



University of Porto
Faculty of Engineering

Conceptual development of a solar PV powered insect trap

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(MSc in Mechanical Engineering)

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Dissertation submitted to the University of Porto
in partial satisfaction of the requirements for the
Master's degree in Mechanical Engineering.

July 2022

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Acknowledgements

I would like to first thank Prof. Szabolcs Varga for the help given throughout this dissertation and for providing me with the opportunity to work on the STOP.SUZUKII project.

I would like to thank Mr. Carlos Pinto and Mr. Tiago Martins for the vast knowledge they shared during this dissertation and for going above and beyond in helping me complete it.

I would like to thank Mr. Ricardo Carvalho for the help provided in designing the control system.

I would also like to thank FEUP and INEGI for providing the equipment and conditions to carry out this work.

Finally, I express immense gratitude to my family and to all my close friends who have provided me with joy and laughter through these years of study in the city of Porto.

Rui Pedro Silva Martins

Abstract

The food sector is constantly being threatened by new diseases and pests that appear over the years. Their control and monitoring must be carried out to prevent economic and environmental damage. Spotted-wing drosophila is a harmful species that appeared for the first time in Portugal in 2012. Since then, it causes significant damage in soft fruits, crops and vineyards. They lay their eggs inside the fruit, causing a 20-50 % rejection rate before commercialisation. In this context, the STOP.SUZUKII project was established with the objective to develop new sustainable control strategies based on integrated pest management and biological agriculture. In this dissertation, the primary goal is the development of an insect trap that is selective, environmentally friendly and sustainable without recourse to pesticides and using stand-alone devices.

The insect trap to be developed should operate using two distinct mechanisms: new selective chemical bait and renewable energy operated LEDs. Besides these initial targets, another set of technical specifications needed to be complied throughout the prototype's development. The trap LEDs are required to work at specific periods of the day and are automatically activated. The energy required should be produced by solar photovoltaic modules and stored in a battery. Therefore, it is necessary to size and select a photovoltaic panel, a battery and design an automatic control system, while satisfying other technical constraints such as size and weight.

The sizing of the photovoltaic panel and the battery cell was carried out by simulations of the complete system using PVsyst 7.2 Software. Later the model results were validated using experiments. The control system was designed by selecting the electronic components required for each function and matching their electrical characteristics to each other. The bait holder is a commercial container, modified according to specifications, with the integration of 3D printed parts.

Laboratory experiments were carried out to evaluate the performance of the developed insect trap and identify technical problems. The photovoltaic panel has a verified power of 1.3 W, the battery has a capacity of 2,200 mAh, the battery management system has a charging efficiency of 58 %, and the electrical system consumes a total power of 2.5 W. The insect trap weighs 325 g and its dimensions are 125x105x165.5 mm. The results showed that the prototype could not work for the predefined period of time. An operating time of more than 80 % was predicted by the simulations and the performance results showed an operating time of 43.75 %. The simulations underestimated the efficiency of electronic components and the photovoltaic panel acquired do not have the power output specified. Future work may be mainly concerned with increasing the power of the photovoltaic panel, the battery capacity and the charging efficiency of the battery management system.

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Abbreviations

AR	Anti-reflective
ADC	Analog-digital converter
BMS	Battery management system
CC-CV	constant current-constant voltage method
CPU	Central processing unit
CRI	Colour rendering index
DAC	Digital-analog converter
DC	Direct current
DoD	Depth of discharge
DRAPN	Direção Regional de Agricultura e Pescas do Norte
ESA-IPVC	Escola Superior Agrária do Instituto Politécnico de Viana do Castelo
FCUP	Faculdade de Ciências da Universidade do Porto
FET	Field effect transistor
FEUP	Faculdade de Engenharia da Universidade do Porto
IC	Integrated circuit
INEGI	Instituto de Ciência e Inovação em Engenharia Mecânica e Engenharia Industrial
IoT	Internet of Things
IT	Insect trap
LCO	Lithium cobalt oxide
LDR	Light dependent resistor
LED	Light-emitting diode
LFP	Lithium iron phosphate
LID	Light induced degradation
LMO	Lithium manganese oxide
LTO	Lithium titanate oxide
MCU	Microcontroller unit
MOSFET	Metal oxide semiconductor field effect transistor
MPPT	Maximum power point tracker
NOCT	Nominal operating cell temperature
NCA	Lithium nickel cobalt aluminium oxide
NMC	Lithium nickel manganese cobalt oxide
OLED	Organic light-emitting diode
PCB	Printed circuit boards
PIR	Passive infrared sensor
PN	Positive-negative

PV	Photovoltaic
PWM	Pulse-width modulation
RTC	Real-time clock
SCL	Serial clock
SDA	Serial data
SoC	State of charge
SoH	State of health
STC	Standard test conditions
SWD	Spotted-wing drosophila
TL	Threshold limit
UV	Ultraviolet

Nomenclature

A	Area [m^2]
a	Modified ideality factor [-]
a_{ref}	Reference modified ideality factor [-]
C	Battery capacity [Ah]
c	Unit conversion constant between lumen and watts [-]
C_{5A}	Discharge current rate for 5 hours [A]
C_p	Battery capacity for one-ampere discharge current [Ah]
E_v	Illuminance [lx]
E_{bat}	Energy stored by battery [Wh]
E_{day}	Daily energy consumption [Wh]
E_{load}	Energy required demand [kWh]
E_{night}	Nightly energy consumption [Wh]
E_{unused}	Unused energy [kWh]
E_{used}	Used energy [kWh]
G_T	Global solar radiation [W/m^2]
$G_{T,NOCT}$	Solar radiation at nominal operating cell temperature conditions [W/m^2]
H	Rated discharge time [h]
I	Electrical current [A]
I_D	Diode current [A]
I_{dis}	Actual discharge current [A]
I_L	LED current [A]
I_o	Diode reverse saturation current [A]
I_{DD}	Drain current [A]

I_{DSS}	Zero gate voltage drain current [A]
$I_{L,ref}$	Reference LED current [A]
$I_{mp,ref}$	Reference maximum current [A]
I_{mp}	Maximum current [A]
$I_{o,ref}$	Reference diode reverse saturation current [A]
I_{out}	Current output to battery [A]
$I_{sc,ref}$	Reference short-circuit current [A]
I_{sc}	Short-circuit current [A]
I_{sh}	Shunt current [A]
$J(\lambda)$	Radiant spectral power distribution [W/nm]
k	Boltzmann's constant [J/K]
$k_{peukert}$	Peukert constant [-]
n	Ideality factor [-]
N_s	Number of cells in series [-]
P	Power [W]
$P_{Arduino+RTC}$	Power consumption of the Arduino and RTC [W]
P_{in}	Power input [W]
P_{Joule}	Power dissipated by joule effect [W]
P_{LEDs}	Power consumption of the LEDs [W]
P_{MOSFET}	Power consumption of the MOSFET [W]
P_{mp}	Maximum power point [W]
q	Electric charge [C]
R	Electrical resistance [Ω]
R_s	Electrical resistance in series [Ω]
$R_{arraySTC}$	PV array resistance at standard test conditions [Ω]
$R_{DS(off)}$	Drain-source off-state resistance [Ω]
$R_{DS(on)}$	Drain-source on-state resistance [Ω]
R_{DS}	Drain-source resistance [Ω]
$R_{s,ref}$	Reference electrical resistance in series [Ω]

$R_{sh,ref}$	Reference shunt resistance [Ω]
R_{sh}	Shunt resistance [Ω]
R_{wiring}	Global wiring resistance [Ω]
t	Time [h]
T_a	Ambient temperature [K]
T_c	Cell temperature [K]
$t_{22:00-5:00}$	Time between 22:00 and 5:00 [h]
$T_{a,NOCT}$	Ambient temperature at nominal operating cell temperature conditions [K]
$T_{c,ref}$	Reference cell temperature [K]
$t_{LEDsOFF}$	Time LEDs OFF per day [h]
t_{LEDsON}	Time LEDs ON per day [h]
T_{NOCT}	Cell temperature at nominal conditions [K]
$U_{L,NOCT}$	Thermal loss coefficient at nominal operating cell temperature conditions [$W/(m^2K)$]
V	Electrical voltage [V]
V_{DD}	Drain voltage [V]
V_{DS}	Drain-source voltage [V]
$V_{GS(th)}$	Gate-source threshold voltage [V]
V_{GS}	Gate-source voltage [V]
$V_{mp,ref}$	Reference maximum voltage [V]
V_{mp}	Maximum voltage [V]
$V_{nominal}$	Nominal voltage [V]
$V_{oc,ref}$	Reference open-circuit voltage [V]
V_{oc}	Open-circuit voltage [V]
$y(\lambda)$	Luminosity function [-]

Greek symbols

λ	Wavelength [nm]
α	Thermal radiation absorption coefficient [-]
η_c	Electric conversions efficiency [-]

λ_p	Peak sensitivity wavelength [nm]
$\mu_{I,sc}$	Temperature coefficient of short-circuit current [A/K]
$\mu_{V,oc}$	Temperature coefficient of open-circuit voltage [V/K]
ϕ	Luminous flux [lm]
τ	Thermal radiation transmittance coefficient [-]

Chapter 1

Introduction

1.1 Motivation and context

Climate change and the increasing warming of the planet lead to climatic phenomena of extreme drought that make access to drinking water difficult in some regions of the planet. The lack of water causes a scarcity of water in the soil, which harms food production. Population growth on the planet leads to an increase in the planet's energy and food needs. These problems have to be tackled with policies that lead society towards sustainable growth. Sustainable practices support ecological, human, economic health and vitality. Sustainability presumes that resources are finite, and should be used conservatively and wisely with a view to long-term priorities and consequences of the ways in which resources are used. In the broadest possible sense, sustainability refers to the ability of something to maintain or "sustain" itself over time [1]. Therefore, it is in this aspect that mechanical engineering has a great importance and contribution, as it has influence in areas such as product development, manufacturing processes, energy production and management, automation, renewable energies, etc., areas that directly influence society, nature and the use of natural resources. This project fits into this sustainability perspective and aims to develop a sustainable insect trap without pesticides and using self-sustaining devices. Sometimes an ideal solution is not possible, but these details have been taken into account to produce a product that is as sustainable as possible.

In the last years, the agriculture and food sector in Europe has been adjusting to a healthier lifestyle, which boosted the production and consumption of some fruits like cherry, blueberry, strawberry, raspberry, and blackberry. In Portugal, the soil and climate are very favourable to produce them, particularly in northern and central Portugal. The production of these fruits has increased significantly, especially blueberries, which increased by 168% from 2016 to 2018 [2]. In 2018 blueberries exports accounted for a value of 200 million [3], putting Portugal in the top 10 producers in the world. The blueberry is considered a superfruit given its richness in vitamins and minerals, as well as being powerful antioxidants [4]. There are several species that produce blueberries, from the genus *Vaccinium*. The characteristics of the species and the fruit varying from species to species, but in general, the species are shrubby, and the fruit is characterised as being a small, globose berry, with colour shades ranging from light to very dark blue [5]. This dissertation is involved in the **STOP.SUZUKII** project, which proposes an operational tool to improve the production of high-quality premium blueberries and

development of new control methodologies based on integrated pest management and biological agriculture. Therefore, the general objective of this project is to decrease pest damage and increase the fruit's conservation time in order to obtain higher quality fruits without infestation. Mirtilandia is the private company involved in the project.

Mirtilandia focuses on the production and sale of a premium product, i.e., of high quality, organic origin and with a very little storage time, with a fresh appearance and taste. One of the main challenges that the company and blueberry growers have encountered is the difficulty of combating pests, especially *DROSOPHILA SUZUKII*, known as the spotted-wing drosophila (SWD). This species attacks all kinds of soft fruits and has already appeared in vineyards, with the rejection rate recorded in blueberry cultivation in Mirtilandia being between 20% and 50%. This fruit fly distinguishes itself from others by preferring to feed and lay eggs on commercially viable fruit, rather than on overripe and/or damaged fruit. It is a species originating from Asia that appeared in Portugal in 2012 and since then its distribution has been monitored in various crops throughout Portugal [6]. The insect trap was developed with the aim of controlling and preventing the growth and proliferation of this pest.

1.2 Objectives of the dissertation

Currently there are no effective control strategies for the SWD plague. Therefore, this project aims to test and implement new concepts for its sustainable control. The objectives of this project are:

- Development of a sustainable insect trap that integrates:
 - LED light source;
 - Photovoltaic energy source;
 - Electrical energy storage;
 - LED control system;
 - Design optimised to attract SWD.
- Validation of the simulations of the stand-alone photovoltaic system;
- Assessment of the selectivity of SWD for different LED colours;
- Validation of SWD selectivity for the new chemical bait.

1.3 Brief presentation of the STOP.SUZUKII project

This dissertation is involved in the **STOP.SUZUKII** project, which proposes an operational tool to improve the production of high-quality premium blueberries and development of new control methodologies based on integrated pest management and biological agriculture [7]. Therefore, the general objective of this project is to decrease pest damage and increase the fruit's conservation time in order to obtain higher quality fruits without infestation. The project leader is the company **Mirtilândia**, with copromotion of Faculdade de Ciências da Universidade do Porto (**FCUP**), Instituto de Ciência e Inovação em Engenharia Mecânica e Engenharia Industrial (**INEGI**), Faculdade de

Engenharia da Universidade do Porto (FEUP), and Escola Superior Agrária do Instituto Politécnico de Viana do Castelo (ESA-IPVC). This is a two and a half year project funded by the P2020 programme.

This stage of the STOP.SUZUKII project included different teams working together to develop the sustainable insect trap with each having different roles. The FCUP and Mirtilândia team did the research on the specifications that the insect trap should have. The INEGI team had different elements involved, some specialised in product and system development, and others specialised in renewable energy.

1.4 Structure of the dissertation

This document is organised into 8 chapters. The first chapter provides an introduction to the project. The second chapter consists of a description of the SWD characteristics and control strategies. The next chapter, Chapter 3, provides a general description of the electronic components used in the insect trap. In Chapter 4, the development of the sustainable insect trap is described in detail. Chapter 5 refers to the initial experimentation and research done to select the main components. In Chapter 6 the characteristics and design of the control system are explained. Chapter 7 provides a conceptual design of the prototype and a performance evaluation. Finally, Chapter 8 presents the conclusions and future improvements on the work done. Detailed information corresponding to each chapter can be found in the Appendices.

Chapter 2

Characterisation of *Drosophila Suzukii*

Drosophila Suzukii is an insect that causes great serious problems in the soft fruits crops so, before focusing on the development of the sustainable trap, it is important to provide a short description of the insect regarding their morphological characteristics, control and monitoring techniques and colour preferences.

2.1 Characterisation of the insect

Spotted wing drosophila is a member of the *Drosophila suzukii* subgroup within the *D. melanogaster* species group of the subgenus *Sophophora* (Diptera: *Drosophilidae*) [6]. Usually, two key morphological characteristics are used to differentiate SWD from other drosophilids. They have a dark spot on the leading wing edge of males and a large serrated ovipositor in females, as shown in Figure 2.1 [6]. While these traits are easily observed with appropriate magnification, they may not be sufficient for diagnostic. This is because wing spots require up to two days to be fully formed and these traits are similar to those found in some closely related species, like *Drosophila subpulchrella* [6].



Figure 2.1: Magnified view of the SWD ovipositor [6].

It's a greatly damaging species, due to its rapid dispersal and proliferation, opportunistic and polyphagous nature [8]. Its preference for feeding and laying eggs on commercially viable fruits, rather than overripe and/or damaged ones distinguishes it

from other drosophila. They penetrate the fruit skin using their serrated ovipositor, laying the eggs under the oviposition scar, with larval development progressing inside the fruit and feeding on internal fruit tissues, as shown in Figure 2.2 [6]. Additionally, the wounds caused by laying allow the opportunistic entry of fungi and bacteria, accelerating rotting [9]. This pest has summer and winter morphotypes, both found in Portugal, as shown in Figure 2.3 [10]. As can be observed, the winter morphotype is darker and has slightly larger wings and body compared to the summer morphotype [11]. This is relevant because, as this project will take into account the characteristics of the summer morphotype, the use of the trap during winter may not be compatible.

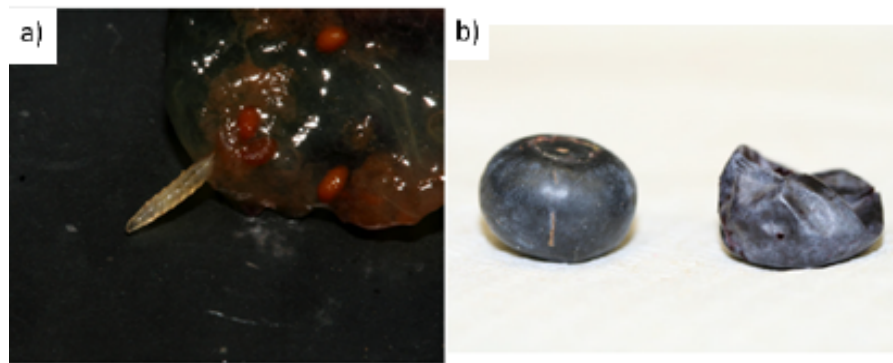


Figure 2.2: a) SWD larva infesting blueberry tissue; b) Comparison of blueberry fruit morphology when undamaged or after 1 week of SWD infestation [6].

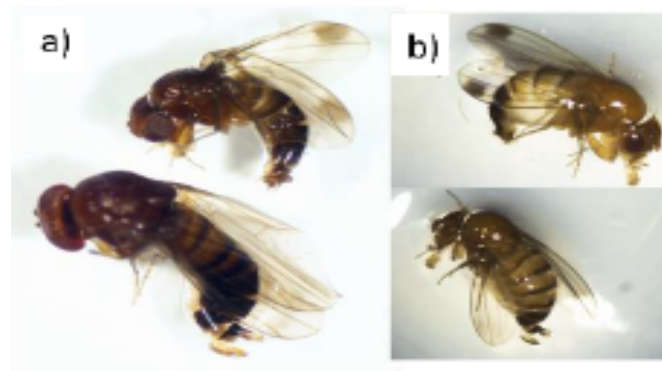


Figure 2.3: a) Winter morphotype; b) Summer morphotype [10].

The life cycle of *Drosophila suzukii* is temperature dependent, lasting between 21-25 days at 15°C, or only 8-11 days at 25°C [12]. Adults are most active at 20-25°C, while less active below 10°C and above 30°C [13][14]. As each female can lay up to 350 eggs during her lifetime, a short life cycle can give rise to millions of offspring in the total months of the fly's reproductive season (up to 10 generations/year) [15]. They have an estimated lower thermal threshold of about 6°C, peaking at about 29°C, then declining to zero at approximately 31°C [6].

It is not known how, and where, this pest spends part of its life cycle when there are no cultivated hosts, especially in winter. There are no effective measures to control this pest worldwide. In France and Italy it has been shown that some wild hosts near

orchards/greenhouses, increase the presence and survival of *D. suzukii* by helping it to hibernate [16]. It is important to have these characteristics well detailed and investigated to make the fight against this pest more effective.

2.2 Worldwide distribution of SWD, monitoring and control strategies

Figure 2.5 shows the distribution of the SWD worldwide. There is also some countries that its presence is expected but not confirmed yet, like north Africa and Russia [6]. SWD was first reported from mainland Japan in 1916. Since then, its distribution has been consolidated throughout Asia. In the USA, it was first recorded in the coastal production regions of California in 2008. In Europe, it was first recorded during the autumn of 2008 in Spain and Italy. It was only recorded in Portugal in 2012, as shown in Figure 2.4. In south America, SWD was first recorded in Costa Rica and Ecuador in 2013, having arrived in Brazil in 2014.

Due to SWD's rapid dispersal and proliferation, it is necessary to monitor their occurrence, especially near soft fruit plantation areas. FCUP has, together with Direção Regional de Agricultura e Pescas do Norte (DRAPN), monitored the distribution of *D. suzukii* in several crops in the North of Portugal since 2017 (relevant captures in vines and blueberries), as shown in Figure 2.6. These data allowed establishing flight curves of the pest and the occurrence rate of summer vs. winter morphotypes. The characteristics of the North and Centre region, where orchards coexist within a short distance from gardens and/or woodlands, should be considered when analysing this type of data. These characteristics helps forming very heterogeneous habitats and where alternative hosts/reservoirs easily occur, which compromise the fight against this pest.



Figure 2.4: Current European SWD distribution map (2015) indicating the year of first SWD report [6].



Figure 2.5: Current worldwide SWD distribution map (2015) [6].

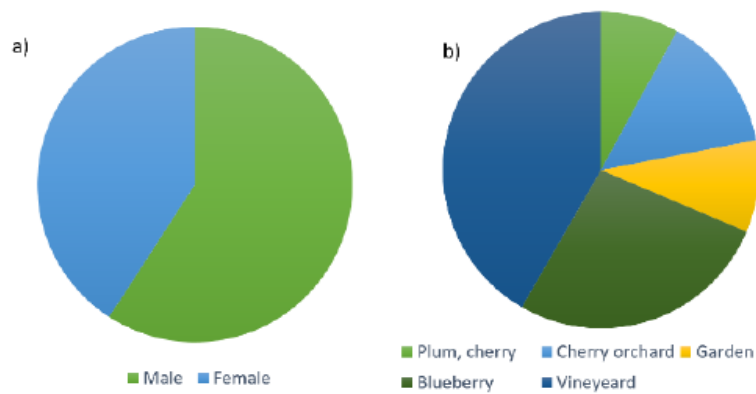


Figure 2.6: Results of trap monitoring between 2017-2018 (FCUP/DRAPN) in the North of Portugal: a) Proportion of males and females; b) Number of individuals per trap in different crops [17].

One way of control the dispersion of SWD is by using chemical control techniques, such as insecticides. It is recommended the use of insecticides at least twice pre-harvest, and the alternation of chemical groups to minimise the occurrence of resistance, since this species presents multiple generations in each season, which increases the risk of the appearance of resistant lineages [18]. Recent trials conducted in highbush blueberries in Michigan showed that the duration of fruit protection is variable among insecticides, and that efficacy declines rapidly if the residues are washed off by rain. Previous studies revealed that eggs and larvae can be controlled after penetration into the fruit, meaning that adult fly control is not the only mechanism to achieve crop protection [6]. Future research on this topic is needed to avoid overuse of non sustainable and harmful products by the farmers.

Alternative strategies include cultural control, such as tillage to bury infested fruit, physical exclusion with netting, fruit cooling, irradiation, and post-harvest sorting. There is an increasing production of fruit crops in high tunnels for manipulating harvest

date and reducing disease incidence [19].

Biological control has been the subject of research in recent years and has gained importance in comparison to chemical control. Although predators and pathogens may play important roles in regulating SWD populations, most efforts in examining biological control options for invaded regions have focused on hymenopteran parasitoids. Parasitoids lay their eggs on or in the bodies of other insects, causing the death of the hosts. Some of the parasitoids were found effective under laboratory conditions, but these results have to be validated under real conditions [6].

Biotechnical traps use the combination of chemical baits with a colour design that attract the SWD, and kills the fly by not letting it off the bait. There are some commercial traps available on the market, like the McPhail Trap and Droso Trap, as shown in Figure 2.7. However, due to their low efficiency, farmers often prefer to use hand-made traps. Commercial baits are based on apple vinegar and red wine (proportion of 40:60). When combined with a detergent, better results can be obtained [20]. The detergent act as a surfactant that prevents the insects from escaping.

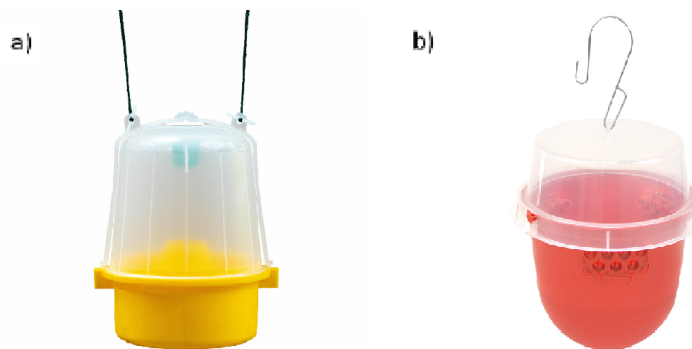


Figure 2.7: a) McPhail Trap; b) Droso Trap.

It can be concluded that the existing strategies are not as efficient as they should be. This means that a lot of traps are used currently per area of cultivated land, representing a great cost for the farmers, while not obtaining the necessary results. Another problem is the selectivity of the strategies, which is practically non-existent and puts the pollinating agents of the habitat at risk. It is therefore necessary to develop sustainable strategies to combat this pest.

2.3 Colour preference

One of the main objectives of this work is the development of a new selective SWD trap by integrating LED lights. The developed trap is expected to work better because many herbivorous insects use multiple cues for host selection, like visual stimuli. It has been shown that colour contrast rather than colour appearance may be of greater importance in orientation and attraction [21]. Differences in reflectance between light wavelengths are important for colour opponency and colour discrimination. These differences provide colour contrast between foreground and background, as occurs between fruit and foliage, and helps the insect to identify the target during the host finding.

Visual spectral sensitivity is thought to be highly present in *Drosophila* species in

comparison to other insects in general. *Drosophila* species are thought to be most sensitive to ultraviolet (UV), blues, and greens [21]. Peak sensitivity wavelength (λ_p) in *D. melanogaster* occurs at 420 nm and 495 nm (violet-blue light spectrum area); however, visual sensitivity is relatively stable and consistent from 406 nm to 525 nm. Sensitivity drops rapidly for longer wavelengths, with lesser sensitivity at 606 nm than at 505 nm. Therefore, the common practice of pairing red and black in the current trap production, may result in decreased attractiveness in traps deployed for *D. suzukii* [21]. Attraction of *D. suzukii* to red might be a combined response to contrast between bright and dark, iridescence, or ultraviolet reflectance rather than just colour [21]. Achromatic features of a visual cue, such as brightness/intensity or contrast may also be important in orientation and attraction. Sensitivity to UV light is found in many insects, associated to sky detection which, when combined with a positive phototactic reflex, naturally guides individuals to the outdoors [22].

Chapter 3

General description of the electronic components

The most important aspects about the electronic components are reviewed.

3.1 General characteristics of PV panels

Solar energy is one of the most important sustainable energy sources due to its abundance in many parts of the globe. Modern solar technologies have been penetrating the market at fast rates. Photovoltaic (PV) technology has the greatest impact, because they are silent, non polluting and can generate electricity in places where no other form of electricity can be obtained (individual devices). Photovoltaic cells are semiconductor devices that convert part of the incident solar radiation directly into electrical energy.

The majority of the first-generation solar PV cells are composed of silicon (Si). However, more than 95% of these cells have power conversion efficiency about 17%, whereas solar cells developed over the last decade in laboratory environment have efficiency as high as 31% [23]. Photovoltaic technology is classified as crystalline, thin film, and nanotechnology [23]. There are many variations on cell material, design, and methods of manufacture. Amorphous or polycrystalline silicon (Si), cadmium sulfide (CdS), gallium arsenide (GaAs), and other semiconductors are used for cells. The most common PV cells are the monocrystalline and the polycrystalline. Monocrystalline cells are made from a single crystal of silicon while polycrystalline cells are made from several fragments of silicon melted together [24]. Making singles crystals leads to a more expensive method of production, consequently, monocrystalline cells are more expensive than polycrystalline cells. Monocrystalline cells have a higher efficiency than polycrystalline cells, plus an all-black appearance that allows a uniform look of the solar system, making them the preferred choice of consumers [25]. Solar cells are being used in a range of applications, from powering watches and calculators to charging batteries for boats and communications systems to medium-scale systems for power generation. Photovoltaic panels have been the means of supplying power to most of the satellites that have been launched since the beginnings of space programs [26].

The assessment of solar cell operation and the design of power systems based on solar cells must be based on the electrical characteristics that is the voltage-current relationships of the cells under various levels of radiation and at various cell temperatures [26]. For system design purposes, the model must provide the means to calculate current,

voltage, and power relationships of cell arrays over the range of operating conditions [26].

Current and power characteristics of a typical PV module as a function of voltage are shown in Figure 3.1. The short-circuit current I_{sc} is the maximum that can be obtained through a module for $V=0$. The maximum voltage (V_{oc}) is measured in an open circuit. The maximum power corresponds to the point where the product between I and V is the highest. The maximum power point is identified by P_{mp} , with current (I_{mp}) and voltage (V_{mp}) shown in Figure 3.1. Ideally, cells should operate at the maximum power point, but in practice cells operate at a point depending on the load.

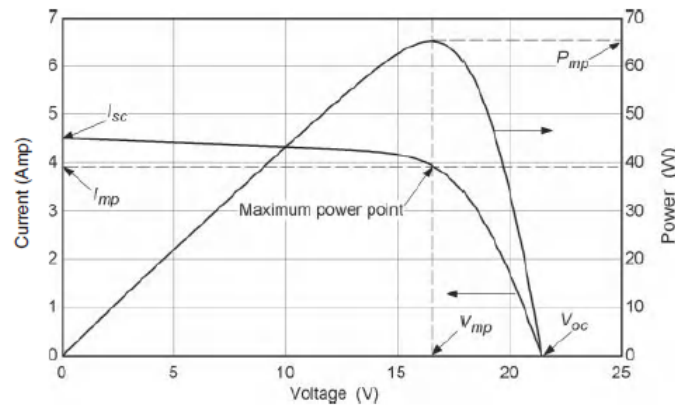


Figure 3.1: Typical I -V and P-V curves for a PV module [26].

Current-voltage curves are shown in Figure 3.2 for a module operating at a constant temperature and at several radiation levels [26]. The locus of maximum power points is also shown. It can be observed that the short-circuit current linearly increases with the solar radiation while the open-circuit voltage increases logarithmically. As long as the curved portion of the I -V characteristic does not intersect the current axis (where $V = 0$), the short-circuit current is nearly proportional to the incident radiation.

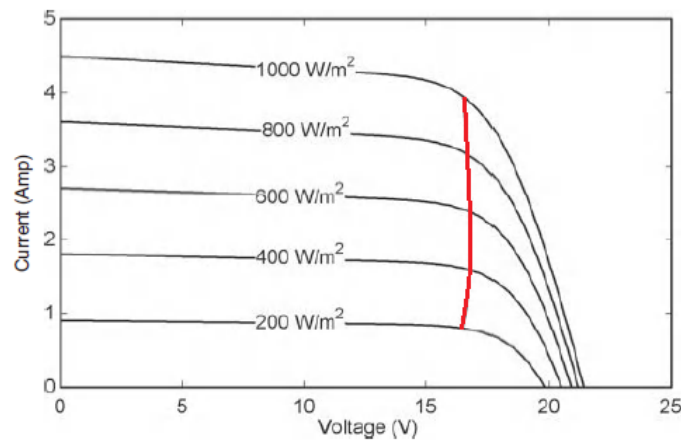


Figure 3.2: The I -V curves for a PV generator at several radiation levels. The locus of maximum power points is shown in red [26].

The model presented here for the current-voltage characteristic of PV converters and its dependence on solar radiation and cell temperature, described in [27], relies only on information available from the PV's manufacturer. This model is used in PVsyst Software, which is the software used for the simulations. Figure 3.3 shows an equivalent electric circuit model that can be used for describing an individual cell, a module consisting of several cells, or an array consisting of several modules. At a constant temperature and solar radiation, the I-V characteristic is given by:

$$I = I_L - I_D - I_{sh} = I_L - I_o \left[\exp \left(\frac{V + IR_s}{a} \right) - 1 \right] - \frac{V + IR_s}{R_{sh}} \quad (3.1)$$

The electric power generated is then given by:

$$P = IV \quad (3.2)$$

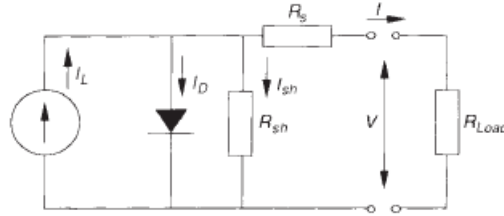


Figure 3.3: Equivalent circuit for a PV generator [26].

To model the electric circuit presented in Figure 3.3, five parameters must be known. These are the light current (I_L), the diode reverse saturation current (I_o), the series resistance (R_s), the shunt resistance (R_{sh}), and the modified ideality factor (a). All five parameters may be functions of cell temperature and absorbed solar radiation as discussed later in this section. The modified ideality factor is given by:

$$a \equiv nkTN_s/q \quad (3.3)$$

In equation 3.3, n is the ideality factor (equal to 1 for an ideal diode and typically between 1 and 2 for real diodes), k is the Boltzmann's constant (1.381×10^{-23} J/K), T is the cell temperature, N_s is the number of cells in series, and q is the electronic charge (1.602×10^{-19} coulomb).

Measurements of PV electrical characteristics traditionally are made under standard test conditions (STC): incident radiation of $1,000 \text{ W/m}^2$, a cell temperature of 25°C , and a spectral distribution corresponding to an air mass of 1.5. They are usually provided by the manufacturer at open-circuit conditions, short-circuit conditions, and maximum-power conditions. In addition, manufacturers usually supply both the temperature coefficient of short-circuit current, $\mu_{I_{sc}}$, and the temperature coefficient of open-circuit voltage, $\mu_{V_{oc}}$. Since five parameters are needed, five different conditions have to be known. The method adopted here is to use the three known I-V points, the condition at the maximum power point where the derivative of power with respect to voltage is zero, and the temperature coefficient of the open-circuit voltage.

