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LEARNING SUSTAINABILITY BY DEVELOPING A SOLAR DRYER FOR MICROALGAE RETRIEVAL

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Abstract

The development of nations depends on energy consumption, which is generally based on fossil fuels. This dependency produces irreversible and dramatic effects on the environment, e.g. large greenhouse gas emissions, which in turn cause global warming and climate changes, responsible for the rise of the sea level, floods, and other extreme weather events. Transportation is one of the main uses of energy, and its excessive fossil fuel dependency is driving the search for alternative and sustainable sources of energy such as microalgae, from which biodiesel, among other useful compounds, can be obtained. The process includes harvesting and drying, two energy consuming steps, which are, therefore, expensive and unsustainable. The goal of this EPS@ISEP Spring 2013 project was to develop a solar microalgae dryer for the microalgae laboratory of ISEP. A multinational team of five students from distinct fields of study was responsible for designing and building the solar microalgae dryer prototype. The prototype includes a control system to ensure that the microalgae are not destroyed during the drying process. The solar microalgae dryer works as a distiller, extracting the excess water from the microalgae suspension. This paper details the design steps, the building technologies, the ethical and sustainable concerns and compares the prototype with existing solutions. The proposed sustainable microalgae drying process is competitive as far as energy usage is concerned. Finally, the project contributed to increase the deontological ethics, social compromise skills and sustainable development awareness of the students.

Keywords – Education for Sustainability, Energy-efficiency, Microalgae dryer, Solar energy.

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1 INTRODUCTION

The "Solar algae dryer" project was proposed in the spring of 2013 and was selected by a team of EPS@ISEP students (Malheiro, Silva, Ribeiro, Guedes & Ferreira, 2014). The developer team was composed of five students from different nationalities and scientific backgrounds. Aleksandra and Bartlomiej were Mechanical Engineering and Computer Science students from Poland, Sven was a German student of International Purchases and Sales Engineering, Paul was a Finnish student of Industrial Management and Engineering and, finally, Bénédicte was a student of Industrial Product Design from Belgium.

In terms of motivation, the team chose this proposal because it: (i) incorporates sustainable techniques, i.e., allows diminishing fossil energy usage when compared with existing solutions; and (ii) contributes to the new green industry, i.e., microalgae production and biodiesel generation, framed by the biorefinery concept. Furthermore, they perceived microalgae production and drying as a field of increased popularity, interest and value, e.g., for the extraction of antioxidants, omega 3, fatty acids, pigments, oils, starch, etc. The team decided to design a solar microalgae dryer prototype suitable for experimentation at the microalgae laboratory of the chemical engineering department at ISEP, incorporating a control process to preserve the microalgae during the drying process (and avoid excessive high temperatures that might affect the quality of microalgae or of high valued products).

The project proposal specified a goal – the design and development of a solar dryer for microalgae retrieval – and a reduced, yet, mandatory set of requirements (EPS@ISEP Team 1, 2013):

- a 5 l capacity tank;
- the reuse of existing components and selection of low cost hardware and open source solutions;
- the adoption of the International System of Units;
- the compliance with the Machines Directive (MD), Low Voltage Directive (LVD) and Restriction of the use of certain Hazardous Substances (RoHS) Directive; and
- a total budget of 500 €.

Since the main specification was the use of solar energy, the team focussed solely on solar powered solutions. There were complementary specifications defined by the client:

- the surface of the container should not exceed 1 m^2;
- the temperature of the microalgae suspension should not rise above 50 °C since algal biomass, for instance oil or pigments, deteriorate at higher temperatures (Pasquet et al., 2013); and the humidity of the microalgae suspension should decrease below 10 % humidity in one day.

Furthermore, the system should be able to process at least 5 l of dense culture of microalgae and include a sensing system (containing, at least, a temperature sensor and a level indicator). The control system should operate according to the microalgae solution temperature and level and the user interface should provide information about the operation state, e.g., working, stopped or finished. Finally, the power system should be chosen according to the best solution, considering the compromise between solar panel and batteries.

Although the focus of this article is on the technical solution, according to the EPS rules, the students also address other components concerning their project, namely the project management, the product marketing plan, the measures to ensure a sustainable development and production of the system (World Commission on Environment and Development, 1987) as well as the ethical and deontological concerns related to the product development and lifecycle (Malheiro et al., 2014). EPS adopts a multidisciplinary problem based learning approach with strong emphasis on multicultural team work, where different project supportive topics are offered and diverse complementary skills are fostered.

One major difference between the concentration method presently used (centrifugation) and the one proposed (distilling) is the power supply. While the power source of the standard solutions is the grid, in this project it is the Sun, i.e., the prototype will use the Sun to directly heat the solution and a solar panel to convert the sunbeams into the energy it will use for the operation of the electronic devices. Solar power is preferable because it is free and eco-friendly. The major disadvantage is that the solar energy is not always available. However, considering the weather and climate in Portugal, the advantages are substantially higher than the disadvantages.

Bearing these ideas in mind, this article is organized as follows. In the next section it is presented a brief state of the art that describes related products and technologies. Section 3 introduces the architecture envisioned for the system and the main characteristics of the used components. After, Section 4 includes the details of project development and Section 5 the main tests performed to check if the prototype fulfilled the requirements. Section 6 presents the final prototype and the paper is concluded with Section 7, presenting the main conclusion of the developed work and some ideas for possible future developments.

2 STATE OF THE ART

This section outlines several microalgae cultivation and drying systems currently available or proposed. First, microalgae are defined as a vast group of photosynthetic, heterotrophic organisms which have an extraordinary potential for cultivation as energy crops, and biodiesel as a vegetable oil- or animal fat-based diesel fuel consisting of long-chain alkyl (methyl, ethyl or propyl) esters (Mata, Martins & Caetano, 2010; Widjaja, 2009).

2.1 Production of biodiesel from microalgae

The Earth is running out of its fuel resources and researchers are looking for alternatives sources. A possible solution is biodiesel obtained from microalgae oil. In order to extract such oil, microalgae must be first selected, grown and harvested, which may be implemented in numerous ways – here lays the relevance of this project. To remove the excess of water, it is necessary to dry the microalgae solution. Then, the oil must be extracted and, finally, such raw material can be transformed into biodiesel. The diagram in Figure 1 represents the simplified process of obtaining biodiesel from microalgae (Oilgae, 2015).

