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Dipartimento di Fisica e Astronomia "Galileo Galilei"

Corso di Laurea Magistrale in Ingegneria dell'energia Elettrica

TESI DI LAUREA MAGISTRALE IN
INGEGNERIA DELL'ENERGIA ELETTRICA

Photovoltaic Teaching Project: a didactic method for approaching the renewable energy

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CORRELATORE: Dott. Cristiano Lino Fontana

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Tesi di Laurea

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List of Acronyms

- IBSE - Inquiry Based Science Education;
- STEM - Science, Technology, Engineering, and Mathematics;
- ELM - Experiential Learning Model;
- PV - Photovoltaic
- MPPT - Maximum Power Point Tracking
- STC - Standard Test Conditions
- QUCS - Quite Universal Circuit Simulator
- GUI - Graphical User Interface
- NOCT - Nominal Operating Cell Temperature
- PhET - Physics Education Technology
- BES - Bisogni Educativi Speciali
- DSA - Disturbi Specifici di Apprendimento

Introduction

The reform that revised the Italian high school in 2010 and is still in force nowadays [1] include the introduction of the 20th century Physics in the teaching program of Italian scientific high schools [2]. The reform also emphasizes the use of experimental and practical activities to encourage students to discuss, build concepts, design and carry out measurements and observations. Because of this reorganization, teachers should introduce students to the bases of Quantum Mechanics during their high school senior year and for this reason the learning path designed in this thesis is specifically thought for teaching the Photoelectric Effect with the aid of laboratory activities, according to the Italian reform themes.

Education is one of the most effective means for providing solutions to the problems faced by society, hence another purpose of this project is that of including a renewable energy education in high school. The lack of energy supply difficulties is an essential commodity in modern industrial society and it guarantees a high standard for the quality of human life. It is an issue that affects everyone but few people have a basic understanding of energy supply options and their impact on society and the environment. We are currently living amidst a growing concern about different energy related topics, such as oil depletion, global warming, climate change, energy security, public health, air pollution, waste disposal and ecological damage. Renewable energy is seen by many as part of the appropriate response to these concerns [3] and a large number of countries across the globe has already prioritized the development and large scale dissemination of renewable energy technologies to provide environmentally sustainable energy supply options and meet the growing energy demand. This require an adequate number of trained and competent personnel, while at the same time a majority of socio-cultural and institutional barriers to the dissemination of renewable energy technologies may be overcome if the potential end users, policy makers and others stake holders are made "energy conscious" by providing them all the relevant informations about involved issues and also about the remedial measures. It is now widely accepted that education in the area of energy, renewable energy in particular, is of prime importance and has to have the entire population as its target audience, with proper efforts to be made at the school level [4]. The objectives of the educational project of this thesis therefore aim to develop awareness among the students about energy related challenges being faced by humankind, renewable and non renewable sources of energy, their potential, the existing technologies to harness them and the socio-cultural, environmental and institutional issues related to their development and utilization.

Among all renewable energy resources, this thesis project focuses on the production of electricity from solar radiation through the use of photovoltaic panels. Partly because this technology has strongly penetrated the electricity production sector over the past 10 years [5], becoming of common use in domestic environments and therefore present in students' everyday life, but above all because it allows to easily connect to the Photoelectric Effect, a topic that is nowadays addressed in high school's Physics courses, as previously mentioned.

Introducing photovoltaic projects in school is an important first step to increase the use of solar energy in the community. As has been the case with recycling programs, which were introduced to many communities by schoolchildren educating their parents, students can carry good ideas from the classroom into the mainstream [6].

The project presented in this thesis has been developed considering a student centered approach to the learning-teaching path, with application of virtual laboratories and hands on activities to engage students in a direct and active way.

The thesis is structured in four chapters: the first introduces to the current theories concerning the didactic method to apply as a teacher, the second describes the photoelectric effect and the solar cell, the third is about the simulator software used and the last develops the lessons representing the teaching project. Finally the appendices contain the working sheets to be used in the laboratory activities.

1 Didactic Methods

This chapter introduce the changes in the teaching strategies and describes the new methodologies applied during the learning path.

1.1 Evolution of the teaching strategies

During the second half of the 20th century, the changes happened in the social, political, cultural and economic structures of the western countries implied a transformation in the instruction and training systems. At the beginning there was a quantitative expansion of schooling, that subsequently led to a loss of the quality that the instruction structures offered. That's because the traditional school education, based on a model of an elite culture, wasn't suitable for a differentiated and heterogeneous mass instruction and it entered in a crisis.

Today's phase is fought between the rethinking about some choices of the past and the refinement of others, in a post-ideological comparison in which the conflict between selection school and inclusion school is still in place. More and more importance is attributed to the analysis of the environmental and psychological conditions of learning, to the techniques of teaching planning, the criteria for evaluating the profit and the tools to support the training action, that have been definitively recognized as fundamental tools in the knowledge baggage of the teaching profession [7].

1.1.1 Changing the paradigms of education

The main idea of the teaching process at the basis of this thesis is that it is needed a change in the reference system of the teaching-learning process normally used in the Italian high-school.

Teachers should no longer be the centre of the process, but they would need to focus on how and what their students are learning to teach more effectively. There should be a student-centred approach. This implies that teachers engage students actively in their learning process, make content challenging and interesting, teach students how to learn, give students choices about what and how they learn and make the learning meaningful, as expressed for example in "La buona scuola" [8].

To have an insight of this paradigm change we can also have a look to an interesting divulgation video, for non expert [9]. Ken Robinson suggests that to obtain the target of student's real involvement, the educational system has to:

- promote diversity, offering a wide and articulated curriculum to stimulate the individualisation of the learning process;
- promote curiosity through the creative teaching;
- promote the creativity in the students themselves, encouraging the divergent thinking though alternative and less standardized didactic processes.

Robinson naturally refers to the educational system of the United States of America, that in his opinion promotes compliance and standardisation rather than creative approaches to learning. From this point of view, in the last years the Italian educational system has seen a number of proposals on this subject, but that remains a work unfinished, with problems of resources both for the school structures and for the daily management.

Robinson also stresses the need to recognize education as an organic, non-mechanical system, in which the climate of "command and control" must be replaced with a climate that fosters collaboration and attentive to relationship. This paradigm shift must therefore be at the level of school structures and organizations, of didactic offers, but above all of teachers' attitude, who must rediscover the profound intellectual and social value of their profession, which aims to develop the potential of the students.

Teacher's' skill in connecting with their students on a social and an emotional level is fundamental to maximize the opportunities for students to learn and help them develop learning skills that are long-lasting, useful, applicable and transferable.

This approach to teaching takes shape from the theories developed by Jean Piaget and Lev Vygotsky, important exponents of the Social Constructivism, a philosophical viewpoint established in the second half of the 19th century about the nature of knowledge, according to which human development is socially situated and knowledge is constructed through interaction with others. Their works also focused on how students learn and they led to a student-centered learning, where students instead of teachers are put at the centre of the learning process and the active learning is strongly encouraged. In a student-centered classroom, teacher acts as a facilitator, as opposed to instructor, and his goal in the learning process is to guide students in making new interpretations of the learning material, thereby experiencing content.

One of the main differences compared to the teacher-centered learning is that the students participate in the evaluation of their learning. This means that students are involved in deciding how to demonstrate their learning. This reflects what is the aim of a learner-centered education: develop learner autonomy and independence by putting responsibility for the learning path in the hands of students.

Student-centered learning places a teacher closer to a peer level, and this enhance knowledge and learning, benefiting the student and classroom overall, because according to Lev Vygotsky's theory of the zone of proximal development, the difference between what a learner can do without help and what they can't do (see Fig. 1 [18]), students typically learn effectively if guided by peers with higher skill set.

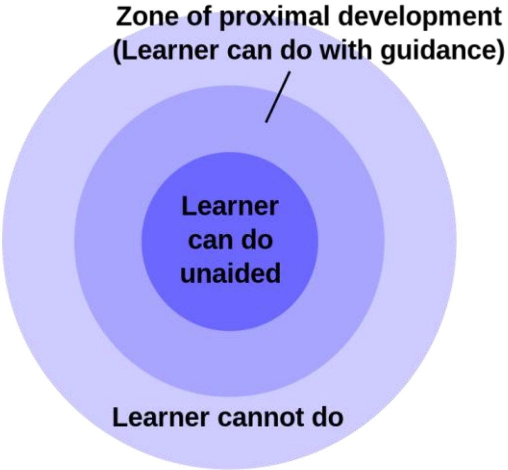


Fig. 1- Zone of proximal development.

A good definition of learning can be:

"learning is the ability to use information after significant periods of disuse and the ability to use information to solve problems that arise in a context different (if only slightly) from the context in which the information was originally learned" [20].

Learning is not just about learning information, it is also the ability to use it. In other words, learning means building competences.

"In the context of socio-constructivism, what makes a competent person is not the set of knowledge deposited in her mind, but how this links with other people's skills and with the different situations in which the person finds himself acting"[21].

Competence arises dealing with other people and the environment, consequently it is important to rethink the teaching in different terms from the simple transmission of knowledge and skills: knowledge must be built by the students as an active process and not passively received.

If this is the new concept of competence, today evaluating can no longer be limited to a mere assessment of skills and knowledge acquired in the school experience, but it is the consideration of how the subject can use his own knowledge to act in a given context. Authentic proves must therefore be prepared, quite similar to those that must be faced in real life, avoiding the types of proof that constitute exercises disconnected from the real context.

1.1.2 Inclusive teaching

Classrooms are more and more an heterogeneous system of teenagers, each of them brings with him a peculiarity linked to particular social contexts, as situations of psychological, social, cultural, economic and linguistic discomfort. Furthermore, High School is part of a very special moment in young people's life: adolescence, which coincides with radical physical, psychological and mental changes. In this phase of transition from child's life to adult life, individuals are called to solve specific tasks of development at social, cultural and relationship level [10].
As stated by the Centre for Teaching Innovation of the Cornell University, an institute centred around effective teaching and innovative learning practise [11]:

“Even though some of us might wish to conceptualize our classrooms as culturally neutral or might choose to ignore the cultural dimensions, students cannot check their sociocultural identities at the door, nor can they instantly transcend their current level of development… Therefore, it is important that the pedagogical strategies we employ in the classroom reflect an understanding of social identity development so that we can anticipate the tensions that might occur in the classroom and be proactive about them” (Ambrose et. al., 2010, p. 169-170).

Therefore teachers also have the task of balancing differences in learning and encouraging the involvement, even emotional, of all their students, regardless of their particular conditions.
For this purpose, it is effective the use of inclusive teaching strategies and teaching methodologies aimed at promoting the collaborative dimension of teaching (see Fig. 2), which sees the school as a community, where teachers cultivate common goals and work together to achieve them.

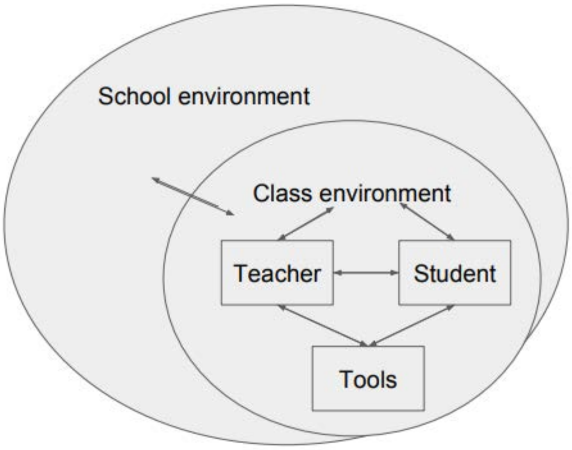


Fig. 2- Collaborative dimension of teaching.

Examples of teaching inclusively are:

- be reflective about how your own cultural-bound assumptions might influence your interactions with students or how the backgrounds and experiences of the students might influence their motivation, engagement, and learning in the classroom;
- be proactive in connecting with and learning about the students;
- be intentional about creating a safe learning environment by utilizing ground rules;

- utilize a variety of teaching strategies, activities, and assignments that will accommodate the needs of students with diverse learning styles, abilities, backgrounds, and experiences;
- be clear about how students will be evaluated and graded, provide justifications;
- take time to assess the classroom climate by obtaining mid-semester feedbacks from students.

It is important to apply an inclusive teaching not only because it answers to the needs of the students but it is also enshrined by the Italian Constitution (art. 3 and 34) and confirmed by international organizations such as UNESCO, which coined the term "inclusive" to qualify a society on the response of the individual's needs.
In particular UNESCO provides the following definitions:

"Inclusion is a process that helps to overcome barriers limiting the presence, participation and achievement of learners, while inclusive education is a process of strengthening the capacity of the education system to reach out to all learners" [12].

UNESCO affirms in his guide the universal right of an inclusive education for every individual.
The presence of students with difficulties should be assessed from the beginning, analyzing the individual documentation, the reports of support teachers, creating opportunities for talks with the family. Depending on the difficulties, students may have a support teacher, a different program with the definition of an IEP (Individualized Educational Plan) or a minimum objectives program with the definition of a PLP (Personalized Learning Plan) containing the definition of a individualized educational activity for every subject, that is realized through didactic strategies, compensatory tools, methods of verification and evaluation tailored on the individual.

1.2 New Teaching Methods

This paragraph describes teaching methods and models adopted in the educational path designed with the thesis.

1.2.1 Laboratory and Inquire Based Science Education

Practical teaching activities are included in this didactic path bearing in mind that physics laboratory is an important part of a physics course. The group activities give the opportunity to promote cooperative learning between students, while the manual work allows students with different skills, less inclined to theoretical study, to approach the subject in a different way.
The two most common points of view, about the goals that physics and science laboratories should have, are:

- laboratories and lectures must share the same purposes: to increase interest and motivation in students, to make pupils improve their understanding of scientific concepts and let them develop problem solving abilities (Hegarty-Hazel, 1990;Tamir, 1990; Hofstein and Lunetta, 2004);
- laboratories should focus more on improving student's practical skills (and not on emphasizing content learning), improving student attitudes about science or their understanding of the nature of science (Hodson, 1993; Trumper, 2003).

So there is no universal agreement on what appropriate goals a laboratory learning environment should have.
A natural laboratory practice in a creative learning environment is represented by the Inquiry Based Science Education (IBSE), an approach to teaching and learning scientific subjects based on the students' learning methods, the nature of the scientific research and a careful reflection on the fundamental contents to be learned. It is important to lead the students to deeply understand what they are learning, and not only to repeat contents and informations. Rather than a superficial learning process directed at the grade, IBSE aims to make students discover that the motivation to learn comes

from the satisfaction of understanding something in a significant way. IBSE doesn't reckon on a lot of informations to learn by heart, but it is interested on building meanings, ideas or concepts bit by bit, through a comprehension that become more and more deep during the students' growth.
For the purpose of this thesis, inquiry will be defined using the definition provided by Abraham and Pavelich:

"A format.. designed to allow each student to work at his/her own intellectual level and to give each student a mini-research experience. This is accomplished by requiring (allowing) the students to define their own analysis and explanation of the data collected." (Abraham and Pavelich, 1999, p.2)

The inquiry approach to teaching laboratory science has quickly risen the top of laboratory best practice pedagogy, recommended by numerous national and international organizations (e.g. National Research Council, 1996; Abd-El-Khalick et al., 2004).
In recent years, IBSE has proven its efficacy in education by expanding on "traditional" lessons and motivating students to actively participate in science [13]. IBSE methods and digital technologies support necessary educational innovations and can be the catalyst for change in educational patterns (in regard to its form, space, functions, services, tools, roles, procedures) [15].
According to the National Science Education Standards (NRC, 1996), high school students

"should have the opportunity to use scientific inquiry and develop the ability to think and act in ways associated with inquiry, including asking questions, planning and conducting investigations, using appropriate techniques to gather data, thinking critically about relationship between evidence and explanations, constructing and analyzing alternative explanations, and communicating scientific arguments." (p.105)

Furthermore, Harwood developed a model for inquiry with the following essential components [14]:

- asking general questions;
- defining a problem;
- forming a question;
- investigating the known
- articulating an expectation;
- carrying out a plan;
- examining results;
- reflecting on findings;
- communicating with others;
- making observations.

Students can perform their inquiry experiments in multiple ways and are offered learning opportunities through assessing their own conjectures, teaching their peers and with individualized teacher's help when needed.

1.2.2 Virtual Laboratory and Simulation

Practical activities and experiments are common, but also the virtual laboratories are an essential and widespread digital tool. In fact, many European schools are equipped with computer classes, tablets and high-speed internet connections.
Thus, students can learn using a huge variety of web-based learning applications, simulations and visualizations [16].
Web-based learning applications, simulations and visualizations (virtual lab) can be very useful in teaching Physics and Science, in particular when:

- the experimental activities are to be done quickly and do not easily allow observation and safe measurement;
- the experimental process is very slow and/or complex and not compatible with the teaching time available;
- the experiments involve risks to the health and physical integrity of learners;
- the learning activities require modeling.

Virtual labs support IBSE in learning science, as a matter of fact:

- laws in science arise from detailed observation processes, with clearly more chances of clarifications, understanding and acceptance if regarded in detail;
- virtual labs encourage collaboration and communication between teachers and students. STEM teachers participate actively in the students' learning process: asking questions, trying to find answers, organizing procedures and commenting on them, helping in formulating conclusions, understanding students' mistakes and highlighting any misconceptions.

The main differences between real life experiences and those formed by representations in a computer screen are:

- with virtual labs, students acquire a tool with which to experiment without limitations of space or time. They are available all year, as opposed to school laboratories, limited to a specific place and for a limited time [17].
- the use of visual environments makes students acquire better computer skills, which can be considered skills for lifelong learning. The use of these technologies also brings together different STEM subjects and provides with great resources for more inclusive workshops [19].

Virtual laboratories aren't meant to substitute real experiment, their role is such of supporting tool for better understanding the principles of demonstrated phenomena. If teachers have the possibility to realize virtual experiment using computer simulations, they can develop important students' skills needed for their professional life not only in STEM fields, buts also in other fields.

1.2.3 Clinical Conversation

The clinical conversation, a survey method initially adopted by Piaget [22], is a semistructured interview whose purpose is to investigate students preconceptions and their mental images about the topic to teach. Teaching is a building process and students have their own foreknowledge that usually represents structures to base new concepts.

In the initial stage the teacher simply gather informations from students' answers, then they are invited to justify their statements. The interviewer have to support them in their speech to clarify and modify what has been said without adding personal opinions. It is important that the teacher reformulates the answers using clarifications given by the students so they can explicit their ideas to themselves and their classmates. Finally the teacher analyses the emerged results, highlights the unanticipated ideas and evaluates them for the teaching project. During the following lessons he will focus more on those aspects of the topic where students showed some misconceptions and he will resume the examples given by the students, both those in harmony and those in contrast with the topic, to outline the new concept to be introduced.

Additional effects that the interview produces, equally important for educational purposes, are the activation of students' attention on the topic and the comparison between the different student experiences. It is important that the interview takes place as a class discussion, during which the interaction and the mutual teaching between students reaches the maximum level, because students learn more easily and quicker through peer education than from the adults.

1.2.4 Game-based learning

Important psychologists as Jean Piaget and Jerome Bruner highlight that game is children's vehicle and environment for learning. According to Bruner, students who engage in hands-on learning and play-based activities experience increased motivation, buoyed creativity, enhanced problem-solving skills, a greater sense of personal responsibility [23].