At short-circuit conditions the voltage is zero and the current ($I_{sc,ref}$) is given by:

$$I_{sc,ref} = I_{L,ref} - I_{o,ref} \left[\exp \left(\frac{I_{sc,ref} R_{s,ref}}{a_{ref}} \right) - 1 \right] - \frac{I_{sc,ref} R_{s,ref}}{R_{sh,ref}} \quad (3.4)$$

At open-circuit conditions the current is zero and can be obtained from:

$$I_{L,ref} = I_{o,ref} \left[\exp \left(\frac{V_{oc,ref}}{a_{ref}} \right) - 1 \right] + \frac{V_{oc,ref}}{R_{sh,ref}} \quad (3.5)$$

The measured I -V pair at maximum-power conditions can be substituted into equation 3.1 resulting in:

$$I_{mp,ref} = I_{L,ref} - I_{o,ref} \left[\exp \left(\frac{V_{mp,ref} + I_{mp,ref} R_{s,ref}}{a_{ref}} \right) - 1 \right] - \frac{V_{mp,ref} + I_{mp,ref} R_{s,ref}}{R_{sh,ref}} \quad (3.6)$$

The fourth condition, where the derivative of power with respect to voltage is equal to zero, results in:

$$\frac{I_{mp,ref}}{V_{mp,ref}} = \frac{\frac{I_{o,ref}}{a_{ref}} \exp \left(\frac{V_{mp,ref} + I_{mp,ref} R_{s,ref}}{a_{ref}} \right) + \frac{1}{R_{sh,ref}}}{1 + \frac{I_{o,ref} R_{s,ref}}{a_{ref}} \exp \left(\frac{V_{mp,ref} + I_{mp,ref} R_{s,ref}}{a_{ref}} \right) + \frac{R_{s,ref}}{R_{sh,ref}}} \quad (3.7)$$

The final condition ensures that the known temperature coefficient of open-circuit voltage is correctly predicted by the model, thus:

$$\frac{\partial V_{oc}}{\partial T} = \mu_{V,oc} \approx \frac{V_{oc}(T_c) - V_{oc}(T_{c,ref})}{T_c - T_{c,ref}} \quad (3.8)$$

In addition, it is necessary to obtain general relationships for the variations of a , I_L and I_o vary with operating conditions. To complete the model the T dependence of the PV performance should be described. With these equations and getting equations for the parameters that change with temperature, the entire model to describe how the PV works can be done. The only thing missing are the equations to describe the PV cells temperature. Figure 3.4 shows the effect of temperature on the I -V curve, for a fixed radiation level. It can be seen that increasing temperature leads to decreased open-circuit voltage and slightly increased short-circuit current.

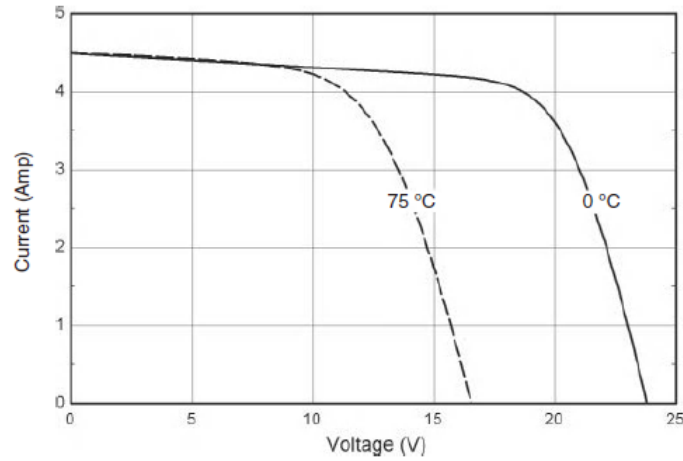


Figure 3.4: The I -V characteristics of a PV module at temperatures of 0 and 75 °C [26].

The operating temperature of a PV module can be determined by applying the energy balance. The solar energy that is absorbed by a module is converted partly into heat and partly into electrical energy which is removed from the cell through the external circuit. An energy balance, per unit area of module cooled by losses to the surroundings, can be written as:

$$(\tau\alpha)G_T = \eta_c G_T + U_L(T_c - T_a) \quad (3.9)$$

In equation 7.4, $(\tau\alpha)$ is the effective transmittance-absorptance product that when multiplied by the incident radiation yields the total absorbed energy. η_c is the electric conversions efficiency of the module varying from zero to the maximum module efficiency at maximum power point operation. The loss coefficient U_L accounts for the heat losses by convection and radiation from top and bottom surface of the cell and by conduction through any mounting framework at ambient temperature (T_a).

The nominal operating cell temperature (NOCT) is defined as the cell or module temperature that is reached when the cells are standard mounted and exposed to a solar radiation level of 800 W/m^2 , a wind speed of 1 m/s , an ambient temperature of 20°C , and no-load operation (i.e., with $\eta_c = 0$). The mounting has a strong impact on the NOCT, thus NOCT value should be carefully interpreted when the cells are mounted differently from test conditions [26]. Measurements of the cell temperature, ambient temperature, and solar radiation can be used in equation 7.4 at NOCT conditions to obtain:

$$(\tau\alpha)G_{T,NOCT} = U_{L,NOCT}(T_{NOCT} - T_{a,NOCT}) \quad (3.10)$$

The cell temperature at any ambient temperature is then found from:

$$\frac{T_c - T_a}{T_{NOCT} - T_{a,NOCT}} = \frac{G_T}{G_{NOCT}} \frac{U_{L,NOCT}}{U_L} \left[1 - \frac{\eta_c}{(\tau\alpha)} \right] \quad (3.11)$$

If the actual mounting is not the same as used in the NOCT test, then estimates given by these equations will not be correct [26].

Maximum power point tracker (MPPT) is an electronic DC to DC converter device that optimises the match between the solar array, PV panel, and load (e.g. the battery bank or utility grid). They typically convert a higher voltage output from solar panels to a lower voltage needed (e.g. to charge batteries). The MPPT adjust the optimal power output from the PV panel to charge the battery. Most MPPT designs consist of three basic components: a switch-mode DC–DC converter, a controller, and a tracking component [28]. The switch-mode converter releases electricity at different potential levels. By setting up the switch-mode section in various topologies, such as buck converter or boost converter, voltage converters are designed to provide a fixed input voltage or current to allow the output resistance to match the battery. A controller is essential to continuously monitor the PV system and ensure its operation at the PV maximum power point, by tracking this maximum power point. The controller's aim is to continuously measure the voltage and current values generated from the PV, and compare them to certain threshold values, in order to apply either voltage feedback control or power feedback control [23].

Voltage Feedback Control refers to the case when the PV array terminal voltage is the controlled variable. Voltage feedback controller forces the PV array to operate at its maximum power by changing the array terminal voltage and neglecting the variation in the temperature and insolation level. Power Feedback Control is applied on the power delivered to the load. To achieve maximum power, dP/dV should be zero. This control scheme is not affected by the characteristics of the PV array, yet it increases power to the load and not power from the PV array. Factors such as fast shadows may cause trackers to miss the maximum power momentarily. It is very critical to ensure that the time lost in seeking maximum power again, which equates the energy lost while the array is off maximum power point, is very short. On the other hand, if irradiation levels change, the tracker needs to quickly respond to the changes to avoid energy loss. Therefore, the controller's most important feature is its capability to quickly adjust the system to operate back at the maximum power.

Batteries are often used in PV systems for storing energy to match time lag between generation and demand. Moreover, batteries are also needed in the tracker systems to operate at MPP in order to provide electrical loads with stable voltages. This topic is discussed in Section 3.2.

3.2 General characteristics of batteries for electric energy storage

A battery is an electrochemical device that can store electric energy in the form of chemical energy. During discharge, the chemical energy translates into electric work when the battery is connected into a circuit where the flow of electrons occur due to specific placement of chemicals [29]. A battery consists of three components: the negative terminal (anode), the positive terminal (cathode), and the electrolyte (the chemical which reacts with both sides). The electrolyte acts as an electron transportation medium between the anode and cathode. The electrochemical reactions, called oxidation and reduction, occur when electrons flow from one terminal to another through an external circuit [29].

Those batteries that are made for one-time use only (not rechargeable), are called

primary batteries. This type of batteries are disposed after discharging. It's a very simple and convenient source of power for portable devices like a watch, camera, torch, etc. The battery which is made for reusable purposes by recharging are called secondary batteries. They have the same electrochemical reaction as other batteries, but the electrochemical reaction can be reversed. This type of battery is used for portable devices like mobile phones, laptops, electric vehicles, and stand-alone PV systems [29].

There are many factors to take into consideration when choosing the battery for a stand alone PV system. Battery capacity, rated in amps-hour [Ah], is the total amount of electricity that a solar battery can store. Although, the science of electrochemistry dictates the lower the current rate of charge, more energy can be stored in the battery. Similarly, the lower the current rate of discharge, the more energy can be delivered from the battery. Hence, charging and discharging the battery differently from the standard continuous charge current and standard continuous discharge current mentioned in the battery datasheet can yield different results from the energy stored and energy delivered by the battery [30]. The typical conversion of battery capacity to energy stored is :

$$E_{bat} = V_{nominal} \times C \quad (3.12)$$

E_{bat} is the energy [Wh], C is the battery capacity [Ah] and $V_{nominal}$ [V] is the nominal voltage. Another characteristic is the lifespan and charge/discharge cycles. The lifespan of the battery is affected by the ambient working temperature, the battery performs better in an ambient temperature of 25 °C or slightly above, because heat stimulates the electrons movement, and worse in colder environments, but if operating at high temperatures the cycle life is reduced. The battery's lifespan is affected by the depth of discharge (DoD), that represents the extent to which the battery is discharged or used, relative to its capacity. Batteries need to retain some charge at all times due to their chemical composition, if you use 100 percent of a battery's charge, its useful life will be significantly shortened. The charge/discharge cycles is the number of cycles that usually the battery can last. The round-trip efficiency is the amount of energy that can be computed as a percentage of the energy used to store it. The electrical characteristics need to be compatible with the system that is being designed, like nominal voltage, maximum charge current, maximum discharge current, charging cut-off voltage and discharging cut-off voltage [31] [32].

When reading the battery's datasheet, there is a term C Rate that is used. The C_5A term, that means the discharge current rate of the battery, in this case, for 5 hours, for a C rated battery capacity. C_5A , as a standard, can be converted to a number when the rated capacity of the battery is known. The advantage of using C_5A is the addition of a specific discharge rate. This is because a battery do not deliver any arbitrary combination of current over time that adds up to the mAh rating. If you discharge a 1 Ah battery at 1 A, depending on the design and chemistry you may or may not be able to get 1 Ah of current from the battery. Some combination of current and time gets you the 1 Ah, others do not. Therefore, the C_5A rating was standardised so batteries could be reasonably compared. The change in capacity of rechargeable batteries at different rates of discharge are approximately described by the Peukert's law. As the rate of discharge increases, the battery's available capacity decreases [33]. The Peukert's law is given by:

$$C_p = I_{dis}^{k_{peukert}} t \quad (3.13)$$

The capacity at a one-ampere discharge rate is not usually given for practical cells. As such, the Peukert's law can be reformulated into:

$$t = H \left(\frac{C}{I_{dis} H} \right)^{k_{peukert}} \quad (3.14)$$

C_p is the capacity at a one-ampere discharge rate [Ah], I_{dis} is the actual discharge current, t is the actual time to discharge the battery [hours], $k_{peukert}$ is the Peukert constant [-], H is the rated discharge time and C is the rated capacity at that discharge rate [Ah].

There are various types of batteries used in stand alone PV systems, like lead-acid batteries, lithium-ion batteries, flow batteries, that have a water-based (saltwater) liquid electrolyte, and sodium-nickel chloride batteries. The most important characteristics about these batteries are [31]:

- **Lead-acid:**

- Cheapest in the market;
- Easy to maintain. Sealed lead-acid batteries require no maintenance;
- Highly reliable;
- Easily recycled or disposed;
- Bulky, and take up a lot of valuable storage space;
- Short lifespan of between 1,000 and 3,000 cycles. On average, a lead-acid battery can last for 5 to 8 years;
- Shallow discharge depth of, approximately 60%;

- **Lithium-ion:**

- Require minimal to no maintenance;
- High battery energy density saves space;
- Longer life cycles and lifespans;
- Highest depth of discharge;
- Expensive;
- Fragile and must be enclosed in metal;
- Use an electronic circuit to provide a stable power output.

- **Flow battery:**

- Over 10,000 cycles with negligible loss of efficiency or storage capacity;
- Fast recharge rates;
- Little to no heat or fire hazard;
- Expensive;
- Hard to dispose of and non-recyclable;

- Large-scale installations.
- **Sodium-Nickel Chloride:**
 - Safe and reliable;
 - Operate normally even in extreme temperatures;
 - Recyclable;
 - Short lifespan;
 - Shallow 80% depth of discharge;
 - Expensive;
 - Large-scale installations.

Lithium solar batteries outperform the competition when it comes to storing energy for a solar system. They're more efficient, charge faster, require no maintenance, and last substantially longer. The efficiency comes from the very low internal resistance that allows the batteries to charge with minimal loss. They have the highest volumetric energy density compared to others technologies, as shown in Figure 3.5. There is various types of lithium-ion batteries, like lithium cobalt oxide (LCO), lithium iron phosphate (LFP), lithium manganese oxide (LMO), lithium nickel cobalt aluminium oxide (NCA), lithium nickel manganese cobalt oxide (NMC) and lithium titanate oxide (LTO) [34].

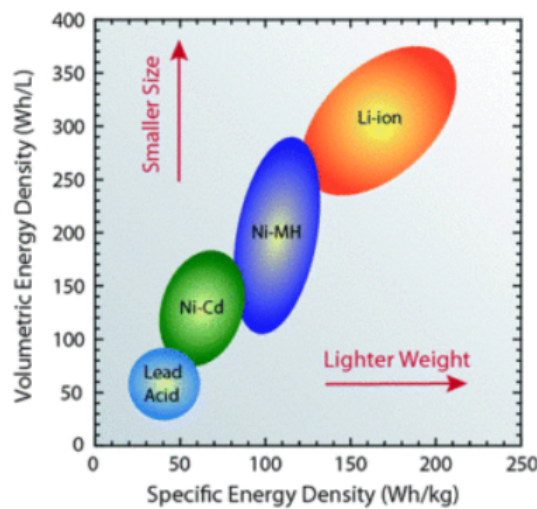


Figure 3.5: Diagram of the specific energy density and volumetric energy density of various battery types [35].

Figure 3.6 shows the charge curve of lithium-ion cell. This charge curve of a lithium-ion cell plots various parameters such as voltage, charging time, charging current, and charged capacity. The recommended charging method, when the cells are assembled as a battery pack for an application, is the constant current-constant voltage (CC-CV) method. The CC-CV method starts with constant charging while the battery voltage rises. When the battery reaches its full charge cut-off voltage, constant voltage mode takes over, and there is a drop in the charging current. The charging current keeps

coming down until it reaches below $0.05C$. When CV mode starts, battery reaches full charge voltage after some time, and estimating the state of charge (SoC) based on the battery voltage would mean that the battery is fully charged, which is not correct. Trickle charge mode kicks in immediately after this stage, where a reducing charging current charges the remaining battery capacity while balancing the cells at the same time. The battery is really 100 % charged when every cell has been balanced and has reached its full charge voltage. One way to know this is when the charging current has reached close to $0.05C$ [30].

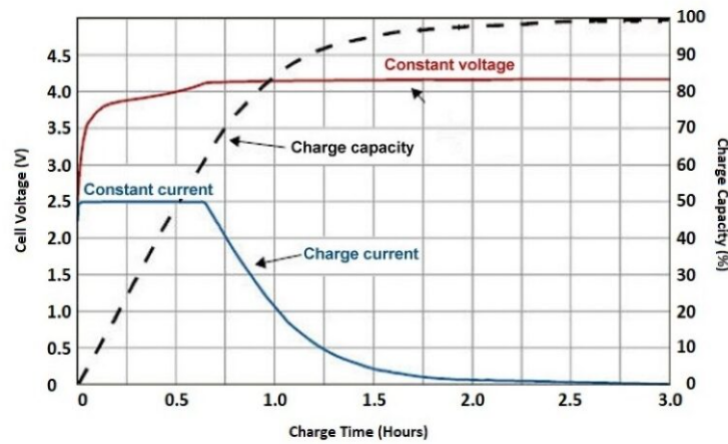


Figure 3.6: Charge curve of lithium-ion cell [30].

Figure 3.7 shows the discharge curve of a lithium-ion cell for different discharge currents. A flat discharge curve is better because it means the voltage is constant throughout the course of battery discharge and would be easier to identify at which capacity the battery is. Although, a flat discharge curve also means the battery might not deliver close to 100% DoD because the battery cuts off if one of the cells reaches its lower cut-off voltage. LFP cells have a flatter discharge curve when compared to NMC cells, hence, LFP cells have a lesser DoD than NMC cells [30].

Figure 3.8 shows the discharge curve of a lithium-ion cell for different ambient temperatures. Lithium-ion cells can charge between 0°C and 60°C and can discharge between -20°C and 60°C . They are supposed to operate between 0 % and 60 % of relative humidity. It can be seen that discharging at low temperatures delivers lower voltage and lower capacity, resulting in lower energy delivered. On the other hand, discharging at high temperatures delivers higher voltage and higher capacity, resulting in higher energy delivered, but reduction in cell cycle life [30].

Cycle life parameter is defined as the number of charge-discharge cycles of the cell by the time it reaches 80 % capacity of its original capacity, and it is for a depth of discharge of 80 %. The DoD makes great influence in the cycle life. Having lower numbers of DoD increases the number of cycles of the cell. Figure 3.9 shows how the capacity retention of a lithium-ion cell varies with the cycle number, for a defined 1C charge rate and 1C discharge rate [30].

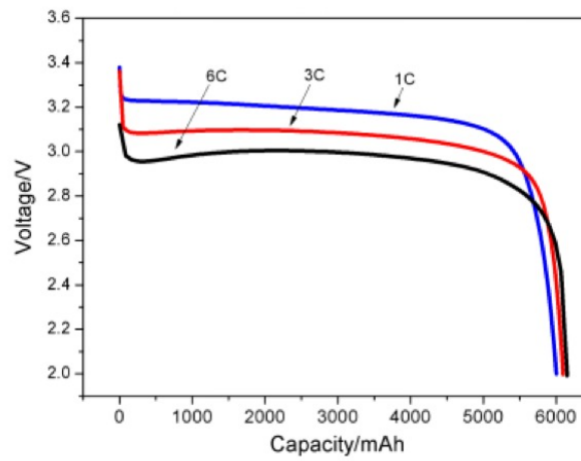


Figure 3.7: Discharge curve of a lithium-ion cell for different discharge currents [30].

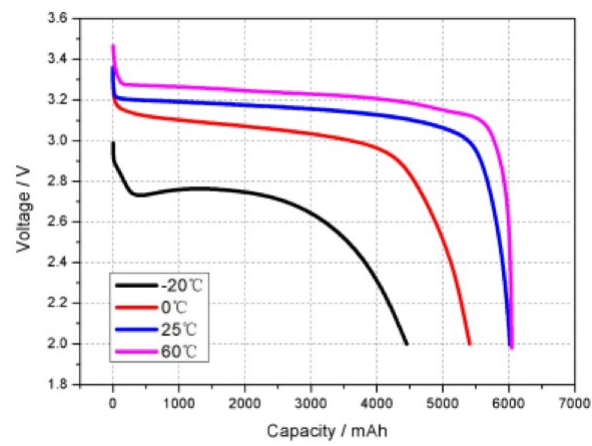


Figure 3.8: Discharge curve of a lithium-ion cell for different ambient temperatures [30].

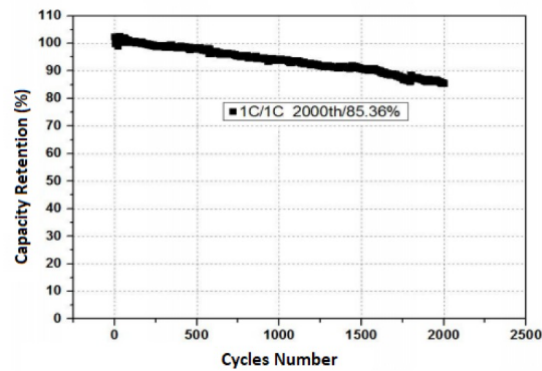


Figure 3.9: Capacity retention vs cycle number of a lithium-ion cell at 1C charge rate and 1C discharge rate [30].

3.3 General characteristics of LEDs

A light-emitting diode (LED) is a semiconductor device that emits light when an electric current is passed through it and this phenomenon is called electroluminescence. Figure 3.10 shows how the process of electroluminescence occurs. A diode is an electrical component that only works in one direction. Basically, an LED is an electrical component that emits light when electricity flows through in one direction, from the anode, positive side, to the cathode, negative side. They use semiconductor materials to allow electrons to pass through a positive-negative (PN) junction. When electrons of the n-type semiconductor fill the holes of the p-type semiconductor, energy is released as photons, or light. There must be a higher voltage potential on the p-side of the LED than the n-side for this atomic interaction to work. The brightness is determined by the current, or the speed of the flow of power [36]. Inside the semiconductor material, the electrons and holes are contained within energy bands. The separation of the bands, i.e., the band-gap, determines the energy of the photons (light particles) that are emitted by the LED. The photon energy determines the wavelength of the emitted light, and hence its colour. Different semiconductor materials with different band-gaps produce different colours of light. The precise wavelength can be tuned by altering the composition of the light-emitting region [37].

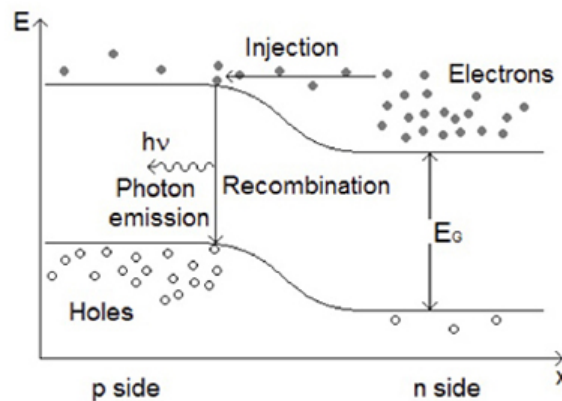


Figure 3.10: Electroluminescence [36].

The main semiconductor materials used to manufacture LEDs are indium gallium nitride (InGaN), used to produce blue, green and ultraviolet high-brightness LEDs, aluminum gallium indium phosphide (AlGaInP), used to produce yellow, orange and red high-brightness LEDs, aluminum gallium arsenide (AlGaAs), used to produce red, and infrared LEDs and gallium phosphide (GaP), used to produce yellow and green LEDs. There is also organic light-emitting diode (OLED) that is also a light-emitting diode in which the emissive electroluminescent layer is a film of organic compound. OLEDs emit light in response to an electric current. They are mostly used to produce displays used in digital devices such as high-end television systems, computer monitors, media players, digital cameras, portable gaming consoles and mini-screens [38].

LEDs main advantages are [39]:

- High luminous efficiency, that is the efficiency of converting power into luminous flux. It is not influenced by their shape or size, like light bulbs;
- Small size;
- Shock resistance;
- Quick switch on time;
- Long lifetime. They can operate between 35,000 and 50,000 hours;
- Low heat generated.

LEDs main disadvantages are [39]:

- Performance decrease with temperature;
- Efficiency drops when increasing the current;
- High contribute to light pollution;
- Very attractive to insects, which in most cases are not desirable;
- Low colour rendering index (CRI), that is the measure of how accurately a light source illuminates objects' true colours [40].

Table 3.1 shows values of luminous efficiency for different types of lightning sources for white colour [41]. From manufacturer ProLight, some values of luminous efficiency for different colour LEDs can be obtained, as can be seen in Table 3.2 [41]. It shows clearly that luminous efficiency change a lot depending on light colour.

Table 3.1: Luminous efficiency of different lightning sources for white colour.

Light source	Luminous efficiency [lm/W]
LED bulb	80 – 150
Energy-saving bulb	40 – 60
Halogen bulb	15 – 20
Incandescent bulb	10 – 15

With high-power LEDs, it is crucial to remove heat through efficient thermal management. Without good heat sinking, the junction temperature of the LED rises, causing the decrease of the forward voltage and the lumen output, as shown in Figure 3.11. The increasing of junction temperature also affects the overall lifetime of the LED. This is why it is crucial to keep your LED junction temperature relatively low [42].

Table 3.2: Luminous efficiency of different colour LEDs.

Light colour	Luminous efficiency [lm/W]
White	120
Warm white	110
Green	90
Orange	50
Red	50
Blue	25

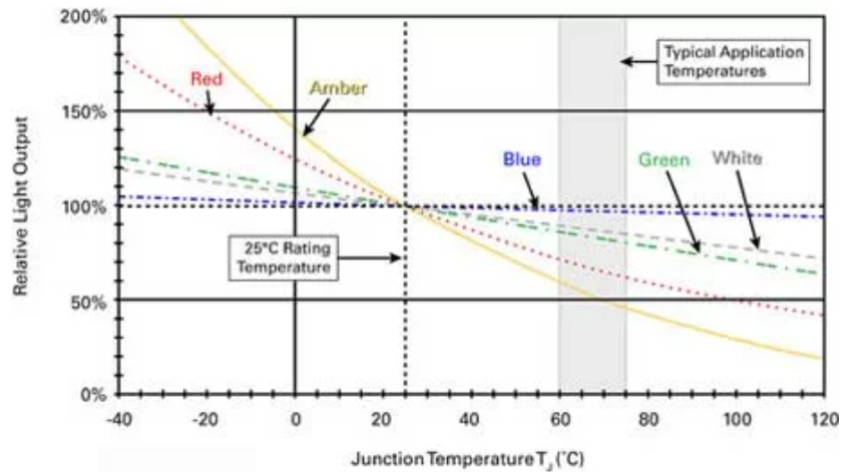


Figure 3.11: Relative light output vs junction temperature for different colour LEDs [42].

The ambient temperature, drive current and thermal conductivity of the place where the LED is installed determines the LED junction temperature. The most important part of LED cooling is the thermal path from the LED junction to the outside of the light fixture. Heat needs to be conducted away from the LED in an efficient manner, and then removed from the area by some sort of cooling or dissipation. Usually, LEDs come fixed to aluminium printed circuit boards (PCB). Aluminium PCB consists of a dielectric metal base with a bonded copper circuit layer to create superior heat transfer to help cool components while eliminating problems associated with managing fragile ceramics [43]. Figure 3.12 shows the layers of the aluminium PCB. This component is usually mounted in heat sinks.

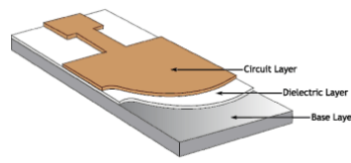


Figure 3.12: Layers of the aluminium PCB [43].

Heat sinks are an important part of LED lighting because they provide the path for heat to flow from the LED light source to outside elements. Heat sinks are able to dissipate power in three ways: conduction (heat transfer from a solid to a solid), convection (heat transfer from a solid to a moving fluid), or radiation (heat transfer from two bodies at different temperatures through thermal radiation). LEDs come in reels as bare emitters that are encapsulated in a transparent resin, which tends to be a poor thermal conductor, so, when they are mounted on an aluminium base, it acts as a heat spreader. The thermal conductivity of the heat sink material directly affects how efficiently the heat dissipates through conduction. Copper is the best material, but because of its price, aluminium is used more widely. Thermoplastics can be used for smaller LEDs with lower heat dissipation requirements. The use of thermoplastics can be useful as they can be moulded in more shapes and are lighter. When mounting the LEDs into the heat sink, or another component, it is recommended to use a thermally conductive material, like a thermal adhesive [42].

3.4 General characteristics of battery management systems

Battery management systems (BMS) are real-time systems controlling many functions vital to the correct and safe operation of the electrical energy storage system. This includes monitoring temperatures, voltages and currents, maintenance scheduling, battery performance optimisation, failure prediction and prevention, and battery data collection/analysis. Battery management systems are usually used in electric vehicles, plug-in hybrid electric vehicle, and battery applications such as material handling, uninterruptible power supplies, off-grid power systems, marine and battery banks for alternative energy sources. All lithium-ion batteries require a BMS. This is due to the fact that all Li-ion batteries will fail if overcharged, completely discharged, or operated outside their safe temperature window. BMS is programmed according to each safe operating area of the lithium-ion cell type [44].

The BMSs functions are [44]:

- Performance management:
 - **Voltage, current and temperature monitoring**, to prevent the battery of being operated outside the threshold conditions;
 - **Cell balancing**. In a multicell battery, small differences in capacity among cells appear due to production tolerances or different operating conditions. These differences tend to increase with each charging cycle, and some cell capacity is lost over time by self-discharge processes. If the temperature distribution in the pack is not equal, hotter cells tend to have higher capacity

losses, leading to an imbalance in the battery pack. Such weaker cells become overstressed during charging. This continuing imbalance causes a drift in capacity, until the weakest cell eventually fail. Cell balancing is a way of equalising the charge of all cells in the chain;

- **Charge control**, to limit the rate at which the electric current is fed into each cell to hold the battery in the safe operation area;
 - **Power save mode**, if a battery stays in fully discharged state for long time, BMS should detect this situation and switch into power-save operation mode, in order to reduce energy consumption and prevent battery depletion.
- Protection functions against:
 - **Short circuit**;
 - **Overload**;
 - **Overcharge**;
 - **Too deep discharge**;
 - **Overheating**;
 - The battery should also be protected by a fuse.
 - Diagnose functions:
 - **State of charge estimation**, that can be based on voltage, knowing the discharge curve of the cells, or based in current, by the Coulomb Counting method. Coulomb Counting method measures the discharging current of a battery and integrates the discharging current over time;
 - **State of health (SoH) estimation**, that measures the capacity retention of the battery and compares it to the capacity of a new battery.

3.5 General characteristics of light sensors

Light sensors generate an output signal indicating the light intensity by measuring the radiant energy that exists in a very narrow range of frequencies, which ranges in frequency from infra-red, to visible and up to ultraviolet light spectrum. The light sensor is a passive device that convert radiant energy into an electrical signal output. Light sensors are commonly known as photoelectric devices or photo sensors. Photoelectric devices can be grouped into two main categories: those which generate electricity when illuminated, such as **photo-voltaic** or **photo-emissive** devices, and those which change their electrical properties in some way, such as **photo-conductor** or **photo-junction** devices. Only the devices that change their electrical characteristics are used to build the light meters used to data collection [45].

Photo-conductor cells vary their electrical resistance when subjected to light. Photo-conductivity results from light hitting a semiconductor material which controls the current flow through it. Higher values of light intensity leads to higher values of current for a given applied voltage. Photo-junction devices are semiconductor devices which use light to control the flow of electrons (current) across their PN-junction. Photo-junction

devices are specifically designed for light penetration with their spectral response tuned to the wavelength of the incident light [45].

The most common type of photo-conductors device is the photo-resistor which changes its electrical resistance in response to changes in the light intensity, such as light dependent resistors (LDR). They change their electrical resistance from several thousand Ohms, in the dark, to only a few hundred Ohms when light falls upon it by creating hole-electron pairs in the material. The net effect is an improvement in its conductivity with a decrease in resistance for an increase in illuminance [45]. The resistance of the cell when unilluminated (dark resistance) is very high at about $10\text{ M}\Omega$ which falls to about $100\ \Omega$ when fully illuminated (lit resistance), as shown in Figure 3.13. Also, photoconductive cells have a long response time, requiring many seconds to respond to a change in the light intensity. LDRs are made from a piece of exposed semiconductor material. Materials used as the semiconductor substrate include, lead sulphide (PbS), lead selenide (PbSe), indium antimonide (InSb) that detect light in the infra-red range, and cadmium sulphide (CdS). Cadmium sulphide is the most used because its spectral response curve closely matches that of the human eye. Typically, it has a peak sensitivity wavelength of about 560 nm to 600 nm in the visible spectral range, which corresponds to the yellow-orange light.

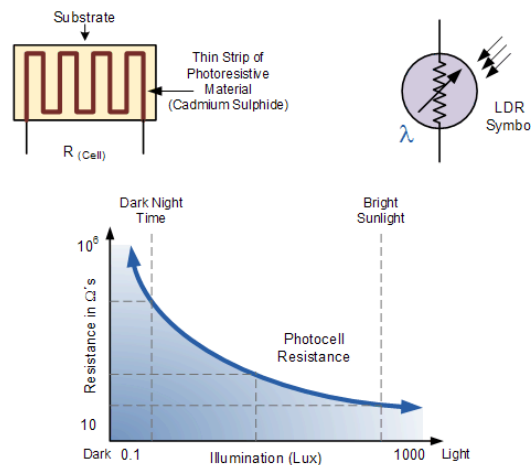


Figure 3.13: LDR resistance dependency of illuminance and type of construction [45].