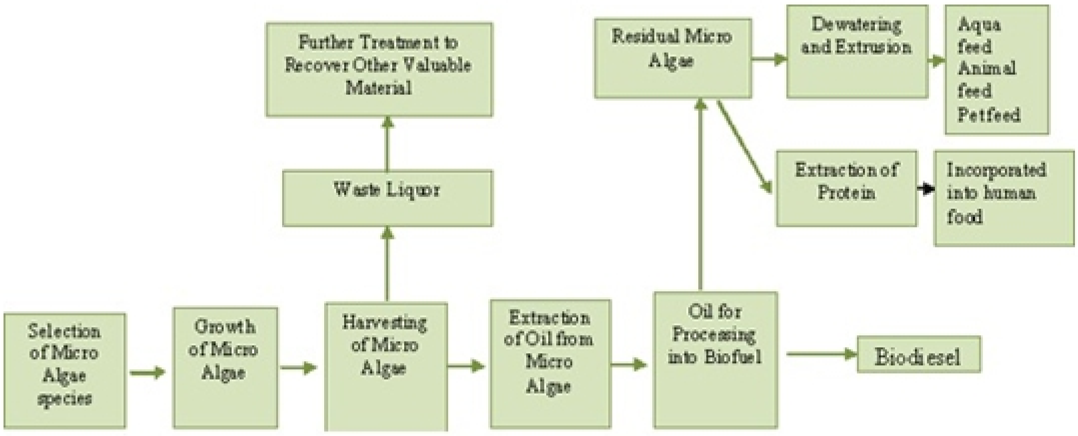

Figure 1. Process of obtaining biodiesel from micro algae (Oilgae, 2015)

The above diagram shows that any side products or leftovers of the process can be reused or recovered. This proves the eco–friendliness of microalgae cultivation. There are also numerous other microalgae sustainable properties, e.g., they are able to grow almost everywhere since different species can easily adapt to the diversity of environmental conditions. Consequently, they are very competitive comparing to other energy crops used to produce bio fuels (rapeseed, corn, soybeans). Their competitiveness justifies also the fact that one can return 10 to 100 more fuels and use from 49 up to 132 times less land area growing algae comparing to the mentioned crops. Table 1 presents the lipid content and productivity of microalgae in comparison to other energy crops. Microalgae have highest oil content and productivity and require the lowest production area.

Plant Source	***Seed Oil Content (% oil by wt in biomass)***	***Oil yield (L oil/ ha.yr)***	***Land Use (m^2.yr /kg biodiesel)***	***Biodiesel productivity (kg biodiesel/ ha.yr)***
Corn/Maize (Zea mays L.)	*44*	*172*	*66.0*	*152*
Hemp (Cannabis sativa L.)	*33*	*363*	*31.0*	*321*
Soybean (Glycine max L.)	*18*	*636*	*18.0*	*562*
Jatropha (Jatropha curcas L.)	*28*	*741*	*15.0*	*656*
Camelina (Camelina sativa L.)	*42*	*915*	*12.0*	*809*
Canola/Rapeseed (Brassica napus L.)	*41*	*974*	*12.0*	*862*
Sunflower (Helianthus annuus L.)	*40*	*1070*	*11.0*	*946*
Castor (Ricinus communis)	*48*	*1307*	*9.0*	*1156*
Palm oil (Elaeis guineensis)	*36*	*5 366*	*2.0*	*4 747*
Microalgae (low oil content)	*30*	*58 700*	*0.2*	*51 927*
Microalgae (medium oil content)	*50*	*97 800*	*0.1*	*86 515*
Microalgae (high oil content)	*70*	*136 900*	*0.1*	*121 104*

Table 1. Comparison of microalgae to other biodiesel crops (Mata et al., 2010)

Moreover, algae are so called "bioremediation agents", meaning that they are able to absorb significant volume of CO_2, which makes them very beneficial as far as fighting excessive emission of CO_2 is concerned. In addition, they are also able to get rid of the dangerous nutrients and toxins from wastewater and sewage by growing in the polluted water and using the contaminants as nutrients. The scheme in Figure 2 demonstrates the microalgae cultivation cycle. As it can be observed, the continuous process is purely sustainable (Oilgae, 2015; Mata, Martins, Sikdar, Costa & Caetano, 2013).

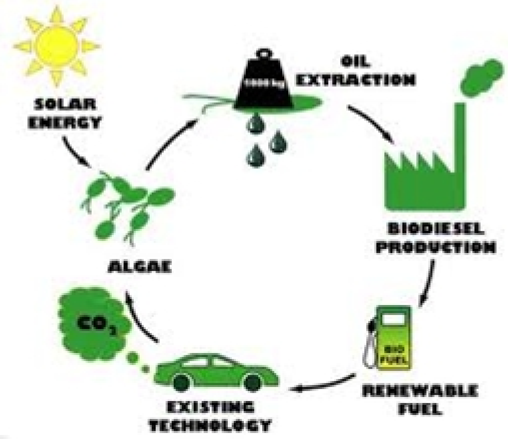

Figure 2. Biodiesel development cycle (Oilgae, 2015)

2.2 Products for microalgae cultivation and drying

There are several methods and products used for microalgae cultivation, most of them being photobioreactors, used for mass cultivation of microalgae species. A photobioreactor is a closed system that does not exchange gases and contaminants with the environment. In the case of the microalgae cultivation, the bioreactor includes a light-supplying system to provide the photonic energy necessary to help the microalgae grow faster. In the most general case, it is a system of pipes holding water and the microalgae suspension. There are several types of photobioreactors, varying mainly in the positioning of the pipes. There are ones which are built and installed parallel to the ground, just like the product depicted in Figure 3 from Solix Biosystems, a United States based company (Solix BioSystems, Inc., 2012).