1.3 Kolb and the Experiential Learning Model (ELM)

David A. Kolb is an American educational theorist born in 1939. He published his learning styles model in 1984, from which he developed his learning style inventory. According to the ELM, learning is considered a holistic process of knowledge creation that takes place through the transformation of experience. This transformation process involves a self-regulation by the subject, who passes through the various phases monitoring its learning path and developing the tools to verify its validity.

The model takes into account the components "heart, mind, hand and eye" (feeling, thinking, doing and watching), considering them all equally important in the learning path. What Kolb wants to highlight is that the active experimentation is guided by both cognitive and affective processes and this is important for the deep understanding of a concept.

Kolb's experiential learning style theory is typically represented by a four-stage learning cycle in which the learner "touches all the bases" [24]:

- Concrete Experience (CE). A new experience or situation is encountered by the learner, who is free to explore it actively and paying particular attention to everything he feels through his sensory system;
- Reflective Observation (RO) of the new experience, to approach the comprehension of the phenomenon. Any inconsistencies between experience and understanding are of particular importance;
- Abstract Conceptualization (AC), where reflection gives rise to a new idea or a modification of an existing abstract concept;
- Active Experimentation (AE), the learner applies the hypothesis to the world around him to see what results.

Those elements are typically represented in a circular graphic to highlight the movement at the basis of the learning process (see Fig. 3). It is possible to enter the cycle at any stage and follow it through its logical sequence.

Kolb explains that different people naturally prefer a certain learning style, which emerges from the combination of two different stages:

- Diverging (CE/RO): these people favour concrete experience and reflective observation, they prefer to watch rather than do. They are able to look at things from different perspectives and to organize the content in significant structures. They are sensitive and more interested in people than things. They establish emotional relationships easily and prefer to work in groups, to listen with an open mind and to receive personal feedback;
- Assimilating (AC/RO): this kind of learning preference involves a concise, logical approach. Ideas and concepts are more important than people. These people require good and clear explanation rather than a practical opportunity. They excel at understanding wide-ranging information and organizing it in a clear, logical format.
- Converging (AC/AE): people with a converging learning style can solve problems and will use their learning to find solutions to practical issues. They prefer technical tasks and are less concerned with people and interpersonal aspects. They learn better when they can have practical experiences about what they are studying and they think than the best theories must have practical applications to be worth.

- Accommodating (CE/AE): this learning style relies on intuition rather than logic. People preferring this approach know how to synthesize between concrete situations and theoretical principles, they are practical thinkers, flexible, intuitive, who like to learn by trial and error rather than scientific rigor. They are fascinated by invention and experimentation. They set their activity more on information coming from other people than on personal data analysis.

It is important to consider this during the development of an educational path, addressing the subject from different points of view so that each student can approach it through the style that is most congenial to him.

Despite having several critical points in the description of the link between learning processes and knowledge, Kolb's model has the merit of providing an excellent working scheme for the design of a scientific learning path, because it explains the importance of exploration and discovery and encourages reflection on what has been learned and the application of knowledge and skills in different contexts.

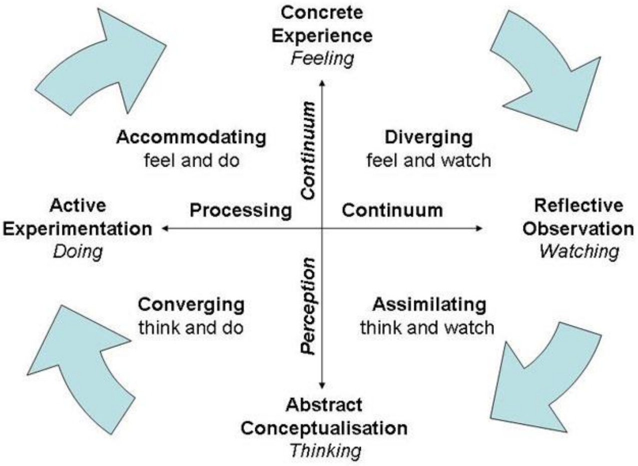


Fig. 3 - The Experiential Learning Model cycle.

2 Photoelectric Effect and Photovoltaic Technology

The chapter presents a description of the photoelectric effect, the photovoltaic technology to use it and it's application in the learning path exposed in the thesis.

2.1 History and explanation of the photoelectric effect

At the end of the 19th century, the classical model of light described it as a transverse electromagnetic wave. There was very little doubt about the wave nature of light among the members of the scientific community because the model was applied successfully to explain such optical phenomena as diffraction, interference, polarization, reflection and refraction.

In 1839 the French physicist Edmund Becquerel first found that certain materials make small amounts of electric current when they are put in light [25], while in 1873 Willoughby Smith observed the same effect in selenium while testing the metal for his high resistance property [26].

But the discovery of a relation between light and electricity, or photoelectric effect as this phenomenon is named today, is generally attributed to Heinrich Hertz in 1887. He observed it while using a spark gap generator during his experiments to prove the effects of the electromagnetic waves predicted by Maxwell and discover the radio waves (see Fig. 4). In these experiments, sparks generated between two small metal spheres in a transmitter induce sparks that jump between two different metal spheres in a receiver. He placed the apparatus in a darkened box to see the spark better. However, he noticed that the maximum spark length was reduced when in the box and that the incidence of visible or ultra-violet light on a spark gap facilitated the passage of the spark. He reported his observations but didn't further pursue the investigation on this phenomenon, that took the name of Hertz's effect [27].

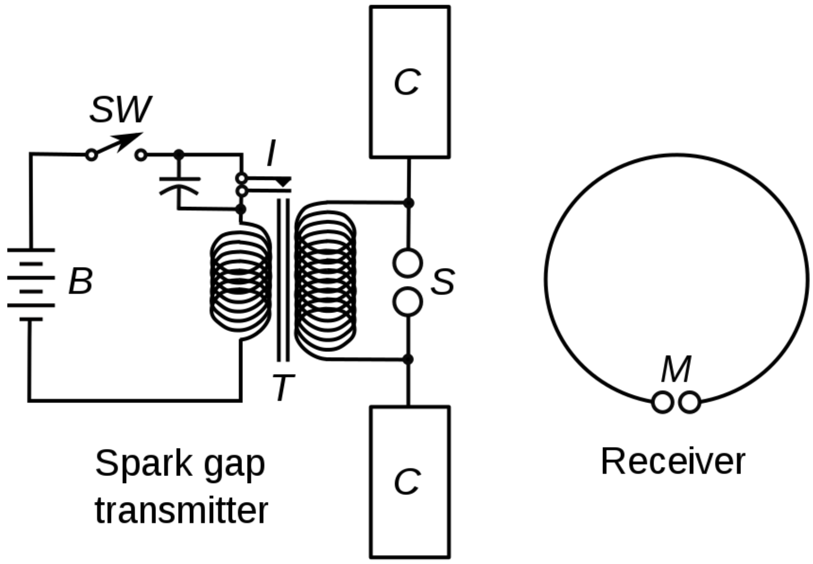


Fig. 4 - Hertz's spark gap generator.

One year before, in 1886, the British physicist J. J. Thomson had researched the ultraviolet light in Crooks tubes and measured the charge/mass ratio of the cathode ray particles, which he called "corpuscles" and that are today identified as electrons [28].

The discoveries of the photoelectric effect and the electrons led to a series of investigations by many scientists in different parts of Europe on the effect of light on charged bodies and those consisted primarily on the following observation: illuminating a metal plate with ultraviolet light initiates a flow of negatively charged particles from the plate.

The nature of the photoelectric current was not clear and led to considerable controversy, because subsequent investigations on the Hertz effect yielded results that did not fit with the classical theory of electromagnetic radiation.

Based on the classical description of light as a wave, classical physicists had made the prediction that the kinetic energy of emitted electrons should increase with light amplitude and that the rate of electron emission, which is proportional to the measured electric current, should increase as the light frequency is increased.

To help understand why they made these predictions, we can compare a light wave to a water wave and we can imagine some beach balls sitting on a dock that extends out into the ocean. The dock represents a metal surface, the beach balls represent the electrons on the metal surface and the ocean waves represent light waves. If a single large wave were to shake the dock, we would expect that the energy from the big wave would send the beach balls flying off the dock with much more kinetic energy compared to a single small wave (see Fig. 5). We would expect also that waves of constant amplitude hitting the dock more frequently would result in more beach balls being knocked off the dock compared to waves of the same size hitting the dock less often. This is also what physicists were expecting to happen: higher amplitude light was predicted to result in electrons with more kinetic energy and higher frequency light at a constant amplitude was expected to increase the rate of electrons being ejected and thus to increase the measurement of the electric current.

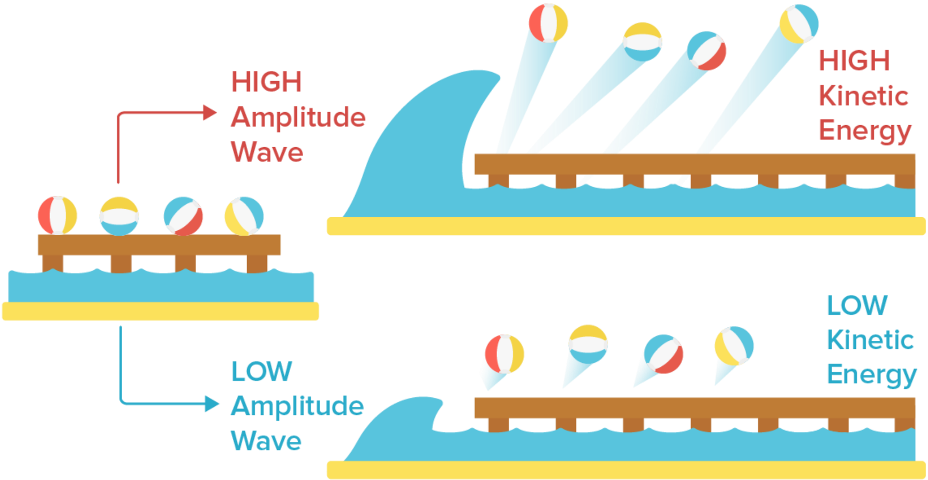


Fig. 5 - Representation of light wave from a classical physics' point of view.

It was Philipp Lenard, an acknowledge expert on cathode rays and assistant of Hertz, who performed in 1902 the earliest studies on the photoelectric effect. He used metal surfaces that were first cleaned and then held under a vacuum so that the effect might be studied on the metal alone, reducing the effects of surface contaminants or oxidation. The metal sample was housed in an evacuated glass tube with a second metal plate mounted at the opposite end. The tube was then positioned or constrained in some manner so that light would only shine on the first metal plate, the one made out of photoemissive material under investigation. Such a tube is formally called photocell. Lenard connected his photocell to a circuit with a variable power supply, a voltmeter and a sensitive galvanometer with a maximum deflection of only a few microampere. He then illuminated the photoemissive surface with different frequencies and intensities (see Fig. 6).

The electric current generated by this means was small but could be measured with the microammetter. Note that the power supply was wired into the circuit with its negative end connected to the plate that wasn't illuminated. This sets up a potential difference that tries to push the photoelectrons back into the photoemissive surface. When the power supply is set to a low voltage it denies the emission of the least energetic electrons, reducing the current measured by the microammetter. An increase of the voltage drives increasingly more energetic electrons back until none of them are able to leave the metal surface and the current through the microammetter is zero. The voltage at which this occurs is called stopping potential.

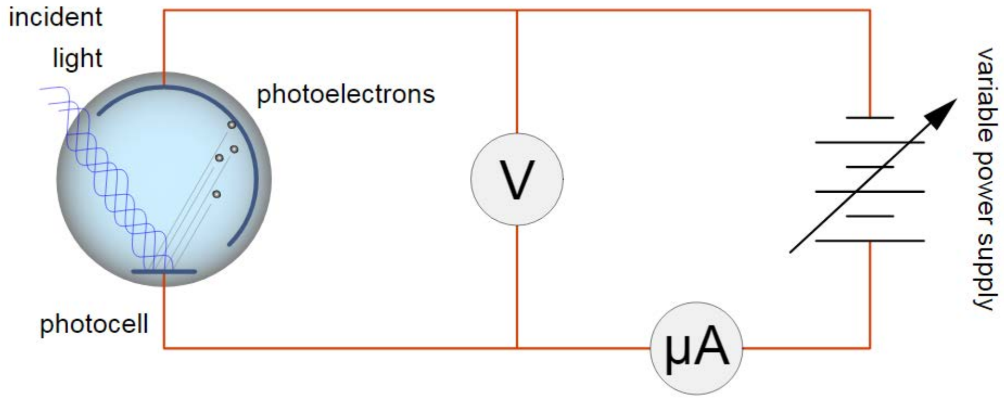


Fig. 6 - Lenard's circuit for studying the photoelectric effect.

Lenard observed that the electrons ejected from exposure to a very bright light had the same kinetic energy as those ejected from exposure to a very dim light of the same frequency (which is related to the colour of the light) [29]. He discovered that the kinetic energy of the emitted electrons increases with light frequency instead. This appeared to be at odds with Maxwell's wave theory of light, which predicted that the electron energy would be proportional the intensity of the radiation. What the light intensity did determine was the number of electrons released from the metal, because it was measured an electric current increment with an increase of light amplitude.

This result convinced him and other physicists that there could be no transformation of light energy into electron kinetic energy. They used existing theories of physics to devise good explanation of the phenomenon and they proposed that electrons in an atom already possesses their photoelectric velocity, or the potential energy equivalent, by virtue of their membership in the atomic system. The light only triggers the release of selected electrons, it does not add energy to them. This "triggering hypothesis" formed the basis of almost all physicists' understanding of the photoelectric effect. Since the structure of the atom was not known at the time, their explanation was quite reasonable although not very detailed.

Differently, the German-born physicist Albert Einstein expressed in his famous paper of 1905, "On a Heuristic Point of View Concerning the Production and Transformation of Light", a new corpuscular theory of light in which light is composed of tiny particles (that he named light quanta) made of a fixed amount of energy that depends on light's frequency [30].

His theory was based upon Max Planck's published law of black-body radiation, in which he postulated that the electromagnetic radiation of a hot body could be emitted only in quantized form [31]. In other words, the energy emitted could only be a multiple of an elementary unit expressed by the equation:

$$E = h\nu$$

(Eq. 1)

where h is Planck's constant and ν is the frequency of the radiation.

Einstein claimed that it was possible for one light quantum, eventually known as photon, to be absorbed by a single electron, imparting to it all its energy. If the electron is near the surface of a metal plate, some of it's new-found energy will be lost in escaping the electrical forces of the grid, a quantity Φ of energy which is a property of the metal itself and is called work function of the surface. The remaining energy is observed as kinetic energy of the electron as it is ejected from the surface of the metal. The energy of the electron so ejected will represent a maximum value, since some may originate from inside the plate and have spent more energy to reach the surface.

Einstein predicted that the stopping potential "should be a linear function of the frequency of the incident light, when plotted in Cartesian coordinates, and its slope should be independent of the nature of the substance investigated"[32].

So Einstein's expression of the maximum energy of an electron ejected by a photon is

$$E = \frac{1}{2}mv^2 = h\nu - \Phi$$

(Eq. 2)

and if the electrons (which have a charge, *e*) are stopped by applying a negative repelling or stopping potential of value V (as in Fig. 6), then the relation becomes

$$E = eV = h\nu - \Phi_C$$

(Eq. 3)

In this relationship the energy Φ to remove the electron from the metal is replaced by a composite value Φc which is a property of the circuit as a whole.

Since it seemed to be an unnecessary rejection of the highly verified classical theory of radiation, Einstein light's quantum theory was refused by the physics community of his period, including Planck the "originator" of the quantum hypothesis. Planck didn't believe that radiation was actually broken up into little bits of energy as his mathematical analysis showed. He thought it was just a contrivance that solved a technical problem and he attempted to interpret the photoelectric effect by suggesting that light energy is not transformed into electron kinetic energy, it already exists within the atom. Planck's theory was the quantum analog of the triggering hypothesis [34].

Chicago physicist Robert Millikan didn't accept Einstein's theory either and he put all his efforts into measuring the photoelectric effect. In 1916 he provided the first direct experimental proof of the exact validity of Einstein equation (see (Eq. 2) and the first direct photoelectric determination of Planck's constant. Simultaneously he described Einstein's light quantum hypothesis as a

"bold, not to say reckless, hypothesis of an electro-magnetic light corpuscle of energy hν which flies in the face of thoroughly established facts of interference. The hypothesis was apparently made solely because it furnished a ready explanation of one of the most remarkable facts brought to light by recent investigations, viz., that the energy with which an electron is thrown out of a metal by ultraviolet light or X-rays is independent of the intensity of the light while in depends on its frequency. This fact alone seems to demand some modification of classical theory or, at any rate, it has not yet been interpreted satisfactorily in terms of classical theory" [33].

So Millikan's paper was not, as we might now consider it to be, an experimental proof of the quantum theory of light. Millikan strongly believed in the wave theory of light and his presuppositions led him to reject Einstein's quantum hypothesis. He failed to disprove Einstein's equation but he was awarded the Nobel Prize in physics in 1923 for the experimental determination of both the elementary electrical charge and Planck's constant based on the Einstein photoelectric equation.

In 1922 Einstein also had received the Nobel Prize in physics for his explanation of the photoelectric effect, even though physicists didn't accept his photon concept.

It was at that time that the American physicist Arthur Compton began to investigate the curious behaviour of X-rays when projected at an aluminium target. Physicists had noticed that the absorption factor of the X-rays was lower than it should be. Compton began to look more closely at the energies of the X-rays after they left the aluminium target. The energy of the X-rays decreased (or their wavelength increased) with the angle of emergence from the target. In 1923 he explained the change in wavelength (or energy) as the result of a billiard-ball-like collision of an X-ray quantum with a nearly-free electron in the target [35]. In Compton's picture, both energy and momentum were perfectly conserved in the collision. At any given angle of emergence of the X-ray, only one wavelength was absorbed and the value shifted downward as the angle increased. The resulting expression was

$$\lambda - \lambda_0 = \frac{h}{m_e c}(1 - \cos\theta)$$

(Eq. 4)

also known as Compton effect, where λ is the wavelength of the X-ray emerging at an angle θ, λ_0 is the incident wavelength, h is Planck's constant, m_e the mass of the electron, and c is the speed of light in vacuum.

By 1925 several experiments had been done that proved that energy and momentum were conserved for each X-ray and electron pair separately.

In 1927 Compton received won the Nobel Prize in Physics and the word "photon" was invented for the light quantum. Compton's experiment and theory served to provide convincing support for Einstein's photon hypothesis and physicists generally accepted it at that time. This was the definitive factor in the acceptance of the photon concept and in the movement to the new physics of quantum mechanics.

The genius of Einstein was in recognizing that Planck's contrivance was in fact a reasonable description of reality. What we perceive as a continuous wave of electromagnetic radiation is actually a steam of discrete particles. Light behave as a wave when studied at a macroscopic level and as a particle when observed at a microscopic level.

