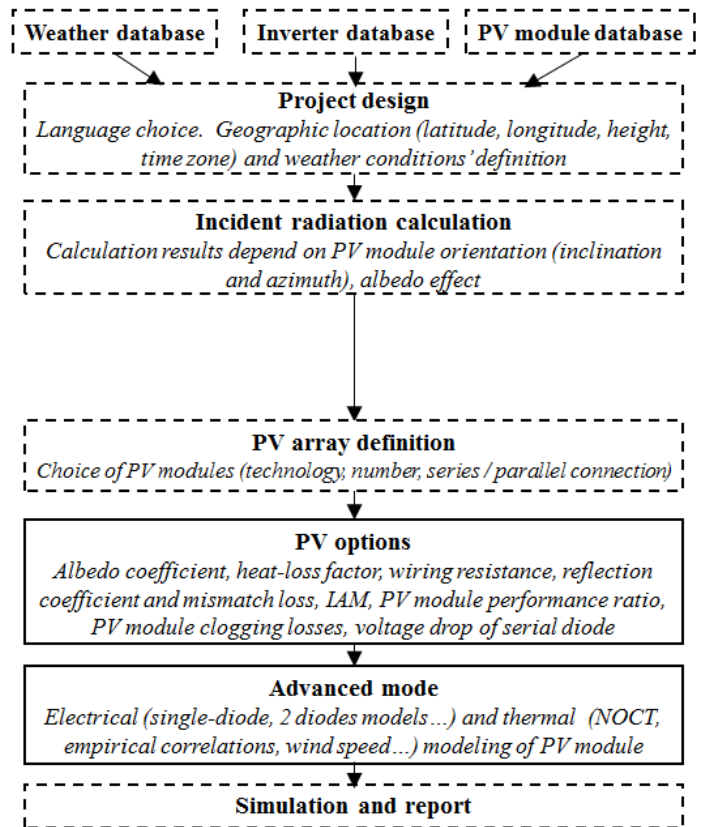
to modify the computational code and the models implemented inside the software (optical, electrical, thermal, etc.). For example, despite its advantages, several parameters used by PVsyst, such as wind speed or direction, cannot be changed. Moreover, the power efficiency of inverters, a voltage-dependent characteristic fundamental to the optimization of DC-AC converter efficiency, cannot be edited.

In view of the limitations of these existing PV software tools, the GREMAN laboratory has developed its own simulator, PVLab, based on the MATLAB environment. This innovative tool provides for maximum flexibility, by allowing several parameters, such as wind speed and wind direction, to be changed, and allowing various external databases (meteorological, PV modules, inverters, etc.) to be used.

Fig. 1 (b) illustrates the simulation block diagram implemented in PVLab. This diagram relies on PVsyst one. Besides, some of the functions, represented by dashed lines in Fig. 1, are the same. PVLab can be used in a highly advanced mode where the user can modify or implement many toolboxes. For example, the single-diode modeling of the PV generator can easily be replaced by 2 diodes model. Moreover, the user can build a thermal model of the PV module to take into consideration all climatic factors (*i.e.*, ambient temperature, wind speed, wind direction, humidity) to better estimate the electricity production of a PV power plant. This is only possible since the development environment of PVLab is totally flexible.



(a)



(b)

Fig. 1 – Simulation block diagrams implemented in PVsyst (a) and PVLab (b).

2.2 General architecture and operating principle

Fig. 2 shows the general architecture of PVLab. The program's core, based on PVsyst one, is composed of four script files.

The electrical production of a PV system is usually estimated in two stages, as described in Fig. 1. Firstly, the effective irradiance on the PV unit must be calculated. The power generated under this level of irradiance is then determined. As shown in Fig. 2, these two steps are implemented in the script file named "Simu.m". In practice, many different variables are used to calculate the irradiance and the generated electrical power. These variables must also be predefined before the simulations can be run. This step is included in two

script files named "PVLab.m" and "Interface.m". More specifically, the "PVLab.m" script file loads the databases (*i.e.*, weather and PV components such as PV modules and inverters) and defines the current work folder, whereas the "Interface.m" script file recalls UI (the user interface) and interrogates several parameters needed to launch the calculations.

At the end of the simulation process of a PV system, a summary report is generated by the script file named "Report.m". This report contains, in particular, most of the important pre-defined parameters and the monthly and/or annual electrical energy production results.