Figure 3. Algae farm (Solix BioSystems, Inc., 2012)

One of the most recent types of photobioreactor is the "Christmas tree" designed by the German company Gicon (Gicon, 2015). The name results from its tree-like shape represented in Figure 4: wider at the bottom and narrower at the top.

This reactor was designed to allow the longest exposure possible of the structure to sunbeams as well as to save space when compared with the traditional linear photobioreactor structure. Because of the pipes double-walled technology, the surrounding temperature can change extremely fast, reducing the time to harvest the microalgae. According to the producer, the design is lightweight, therefore, easy to build and manage, and power-efficient, when compared to other existing technologies.

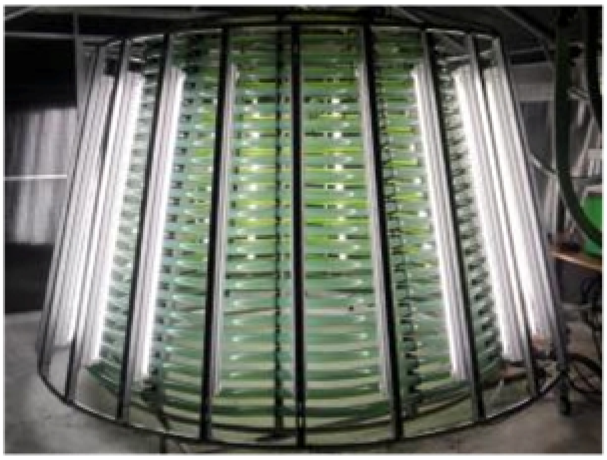

Figure 4. Gicon photo bioreactor (Gicon, 2015)

In terms of the drying process, i.e. the extraction of excess water from the microalgae suspension, while the current approach adopts solar energy, most facilities rely on electric centrifuges. Figure 5 depicts the centrifuge used in the microalgae laboratory at ISEP, which is expensive and consumes too much energy.

Figure 5. Centrifuge used in the microalgae laboratory at ISEP

Few systems use solar radiation for microalgae drying and harvesting. AlgaeLink NV is a Belgian company which produces a solar algae dryer (AlgaeLink, 2015). Figure 6 shows the AlgaeLink solar dryer for large volumes of microalgae suspensions. It is basically a table with a length of 18 m and a drying area of 20 m^2. In this case, the water also evaporates with the help of the Sun, but the process is unmonitored and uncontrolled. This is a drawback of this product since the monitoring and control of the drying process is fundamental in order to guarantee that the compounds of the microalgae are not deteriorated during the process. On the other hand, since there are several systems that take advantage of the Sun to destill water, e.g. to desalinate water (Harris, Nagarajan, Arunkumar, Kannan & Sathyamurthy, 2015), and enough knowledge regarding solar still technologies, we believe that our approach is a sustainable procedure.

The next section presents the components needed to develop the solar microalgae dryer prototype and describes their main characteristics.

Figure 6. AlgaeLink solar dryer for microalgae (AlgaeLink, 2015)

3 PROPOSED ARCHITECTURE AND COMPONENTS

After reviewing the state-of-the-art and brainstorming, the team decided to focus on the hydrocyclone, distilling and filtering methods for algae drying. These methods were thoroughly analysed, compared and discussed with the supervisors in the weekly meetings. The team's final decision was to use distilling because filtering suffered from the saturation of the membrane problem and the hydrocyclone suffered from the problem of powering with a solar panel. According to the team, these problems were too complex for a group of 3rd year students from "Mechanical Engineering and Computer Science", "International Purchases and Sales Engineering", "Industrial Management and Engineering" and "Industrial Product Design". Figure 7 illustrates graphically the adopted concept.

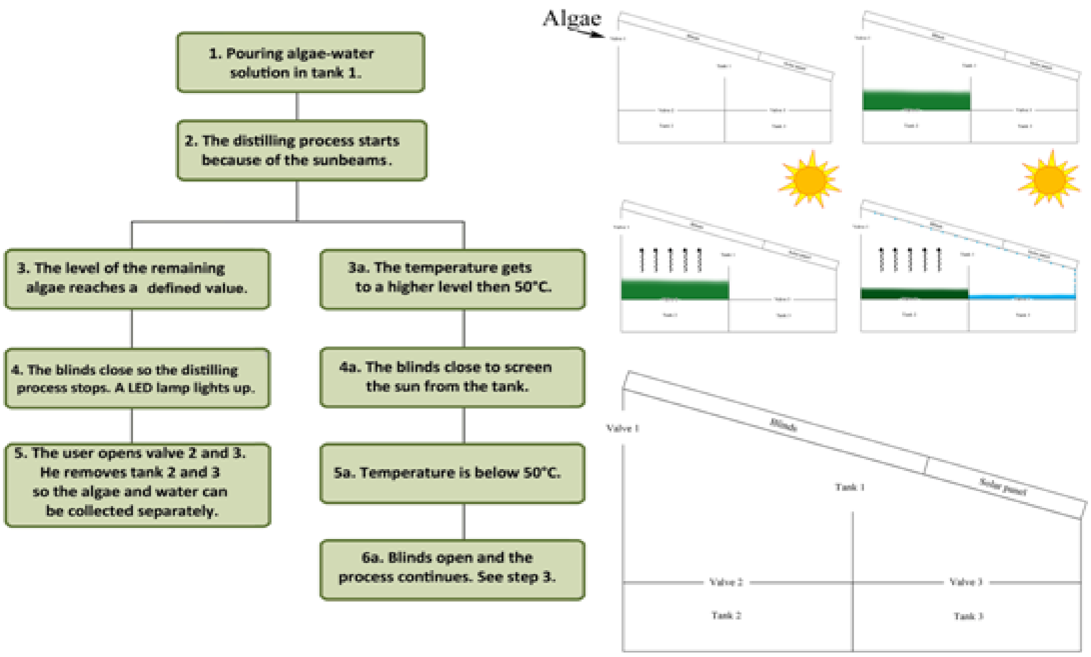

Figure 7. Working concept for the solar microalgae dryer

Figure 8 shows the block diagram of the proposed microalgae dryer system. The main components are:

- an ultraviolet (UV)-resistant tank;
- one Arduino Uno microcontroller board;
- a temperature sensor;
- one ultrasound sensor;
- a fan;
- a stepper motor;
- a solar panel; and
- a battery.