2.2 The photoelectric effect inside a solar cell

After the first observations of the so called Hertz's effect, scientists and inventors developed different kind of solar cells, devices able to absorb light and to deliver a portion of the absorbed energy of the absorbed photons to carriers of electrical current. It led to the evidence that semiconductors materials are the favourable choice as metallic surface to irradiate. Silicon has been a common choice since today due to the fact that his absorption characteristics very well match the solar spectrum and because his fabrication technology is well developed and has a low cost as a result of its pervasiveness in the semiconductor electronics industry [37].

2.2.1 Atomic description of silicon

The silicon atom has fourteen electrons and can be found in column IV of the periodic table of elements. This means that his electrons are arranged in such a way that the outer four can be shared with neighbouring atoms to form covalent bonds with those atoms. These four outer electrons are called valence electrons. Large numbers of silicon atoms can bond together to form a solid. As a solid, each silicon atom usually shares each of its four valence electrons with another silicon atom. Each basic silicon unit, forming a tetrahedral arrangement, thereby contains five atoms. Each atom in the silicon solid is held in place at a fixed distance and angle with each of the atoms with which it shares a bond. This regular, fixed formation is called crystal lattice. In silicon the atoms are located so as to form the vertices of a cube with single atoms centred at each of the faces of the cubic pattern (see Fig. 7). The cubic arrangement repeats throughout the crystal [38]. Some properties of semiconductors are dependent on the orientation of the crystal lattice.

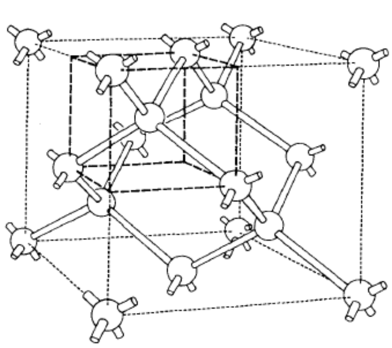


Fig. 7 - Representation of the silicon crystal lattice arrangement.

2.2.2 Properties of the semiconductors

There are three categories of solids, based on their conducting properties: conductors, semiconductors and insulators. Semiconductors are materials that lack enough free electrons to conduct on a free-electron mode, there is a different conduction mechanism for semiconductors than for normal conductors. This fact is evident in a graph presenting the resistivity-versus-temperature for conductors and semiconductors (see Fig. 8).

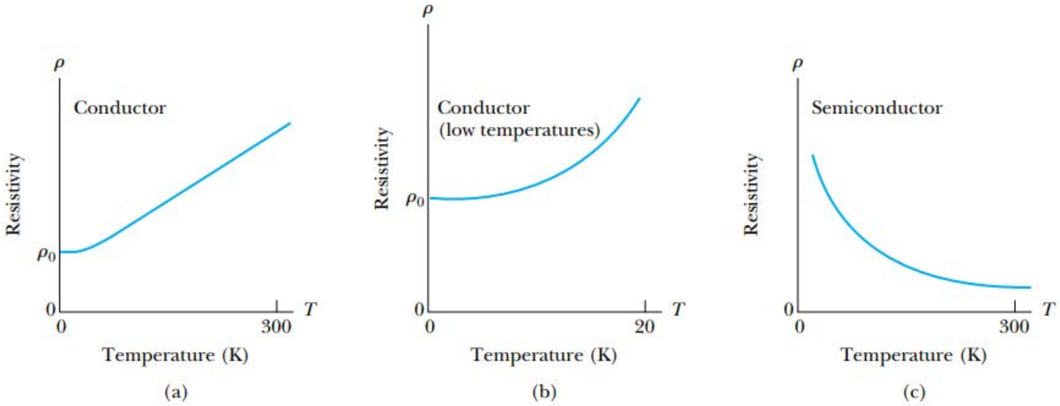


Fig. 8 - Resistivity versus temperature for conductors and semiconductors.

Although the free electron model correctly predicts a linear increase in resistivity with temperature for the conductors, semiconductors generally exhibit a decreasing resistivity with increasing temperature.

To account for this and others properties of semiconductors it is needed the use of the band theory, which essential feature is that the allowed energy states for electrons are nearly continuous over certain ranges, called energy bands, with forbidden energy gaps between the bands [36].

In the band structure of semiconductors exists a filled energy band, referred to as valence band, separated from the next higher band, referred to as the conduction band, by and energy gap (see Fig. 9). Insulators have an energy gap of several electron volts, it is too difficult for an applied field to overcome that large an energy gap and thermal excitation lack the energy to promote sufficient numbers of electrons to the conduction band. But semiconductors have a smaller gap, typically on the order of about 1 eV (for example silicon has a band gap of 1.1 eV), and it is possible for enough electrons to be excited thermally into the conduction band, so that an applied electric field can produce a modest current. The increased number of electrons in excited states explains the temperature dependence of the resistivity of semiconductors. Only those electrons that have jumped from the valence band to the conduction band are available to participate in the conduction process in a semiconductor. More and more electrons are found in the conduction band as the temperature increases, and the resistivity of the semiconductor therefore decrease.

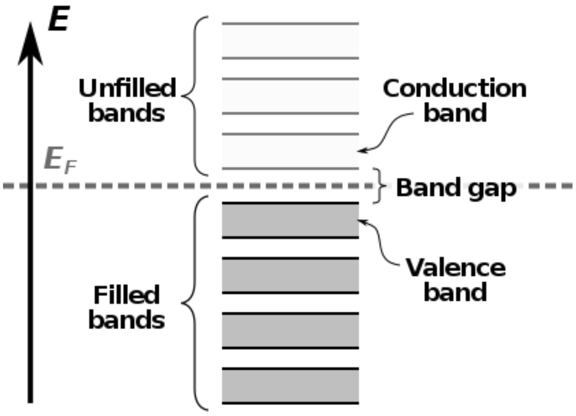


Fig. 9 - Band structure of a semiconductor material.

When electrons move into the conduction band, they leave behind vacancies in the valence band that are called holes. Because holes represent the absence of negative charges, it is useful to think of them as positive charges. As electrons move in a direction opposite to the applied electric field, holes move in the same direction of the applied electric field.

It is possible to fine-tune a semiconductor's property by adding a small amount of another material, called dopant, to the semiconductor. The resulting compound is called impurity semiconductor.

In the case of silicon, if a group V element, like phosphorus for example, is substituted for a silicon atom, four of the five valence electrons will tightly bind to neighbouring silicon atoms, but the fifth electron will be very weakly bound to the phosphorus atom. With a little bit of thermal energy, only about 0.05 eV, the electron will hop up into the bottom of the conduction band and move freely throughout the crystal. The effect is that adding only a small amount of a V column element to silicon greatly increases the electrical conductivity. This addition to silicon creates what is known as n-type semiconductor (n for negative).

Similarly, if a group III element, like boron, is substituted for a silicon atom, all three boron valence electrons will bind with neighbouring silicon atoms, leaving boron atom with a missing electron (a hole). Again the result is a lower electrical resistance as the electrons move to fill holes under an applied electric field. This is called p-type semiconductor because it is always easier to think in terms of the flow of positive charges in the direction of the applied field.

Doping one side of a piece of silicon with boron (a p-type dopant) and the other side with phosphorus (an n-type dopant) forms a p-n junction. It is the fundamental element of semiconductor electronic devices such as diodes and solar cells.

2.2.3 Diodes

Diodes are semiconductor devices made of a p-n junction, in which p-type and n-type semiconductors are joined together. The principal characteristic of a p-n junction diode is that it allows current to flow easily in one direction (forward bias) but hardly in the opposite (reverse bias).

When no external voltage is applied, free electrons from the n-type region near the junction diffuse into the p-type region and their migration leaves a small net positive charge on the n side (see Fig. 10). What remains is an n-type region positively charged and a p-type region negatively charged, both regions depleted of almost all mobile charges and forming what is called the depletion region. This set up an electric field that tends to prohibit further migration and an equilibrium condition is reached [39].

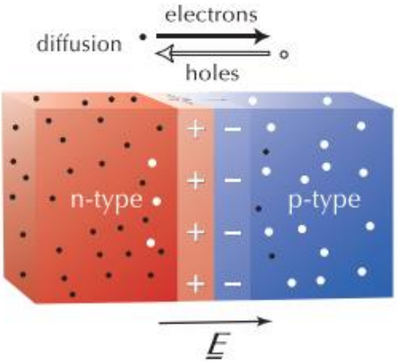


Fig. 10 - The p-n junction diode in equilibrium state.

In the reverse bias case, when a negative voltage is applied to the p-type side and a positive voltage to the n-type side, the "built in" electric field and the applied electric field are in the same direction (see Fig. 11). When these two fields add, the resultant larger electric field is in the same direction as the "build-in" electric field and this creates a thicker, more resistive depletion region and a very small current flow, called saturation current.

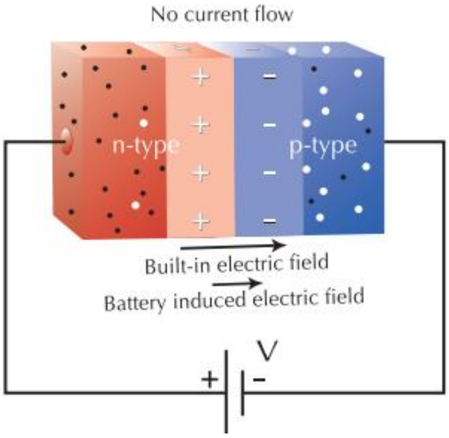


Fig. 11 - Reverse bias in the p-n junction.

In the forward bias a potential difference is applied with the positive terminal connected to the p side and the negative terminal to the n side of the junction (see Fig. 12). The "built-in" electric field and the applied electric field are in opposite directions. The resultant field at the junction is smaller in magnitude than the original "built-in" electric field. This results in a thinner, less resistive depletion region. If the applied voltage is enough, the depletion region's resistance becomes negligible (in silicon, this occurs at about 0.6 V), and the expression of the flowing current is

$$I = I_0 (e^{V/mV_T} - 1)$$

(Eq. 5)

where I_0 is the reverse bias saturation current, V is the potential applied, m is a constant named ideality factor that depends on the material of the cell and V_T is the thermal voltage, a constant defined by

$$V_T = \frac{kT}{q}$$

(Eq. 6)

where k is the Boltzmann constant, T [K°] is the absolute temperature of the p-n junction, and q is the electron elementary charge.

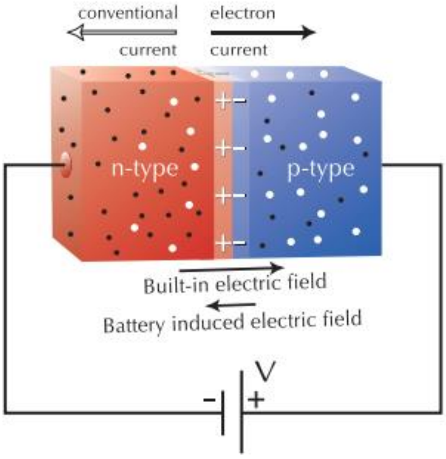


Fig. 12 - Forward bias in the p-n junction.

A good approximation of the (Eq. 5) can be the graphic illustrated in Fig. 13.

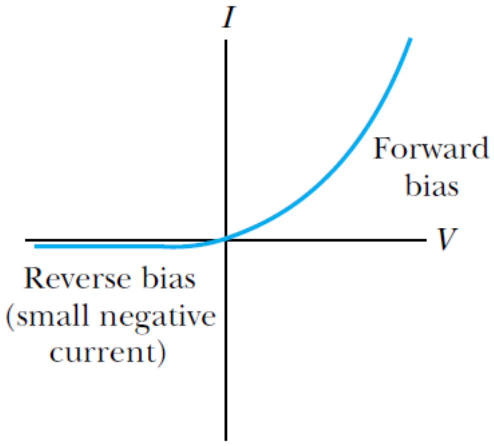


Fig. 13 - A typical I-V curve for a p-n junction.

2.2.4 Photovoltaic cell

The photovoltaic cell, or solar cell, is a particular p-n junction diode that has been carefully designed and constructed to absorb light energy from the sun and convert it into electrical energy, as efficiently as possible.

A simple conventional solar cell structure is depicted in Fig. 14. With the sunlight incident from the top, a metallic grid forming one of the electrical contacts of the diode allows light to fall on the semiconductor between the grid lined. An antireflective layer is present to increase the amount of light transmitted to the semiconductor. The diode's other electrical contact is formed by a metallic layer on the back of the solar cell.

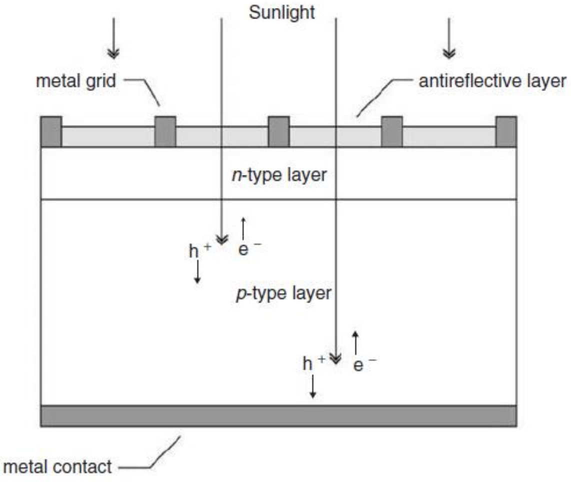


Fig. 14 - Simple solar cell section.

One photon carried by the light is absorbed by one electron at a time, promoting with his energy an electron from the valence band to the conduction band. As expressed by (Eq. 1, photon's energy depends on their wavelength. For example, a valence electron in silicon 0.3 eV below the top of the valence band might absorb a red photon (1.9 eV) and be energized into a state 0.5 eV above the bottom of the conduction band, leaving a hole in the valence band, as shown in Fig. 15. Notice that energy is conserved in this absorption process, so the energy by the electron equals the energy of the absorbed photon. This means that photons with energies less than 1.1 eV, the band gap of silicon, will not be absorbed.

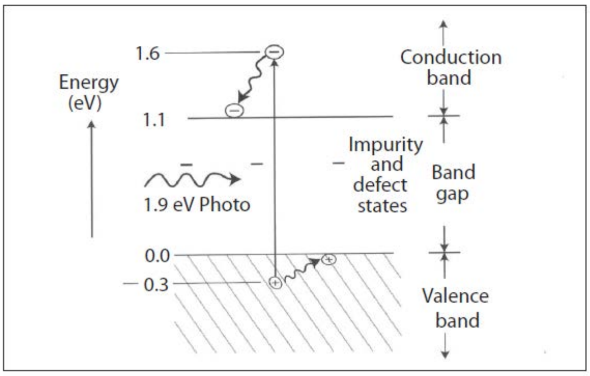


Fig. 15 - Energy levels of a silicon single crystal.

When a conducing electron and a hole pair is created by a photon, the first quickly fall down to the bottom of he conduction band while the second reach the top of the valence band, creating thermal heat. In the absence of an electric field, the electron would be likely to fall into an impurity or defect state in the band gap and eventually reach a hole state at the top of the valence band. But in presence of the build-in electric field inside the p-n junction, the energetic electron is separated from its initial hole state before it is trapped by an impurity or defect.

If a circuit is connected to the p-n junction, the motion of holes and electrons creates an electric current. The energetic electron in the p-type region near the junction will be accelerated into the n-type region, creating the charge separation that repels the high-energy electron from the n-type region into the external circuit and attracts a low-energy electron from the other end of the external circuit into the p-type region to fill the low-energy hole (see Fig. 16). It is like musical chairs where a current of electrons all move one chair over, each one repelling the next one into the next chair.

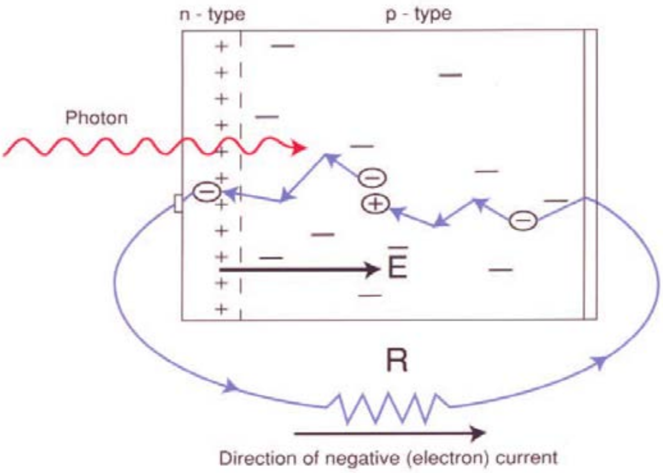


Fig. 16 - Schematic diagram of an electron-hole pair creation inside a p-n junction.

The optimization of solar cell performance depends on some details.

First it is important the material of what should be fabricated the solar cell. Different semiconductors have different band gaps. If the band gap is too small, lots of electrons will be promoted to the valence band from the photons' energies, but most of the energy will be lost in thermal heat when electrons fall to the bottom of the conduction band and the holes fall to the top of the valence band. However, if the band gap is very large, there will be very little energy lost to thermalization but also very few photons absorbed. There is an optimum band gap, 1.4 eV, between these two extremes that will cover up to 33% of the solar energy into electrical energy. But also economics plays a critical role in choosing a solar cell material. It is his optimization of power per dollar that presently gives single crystal silicon the advantage over other materials for most applications.

The efficiency of a solar cell also depends on the doping profile, the concentration and size of the n and p regions. What is wanted is electron concentration, instead of holes concentration, because electrons travel much faster than holes and thus are more likely to be collected before thermalization. To maximize electron collection, a thin heavily doped n-type region and a thick lightly doped p-type region are used. Then most of the photons will be absorbed in the p-type region.

Mass-produced panels of single crystal silicon solar cells today achieve an efficiency of about 15% [40].

2.2.5 Equivalent circuit of a solar cell

The electric behaviour of an ideal cell can be represented by an equivalent electric circuit formed by a current source in parallel with a diode (see Fig. 17) [41].

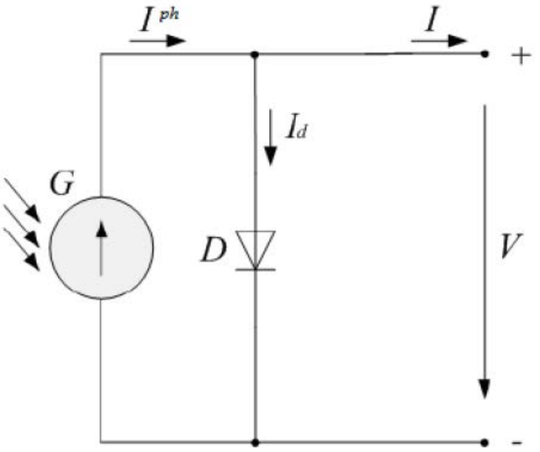


Fig. 17 - Ideal solar cell equivalent circuit.

In Fig. 17, G is the solar radiance, I_{ph} is the photo generated current, I_d is the diode current, I is the output current and V is the terminal voltage.

Based on the forward bias diode current represented in (Eq. 5), the I-V characteristic of the ideal solar cell is given by

$$I = I_{ph} - \mathrm{I_d} = I_{ph} - I_0\left(e^{\frac{qV}{mkT}} - 1\right)$$

(Eq. 7)

A solar cell is characterized by a short circuit current I_{sc} and an open voltage V_{oc}.