The most common types of photo-junction devices are the photo-diode and the photo-transistor. The construction of the photo-diode light sensor is similar to that of a conventional PN junction diode, except that the external casing of the diodes is transparent or has a clear lens to focus light on the PN junction to increase sensitivity. The junction responds particularly to longer wavelengths, such as red and infra-red, rather than visible light. The current-voltage characteristic curves of a photodiode with no light on its junction (dark mode) is very similar to a normal signal or rectifying diode. When the photo-diode is forward biased, there is an exponential increase in the current. When a reverse bias is applied, a small reverse saturation current appears which causes an increase of the depletion region, which is the sensitive part of the junction. Photo-diodes can also be connected in a current mode using a fixed bias voltage across the junction. The current mode is linear over a wide range. Photo-diodes dark current (0 lux) is about

$10\ \mu\text{A}$ for germanium and $1\ \mu\text{A}$ for silicon type diodes. When light falls upon the junction more hole/electron pairs are formed and the leakage current increases. The leakage current increases as the illumination of the junction increases, as shown in Figure 3.14 [45]. One main advantage of photo-diodes is their fast response to changes in the light levels, but one disadvantage is the relatively small current even when fully lit.

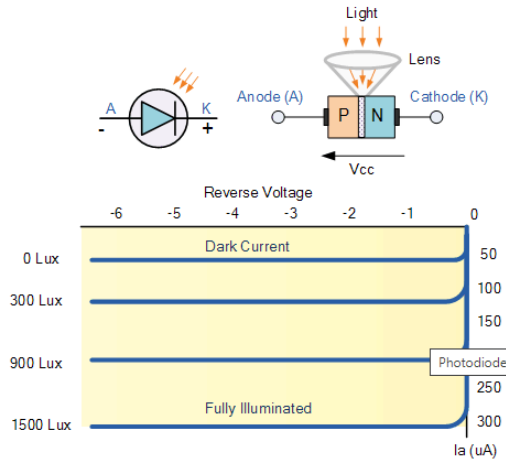


Figure 3.14: Photo-diode electrical characteristics dependency of illuminance and type of construction [45].

Photo-transistor devices are a photodiode with amplification by a transistor. Photo-transistor have their collector-base PN-junction reverse biased exposing it to the radiant light source. They operate in a similar way to the photodiode, except they can provide current gains and are much more sensitive, having current values 50 to 100 times greater, as shown in Figure 3.15. They consist of a bipolar NPN transistor with their large base region electrically unconnected. Although, some photo-transistors allow a base connection to control the sensitivity, which uses photons of light to generate a base current that in turn causes a current to flow from the collector to the emitter [45].

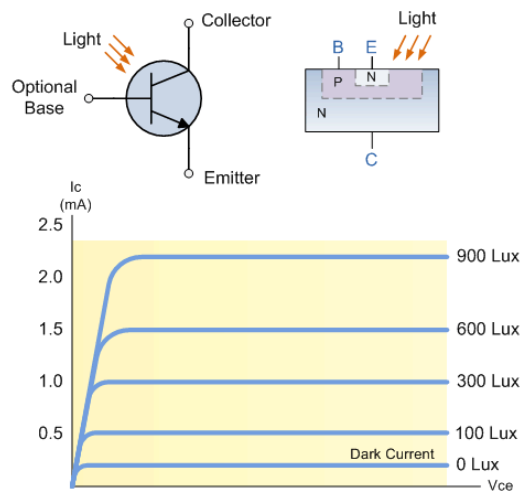


Figure 3.15: Photo-transistor current dependency of illuminance and type of construction [45].

3.6 General characteristics of real-time clocks

Real-time clock (RTC) are an electronic device designed in the form of an integrated circuit (IC) to measure the passage of real-time. RTCs maintain accurate time measurements within an embedded system even when the main power is off. They count hours, minutes, seconds, months, days, and even years. These modules can be found in nearly every electronic device, especially when the device requires a form of accurate time-keeping, like computers. The need for accurate timekeeping is often used as a trigger for specific events like turning the device on or sounding off an alarm clock. While some RTCs are designed to be installed into a device's microcontroller unit (MCU), real-time clock integrated circuits run on an independent power source from the main device which allows for more accurate tracking and prevents data loss [46].

In the past, RTCs were run off of lithium batteries. Newer systems use a supercapacitors. These newer RTCs are rechargeable and can be soldered to other devices. Most consumer-grade motherboards make use of a single battery to power the RTC. When this battery is removed, the RTC is reset to its starting point. The reason independent power is necessary comes down to the functional use of RTC modules in laptops, computers, tablets, and other electronic devices. As most devices are often powered on and off in continuous cycles, keeping track of data for process synchronization can be messy if the system clock is not completely accurate. The system clock in a device checks its timestamp against an RTC module. As the RTC module never shuts down, it keeps an accurate measure of time passed even when the main device is powered down [46]. The main advantages of a RTC are [46]:

- RTCs are more precise than software clocks;
- By using an independent time-keeping module, it frees up resources on the main system for time-critical tasks;
- The use of an independent power source improves overall power consumption and frequency stability;
- A RTC battery should last for three to five years or more.

In the computing world, the term 'clock' is used for more than just tracking accurate time. Hardware clocks and clock cycles are often used to measure the speed of signals that happen between specific components on the motherboard. Hardware clocks are used to measure signals that govern functionality or computing power in an electronic device, for example, it is used to measure the speed of cycle completion of the computer's central processing unit (CPU). The term real-time clock is used as a way of avoiding confusion with hardware clocks. The three-letter acronym for real-time clocks, RTC, is also shared with other computing terms like real-time computing and real-time counter. This often leads to confusion early on for beginners, especially as real-time counters are sometimes similarly used in software programming to RTCs. The best way to keep the terms easily separated and defined is to think of real-time clocks as physical computer chip modules usually embedded in the microcontroller unit while the other terms are used for software functions resulting from hardware performance.

3.7 General characteristics of Arduinos for programmable controlling

Arduino is an open-source prototyping platform in electronics based on easy-to-use hardware and software. Arduino is a microcontroller based prototyping board which can be used in developing digital devices that can read inputs, like finger on a button, touch on a screen, light on a sensor, etc, and turning it in to output, like switching on an LED, rotating a motor, playing songs through a speaker, etc. The Arduino board consists of a USB plug to communicate with your computer and a bunch of connection sockets that can be wired to external devices. The aim of Arduino is to introduce the world of electronics to people who have small to no experience in electronics. Arduino is based on open source electronics project, i.e., all the design specifications, schematics, software are available openly to all the users [47]. Arduino was born at the Ivrea Interaction Design Institute as an easy tool for fast prototyping, aimed at students without a background in electronics and programming. As soon as it reached a wider community, the Arduino board started changing to adapt to new needs and challenges, differentiating its offer from simple 8-bit boards to products for Internet of Things (IoT) applications, 3D printing, and embedded environments [48].

Arduino boards are generally based on microcontrollers from Atmel Corporation. A important feature of the Arduino boards is the standard connectors. The boards can be connected to other devices like LEDs or add-on modules called Shields. They also consist of on-board voltage regulator and crystal oscillator. Arduino IDE Software is used to program them. The Arduino IDE Software is based on processing programming language and supports a simplified version of C and C++. The Arduino boards are very cheap and Arduino IDE runs in any operating systems, like Windows, Macintosh OSX, and Linux [47]. There are many possible choices for an Arduino, with different functions and features [49]. The functions and features available on Arduinos are:

- Voltage supply 5V or 3.3V;
- Different central processing units (CPU) and memory capacity;
- Different software compatibility, like Arduino IDE, CircuitPython and MicroPython;
- USB or FTDI cable to computer connection;
- Different communication interfaces, like I^2C interface, UART interface and SPI interface;
- Wireless connectivity;
- Built-in sensors, like temperature sensors;
- Onboard control buttons;
- Battery charging systems;
- Input/output analog or digital signals, with pulse-width modulation (PWM) and digital-analog converter (DAC);
- Onboard LEDs, for status indication;

3.8 General characteristics of power MOSFET transistors to act as a switch

Transistors are semiconductor devices which are used to either amplify the signals or to act as an electrically controlled switch. They are an essential component in almost every electronic circuit like amplifiers, switching, oscillators, voltage regulators, power supplies and digital logic internal circuits. Transistors are classified into different types depending either on their construction or their operation, as shown in Figure 3.16. Transistors are also classified depending on the functions they perform: Small signal transistors act like an amplifier for small signals; Small switching transistors are used in applications that require a switch, but with a low current value involved; High frequency transistors are used for high-speed switching applications; Photo transistors change its electrical characteristics depending on the light intensity and are used in light meters; Power transistors are used in high-power amplifiers and power supplies [50].

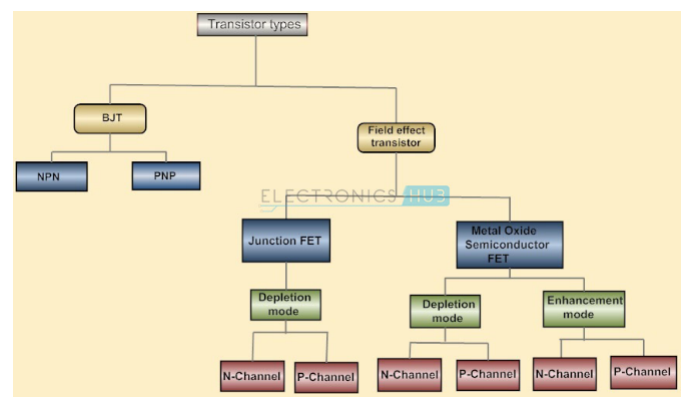


Figure 3.16: Classification of different transistor types [50].

This project requires a transistor to act as a switch, to turn the LEDs on/off, but also to deliver the necessary current for correct operation. In applications where it is used high power LEDs, the most used transistors are the power MOSFET [51]. Metal oxide semiconductor field effect transistor (MOSFET) is the most commonly used and most popular type of among all transistors. Their terminals designation are: gate (G), drain (D), source (S) and body or substrate. The name 'metal oxide' indicates that the gate region and the channel are separated by a thin layer of metal oxide (SiO_2). The gate region is completely insulated from the source – drain region. There is an extra terminal known as substrate or body, which is the main semiconductor (Si) in which the field effect transistor (FET) is fabricated [50]. MOSFETs have some advantages over others transistors because they offer high input impedance and low output impedance. MOSFETs have two different modes of operation. The depletion mode MOSFET transistor is equivalent to a normally closed switch. It requires gate–source voltage (V_{GS}) higher than 0 to switch off the device. The enhancement mode MOSFET is equivalent to normally open switch. It requires a gate–source voltage higher than 0 to switch on the device [52]. The MOSFETs are also classified depending on what type of material is placed in the region between source and drain. If it is a n-type material doped in the source and gate terminals, it is called a NPN MOSFET. If it is a p-type material doped in the source and gate terminals, it is called a PNP MOSFET [50]. Figure 3.17 shows the

schematic electrical representation of the enhancement mode NPN MOSFET and PNP MOSFET.

For driving LEDs applications, the power NPN MOSFETs are recommended because of the lower drain-source on-state resistance $R_{DS(on)}$ that leads to lower power dissipation by joule effect [51]. The power dissipation by joule effect is given by:

$$P = R_{DS(on)} I_{DD}^2 \quad (3.15)$$

I_D is the drain current. It can be observed that low drain source on-state resistance values leads to low power dissipation values. Figure 3.18 shows the characteristic curve of a enhancement mode NPN MOSFET.

When the input voltage at the gate terminal of the transistor is 0, the MOSFET is off, meaning that the gate and source terminal is not connected. The MOSFET is at point B represented in the figure. This configuration represents the cut-off region and leads to the gate-source voltage being equal to 0 and to the drain-source voltage (V_{DS}) being equal to the drain voltage (V_{DD}). Although there is virtually no current passing through the drain-source connection. In fact, there is current passing through the drain-source connection. In the off state, the MOSFET drain-source off-state resistance $R_{DS(off)}$ is very high that leads to a zero gate voltage drain current (I_{DSS}) of a few micro amperes [53].

The MOSFET switches on when the gate-source voltage is higher than the gate-source threshold voltage ($V_{GS(th)}$). Therefore, the MOSFET enters the saturation region and moves to the point A in the figure. $V_{GS(th)}$ is a characteristic of the MOSFET itself and can vary a lot depending on the application. I_{DD} depends on the R_{DS} of the MOSFET and on the V_{DD} applied. Although, there is maximum I_{DD} limit imposed by the mechanical characteristics of the MOSFET [53].

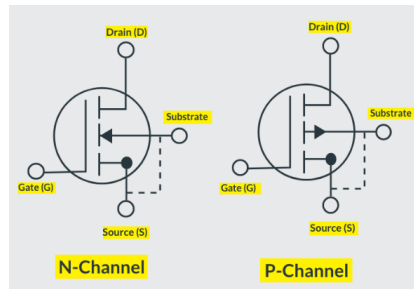


Figure 3.17: Schematic electrical representation of the enhancement mode NPN MOSFET and PNP MOSFET [52].

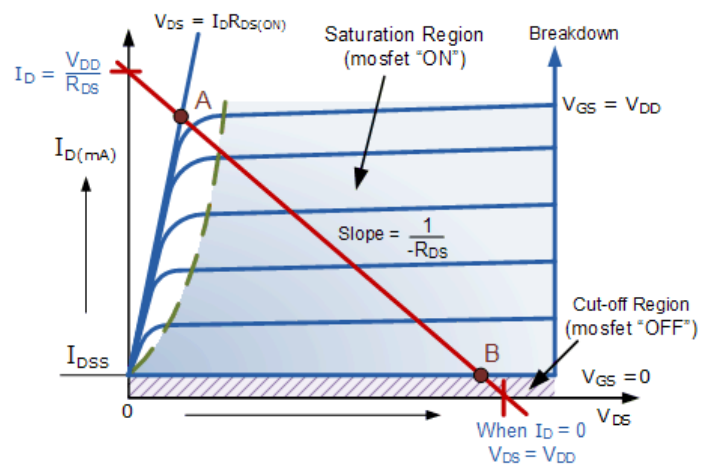


Figure 3.18: Enhancement mode NPN MOSFET characteristic curve showing the cut-off region (MOSFET OFF) and the saturation region (MOSFET ON) [53].

Chapter 4

Development of the sustainable insect trap

The development of the sustainable insect trap is the main goal of this project. In this chapter, the operation of the developed trap and its implementation is explained. Additionally, details regarding the technical specifications and operation modes is provided.

4.1 General features of the developed insect trap

The developed sustainable insect trap is indirectly powered by a photovoltaic panel. The PV panel charges a battery. Electricity is needed for supplying energy to the LED lights and the control components. There are two ways of attracting the insects into the trap: LEDs and a chemical bait. This latter kills the trapped SWDs by drowning. The electric components of the insect trap (IT) are composed by the following main components: the PV module, battery and LEDs. The PV panel should supply sufficient electric energy to charge the battery during the day, while the battery should have the capacity to keep the control system running and the LED light operational during predefined periods of the day. The LEDs with specific brightness had to be implemented in order to attract the insects. Because the main electronic components comply with the individual specifications, their integration into the IT needed special attention. The trap should operate the LEDs at a specific time of the day. The time of operation is defined by the control system.

Different LED colours might attract SWD with different sensitivity. Therefore, different colours were taken into consideration. The LED light of the IT should be on twice a day from 7:00 to 11:00 and from 18:00 to 22:00 during the period of month to month, when the insect is most active. Please note that the trap is working all the time, only the LEDs are not. Regarding the design, there is a preferable size and weight for the trap, depending on the installation method. It can be either hanged on the blueberry tree or inserted into the ground using a stick. The trap should be selective. The entrance holes on the trap need to be large enough to permit the SWD enter the trap, but not too large to prevent killing other desirable insects. The lower part of the trap should be transparent to the light, with some red coloured stripes, because it is thought to improve the attractiveness of the trap. The bait can reach high temperatures during the summer, which causes evaporation. Therefore, the electronic part must be well isolated from the vapours to avoid corrosion. The bait must be regularly replaced to remove captured in-

sects, thus the trap design should facilitate maintenance. Lastly, the insect trap needs to have enough mechanical resistance to withstand fall, severe meteorological conditions, like heavy rain, hail and strong wind.

A number of the developed prototypes will be tested under real conditions in a blueberries field located on the premises of Mirtilândia in Portejões, Viseu, for that reason the characteristics of that local were taken into consideration and the available solar radiation should be considered during the design phase.

In short, the main components of the insect trap and their function are:

- **Bait holder** : Container where the bait is placed, with holes to permit the SWD enter the trap ;
- **Lid** : Component where the photovoltaic panel is installed, along with the control system;
- **Photovoltaic panel** : Electricity producer component;
- **Battery** : Energy storage component;
- **LEDs** : Source of attraction for the SWD;
- **Control system** : System responsible to operate the trap LEDs at a specific time.

4.2 Short presentation of the work methodology applied

The work methodology followed in this project is summarised in a diagram in the Figure 4.1. Initially, technical specifications were proposed by the FCUP team and the Mirtilândia company. They were the ones who participated in the elaboration of the intrinsic idea of this project, which is to explore the hypothesis of developing a sustainable insect trap with the integration of LEDs. From the specifications for each stage in the development of the trap, an analysis and experimentation of the feasibility of the specifications began. The INEGI team, responsible for the development of the trap, had to take into account the mechanical integration of the specifications into the design. After this research and design phase, certain decisions had to be made regarding the feasibility of the solutions. If necessary, the specifications were discussed with the FCUP team and the Mirtilândia company, and adjusted as required. These technical compromises were weighted in order to obtain the best possible solution.

The stages followed in this project are shown in Figure 4.2. First stage was aimed to size the main components, such as the photovoltaic panel, the battery and the LEDs. Next, the design of the control system to operate the trap LEDs as required by the specifications. Consequently, all the components involved were assembled and integrated into a conceptual design. Finally, experiments and measurements were carried out to quantify the performance of the trap components, to validate the trap design, and to understand what future improvements would be possible to implement.

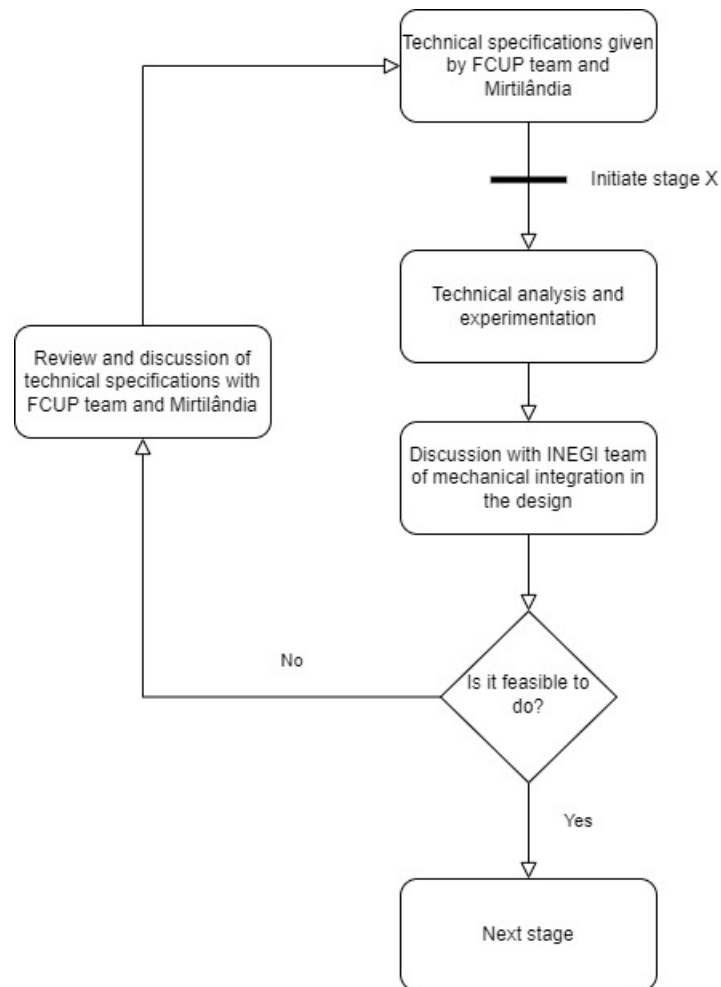


Figure 4.1: Work methodology.

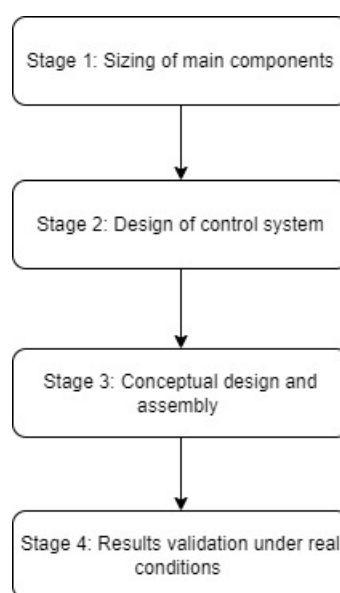


Figure 4.2: Sequential stages followed in this project.

4.3 Technical specifications for the prototypes

The initial technical specifications given by the FCUP team and Mirtilândia are presented in Table 4.1. These specifications were taken into consideration and modified due to design constraints and feasibility limitations. The holes and red stripes arrangement is presented in Figure 4.3.

Table 4.1: Initial technical specifications for the insect trap.

Initial technical specifications
LED colour: Yellow or Orange / Red / UV-A
Brightness: 240 lm
Continuous light
Operating time: 7-11h and 18-22h
Months of operation: May-September
Total weight: 200 g (without bait)
Dimensions: 100x100 mm base; 150 mm height
14 holes per face; 2.5 mm diameter
Holes with alternating arrangement
2 red stripes per face
Transparent bottom part (bait holder)
Removable top part (lid)
Vertical mounting
Waterproof
Good stability and mechanical resistance

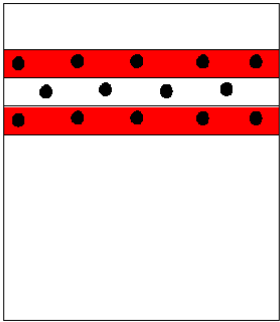


Figure 4.3: Holes and red stripes arrangement.

4.4 Modes of operation of the LEDs

One of the fundamental criteria for the development of the IT prototype was that it should be automated, since there is no possibility to activate them manually due to their large number and dispersion on the land.

Considering several possibilities to automatically activate the trap's LEDs, such as to use a frequency transmitter or to connect all traps to a central system via wiring, it was found that the most suitable options would be to use an universal timer or use a light sensor, inside the trap. An timer would make operation precise, while the light sensor may not. To use the light sensor is necessary to know the light intensity at the predefined operation period of the day, which varies greatly throughout the day, and from day to day.

One disadvantage of using an universal timer in comparison to using a light sensor, is that the timer should have a backup source of energy. The backup battery assures that time information is not lost even under the circumstances when the PV connected battery is fully discharged. Otherwise, without an external connection, e.g., computer or mobile device, the information about the real time would not be possible to recover. Therefore, a control system with an universal timer should integrate a battery in the component itself that is capable to power the timer all the time. This backup battery will supply very little energy, so it is expected to last several years without replacement.

Light or photo sensors are photodetectors that detect visible light intensity. Different types of light sensors can be used to measure illuminance as they respond to the change in the amount of light received. One disadvantage of using a light sensor instead of a timer is that the should be exposed to the sunlight, which represents some additional problems in terms of design and can originate some additional difficulties because the traps are typically placed in locations with variable light conditions.

Light sensors generally convert light intensity to units of lux [lx], which is the unit used to measure illuminance. Illuminance is a term that expresses the amount of visible light falling onto a given surface area [54]. Illuminance also correlates with how humans perceive the brightness of an illuminated area [54]. Luminance describes the measurement of the amount of light emitting, passing through or reflected from a surface at a solid angle. Luminance indicates the brightness of light emitted or reflected off a surface. In the display industry, luminance is used to quantify the brightness of displays [54]. The illuminance E_v is defined as:

$$E_v = \phi / A \quad (4.1)$$

$$\phi = c \int J(\lambda)y(\lambda)d\lambda \quad (4.2)$$

In equations 4.1 and 4.2 A is the area of the surface [m^2], ϕ is the luminous flux [lm], c is the unit conversion constant between lumen and watts [-], λ is the wavelength [nm], $J(\lambda)$ is the radiant spectral power distribution [W/nm] and $y(\lambda)$ is the luminosity function [-], that represents the average spectral sensitivity of human visual perception of light.

4.4.1 Illuminance Analysis

In order to identify the threshold to be used to activate the LEDs in the trap pro-

totypes, an illuminance analysis was carried out using meteorological data for Porto. The farm Mirtilandia is situated in Viseu, Portejões, however data was only available for Porto. The data were obtained from the Meteonorm Software [55], for the year 2019. Only hourly data is available in the software, which limits the accuracy of the analysis, but higher frequency data was not possible to obtain. The data was analysed for the period between May and September, that are the interesting ones for this project. Meteonorm data includes two variables related to illuminance, Global Illuminance and Diffuse Illuminance. Global illuminance is the quantity measured by the light sensor. Typical illuminance values are shown in Table 4.2 [56].

Table 4.2: Table of typical illuminance values.

Typical illuminance values [lux]	
Moonless, overcast night sky	0.0001
Moonless, clear night sky	0.002
Full moon on a clear night	0.05-0.3
Dark limit of civil twilight under a clear sky	4
Public areas with dark surroundings	20-50
Family living room lights	50
Office building hallway/toilet lighting	80
Very dark overcast day	100
Train stations platforms	150
Office lighting	320-500
Sunrise or sunset on a clear day	400
Overcast day	1000
Full daylight (not direct sun)	10,000-25,000
Direct sunlight	32,000-130,000

As mentioned in Section 4.3, the trap LEDs should operate in two periods of the day, one in the morning 7-11 and another in the afternoon 18-22. The light sensor should measure the illuminance and in accordance with the imposed threshold, control system triggers the LEDs to active. The four-hour timing delay is executed by the control system, a programmable microcontroller. Therefore, it is necessary to identify an illumination value that corresponds to the start time of the first and second operating periods, 7:00 and 18:00, respectively. The 7:00 illuminance value is easy to identify because corresponds to the sunrise and has an approximately value of 400, although, for the 18:00 is more difficult and the analysis is focused on this. It is noted that sunset and sunrise times vary throughout the year considerably. Therefore, the imposed operation time makes the LEDs active for one or two hours at night time, both in the morning and

afternoon periods, as can be seen in the Meteonorm data relative to Global Illuminance for the different months, shown in Table A.1, A.2, A.3, A.4 and A.5 in the Appendices A.1.

The illuminance analysis was performed for different threshold limits for the different months. In Appendices A.1 can be found Table A.6, A.7, A.8, A.9, A.10, A.11, A.12, A.13, A.14, A.15, A.16, A.17, A.18, A.19, A.20, A.21, A.22, A.23, A.24 and A.25 that have the threshold limits (TL) high-lighted for the first values per day after 12:00. The analysis was only performed after 12:00 because before this time the LEDs are activate for the first period. Summary data about this analysis is present in Table 4.3, 4.4, 4.5, 4.6 and 4.7. The following criteria was used to classify the time the light sensor activates the trap's LEDs: number of days on correct time (at 18:00), number of days early on time (1 hour before 18:00), number of days late on time (1 hour after 18:00), number of days too early on time (2 hours or more before 18:00) and number of days too late on time (2 hours or more after 18:00). A higher threshold limit leads to more days too early on time and a lower threshold limit leads to more days too late on time. One hour after or before the correct time may be reasonable, although 2 hours or more after or before the correct time it is inadequate.

For May, the TL that leads to more number of days on correct time is $E_v < 60,000$ lux, but it is also the one that leads to more number of days too early on time. $E_v < 30,000$ lux is the one that leads to more number of days too late on time. The TLs $E_v < 50,000$ lux and $E_v < 40,000$ lux are the ones which leads the LEDs to not operate too far away from the time intended and may be more acceptable than the others.

For June, it is clearly that the TLs $E_v < 40,000$ lux and $E_v < 30,000$ lux are inadequate because they lead to a large number of days too early or too late on time. The TL $E_v < 60,000$ lux leads to more number of days on correct time but it is also the one that leads to more number of days too early on time, while the TL $E_v < 50,000$ lux leads to a large number of days late on time. Therefore, the final decision would rely on one of these two.

For July, the TLs have a similar behaviour to that observed in June, with the TLs $E_v < 40,000$ lux and $E_v < 30,000$ lux being excluded due to their large number of days too early or too late on time. While the TL $E_v < 60,000$ lux has more number of days on correct time, the TL $E_v < 50,000$ lux has less number of days too early or too late on time, which is more acceptable.

For August, the TL $E_v < 60,000$ lux has a large number of days correct on time, with the difference for the other threshold limits being very significant. For that reason this is the one that is more acceptable, although, it is the one with more number of days too early on time. The other reasonable option could be the TL $E_v < 50,000$, but it has a large number of days late on time. TLs $E_v < 40,000$ and $E_v < 30,000$ have a lower number of days correct on time.

For September, the best options would be the TLs $E_v < 50,000$ and $E_v < 40,000$ because of their large number of days on correct time. TL $E_v < 50,000$ may be more acceptable because it has 0 number of days late on time than TL $E_v < 40,000$. TL $E_v < 60,000$ has a large number of days too early on time and TL $E_v < 30,000$ has a large number of days late on time.

Based on the analysis performed using only Meteonorm data, it can be concluded that the efficient integration of a light sensor into the control of the trap is not easy for triggering the trap LEDs under the required conditions. Therefore, this configuration

should be further tested in real conditions to identify more suitable control parameters that better match LED operation with the required specifications.

Table 4.3: Summary data on the time the light sensor activates the trap LEDs for May.

Threshold	$E_v < 60,000$ [lux]	$E_v < 50,000$ [lux]	$E_v < 40,000$ [lux]	$E_v < 30,000$ [lux]
N° days correct on time	12	7	5	2
N° days early on time	4	2	1	1
N° days late on time	3	12	15	12
N° days too early on time	12	10	6	3
N° days too late on time	0	0	4	13

Table 4.4: Summary data on the time the light sensor activates the trap LEDs for June.

Threshold	$E_v < 60,000$ [lux]	$E_v < 50,000$ [lux]	$E_v < 40,000$ [lux]	$E_v < 30,000$ [lux]
N° days correct on time	7	4	2	0
N° days early on time	0	0	0	0
N° days late on time	16	21	7	1
N° days too early on time	7	5	5	5
N° days too late on time	0	0	16	24

Table 4.5: Summary data on the time the light sensor activates the trap LEDs for July.

Threshold	$E_v < 60,000$ [lux]	$E_v < 50,000$ [lux]	$E_v < 40,000$ [lux]	$E_v < 30,000$ [lux]
N° days correct on time	7	3	1	2
N° days early on time	3	1	2	0
N° days late on time	11	21	9	5
N° days too early on time	10	6	4	3
N° days too late on time	0	0	15	21

Table 4.6: Summary data on the time the light sensor activates the trap LEDs for August.

Threshold	$E_v < 60,000$ [lux]	$E_v < 50,000$ [lux]	$E_v < 40,000$ [lux]	$E_v < 30,000$ [lux]
N° days correct on time	17	8	2	1
N° days early on time	2	1	1	1
N° days late on time	3	16	19	10
N° days too early on time	9	6	6	3
N° days too late on time	0	0	3	16

Table 4.7: Summary data on the time the light sensor activates the trap LEDs for September.

Threshold	$E_v < 60,000$ [lux]	$E_v < 50,000$ [lux]	$E_v < 40,000$ [lux]	$E_v < 30,000$ [lux]
N° days correct on time	8	17	12	6
N° days early on time	10	5	3	1
N° days late on time	0	0	9	19
N° days too early on time	12	8	6	4
N° days too late on time	0	0	0	0

Chapter 5

Selection of the main components

The experimental and simulation work that led to the final selection of the main components for the prototypes, using the methodology described in Section 4.2, are presented in this chapter.

5.1 Initial Experimental test using a commercial PV assembly

The first approach to the problem was to find and acquire a commercial product with similar functions, namely solar energy operated LEDs, with storage and control. The strategy was to analyse the operation mode and the required list of components. An outdoor solar stand-alone wall lamp with a motion detector and a twilight sensor. The motion detector is a passive infrared (PIR) sensor and the twilight sensor is a light sensor that activates when the illuminance is under 10 lx, as shown in Figure 5.1. It is equipped with a push button to choose between different operating modes, and a timer for 10 seconds activation. The LEDs consume a power of 2.8 W. It has a small PV panel, of unknown characteristics, and a 1,200 mAh rechargeable battery. The control is done by an integrated circuit board. The lamp is ought to be installed outdoors and automatically activate when someone passes by during the night, illuminating the way.



Figure 5.1: Sulation Solar Sensor Light acquired to do the initial experimentation [57].

The LEDs provide a visible light intensity of 320 lm, which should be around 3 W

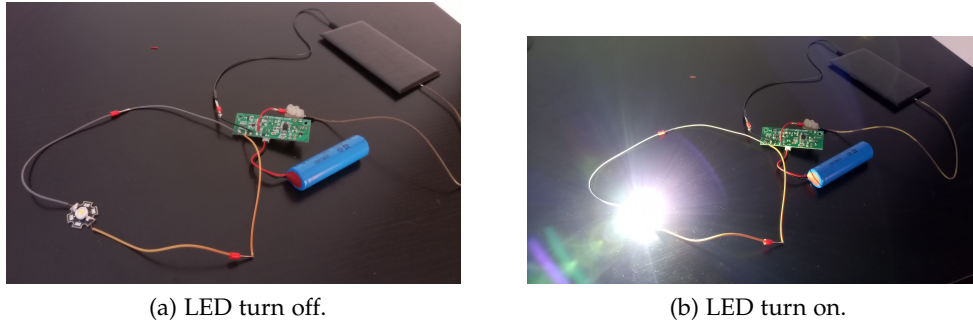


Figure 5.3: Experimentation white colour LED with 1 W of power and battery with 1,200 mAh of capacity.

power. This values is too high for the trap in terms of both light intensity and electric consumption. Even so, an experimental test was performed to determine how long the lights could be ascended with the installed battery capacity. The product was exposed to direct sun for sufficiently long time, to achieve full charge of the battery. The electrical circuit had to be for constant operation without the controller's interference. The results indicated that LEDs worked with their brightness during **1:15h**. Then, the brightness started to decrease until the LED stopped working 30 minutes later.