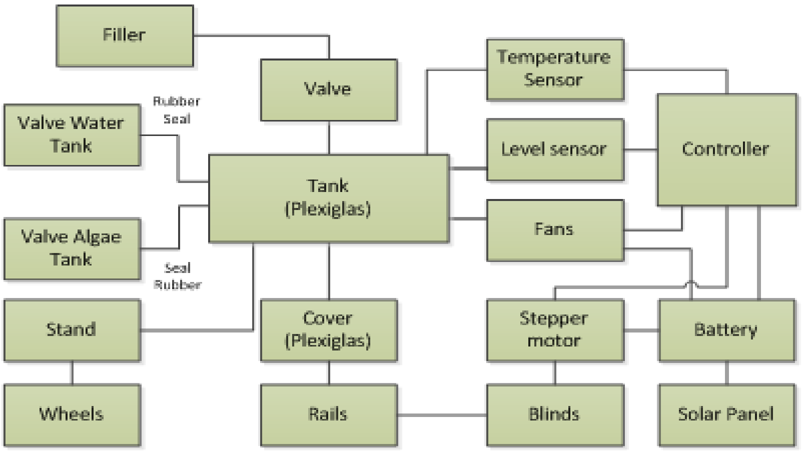

Figure 8. Block diagram of the system architecture

The main component of the prototype is the tank where the microalgae suspension will be dried. The remaining parts of the structure as well as the sensing and control system must interface with the tank and, therefore, the tank is the centre piece of the project implementation. In terms of requirements, the tank material should be:

- waterproof,
- UV-resistant,
- transparent (at least, the top),
- easy to assemble,
- light,
- eco-friendly, and
- compatible with the available budget.

Considering these requirements, aluminium, Plexiglas and plastic were contemplated (Brygider, Marciniak, Verbraeken, Ahlskog & Petersen, 2013). The team chose Plexiglas because it is waterproof, 99 % UV-resistant (microalgae suffer from exposure to UV), transparent (not only the top is transparent, but the whole tank), easy to assemble, cheaper than aluminium and not too heavy.

The microcontroller is the core element of the control system. The microcontroller board is programmed to read from the sensors (the temperature and water level sensors) and, if required, instruct the actuator (the stepper motor) to operate the blinds. This action controls the temperature inside the tank, ensuring that it does not rise above 50 °C. Additionally, it switches on/off the fan and three light emitting diodes (LED). The yellow LED indicates power on, the green LED signals the end of the drying process and the red LED excessive temperature (≥ 50 °C) in the tank. The board chosen is the Arduino Uno, containing the ATmega328 microcontroller. Arduino is a single-board microcontroller easy to use and integrate with other electronic components. It is an open source prototyping platform based on flexible, easy-to-use hardware and software. It was adopted because of its simplicity, but, at the same time, because it has sufficient number of analogue and digital ports (this project requires one analogue port and a few digital ports).

The temperature sensor is needed to measure the temperature of the microalgae solution. This information will support the decision to open/ close of the blinds, ensuring that the temperature of the solution does not exceed 50 °C. The team decided to install the DS18B20, a waterproof temperature sensor, to measure the temperature of the microalgae solution. This sensor is connected to the Arduino microcontroller and, if the temperature reaches or rises above 50 °C, the blinds close, otherwise the blinds remain open.

The level sensor is used to detect the end of the drying process. When the suspension volume reaches 10 % of the initial volume, it is time to stop the process. The microcontroller periodically reads the level sensor value and verifies if the suspension volume has decreased 90 %. The requirements for this sensor are: (i) adequate resolution (2 mm < *level* < 20 mm), and (ii) appropriate working temperature range (0 °C < T < 60 °C). The team, when faced this problem, considered and analysed different solutions, namely the use of a liquid level sensor, an optical sensor or an ultrasound level sensor (Brygider et al., 2013). The easiest and cheapest way to control the water level is with a liquid level sensor. It uses a floating body to measure the water level, which can be adjusted to the desired water level. The problem is that liquid level sensors do not have sufficient resolution to measure the small levels required in this project. To overcome this problem, the team selected an ultrasound sensor. Ultrasound sensors determine the distance to a given surface by transmitting high frequency sound waves, receiving the echo and calculating the time elapsed between the sending of the original signal and the receiving the echo signal. The Arduino reads periodically the ultrasound sensor level and, when the suspension level drops to 10 %, switches a LED to indicate that the drying process has finished and shuts down. The chosen sensor, a Devantech SRF04 Ultrasonic Range Finder, was attached to the side of the tank.

The speed of the distilling process depends on the rate of evaporation. The evaporation rate depends on the temperature of the air, the temperature of the microalgae solution, the dimensions of the surface exposed to the air, the concentration of the substance evaporating, the pressure and the air flow rate. The team decided to increase the air circulation inside the tank by adding a fan, i.e., the air flow rate, and considered two types of fans: a fan with a heater and a standard fan. The fan with heater was discarded because the gain obtained by heating the air did not compensate the energy consumed.

The team also discussed whether the system should be closed or open. The main difference between the two approaches is that in an open system there is a continuous supply of colder air. However, since the speed of the drying process depends on the flow rate and temperature of the air inside the tank, the team decided to build a closed system. Another advantage of a closed system is the fact that it is more weather proof, e.g., no rain will fall into the tank. Finally, in order to select a fan, the team took into account the fan power consumption and the expected power output of the chosen solar panel to verify that it could properly work for the time span of the evaporation. The selected fan was the Humid protect 12 V Direct Current (DC), 0.2 A (Brygider et al., 2013).

The temperature inside the tank is regulated through the opening / closing of the blinds. The operation of the blinds requires an actuator such as a stepper motor. A stepper motor is a brushless DC electric motor that divides a full rotation into a number of equal steps. The motor can then be commanded to rotate and hold at a given position or step without any feedback sensor. In this case, the stepper motor is mounted on the top of the tank and is connected to the blinds. When the motor rotates, depending on the direction, it opens / closes the blinds, controlling the temperature inside the tank. In terms of the heating and drying process, when the blinds open, the process starts and, when the blinds close, it stops. When the drying process finishes, the motor closes the blinds. The stepper motor, which will be controlled by the Arduino, must have:

- enough torque to operate the blinds, and
- reduced power consumption.