For the same irradiance G and cell temperature T conditions, the short circuit I_{sc} is the greatest value of the current generated by the cell and it is produced by the short circuit condition

$$I_{sc} = I = I_{ph} \quad \text{for} \quad V = 0$$

(Eq. 8)

while the open circuit voltage V_{oc} is the greatest value of the voltage at the cell terminals and it is given by

$$V = V_{oc} = \frac{mkT}{q}\ln\left(1 + \frac{I_{sc}}{I_0}\right) \quad \text{for} \quad I = 0$$

(Eq. 9)

The output power is given by

$$P = VI = V\left[I_{sc} - I_0\left(e^{\frac{qV}{mkT}} - 1\right)\right]$$

(Eq. 10)

More accuracy can be introduced to the model by adding the series resistance R_S, which represents the junctions between the semiconductor and the metal contacts and the internal losses due to the current flow, and the resistance R_{Sh}, in parallel with the diode, also known as Shunt resistance, which corresponds to the leakage current to the ground (see Fig. 18) [42].

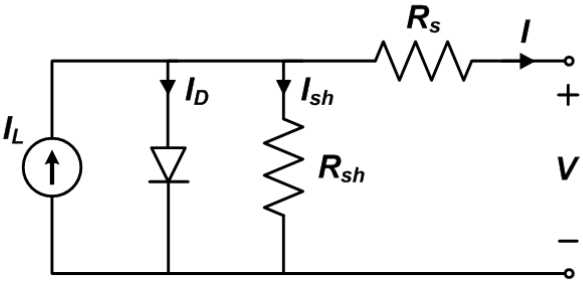


Fig. 18 - Circuit diagram of a PV cell.

In this model, the most commonly used to describe practical PV cells [43], the net current of the cell is

$$I = I_{ph} - I_d - I_{sh} = I_{ph} - I_0\left[e^{\frac{q(V+I\cdot R_S)}{mkT}} - 1\right] - \frac{V + I\cdot R_S}{R_{Sh}}$$

(Eq. 11)

and it can be represented in a typical I-V characteristic of the solar cell for a certain irradiation G and a certain fixed cell temperature T, as shown in figure Fig. 19. The figure also shows three remarkable points that characterize a solar cell: the short circuit current I_{sc}, the open voltage V_{oc} and the maximum power point P_m, that is obtained with the biggest rectangle under the I-V curve, at which the power flow reaching the load is maximum. At the maximum power point correspond the maximum current I_{max} and the maximum voltage V_{max} values of the cell. It should be pointed out that the power delivered to the load depends on the value of the load resistance only. Usually techniques of maximum power point tracking (MPPT) are implemented in PV systems to maximize the power extraction under all load conditions.

Other fundamental parameters are the *maximum efficiency* of a cell, the ratio between maximum power and incident light

$$\eta = \frac{P_{MAX}}{P_{IN}} = \frac{V_{MAX}\cdot I_{MAX}}{A\cdot G}$$

(Eq. 12)

where A is the cell area, and the *fill factor*, the ratio of the maximum power and the product of I_{sc} and V_{oc}

$$FF = \frac{P_{MAX}}{V_{OC} I_{SC}} = \frac{V_{MAX} \cdot I_{MAX}}{V_{OC} I_{SC}}$$

(Eq. 13)

Parameters of the I-V characteristic depends on the cell temperature and the irradiance:

- I_{SC} is a linear function of the ambient radiation and also slightly increase with the cell temperature;
- V_{OC} increases logarithmically with the ambient radiation and decreases linearly with the increasing of the cell temperature;
- η decreases with the increasing cell's temperature;
- FF diminishes as the cell temperature is increased.

Datasheets of the PV cells present parameter informations in standard test condition of measurement (STC): 25 °C for cell temperature (T), 1000 W/m^2 for irradiance (G), 1,5 for solar spectrum and 3 m/s for wind speed.

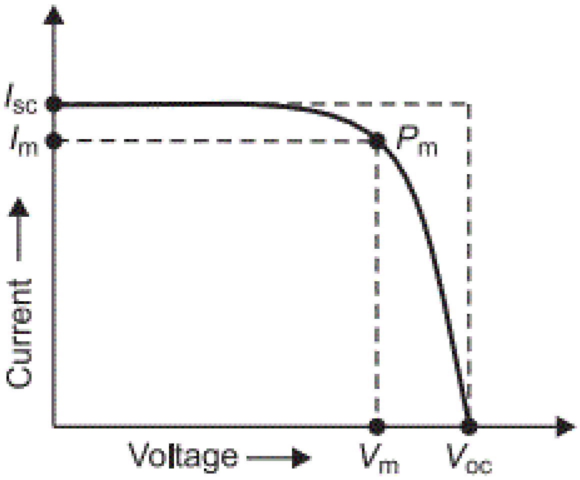


Fig. 19 - Solar cell I-V characteristic.

3 Photovoltaic model simulation with QUCS

There are several models that develop the mathematical modeling of PV cells [44]. The model presented on this thesis is based on an equivalent circuit implemented with Quite Universal Circuit Simulator. QUCS is an open source software that can be used for teaching photovoltaic solar energy while approaching students to simulation software [45]. It is free and for this reason it could be easily applied in any school with access to computers.

With this integrated circuit simulator it is possible to setup a circuit with a graphical user interface (GUI) and simulate it using subcircuits, curves, tables and equations. After the simulation has finished, it is possible to view the simulation results on a presentation page or window [46].

3.1 Model description

For the model simulation of the PV cell, we refer to the equivalent circuit in Fig. 18 and to the I-V characteristic given by the (Eq. 11). All the parameters of the equations that define the model are in STC.

Nowadays Shunt resistances have high values and is therefore possible to simplify the last term of (Eq. 11) with a high value of R_{Sh} (for example 100 kΩ) [47]. Furthermore, I_{ph} can be considered equal to the short circuit current in STC (I_{SC_STC}) in a high-quality PV module [48][49]. Then we obtain the equation

$$I = I_{SC\_STC} - I_{0\_STC}\left[e^{\frac{q(V+I\cdot R_S)}{m\cdot k\cdot T_{STC}}} - 1 \right]$$

(Eq. 14)

The value of I_{0_STC} can be obtained considering (Eq. 14) at the open circuit voltage V_{OC_STC} condition. This corresponds to a value $I=0$, as expressed by (Eq. 9), so no current flows through the resistance R_S.

$$I_{0\_STC} = \frac{I_{SC\_STC}}{\left(e^{\frac{q\cdot V_{OC\_STC}}{m\cdot k\cdot T_{STC}}} - 1 \right)}$$

(Eq. 15)

Variations in cell temperature and irradiance affect the values of the I_{SC}, V_{OC} and P_{MAX} .

Datasheets presents parameters that can be used in the model to consider the cell temperature variation (see Table 1).

Parameters	Affect to...	Units
α	I_{SC}	mA/°C
β	V_{OC}	mV/°C
γ	P_{MAX}	mW/°C

Table 1- Parameters that include temperature variation in the PV cell model.

Therefore to calculate I_{ph} considering its linear dependency on the G and that it is also slightly influenced by T, it is possible to apply [52]

$$I_{ph} \cong I_{SC} = \left[I_{SC\_STC} + \alpha \cdot (T - T_{STC}) \right] \frac{G}{G_{STC}}$$

(Eq. 16)

and obtain a prediction of the saturation current value from (Eq. 15)

$$I_0 = \frac{\left[I_{SC\_STC} + \alpha \cdot (T - T_{STC}) \right] \cdot \dfrac{G}{G_{STC}}}{\left(e^{\left[\frac{q \cdot (V_{OC\_STC} + \beta \cdot (T - T_{STC}))}{m \cdot k \cdot T_{STC}} \right]} - 1 \right)}$$

(Eq. 17)

where the cell temperature T is obtained through the relation with ambient temperature T_A [53]

$$T = C \cdot G + T_A$$

(Eq. 18)

$$C = \frac{T_{NOCT} - 20}{800 \left[W/m^2 \right]}$$

(Eq. 19)

and T_{NOCT} is the Nominal Operating Cell Temperature, defined as the temperature reached by open circuited cells under the conditions of an irradiance of 800 W/m^2 , ambient temperature of 20°C and wind velocity of 1 m/s. It is a parameter that can be found in PV cell's datasheets.

For the determination of R_S, there is an empirical relation between V_{OC_STC}, I_{SC_STC} and R_S when R_{Sh} is considered with a high value [50]

$$R_S = \left(1 - \frac{FF}{FF_0} \right) \cdot \left(\frac{V_{OC\_STC}}{I_{SC\_STC}} \right)$$

(Eq. 20)

where the Fill Factor is calculated as in (Eq. 13)

$$FF = \frac{V_{MAX\_STC} \cdot I_{MAX\_STC}}{V_{OC\_STC} \cdot I_{SC\_STC}}$$

(Eq. 21)

and FF_0 is the empirical expression for the fill factor of an ideal device [51]

$$FF_0 = \frac{voc - \ln(voc + 0{,}72)}{voc + 1}$$

(Eq. 22)

voc is defined as normalized V_{OC} and is the ratio between the open circuit voltage and the thermal voltage (see (Eq. 6)

$$voc = \frac{V_{OC\_STC}}{V_T} = \frac{q \cdot V_{OC\_STC}}{k \cdot T_{STC}}$$
(Eq. 23)

3.2 Model application with QUCS

The model described above has been applied to simulate a PV cell from a STP005P solar panel, it is produced by PV LOGIC and it is of easy access as laboratory material for a high school [54].
The panel consists of 36 solar cells (*N*=36) in series connection and his datasheet parameters are represented in Table 2 and Table 3.

Model	Output [Wp]	Size [mm]	Weight [Kg]	Pmax [W]	Vmp [V]	Imp [A]	Voc [V]	Isc [A]
STP005P	5	306 x 218 x 25	0.8	5	17.5	0.29	22	0.32

Table 2 - PV module STP005P characteristics made with IEC 61215 certification.

Current temperature coefficient	α	+0.003 A/°K
Voltage temperature coefficient	β	-0.13 V/°K
Power temperature coefficient	γ	-0.675 W/°K
Nominal Operating Cell Temperature	T_{NOCT}	48 °C

Table 3 - Temperature coefficients of the STP005P solar panel model.

The first step is the creation of the equivalent circuit of a single PV cell (see Fig. 20).
It is formed by a dc current source from the source library, a diode from the non linear components library and resistors from the lumped components library.
Equation section Eqn1 in Fig. 20 contains the values of the solar cell's parameters. The open circuit voltage *Voc_stc*, the maximum power point voltage *Vmax* and the voltage temperature coefficient of a single cell *beta* were obtained dividing the respective datasheet parameter for the number of the cells [45]

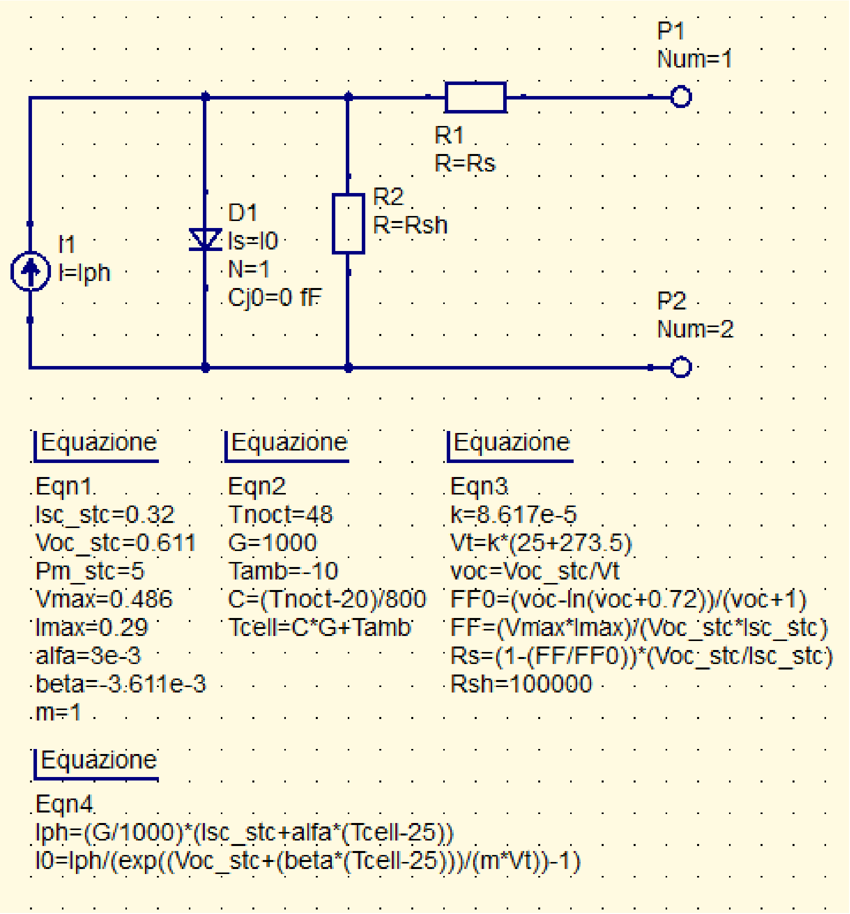
$$Voc\_stc = \frac{Voc}{N} = \frac{22}{36} = 0.611[V]$$

$$V\max = \frac{Vmp}{N} = \frac{17.5}{36} = 0.486[V]$$

$$beta = \frac{\beta}{N} = \frac{-0.13}{36} = 3.611 \cdot 10^{-3}$$
(Eq. 24)

In Eqn2 section are represented (Eq. 18) and (Eq. 19), it is also possible to set up different values of the radiation *G* and the ambient temperature *Tamb*.
Eqn3 contains (Eq. 20), (Eq. 21), (Eq. 22) and (Eq. 23) for the estimation of the series resistance *Rs*, while for the Shunt resistance *Rsh* it has been chosen a high value of 100 kΩ.
The value of the current source is calculated on variable *Iph* based on (Eq. 16) while the value of the saturation current of the diode is calculated on variable *I0* based on equation (Eq. 17). Both variables can be seen in the Eqn4 equation section.
After modeling the equivalent circuit, it has been created it's subcircuit by connecting the PV cell output with external port connections (positive for *P1* and negative for *P2*). By pressing *F9,* it is possible to edit a representation of the subcircuit and to name it (*CellN*).

The subcircuit is used to create a model of the PV module by connecting the PV cell subcircuits in series (see Fig. 21). Subsequently also for this model it is applied the subcircuit creation procedure (*ModuleN*).



```
Equazione
Eqn1
Isc_stc=0.32
Voc_stc=0.611
Pm_stc=5
Vmax=0.486
Imax=0.29
alfa=3e-3
beta=-3.611e-3
m=1

Equazione
Eqn2
Tnoct=48
G=1000
Tamb=-10
C=(Tnoct-20)/800
Tcell=C*G+Tamb

Equazione
Eqn3
k=8.617e-5
Vt=k*(25+273.5)
voc=Voc_stc/Vt
FF0=(voc-ln(voc+0.72))/(voc+1)
FF=(Vmax*Imax)/(Voc_stc*Isc_stc)
Rs=(1-(FF/FF0))*(Voc_stc/Isc_stc)
Rsh=100000

Equazione
Eqn4
Iph=(G/1000)*(Isc_stc+alfa*(Tcell-25))
I0=Iph/(exp((Voc_stc+(beta*(Tcell-25)))/(m*Vt))-1)
```

Fig. 20 - Equivalent circuit of a STP005P solar cell represented in QUCS.

The last step is represented by connecting the PV module subcircuit to a load resistance *Rl* (see Fig. 22). The current on the load is measured with a current probe (*I_modul*) from the probes library, while the voltage can be acquired by labelling the wire on one node of the load (*V_modul*) with the other one on ground. The power *P_module* generated by the module is calculated in Eqn1 of Fig. 22 as the product of current *I_module.I* and the voltage *V_module.V* measured. In the same section are represented the variables *I* and *P* to get respectively the I-V and the P-V curves of the panel using the *PlotVs()* function.

In QUCS to configure a simulation it is needed the use of components from the simulations library. In particular to get the module's curves *dc simulation* and *parameter sweep* are needed, as in the simulation configuration of Fig. 22. The first because of the nature of the solar panel that produces in direct current, the second changes the value of variable *Rl* from 0Ω to 1000Ω.

After launching the simulation, the results are shown on graphics from the *Cartesian* section in *Diagrams* library, while the table is from the *Tabular* one and represents the values of current, voltage and power of the module in function of the resistance load.

The simulation can be launched with different values of irradiance and temperatures to show the variations of the panel's curves. In particular the graphics in figure Fig. 22 represents a simulation with irradiance G=1000 W/m^2 and cell temperature Tcell= 25°C and it corresponds with the values expressed in the datasheet.

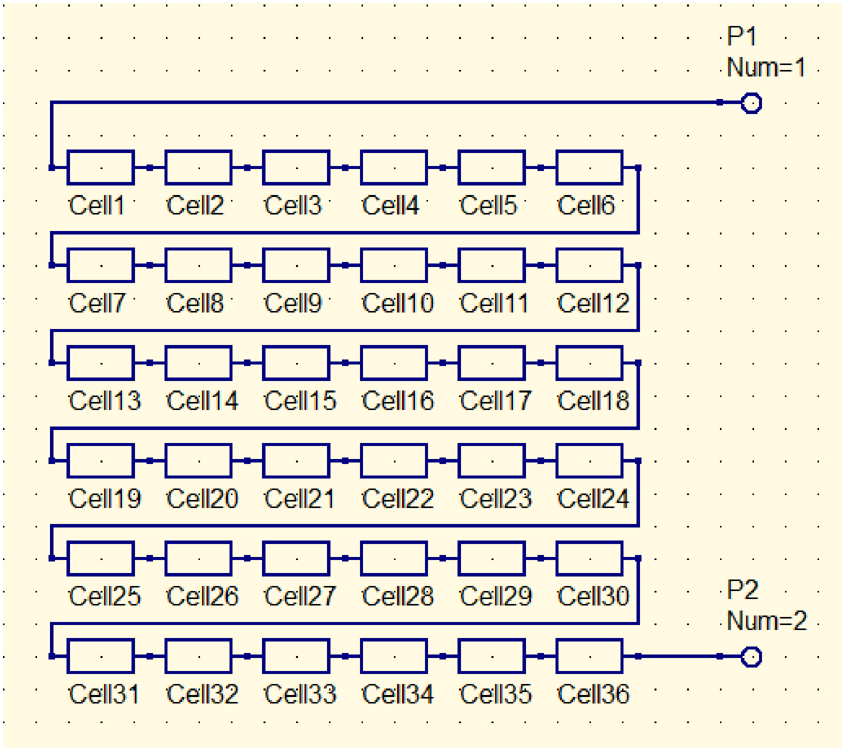
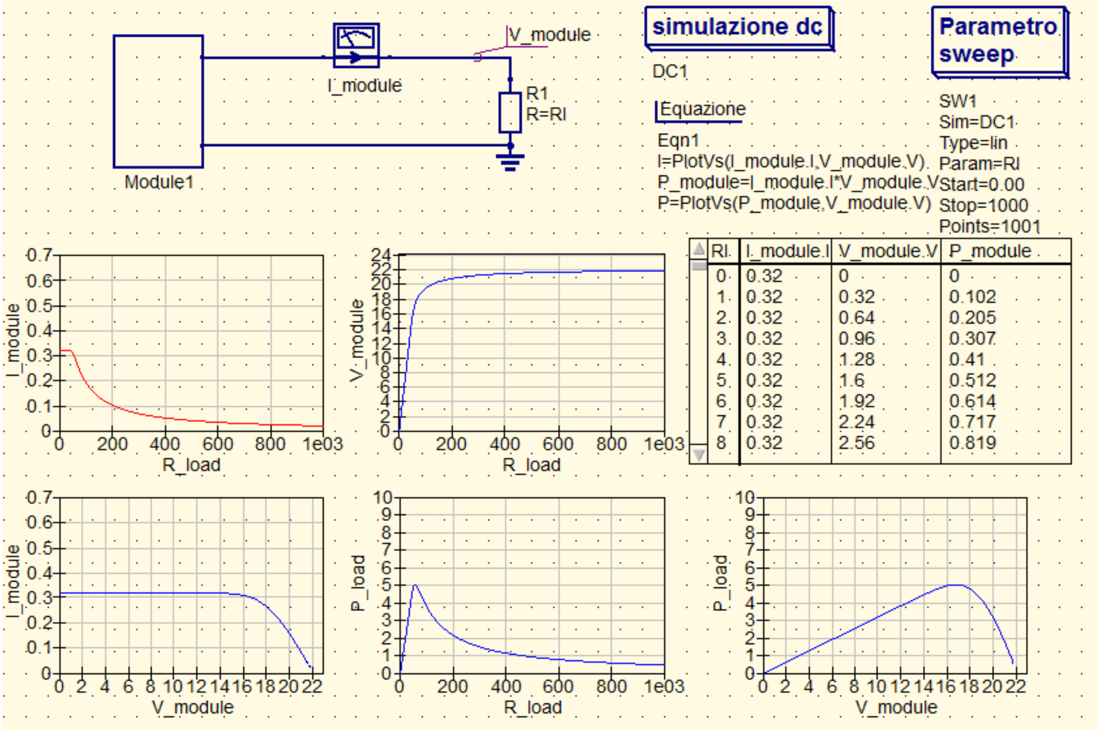


Fig. 21 - Model of the PV module based on the series of the PV cell's subcircuits.