The power of LEDs available in the market below 3W is 1W. A white colour LED with 1W of power was acquired, corresponding to 110 lm, as shown in Figure 5.2. As it shown in the figure, the LED has a aluminium-core PCB for enhancing heat dissipation.

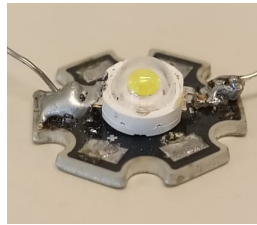


Figure 5.2: White colour 1W LED 1W mounted on an aluminium PCB [58].

After analysing the LED brightness, it was decided that 100 lm is adequate for the IT. Another experiment was carried out with the 1 W LED and the 1,200 mAh capacity battery. The results showed that the LED worked with its brightness during about **6h**, then the brightness started to decrease until the LED stopped working 30 minutes later. From this experiment, it can be concluded that a 1,200 mAh capacity battery is not enough for the IT because the target operating time should be as long as eight hours. Figures 5.3 shows the experimentation setup.

Selecting the battery capacity is an important part of the design process that influences mostly the size of the battery. It was important to have an indicator of the maximum battery capacity required. The maximum battery capacity required is equivalent to the case where all the power for the LEDs has to be supplied by the battery. A battery with 2,700 mAh of capacity was acquired, as shown in Figure 5.4. Another experiment was carried out with the 1 W LED and the 2,700 mAh capacity battery. The results showed that the LED worked with their brightness during **12h**, then the brightness started to decrease until the LED stopped working 30 minutes later. From this

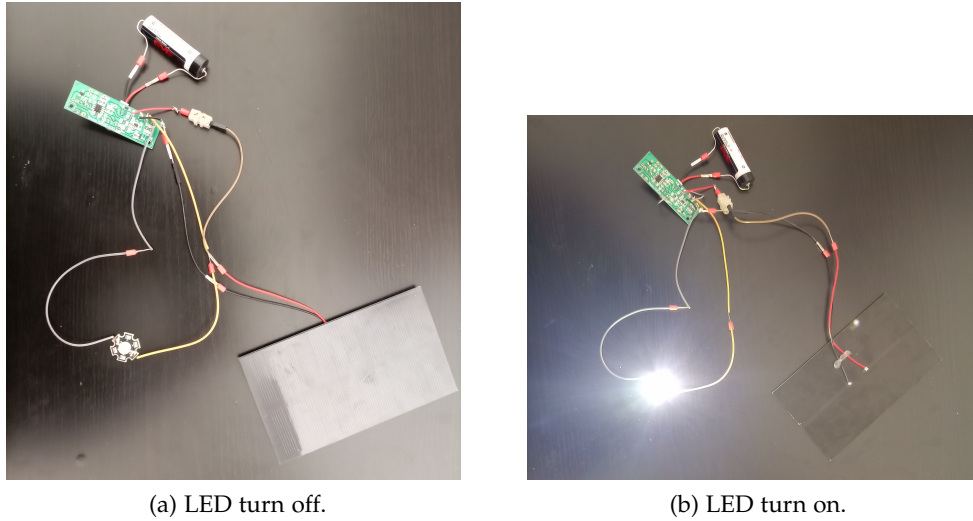


Figure 5.5: Experimentation white colour LED with 1 W of power and battery with 2,700 mAh of capacity.

experiment, it can be concluded that a 2,700 mAh battery can power a 1W LED for more than 8 hours. At this stage, energy consumption by the control system is not being considered. Figures 5.5 show this final experimentation setup.



Figure 5.4: Battery with 2,700 mAh of capacity [59].

5.2 System simulations using PVsyst

The PV system simulations were performed using the PVsyst 7.2 Software. PVsyst is a computer software package for the assessment and design of complete PV systems in different configurations, such as grid-connected, stand-alone, pumping and DC-grid (public transportation) PV systems. The software includes meteorological data and PV systems components database, as well as general solar energy tools [60].

A LED with 100 lm was considered corresponding to an electric consumption of 1W. Assuming an 8 hours operation per day, the daily energy is about **8 Wh**. The energy consumption of the control system was assumed to be negligible.

The IT is fixed to the ground by a stick or hung from the blueberry tree. Therefore, the PV panel is constantly exposed to the sun, with no shadow covering. Regarding the PV panel inclination, it was decided to keep it in the horizontal with 0 degrees of inclination. The use of the PV panel inclined, would imply installing the IT oriented to the south, which would complicate the use and installation by regular farmers.

The stand-alone system is usually composed of PV array, a regulator, batteries, the

user load equipment (LEDs in this case), and a back-up generator, that is not used in this project, as shown in Figure 5.6. In PVsyst, it can be chosen exactly the site where the PV system is installed. In this case, it is going to be installed in Portejões, Viseu, latitude 41.1204° N, longitude -7.8886° W and altitude 275 meters. The meteorological data is obtained from Meteonorm Software. For this specific site, it is only available monthly values of solar irradiation. The PVsyst synthetically generate hourly values, using a model based on the Perez model [61]. Data about the meteorological conditions used in PVsyst can be found in the Appendices B.1. The components database in PVsyst do not have the PV panels and batteries sizes necessary for the simulations. A battery of similar size was taken from the database and the known parameters changed. There is almost no technical information on PV panels of the required size. Therefore, a similar component was taken and changed to obtain the desired sizes. The regulator used is a MPPT controller system. At this point, the electrical characteristics of it are unknown. Therefore, in PVsyst was chosen the option of an universal MPPT controller. This option adapts the electrical characteristics of the components to each other, considering zero losses in the MPPT due to mismatched electrical characteristics. PVsyst has a field of detailed losses that describes various parameters about the losses in energy that happens in this kind of systems. In stand alone systems, it can be defined the following parameters:

- **Field thermal loss factor**, which represents the thermal behaviour of the field. It strongly influences the electrical performances and it is determined by an energy balance between ambient temperature and cell's heating up due to incident irradiance. It uses a thermal loss factor U_L , that varies according the type of mounting. It was chosen the option "Integration with fully insulated back", that considers no heat exchange at the backside, assuming an average wind velocity. PVsyst recommends a value of $15 \text{ W/m}^2 \cdot \text{K}$. This consideration is not completely true, because the PV is not insulated at the backside on the IT, but the value is a good approximation to reality;
- **Ohmic losses**, that represents the losses by heat due to Joule effect. This parameter can be set either by specifying the global wiring resistance (R_{wiring}) of the system or by specifying the power loss ratio. PVsyst defines a power loss ratio with respect to the standard test conditions power, taking a equivalent "resistance" of the STC operating point, $R_{arraySTC} = V_{mp} / I_{mp} [\Omega]$ and $Wiringlossfraction = R_{wiring} / R_{arraySTC} [\%]$. As it was not possible at this point to calculate the global wiring resistance, it was chosen a default value using the wiring loss fraction, that PVsyst defines as **1.50 %**;
- **Incidence Angle Modifier losses**, that represents the incidence effect corresponding to the decrease of the irradiance really reaching the PV cells's surface, with respect to irradiance under normal incidence. This decrease is mainly due to reflections on the glass cover, which increases with the incidence angle. PVsyst uses a model based on the Fresnel's laws describing transmission and reflections at the interface of two transparent materials of different refraction indexes. It was chosen a default value of the Fresnel model with an anti-reflective coating (AR), that is very common in almost PV panels. The model is shown in Figure 5.7;
- **Yearly soiling loss factor**, that represents the accumulation of dirt and its effect on

the system performance strongly depends on the environment of the system. The accumulation of dusts and the growth of mosses and lichens along the frame of the modules produces partial shadings on the bottom cells, and tend to retain more dust. Moreover these pollution are not removed by the rainfalls. It was chosen a default value that PVsyst defines as **3 %**;

- **Module quality loss**, that should express the confidence on the real module's performance, with respect to the manufacturer's specifications. In the past, it was well-known that most of PV modules series did not match the manufacturer nominal specifications. It was chosen an default value that PVsyst defines as **-0.8 %**, indicating that the PV performs slightly better than the specification indicated by the manufacturer;

- **Light Induced Degradation (LID)**, that represents a loss of performances arising in the very first hours of exposition to the sun, with crystalline modules, due to traces of oxygen included in the molten silicon during the Czochralski process. As there is almost no information about this, PVsyst recommends to use a value of **0** in this parameter;

- **Strings voltage mismatch loss**. The PV array is made of strings of PV modules in series and the PV array has one or several strings connected in parallel. The mismatch loss is defined as the difference between the sum of all P_{mp} of each independent module, and the P_{mp} resulting from the I/V characteristics of the array. It was chosen a default value that PVsyst defines as **0.1 %**;

- **Module mismatch loss**, that is mainly due to the fact that in a string of modules (or cells), the lowest current drives the current of the whole string. This happens because when installing real modules in the field, the characteristics of each module are never rigorously identical. In PVsyst, it groups two types of losses, power loss at MPP and loss when running at fixed voltage. When a MPPT controller is chosen as the regulator, PVsyst considers this losses as **0**.

Typical layout of a stand-alone system

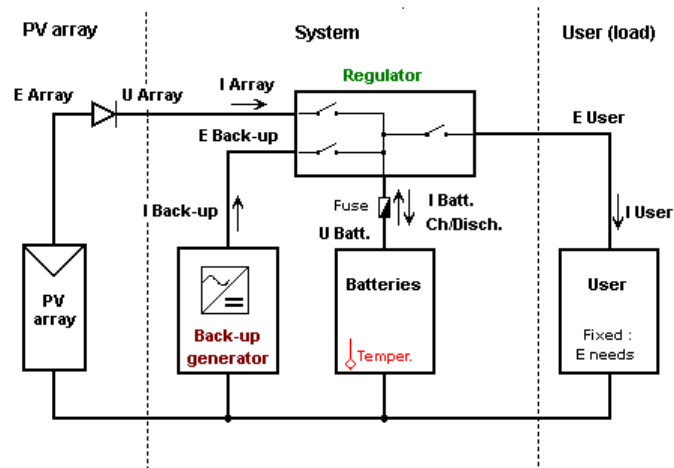


Figure 5.6: Typical layout of a stand-alone system.

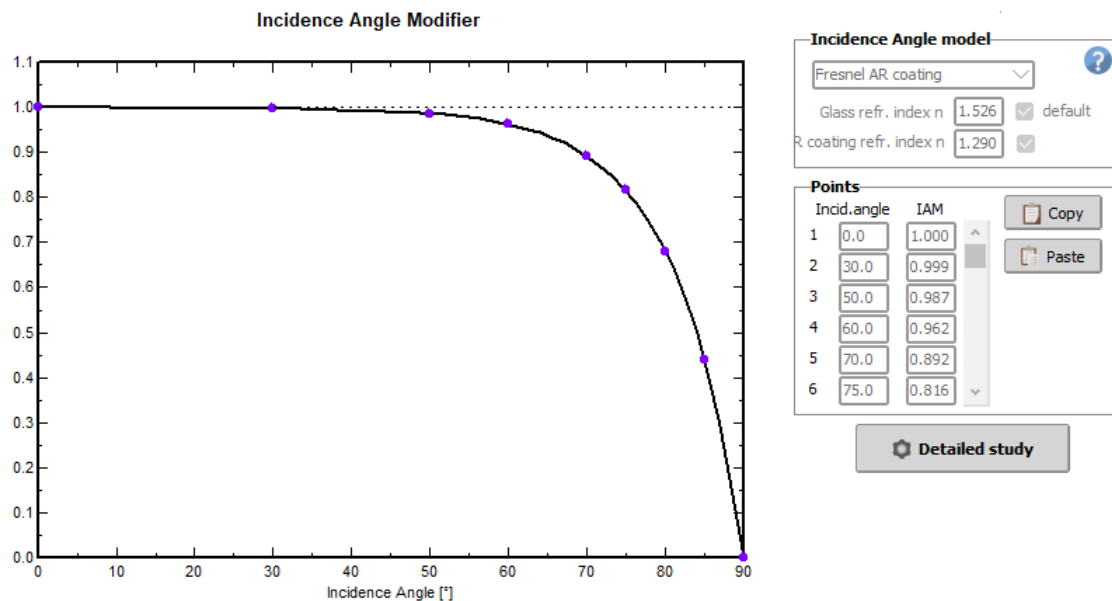


Figure 5.7: Fresnel model with AR coating.

The simulations started using a PV panel with 1W of power and a battery with 1,200 mAh of capacity and then increasing or decreasing the size of them until the goal was reached. The 1W PV panel was recommended by the PVsyst pre-sizing function that gives an estimation of the power required before starting the simulations. This battery capacity was chosen to start the simulations because the initial experimentation showed that an acceptable operation time could be achieved. After doing the first simulation, an error appeared saying "Incoherency in the simulation results: Energy balance error in the array losses (260 %). Please contact technical support.". After analysing the results

reports, it was notice that the energy produced results were very little, because a lot of energy was considered to be lost. Therefore, the technical support was contacted and sent this project, to which they replied that PVsyst is not really adapted to such small components. It was recommend to scale the system,e.g. multiply the PV power, the battery capacity and the user needs by 10 or 100, to check if the results get better. The simulations were repeated for a system scaled by 10. The energy production increased a lot in comparison to the normal setup. Therefore, the strategy of scaling the system is adopted. The LEDs power is 10 W, that consumes **80 Wh** of energy per day. The first setup of the simulations is for a 10 W PV and 12,000 mAh battery and increased the battery capacity if necessary.

As can be seen in Table 5.1, the necessary energy is not delivered, not even if the battery capacity is increased. A requirement of at least **90 %** of operating time by the trap LEDs during the most important months, which are June, July and August, has been imposed by the FCUP team. These are the months that SWD has higher activity on the blueberry crops. The next step is to increase the PV power.

Table 5.1: Results of PVsyst simulations for 10 W/12,000 mAh and 10 W/17,000 mAh of PV power/battery capacity in the different months, with respect to the energy that is used [kWh] and the energy that is unused [kWh] because the battery is full.

		10 W/12,000 mAh	%	10 W/17,000 mAh	%
May	E_{used} / E_{load}	1.637/2.480	66.0	1.887/2.480	76.1
	E_{unused}	0.437		0.161	
June	E_{used} / E_{load}	1.679/2.400	70.0	2.076/2.400	86.5
	E_{unused}	0.557		0.132	
July	E_{used} / E_{load}	1.737/2.480	70.1	2.148/2.480	86.6
	E_{unused}	0.617		0.180	
August	E_{used} / E_{load}	1.599/2.480	64.5	1.836/2.480	74.0
	E_{unused}	0.513		0.254	
September	E_{used} / E_{load}	1.291/2.400	53.8	1.431/2.400	59.6
	E_{unused}	0.267		0.092	

Increasing the PV power and setting up a battery with adequate capacity, the necessary energy is delivered as wanted ($\geq 90\%$), except in September, as can be seen in Table 5.2. It can also be seen that if the battery capacity is increased from 17,000 to 18,000 there is almost no difference in the results. More information about the energy produced in the whole year can be found in Figure B.12 in Appendices B.2.

Figure 5.10 shows the loss diagram of the 15 W/17,000 mAh system in June. The other loss diagrams for the different months can be found in Appendices B.2. It can be seen that the ohmic wiring loss represents the biggest loss of energy, followed by the converter loss over nominal conversion power, PV loss due to temperature and battery efficiency loss. Ohmic wiring loss represents **12.3 %** of the possible produced energy by the PV array. It is a problem transversal to any electrical system, especially with system that requires high currents. The controller's loss represents **11.5 %** of the

Table 5.2: Results of PVsyst simulations for 15 W/12,000 mAh, 15 W/17,000 mAh and 15 W/18,000 mAh of PV power/battery capacity in the different months, with respect to the energy that is used [kWh] and the energy that is unused [kWh] because the battery is full.

		15 W/12,000 mAh	%	15 W/17,000 mAh	%	15 W/18,000 mAh	%
May	E_{used}/E_{load}	1.893/2.480	76.3	2.352/2.480	94.8	2.412/2.480	97.2
	E_{unused}	1.609		0.921		0.855	
June	E_{used}/E_{load}	1.902/2.400	79.2	2.357/2.400	98.2	2.362/2.400	98.4
	E_{unused}	1.609		1.146		1.146	
July	E_{used}/E_{load}	1.962/2.480	79.1	2.443/2.480	98.5	2.444/2.480	98.6
	E_{unused}	1.732		1.241		1.242	
August	E_{used}/E_{load}	1.815/2.480	73.2	2.432/2.480	98.1	2.461/2.480	99.2
	E_{unused}	1.531		0.898		0.872	
September	E_{used}/E_{load}	1.529/2.400	63.7	1.992/2.400	83.0	2.057/2.400	85.7
	E_{unused}	0.950		0.480		0.418	

energy produced by the PV array, which means that is considered a 88.5 % efficiency of the MPPT controller. The efficiency of the PV is reduced with the increase of its cells temperature. In this case, Figure 5.11 shows that it can get to **45° C**. Batteries have an efficiency that degrade in time, so it should be used a battery from a reliable manufacturer. However, price is an important factor to take into account in this project and it is decisive when choosing the components. It can also be noted that **41.6 %** of the energy is used directly and **58.6 %** is used after being stored, showing well the importance of the storage system in this case. These values are very similar to the others months as can be seen in Appendices B.2.

Figure B.13 in the Appendices B.2, shows at which time the PV is producing energy, during the day throughout the year. It can be seen that it works from 6h until 19h in the most important months. After 19h the irradiation is not big enough to activate the PV. Figure 5.8 shows the effective output of the PV to battery system and to the user on a random day in June. It shows that after 15/16h the PV stops to deliver energy. This happens because the battery system is already full at this time and after that the energy produced is wasted. Figure B.14 in Appendices B.2, shows the monthly hourly sum of energy delivered to the user. It can be seen, by the difference in the values, that the second period in the day is always fulfilled in terms of energy delivered. Although, in the first period of the day, particularly after 9h until 11h, sometimes the user needs are not fulfilled. This happens because at that time the battery system starts to get empty and the PV may not respond in time. Therefore, it is predicted that, if the insect trap fails to power the LEDs, will be during the first period in the day.

Figure 5.9 shows the state of charge of the battery system during a random day in June. This figure confirms the point that after 15/16h the battery system is full. Relatively to the time that the PV take to fully charge the battery system, it can be seen that it takes from 7h until 15/16h, but during this time it is also delivering energy because of the first operation period of the day. Therefore, the PV panel is expected

to need more than 7h of sun exposure to fully charge the battery system. In Figure B.15 in Appendices B.2 is shown the monthly hourly averages of the state of charge of the battery system throughout the year. It confirms the same point, that after 15/16h the battery system is full until it starts to deliver energy again when the second period starts.

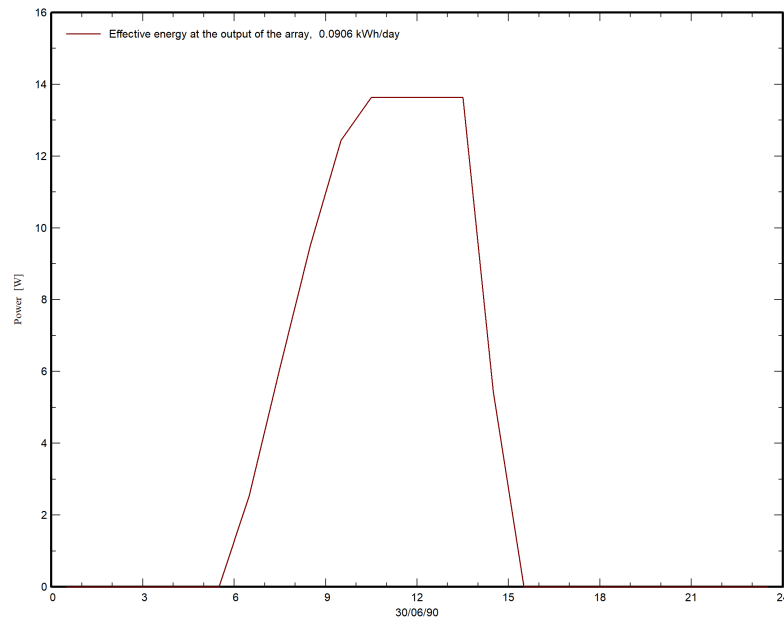


Figure 5.8: Effective energy produced in the PV during a random day (30/06) in the 15 W/17,000 mAh system.

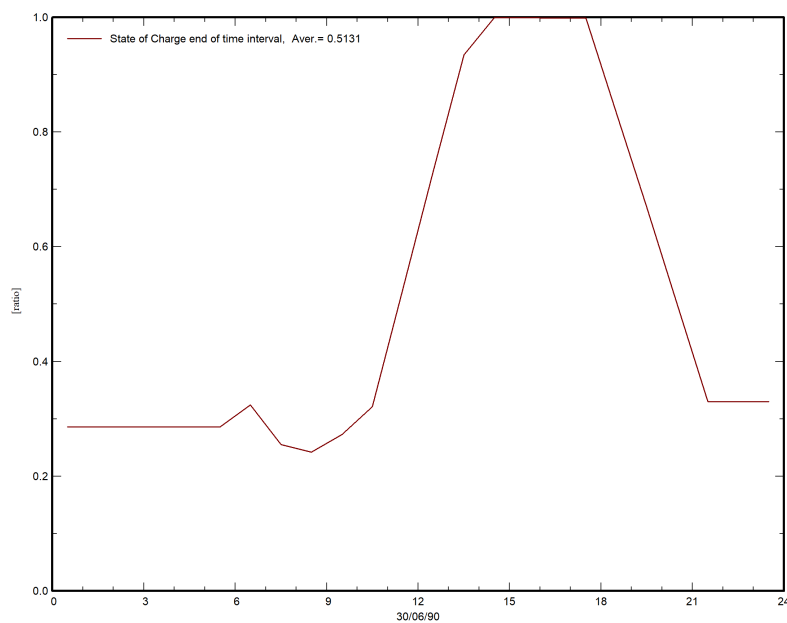


Figure 5.9: State of charge of the battery during a random day in the 15 W/17,000 mAh system.

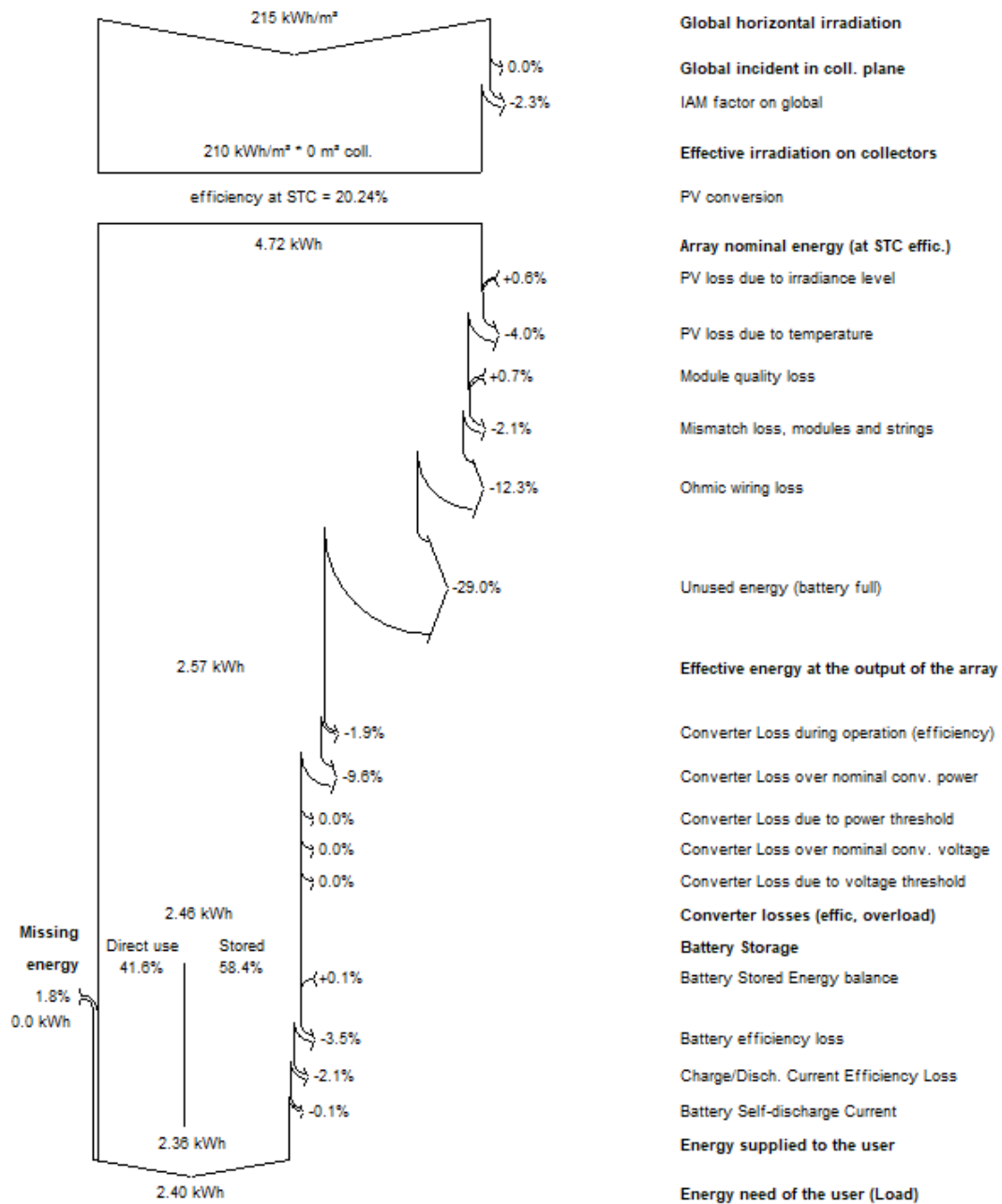


Figure 5.10: Loss diagram of the 15 W/17,000 mAh system in June.

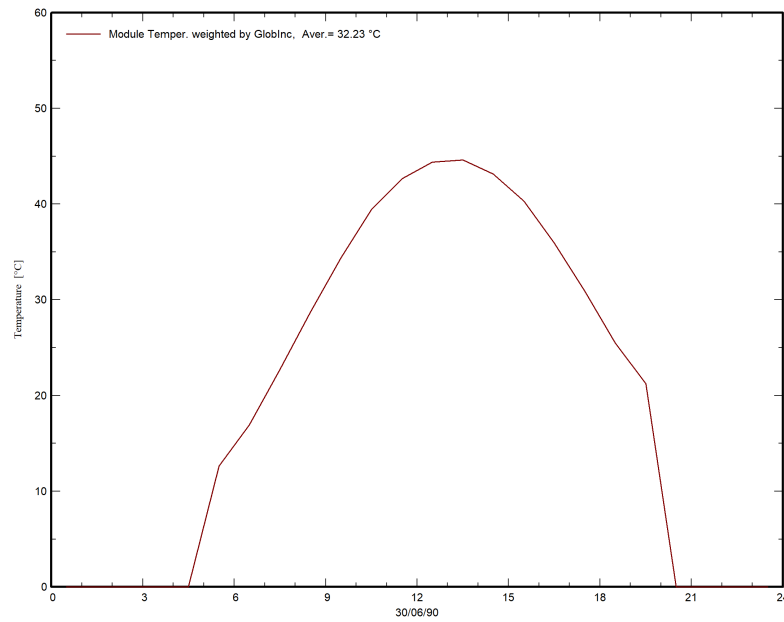


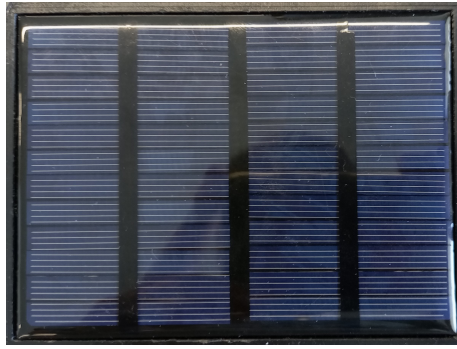
Figure 5.11: PV temperature during a random day (30/06) in the 15 W/17,000 mAh system.

5.3 Selection of the main components

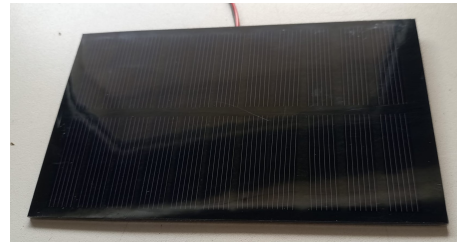
The choice of the main components was done after the initial simulations. It was wanted a PV panel with 1.5 W of power, and dimensions below or similar to 100x100 mm, due to the initial technical specifications. The PV panel dimensions affects directly the lid dimensions. Figures 5.12 show the components that were acquired.

The PV panel 12 V has dimensions 115x85x3 mm and its typical voltage is 12V and the PV panel 5V has dimensions 131x81x2.5 mm and its typical voltage is 5V. These were the smallest PV panels with 1.5 W of power available on the market. Their electrical characteristics are not a problem, because they can be adapted to the rest of the system. The choice between the two was based on their dimensions. The PV panel 5V has a rectangular shape and the PV panel 12V has a more squared shape. The choice was to use the PV panel 12V because of its shape, that is easier to implement on the design. No data sheet with detailed information about this PV panel was found available on the internet.

For the battery, it was wanted a battery cell with at least 1,700 mAh of capacity. Most of the battery cells can be recharged, but only the rechargeable are designed to support a high number of charging/discharging cycles. Lithium battery cells are the ones with the highest volumetric energy density, meaning they can store more energy in a smaller space than the other ones. This is an important factor because it is required that the IT does not have dimensions much larger than specified. Lithium polymer batteries would be the ideal choice for this case. They are flatter, thinner and lighter than the common cylindrical lithium battery cells. Although, they are usually more expensive. A 18500 2,200 mAh rechargeable cylindrical lithium ion battery was acquired because it was found a cheaper one than the 1,700 mAh available on the market, as shown in Figure 5.12.



(a) PV panel 12V [62].



(b) PV panel 5V [63].

Figure 5.12: PV panels bought.



Figure 5.13: Rechargeable cylindrical lithium ion battery with 2,200 mAh capacity [64].

This battery has 2,200 mAh of capacity, 3.7 nominal voltage, 18.25 mm of diameter and 65 mm of length. No data sheet with detailed information about this PV panel was found available on the internet from this specific manufacturer, but a data sheet from a similar battery was found, from the manufacturer Hunan Sounddon New Energy Co., Ltd, and it is expected that behaves in a similar way. The data sheet can be found in Appendices B.3.

For the LEDs, it was wanted LEDs of different colours, such as, UV-A, red and yellow or orange of 1W of power. The battery needs to be able to power them, so the LEDs voltage should be equal or below to 3.7 V. Two LEDs of each colour required were acquired, including white, warm white, orange, red, yellow and UV-A. It was decided to use the warm white colour LEDs, which can be used as a replacement for yellow. In this way, the warm white LEDs have a higher light intensity than the yellow LEDs. Figure 5.14 shows the warm white LED that was acquired.

All the LEDs have the same dimensions, 8 mm of diameter, 5.5 mm of height and 14.2 mm of length, including the leads to do the power connection. The most important characteristics about them are present in Table 5.3. Just to mention that was only found a UV-A LED of 2.5 W of power for a reasonable price. These LEDs are manufactured by ProLight. In Appendices B.3 can be found more information about the behaviour of the LEDs, provided by the manufacturer.



Figure 5.14: Warm white LED [65] [66] [67] [68] [69].

Table 5.3: LEDs characteristics.

LED colour	Warm White	Red	UV-A	White	Orange
Voltage [V]	2.85-3.85	2.2-2.4	3.2-3.6	3-3.2	2.2-2.4
Current [mA]	350	300	700	300	300
Luminous Flux [lm]	120-130	40-50	5-8	120-130	40-50
Beam Angle [°]	130	120	140	130	120
Wavelength [nm]	-	620-625	395-405	-	590-595
Colour Temperature [K]	2,850-3,250	-	-	4,500-5,640	-
Minimum CRI [-]	80	-	-	70	-

5.4 Final system simulations using PVsyst

As mentioned before, it was chosen to use the 1.5 W PV panel, 2,200 mAh battery and 1 W LEDs. After the main components selection, a decision was taken to change some technical specifications relating to the operation of the insect trap. Due to the fact that the LEDs only have a beam angle of 130°, it was decided to use two LEDs per trap, to cover as much ground as possible in the horizontal plane. Ideally, it would be necessary three to cover the entire horizontal plane, making more than 360°, but in this way it would increase too much the power consumption of the LEDs. Other change that was made was to decrease two hours in each period of operation, because it was agreed that would be enough. The new schedule is 5-7h and 20-22h. This period happens when there is less solar irradiation available to produce energy. When this changes were made, the design of the prototype was already complete and produced. Changing the capacity of the battery is not a problem because rechargeable batteries have standard dimensions. Although, changing the PV panel to a larger one requires to change the dimensions of the lid. These components were used to make the first prototype and to do some experiment. After that the performance results are evaluated to see what modifications are required. The PVsyst simulations were repeated to know what is the

expected behaviour of the trap. It was used the same strategy of scale the systems by 10.