The stepper motor chosen was the 12 V Astrosyn Y129 (Brygider et al., 2013).

The main idea behind this project was to have the entire system working solely on solar energy. To fulfil this requirement the team had to choose a solar panel, to be mounted on the tank, responsible for supplying power to all electrical devices: the Arduino board, the temperature and level sensors, the three LED, the stepper motor and the fan. To select an appropriate solar panel, i.e., one with sufficient power output for the whole system, the team calculated, first, the maximum current, then, the maximum power dissipated and, finally, the maximum energy required for the operation of the system.

The power dissipated in a component is the product of the applied voltage V by the current I flowing through the component (Equation 1). The electric energy E consumed by an electric component measured in Wh is calculated using Equation 2, where P is the dissipated power and Δt is the duration of the operation within one hour.

$P = V \times I$ (W) Equation (1)

$E = P \times \Delta t$ (Wh) Equation (2)

According to the specifications, the Arduino board consumes at most 12 Wh/d. The temperature sensor is a 5 V device with a maximum current of 1 mA and the level sensor is a 5 V component with a maximum current of 50 mA. In terms of operation, the Arduino will check the temperature every 5 min for 1 min and the water level every 5 min during 1 s. Each LED has an applied voltage of 5 V, a maximum current of 10 mA and will, in a worst case scenario, be always on. The 12 V fan has a maximum current of 200 mA and operates continuously during the drying process. Regarding the stepper motor, considering the worst case scenario, i.e., in a summer day with a temperature above 30 °C, the motor may need to open/close the blinds six times. Each operation (closing or opening) will take at most 1 min. Table 2 presents for each component the voltage V and the maximum values for the current (I_{max}), power (P_{max}), duration of the operation Δt_{max}) per hour and consumed energy (E_{max}) per hour.

Component	***Qty***	***V*** (V)	I_{max} (A)	P_{max} (W)	Δt_{max} (h)	E_{max} (Wh)
Arduino	1	12	0.042	0.500	1	0.500
Fan	1	12	0.200	2.400	1	2.400
Stepper motor	1	12	0.200	0.240	1/120	0.002
Level sensor	1	5	0.050	0.250	1/5	0.050
Temperature sensor	1	5	0.001	0.005	1/300	0.000
LED	3	5	0.030	0.150	1	0.150
Total			0.523	3.545		3.102

Table 2. Maximum current, power and energy budget per hour

The maximum input current required is 523 mA, the maximum power consumed is approximately 3.5 W and the maximum energy consumed is approximately 3.1 Wh. As a result, the algae dryer will consume, in case of non-stop operation, approximately 74.4 Wh/d (Equation 3) and 27.2 kWh/yr (Equation 4).

$E_{max,d}$ = 3.1 Wh × 24 h = 74.4 Wh Equation (3)

$E_{max,yr}$ = 0.074 kWh × 365 d = 27.2 kWh Equation (4)

Based on this result, the team selected the Multicomp MC-SP15-GCS polycrystalline photovoltaic (PV) solar panel with the nominal characteristics described in Table 3.

Nominal Peak Power ($P_{P@STC}$)	15 Wp
Nominal Peak Voltage ($V_{P@STC}$)	17 Vp
Nominal Peak Current ($I_{P@STC}$)	890 mA
Open Circuit Voltage	21.5 V
Short Circuit Current	970 mA
Length	507 mm
Width	296 mm
Height	25 mm
Weight min.	2.56 kg

Table 3. Solar panel characteristics at STC

According to the manufacturer, this PV array can produce under standard test conditions (STC), i.e., with a constant solar irradiation of 1000 W/m^2 in the plane of the array, an array temperature of 25 °C and a solar spectrum corresponding to an air mass of 1.5, a peak power $P_{P@STC}$ of 15 Wp. According to the STC characteristics, the panel is able to provide sufficient voltage, current, power and energy to the prototype: $V_{P@STC}$ > 12 V, $I_{P@STC} > I_{max}$, $P_{P@STC} > P_{max}$ and $E_{P@STC} > E_{max}$. There is, however, an important panel performance factor to consider – the ratio of power output per hour and peak power of the solar panel at the installation location – called final yield (*Yf*). *Yf* is defined as the annual, monthly or daily (τ) net energy output of the system ($E_{O,,\tau}$) divided by the peak power of the installed PV array at STC ($P_{P@STC}$), as expressed in Equation 5 (Palmero-Marrero, Matos & Oliveira, 2015).

$Y_{f,\tau} = E_{O,,\tau}$ [kWh] / $P_{P@STC}$ [kWp] Equation (5)

Using the PVGIS site (http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php?lang=en&map=europe) and inserting the characteristics of a PV panel, it is possible to obtain an estimate of the average $E_{O,,\tau}$ for different areas of the world (Bertoldi, Hirl & Labanca, 2012). The estimated average yearly energy $E_{E,yr}$ produced by the selected panel in Porto, Portugal is, according to PVGIS, 19.1 kWh, resulting in an estimated annual final yield $Y_{f,yr}$ of 1273 kWh/kWp (Equation 6).

$Y_{f,yr}$ = 19.1 [kWh] / 0.015 [kWp] = 1273 kWh/kWp Equation (6)

Taking into account this factor, the estimated peak power P_{PE} needed to power the system in this region is 21 Wp (Equation 7).

P_{PE} = 27.2 [kWh] / 1273 [kWh/kWp] = 0.021 kWp Equation (7)

Equation 8 shows that the panel provides approximately 71 % of the estimated peak power required to operate the system under worst case conditions (Equation 8).

$P_{P@STC}$ / P_{PE} (%) = 15 [Wp] / 21 [Wp] = 71 % Equation (8)

These calculations, however, refer to weather conditions throughout the whole year, including cloudy and rainy days, and to extreme operation conditions. On the one hand, the system will not be effective and, probably, will not be used in cloudy or rainy days and, on the other hand, the prototype is not expected to be continuously under worst case operation conditions. The team decided to buy the selected solar panel because it was confident that the panel, under regular operation conditions, would provide sufficient power to the system.