DC1

Equazione

Eqn1
I=PlotVs(I_module.I,V_module.V)
P_module=I_module.I*V_module.V
P=PlotVs(P_module,V_module.V)

SW1
Sim=DC1
Type=lin
Param=Rl
Start=0.00
Stop=1000
Points=1001

Rl	I_module.I	V_module.V	P_module
0	0.32	0	0
1	0.32	0.32	0.102
2	0.32	0.64	0.205
3	0.32	0.96	0.307
4	0.32	1.28	0.41
5	0.32	1.6	0.512
6	0.32	1.92	0.614
7	0.32	2.24	0.717
8	0.32	2.56	0.819

Fig. 22 - Final result of the STP005 PV panel simulation with QUCS.

4 Didactic Project

The didactic project designed in this thesis is thought to introduce in a physics course the photoelectric effect and the use of it to produce electricity with solar panels. It is addressed to a class of no more than 30 students attending their senior year of an Italian scientific high school, but with the appropriate changes it could be addressed to students of different high schools and courses, such as electronic classes in technical institutes. It is important to highlight that this project must be considered as a general guideline. Teachers interested in applying it are expected to modify it according to their needs on the basis of the particular kind of students attending their course.

The disciplinary objectives to be reached with this project are in accordance with the ministerial guidelines [55] and are shown in Table 4.

The project has been designed to be comprehensive solution that takes into account web based application simulation and hands-on activities, in compliance with the Italian reform themes [56]. Moreover, the social competences and critical aspects on energy problems have an important additional value.

Concerning the practical activities, the experiences proposed can be carried by getting the typical instruments of an electronic laboratory (multimeters and conductors) and some photovoltaic modules, that result to be low cost and thus very affordable for a school.

Considering that the project introduces Quantum Physics and the Photoelectric Effect, it is proposed to students close to the end of the academic year, after teaching electrical circuits and the classical model of light wave, that represent important prerequisite knowledge to understand the photoelectric effect.

The educational path is articulated in 5 lessons of 1 hour each:

- Lesson 1 is centered on verify that all students are aware of the basic principles to deal with the new topic and on the explanation to the students about the focus of the project;
- Lesson 2 concerns the to the photoelectric effect with use of virtual laboratory and a simulation;
- Lesson 3 is focussed on the application of the photoelectric effect on p-n junctions and solar cells;
- Lesson 4 is dedicated to the QUCS simulations about solar cells and solar modules;
- Lesson 5 is spent on active experimentations with real solar panels.

Finally an evaluation test will be assigned with the purpose of verifying the knowledge acquired by the students through the development of a project, that represents a portion of their final note that will sum with other evaluations of their activities during the learning path.

In this program, students are asked to work in groups during all laboratory and practical activities, to promote the growth of a cooperative and inclusive behaviour that is essential in any scientific field and in a general social environment. Through laboratory experiences, students can learn how to exchange ideas respecting each others, to listen to classmates' opinions, to explain personal ideas and to sustain ideas on the basis of empirical evidences. Moreover, they will be incited to help other team members to understand difficult topics or perform practical tasks.

This collaborative strategy should also be effective in helping students with special educational needs (BES students) or students with learning-specific problems (DSA students) to integrate and interact with their peers.

Teacher's knowledge of his students is fundamental to form balanced working groups. As described in paragraph 1.3, he should group pupils showing different learning mechanisms to enhance their collaborative behaviour and to switch their roles during the practical experiences so that any student is allowed to perform different tasks, even the unfamiliar ones, in order to acquire new skills and to improve those already possessed.

During the laboratory activities it is a good practice for the teacher to adopt some basic rules to correctly manage the lesson, such as:

- to maintain an active role of interaction with the students throughout the laboratory period;

- to move around the room to be accessible to students, focusing equal time on groups that ask and those that do not ask for help,
- to be aware of the progress of all student teams and address students by name whenever possible;
- listen to what is being said in groups to anticipate and diagnose instructional problems.

PROFICIENCY	KNOWLEDGE	CAPACITY
Basic citizenship skills	• Learn to learn, design, communicate, collaborate, participate and to act autonomously and responsibly	• Problem solving • identify links and relationship • acquire and interpret information
Observe, describe and critically reflect on the phenomena belonging to the physical world	• How to evaluate the physical quantities involved in the natural phenomenon under examination • to grasp the qualitative relationships existing between the different physical quantities • measure concept and his approximation	• Collect data through direct observation of the phenomenon • organize and represent the collected data
Analyze and interpret data obtained through observation of a physical phenomenon	• Wave and particle models of light • energy quantization • photoelectric effect and solar cell • electrical circuits	• use of simulation software to elaborate data • to present on a graph the physical quantities involved in the laboratory experiences
Communicate in a scientific context	• The specific language of the discipline	• Argue their ideas and decisions • know how to expose the description of a physical phenomenon

Table 4 - Disciplinary objectives

According to this learning path, students will be engaged half of the times in laboratory activities, but also theoretical face to face lessons are planned to introduce the topics. Nevertheless, students are asked to follow an original learning path, different from the most common didactic approach that usually consists in a wide explanation of the theory beforehand, a later practical experience in the laboratory and a final data analysis to check that the experimental results match the theory already explained. In the following part of the chapter, all the lessons designed are described in detail.

4.1 Lesson 0

The project has a student centered approach to the teaching, for this reason it has been thought a Lesson 0, that should take around fifteen minutes at the end of a lesson before the start of the project, in which the teacher asks the students to collect some informations and to speak with their parents about the electrical consumption of their homes, by having a look to the light bill or checking the power consumption of their domestic appliances for example. These informations will be reported in class as a starting point of discussion in the next lesson and this should help students to feel personally involved in what they will learn during the project.

4.2 Lesson 1

The main purpose of this first lesson is to assure that all students begin the learning path with the same foundations and to address all the possible misconceptions students present.

During the lesson, the didactic strategy adopted by the teacher is the clinical conversation described in paragraph 1.2.3, to set up a debate with the students about electrical energy consumptions. This conversation is performed in classroom and every pupil should be allowed to speak in turn. To make the conversation more interactive and to establish a more informal environment, the teacher should assure the students that they are not going to be judged for their interventions about the subject. This is thought to avoid a stressing environment.

Taking inspiration from the students' debate, probably someone of them has a solar system producing electricity at home or uses a PV generator for charging his electronic devices, the teacher should focus the attention of the students about the production of electricity from renewable resources, in particular with solar panels. Students are supposed to have a minimal information about the production of electricity from light, maybe gained during past physical classes or out of the school, and this conversation is conceived to let the teacher understand what prior knowledge students have about the topic, but also to discuss the social and technical aspects that concern energy supply.

A variation or integration to this method could be the administration of a test to the students for the sole purpose of understanding students' prior knowledge, avoiding the assignation of a score to every student for the same reasons previously explained. The test could be in the form of a multiple choice test about electromagnetic and wave physics, the main prerequisite knowledge for the project, and, even more interesting from a didactic point of view, a practical laboratory experience to develop in groups about electrical circuits. For example the teacher could ask the students to create a lamp circuit that will continue to work even after some light bulbs break, to verify the understanding of parallel and series in an electrical circuit.

If the test shows some holes in the students knowledge, the teacher is expected to dedicate some of the time of the following lesson to clarify the concepts with a frontal lecture and the use of a Power Point presentation.

In the second part of the lesson, the teacher briefly instructs the students on what they are supposed to do during the didactic path and what is its goal, without giving to many details. This is done to prepare the students to the following lessons and make them work more effectively. The students are said that the focus of the project is to design a solar system to produce electricity for a common house. For this purpose they will be introduced to the photoelectric effect and the technology that takes advantage of this effect, the solar cell, through computer simulations and also practical activity, working most of the time by groups.

It may be helpful to give the students some "advance organizers", such as graphical schemes or general outlines to be followed during the project.

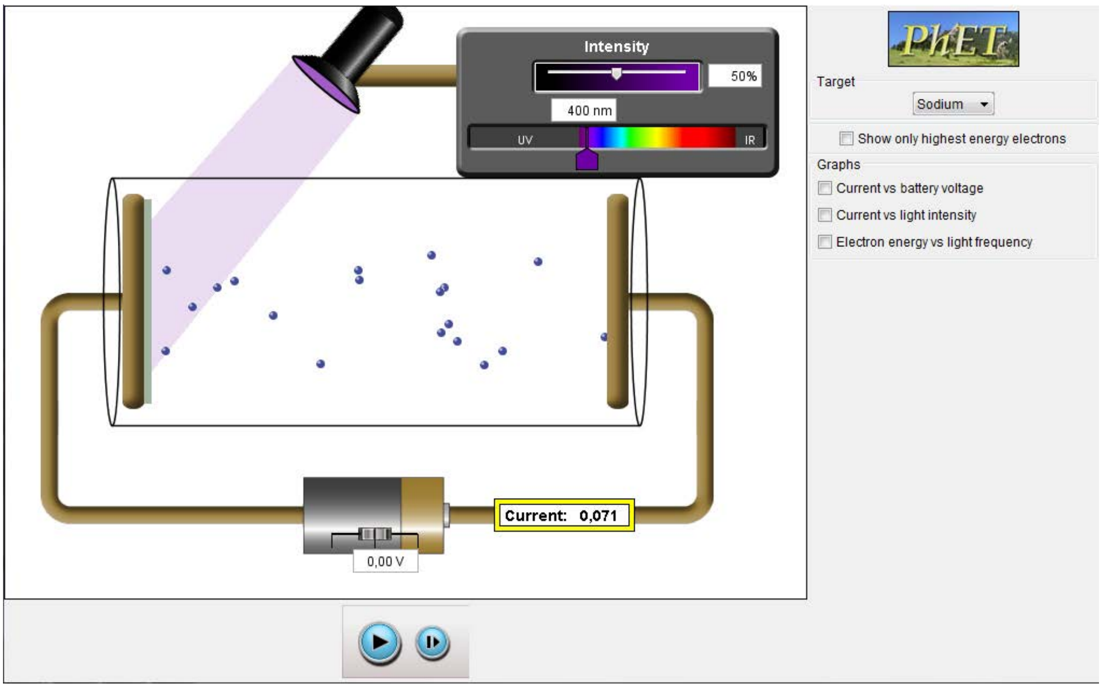
4.3 Lesson 2

The second lesson is focussed on the concept of photon and the explanation of the photoelectric effect. It is structured in a frontal lecture about the topic, followed by the application of a virtual laboratory as didactic method (see paragraph 1.2.2). It takes place in a laboratory room with access to computers, where the teacher instruct the students on what they will do and he divides them in group of two. At the beginning of the hour the teacher gives them a written text on a paper sheet about the history of the photoelectric effect to read and discuss together in classroom. For this purpose, an extract from paragraph 2.1 of this thesis could be suitable. The historical lecture allows to create a link between the previous knowledge acquired by the students about classical physics and to introduce the topic of quantum physics from a multidisciplinary point of view, thus involving the pupils more interested in humanistic and literary subjects.

The activity goes on using a virtual laboratory called *The Photoelectric Effect*, which is part of the PhET Interactive Simulation Project at Colorado University and can be downloaded for free at [57].

Several studies have revealed that students have difficulty to understand the photoelectric effect's underlying processes [58] and this software can be an important tool to help them identify its relevant concepts.

The interactive simulation represents a circuit similar to the one Lenard created to study the photoelectric effect, as described in paragraph 2.1 (see Fig. 23), and students can use it to construct a mental model of the experiment. The teacher demonstrates its main features, focusing the attention on the quantities affecting the photocurrent and the students are inducted to reproduce Lenard's experience. From the software interface, they can control inputs such as light intensity, wavelength, battery voltage, and to receive immediate feedback on the results.



Intensity 50%
400 nm
Target Sodium
Current: 0,071
0,00 V

Fig. 23 - *The Photoelectric Effect* simulation interface and demonstration of ejecting electrons from a sodium plate.

Initially the variable voltage supply is set to zero, so there is no potential difference in the circuit that would stop or speed up the ejected electrons. This strategy is adopted to help students realize that the only condition for initiating the photocurrent is giving the ejected electrons a sufficient amount of kinetic energy. As suggested in [59], a prior case illustrating no electrons moving in the vacuum chamber and with zero intensity of current, even with the battery potential set at its maximum value, should be shown to students to help them understand correctly the purpose of the battery and that it doesn't contribute to the intensity of the photocurrent (see Fig. 24).

Differently to a real experiment, the electrons passing from one plate to the other are visible. This aspect of the simulation is extremely useful in helping students visualize the effect of changing the voltage. They can see in a very concrete way that increasing the voltage accelerates the electrons and making the voltage negative decelerates them, and that increasing the speed of the electrons does not increase the number arriving per second on the plate and therefore does not increase the current.

The electrons also provide a compelling way to visualize the meaning of the stopping potential, in fact when the battery voltage is tuned to exactly the stopping potential, the students can see the electrons just make it to the opposite plate and the turn around.

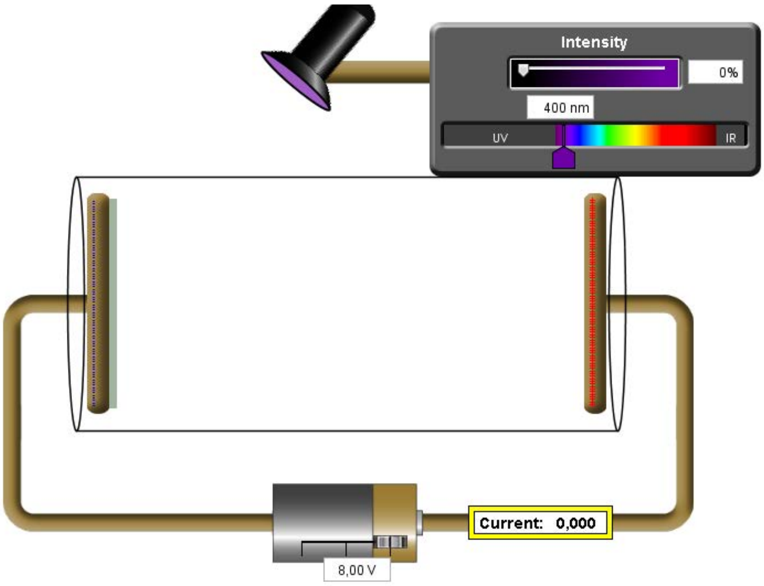


Fig. 24 - Demonstration of no current flow with the potential of the battery at his maximum value.

There are several plates of different materials that can be chosen as source of ejected electrons, and this offers the opportunity to help students understand the concept of working function Φ, as they can see that every material has a different wavelength value to initiate the photocurrent.

The simulation also allows students to interactively construct the graphs commonly found in textbooks, such as current vs. voltage and current vs. radiation (see Fig. 25). By seeing these graphs created in real time as they change the controls on the experiment, students are able to see the relationship between the graphs and the experiment more clearly than when viewing static images.

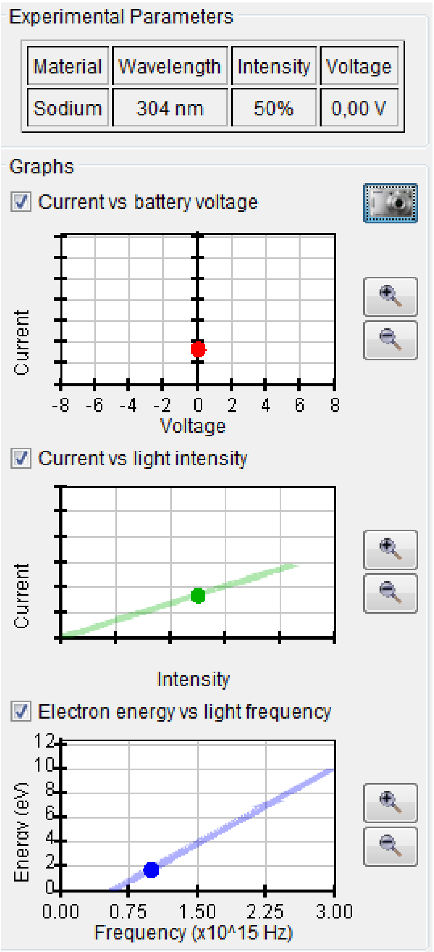
The electron energy vs. frequency graph is of particular importance because it represents Einstein's equation (see (Eq. 2). The teacher discuss the equation by asking to the different groups of students to plot a graph of the electron kinetic energy depending on the frequency of the radiation and what fundamental quantities can be determined from it. At the end of the activity, with the help of the simulation, the peers and the teacher, students should have a clear representation of the graph in Fig. 26. It is important they understand the meaning of the function. A positive energy value represent the kinetic energy acquired by ejected electron, while a negative one is the energy the electron is lacking to leave the metal plate. When the energy is zero, corresponding to the threshold frequency, the electron has just enough energy to be knocked of the surface. The y-interception is the work function of the material and it appears as a negative value on the graph to represent that when there is no radiation (frequency = 0 Hz), the electron is completely attached to the material. Finally it must be highlight that the slope always corresponds to Planck's constant and it is possible to notice this by taking a look at the values to use to calculate the slope of the line (Δx and Δy) and at the "rise over run" that is a change in energy over a change in frequency

$$E = h\nu \Rightarrow h = \frac{E}{\nu}$$

$$slope = \frac{\Delta y}{\Delta x} = \frac{rise}{run} = \frac{E}{\nu} = h$$

(Eq. 25)

To strengthen the concepts learned during the activity, the students are assigned questions and exercises to answer at home that will be evaluated by the teacher. Fig. 27 and Fig. 28 show exam questions that were designed in [58] as final assessment.