As can be seen in Table 5.4, the necessary energy is not delivered with the 15 W/22,000 mAh system. By increasing the battery system to 25,000 mAh, it can be achieved the requirement of $> 90\%$. More information about the energy produced in the whole year can be found in Figure B.27 in Appendices B.4.

Table 5.4: Results of PVsyst simulations for 15 W/22,000 mAh and 15 W/25,000 mAh of PV power/battery capacity in the different months, with respect to the energy that is used [kWh] and the energy that is unused [kWh] because the battery is full.

		15 W/22,000 mAh	%	15 W/25,000 mAh	%
May	E_{used}/E_{load}	2.066/2.480	83.3	2.253/2.480	90.8
	E_{unused}	1.179		0.974	
June	E_{used}/E_{load}	2.043/2.400	85.1	2.231/2.400	93.0
	E_{unused}	1.428		1.228	
July	E_{used}/E_{load}	2.134/2.480	86.0	2.331/2.480	94.0
	E_{unused}	1.516		1.299	
August	E_{used}/E_{load}	2.134/2.480	86.1	2.309/2.480	93.1
	E_{unused}	1.163		0.973	
September	E_{used}/E_{load}	1.882/2.400	78.4	2.005/2.400	83.5
	E_{unused}	0.561		0.433	

Figure 5.18 shows the loss diagram of the 15 W/22,000 mAh system in June. The other loss diagrams for the different months can be found in Appendices B.4. It can be seen that the ohmic wiring loss represents the biggest loss of energy, followed by the converter loss over nominal conversion power, battery efficiency loss and PV loss due to temperature. Ohmic wiring losses, converter losses over nominal conversion power and PV losses due to temperature remains similar to the previous system. Figure 5.15 shows that it can get to 45°C , that is the same that would happened with the previous system. Although, in this case, losses due to battery efficiency increased. This occurs because the battery gets fully charged sooner compared to the previous system. The big difference in this case is that the energy is almost entirely used after being stored (98.1 %). This is due to the new schedule implemented, i.e., the energy is demanded mainly during the time of day when irradiation levels are low, in the early morning and late afternoon. The energy storage system is even more important in this case.

Figure B.28 in the Appendices B.4, shows at which time the PV is producing energy, during the day throughout the year. It can be seen that it works from 6h until 19h in the most important months. After 19h the irradiation is not big enough to activate the PV, as happened with the previous system. Figure 5.17 shows the effective output of the PV to battery system and to the user on a random day in June. After 14/15h the PV stops to deliver energy. This happens because the battery system is already full at this time and after that the energy produced is wasted. This happens early than the previous system because the battery system gets full early. Figure B.29 in Appendices B.4, shows the

monthly hourly sum of energy delivered to the user. It can be seen, by the difference in the values, that the second period in the day is always fulfilled in terms of energy delivered. Although, in the first period of the day, particularly after 6h, the user needs is never fulfilled completely. This means that the battery system does not have enough capacity and it needs to be increased. Therefore, it is predicted that the insect trap, with this configuration, will never work properly during the first period of the day and the second period of the day will always be guaranteed.

Figure 5.16 shows the state of charge of the battery system during a random day in June. It confirms the fact that after 14/15h the battery system is full. It can be concluded that the battery system is completely charged in 8 hours. Also, the MPPT regulator do not let the battery capacity goes below the 5-10% of capacity, to avoid damaging the battery due to deep discharges. In Figure B.30 in Appendices B.4, is shown the monthly hourly averages of the state of charge of the battery system throughout the year, and confirms the same point, that after 14/15h is full until it starts to deliver energy again when the second period starts.

Comparing this system configuration to the previous one, it can be seen that the energy needed is the same, because the power consumption doubled but the time operation have decrease in half. As the period of operation has changed to a period in time when there is almost no solar irradiation, the current configuration can not fulfil the energy required by the trap LEDs. The battery capacity needs to increase to at least 2,500 mAh, taken into account the assumptions presented.

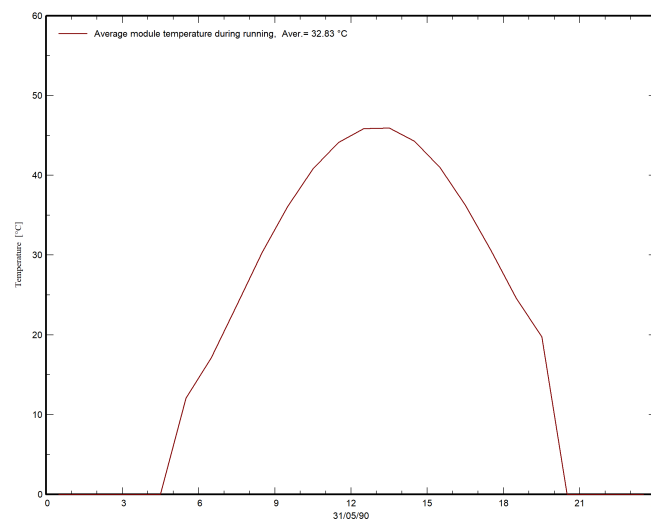


Figure 5.15: PV temperature during a random day (30/06) in the 15 W/22,000 mAh system.

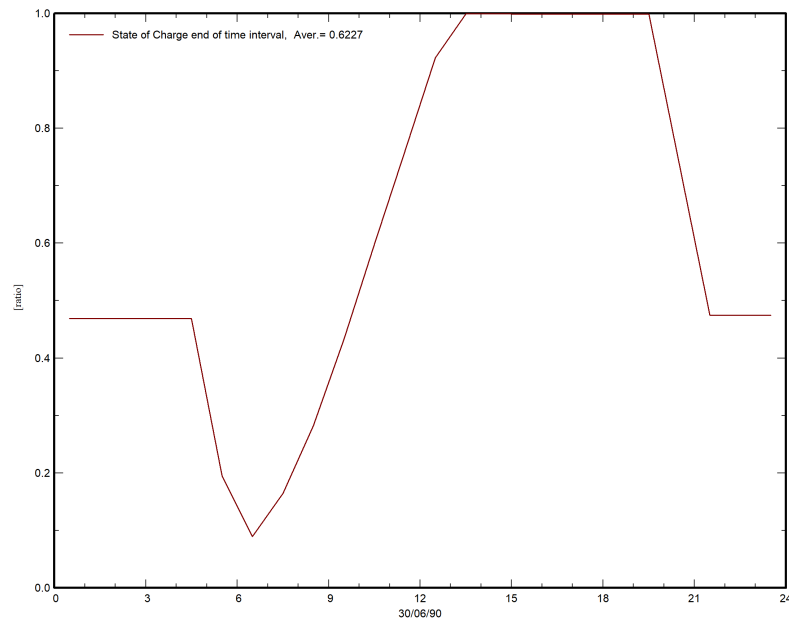


Figure 5.16: State of charge of the battery during a random day in the 15 W/22,000 mAh system.

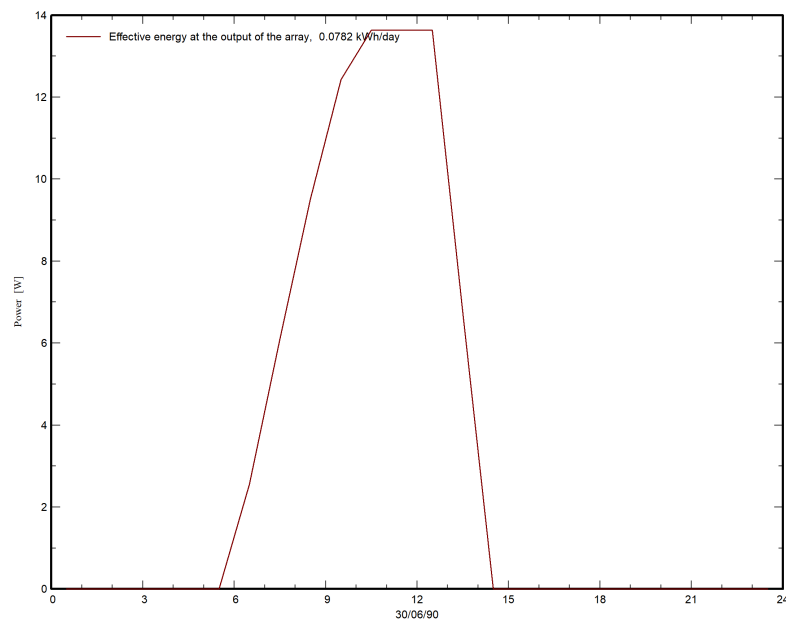


Figure 5.17: Effective energy produced in the PV during a random day (30/06) in the 15 W/22,000 mAh system.

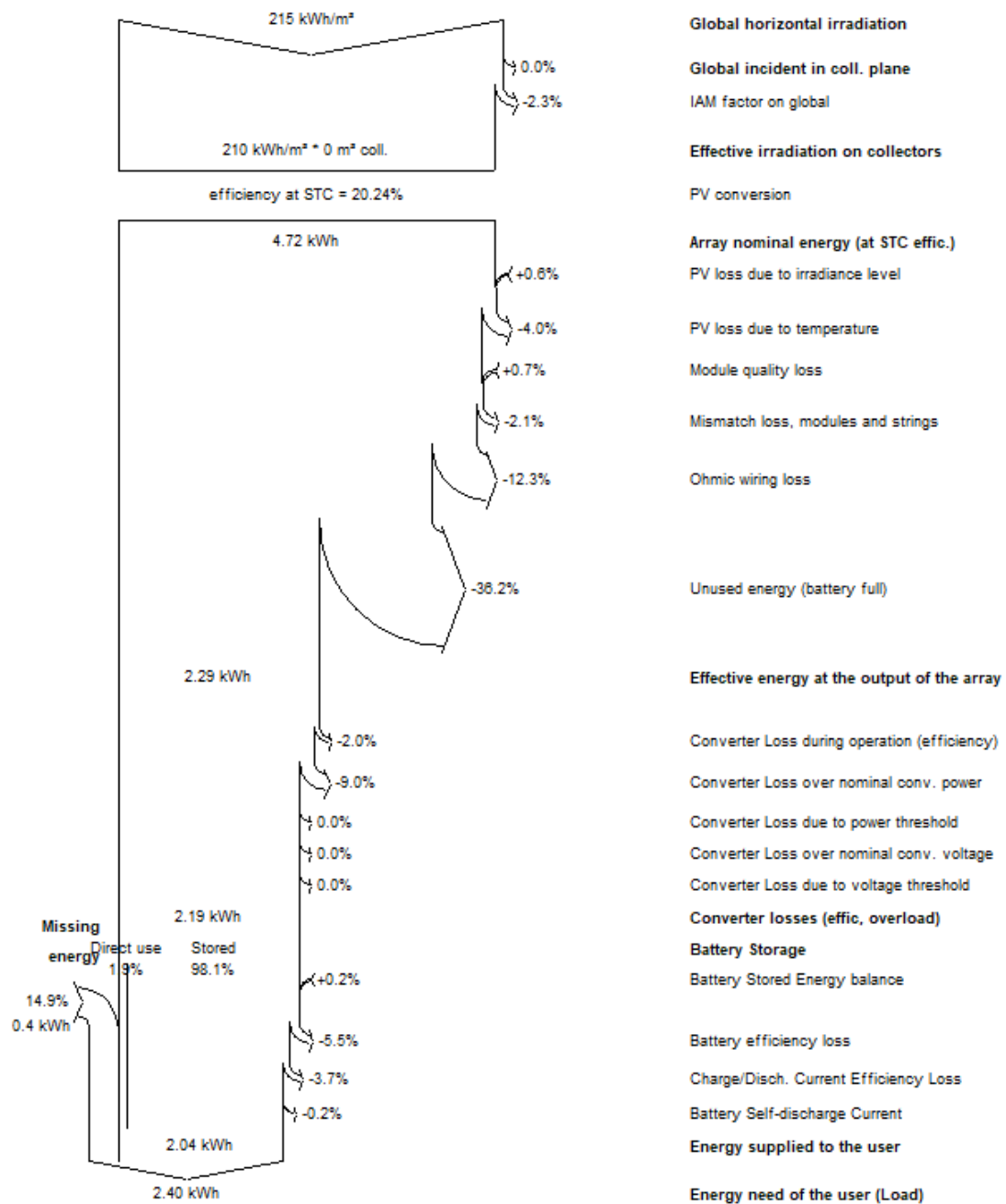


Figure 5.18: Loss diagram of the 15 W/22,000 mAh system in June.

Chapter 6

Control system design

The research and selection work that led to the final design of the control system are presented.

6.1 General description of the control system

The insect trap LEDs are required to operate at a specific time of the day. The battery cell and the PV panel electrical characteristics do not match. Also, the electrical characteristics of the LEDs do not match. Therefore, the functions of the control system are to manage the charging and discharging of the battery in an efficient way, make the electrical characteristics of the different components compatible, provide a sufficient and constant current to the LEDs in order for them to operate with the required light intensity, and activate the trap LEDs at the desired specific time. The electronics components needed are:

- Battery management system;
- Arduino;
- Real-time clock or light meter;
- Power MOSFET transistor.

The BMS is responsible to do the efficient charge/discharge of the battery cell. The Arduino is responsible for the control function needed to automatically operate the LEDs in the trap. The RTC provides accurate current time information and prevents this information from being lost in the event of a power failure. The light meter offers a different approach and allows the system to work, not on the basis of time information, but on the intensity of daylight. The power MOSFET transistor act as switch and allows the necessary current to flow through the LEDs.

6.2 Battery management system selection

The first component to choose for the control system is a component with the function of charging and discharging the battery cell. Its electrical characteristics need to be compatible with the PV electrical characteristics, such as, the voltage input and current input, and with the battery cell used, a 18500 cylindrical rechargeable battery cell,

with 3.7V of nominal voltage. Also, dimensions and cost were taken into account. It is necessary to be compact to assemble it in the insect trap.

For the first prototype, the 12V PV is used. Therefore, a MPPT 12 V solar panel regulator controller module was acquired, as shown in Figure 6.1, that uses a CN3791 solar power management chip [70]. It has 2 PH2.0 interfaces for PV panels, 2 PH2.0 interfaces for lithium battery cells and 4 JST plug connectors. Its dimensions are 45x20x9.5 mm.

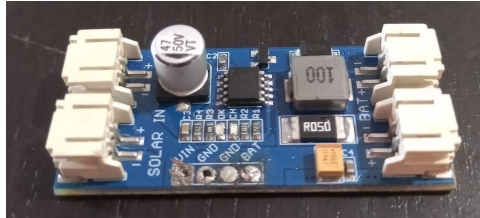


Figure 6.1: MPPT 12 V solar panel regulator controller module [71].

The CN3791 is a PWM switch-mode lithium ion battery charger controller. It can be powered by photovoltaic cell with maximum power point tracking function with few external components. The CN3791 is specially designed for charging lithium ion batteries with constant current and constant voltage mode. Figure 6.2 shows the electrical circuit for the application of the CN3791 chip. Detailed electrical characteristics can be found in Appendices C. The main features of the CN3791 chip are:

- Photovoltaic cell maximum power point tracking;
- Wide input voltage: 4.5V to 28V;
- Complete charge controller for single cell lithium-ion battery;
- Charge current up to 4A;
- High pulse-width modulation (PWM) switching frequency: 300 kHz;
- Constant voltage: $4.2V \pm 1\%$;
- Charging current is programmed with a current sense resistor;
- Automatic conditioning of deeply discharged batteries;
- Automatic recharge;
- Charging status indication: red LED on indicates charging, green LED on indicates charge termination, the two LEDs blinking indicates the battery is not present;
- Soft start;
- Battery overvoltage protection;
- Operating ambient temperature: -40 to $+85\text{ }^{\circ}\text{C}$;
- Power consumption of 0.00481 W.

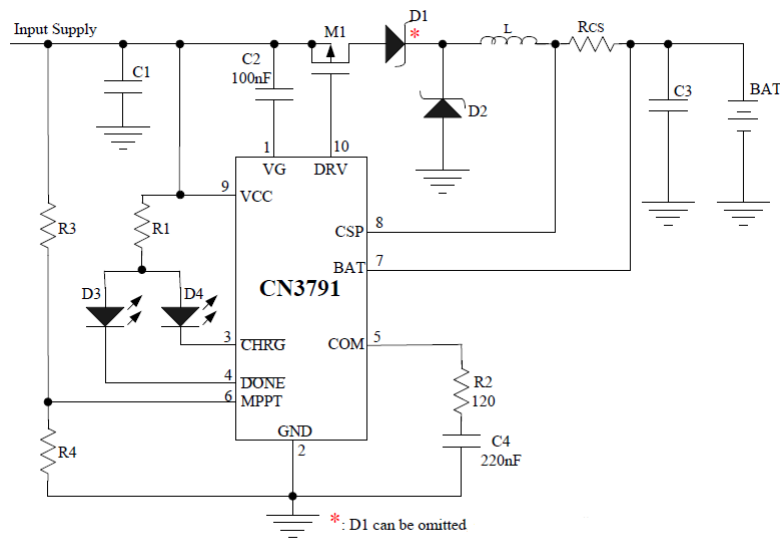


Figure 6.2: Typical application circuit of CN3791 chip [70].

Although the chip can deliver 4 A of charging current, the module is limited to 2 A. The input voltage should be around 12 V. Beside these constraints, the module should operate in a similar way to the chip specifications.

The use of 5V PV is still a possibility. Therefore, it was chosen a CN3065 Mini Solar Lithium Charger Board, as shown in Figure 6.3, that uses a CN3065 solar power management chip [72]. It has 1 PH2.0 interface1 for PV panel, 1 PH2.0 interface for lithium battery cell, 1 PH2.0 interface for system output and 2 JST plug connectors. It supports USB charging (Mini USB connector). Its dimensions are 40x20x7 mm.

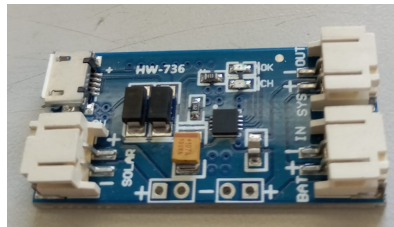


Figure 6.3: CN3065 Mini Solar Lithium Charger Board [73].

The CN3065 is a complete constant-current/constant voltage linear charger for single cell Li-ion and Li-polymer rechargeable batteries. It can adjust charging current automatically based on the output capability of input power supply. Figure 6.4 shows the electrical circuit for the application of the CN3065 chip. Detailed electrical characteristics can be found in Appendices C. The main features of the CN3065 chip are:

- On-chip 8-bit analog-digital converter (ADC) can adjust charging current automatically based on the output capability of input power supply;
- Suitable for solar-powered system;
- On-chip power MOSFET;

- No external blocking diode or current sense resistors required;
- Preset 4.2V regulation voltage with 1% accuracy, adjustable with an external resistor;
- Precharge conditioning for reviving deeply discharged cells and minimising heat dissipation during initial stage of charge;
- Continuous programmable charge current up to 1,000 mA;
- Constant-current/constant-voltage operation with thermal regulation to maximise charge rate without risk of overheating;
- Automatic low-power sleep mode when input supply voltage is removed;
- Charging status indication: red LED on indicates charging and green LED on indicates charge termination;
- Automatic recharge;
- Battery temperature sensing;
- Short circuit protection;
- Operating ambient temperature: -40 to +85 °C;
- Power consumption of 0.003515 W.

Although the chip can deliver 1 A of charging current, the module is limited to 0.5A. The input voltage should be 4.4-6V . Beside these constraints, the module should operate in a similar way to the chip specifications.

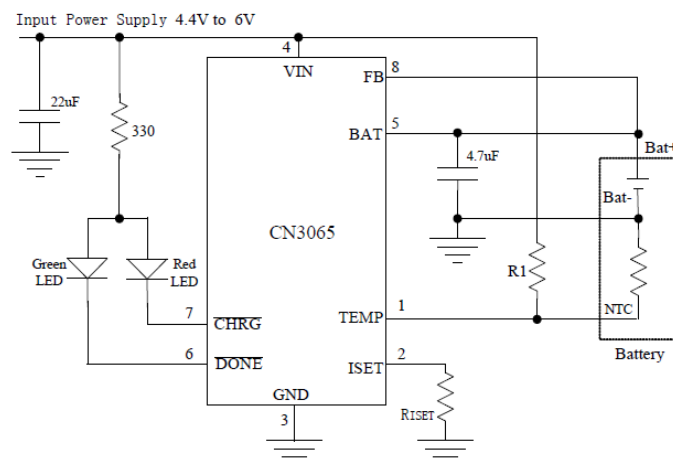


Figure 6.4: Typical application circuit of CN3065 chip [72].

6.3 Light meter selection

As explained before, one way of automatically operate the trap LEDs is using a light meter. The light meter needs to read light illuminance in a wide range, have communication interface compatible with the programmable microcontroller, and have compatible electrical characteristics. Also, dimensions and cost were taken into account. It is necessary to be compact to assemble it in the insect trap.

A Digital Light Intensity Sensor Module BH1750FVI was acquired, as shown in Figure 6.5, that is a photo-diode light sensor [74]. It was the light meter with the widest reading range available in market. Another option could be to use LDRs. They are cheaper, but have limited reading range and slower response time. Its dimensions are 32x15 mm. More detailed information can be found in Appendices C. The main features of the photo-diode light sensor are:

- I^2C bus interface;
- It is possible to select 2 types of I^2C slave-address;
- Spectral responsibility is approximately human eye response;
- Illuminance to Digital Converter;
- Wide range: 1 - 65,535 lx;
- Three resolution modes: 0.5 lx, 1 lx and 4 lx;
- Low current by power down function;
- 50Hz / 60Hz light noise reject-function;
- No need any external parts;
- Light source dependency is little, i.e, detect illuminance from any light source with little variation, including various types of lamps and sun light;
- The influence of infrared is very small.



Figure 6.5: Digital Light Intensity Sensor Module BH1750FVI [75].

6.4 Real-time clock selection

Another way of automatically activate the trap LEDs is triggering it at a specific time. Therefore, it is necessary to have always accurate time data. The RTC provides accurate time information. It is necessary that the RTC has communication interface compatible with the programmable microcontroller, and has compatible electrical characteristics. Also, dimensions and cost were taken into account. It is necessary to be compact to assemble it in the insect trap.

A RTC DS1307 Precision Digital Clock Module was acquired, as shown in Figure 6.6, that is a RTC that runs with a CR2032 lithium non rechargeable battery cell. It has incorporated a DS1307 chip [76] and a AT24C32 memory chip [77]. Its dimensions are 27x28x8.4 mm. Figure 6.7 shows the typical operating circuit for a DS1307 chip. More detailed information can be found in Appendices C. The main features of the RTC DS1307 are:

- Counts seconds, minutes, hours, day of the month, month, day of the week, and year with leap-year compensation valid up to 2100;
- 56-Byte, battery-backed, general-purpose RAM with unlimited writes;
- I^2C bus interface;
- Programmable square-wave output signal: 1 Hz, 4 kHz, 8 kHz and 32 kHz;
- Automatic power-fail detect;
- Optional Industrial Temperature Range: -40 to +85 °C;

Another option could be to use the RTC DS3231 Precision Digital Clock Module has incorporated a DS3231 chip [78]. The main difference between the RTC DS3231 and the RTC DS1307 is that the RTC DS3231 has alarm outputs. The alarm output function produces an analog output signal at a specific time. It can be programmed to interrupt the sleep mode of the Arduino. Sleep mode is a feature of the Arduino that disable some functions to reduce the power consumption.

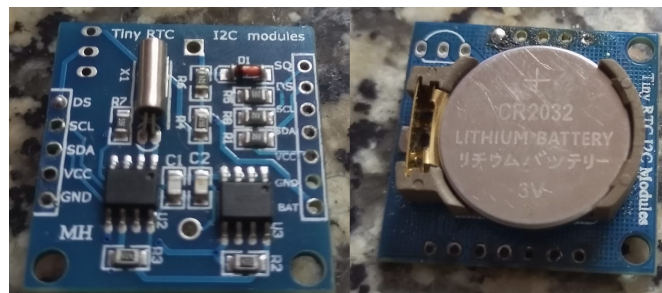


Figure 6.6: RTC DS1307 Precision Digital Clock Module [79].

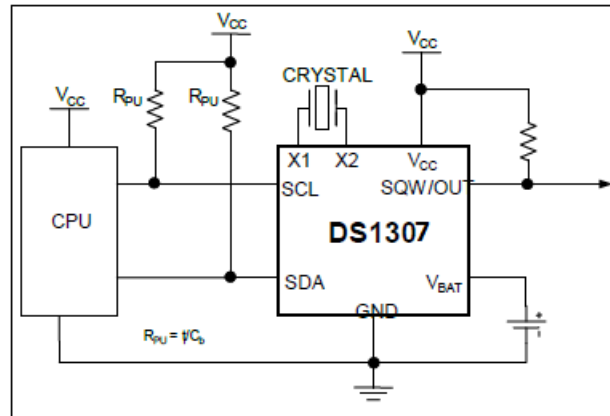


Figure 6.7: Typical operating circuit of the DS1307 chip [76].

6.5 Arduino selection

For this project it is necessary a programmable microcontroller that can connect to a RTC or to a light meter. For prototype development, the reasonable choice is an Arduino because of its price and its availability on the market.

For this application, taken into account the other electronic components, the Arduino requirements are:

- Power supply less than 3.7V due to voltage supply by the battery cell;
- Analog signal output, to turn on/off LEDs;
- I^2C bus interface connection protocol, for communication with RTC and light meter;
- Compact size to be able to assemble in the insect trap.

A Seeeduino XIAO was acquired that has SAMD21 Cortex M0+ CPU [80]. It is one of the smallest Arduinos available on the market. Its dimensions are 20x17.5x3.5 mm which makes it suitable for this application. The Seeeduino XIAO main features are:

- CPU: ARM Cortex-M0+ CPU (SAMD21G18) running at up to 48MHz;
- Memory storage: 256KB Flash, 32KB SRAM ;
- I^2C bus interface connection protocol, for communication with RTC and light meter;
- I/O PINs: 14 GPIO PINs, 11 analog PINs, 11 digital PINs and 1 DAC output PIN;
- Interface: I^2C interface, UART interface and SPI interface;
- Downloading interface: USB type-C;
- Built-in LEDs: user LED, power LED and two LEDs for serial port downloading;
- Reset button: two reset button (short connect them to reset);

- Serial wire debug pads for debugging;
- Software compatibility with Arduino IDE and CircuitPython;
- Projection cover for protecting the circuit.

The Seeduino XIAO board operates with 5V, but has a voltage regulator that makes it possible to be powered by 3.3V, by connecting the battery cell to 3V3 PIN. The hardware pinout is shown in Figure 6.8. It uses a chip's inner crystal oscillator for time fixing, in order to make the clock more accurate, although it has an extra 32,768 kHz crystal oscillator to make the clock more stable. All the output PINs are 3.3 V and can deliver a maximum current of 10 mA. It is possible to implement a sleep mode to reduce the power consumption. It can be implemented two types of sleep modes. The idle mode, which stops the CPU and some clock domains. The main clock is running and the regulator and RAM are running normally. It has the fastest wake-up time. The stand-by mode, which stops the CPU, all the clock domains and the regulator and RAM runs in low power mode [80]. In the stand-by mode, it needs to be woken up by an external interrupt signal. It consumes 13.5mA (66.8 mW) while a program is running and consumes 2.2mA (10.89 mW) in the stand-by mode [81].

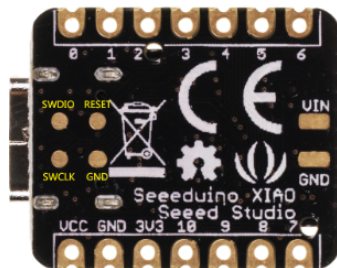
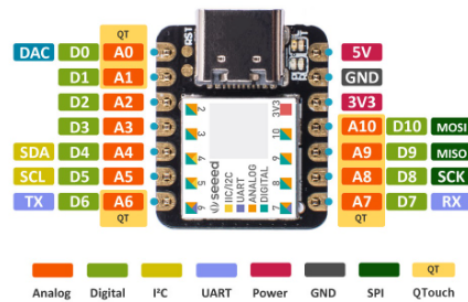


Figure 6.8: Seeduino XIAO [82] and hardware pinout [83].

6.6 Power MOSFET selection

The Arduino PINs can not output the necessary current to power the LEDs at their maximum light intensity. Arduino PINs can deliver a maximum current of 10 mA and the two warm white LEDs need a current of 700 mA in total. Therefore, it is necessary to implement a power MOSFET to drive the LEDs. The Arduino PIN connects to the gate terminal of the MOSFET, the positive terminal of the battery cell is connected to the drain terminal and the negative terminal of the battery cell is connected to the source terminal. It is recommended the use of an enhancement mode NPN power MOSFET [51]. The enhancement mode is suitable because it acts as a normally open switch, therefore the MOSFET is normally off when there is no voltage output from the Arduino. Take into account the LEDs characteristics and voltage output of the Arduino PINs, the power MOSFET requirements are:

- Gate-source threshold voltage lower than 3.3 V, because the Arduino PINs output voltage needs to be higher than it to switch on the MOSFET;
- Drain-source on-state resistance low as possible to reduce power dissipation by joule effect;
- Maximum drain current bigger than the maximum current necessary by the LEDs;
- Drain-source voltage 1.5 times bigger than the LEDs voltage.

A STP22NF03L NPN power MOSFET was acquired, as shown in Figure 6.9. The terminals identification are shown in Figure 6.9. MOSFET top metal part (TAB) also corresponds to connect to the terminal drain. Its dimensions are 28.9x10.4x4.60 mm [84]. The main electrical characteristics of the STP22NF03L MOSFET are:

- Maximum $V_{DS}=30$ V;
- Maximum $V_{GS}=15$ V;
- Maximum $I_{DD}=22$ A at 25 °C;
- Maximum power dissipation equal to 45 W;
- Operating junction temperature: -55 to 175 °C;
- $I_{DSS}=10$ μ A;
- $V_{GS(th)}=1$ V;
- $R_{DS(on)}=0.038$ Ω ;
- Turn-on delay time equal to 13 ns;
- Turn-off delay time equal to 12 ns.

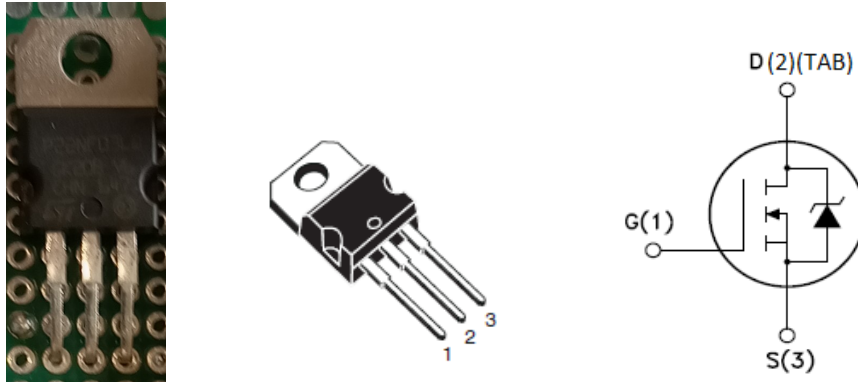


Figure 6.9: STP22NF03L NPN power [85] and terminals identification [84].

6.7 Codes description

The programming of the Seeduino XIAO was executed using the Arduino IDE software. Arduino IDE programming language is a simplified version of C/C+ programming language. In this section the developed codes are described. These codes are open source and were modified according to the requirements. Codes were developed for the application of the BH1750FVI light meter, the RTC DS1307 and sleep mode. The codes can be found in Appendices C.1.

6.7.1 Light meter code description

It was decided to not apply the light meter on the first prototypes due to problems of inefficient application. The RTC ensures better accuracy on the time of operation. Even so, the code for its application was developed. The code was not tested under real conditions, although it was tested in the laboratory and is expected to work if required.

The code initialises the correct connection of the light meter to the Arduino. Information about the correct connection of the light meter and the measurements can be seen in the computer using the serial software. The serial software used was the Putty Software that shows the information given by the light meter to the Arduino. The code sets a range of read values that activates the LEDs. When activated, the Arduino temporizes according to the desired time and keeps the LEDs active. After that, the LEDs are turn off. The operating time of the trap LEDs was changed to 5-7h and 20-22h according to the instructions given by the FCUP team. The illuminance analysis done in Section 4.4.1, does not apply to this operating time. The lighting analysis suggests that to activate the LEDs at 20:00, the threshold limit should be below 30,000 lux, as this is the threshold that causes the LEDs to turn on at 20:00 on more days. To activate the LEDs at 5:00, the threshold should be below 4 lux, according to Table 4.2, as this is the threshold that represents the illuminance during the night. However, it may not specifically represent the 5:00 time, therefore it would be very difficult to set the light meter to trigger the trap LEDs at this time.