In order to power the system when the energy harvested from the Sun is not sufficient, the team searched for a battery. The solar panel will be connected to the battery and charge it when there is an excess of power available. There are many different types of batteries and the characteristics of several types were analysed, namely Nickel Cadmium (NiCd), Nickel-Metal Hydride (NiMH), Lead Acid, Lithium Ion (Li – ion), Lithium Ion Polymer (Li – ion polymer) and reusable Alkaline (Cadex Electronics Inc., 2015). After comparing the characteristics of these six most commonly used rechargeable battery systems in terms of energy density, life cycle, exercise requirements and cost, it was decided to adopt a 12 V 2.3 Ah Lead Acid battery from Yuasa for the solar microalgae dryer (Brygider et al., 2013).

4 PROJECT DEVELOPMENT

This section presents the design of the prototype as well as the planning and building stages. Table 4 presents the list of components selected to build the solar microalgae dryer system and their unit prices, totalling 394.37 €. The system consists of the structure, the control system and the power supply module.

Description	***Quantity***	***Price (€) / unit***
UV-resistant plastic tank (118 × 126) cm^2 in 6 mm Plexiglas	1	122.88
Microcontroller board Arduino Uno	1	20.00
Waterproof temperature sensor DS18B20	1	8.95
Ultrasound level sensor	1	(*)
Fan 12 V DC	1	30.00
Stepper motor Astrosyn Y129	1	(*)
Solar panel 15 W	1	105.80
Battery 12 V	1	(*)
LED	3	(*)
Blinds (60 × 130) cm^2	1	4.99
Valve 13 mm	3	7.25
Connecting pipe	2	(*)
Mirror (20 × 50) cm^2	1	(*)
Stand	1	(*)
Wheels	4	20.00

(*) Available at ISEP

Table 4. List of materials for the solar microalgae dryer

The tank was designed with a capacity for 5 l and includes a large compartment for the microalgae solution and a smaller compartment for the “clean” evaporated water, as depicted in Figure 9. This means that the evaporated water is collected rather than wasted. During the process, the evaporated water will rise to the cover of the tank and slide down to the water tank. The concentrated microalgae suspension will remain in the larger tank till the process finishes.

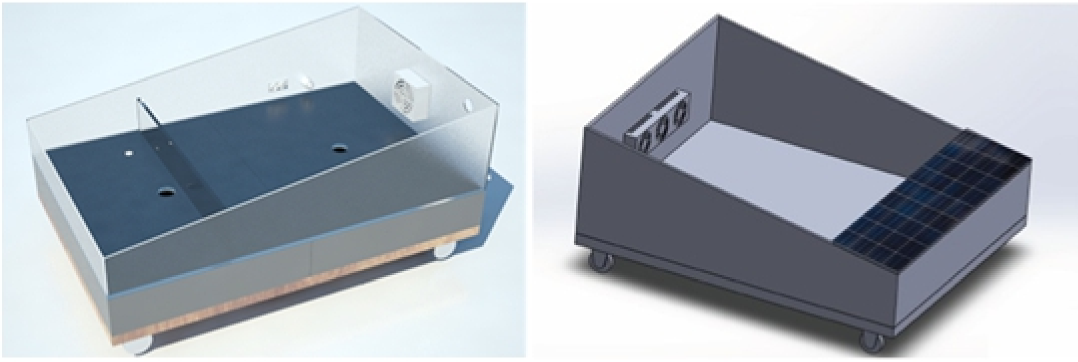

Figure 9. 3D CAD model of the tank (left) and rendered view with the solar panel placed in position (right)

After designing the tank, the team addressed the control system. This system includes the temperature and level sensors, the microcontroller Arduino Uno board, the stepper motor and the fan. The microcontroller board communicates with both sensors to obtain measurements, with the fan and the motor to operate the blinds. It controls the stepper motor according to the sensor readings and, thus, the drying process. The fan is connected to the microcontroller and runs continuously until shutdown. The temperature sensor measures the temperature of the microalgae suspension and is used to control the blinds and one LED. The ultrasonic SRF04 sensor level reads the level of the microalgae suspension and is used to determine the end of the drying process. When the water level reaches 2 mm (only 0.5 l of water remaining), the microcontroller shuts down the system. The shutting down consists of closing the blinds, stopping the fan and lighting a LED. Figure 10 presents the flowchart of the control system.

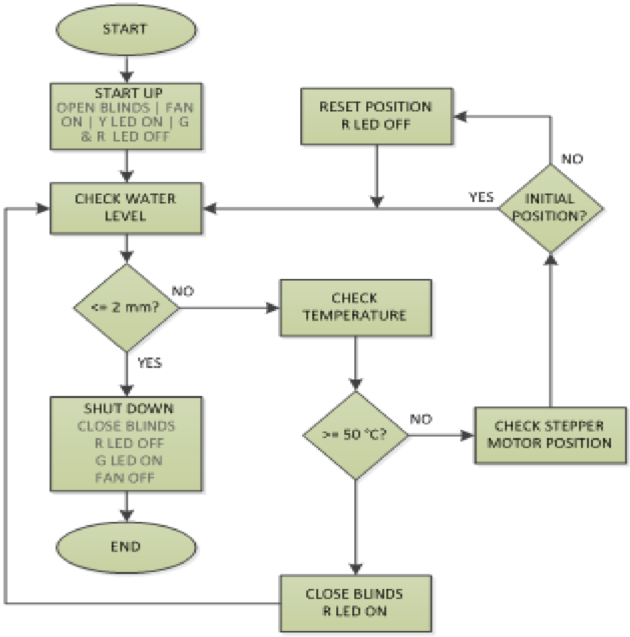

Figure 10. Flowchart of the control system

First, the Arduino starts the fan and checks if the water level has reached 0.5 l. If this is the case the system shuts down, otherwise proceeds. The shutdown procedure includes closing the blinds, stopping the fan and switching on the green LED. Then, the Arduino checks the temperature. If the temperature is under 50 °C, then, if the blinds are closed, it opens the blinds and, if the red LED is on, switches it off. If the temperature is equal to or higher than 50 °C, it closes the blinds and switches the red LED on. This flowchart is implemented in the Arduino Uno control program (Brygider et al., 2013).