Experimental Parameters

Material	Wavelength	Intensity	Voltage
Sodium	304 nm	50%	0,00 V

Graphs

☑ Current vs battery voltage

☑ Current vs light intensity

☑ Electron energy vs light frequency

Fig. 25 - Example of graphs obtained with the simulation.

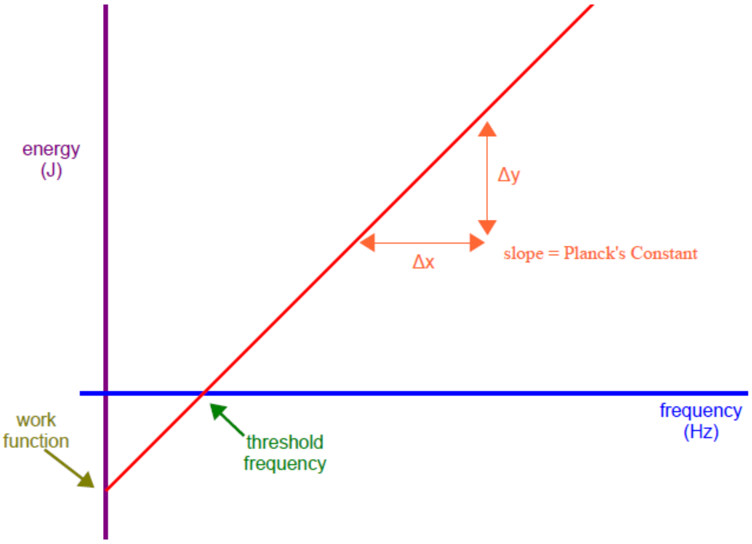
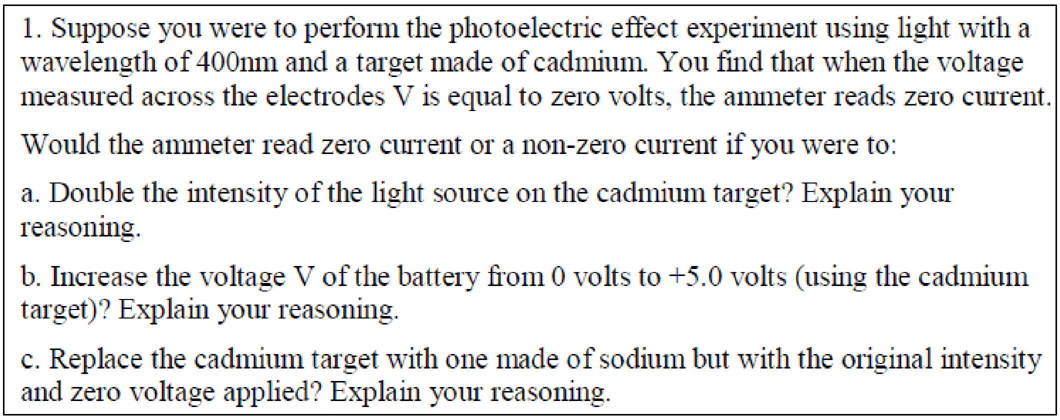


Fig. 26 - Electron energy as a function of the radiation's frequency.



1. Suppose you were to perform the photoelectric effect experiment using light with a wavelength of 400nm and a target made of cadmium. You find that when the voltage measured across the electrodes V is equal to zero volts, the ammeter reads zero current.

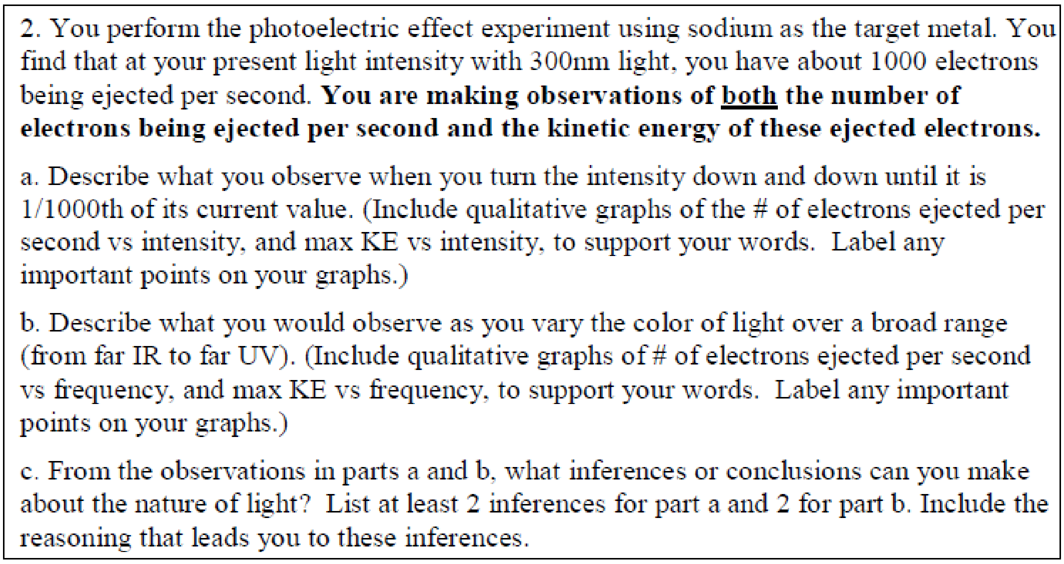
Would the ammeter read zero current or a non-zero current if you were to:

a. Double the intensity of the light source on the cadmium target? Explain your reasoning.

b. Increase the voltage V of the battery from 0 volts to +5.0 volts (using the cadmium target)? Explain your reasoning.

c. Replace the cadmium target with one made of sodium but with the original intensity and zero voltage applied? Explain your reasoning.

Fig. 27 - Example of questions to work on the prediction of photoelectric effect experiment results.



2. You perform the photoelectric effect experiment using sodium as the target metal. You find that at your present light intensity with 300nm light, you have about 1000 electrons being ejected per second. **You are making observations of both the number of electrons being ejected per second and the kinetic energy of these ejected electrons.**

a. Describe what you observe when you turn the intensity down and down until it is 1/1000th of its current value. (Include qualitative graphs of the # of electrons ejected per second vs intensity, and max KE vs intensity, to support your words. Label any important points on your graphs.)

b. Describe what you would observe as you vary the color of light over a broad range (from far IR to far UV). (Include qualitative graphs of # of electrons ejected per second vs frequency, and max KE vs frequency, to support your words. Label any important points on your graphs.)

c. From the observations in parts a and b, what inferences or conclusions can you make about the nature of light? List at least 2 inferences for part a and 2 for part b. Include the reasoning that leads you to these inferences.

Fig. 28 - Example of questions to work on the description of how the photoelectric effect experiments results lead to the photon model of light.

4.4 Lesson 3

This lesson aims to teach students the p-n junction as basis of diodes and solar cells functioning.
The teaching strategies adopted are the frontal lecture at the beginning of the lesson, to introduce students to the semiconductor properties and the band gap theory, and in the second part of the lesson a game-based learning activity about the movement of electrons in the p-n junction.
This activity, that should preferably take place in an open space free of obstacles, is a modified game of musical chairs, where teams compete against each other while creating their own electricity. In this way they are able to "see" how electricity is created in a PV cell at the atomic level.
Students are asked to form two or three teams, depending on the number of students in the classroom, with an odd number of members each. Members of every team have to divide in one student starting the game as a photon and an equal number of P-type silicon players and N-type silicon players. The teacher arranges these last two groups of players into two parallel lines facing each other. The space between the P-type group and the N-type group represents the p-n junction. The photon student stands at the end of the lines with a die in his hand.
It is explained to the students that the junction made by the two types of silicon is what creates the electrical field that forces the free electrons to travel in one direction, and to represent it they will have to move only in a clockwise direction during the game.

A basket for each team, representing a load powered by the solar cell, like a battery to charge for example, is then placed somewhere in the path that the electron students will travel.
Now the teacher describes the rules of the game. Before each turn, students facing each other will play "rock, paper, scissors" to determine who is a hole and who is an electron. The choice is let to the winner and the teacher will hand a ping pong ball to students chosen to be electrons. Next, the teacher will choose a photon absorption number, representing the changing environmental conditions (weather, angle of the sun and age of the solar panel for example) that are responsible for the rate at which photons make their way into the p-n junction. The photon students will have to roll their die as many times as needed until the sum of the rolls matches or exceeds the absorption number before they can be released. The photon absorption number will be changed periodically and posted on the board, this will require the photon to be alert. Students should be made aware that not every photon is absorbed in the p-n junction, some bounce off the glass coating of the solar cell and others don't have the right amount of energy to allow an electron to move from the valence band to the conduction band. For this reason they have to roll accordingly to number chosen by the teacher before they move into the p-n junction and be absorbed in the cell.

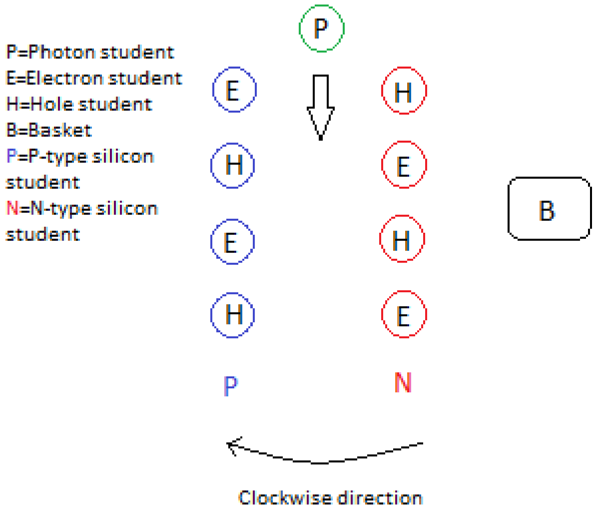


Fig. 29 - Solar cell simulation game setup scheme.

After being released, photon students makes their way into the middle of the p-junction, between the parallel lines of students, to be "absorbed". Each of them will chose three electron students among their teammates to dislodge and they will take one of the electron's places. It is important to specify the students that the photon taking an electron's place does not represent what actually happens in a PV cell. This motion has been added to the game to provide added musical chairs-type motivation.
Dislodged by the energy of the photon, students become energetic free electrons and must step out of their line and make at least one circuit around the group in clockwise direction while remembering to deposit their electricity orb into the basket, representing the power being delivered to the load. The teacher should emphasize on the correlation between physical movement and electricity, that is generated through the movement of electrons: greater movement can generate greater amounts of electricity in a solar cell.
After this, dislodged students will fill an open space in the p-n junction, but only two spots are available, so there will be one free student that will take the role of the photon and he should begin rolling the die to reach the absorption number. Meanwhile, the students in the p-n junction should once again determine who will be the electrons.
The game goes on for about 10 minutes, after which it is over and the balls inside the baskets are counted. The team that has most efficiently reached the absorption number will end up with more power-balls in their battery-basket and be declared the winner. This should reinforce in the students the concept that better equipment and more favourable environmental conditions will lead to a better photon absorption rate.

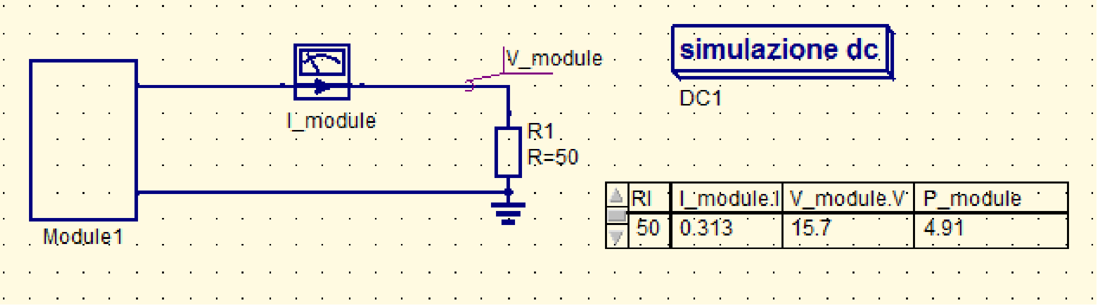
4.5 Lesson 4

The fourth lesson focuses on the solar cell equivalent circuit. Using the simulation described in Chapter 3 as didactic method, students reproduce the working functions of a solar panel and learn how different values of cell temperature and irradiance affect a solar panel.

The lesson is carried out in the laboratory room where the students practice with the simulation described in chapter 3. They are asked to form the same groups of the second lesson and a computer is assigned to every group. The teacher, having installed and launched the software previously, shows the pupils the simulation of a solar panel designed with QUCS as a tool to explain them the equivalent circuit of a solar cell in an interactive way. They are told that the simulation runs using the parameters of a STP005P solar panel and the teacher gives to each group a physical module to have a manual contact with the object of study and read the datasheets.

After a short introduction on the solar cell equivalent circuit elements and the series of solar cells representing the solar panel, the students receive the worksheet with the activities to do during the hour in the laboratory (see Appendix A).

The first simulation consists in obtaining the IV curve of the solar panel by connecting a resistor to it (see Fig. 30). The students have to modify the values of the load and to take measurements of the voltage and the current generated by the module. They will also represent the curve of the power depending on the load resistance (see Fig. 31).



Rl	I_module.I	V_module.V	P_module
50	0.313	15.7	4.91

Fig. 30 - The table in the simulation represents current, voltage and power measurements depending on the load.

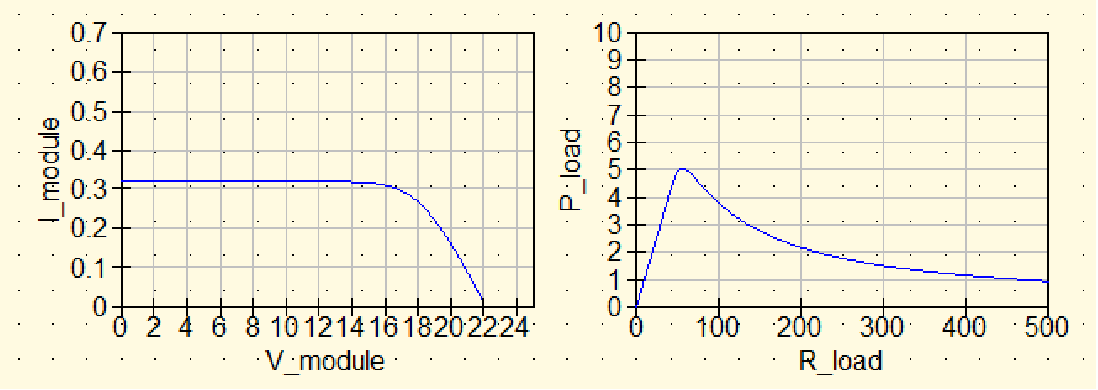
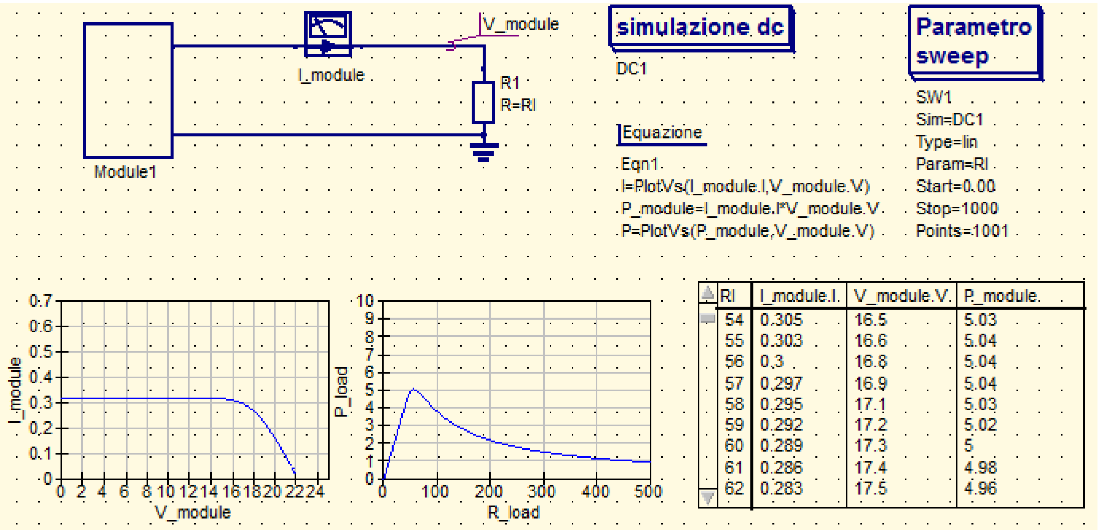


Fig. 31 - Example of I-V and power curves represented by the students.

The second simulation allows the representation of the I-V curve in a diagram thanks to the automatic variation of the load and the students have to graphic different I-V curves depending on the ambient temperature and the irradiance (Fig. 32). The teacher could provide the students with some typical irradiation and temperature values at different latitudes of the globe to use in the simulation. The graphics' creation should help them visualize how irradiance and cell temperature influence the outputs of the solar panel.



DC1

Equazione
Eqn1
I=PlotVs(I_module.I,V_module.V)
P_module=I_module.I*V_module.V
P=PlotVs(P_module,V_module.V)

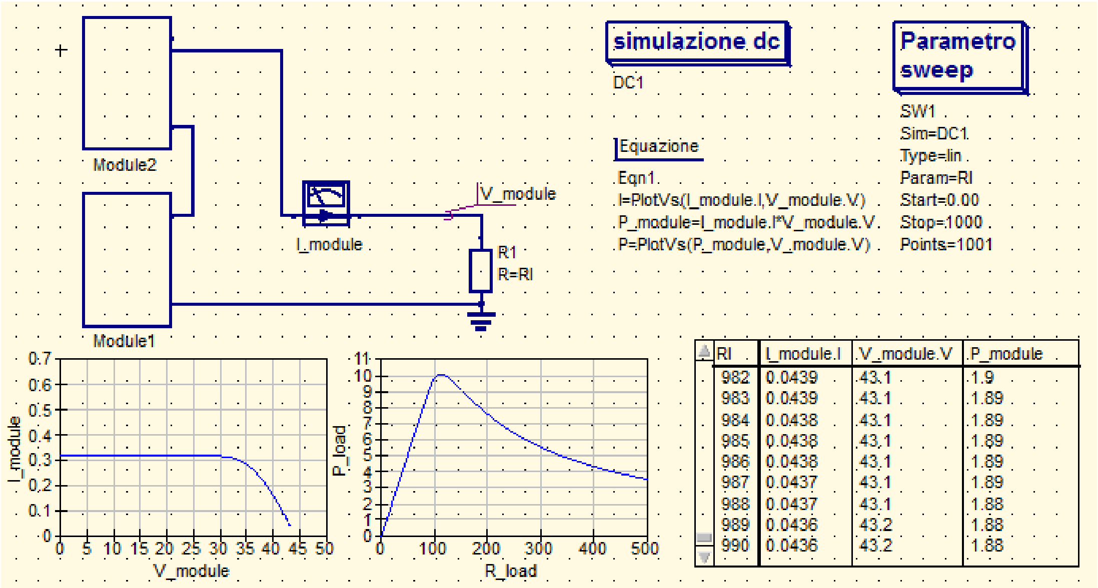
SW1
Sim=DC1
Type=lin
Param=Rl
Start=0.00
Stop=1000
Points=1001

Rl	I_module.I	V_module.V	P_module
54	0.305	16.5	5.03
55	0.303	16.6	5.04
56	0.3	16.8	5.04
57	0.297	16.9	5.04
58	0.295	17.1	5.03
59	0.292	17.2	5.02
60	0.289	17.3	5
61	0.286	17.4	4.98
62	0.283	17.5	4.96

Fig. 32 - Second activity simulation sheet.