6.7.2 RTC code description

The RTC code is based on the application of alarms to activate the LEDs. Before this, it is necessary to specify which is the current time to the RTC. They do not come already

programmed with the current time. It can be programmed the seconds, minutes, hours, day of the month, month, day of the week, and year. The information can be seen in the serial software to confirm the correct application of the code. The only way for the RTC to lose this information is the removal of the back up battery cell.

The alarm code turns on the LEDs at the beginning of the operating period and turns them off at the end of the operating period. The strategy of the code is to count the total seconds of the current time and compare it with the alarm time. Different alarms can be set for different months, even different days. For example, in the code alarms are set for May, between the 1st and the 25th.

6.7.3 Sleep mode code description

The RTC chosen for the first prototypes is the RTC DS1307. This RTC can not act as an external interrupt for the Arduino, as explained in Section 6.4. For the application of the sleep mode, it is necessary to use the RTC DS3231. The code sets an external interrupt by changing the specified Arduino PIN voltage. This can be done by receiving a signal from the RTC DS3231. After that, the Arduino enters sleep mode infinitely until it is waken up. The only thing missing in the code is the instructions to specify the RTC DS3231 external interrupt alarms. This was not done because it was not acquired the DS3231 and it could not be tested. Although, the code described here was tested, by triggering manually the wake up PIN, and it works. It may be useful later if it is decided to acquire the RTC DS3231 and apply sleep mode to reduce power consumption.

6.8 Electrical schematic diagram

The electronic components that have been chosen for the first prototype are:

- PV panel 1.5 W 12V;
- Rechargeable cylindrical lithium ion battery cell 2,200 mAh;
- Two warm white LEDs 1W each;
- MPPT 12 V solar panel regulator controller module CN3791;
- RTC DS1307 Precision Digital Clock Module;
- Seeeduino XIAO;
- STP22NF03L NPN power MOSFET.

The connections among the different components are shown in the electrical schematic diagram, Figure 6.10. The PV panel connects to the BMS through the PH2.0 interface. The battery cell connects to the BMS through the PH2.0 interface too. The power is supplied by the BMS to the remaining components via the JST plug connectors. The power supply of the RTC is 5V. Therefore, it is connected to the VCC (5V) and GND PINs of the Seeeduino XIAO. The serial data (SDA) and serial clock (SCL) PINs establishes the I²C communication protocol. The LEDs are connected to the positive terminal of the power supply and to the drain terminal of the MOSFET. In that way, the LEDs are only powered when the MOSFET is triggered. Seeeduino XIAO is power supplied by the 3V3

PIN. PIN 10 triggers MOSFET, when commanded. LEDs are connected in parallel to divide current and to be able to supply both with a voltage of 3.7V. LEDs do not operate with 3.7V, therefore it is necessary the resistor R2 to divide the voltage. Resistor R1 acts as a pull-down resistor in order to keep MOSFET off if the PIN 10 has a high input impedance [51].

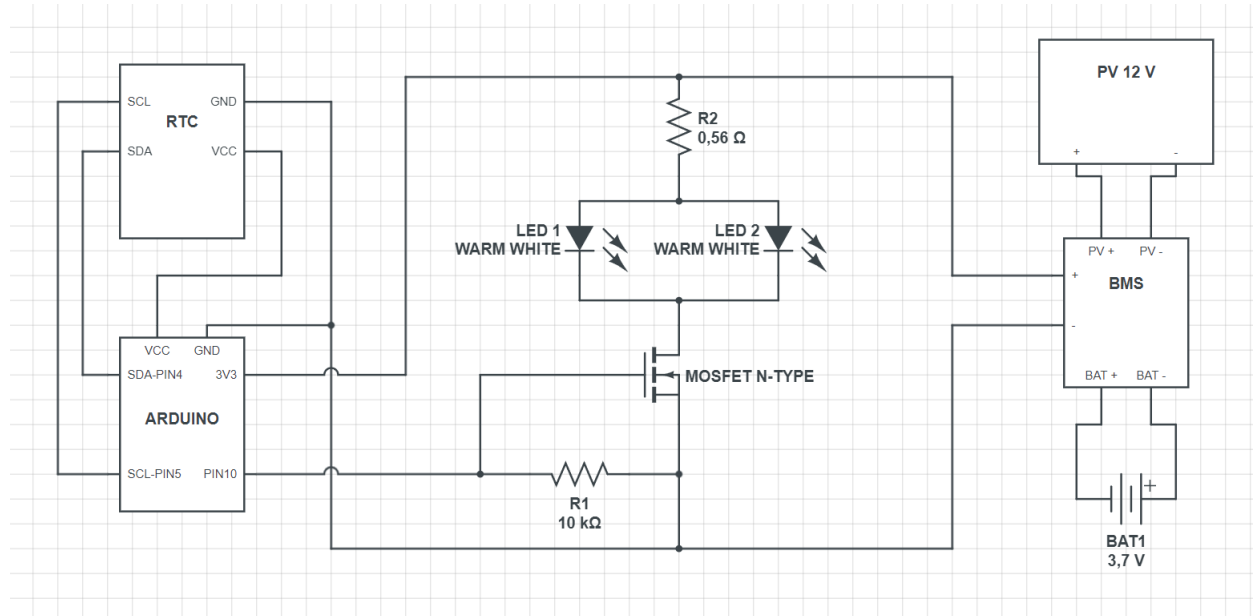


Figure 6.10: Electric schematic diagram warm white LEDs.

It can be necessary to change some components. Different colour LEDs have different voltage supplies. Therefore, it is necessary to change the resistor R2 in order to change the LEDs. Increase the battery capacity is not a problem because 18500 rechargeable cylindrical lithium ion battery cells have a standard dimension and voltage and there are this type of batteries with higher capacity available on the market. As there are PV panels with different voltages, increasing their power may imply having to change the BMS. Changing the RTC, for example, to the RTC DS3231, does not imply any change in the electrical system. Changing the Arduino would imply acquiring one that could be powered by 3.7V. Table 6.1 presents the different R2 resistor values for the different colour LEDs, taking into account that it was decided to use two LEDs per trap. The LEDs can operate over a range of voltage, hence the range of resistance values.

Table 6.1: R2 resistor values for different colour LEDs.

LEDs	Resistor [Ω]
Warm white	0.2 - 1.1
Red	1.8 - 2.3
UV-A	0.1 - 0.3
White	0.7 - 1.0
Orange	1.8 - 2.3

Chapter 7

Prototype conceptual design and performance results

The prototype conceptual design and components assembly are presented here. An evaluation of the performance of the insect trap was made. Taken into account the results, improvements were made.

7.1 Design Specifications

The initial technical specifications were presented in Section 4.3, including the design specifications. The preferable dimensions for the insect trap are 100x100x150 mm and weight of 200 g. The bait holder should be transparent to the light and the lid removable. It is to be installed vertically, or inserted into the ground using a stick or hanged on the blueberry tree. Hanging it on the blueberry tree implies that the trap cannot swing, requiring the gravitational centre of mass to be centred. The insect trap needs to have enough mechanical resistance to withstand fall and severe meteorological conditions. Two red stripes needs to be added to increase the attractiveness of the trap. The LEDs should be placed in the space between the two red stripes. The entrance holes should be drilled with 2.5 mm of diameter, with an alternating arrangement, as shown in Figure 4.3. Note that this is a prototype in which an attempt was made to have a final product in a short space of time.

7.2 Conceptual Design: Bait holder

Figure 7.1 shows the conceptual design for the bait holder in an isometric perspective. The technical drawing can be found in Appendices D.1. The bait holder has a protrusion on the top that allows a piece to be clamped. This piece is used to attach the lid to the bait holder.

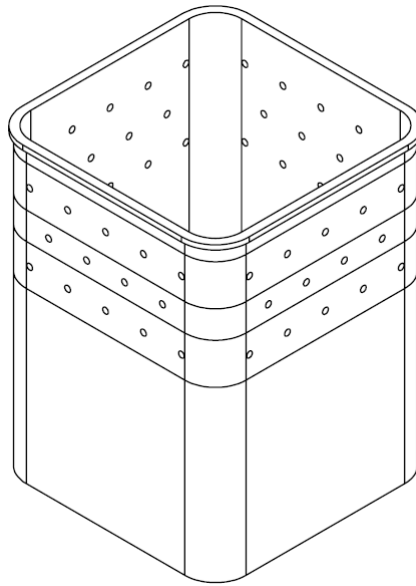


Figure 7.1: Bait holder conceptual design in an isometric perspective.

7.3 Conceptual Design: Lid

Figure 7.1 shows the conceptual design for the lid in an isometric perspective, upside down. The technical drawing can be found in Appendices D.1. The bait holder has a slot on top to assemble the PV panel and two holes to connect the PV panel to the rest of the electronic components. There is a mechanism to fix the battery and 4 protrusions to screw the electronic components. On the bottom, it has 4 ends to execute the fixation on the bait holder.

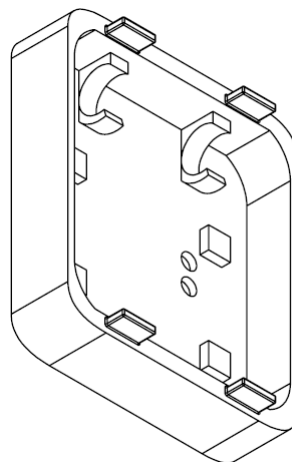


Figure 7.2: Bait holder conceptual design in an isometric perspective, upside down.

7.4 Conceptual Design: Lid fixing mechanism and LEDs support

Figure 7.3 shows the conceptual design for lid fixing mechanism and LEDs support in an isometric perspective. The technical drawing can be found in Appendices D.1. The bottom piece has a recess where the bait holder is supported. It also has two holes to tie a string to hang the insect trap in the blueberry tree. The two slots on the bottom and mid piece are to clamp the ends in the lid. The mid piece has four holes to do the electrical connection of the LEDs. The LEDs support is supported in the centred slot of the mid piece.

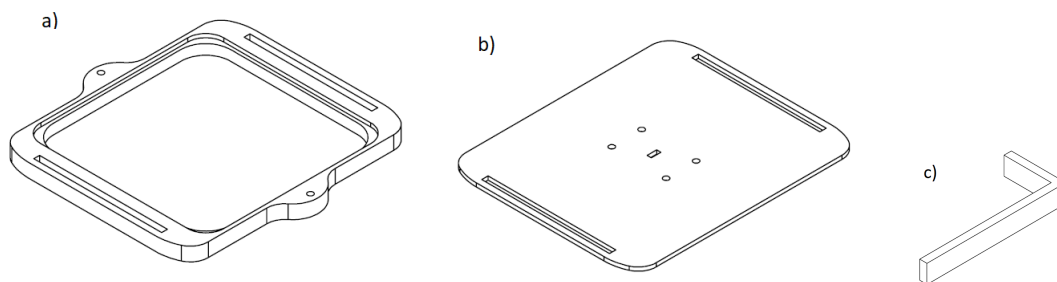


Figure 7.3: Bottom piece (a), mid piece (b) and LEDs support (c) conceptual design in an isometric perspective.

7.5 Insect trap assembly

The mechanical assembly drawing conceptual design can be found in Appendices D.1. It was acquired a polycarbonate (PC) container for the bait holder. PC is a thermoplastic that is fully recyclable. The holes need to be drilled with low velocities to avoid fracturing. The red stripes were done using duct tape. Figures 7.4 show the bait holder with the bottom piece and the bottom piece in more detail. The bottom piece has a small angle inclination in the inner part that allows to be clamped in the bait holder.

The lid, mid piece, bottom piece and LEDs support were done by 3D printing. The material used was polyethylene terephthalate glycol-modified (PETG) filament that is durable like acrylonitrile butadiene styrene (ABS), 3D prints easily like polylactic acid (PLA) and it is recyclable [86]. Figure 7.5 shows the lid with the PV panel attached. The PV was attached using cyanoacrylate adhesive, commonly known as superglue. Figures 7.6 show the lid upside down view and the battery mechanism fixation in more detail. The protrusions seen are to fix the electronic components of the control system with self-tapping screws. The ends are to fix the lid to the bottom and mid piece.

The electronic components of the control system were welded to a drilled PCB board, as shown in Figure 3.12. After screwing the PCB board to the cover and attaching the battery cell, some space management problems were encountered. Then, the electronic components arrangement was changed. Figure 7.8 shows the mid piece with the LEDs fixed into the LEDs support piece. They were glued with superglue. Superglue was used because no other adhesive was available at that time. In this way, an idea of the

thermal behaviour of PETG and the heat released by the LEDs can be understood. This matter is discussed in Section 7.6. Figures 7.9 show the insect trap after completing the assembly.



Figure 7.4: Bait holder with bottom piece clamped and bottom piece with string tied.



Figure 7.5: Lid with PV panel attached.

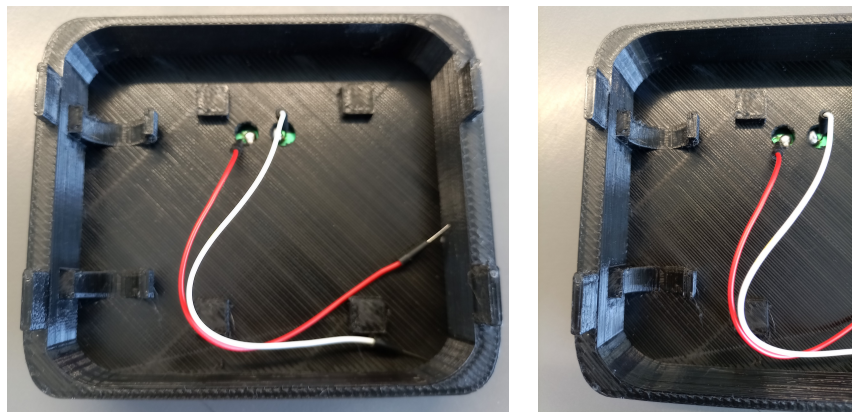


Figure 7.6: Lid upside down view and battery mechanism fixation in more detail.

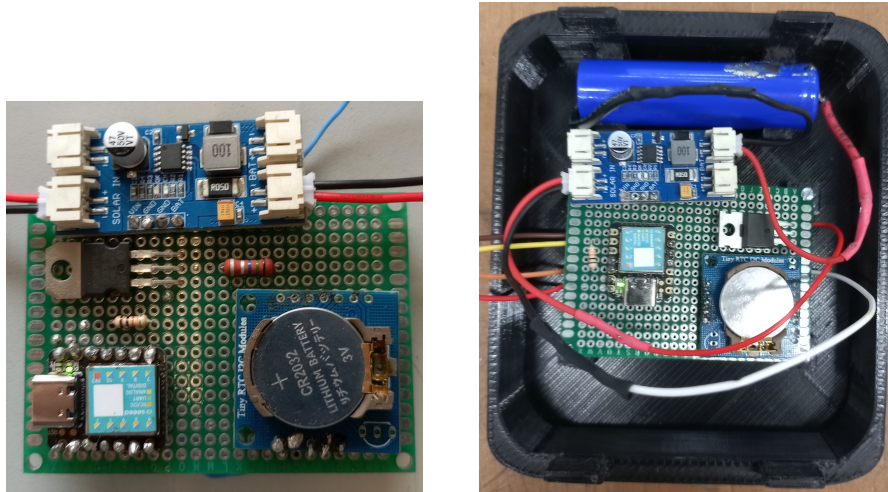


Figure 7.7: Control system components arrangement in the PCB board and assembly in the lid.

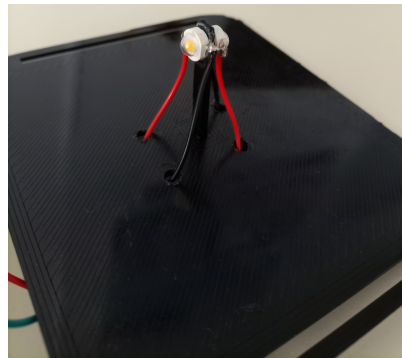


Figure 7.8: Mid piece and LEDs fixation.

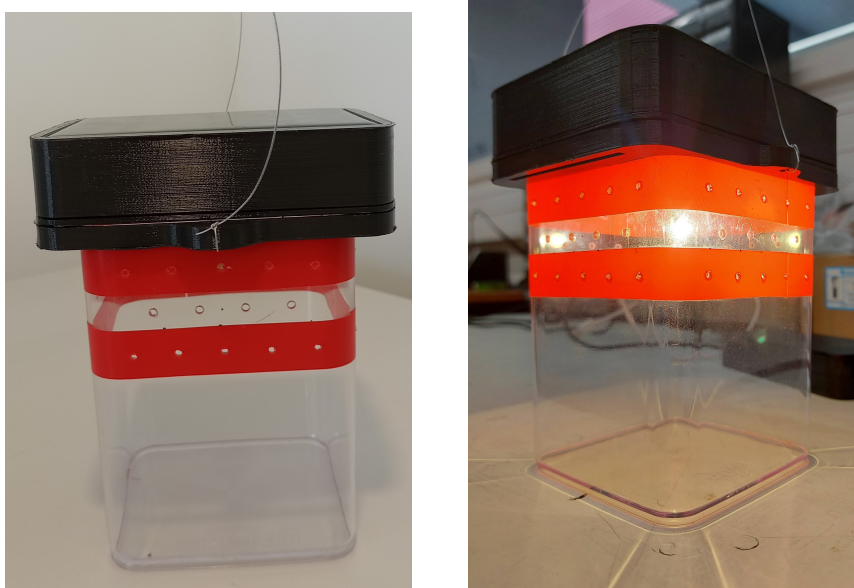


Figure 7.9: Insect trap after completing the assembly.

7.6 Performance results and discussion

The first test carried out was to expose the insect trap to the sun throughout the day and see how long the LEDs are on during their respective operating periods. The LEDs operated during **1:30h** at maximum light intensity and then **15** minutes later they turned off, for three different days. This is considerably less than the time foreseen by the simulations (43.75 %). It is expected that the PV panel did not produce the required energy or a big amount of energy were lost in the electronic system. Therefore, the energy consumption of the system and the efficiency of the components were underestimated. The gravitational centre of mass of the IT is not centred. The components have to be rearranged or a dead weight has to be added to balance it when hanging on the blueberry tree. Another relevant aspect noted was that the LEDs overheated the support piece and detached.

From the simulations was concluded that the 2,200 mAh battery cell wouldn't be enough and at least a 2,500 mAh battery cell would be needed. It was acquired a **3,000 mAh** rechargeable cylindrical lithium-ion battery cell [87]. It is important to know the capacity of the battery cell at each moment in time in order to know how much energy is supplied by the photovoltaic panel to the battery cell. There was no battery capacity measuring device available. Usually, the battery capacity is estimated knowing the discharge curve of the battery cell and measuring the voltage. As the discharge curve of the acquired battery cell is not known, an experimental test was performed to obtain the discharge curve. The battery was fully charged and then discharged at **380 mA** constant current and measured the voltage until it reached voltage less than the discharge cut-off voltage (2.75 V) of the battery cell. After the discharge cut-off voltage, the battery cell only has less than 5 % of capacity left, as can be seen in Figure 3.7, that represents the typical discharge curves for lithium-ion battery cells. Assuming this, the graph represented in Figure 7.10 was obtained for the discharge test. The test lasted about 7:45h. The detailed information about it can be found in Table D.1 in Appendices D.2. It was also performed an experimental test for the charge curve of the battery cell. It was used a charging device that outputs 2 A of maximum current. There is no information about the charging method implemented on the device. Figure 7.11 shows the charging curve of the battery cell. The test lasted about 3:30h. The detailed information about it can be found in Table 7.11 in Appendices D.2.

The next step was to measure the power consumption of the system when the LEDs are turned off and when the LEDs are turned on. It was measured a current of **16 mA** when the LEDs are turned off, representing the consumption of the Arduino and the RTC. When the LEDs are turned on, it was measured a current of **760 mA**. The BMS also consumes energy but it is very small that is ignored. The LEDs have an overall current of 700 mA, therefore, the remaining 44 mA of current are consumed by the power MOSFET. It is also needed to the heat dissipated by the joule effect. The resistor used on the electronic system has a value of 0.56 Ω . The wires used to connect the system also have some resistance, but it is very small that is ignored.

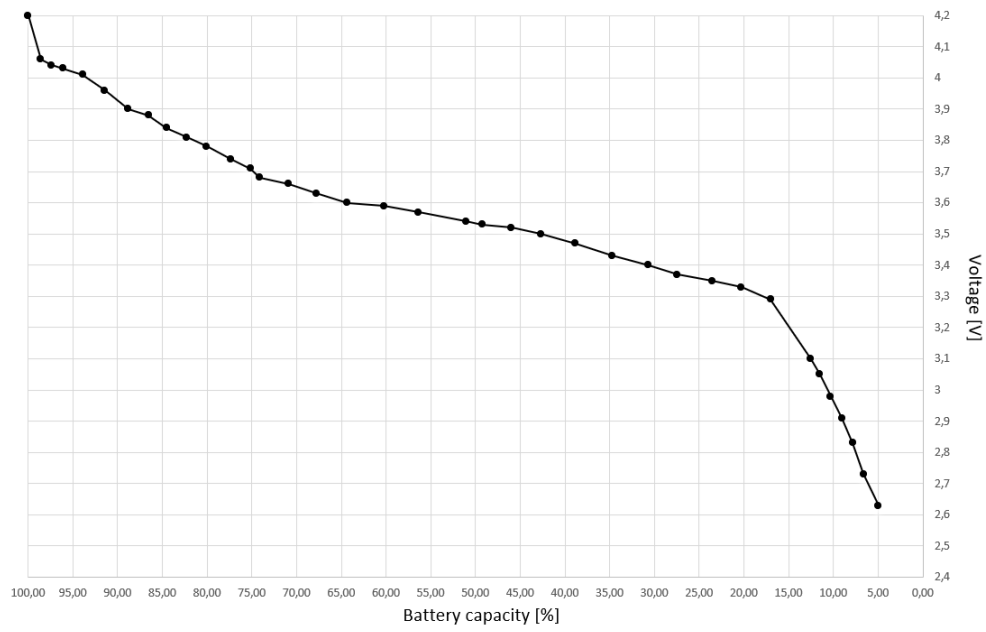


Figure 7.10: Discharging curve obtained from the experimental test.

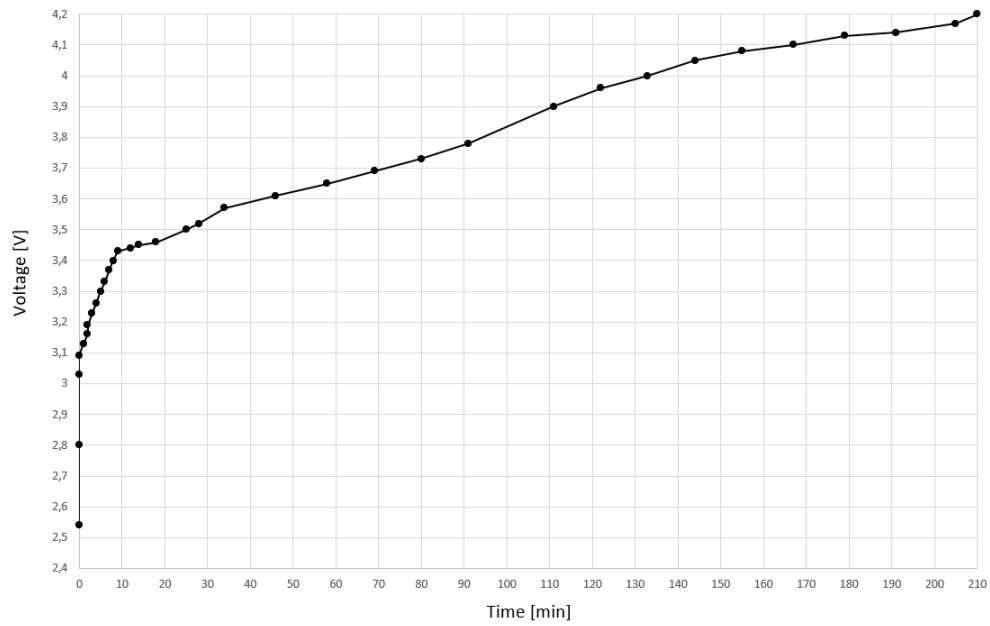


Figure 7.11: Charging curve obtained from the experimental test.

The power dissipated by joule effect when the LEDs are turn on is:

$$P_{\text{joule}} = I \times R^2 = 0.3235[W] \quad (7.1)$$

The power consumption of the system components is presented in Table 7.1.

Table 7.1: Power consumption of the system components.

Components	Current [mA]	Voltage [V]	Power [W]
LEDs	700	2.85	1.995
MOSFET	44	2.85	0.1254
Arduino + RTC	16	5	0.0800

Taken into account this conditions, the energy consumption per day (E_{day}) of the insect trap is given by:

$$E_{day} = (P_{LEDs} + P_{MOSFET} + P_{Arduino+RTC} + P_{Joule}) \times t_{LEDsON} + P_{Arduino+RTC} \times t_{LEDsOFF} = 11.69[Wh] \quad (7.2)$$

The energy required to be supplied by the battery cell during the night (E_{night}), i.e., between 20:00 and 7:00, is given by:

$$E_{night} = (P_{LEDs} + P_{MOSFET} + P_{Arduino+RTC} + P_{Joule}) \times t_{LEDsON} + P_{Arduino+RTC} \times t_{22:00-5:00} = 10.65[Wh] \quad (7.3)$$

The energy of the battery when fully charged (E_{bat}) is given by:

$$E_{bat} = V_{nominal} \times C = 11.10[Wh] \quad (7.4)$$

It can be concluded that the battery cell can provide the necessary energy for the periods of operation if it is fully charged. The next step was to measure the 12 V PV panel output and efficiency of battery charging of the CN3791 BMS. Measurements were taken at four different times of the day. The sun irradiation is not the same throughout the day, producing different power outputs on the PV panel. The results are shown in Table 7.2. The efficiency of battery charging of the CN3791 BMS is very low and the PV panel also does not produce electricity as much as thought, as one of the measurements was taken at 13:00 with clear sky (1.32 W).

Table 7.2: Charging efficiency of the CN3791 BMS for different power inputs.

PV power output [W]	CN3791 battery charging efficiency [%]
0.8960	44.6
1.160	54.0
1.295	56.8
1.320	57.9

It was decided to increase the PV panel power. The new PV panel operates with 6 V [88], therefore it will be used the CN3065 BMS, as it has an input voltage of 4.4-6 V. Measurements were taken using different power inputs. The results are shown in Table 7.3. It can be concluded that the CN3065 BMS works with higher efficiency when

the power input is higher. Although, it restricts the current output to the battery to a maximum of 332 mA.

Table 7.3: Charging efficiency and output efficiency of the CN3065 BMS for different power inputs.

P_{in} [W]	I_{out} [A]	CN3065 battery charging efficiency [%]
1.742	0.332	80.0
0.9730	0.156	67.3
0.8775	0.135	64.6
0.7800	0.115	61.9
0.6210	0.083	56.2
0.5510	0.063	48.0

The FCUP team needed to assess and validate some aspects of the IT, like dimensions of the IT, dimensions of the entrance holes and colours used in the design. To overcome the problem of not being able to guarantee the operation of the LEDs for the desired time, the system was modified to be powered by a power bank. The weight of the IT is about 325 g, representing a weight 62.5 % higher than specified. The total dimensions of the IT when assembled are 125x105x165.5 mm. The FCUP team carried out experiments with the SWD. The IT with the LEDs activated with the new chemical bait was placed inside a controlled SWD environment. The conditions of the experiment were not suitable to conclude about the attraction of the LEDs colour and the chemical bait. The conclusions regarding this experiment are presented in Section 8.1.

Chapter 8

Conclusions and suggestion for future work

8.1 Conclusions

This dissertation aimed to develop a sustainable insect trap for the control of the pest SWD. The development included the analysis and selection of the electronic components, the quantification of the energy and power requirements for the trap LEDs operation, the design of a control system and the production of a prototype.

The selection of the PV panel, the battery and the power of the LEDs was based on the simulation results. According to the final technical specifications, the simulations indicated the operation of the LEDs for more than 80 % of the specified time. It can be concluded that the factors that would lead to the highest loss of available energy would be the efficiency of the controller, the electrical losses in the conductive wires by joule effect and the efficiency of the PV panel, which decreases with temperature increase.

An assessment of the use of a light meter was made through an illuminance analysis. Although the analysis was not done for the final operating time, it can be concluded that it would not work properly either because at 5:00 there is almost no light.

The control system was designed to activate the trap LEDs with maximum intensity at the specified time, aiming to be small and with low energy consumption. A compact solution with the intended function has been achieved consuming a total of 0.2054 W.

The prototype design includes the features required by the specifications. The bait holder is a commercial container with the integration of 3D printed parts. Its weight is 62.5 % higher than specified, therefore, it needs to be decreased. The total dimensions of the IT when assembled are 125x105x165.5 mm, which is very close to the specified dimensions (100x100x150 mm). The gravitational centre of mass of the IT is not centred, which causes the IT to swing when hung up. The electronic components have to be rearranged or a dead weight has to be added to balance it.

In the experiments carried out, the trap LEDs operated 43.75 % of the desired time. It can be concluded that the discrepancy of results between the simulations and the experiments is mainly due to the fact that the 12V PV panel does not produce the specified power and the efficiency of the BMS is very low. Measuring the PV panel power output at 13:00 in a clear sky, it only produces 1.32 W. The CN3791 BMS battery charging efficiency is 57.9 % for the best case, while the simulations considered 88.5 % of controller's efficiency. The other acquired CN3065 BMS has a higher battery charging

efficiency and it is expected that the future improvements get better results. The total power consumption of control system is 0.2054 W and the power dissipated by joule effect is 0.3235 W. The total power consumption of the IT when the LEDs are activated is 2.524 W. The considered energy consumption per day in the simulations (8 Wh), increases 46.2 % (11.694 Wh) for the real system. It was verified that the newly acquired 3,000 mAh battery is capable of providing the necessary energy if fully charged.

In the experiments carried out by the FCUP team with the SWD, it was verified the entrance of at least 1 SWD during one day of experiment. Therefore, it can be concluded that the entrance holes dimensions are acceptable and the SWD can enter the IT. Although the conditions of the experiment do not allow to conclude about the attractiveness of the IT, some evidence was taken from the behaviour of SWD. High SWD activity was verified around the lid, suggesting its preference for the colour black. Therefore, it suggests that the lid interfered with the attractive mechanisms of IT, which are the LEDs, chemical bait and stripes.

The progress made in this dissertation is essential to future improvements and to achieve a final product. The main goal was achieved, which was to develop a sustainable insect trap. The IT is powered by solar photovoltaic energy. The IT design is compact and the structural components are made of recyclable materials. It has been shown that the integration of LEDs is possible for the required dimensions and different colours to be tested. The control system is functional and compact. Additional information on electrical components not supplied by the manufacturers has been obtained. A PV stand alone system model was designed and it is not completely accurate because the real characteristics of the electronic components were not known.

8.2 Suggestions for future work

The main aspect to take into account is that the trap LEDs do not operate during the specified time. Some technical problems were identified that led to worse performance than expected, such as the output PV power and charging efficiency of the BMS. Taking into account the performance results, the analysis performed of the components and the experiments carried out, the suggestions for future work are:

- Installation of a 3,000 mAh rechargeable cylindrical lithium-ion battery cell [87];
- Installation of a PV panel with 2W of power [89];
- Installation of a more efficient BMS [90];
- Optimisation of the lid dimensions to reduce weight and accommodate a bigger PV panel;
- Changing the colour of the lid to white, to have less interference with SWD behaviour;
- Addition of more entrance holes, to increase the entrance holes area;
- Changing the colour of the stripes to black, to increase the attractiveness of the stripes;
- Changing the LEDs support material to a metal to dissipate heat more efficiently;

- Fixation of the LEDs with a thermal adhesive [91].

If it is decided to produce the insect trap by industrial processes, the dimensions, weight, design and control system efficiency can be further optimised. The bait holder and lid can be produced by plastic injection moulding. Plastic injection moulding is a process where heated up fluid polymer is injected at high pressure into a mould, creating the desired shape [92]. Almost all types of polymers can be used in injection moulding, offering a variety of possible material choices [93]. The different components of the control system can be all implemented in an integrated circuit, reducing a lot the dimensions and increasing the processes efficiency. In an integrated circuit the different components are implanted in a wafer, made of a semiconducting material, usually silicon [94]. Integrated circuits are custom designed for each application. This means that the process characteristics are optimised. As they have smaller dimensions, the capacitance and power requirements are reduced a lot. These aspects leads to a higher efficiency compared to discrete circuits [95].