After the definition of the flowchart, the team created the control system schematic, including electrical and electronic components and their connections (see Figure 11). The components with high power consumption require additional circuits as can be seen in this figure. For instance, the stepper motor can only be operated with the use of a current driver, two capacitors and inverters. There is also the need to connect a transistor to the fan and place resistors in series with the LED and temperature sensor.

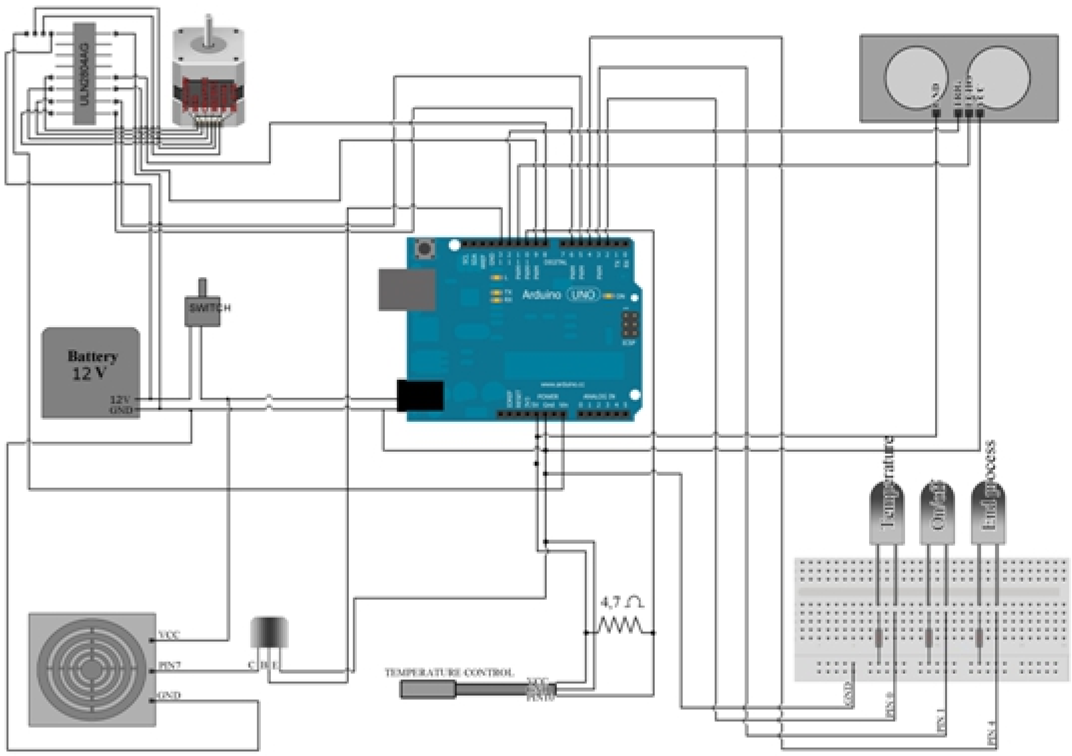

Figure 11. Schematic of the control system

5 TESTS AND RESULTS

During the assembly of the system, several tests were conducted to ensure that the final prototype would work as intended, i.e., fulfils the specified requirements. This section reports these tests.

5.1 Sensors tests

The goal of the temperature sensor test was to verify that the blinds close when the temperature of the microalgae suspension rises above 50 °C, i.e., if the system protects the microalgae from high temperatures. In order to check this, water was poured into the tank at a temperature above 50 °C and the blinds closed.

The goal of the level sensor test was to check that the blinds close when the level of the microalgae solution reaches 10 % of the initial volume, i.e., when the drying process finishes. This means that at the end of the process the solution left in the tank should be 0.5 l, i.e., 10 % of the initial 5.0 l.

This test was conducted using a plastic Tupperware tank, the Arduino microcontroller board, the ultrasound sensor, a vertical scale in mm and water. The goal of the test was to verify if the ultrasound sensor was able to measure the microalgae solution level correctly. The test consisted in pouring water until reaching predefined levels of water in the vertical scale (Figure 12) and comparing with the values measured by the sensor (the microcontroller program returns the distance read by sensor). The process started with the tank empty and was repeated, with 5 mm level increments, until reaching 30 mm of water level.

Figure 12. Ultrasound sensor test

The team concluded that the sensor had to be placed horizontally. Any change in the angle of the sensor position affected the sensor reading. Additionally, the sensor detected the surface of the water with and without a floating body in the water. The sensor readings, which correspond to the level in millimetres, are always rounded to the nearest integer value.

This set of experiments illustrated the usefulness of the ultrasonic sensor to detect the end of the drying process. It also provided a valuable insight on how to apply the sensor in the final product, i.e., the need to ensure that it is placed horizontally to the surface of the microalgae solution. Finally, the team concluded that the sensor worked without the need of a floating body.

5.2 Charging algae tests

The team explored the hypothesis of the microalgae having an electrical charge in order to see if this property could be used to separate the microalgae from the water. To test this hypothesis, a set of experiments was performed at Instituto Nacional de Engenharia Biomédica (INEB). The set up can be seen in Figure 13.

First, the size of the particles was determined using a method called Dynamic Light Scattering. Then, a set of charging tests was performed to find the Zeta Potential. This was done through Laser Doppler Electrophoresis. In the first attempts the suspension was diluted and it was discovered that the microalgae were negatively charged. These tests were made with the different types of algae available and each test was repeated three times for each type of algae. In the end, the team concluded that the microalgae have a negative charge and that this could be used as an advantage (Brygider et al., 2013).