In the third activity students have to simulate the connection in series and parallel of two solar panels. The teacher will explain them how to add another module subcircuit to the simulation and to connect it to the circuit, so that the students can register the current, voltage and power values and how they change in comparison to the values obtained from a single module (see Fig. 33 and Fig. 34).

Finally the teacher submits to the students a simple exercise to be delivered by the end of the hour that will be evaluated. The teacher should provide the students with the numerical solution of the exercise so they can compare their results with it.



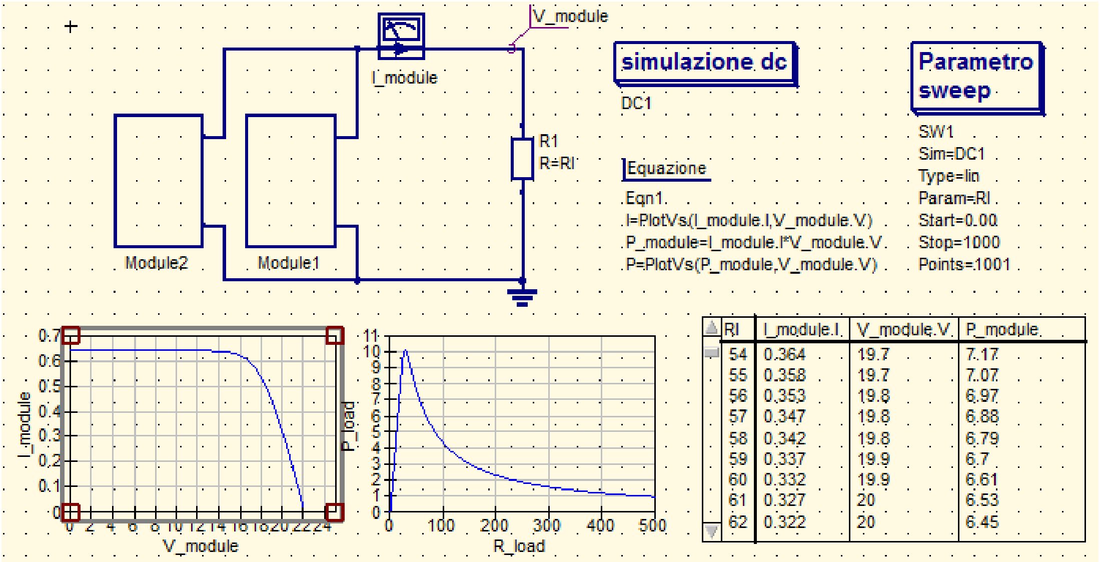
DC1

Equazione
Eqn1
I=PlotVs(I_module.I,V_module.V)
P_module=I_module.I*V_module.V
P=PlotVs(P_module,V_module.V)

SW1
Sim=DC1
Type=lin
Param=Rl
Start=0.00
Stop=1000
Points=1001

Rl	I_module.I	V_module.V	P_module
982	0.0439	43.1	1.9
983	0.0439	43.1	1.89
984	0.0438	43.1	1.89
985	0.0438	43.1	1.89
986	0.0438	43.1	1.89
987	0.0437	43.1	1.89
988	0.0437	43.1	1.88
989	0.0436	43.2	1.88
990	0.0436	43.2	1.88

Fig. 33 - QUCS simulation of two PV modules in series connection.



simulazione dc

DC1

Equazione

Eqn1
I=PlotVs(I_module.I,V_module.V)
P_module=I_module.I*V_module.V
P=PlotVs(P_module,V_module.V)

Parametro sweep

SW1
Sim=DC1
Type=lin
Param=Rl
Start=0.00
Stop=1000
Points=1001

Rl	I_module.I	V_module.V	P_module
54	0.364	19.7	7.17
55	0.358	19.7	7.07
56	0.353	19.8	6.97
57	0.347	19.8	6.88
58	0.342	19.8	6.79
59	0.337	19.9	6.7
60	0.332	19.9	6.61
61	0.327	20	6.53
62	0.322	20	6.45

Fig. 34 - QUCS simulation of two PV modules in parallel connection.

4.6 Lesson 5

The last lesson is centered around an active experimentation with solar panels connected to a circuit and subjected to a light source. This laboratory is conducted according to the guidelines of the IBSE described in paragraph 1.2.1.

If possible, the teacher should drive the students outdoor to place the modules under the sunlight, otherwise he will appeal to the laboratory room and assign a lamp to every group to irradiate the solar panels.

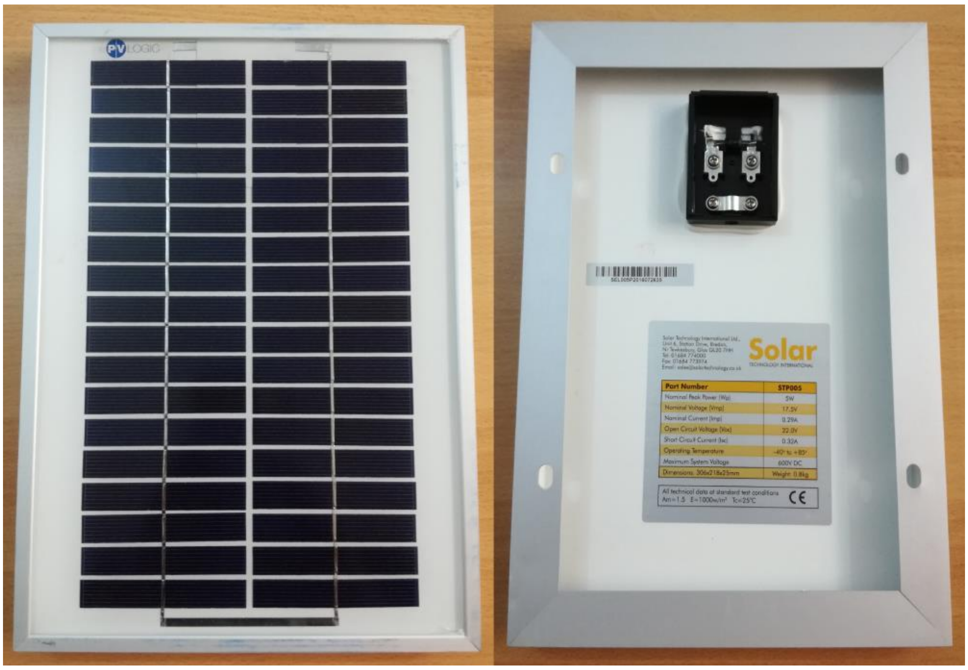


Fig. 35 - Images of a STP005P solar panel.

Right at the beginning the teacher forms the same groups of students like the previous lessons and gives them the prepared material to set up their working stations. Each group will use, a cardboard, a set square, a shoes box, two STP005P solar panels (see Fig. 35), a digital multimeter, four alligators clips and a load resistance of a known value (see Fig. 36).

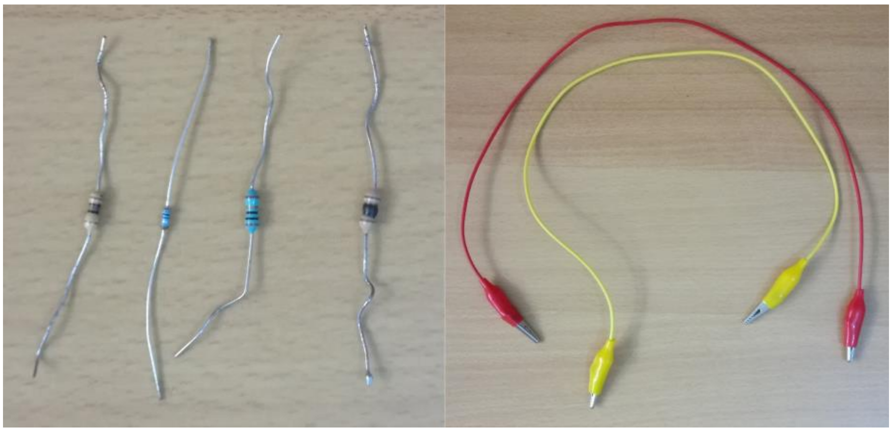


Fig. 36 - Examples of alligator clips and load resistances used during the activities.

After this, the teacher discuss how to use and read the digital multimeter (see Fig. 37) and explain the procedure to connect the load resistance to the solar panel to have the students to complete their activities (see Appendix B).

Fig. 37 - Digital multimeter that the students can use to take current and voltage measurements.

In the first activity they will take current and voltage measurement while a single solar panel is connected to the resistance (see Fig. 38). They have to repeat the activity with different angles between the module and the ground to observe how the inclination influence the output values. The angles should be determined by using a set square and maintained by one of the members of the group, while the other is measuring. The teacher will focus their attention on the values obtained and on the importance to have a solar panel as perpendicular as possible to the incident light to have higher value of power produced.

Then, using the shoes box as support for the panel, the next activity consists in gradually covering the solar panel with the card board while recording data, so that the students can practically experiment the shadowing problem of solar panels. In this activity the teacher should point out that the current value doesn't drop to zero because it's difficult to completely cover a solar cell, it still receive diffused light even from his back side (see Fig. 39).

As third activity, the students will connect the two modules in series and in parallel to have a confrontation with the simulations of the previous lesson.
Finally the teacher will assign to each group a report to do at home about the use of solar panels to power their houses. He will collect them during the next class to evaluate the students learning during this practical experience.

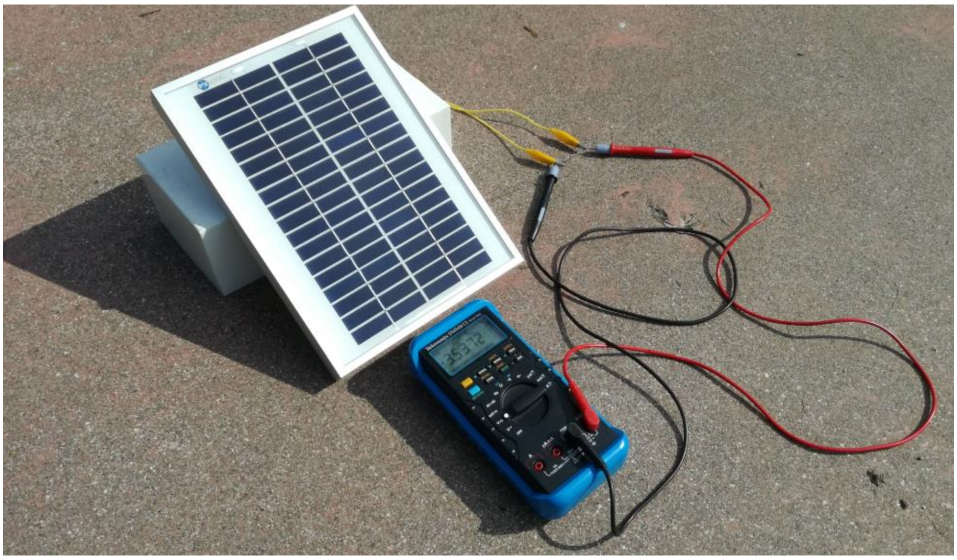


Fig. 38 - Electrical circuit with a single solar panel connected to the resistance.

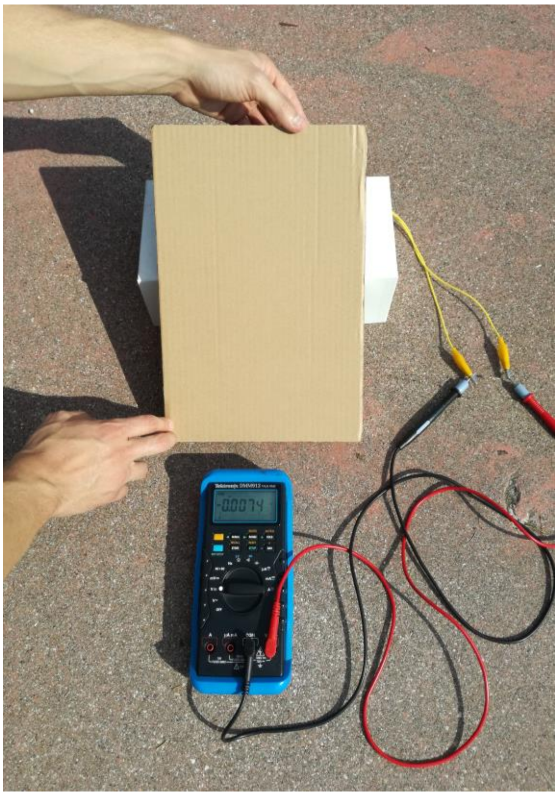


Fig. 39 - Solar panel completely covered.

5 Conclusions

In this thesis an original learning program has been developed to introduce students attending their high school last year to the Photoelectric Effect, a topic introduced in Physics programs after the school reform in 2010. What motivated the formulation of this teaching plan was the need of a change in the learning-teaching process commonly found in Italian high school, introducing a more student centered approach while developing awareness on students about energy issues, in particular renewable energy from the solar radiation. Teachers should focus more on how and what students learn, adopting a whole set of didactic methods and strategies to teach students how to learn and how to transfer their knowledge in different contexts. More specific teaching approaches should be applied to engage students actively in their learning, make contents interesting and give choices about what and how to learn. This didactic plan was thus designed to help teacher adopt a more "active teaching". As described in Chapter 1, the IBSE approach is well suited for this purpose and in Physics classes it can be successfully supported by laboratory activities and digital technologies. These represent important didactic instruments to complement the traditional lectures in classroom. In particular virtual laboratory proves to be extremely useful when the experimental process is complex and do not easily allow observation of the phenomenon, as in the case of the absorption of photons by the electrons. Furthermore the use of virtual environments makes students develop lifelong computer skills. Because of the reasons just explained, it was considered adequate to apply *The Photoelectric Effect* simulation by PhET to let students actively participate in the learning path of Chapter 4.

Similarly it has been chosen to create a simulation with QUCS to deal with the explanation of solar cells and PV modules. Compared to other simulation environments, QUCS has the advantage of being a free software with a suitable interface to approach even young students to electrical circuits simulation. The activities described in Chapter 3 has been applied in Lesson 4 to let students practice with the work functions of solar cells and PV panels connections. This lesson could be improved adding a partial and total shadowing effect simulation, so students can extract conclusion about the shadow problem on PV cells from current and voltage it generates, but considering the short time available to teachers during the academic year for a similar project, it has been chosen to insert an activity on the shadow effect only in the practical activities of Lesson 5. Following Kolb's theory, these active experimentations have been developed to deal with the topic from an ideal perspective for those students naturally preferring a Converging or Accommodating learning style. Concerning this lesson, another improvement could be done by obtaining adjustable supports incorporated with the solar panels, so the students can avoid using the set square and have more control on panel's inclination angle.

Appendix A

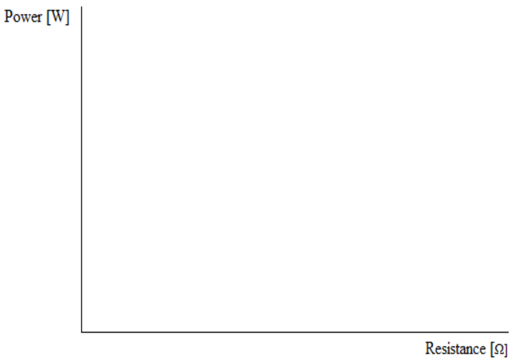
Lesson 4

Solar Panel Simulation Worksheet

During this hour you and your group will simulate how a solar panel works depending on the load and some environmental conditions.

First activity: representation of the solar panel I-V curve

The first simulation sheet allows you to modify the resistance value of the load and to obtain current, voltage and power measurements.
Thinking about the ohmic circuits you studied before, could you graphic the I-V curve and the power versus resistance curve of a resistor?



Try different values of resistance and complete the table below with the measurements. Represent the collected data in an appropriate graphic.

Resistance [Ω]	Current [A]	Voltage [V]	Power [W]

What differences do you observe between the curves of a solar panel and the ohmic ones?

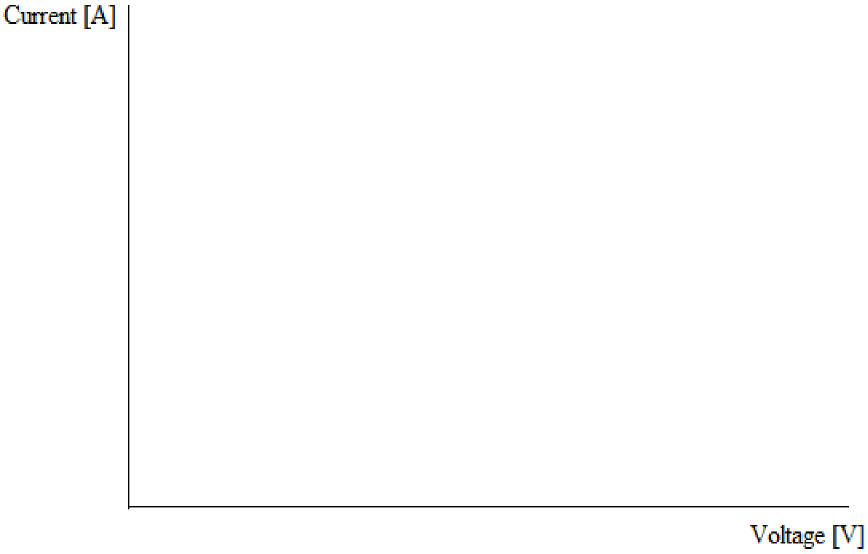
Take a look to the datasheet of the solar panel and, discussing with your group mates, give an explanation of what is the *short circuit current Isc*, the *open circuit voltage Voc* and the *peak power Wp*.