Bibliography

- [1] Sustainability definition. URL <https://www.investopedia.com/terms/s/sustainability.asp>. [Online; accessed 22-July-2022].
- [2] Portal do ine. URL https://www.ine.pt/xportal/xmain?xpid=INE&xpgid=ine_publicacoes&PUBLICACOESpub_boui=358632037&PUBLICACOESmodo=2. [Online; accessed 22-July-2022].
- [3] Exportações: Os pequenos frutos são os maiores! — revista frutas legumes e flores. URL <https://www.flfrevista.pt/2019/06/exportacoes-os-pequenos-frutos-sao-os-maiores/>. [Online; accessed 22-July-2022].
- [4] Huailing Wang, Xinbo Guo, Xiaodan Hu, Tong Li, Xiong Fu, and Rui Hai Liu. Comparison of phytochemical profiles, antioxidant and cellular antioxidant activities of different varieties of blueberry (*vaccinium* spp.). *Food Chemistry*, 217:773–781, 2 2017. ISSN 18737072. doi: 10.1016/j.foodchem.2016.09.002.
- [5] A planta de mirtilo morfologia e fisiologia. 2007.
- [6] Mark K. Asplen, Gianfranco Anfora, Antonio Biondi, Deuk Soo Choi, Dong Chu, Kent M. Daane, Patricia Gibert, Andrew P. Gutierrez, Kim A. Hoelmer, William D. Hutchison, Rufus Isaacs, Zhi Lin Jiang, Zsolt Kárpáti, Masahito T. Kimura, Marta Pascual, Christopher R. Philips, Christophe Plantamp, Luigi Ponti, Gábor Véték, Heidrun Vogt, Vaughn M. Walton, Yi Yu, Lucia Zappalà, and Nicolas Desneux. Invasion biology of spotted wing drosophila (*drosophila suzukii*): a global perspective and future priorities, 9 2015. ISSN 16124758.
- [7] Fcup - project: Poci-01-0247-feder-047034. URL https://sigarra.up.pt/fcup/en/PROJECTOS_GERAL.FICHA_PROJECTO?P_ID=77720. [Online; accessed 22-July-2022].
- [8] Thomas Enriquez, David Renault, Maryvonne Charrier, and Hervé Colinet. Cold acclimation favors metabolic stability in *drosophila suzukii*. *Frontiers in Physiology*, 9, 11 2018. ISSN 1664042X. doi: 10.3389/fphys.2018.01506.
- [9] Mark P. Bolda, Rachael E. Goodhue, and Frank G. Zalom. Spotted wing drosophila: Potential economic impact of a newly established pest.
- [10] Sario S. Relatório de ano probatório. *Programa Doutoral FCUP*, 2019.
- [11] Anh K. Tran, W. D. Hutchison, and Mark K. Asplen. Morphometric criteria to differentiate *drosophila suzukii* (diptera: Drosophilidae) seasonal morphs. *PLoS ONE*, 15, 2 2020. ISSN 19326203. doi: 10.1371/journal.pone.0228780.

- [12] Phuong Nguyen, A. Young Kim, Jin Kyo Jung, Kelly M. Donahue, Chuleui Jung, Man Yeon Choi, and Young Ho Koh. The biochemical adaptations of spotted wing drosophila (diptera: Drosophilidae) to fresh fruits reduced fructose concentrations and glutathione-s transferase activities. *Journal of Economic Entomology*, 109:973–981, 4 2016. ISSN 1938291X. doi: 10.1093/jee/tow019.
- [13] Gülay Kaçar, Xin Geng Wang, Thomas J. Stewart, and Kent M. Daane. Overwintering survival of drosophila suzukii (diptera: Drosophilidae) and the effect of food on adult survival in california’s san joaquin valley. *Environmental Entomology*, 45: 763–771, 8 2016. ISSN 19382936. doi: 10.1093/ee/nvv182.
- [14] Kunimi Y. Nakai M. Kinjo H. Effects of temperature on the reproduction and development of drosophila suzukii (diptera: Drosophilidae). *applied entomology and zoology*. page 297–304, 2014. doi: 10.1007/s13355-014-0249-z.
- [15] Omar Rota-Stabelli, Mark Blaxter, and Gianfranco Anfora. *Drosophila suzukii*, 1 2013. ISSN 09609822.
- [16] Torres L. Santos C. Sario S., Gonçalves F. *Drosophila suzukii e espécies hospedeiras alternativas. Capítulo X Livro do Plano de Ação para Controlo da D. suzukii*, 2020.
- [17] MAFDR/DRAPN. Textos de divulgação técnica da estação de avisos de entre dourado e minho, nº 01-2017 (ii série) (janeiro 2017). *Ministério da Agricultura, das Florestas e do Desenvolvimento Rural/ DRAP Norte/ Divisão de Apoio ao Setor Agroalimentar*, 2017.
- [18] Jana C. Lee, Denny J. Bruck, Amy J. Dreves, Claudio Ioriatti, Heidrun Vogt, and Peter Baufeld. In focus: Spotted wing drosophila, drosophila suzukii, across perspectives, 11 2011. ISSN 1526498X.
- [19] Daniel Cormier. Exclusion net to control spotted wing drosophila in blueberry fields impact of pesticides on pest’s natural enemies view project fertile and efficient garden view project, 2015. URL <https://www.researchgate.net/publication/273458102>.
- [20] Rogg H. Landolt P.J., Adams T. Trapping spotted wing drosophila, drosophila suzukii (matsumura) (diptera:drosophilidae), with combinations of vinager and wine,and acetic acid and ethanol, 2011. ISSN 1526498X.
- [21] Color preference of the spotted wing drosophila, drosophila suzukii. *Scientific Reports*, 9, 12 2019. ISSN 20452322. doi: 10.1038/s41598-019-52425-w.
- [22] The use of light spectrum blocking films to reduce populations of drosophila suzukii matsumura in fruit crops. *Scientific Reports*, 10, 12 2020. ISSN 20452322. doi: 10.1038/s41598-020-72074-8.
- [23] Lana El Chaar. Photovoltaic system conversion, 2011.
- [24] What is the difference between monocrystalline and polycrystalline solar panels? URL <https://quebecsolar.ca/what-is-the-difference-between-monocrystalline-and-polycrystalline-solar-panels/>. [Online; accessed 22-July-2022].

- [25] Choose your solar technology: Monocrystalline vs. polycrystalline. URL <https://www.renvue.com/Choose-your-solar-technology-Monocrystalline-vs-Polycrystalline>. [Online; accessed 22-July-2022].
- [26] John A. Duffie and William A. Beckman. *Solar engineering of thermal processes*. Wiley, 2013. ISBN 9780470873663.
- [27] John A. Duffie and William A. Beckman. *Solar engineering of thermal processes*. Wiley, 2013. ISBN 9780470873663.
- [28] What is maximum power point tracking (mppt) — northern arizona wind sun. URL <https://www.solar-electric.com/learning-center/mppt-solar-charge-controllers.html/>. [Online; accessed 22-July-2022].
- [29] Introduction to batteries and their types. URL <https://www.engineersgarage.com/introduction-batteries-their-types/>. [Online; accessed 22-July-2022].
- [30] Understanding charge-discharge curves of li-ion cells • evreporter. URL <https://evreporter.com/understanding-charge-discharge-curves-of-li-ion-cells/>. [Online; accessed 22-July-2022].
- [31] How to choose the best solar battery for your needs - aurora solar, . URL <https://www.aurorasolar.com/blog/how-to-choose-the-best-solar-battery-for-your-needs/>. [Online; accessed 22-July-2022].
- [32] How to choose the best battery for a solar energy system - infinity renewables, . URL <https://infinity-renewables.com/how-to-choose-the-best-battery-for-a-solar-energy-system/>. [Online; accessed 22-July-2022].
- [33] Peukert's law - wikipedia. URL https://en.wikipedia.org/wiki/Peukert%27s_law. [Online; accessed 22-July-2022].
- [34] Manufacturing lithium-ion batteries. URL <https://www.techsciresearch.com/blog/manufacturing-lithium-ion-batteries/29.html>. [Online; accessed 22-July-2022].
- [35] Lithium-ion battery - clean energy institute. URL <https://www.cei.washington.edu/education/science-of-solar/battery-technology/>. [Online; accessed 22-July-2022].
- [36] Led brightness. URL <https://www.diodedynamics.com/info/research/led/led-brightness.html>. [Online; accessed 22-July-2022].
- [37] What is an led? — leds magazine, . URL <https://www.ledsmagazine.com/leds-ssl-design/materials/article/16701292/what-is-an-led>. [Online; accessed 22-July-2022].
- [38] Oled - wikipedia. URL https://en.wikipedia.org/wiki/OLED#Practical_OLEDs. [Online; accessed 22-July-2022].

- [39] Light-emitting diode - wikipedia, . URL https://en.wikipedia.org/wiki/Light-emitting_diode#cite_note-150. [Online; accessed 22-July-2022].
- [40] High cri led lighting — yujileds. URL <https://www.yujiintl.com/high-cri-led-lighting.html>. [Online; accessed 22-July-2022].
- [41] All about energy efficiency and efficacy of modern led lighting - lamphq. URL <https://lamphq.com/led-energy-efficiency/>. [Online; accessed 22-July-2022].
- [42] Why you need an led heat sink - ledsupply blog, . URL <https://www.ledsupply.com/blog/why-you-need-an-led-heat-sink/>. [Online; accessed 22-July-2022].
- [43] Aluminum pcbs - high performance and low-cost materials. URL <https://www.epectec.com/pcb/aluminum-circuit-boards.html>. [Online; accessed 22-July-2022].
- [44] Andrea Vezzini. Lithium-ion battery management, 2014.
- [45] Light sensor including photocell and ldr sensor. URL https://www.electronics-tutorials.ws/io/io_4.html. [Online; accessed 22-July-2022].
- [46] What is a real-time clock (rtc) and why are they important in computing? - history computer, . URL <https://history-computer.com/real-time-clock/>. [Online; accessed 22-July-2022].
- [47] Arduino introduction, . URL <https://www.electronicshub.org/arduino-introduction/>. [Online; accessed 22-July-2022].
- [48] What is arduino? — arduino, . URL <https://www.arduino.cc/en/Guide/Introduction>. [Online; accessed 22-July-2022].
- [49] Overview of the samd21 arm cortex-m0+ based seeeduino xiao, . URL https://www.sigmdel.ca/michel/ha/xiao/seeeduino_xiao_01_en.html. [Online; accessed 22-July-2022].
- [50] Types of transistors - junction transistors and fets, . URL <https://www.electronicshub.org/transistors-classification-and-types/>. [Online; accessed 22-July-2022].
- [51] How to drive many leds / high powered leds with gpio — a beginners guide - okdo. URL https://www.okdo.com/project/gpio-led/?ok_ts=1650658331423. [Online; accessed 22-July-2022].
- [52] Introduction to mosfet — depletion and enhancement mode, applications, . URL <https://www.electronicshub.org/mosfet/>. [Online; accessed 22-July-2022].
- [53] Mosfet as a switch - using power mosfet switching, . URL https://www.electronics-tutorials.ws/transistor/tran_7.html. [Online; accessed 22-July-2022].
- [54] Luminance vs. illuminance. URL <https://sensing.konicaminolta.us/us/blog/luminance-vs-illuminance/>. [Online; accessed 22-July-2022].

- [55] Features - meteonorm (en). URL <https://meteonorm.com/en/meteonorm-features>. [Online; accessed 22-July-2022].
- [56] Lux. URL <https://en.wikipedia.org/wiki/Lux>.
- [57] Candeeiro de parede exterior - iluminação — leroy merlin. URL https://www.leroymerlin.pt/Produtos/Iluminacao/Iluminacao-exterior/Iluminacao-para-parede/WPR_REF_81883088. [Online; accessed 22-July-2022].
- [58] Led array alto brilho 1w branco frio prok, . URL <https://www.electrofun.pt/componentes-eletronicos/led-array-alto-brilho-1w-branco-frio-prok>. [Online; accessed 22-July-2022].
- [59] Pilha de lithium aa (er14505) - 3,6v 2700ma — castro electrónica, lda. URL <https://www.castroelectronica.pt/product/pilha-de-lithium-aa-er14505--36v-2700ma>. [Online; accessed 22-July-2022].
- [60] Overview & general description of the pvsyst software. URL https://www.pvsyst.com/help/general_descr.htm. [Online; accessed 22-July-2022].
- [61] Physical models used & synthetic data generation & synthetic hourly irradiance. URL https://www.pvsyst.com/help/models_meteo_synthetic_generation_irradiance.htm. [Online; accessed 22-July-2022].
- [62] Diy 12v 1.5w painel solar. URL <https://soelectroshop.com/pt/dispositivos-solares/1076-12v-15w-painel-solar-diy-celulas-carregadora-fotovoltaica.html>. [Online; accessed 22-July-2022].
- [63] Painel solar 1.5w 81x137mm. URL <https://www.electrofun.pt/es/paineis-fotovoltaicos/painel-solar-15w-81x137mm>. [Online; accessed 22-July-2022].
- [64] Pilha recarregável 3,7v 2200mah (icr18650) — castro electrónica, lda, . URL <https://www.castroelectronica.pt/product/pilha-recarregavel-36v-2200mah-icr18650>. [Online; accessed 22-July-2022].
- [65] Diodo led 1w smd branco quente. URL <https://soelectroshop.com/pt/smd-led-diodes/1731-diodo-de-led-1w-branco-quente-smd-130lm.html>. [Online; accessed 22-July-2022].
- [66] Diodo led 1w smd vermelho. URL <https://soelectroshop.com/pt/smd-led-diodes/398-led-diodo-1w-red-smd.html>. [Online; accessed 22-July-2022].
- [67] Diodo led 1w uv smd - ultravioleta. URL <https://soelectroshop.com/pt/smd-led-diodes/5217-diodo-led-1w-smd-uv-ultravioleta.html>. [Online; accessed 22-July-2022].
- [68] Diodo led 1w smd branco frio. URL <https://soelectroshop.com/pt/smd-led-diodes/397-diodo-liderado-1w-branco-smd-130lm.html>. [Online; accessed 22-July-2022].

- [69] Led diodo 1w smd laranja. URL <https://solectroshop.com/pt/smd-led-diodos/400-diodo-de-led-1w-smd-laranja.html>. [Online; accessed 22-July-2022].
- [70] Cn3791 datasheet, . URL <https://datasheetspdf.com/pdf-file/1257610/CONSONANCE/CN3791/1>. [Online; accessed 22-July-2022].
- [71] Mppt 12v solar panel regulator controller module for 1 cell lithium battery charging 3.7v 4.2v - cn3791. URL <https://www.botnroll.com/en/renewable-energy/4074-mppt-12v-solar-panel-regulator-controller-module-for-1-cell-lithium-battery-charging.html>. [Online; accessed 22-July-2022].
- [72] Cn3065 datasheet, . URL <https://datasheetspdf.com/pdf-file/1257615/CONSONANCE/CN3065/1>. [Online; accessed 22-July-2022].
- [73] Cn3065 mini solar lithium charger board — alimentação — ptr007199. URL <https://www.ptrobotics.com/alimentacao/7199-cn3065-mini-solar-lithium-charger-board.html?gclid=Cj0KCQjwl7qSBhD-ARIsACvV1X2tKamPiedowdgII6KpblmBKAXfXQ6QdE3007gkCemQWiVC0qdAzbkaAkJ-EwcB>. [Online; accessed 22-July-2022].
- [74] Bh1750fvi datasheet, . URL <https://datasheetspdf.com/pdf-file/679289/Rohm/BH1750FVI/1>. [Online; accessed 22-July-2022].
- [75] Módulo sensor de intensidade de luz digital bh1750fvi, . URL <https://www.electrofun.pt/sensores-arduino/modulo-sensor-de-intensidade-de-luz-digital-bh1750fvi>. [Online; accessed 22-July-2022].
- [76] Ds1307 datasheet, . URL <https://datasheetspdf.com/pdf-file/925278/Maxim/DS1307/1>. [Online; accessed 22-July-2022].
- [77] At24c32 datasheet. URL <https://datasheetspdf.com/pdf-file/1261673/ATMEL/AT24C32/1>. [Online; accessed 22-July-2022].
- [78] Ds3231 datasheet. URL <https://datasheetspdf.com/pdf-file/1081920/MaximIntegrated/DS3231/1>. [Online; accessed 22-July-2022].
- [79] Módulo rtc ds1307 relógio digital de precisão. URL <https://www.electrofun.pt/comunicacao/modulo-rtc-ds1307-relogio>. [Online; accessed 22-July-2022].
- [80] Samd21 datasheet. URL <https://datasheetspdf.com/pdf-file/1367853/Microchip/SAMD21/1>. [Online; accessed 22-July-2022].
- [81] Seeeduino xiao - a tiny arduino zero variation — web-engineering.info. URL <https://web-engineering.info/node/82#fig3>. [Online; accessed 22-July-2022].
- [82] Microcontrolador seeeduino xiao samd21 compatível com arduino - seeed, . URL <https://www.electrofun.pt/inicio/microcontrolador-seeeduino-xiao-samd21-compativel-com-arduino-seeed>. [Online; accessed 22-July-2022].

- [83] Seeeduino xiao - arduino microcontroller - samd21 cortex m0+ - seeed studio, . URL <https://www.seeedstudio.com/Seeeduino-XIA0-Arduino-Microcontroller-SAMD21-Cortex-M0+-p-4426.html>. [Online; accessed 22-July-2022].
- [84] Stp22nf03l pdf, stp22nf03l description, stp22nf03l datasheet, stp22nf03l view ::: Alldatasheet :::, . URL <https://pdf1.alldatasheet.com/datasheet-pdf/view/24356/STMICROELECTRONICS/STP22NF03L.html>. [Online; accessed 22-July-2022].
- [85] Transistor n-channel 30v 0.0038o 22a to-220 — aquário electrónica, . URL <https://www.aquario.pt/product/fr-transistor-n-channel-30v-00038o-22a-to-220-stp22nf03l>. [Online; accessed 22-July-2022].
- [86] 3d printing with petg - ninjatek. URL <https://ninjatek.com/learn/3d-printing-materials/petg/>. [Online; accessed 22-July-2022].
- [87] Pilha recarregável 3,7v 3000mah (icr18650) - well — castro electrónica, lda, . URL <https://www.castroelectronica.pt/product/pilha-recarregavel-37v-3000mah-icr18650--proftc>. [Online; accessed 22-July-2022].
- [88] Pannel solar diy 6v 2w. URL <https://solectroshop.com/pt/dispositivos-solares/1192-6v-2w-pannel-solar-diy-celulas-carregadora-fotovoltaiica.html>. [Online; accessed 22-July-2022].
- [89] Pannel solar diy 6v 2w. URL <https://solectroshop.com/pt/dispositivos-solares/1192-6v-2w-pannel-solar-diy-celulas-carregadora-fotovoltaiica.html>. [Online; accessed 22-July-2022].
- [90] Solar power management module, for 6v 24v solar panel. URL <https://www.botnroll.com/en/renewable-energy/3507-solar-power-management-module-for-6v-24v-solar-panel.html>. [Online; accessed 22-July-2022].
- [91] Cola cola adesiva térmica cpu 10g. URL <https://solectroshop.com/pt/pastas-termicas/75-cola-de-pasta-termica-adesiva-10g-cpu.html>. [Online; accessed 22-July-2022].
- [92] Application overview: Injection molding. URL <https://web.archive.org/web/20060412020436/http://www.yaskawa.com/site/Industries.nsf/applicationDoc/appinjmold.html>. [Online; accessed 22-July-2022].
- [93] Plastic injection moulding, rapid prototyping — protolabs. URL <https://www.protolabs.co.uk/services/injection-moulding/plastic-injection-moulding/>. [Online; accessed 22-July-2022].
- [94] How integrated circuit is made - material, making, used, processing, components, dimensions, composition, industry. URL <http://www.madehow.com/Volume-2/Integrated-Circuit.html>. [Online; accessed 22-July-2022].

- [95] Ecstuff4u for electronics engineer. URL <https://www.ecstuff4u.com/2019/04/advantages-disadvantages-integrated-circuits.html>. [Online; accessed 22-July-2022].
- [96] Prolight pm2e-1lxe-xx 1w power led technical datasheet version: 1.7, . URL <https://www.tme.eu/en/details/pm2e-1lve-r7/white-power-leds-emiter/prolight-opto/>.

Appendices

Appendix A

Development of the sustainable insect trap

A.1 Illuminance analysis

Table A.1: Illuminance values [lux] in Porto for May using Meteonorm data for 2019. Columns are the day of the month and lines are the hour of the day.

	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	0	0	6700	29700	47100	64500	78000	85700	92300	94400	81500	70300	50000	29200	7900	0	0	0
2	0	0	8800	29400	49000	66400	75700	87300	91200	94700	85300	68200	44500	26600	11000	0	0	0
3	0	0	8800	28300	54700	60100	59100	60300	59800	52200	31900	46200	37400	27300	9900	0	0	0
4	0	0	7400	24600	13200	29500	43700	41900	47000	65700	96000	64500	35400	27300	12500	0	0	0
5	0	0	10100	19500	12400	12900	47300	70300	64300	74700	77100	60600	46900	23500	12000	0	0	0
6	0	0	3800	12300	5400	24300	38600	61200	83800	89300	66900	54000	46500	24800	11600	0	0	0
7	0	0	13000	26700	39400	57300	72500	86300	90800	91200	78300	68000	53600	29400	13900	0	0	0
8	0	0	7500	29300	41400	48300	41200	27100	35600	50900	63400	55100	43400	30500	12700	0	0	0
9	0	0	15900	37500	56300	75000	88200	95600	101500	101000	91900	77800	58600	33900	12800	0	0	0
10	0	0	14000	32900	51400	71500	84700	96500	104000	96900	89100	75100	57400	35400	14400	0	0	0
11	0	0	9200	31000	45600	55600	70800	82900	90400	72700	63000	46100	30700	33300	13700	1700	0	0
12	0	0	14000	38300	47200	79100	81100	89100	82800	76400	64600	58100	49000	36300	14000	1700	0	0
13	0	1300	8400	9600	38500	49800	58600	34100	71800	85200	58000	54600	27800	37900	16500	1700	0	0
14	0	1600	14800	26900	42800	56800	72700	87400	89000	85500	78600	75100	52200	27500	12800	2400	0	0
15	0	2000	14600	31500	50200	47500	53500	59300	73000	59500	73200	50900	50300	22900	9200	1500	0	0
16	0	1400	15400	38500	51700	69200	78600	90900	80200	81400	81200	69000	46300	35600	12200	2100	0	0
17	0	2200	14600	23900	38000	47900	45900	55800	57800	71700	53100	47500	32200	22500	6400	2100	0	0
18	0	800	14700	32000	56600	62800	52000	43000	41200	60100	75100	56800	29200	24000	9400	900	0	0
19	0	2800	18300	37900	61500	79000	90900	98900	104400	101600	92100	76400	59500	40700	11800	2200	0	0
20	0	2800	17100	30700	41400	63300	80200	87100	93200	90700	83000	63500	51300	33200	18500	1400	0	0
21	0	2100	16100	38400	52100	67300	62900	74100	74500	74600	63000	54400	32700	29400	11800	2800	0	0
22	0	700	5200	1800	21600	26400	27500	46600	69600	63600	42600	31700	15200	17800	15300	3000	0	0
23	0	2100	12700	27400	49900	71800	85300	82500	95000	86100	80400	68600	51200	32600	12500	3000	0	0
24	0	3200	17200	34900	51800	71500	87100	92200	96500	93400	85400	72700	60600	39400	20000	3700	0	0
25	0	1800	16100	37500	56900	75400	89600	98200	99900	99100	89700	75000	50000	31200	16200	2800	0	0
26	0	3000	20200	43200	65400	84500	98100	103800	105900	100600	93200	79200	59300	41600	19700	3900	0	0
27	0	3400	12400	29500	48300	59600	32700	36300	33600	5500	46900	52300	34000	24400	16000	2400	0	0
28	0	3000	11900	31700	40800	42300	71200	74900	63400	55600	45900	26300	16700	13900	600	900	0	0
29	0	3500	16400	30900	59900	61700	69900	79200	90900	90000	76500	52400	48200	24300	17200	4400	0	0
30	0	3900	17900	32600	52800	75700	88500	96800	102000	103500	95400	82500	65600	43500	20900	3900	0	0
31	0	4000	19700	36100	52000	72900	85900	95900	101600	99800	91100	77000	62800	42900	22300	4200	0	0

Table A.2: Illuminance values [lux] in Porto for June using Meteonorm data for 2019. Columns are the day of the month and lines are the hour of the day.

	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	0	3500	17400	36600	56600	69500	80200	94400	96100	93300	78800	68700	59200	44100	19200	4600	0	0
2	0	3300	17400	46100	42500	52800	49800	61600	59300	35200	26500	10400	12400	16600	14400	3300	0	0
3	0	2200	9800	29300	56100	65700	64400	70900	91000	86500	69700	62100	50400	32500	12000	3300	0	0
4	0	3300	16800	42300	58600	80000	92700	103900	106300	102500	94400	79700	63400	38500	14600	4800	0	0
5	0	3800	20600	38700	59700	79700	96100	104500	109900	107300	96300	85600	65300	45400	22400	5400	0	0
6	0	2500	17300	39400	54700	76100	87100	99500	98900	97600	89000	69300	56600	41400	16300	1700	0	0
7	0	1000	3500	10800	17100	21600	52700	89400	67600	90700	78500	53500	37600	31300	23800	3200	0	0
8	0	2900	9600	34500	59700	78700	95900	102900	105700	103400	94300	79800	63500	44700	15700	5700	0	0
9	0	4100	16800	38300	60500	77100	91400	99800	105600	104200	96100	84100	62500	45600	23100	3700	0	0
10	0	900	6900	15800	29400	30300	24600	44700	34900	32700	38200	25900	17500	1400	4900	800	0	0
11	0	3800	19400	41800	61700	78600	93300	102100	103500	102700	96400	83300	62800	45200	20700	5700	0	0
12	0	4600	21700	43600	62000	78700	94800	103100	105400	103000	96800	84000	68100	45500	17700	4700	0	0
13	0	4200	21400	38700	56500	73300	89000	93400	99400	99500	91500	74900	58200	44200	24600	4200	0	0
14	0	4600	20400	41800	60400	77800	91700	99300	103200	99100	92900	77900	65400	47600	24000	5000	0	0
15	0	4500	15700	38800	61200	77500	92200	99800	103700	101100	93500	82800	68000	47600	24500	5700	0	0
16	0	4000	19900	37200	63500	82400	97100	103100	105200	104500	95800	84400	65300	44700	22100	4100	0	0
17	0	2300	8700	14700	34000	29200	54200	28800	20500	14700	27100	38100	35700	11400	2100	1100	0	0
18	0	1700	17800	36900	61000	80400	95100	104600	110200	106700	99200	84700	69000	47800	23500	5500	0	0
19	0	2400	21600	41900	56000	72400	90300	99200	104400	104100	97400	82300	62900	42800	23300	5700	0	0
20	0	3900	18500	30500	45000	66000	83600	83000	89600	87400	87500	75300	69200	37700	21100	3500	0	0
21	0	3300	15300	30200	51100	71300	84700	89700	100100	100200	92100	75000	59400	37200	17200	6600	0	0
22	0	4100	13300	33200	51000	66500	84100	92600	89800	96000	83600	75800	63900	42300	25200	7100	0	0
23	0	4000	20400	30600	46000	62400	89300	87400	83900	82100	71200	68400	38600	32900	15600	7100	0	0
24	0	2400	12600	29300	45900	41200	62700	56700	83400	72800	68000	64800	40800	29900	15100	2900	0	0
25	0	1900	10800	29200	54500	79800	93700	103500	106800	105700	95600	85500	64500	43400	25700	3600	0	0
26	0	500	3500	3400	11900	12100	19100	12400	13400	16700	14200	16400	4700	9700	3800	1800	0	0
27	0	1900	10200	24300	10400	8300	19700	11500	31300	37300	28500	38400	20400	10400	6000	2900	0	0
28	0	2800	19400	34700	51800	72500	72900	67500	77700	81000	71900	69300	47800	36100	18400	5200	0	0
29	0	2800	19100	40100	62400	79100	94300	104500	108500	106300	98100	86000	69300	47500	25500	6700	0	0
30	0	2700	15600	30200	52200	70300	83100	93300	97700	94100	85500	77500	64500	36600	23400	7200	0	0

Table A.3: Illuminance values [lux] in Porto for July using Meteonorm data for 2019. Columns are the day of the month and lines are the hour of the day.

	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	0	2700	17100	40600	63700	83600	98300	107300	108300	106500	100300	86400	66500	46100	22800	1300	0	0
2	0	2000	9500	29000	35700	60300	76600	91700	95100	93400	78000	67400	52700	35500	19000	4500	0	0
3	0	3700	18500	38900	47800	57600	57500	58200	85100	79900	88300	61200	52500	43400	21900	5100	0	0
4	0	1900	17100	26500	36800	59200	74200	80500	93000	82800	76200	55000	37200	30900	23100	4400	0	0
5	0	3400	14500	23500	45600	54700	69000	73700	76200	73600	77800	68500	59900	48600	23900	7100	0	0
6	0	2100	11700	28400	30500	52400	49400	56800	70600	78700	60000	40600	47900	29400	11200	2500	0	0
7	0	3000	18700	41000	62700	79200	92700	103500	110900	108100	99400	87100	67400	45600	24300	2600	0	0
8	0	3100	18600	41100	62200	81300	96300	103400	106900	106400	98700	84500	68700	47300	19100	6600	0	0
9	0	1500	17700	40000	60800	76000	88400	98500	106500	103700	99200	83600	61700	45600	24000	6600	0	0
10	0	2400	14000	31700	60100	76100	90200	102400	104400	104100	94200	80900	68400	48200	24500	5100	0	0
11	0	2200	11200	28100	48300	70100	81200	81800	92900	83400	75400	67500	51900	30000	19800	5800	0	0
12	0	2300	13600	23200	42000	54500	67200	83000	105700	94000	82200	58800	51200	31200	11300	3600	0	0
13	0	1300	15400	31300	44800	65100	80800	93300	96000	100300	86300	68900	59200	47600	19900	4500	0	0
14	0	2000	11900	30400	54000	74100	83000	90200	93400	94500	87000	74600	57000	34700	20700	5700	0	0
15	0	2000	12000	33000	50900	69800	87100	95600	102600	99400	91600	81900	63900	35400	23800	4800	0	0
16	0	1500	15100	34900	55900	74900	86300	87700	93100	89100	88800	78700	61800	47200	21500	6100	0	0
17	0	700	9900	20000	19100	28000	46400	33800	41300	33300	7400	8900	19400	14500	4100	1800	0	0
18	0	1800	16800	33200	54700	77000	93400	98200	96700	94700	92600	75300	62300	44000	19800	4600	0	0
19	0	1200	12500	30900	50300	71200	84800	93700	98400	99600	85600	72500	56000	46100	23900	4900	0	0
20	0	1900	12200	26600	52900	73100	86000	96700	99800	100100	91300	81200	64100	41600	21200	4000	0	0
21	0	0	4900	10100	35200	32600	40300	46100	67800	58600	86200	69000	63500	33600	24100	5700	0	0
22	0	0	8900	26100	33600	39400	53400	76600	93000	70200	71800	70600	52000	22500	17600	3200	0	0
23	0	0	13700	26000	45700	62400	59000	81700	69800	66300	36100	37200	44100	16400	15000	2200	0	0
24	0	0	7300	24500	30700	49900	55400	50700	41600	74600	52300	34400	13100	24600	7200	1400	0	0
25	0	0	9700	30600	50200	74300	90400	102800	108000	105700	95600	83600	67400	45600	22400	3200	0	0
26	0	0	14300	37100	57800	71900	90200	95700	95600	93500	91000	79200	67100	41700	20600	3700	0	0
27	0	0	5500	12100	24900	29000	21300	23700	65400	66200	68600	53600	48600	32300	12100	3200	0	0
28	0	0	9100	32300	48800	61700	65600	63000	82000	92000	73400	54700	45600	27900	10900	3000	0	0
29	0	0	7200	15700	41300	62800	76300	91000	95300	92200	89300	72700	57400	41700	18700	2900	0	0
30	0	0	8300	29100	23300	17300	29500	34000	40600	28900	42200	38800	37800	27500	18100	2900	0	0
31	0	0	7700	25900	32400	29300	56200	66500	74800	71300	61100	35900	18300	20400	20900	800	0	0

Table A.4: Illuminance values [lux] in Porto for August using Meteonorm data for 2019. Columns are the day of the month and lines are the hour of the day.