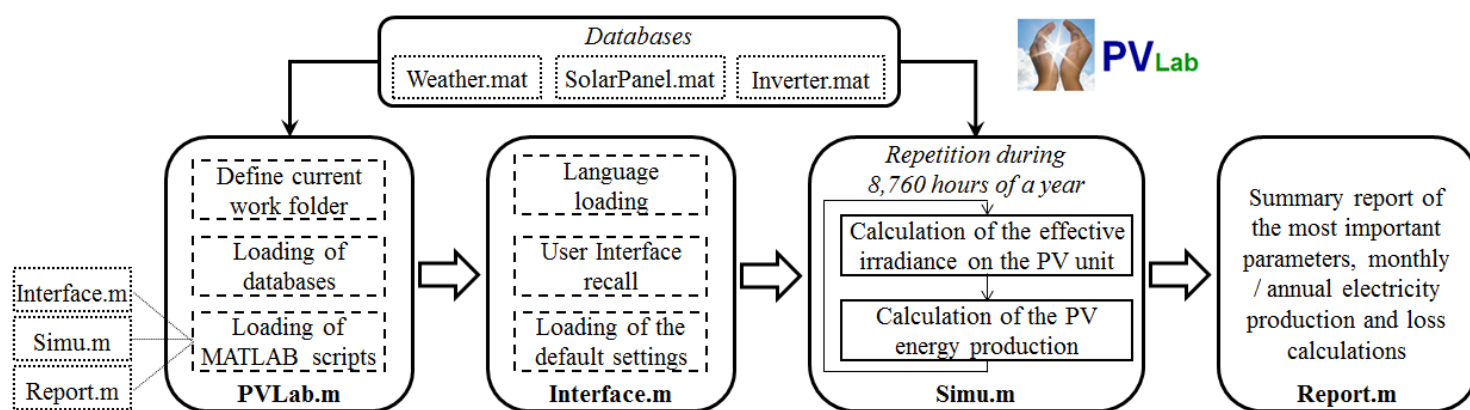


Fig. 2 – General architecture of PVLab.

3 Examples of practical work

3.1 Learning objectives and outcomes

The engineering students (first year of the engineering program) of the Electronics and Energy department of Polytech Tours (France) receive a course entitled "Renewable energy system sizing". Theoretical and practical aspects covering the photovoltaic conversion area are discussed in this course. In particular, the main issues addressed include solar energy systems, photovoltaic cells, modules and characteristics, modeling and control of photovoltaic system engineering, power electronics and control of PV systems.

The course consists of 8 hours of lectures and 12 hours of practical using PVLab to illustrate the technical concepts explained during the lessons. As

can be seen in Table 1, the main competence assessed is to master the methods and engineering software tools in order to model, develop and analyze a photovoltaic system (*i.e.*, PV grid connected or off grid).

Upon successful completion of this course, the engineering students are expected to explain working principles and design of various PV power plants and size a whole system to meet the required load demand. Acquired skills are evaluated in various forms (multiple-choice questions, oral presentations, reports, written exams). In particular, regarding the whole sizing of a PV power plant using PVLab, the competences are assessed through a report at the end of the practical work sessions.

The students' performance is rated on a scale of 1 to 3 for each learning outcome, where "1" corresponds to a learned skill. "2" and "3" mean

that the competence is in the process of being acquired and not acquired, respectively.

Hereafter in this article, two practical works are detailed. The first exercise consists in sizing a domestic photovoltaic power plant taking into consideration the electricity needs and the comfort of the occupants. The second practical work is related to building a new toolbox to be

implemented in the software package. The aim of this exercise is to get a better understanding of the physical models' precision influence on the electricity 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 section.

Table 1 – Competency assessed, learning outcomes and methods of assessment.

Competency assessed	Learning outcome	Method of assessment
Mastery of the methods and engineering software packages in order to model, develop and analyze a grid-connected or off grid photovoltaic system	Apply engineering principles to complex energy problems	Multiple choice exam and formal exam during teaching term
	Select and use appropriate engineering design and simulation tools	Evaluation during the practical work sessions (reports)
	Design a system to satisfy a given criteria and resources	Evaluation during the practical work sessions (reports)
	Communicate technical system design information in a clear and effective manner	Oral presentation

3.2 Example of practical work: domestic PV power plant sizing

This exercise deals with an individual who wishes to fit solar panels on a roof of his home. In such scenario, the engineering students serve as consultants. Their objective is to design an off grid PV system using PVLab. The methodology consists of three parts: on-site electricity

consumption analysis, photovoltaic system sizing, and profitability analysis of the whole system.

The first part of this practical work consists in analyzing electricity use and tracking consumption patterns. Firstly, all the energy-inefficient appliances and their utilization must be identified. Table 2 gives an example of electricity consumption for a house of 80 square meters of living space (with 3 occupants).