The next step was to test if it was possible to attract the microalgae with a positive charge. The first experiment was performed with two titanium electrodes, which proved to be inadequate (it created a current and oxidized the microalgae). In the sequel, a sort of capacitor was built (two charged plates, one positive and one negative) and the algae suspension was placed in a small plastic box between the plates. The plates were charged with 12 V and the density of the algae on both sides of the box was measured every half an hour, using a spectrometer, to check if the algae were attracted to one side. When using the capacitor, the microalgae were attracted to the negative side of the box, as can be observed in Figure 14. Initially, the density of the microalgae suspension sample was 0.385 and, in the end of the test, the density of the concentrated microalgae sample was 1.074, i.e., the density increased three times.

Figure 13. Set up for the algae charging tests

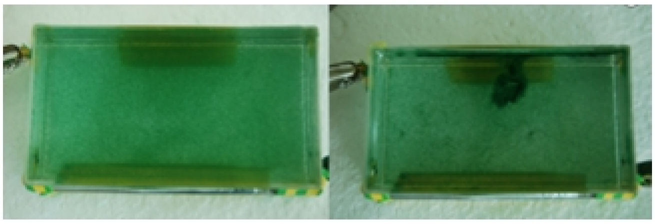

Figure 14. Plastic box with algae in the beginning (left) and end (right) of the charging test

Additional tests were performed with different voltages and set ups. The team discovered that with a voltage of 35 V the separation was faster, but higher voltages had no noticeable effect on separation rate. The team suspected that a voltage of 12 V should be sufficient since distilling is a long process.

Although the results of these tests were very promising, since the project development was already in a final stage, the team decided not to integrate this technology in the prototype.

6 PROTOTYPE

At the end of the project, the prototype was built, as can be observed in Figure 15. Once the complete prototype was assembled, a final set of tests was performed to ensure the fulfilment of the client's requirements.

The main tests that the solar microalgae dryer needs to fulfil are the following:

- check if the process is interrupted when the temperature inside the tank rises above 50 °C – it is necessary to fill the tank with water over 50 °C and verify if the stepper motor closes the blinds and the corresponding LED turns on; and
- check if the process stops when the suspension level reaches 2 mm – it is necessary to pour 5 l of water in the tank and slowly empty the tank and verify if, when the water level drops to 2 mm, the blinds close and the corresponding LED lights on.

The prototype passed both tests.

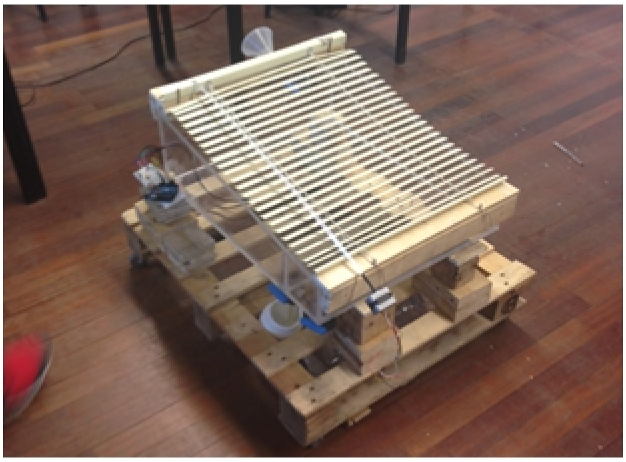

Figure 15. Set up of the final prototype tests

To forecast the efficiency of the prototype, data was gathered concerning the weather and atmospheric conditions for the years 2012 and 2013, namely the average heat index and the average temperature in °C, solar irradiation in W/m^2 and percentage of relative humidity (Solix BioSystems, Inc., 2012). From this data, the team forecasted that the best performance should occur between April and October. The high solar irradiation and average temperature together with the low relative humidity typical of this period contribute to increase the rate of the evaporation.

7 CONCLUSIONS AND IDEAS FOR FUTURE DEVELOPMENTS

The work described in this paper was developed during the EPS@ISEP 2013 spring edition. This capstone project/internship program, offered at the School of Engineering of the Polytechnic of Porto, intends to train engineers to face the challenges of the 21st century, including those related with sustainability, ethics and deontology and social compromises. This particular project, the microalgae dryer, is aligned with UNESCO Millennium Development Goal 7 (Ensure environmental sustainability) (UNESCO, 2010) and also related with some of the Grand Challenges for Engineering (National Academy of Engineering, 2008).

The microalgae dryer is a distiller, i.e., the microalgae dry with direct solar radiation, which will warm up the solution, making the water evaporate. The solar radiation is also used for supplying the electrical energy to the electronics controlling the process, through the use of a solar panel. The control system is based on an Arduino board and the functions implemented ensure that the microalgae suspension does not overheat and that when the process finishes, the distilling stops. All electronic devices were programmed and the prototype passed the operational tests. Last but not least, the project was supported by marketing, sustainability and ethical and deontological studies. In the specific case of this project, the sustainability issues were essential in the design and selection of components. In fact, the team was able to devise a technical solution with long life cycle and low negative environmental impacts, contributing, in a larger extent, to a better quality of life on Earth. This is an essential engineering skill for future professionals.

According to the team, "*Looking back at the past four months that we dedicated to develop our project, there are some things that come to our minds. From the beginning our thoughts were to develop a product with low power consumption that would work and replace the centrifuge that our client (ISEP Chemical Technology Laboratory) is using now. That was the expected result from the beginning. After we had some troubles with the ordering and delivery of the materials and because of that got delayed in our process we can state that we did not fulfil all of our expected results. Also the electronic devices and connections caused us some problems because we did not have any experience in that field. Throughout the process we learned that a better planning, and proper deadlines, for ourselves would have helped us finish in time*." (Brygider et al., 2013).

Concerning possible future developments, the results obtained from the microalgae charging tests were promising and, thus, worth of further exploration in order to understand how they could be included in the prototype. For example, if the microalgae could be attracted to the bottom of the tank, the excess water could be easily removed from the top levels of the solution before starting the distilling process, reducing dramatically the process time. To increase the usability of the system, the automatic removal of the microalgae from the tank in the end of the process should be addressed, e.g., with an electrical pump. Finally, in the long perspective, the integration of the solar microalgae dryer concept with a microalgae growth farm and a biodiesel production system could be investigated. This would allow the design of an entire biodiesel chain of production, from the raw substrate to the extracted product.

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