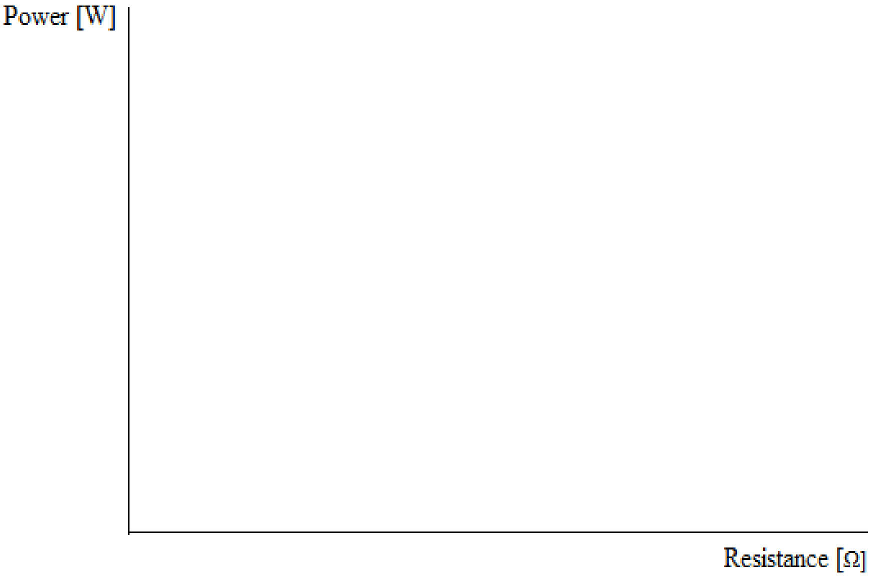
Second activity: effects of irradiance and temperature on PV cells

The panel in the previous simulation was working in Standard Test Conditions (STC), it means that the cell temperature *Tcell* was 25°C and the irradiance *G* was 1000 W/m^2. Those are the values chosen to measure the technical data in the datasheet of the panel, but the panel will work in different conditions for most of the time.

In the second simulation there is an automatic variation of the load value that allows you to obtain the I-V curve of the panel. First use different values of ambient temperature at the same irradiance and represent in a graphic the I-V curves and the power curves obtained, then do the same for different values of irradiance with the same ambient temperature. Use a different colour to distinguish every curve. Helping yourself with the graphics and the table in the simulation sheet, register on the tables below the values of the short circuit current, the open circuit voltage and the peak power that you measure at different temperatures and irradiance values.

Same irradiance graphics (G=1000 W/m^2):





Temperature [°C]	Short circuit current [A]	Open circuit voltage [V]	Peak power [W]

Same cell temperature graphics (Tcell=25°C):

Irradiance [W/m^2]	Short circuit current [A]	Open circuit voltage [V]	Peak power [W]

Observing the graphs, what are your conclusions about the influence of ambient temperature and irradiance on a solar panel on the different solar panel parameters?

Third activity: series and parallel connections of two solar panels

Usually more modules connected together are used to power a building with a solar system.
In this activity you will simulate how solar panels work in STC when they are connected in series and in parallel. To realize the connection, select the module subcircuit in the content list, transport it on the simulation sheet and connect in to the circuit. First apply a series connection and report the Isc, the Voc and the Wp values on the table below, then do the same with a parallel connection.

	Short circuit current [A]	Open circuit voltage [V]	Peak power [W]
Series connection			
Parallel connection			

How do the parameters' values have changed compared to the ones observed in the first activity with a single solar panel?

Now imagine to connect in series all the PV modules of the different working groups in the laboratory, what values of short circuit current, open circuit voltage and power peak do you expect? Use the simulation software considering an ambient temperature of 20°C and an irradiance of 1300 W/m^2. Write a report to give at the end of the lesson to the teacher describing the achieved results complete with the simulation graphs.

Appendix B

Lesson 5

Solar Panel Experiment Worksheet

During this hour you will have a practical experience with real PV modules exposed to a source of light. The objective is to take current and voltage measurements of working panels in different conditions and to elaborate the obtained data.

The first thing to do is to connect one of the solar panels to the resistance using the alligator clips to create the electrical circuit. We are going to use a digital multimeter, an instrument that can read resistance, voltage and current values. Make sure that the black lead is always plugged into the "COM" connection of the multimeter. Plug the red lead into the "A" connection and turn the multimeter to the A setting to take current measurements, while to take voltage measurements plug the red lead into the "VΩ" connection and turn the multimeter to the V DC setting. Connecting the other ends of the plugs to the resistance you will be able to read the corresponding measure value on the screen of the multimeter.

First activity: different inclinations of the solar panel

Helping yourself with the set square, take current and voltage measurements at different angles of the solar panel with the ground, then calculate the respective power.

Angle	Current [A]	Voltage [V]	Power [W]

Observe the collected data and discuss what factors affect the results. How do you think you should tilt the panel to maximize the power produced?

Second activity: shadowing effect

Using a shoes box as support to the solar panel, take current measurements with the cardboard covering different portions of the module surface.

Percentage of covered surface	Current [A]
0%	
25%	
50%	
75%	
100%	

Now try to cover just a single PV cell and compares the resulting current value with the previous data. Explain which are the consequences of the shadowing effect citing your experimental data to support your explanation.

Third activity: solar panels in series and parallel connection

Think about the last simulations of the previous lesson and reproduce an electrical circuit with two solar panels in series. Considering the current conditions of irradiation, ambient temperature and the fact you are using a resistance of low value (10Ω), what current value can be expected? And in a circuit with two solar panels in parallel?
Carry out the two current measurements and compare them with the graphs obtained with the simulations.

Homework activity

If you would like to install PV panels to power your home with a peak power of 3 kW, how many modules should you use and what particular precautions should you take for an efficient installation?
The parameter of the modules to use are listed in the table below.

Peak power [W]	Open circuit voltage [V]	Short circuit current [A]
435	85.6	6.43

Riassunto in lingua italiana

La tesi esposta rappresenta un percorso didattico nato dall'intenzione di voler affrontare in classe temi legati all'energia e all'ambiente, in modo da accrescere negli studenti la consapevolezza che tali tematiche li coinvolgano direttamente. Oggigiorno numerosi paesi, consci dei rischi ambientali prodotti dai combustibili fossili, stanno investendo in tecnologie per lo sfruttamento di energia da fonte rinnovabile. Tra queste suscita particolare interesse la produzione di energia elettrica da radiazione solare per mezzo di pannelli fotovoltaici.

La riforma della scuola emanata nel 2010 ha introdotto nel Liceo Scientifico l'insegnamento della meccanica quantistica nel programma di fisica del quinto anno. Si introduce con l'effetto fotoelettrico, che rappresenta l'argomento ideale su cui sviluppare un progetto riguardante l'energia rinnovabile. La riforma inoltre pone enfasi sull'uso di attività pratiche di laboratorio che aiutino e incoraggino gli studenti a lavorare in gruppo, far propri i concetti appresi, condurre osservazioni e misurazioni.

Il percorso è stato pensato dunque per affrontare l'effetto fotoelettrico in una classe quinta di Liceo Scientifico, tenendo conto dei temi affrontati dalla riforma.

Nel primo capitolo vengono affrontati il ruolo dell'insegnate e le metodologie didattiche applicate nel progetto di tesi stesso.

Le teorie sviluppate nella seconda metà del diciannovesimo secolo da Jean Piaget e Lev Vygotsky, importanti esponenti della corrente filosofica del Socio-costruttivismo, affermano che lo sviluppo umano è fortemente legato alla società e che la conoscenza si costruisce attraverso l'interazione con gli altri. Queste forme di pensiero hanno portato alla rivalutazione del ruolo dell'insegnate, il quale deve essere non solo competente nella propria materia, ma anche in grado di connettersi con i suoi alunni a livello sociale ed emotivo al fine di ottimizzare il processo d'insegnamento. Più che un istruttore, egli dovrebbe agire da guida per gli studenti, porli al centro del percorso d'apprendimento rendendoli partecipi di ciò che studiano, coinvolgendoli attivamente e facendo fare loro esperienza degli argomenti insegnati.

La classe è un ambiente sempre più eterogeneo, dove ciascun ragazzo porta con se le peculiarità legate al proprio contesto sociale e culturale. Queste possono portare a condizioni di disagio psicofisico, economico e linguistico. E' compito dell'insegnante adottare metodologie d'insegnamento inclusivo per bilanciare le differenze d'apprendimento e incoraggiare il coinvolgimento di tutti gli studenti indipendentemente dalle loro particolari condizioni.

Nel corso del progetto vengono applicare le seguenti metodologie didattiche:

- L'Inquiry Based Science Education (IBSE), un approccio all'insegnamento basato sulla natura della ricerca scientifica. Il suo interesse è la costruzione di idee, significati e concetti che conducano gli studenti a capire ciò che stanno imparando attraverso esperienze di laboratorio in cui sono invitati ad assumere un atteggiamento investigativo, ovvero fare domande, usare tecniche appropriate per la raccolta dei dati, pensare in modo critico e giungere loro stessi a un'analisi del fenomeno osservato attraverso i dati raccolti. Ciò a cui mira è far scoprire agli studenti che la motivazione all'apprendimento nasce dalla soddisfazione di comprendere gli argomenti in modo significativo.
- I laboratori virtuali e le simulazioni rappresentano strumenti essenziali, moltissime scuole sono infatti dotate di aule computer, di grande aiuto per l'insegnamento delle materie scientifiche, in particolare quando le attività sperimentali risultano complesse e non compatibili con il tempo disponibile o quando non permettono l'osservazione del fenomeno e la sua misurazione in sicurezza. Il compito dei laboratori virtuali non è quello di sostituire gli esperimenti reali, bensì quello di fornire loro supporto per una migliore comprensione degli argomenti. La collaborazione e la comunicazione tra studenti e insegnante viene incoraggiata attraverso tale modalità didattica, poiché l'insegnante partecipa attivamente nel processo d'apprendimento ponendo domande, organizzando le procedure e commentandole, aiutando a formulare conclusioni, comprendendo gli errori degli studenti ed evidenziando qualunque concetto errato. Inoltre l'uso di un ambiente virtuale permette agli studenti di acquisire abilità informatiche utili per l'apprendimento permanente.
- La conversazione clinica è un metodo d'indagine, inizialmente adottato da Piaget, strutturato sulla base di un'intervista il cui scopo è l'investigazione delle preconoscenze degli alunni in

merito all'argomento che si vuole trattare. L'insegnate inizialmente raccoglie informazioni dalle loro risposte, supportandoli nel loro discorso senza l'aggiunta di opinioni personali. Successivamente analizza i risultati ottenuti al fine di evidenziare le loro conoscenze errate e concentrare maggiormente le successive lezioni su quei punti in cui gli alunni hanno mostrato avere più difficoltà.

- Il game-based learning, ovvero l'apprendimento di un argomento attraverso un gioco, nasce dalle teorie di Piaget e Bruner secondo cui l'apprendimento nei bambini viene veicolato attraverso il gioco. Esperienze d'apprendimento di questo tipo aiutano gli studenti a rafforzare la motivazione, la creatività ed il senso di responsabilità.
- Il modello di apprendimento esperienziale (Experiential Learning Model) è stato sviluppato dal teorico dell'educazione americano David Kolb, secondo il quale la creazione di conoscenza avviene secondo un processo di trasformazione dell'esperienza che passa per un ciclo di quattro fasi sequenziali in cui l'allievo apprende attraverso l'esperienza concreta, l'osservazione riflessiva, la concettualizzazione astratta e la sperimentazione attiva. Dalla combinazione di due differenti fasi emerge uno stile d'apprendimento verso cui ciascuna persona è portata per natura a propendere. Questi sono lo stile divergente, caratteristico delle persone che sono sensibili e preferiscono osservare piuttosto che fare, lo stile assimilativo, verso cui propende chi predilige l'approccio logico e conciso, lo stile convergente, preferito da chi apprende meglio attraverso l'esperienza pratica, e lo stile accomodante, che fa affidamento all'intuito piuttosto che alla logica. E' importante considerare tali propensioni durante lo sviluppo di un percorso educativo, in modo da affrontare gli argomenti da diversi punti di vista e permettere a ciascuno studente di approcciarvisi seguendo lo stile che gli è più congeniale.

Il secondo capitolo è dedicato alla trattazione dell'effetto fotoelettrico, l'argomento che si intende affrontare. Esso viene inquadrato in un contesto storico attraverso un'introduzione che parte dalla sua scoperta nel 1887 da parte di Hertz e i successivi studi di Lenard sull'energia cinetica degli elettroni emessi da superfici metalliche sottoposte a una sorgente luminosa, fino a giungere alla teoria dei quanti di Einstein e alla descrizione dell'effetto fotoelettrico per cui ottenne il premio Nobel nel 1922.

Il capitolo procede nella trattazione della cella fotovoltaica come tecnologia sviluppata per sfruttare l'effetto fotoelettrico e produrre una corrente elettrica dalle radiazioni solari. Vengono affrontate le proprietà dei semiconduttori e la teoria della struttura a bande, in quanto considerate concetti fondamentali per la comprensione della giunzione p-n, che sta alla base del funzionamento della cella fotovoltaica.

Infine viene descritto il circuito elettrico equivalente della cella e ai parametri che lo costituisco. Tali elementi sono ripresi nel terzo capitolo, che è dedicato a una simulazione da applicare nel progetto, per trattare il modello della cella fotovoltaica attraverso un laboratorio virtuale. La simulazione è stata realizzata utilizzando QUCS, un software gratuito per progettare e simulare circuiti elettrici tramite un'interfaccia grafica e che può essere facilmente applicato come strumento per l'insegnamento attivo in qualunque scuola con accesso al computer. Tramite la simulazione si interagisce con i parametri che caratterizzano il circuito equivalente della cella fotovoltaica per ricavare in un grafico cartesiano la curva di lavoro della cella, al variare dei valori di irraggiamento e temperatura. Inoltre usando la funzione sottocircuito sono state connesse tra loro più celle per formare un unico pannello, i cui valori di corrente, tensione e potenza in uscita al variare del carico vengono forniti e visualizzati tramite una tabella.

Il progetto didattico viene affrontato nel dettaglio nel quarto capitolo. Esso è da considerare come linea guida generale, gli insegnanti interessati ad applicarlo sono liberi di modificarlo secondo i loro bisogni e sulla base degli studenti a cui è rivolto. Gli obiettivi disciplinari da raggiungere seguono le indicazioni del ministero dell'istruzione e, in accordo con la riforma scolastica, il progetto prende in considerazione l'uso di applicazioni informatiche e attività pratiche di laboratorio. Queste ultime vengono condotte utilizzando strumenti solitamente presenti nelle aule di laboratorio, come multimetri e conduttori a coccodrillo, e pannelli fotovoltaici da acquistare appositamente. Questi risultano avere un basso costo che li rende di facile reperibilità per le scuole.

Durante i laboratori gli studenti sono chiamati a lavorare in gruppi di 2 in modo da promuovere lo sviluppo di un atteggiamento cooperativo, essenziale in ogni campo scientifico e in qualunque ambiente sociale in generale.

Il percorso educativo è articolato in cinque lezioni da un'ora ciascuna. Poiché si intende adottare un approccio all'insegnamento centrato sugli studenti, l'insegnate prima di cominciare le attività richiede agli studenti di raccogliere informazioni riguardo il consumo elettrico nelle loro case, ad esempio parlando con i genitori delle bollette della luce e del consumo degli elettrodomestici più diffusi. Questo al fine di aiutare gli studenti a sentirsi coinvolti personalmente in ciò che apprenderanno durante il progetto. Inoltre le informazioni raccolte fungeranno da punto di partenza per la discussione con cui si aprirà la prima lezione.

- Lezione 1: si prefigge lo scopo principale di verificare che gli studenti comincino il progetto con le preconoscenze necessarie e ed individuare eventuali lacune o conoscenze errate da colmare nelle successive lezioni. Il dibattito sul consumo elettrico domestico viene condotto seguendo il metodo della conversazione clinica. Inoltre l'insegnante istruirà brevemente gli studenti sul progetto che affronteranno nei giorni successivi.
- Lezione 2: si focalizza sull'insegnamento del concetto di fotone e sulla spiegazione dell'effetto fotoelettrico. Viene svolta in un'aula attrezzata di computer ed è strutturata in una iniziale lettura frontale, seguita dall'applicazione di un laboratorio virtuale sviluppato dalla Colorado University come parte del PhET Interactive Simulation Project. Si tratta di una simulazione interattiva in cui due piastre metalliche sono collegata tramite un circuito a una batteria e una delle due può essere irradiata da una fonte luminosa per emettere elettroni è produrre una corrente nel circuito. Attraverso l'interfaccia grafica del software, si possono controllare l'intensità e la frequenza luminosa, il voltaggio imposto dalla batteria e il materiale della superficie illuminata. In uscita si osserva il valore della corrente prodotta dal moto degli elettroni. Differentemente da un esperimento reale, gli elettroni che passano da una piastra all'altra sono visibili e questo è un aspetto utile agli studenti per visualizzare il fenomeno e costruire un modello mentale. A fine lezione come valutazione delle competenze acquisite sono assegnati degli esercizi a cui rispondere a casa.
- Lezione 3: viene trattato il meccanismo della giunzione p-n come base del funzionamento della cella fotovoltaica. La strategia didattica adottata è una lettura frontale a inizio lezione e una successiva attività d'apprendimento basata su una versione modificata del gioco delle sedie. Si tratta di una simulazione del movimento degli elettroni all'interno della giunzione p-n in cui i ragazzi si dividono in squadre ai cui membri viene assegnato un ruolo iniziale. In ciascuna squadra un giocatore rappresenta un fotone mentre gli altri si dividono in coppie di giocatori rappresentanti un elemento di silicone drogato tipo p e uno di tipo n, divisi per tipo in due file parallele uno di fronte all'altro, a formare la giunzione p-n. Lo scopo di ogni squadra è quello di riempire con delle palline un proprio contenitore, che funge da batteria immaginaria da caricare. Una volta libero infatti, ciascun giocatore fotone permetterà ai compagni di divenire elettroni liberi con il compito di abbandonare la propria posizione e andare a deporre nel contenitore la pallina di cui sono stati forniti. La vittoria viene assegnata alla squadra che allo scadere del tempo ha collezionato il maggior numero di palline.
- Lezione 4: come metodologia didattica si ricorre al laboratorio virtuale, applicando la simulazione descritta nel terzo capitolo per trattare il circuito equivalente delle celle fotovoltaiche. Ad ogni gruppo di lavoro viene consegnato un pannello fotovoltaico i cui parametri presenti nel datasheet sono inseriti nella simulazione. Come prima attività viene richiesto di ottenere la curva corrente-tensione del pannello variando il carico resistivo a cui è collegato, per poi graficare la curva al variare di temperatura e irraggiamento, in modo da visualizzare come questi parametri influenzino i valori in uscita. Dopo aver simulato anche una connessione in serie e una in parallelo di due pannelli, l'insegnante assegna un esercizio da svolgere in aula per valutare le competenze acquisite durante il laboratorio.
- Lezione 5: viene condotta una sperimentazione attiva sul funzionamento di moduli fotovoltaici reali connettendoli a un carico resistivo e irraggiandoli con una sorgente luminosa. La prima attività consiste in misurazioni di corrente e tensione un pannello posto a differenti angolazioni rispetto alla sorgente. Lo studio dei dati raccolti rivela che i valori più elevati si ottengono quando il pannello è posto perpendicolarmente alla radiazione luminosa. Successivamente i dati vengono raccolti oscurando gradualmente il modulo in modo che gli studenti facciano esperienza pratica con il problema dell'ombreggiamento dei pannelli fotovoltaici. Come ultima attività è richiesto di connettere due pannelli prima in serie e poi in

parallelo per avere un confronto con i dati ottenuti durante le simulazioni della lezione precedente. Prima del termine dell'ora viene assegnato un breve progetto come compito per casa da valutare.

La tesi si chiude con le appendici A e B in cui sono riportate le schede di lavoro pensate per condurre rispettivamente le lezioni 4 e 5.

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