Table 2 – Example of electricity consumption for a house of 80 square meters of living space (with 3 occupants).

	Annual electricity consumption (kWh)
Electric heat / Electric water heater	7,000
Lighting	729
Refrigerator / Freezer	519
Dishwasher	108
Washing machine	187
Dryer	302
TV / Computer / Internet box	791
Total	9,636

The result of the annual electricity consumption (*i.e.*, 9,636 kWh per year, or 803 kWh per month in an approximate manner) is the key point to size the photovoltaic power plant. The exercise addressed here is a PV power plant to be installed in Tours (latitude: 47.27° N, longitude: 0.43° E, altitude:

108 m). As can be seen in Fig. 3, all the simulation parameters (site location and meteorological data, characteristics of PV components *i.e.* PV modules and inverters etc.), are totally adjustable using the user-friendly interface.

The screenshot shows the PVLab v3.0 software interface. At the top, there are three small images of solar panels. Below them, the 'Name of the project' field is set to 'TOURS - synthetic data - monthly bases PVGIS'. The 'Weather Site' is also 'TOURS - synthetic data - monthly bases PVGIS'. The 'Choice of language' is set to French. The 'Generator' section includes 'Slope: 45°', 'Azimuth: 0°', 'Number of panels in parallel: 6', and 'Number of panels in serial: 6'. The 'Panel' is 'SolarWorld SW 220 P' and the 'Inverter' is 'SMA SMC 9000 TL'. The 'Simulation' section has 'Albedo coef.: 0.2', 'IAM Coef. (Ashrae): 0.05', 'Panel quality loss: 3%', 'Mismatch loss coef.: 2%', 'Clogging loss: 0%', 'Wiring resistor: 77 mOhm', 'Serial diode voltage drop: 0.7 V', and 'Calculation precision: 1 V'. The 'System overview' shows '36 panels', '60.36 m²', '7920 Wc', and 'RPN: 114%'. The 'Advanced' section has 'Diode Model', 'Thermal Model', and 'Wind Speed' options. The 'Losses graph' and 'Annual simulation' buttons are at the bottom.

Define the site location and its meteorological data
 → The user can also create its own database

Define the characteristics of the PV power plant (PV modules and inverter)
 → Use of existing databases
 → The user can also create its own database

Simulation parameters to be set up
 → All the parameters are adjustable

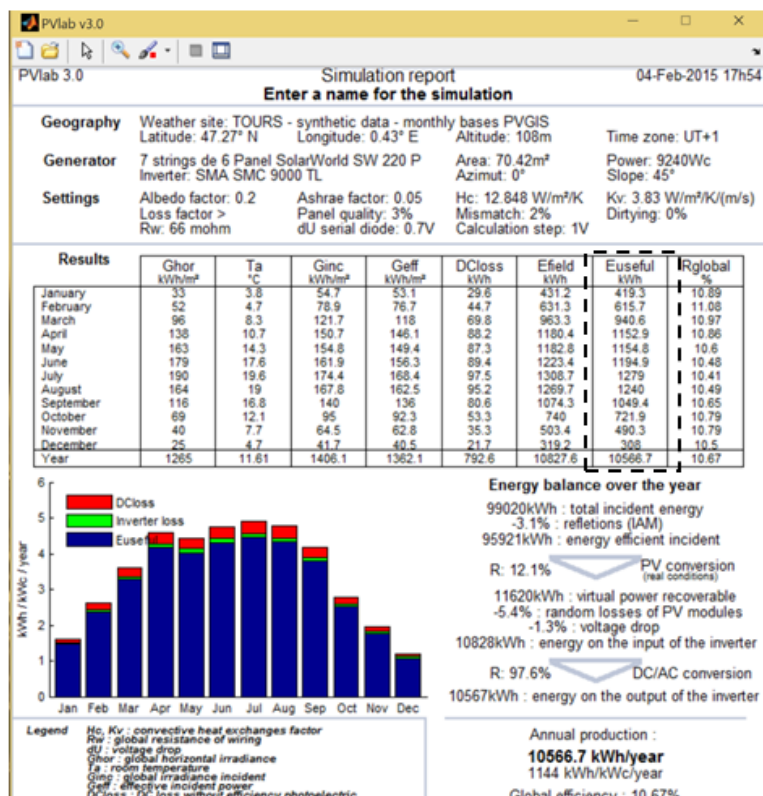
Advanced mode of PVLab
 → The user can build its own electrical and/or thermal model of the PV module taking into consideration weather conditions (wind speed, wind direction...)

Fig. 3 – User-friendly interface of PVLab.

During this practical work, the students become particularly aware that three factors are especially important. The first one is the capacity of the PV power plant. This choice depends on the roof surface. In this example, the surface of PV modules must not exceed 100 square meters. As can be seen in Fig. 4, the simulation results show that 70 square meters of PV modules (string connection of 42 SolarWorld's Sunmodule Plus™ 220 Wp polycrystalline solar panels) are enough to meet the electrical energy needs.

The remaining two factors are the orientation and inclination of the PV modules. In this example, the PV modules are supposed to be south-facing. In practice, the PV installation sizing is based on the worst months. The solar panels' inclination is calculated to maximize the electricity production during winter months. The coordinates of the site location (in particular, its latitude) is crucial to calculate the optimal inclination of the PV modules. The students proceed from a literature review before launching PVLab. Many books and articles on solar energy often highlight that the tilt of PV modules should be equal to the latitude of

the site location, plus 15 degrees in winter or minus 15 degrees in summer [18]. Thus, this assumes that, in that case, the PV modules' inclination can be adjustable, which is not the case in domestic houses. As a consequence, the students used the PVLab software tool to determine the best tilt angle value to optimize the electricity production throughout the year. As can be seen in Fig. 4, the simulation results show that the best results were obtained with a tilt angle equal to 45°. On average over the year, the PV energy production (10,567 kWh) meets the requirements (9,636 kWh). Nonetheless, this electricity production is lower than the requested value (803 kWh per month) during the winter months (in particular, from October to January). The simulation results point out that it would be necessary to multiply the size of the PV installation by 2.5 to obtain the desired result (*i.e.* 803 kWh whatever the month). Obviously, this result is not an acceptable outcome. At the end of this exercise, the students can clearly get a better understanding of the advantage of PV installation connection to the electricity grid.



Summary of the main input parameters used for the simulation
 → Site location, characteristics of the PV components and settings

Simulation results
 → In particular, the useful energy is calculated according to the months of the year

Energy balance over the year
 → Identification of the losses in the PV system (DC losses, inverter losses)

Fig. 4 – Example of simulation report.

4 Students’ feedback

Thirty-nine third year engineering students of the Electronics and Energy department of Polytech Tours (France) were able to discover all the amazing features of the PVLab simulation package during the practical works.

Each student filed a questionnaire at the end of the sessions. The aim of this questionnaire is to give an overall satisfaction score of the simulation

tool, 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.

Table 3 summarizes the results. A total satisfaction score of 83.5% was obtained. The students’ feedback is helpful to improve the functioning of the simulation package.

Table 3 – Satisfaction survey summary.

Question	Poor = 1	Good = 2	Very good = 3	Excellent = 4	Average score	Satisfaction score
1. Score the easy way to use PVLab.	2.6%	7.7%	51.3%	38.5%	3.26	81.5%
2. The software package is engineered to be compatible with all types of users.	0.0%	10.3%	33.3%	56.4%	3.46	86.5%
3. The software development process based on MATLAB is intuitive and easy to learn for the user.	5.1%	7.7%	46.2%	41%	3.23	80.8%

4. Score the advanced mode of PVLab (creation of toolboxes).	2.6%	5.1%	56.4%	35.9%	3.26	81.5%
5. Did you benefit from this teaching approach to learn basics of photovoltaic system sizing?	2.6%	2.6%	41.0%	53.8%	3.46	86.5%
Total score						83.3%

5 Conclusion

The University of Tours (France) has developed an innovative and flexible PV software tool, named "PVLab", based on a numerical computing environment (MATLAB code), which allows the user to modify its internal physical models (electrical, optical and thermal models) and databases (PV modules, inverters and PV components).

Initially dedicated to laboratory activities to help researchers to get a better understanding of various factors (in particular, weather-related factors) that affect the electricity production of a PV power plant, PVLab has been quickly extended to learning programs and teaching practices.

In particular, this powerful software package has been adapted and integrated into educational curriculum in the engineering school named Polytech Tours (France). The engineering students take advantage of this simulation package to learn the foundations of photovoltaic system sizing. During the practical works, they may play a consulting role in designing grid-connected or off grid PV systems, from their sizing up to their profitability analysis. Most importantly, the students can implement their own physical models in the simulation tool through the MATLAB code. The main interest of this part is to try to get a better understanding of the factors (for instance, weather-related factors) that affect the electricity production of a PV power plant.

Finally, the use of PVLab helps the engineering students' profiles to match the skill requirements of photovoltaic installers.

To conclude, the quality of teaching is strengthened through a competency-based approach. The PVLab simulation package contributes enormously to reinforcing the attractiveness of higher education for students. The responses to the survey also indicated a high level of satisfaction among the engineering students.

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