	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	0	0	11200	18400	39300	59000	85900	84300	89200	91800	73900	53600	46400	21300	13700	3000	0	0
2	0	0	9900	29300	52900	71000	84100	94000	97700	97600	90400	80500	64200	42400	20300	3300	0	0
3	0	0	9900	26100	50000	67200	80100	88500	92100	96100	88700	75200	54000	40500	16300	1600	0	0
4	0	0	9800	31000	52600	76400	90500	97000	99400	100100	90800	78600	55800	37000	11200	1300	0	0
5	0	0	12400	27500	47500	71100	85400	87600	96300	94300	82900	74000	58600	29000	11400	200	0	0
6	0	0	7300	25700	48600	71800	87300	98900	102500	101500	95500	80500	61200	40100	16600	1300	0	0
7	0	0	10300	23200	43100	63200	82300	94800	103000	98700	91600	76700	53200	35500	17200	1500	0	0
8	0	0	10100	27000	46700	63100	72800	85400	90900	86300	79200	68700	52900	35300	15400	2000	0	0
9	0	0	11400	33500	54200	72600	87500	96900	99000	93000	90200	77200	59400	39700	16500	2100	0	0
10	0	0	9000	30400	52000	70100	81500	93900	100200	96400	87900	75200	59900	39400	16000	1800	0	0
11	0	0	10900	33100	56300	76700	92600	102900	106100	104500	96600	80000	62700	37600	6700	0	0	0
12	0	0	6500	20300	32600	52500	58900	78100	80700	84200	87500	59700	44300	17500	9800	0	0	0
13	0	0	10200	31600	52100	75600	73800	78200	84100	77700	65100	60500	48200	33000	15700	0	0	0
14	0	0	10100	29800	51300	73300	85800	95100	100500	101200	85600	73600	56600	31800	11500	0	0	0
15	0	0	6800	30400	55200	75800	91800	102100	106300	103900	94600	79600	59300	37100	10000	0	0	0
16	0	0	9400	25500	51600	73300	90900	99700	104100	101800	89200	74400	57400	37300	10700	0	0	0
17	0	0	9400	31500	53100	75700	90600	95900	99100	96600	87000	73500	52000	36800	14700	0	0	0
18	0	0	3000	15700	6700	33600	51300	62300	54100	42500	38900	17000	29100	28600	7900	0	0	0
19	0	0	5800	15400	30500	45300	67300	86500	89600	81100	61600	54200	46200	31900	14100	0	0	0
20	0	0	6700	16700	12000	43800	22300	39600	60800	78200	54300	50700	37400	26900	9500	0	0	0
21	0	0	4100	6600	13000	15500	40600	38800	46600	43500	55600	51700	49300	25200	8600	0	0	0
22	0	0	2900	13000	21500	36200	32000	34500	39000	12900	14100	21300	25800	21900	11800	0	0	0
23	0	0	1200	9300	13200	21000	55500	84100	59400	70700	51100	39500	27000	25000	9400	0	0	0
24	0	0	4300	20500	47000	47800	37600	25700	44900	49500	44900	32900	16400	19100	10200	0	0	0
25	0	0	4000	13000	39900	56800	63800	64200	59000	59800	65100	51600	37900	23000	4600	0	0	0
26	0	0	5800	12000	27100	30000	33900	56800	66900	57800	49900	38500	42800	14400	4700	0	0	0
27	0	0	5600	20000	46900	63700	76800	88900	94600	85100	79300	71900	53300	29700	10300	0	0	0
28	0	0	5500	22200	43600	58300	72300	81700	83200	80400	72800	61700	47500	28800	7600	0	0	0
29	0	0	3400	19200	35600	61400	79000	86000	91500	90100	85600	71500	49600	30100	8400	0	0	0
30	0	0	5800	24100	44300	63000	80700	89500	94300	91900	84900	71900	50700	25700	6400	0	0	0
31	0	0	5000	18800	32600	56400	67700	84000	82000	88500	79200	61300	35500	17200	3700	0	0	0

Table A.5: Illuminance values [lux] in Porto for September using Meteonorm data for 2019. Columns are the day of the month and lines are the hour of the day.

	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
1	0	0	5700	21500	46600	70200	71100	80600	83800	86300	83500	70500	48400	28900	5500	0	0	0
2	0	0	3200	16400	32900	46700	61900	69900	67700	65100	52800	29600	9000	10200	3400	0	0	0
3	0	0	4900	24800	42700	57900	81000	82500	82600	71100	62500	51400	42500	25300	5000	0	0	0
4	0	0	5000	20300	41000	65100	84500	94200	94000	92800	81100	65100	39500	24900	4500	0	0	0
5	0	0	4800	18900	43600	65700	83200	91800	96900	91200	80500	66200	45500	23600	4100	0	0	0
6	0	0	3400	19900	32200	46000	47100	58600	83600	58700	43900	44200	31100	21600	4700	0	0	0
7	0	0	3400	18000	33300	47500	71400	79600	76500	70800	59000	57400	35900	18700	4700	0	0	0
8	0	0	3900	20100	39300	59100	76500	88400	91800	89700	83500	68100	47100	22900	3400	0	0	0
9	0	0	1900	20500	42000	63100	81600	92500	92600	88600	80300	63900	46100	18900	4100	0	0	0
10	0	0	3500	16700	28300	42000	65100	70600	73100	69400	58100	49100	35700	18800	4000	0	0	0
11	0	0	3200	20100	36900	55500	73900	87900	88900	88300	78100	63600	44200	19900	2700	0	0	0
12	0	0	3300	19900	43000	61600	79100	87700	89500	84400	76700	55500	39300	21300	3500	0	0	0
13	0	0	2500	16500	32800	56200	75900	81500	80900	75600	66000	52000	36600	14000	1500	0	0	0
14	0	0	3000	18700	37300	51900	68000	79200	84500	79600	69000	59500	42100	20500	2900	0	0	0
15	0	0	1400	19400	40600	63200	80400	90100	91900	85300	77900	60300	42000	17400	2000	0	0	0
16	0	0	2200	14400	39300	58900	74100	82900	88600	85400	75900	62200	40900	16800	2200	0	0	0
17	0	0	2300	13500	39000	58300	70000	79400	79900	82300	75300	52000	38800	13500	1600	0	0	0
18	0	0	900	12700	23400	45100	64700	78900	85600	79600	70400	54800	35800	17800	0	0	0	0
19	0	0	1800	15100	32200	58300	70600	73300	66600	69900	55900	40000	27600	14600	0	0	0	0
20	0	0	1600	15800	33600	52100	71700	68400	69300	67200	65500	55800	33300	7800	0	0	0	0
21	0	0	900	9000	25800	41400	58300	46000	62000	63000	38700	42200	26700	13200	0	0	0	0
22	0	0	0	200	3800	4300	12500	11300	13100	9300	10400	8500	5800	2800	0	0	0	0
23	0	0	0	6400	19000	26100	25300	29300	12600	22500	18200	15200	4100	1900	0	0	0	0
24	0	0	0	5100	9900	14100	7200	13100	25900	24600	25600	14700	10900	4200	0	0	0	0
25	0	0	0	3400	9900	7800	20600	32200	32300	50200	51000	15300	4900	5100	0	0	0	0
26	0	0	0	11600	22500	28700	39000	61800	54400	33400	47100	42800	29300	6600	0	0	0	0
27	0	0	0	15500	36000	50700	69600	77700	85400	78200	68500	56000	33900	10900	0	0	0	0
28	0	0	0	11200	27800	49100	61100	63400	80000	66200	64700	44800	28800	8800	0	0	0	0
29	0	0	0	15300	33300	42000	54600	58300	59700	65600	46600	33500	25900	9400	0	0	0	0
30	0	0	0	11300	32200	48800	66100	71100	76700	74200	63600	44000	24600	9200	0	0	0	0

Table A.6: Illuminance values in Porto for May using Meteonorm data for 2019: Highlighted first values $E_v < 60,000$ [lux] per day after 12:00. Columns are the day of the month and lines are the hour of the day.

	12	13	14	15	16	17	18	19	20	21	22	23
1	78000	85700	92300	94400	81500	70300	50000	29200	7900	0	0	0
2	75700	87300	91200	94700	85300	68200	44500	26600	11000	0	0	0
3	59100	60300	59800	52200	31900	46200	37400	27300	9900	0	0	0
4	43700	41900	47000	5700	96000	64500	35400	27300	12500	0	0	0
5	47300	70300	64300	74700	77100	60600	46900	23500	12000	0	0	0
6	38600	61200	83800	89300	66900	54000	46500	24800	11600	0	0	0
7	72500	86300	90800	91200	78300	68000	53600	29400	13900	0	0	0
8	41200	27100	35600	50900	63400	55100	43400	30500	12700	0	0	0
9	88200	95600	101500	101000	91900	77800	58600	33900	12800	0	0	0
10	84700	96500	104000	96900	89100	75100	57400	35400	14400	0	0	0
11	70800	82900	90400	72700	63000	46100	30700	33300	13700	1700	0	0
12	81100	89100	82800	76400	64600	58100	49000	36300	14000	1700	0	0
13	58600	34100	71800	85200	58000	54600	27800	37900	16500	1700	0	0
14	72700	87400	89000	85500	78600	75100	52200	27500	12800	2400	0	0
15	53500	59300	73000	59500	73200	50900	50300	22900	9200	1500	0	0
16	78600	90900	80200	81400	81200	69000	46300	35600	12200	2100	0	0
17	45900	55800	57800	71700	53100	47500	32200	22500	6400	2100	0	0
18	52000	43000	41200	60100	75100	56800	29200	24000	9400	900	0	0
19	90900	98900	104400	101600	92100	76400	59500	40700	11800	2200	0	0
20	80200	87100	93200	90700	83000	63500	51300	33200	18500	1400	0	0
21	62900	74100	74500	74600	63000	54400	32700	29400	11800	2800	0	0
22	27500	46600	69600	63600	42600	31700	15200	17800	15300	3000	0	0
23	85300	82500	95000	86100	80400	68600	51200	32600	12500	3000	0	0
24	87100	92200	96500	93400	85400	72700	60600	39400	20000	3700	0	0
25	89600	98200	99900	99100	89700	75000	50000	31200	16200	2800	0	0
26	98100	103800	105900	100600	93200	79200	59300	41600	19700	3900	0	0
27	32700	36300	33600	5500	46900	52300	34000	24400	16000	2400	0	0
28	71200	74900	63400	55600	45900	26300	16700	13900	600	900	0	0
29	69900	79200	90900	90000	76500	52400	48200	24300	17200	4400	0	0
30	88500	96800	102000	103500	95400	82500	65600	43500	20900	3900	0	0
31	85900	95900	101600	99800	91100	77000	62800	42900	22300	4200	0	0

Table A.7: Illuminance values in Porto for May using Meteonorm data for 2019: Highlighted first values $E_v < 50,000$ [lux] per day after 12:00. Columns are the day of the month and lines are the hour of the day.

	12	13	14	15	16	17	18	19	20	21	22	23
1	78000	85700	92300	94400	81500	70300	50000	29200	7900	0	0	0
2	75700	87300	91200	94700	85300	68200	44500	26600	11000	0	0	0
3	59100	60300	59800	52200	31900	46200	37400	27300	9900	0	0	0
4	43700	41900	47000	5700	96000	64500	35400	27300	12500	0	0	0
5	47300	70300	64300	74700	77100	60600	46900	23500	12000	0	0	0
6	38600	61200	83800	89300	66900	54000	46500	24800	11600	0	0	0
7	72500	86300	90800	91200	78300	68000	53600	29400	13900	0	0	0
8	41200	27100	35600	50900	63400	55100	43400	30500	12700	0	0	0
9	88200	95600	101500	101000	91900	77800	58600	33900	12800	0	0	0
10	84700	96500	104000	96900	89100	75100	57400	35400	14400	0	0	0
11	70800	82900	90400	72700	63000	46100	30700	33300	13700	1700	0	0
12	81100	89100	82800	76400	64600	58100	49000	36300	14000	1700	0	0
13	58600	34100	71800	85200	58000	54600	27800	37900	16500	1700	0	0
14	72700	87400	89000	85500	78600	75100	52200	27500	12800	2400	0	0
15	53500	59300	73000	59500	73200	50900	50300	22900	9200	1500	0	0
16	78600	90900	80200	81400	81200	69000	46300	35600	12200	2100	0	0
17	45900	55800	57800	71700	53100	47500	32200	22500	6400	2100	0	0
18	52000	43000	41200	60100	75100	56800	29200	24000	9400	900	0	0
19	90900	98900	104400	101600	92100	76400	59500	40700	11800	2200	0	0
20	80200	87100	93200	90700	83000	63500	51300	33200	18500	1400	0	0
21	62900	74100	74500	74600	63000	54400	32700	29400	11800	2800	0	0
22	27500	46600	69600	63600	42600	31700	15200	17800	15300	3000	0	0
23	85300	82500	95000	86100	80400	68600	51200	32600	12500	3000	0	0
24	87100	92200	96500	93400	85400	72700	60600	39400	20000	3700	0	0
25	89600	98200	99900	99100	89700	75000	50000	31200	16200	2800	0	0
26	98100	103800	105900	100600	93200	79200	59300	41600	19700	3900	0	0
27	32700	36300	33600	5500	46900	52300	34000	24400	16000	2400	0	0
28	71200	74900	63400	55600	45900	26300	16700	13900	600	900	0	0
29	69900	79200	90900	90000	76500	52400	48200	24300	17200	4400	0	0
30	88500	96800	102000	103500	95400	82500	65600	43500	20900	3900	0	0
31	85900	95900	101600	99800	91100	77000	62800	42900	22300	4200	0	0

Table A.8: Illuminance values in Porto for May using Meteonorm data for 2019: Highlighted first values $E_v < 40,000$ [lux] per day after 12:00. Columns are the day of the month and lines are the hour of the day.

	12	13	14	15	16	17	18	19	20	21	22	23
1	78000	85700	92300	94400	81500	70300	50000	29200	7900	0	0	0
2	75700	87300	91200	94700	85300	68200	44500	26600	11000	0	0	0
3	59100	60300	59800	52200	31900	46200	37400	27300	9900	0	0	0
4	43700	41900	47000	65700	96000	64500	35400	27300	12500	0	0	0
5	47300	70300	64300	74700	77100	60600	46900	23500	12000	0	0	0
6	38600	61200	83800	89300	66900	54000	46500	24800	11600	0	0	0
7	72500	86300	90800	91200	78300	68000	53600	29400	13900	0	0	0
8	41200	27100	35600	50900	63400	55100	43400	30500	12700	0	0	0
9	88200	95600	101500	101000	91900	77800	58600	33900	12800	0	0	0
10	84700	96500	104000	96900	89100	75100	57400	35400	14400	0	0	0
11	70800	82900	90400	72700	63000	46100	30700	33300	13700	1700	0	0
12	81100	89100	82800	76400	64600	58100	49000	36300	14000	1700	0	0
13	58600	34100	71800	85200	58000	54600	27800	37900	16500	1700	0	0
14	72700	87400	89000	85500	78600	75100	52200	27500	12800	2400	0	0
15	53500	59300	73000	59500	73200	50900	50300	22900	9200	1500	0	0
16	78600	90900	80200	81400	81200	69000	46300	35600	12200	2100	0	0
17	45900	55800	57800	71700	53100	47500	32200	22500	6400	2100	0	0
18	52000	43000	41200	60100	75100	56800	29200	24000	9400	900	0	0
19	90900	98900	104400	101600	92100	76400	59500	40700	11800	2200	0	0
20	80200	87100	93200	90700	83000	63500	51300	33200	18500	1400	0	0
21	62900	74100	74500	74600	63000	54400	32700	29400	11800	2800	0	0
22	27500	46600	69600	63600	42600	31700	15200	17800	15300	3000	0	0
23	85300	82500	95000	86100	80400	68600	51200	32600	12500	3000	0	0
24	87100	92200	96500	93400	85400	72700	60600	39400	20000	3700	0	0
25	89600	98200	99900	99100	89700	75000	50000	31200	16200	2800	0	0
26	98100	103800	105900	100600	93200	79200	59300	41600	19700	3900	0	0
27	32700	36300	33600	5500	46900	52300	34000	24400	16000	2400	0	0
28	71200	74900	63400	55600	45900	26300	16700	13900	600	900	0	0
29	69900	79200	90900	90000	76500	52400	48200	24300	17200	4400	0	0
30	88500	96800	102000	103500	95400	82500	65600	43500	20900	3900	0	0
31	85900	95900	101600	99800	91100	77000	62800	42900	22300	4200	0	0

Table A.9: Illuminance values in Porto for May using Meteonorm data for 2019: Highlighted first values $E_v < 30,000$ [lux] per day after 12:00. Columns are the day of the month and lines are the hour of the day.

	12	13	14	15	16	17	18	19	20	21	22	23
1	78000	85700	92300	94400	81500	70300	50000	29200	7900	0	0	0
2	75700	87300	91200	94700	85300	68200	44500	26600	11000	0	0	0
3	59100	60300	59800	52200	31900	46200	37400	27300	9900	0	0	0
4	43700	41900	47000	65700	96000	64500	35400	27300	12500	0	0	0
5	47300	70300	64300	74700	77100	60600	46900	23500	12000	0	0	0
6	38600	61200	83800	89300	66900	54000	46500	24800	11600	0	0	0
7	72500	86300	90800	91200	78300	68000	53600	29400	13900	0	0	0
8	41200	27100	35600	50900	63400	55100	43400	30500	12700	0	0	0
9	88200	95600	101500	101000	91900	77800	58600	33900	12800	0	0	0
10	84700	96500	104000	96900	89100	75100	57400	35400	14400	0	0	0
11	70800	82900	90400	72700	63000	46100	30700	33300	13700	1700	0	0
12	81100	89100	82800	76400	64600	58100	49000	36300	14000	1700	0	0
13	58600	34100	71800	85200	58000	54600	27800	37900	16500	1700	0	0
14	72700	87400	89000	85500	78600	75100	52200	27500	12800	2400	0	0
15	53500	59300	73000	59500	73200	50900	50300	22900	9200	1500	0	0
16	78600	90900	80200	81400	81200	69000	46300	35600	12200	2100	0	0
17	45900	55800	57800	71700	53100	47500	32200	22500	6400	2100	0	0
18	52000	43000	41200	60100	75100	56800	29200	24000	9400	900	0	0
19	90900	98900	104400	101600	92100	76400	59500	40700	11800	2200	0	0
20	80200	87100	93200	90700	83000	63500	51300	33200	18500	1400	0	0
21	62900	74100	74500	74600	63000	54400	32700	29400	11800	2800	0	0
22	27500	46600	69600	63600	42600	31700	15200	17800	15300	3000	0	0
23	85300	82500	95000	86100	80400	68600	51200	32600	12500	3000	0	0
24	87100	92200	96500	93400	85400	72700	60600	39400	20000	3700	0	0
25	89600	98200	99900	99100	89700	75000	50000	31200	16200	2800	0	0
26	98100	103800	105900	100600	93200	79200	59300	41600	19700	3900	0	0
27	32700	36300	33600	5500	46900	52300	34000	24400	16000	2400	0	0
28	71200	74900	63400	55600	45900	26300	16700	13900	600	900	0	0
29	69900	79200	90900	90000	76500	52400	48200	24300	17200	4400	0	0
30	88500	96800	102000	103500	95400	82500	65600	43500	20900	3900	0	0
31	85900	95900	101600	99800	91100	77000	62800	42900	22300	4200	0	0

Table A.10: Illuminance values in Porto for June using Meteonorm data for 2019: Highlighted first values $E_v < 60,000$ [lux] per day after 12:00. Columns are the day of the month and lines are the hour of the day.

	12	13	14	15	16	17	18	19	20	21	22	23
1	80200	94400	96100	93300	78800	68700	59200	44100	19200	4600	0	0
2	49800	61600	59300	35200	26500	10400	12400	16600	14400	3300	0	0
3	64400	70900	91000	86500	69700	62100	50400	32500	12000	3300	0	0
4	92700	103900	106300	102500	94400	79700	63400	38500	14600	4800	0	0
5	96100	104500	109900	107300	96300	85600	65300	45400	22400	5400	0	0
6	87100	99500	98900	97600	89000	69300	56600	41400	16300	1700	0	0
7	52700	89400	67600	90700	78500	53500	37600	31300	23800	3200	0	0
8	95900	102900	105700	103400	94300	79800	63500	44700	15700	5700	0	0
9	91400	99800	105600	104200	96100	84100	62500	45600	23100	3700	0	0
10	24600	44700	34900	32700	38200	25900	17500	1400	4900	800	0	0
11	93300	102100	103500	102700	96400	83300	62800	45200	20700	5700	0	0
12	94800	103100	105400	103000	96800	84000	68100	45500	17700	4700	0	0
13	89000	93400	99400	99500	91500	74900	58200	44200	24600	4200	0	0
14	91700	99300	103200	99100	92900	77900	65400	47600	24000	5000	0	0
15	92200	99800	103700	101100	93500	82800	68000	47600	24500	5700	0	0
16	97100	103100	105200	104500	95800	84400	65300	44700	22100	4100	0	0
17	54200	28800	20500	14700	27100	38100	35700	11400	2100	1100	0	0
18	95100	104600	110200	106700	99200	84700	69000	47800	23500	5500	0	0
19	90300	99200	104400	104100	97400	82300	62900	42800	23300	5700	0	0
20	83600	83000	89600	87400	87500	75300	69200	37700	21100	3500	0	0
21	84700	89700	100100	100200	92100	75000	59400	37200	17200	6600	0	0
22	84100	92600	89800	96000	83600	75800	63900	42300	25200	7100	0	0
23	89300	87400	83900	82100	71200	68400	38600	32900	15600	7100	0	0
24	62700	56700	83400	72800	68000	64800	40800	29900	15100	2900	0	0
25	93700	103500	106800	105700	95600	85500	64500	43400	25700	3600	0	0
26	19100	12400	13400	16700	14200	16400	4700	9700	3800	1800	0	0
27	19700	11500	31300	37300	28500	38400	20400	10400	6000	2900	0	0
28	72900	67500	77700	81000	71900	69300	47800	36100	18400	5200	0	0
29	94300	104500	108500	106300	98100	86000	69300	47500	25500	6700	0	0
30	83100	93300	97700	94100	85500	77500	64500	36600	23400	7200	0	0

Table A.11: Illuminance values in Porto for June using Meteonorm data for 2019: Highlighted first values $E_v < 50,000$ [lux] per day after 12:00. Columns are the day of the month and lines are the hour of the day.

	12	13	14	15	16	17	18	19	20	21	22	23
1	80200	94400	96100	93300	78800	68700	59200	44100	19200	4600	0	0
2	49800	61600	59300	35200	26500	10400	12400	16600	14400	3300	0	0
3	64400	70900	91000	86500	69700	62100	50400	32500	12000	3300	0	0
4	92700	103900	106300	102500	94400	79700	63400	38500	14600	4800	0	0
5	96100	104500	109900	107300	96300	85600	65300	45400	22400	5400	0	0
6	87100	99500	98900	97600	89000	69300	56600	41400	16300	1700	0	0
7	52700	89400	67600	90700	78500	53500	37600	31300	23800	3200	0	0
8	95900	102900	105700	103400	94300	79800	63500	44700	15700	5700	0	0
9	91400	99800	105600	104200	96100	84100	62500	45600	23100	3700	0	0
10	24600	44700	34900	32700	38200	25900	17500	1400	4900	800	0	0
11	93300	102100	103500	102700	96400	83300	62800	45200	20700	5700	0	0
12	94800	103100	105400	103000	96800	84000	68100	45500	17700	4700	0	0
13	89000	93400	99400	99500	91500	74900	58200	44200	24600	4200	0	0
14	91700	99300	103200	99100	92900	77900	65400	47600	24000	5000	0	0
15	92200	99800	103700	101100	93500	82800	68000	47600	24500	5700	0	0
16	97100	103100	105200	104500	95800	84400	65300	44700	22100	4100	0	0
17	54200	28800	20500	14700	27100	38100	35700	11400	2100	1100	0	0
18	95100	104600	110200	106700	99200	84700	69000	47800	23500	5500	0	0
19	90300	99200	104400	104100	97400	82300	62900	42800	23300	5700	0	0
20	83600	83000	89600	87400	87500	75300	69200	37700	21100	3500	0	0
21	84700	89700	100100	100200	92100	75000	59400	37200	17200	6600	0	0
22	84100	92600	89800	96000	83600	75800	63900	42300	25200	7100	0	0
23	89300	87400	83900	82100	71200	68400	38600	32900	15600	7100	0	0
24	62700	56700	83400	72800	68000	64800	40800	29900	15100	2900	0	0
25	93700	103500	106800	105700	95600	85500	64500	43400	25700	3600	0	0
26	19100	12400	13400	16700	14200	16400	4700	9700	3800	1800	0	0
27	19700	11500	31300	37300	28500	38400	20400	10400	6000	2900	0	0
28	72900	67500	77700	81000	71900	69300	47800	36100	18400	5200	0	0
29	94300	104500	108500	106300	98100	86000	69300	47500	25500	6700	0	0
30	83100	93300	97700	94100	85500	77500	64500	36600	23400	7200	0	0

Table A.12: Illuminance values in Porto for June using Meteonorm data for 2019: Highlighted first values $E_v < 40,000$ [lux] per day after 12:00. Columns are the day of the month and lines are the hour of the day.

	12	13	14	15	16	17	18	19	20	21	22	23
1	80200	94400	96100	93300	78800	68700	59200	44100	19200	4600	0	0
2	49800	61600	59300	35200	26500	10400	12400	16600	14400	3300	0	0
3	64400	70900	91000	86500	69700	62100	50400	32500	12000	3300	0	0
4	92700	103900	106300	102500	94400	79700	63400	38500	14600	4800	0	0
5	96100	104500	109900	107300	96300	85600	65300	45400	22400	5400	0	0
6	87100	99500	98900	97600	89000	69300	56600	41400	16300	1700	0	0
7	52700	89400	67600	90700	78500	53500	37600	31300	23800	3200	0	0
8	95900	102900	105700	103400	94300	79800	63500	44700	15700	5700	0	0
9	91400	99800	105600	104200	96100	84100	62500	45600	23100	3700	0	0
10	24600	44700	34900	32700	38200	25900	17500	1400	4900	800	0	0
11	93300	102100	103500	102700	96400	83300	62800	45200	20700	5700	0	0
12	94800	103100	105400	103000	96800	84000	68100	45500	17700	4700	0	0
13	89000	93400	99400	99500	91500	74900	58200	44200	24600	4200	0	0
14	91700	99300	103200	99100	92900	77900	65400	47600	24000	5000	0	0
15	92200	99800	103700	101100	93500	82800	68000	47600	24500	5700	0	0
16	97100	103100	105200	104500	95800	84400	65300	44700	22100	4100	0	0
17	54200	28800	20500	14700	27100	38100	35700	11400	2100	1100	0	0
18	95100	104600	110200	106700	99200	84700	69000	47800	23500	5500	0	0
19	90300	99200	104400	104100	97400	82300	62900	42800	23300	5700	0	0
20	83600	83000	89600	87400	87500	75300	69200	37700	21100	3500	0	0
21	84700	89700	100100	100200	92100	75000	59400	37200	17200	6600	0	0
22	84100	92600	89800	96000	83600	75800	63900	42300	25200	7100	0	0
23	89300	87400	83900	82100	71200	68400	38600	32900	15600	7100	0	0
24	62700	56700	83400	72800	68000	64800	40800	29900	15100	2900	0	0
25	93700	103500	106800	105700	95600	85500	64500	43400	25700	3600	0	0
26	19100	12400	13400	16700	14200	16400	4700	9700	3800	1800	0	0
27	19700	11500	31300	37300	28500	38400	20400	10400	6000	2900	0	0
28	72900	67500	77700	81000	71900	69300	47800	36100	18400	5200	0	0
29	94300	104500	108500	106300	98100	86000	69300	47500	25500	6700	0	0
30	83100	93300	97700	94100	85500	77500	64500	36600	23400	7200	0	0

Table A.13: Illuminance values in Porto for June using Meteonorm data for 2019: Highlighted first values $E_v < 30,000$ [lux] per day after 12:00. Columns are the day of the month and lines are the hour of the day.

	12	13	14	15	16	17	18	19	20	21	22	23
1	80200	94400	96100	93300	78800	68700	59200	44100	19200	4600	0	0
2	49800	61600	59300	35200	26500	10400	12400	16600	14400	3300	0	0
3	64400	70900	91000	86500	69700	62100	50400	32500	12000	3300	0	0
4	92700	103900	106300	102500	94400	79700	63400	38500	14600	4800	0	0
5	96100	104500	109900	107300	96300	85600	65300	45400	22400	5400	0	0
6	87100	99500	98900	97600	89000	69300	56600	41400	16300	1700	0	0
7	52700	89400	67600	90700	78500	53500	37600	31300	23800	3200	0	0
8	95900	102900	105700	103400	94300	79800	63500	44700	15700	5700	0	0
9	91400	99800	105600	104200	96100	84100	62500	45600	23100	3700	0	0
10	24600	44700	34900	32700	38200	25900	17500	1400	4900	800	0	0
11	93300	102100	103500	102700	96400	83300	62800	45200	20700	5700	0	0
12	94800	103100	105400	103000	96800	84000	68100	45500	17700	4700	0	0
13	89000	93400	99400	99500	91500	74900	58200	44200	24600	4200	0	0
14	91700	99300	103200	99100	92900	77900	65400	47600	24000	5000	0	0
15	92200	99800	103700	101100	93500	82800	68000	47600	24500	5700	0	0
16	97100	103100	105200	104500	95800	84400	65300	44700	22100	4100	0	0
17	54200	28800	20500	14700	27100	38100	35700	11400	2100	1100	0	0
18	95100	104600	110200	106700	99200	84700	69000	47800	23500	5500	0	0
19	90300	99200	104400	104100	97400	82300	62900	42800	23300	5700	0	0
20	83600	83000	89600	87400	87500	75300	69200	37700	21100	3500	0	0
21	84700	89700	100100	100200	92100	75000	59400	37200	17200	6600	0	0
22	84100	92600	89800	96000	83600	75800	63900	42300	25200	7100	0	0
23	89300	87400	83900	82100	71200	68400	38600	32900	15600	7100	0	0
24	62700	56700	83400	72800	68000	64800	40800	29900	15100	2900	0	0
25	93700	103500	106800	105700	95600	85500	64500	43400	25700	3600	0	0
26	19100	12400	13400	16700	14200	16400	4700	9700	3800	1800	0	0
27	19700	11500	31300	37300	28500	38400	20400	10400	6000	2900	0	0
28	72900	67500	77700	81000	71900	69300	47800	36100	18400	5200	0	0
29	94300	104500	108500	106300	98100	86000	69300	47500	25500	6700	0	0
30	83100	93300	97700	94100	85500	77500	64500	36600	23400	7200	0	0

Table A.14: Illuminance values in Porto for July using Meteonorm data for 2019: Highlighted first values $E_v < 60,000$ [lux] per day after 12:00. Columns are the day of the month and lines are the hour of the day.

	12	13	14	15	16	17	18	19	20	21	22	23
1	98300	107300	108300	106500	100300	86400	66500	46100	22800	1300	0	0
2	76600	91700	95100	93400	78000	67400	52700	35500	19000	4500	0	0
3	57500	58200	85100	79900	88300	61200	52500	43400	21900	5100	0	0
4	74200	80500	93000	82800	76200	55000	37200	30900	23100	4400	0	0
5	69000	73700	76200	73600	77800	68500	59900	48600	23900	7100	0	0
6	49400	56800	70600	78700	60000	40600	47900	29400	11200	2500	0	0
7	92700	103500	110900	108100	99400	87100	67400	45600	24300	2600	0	0
8	96300	103400	106900	106400	98700	84500	68700	47300	19100	6600	0	0
9	88400	98500	106500	103700	99200	83600	61700	45600	24000	6600	0	0
10	90200	102400	104400	104100	94200	80900	68400	48200	24500	5100	0	0
11	81200	81800	92900	83400	75400	67500	51900	30000	19800	5800	0	0
12	67200	83000	105700	94000	82200	58800	51200	31200	11300	3600	0	0
13	80800	93300	96000	100300	86300	68900	59200	47600	19900	4500	0	0
14	83000	90200	93400	94500	87000	74600	57000	34700	20700	5700	0	0
15	87100	95600	102600	99400	91600	81900	63900	35400	23800	4800	0	0
16	86300	87700	93100	89100	88800	78700	61800	47200	21500	6100	0	0
17	46400	33800	41300	33300	7400	8900	19400	14500	4100	1800	0	0
18	93400	98200	96700	94700	92600	75300	62300	44000	19800	4600	0	0
19	84800	93700	98400	99600	85600	72500	56000	46100	23900	4900	0	0
20	86000	96700	99800	100100	91300	81200	64100	41600	21200	4000	0	0
21	40300	46100	67800	58600	86200	69000	63500	33600	24100	5700	0	0
22	53400	76600	93000	70200	71800	70600	52000	22500	17600	3200	0	0
23	59000	81700	69800	66300	36100	37200	44100	16400	15000	2200	0	0
24	55400	50700	41600	74600	52300	34400	13100	24600	7200	1400	0	0
25	90400	102800	108000	105700	95600	83600	67400	45600	22400	3200	0	0
26	90200	95700	95600	93500	91000	79200	67100	41700	20600	3700	0	0
27	21300	23700	65400	66200	68600	53600	48600	32300	12100	3200	0	0
28	65600	63000	82000	92000	73400	54700	45600	27900	10900	3000	0	0
29	76300	91000	95300	92200	89300	72700	57400	41700	18700	2900	0	0
30	29500	34000	40600	28900	42200	38800	37800	27500	18100	2900	0	0
31	56200	66500	74800	71300	61100	35900	18300	20400	20900	800	0	0

Table A.15: Illuminance values in Porto for July using Meteonorm data for 2019: Highlighted first values $E_v < 50,000$ [lux] per day after 12:00. Columns are the day of the month and lines are the hour of the day.

	12	13	14	15	16	17	18	19	20	21	22	23
1	98300	107300	108300	106500	100300	86400	66500	46100	22800	1300	0	0
2	76600	91700	95100	93400	78000	67400	52700	35500	19000	4500	0	0
3	57500	58200	85100	79900	88300	61200	52500	43400	21900	5100	0	0
4	74200	80500	93000	82800	76200	55000	37200	30900	23100	4400	0	0
5	69000	73700	76200	73600	77800	68500	59900	48600	23900	7100	0	0
6	49400	56800	70600	78700	60000	40600	47900	29400	11200	2500	0	0
7	92700	103500	110900	108100	99400	87100	67400	45600	24300	2600	0	0
8	96300	103400	106900	106400	98700	84500	68700	47300	19100	6600	0	0
9	88400	98500	106500	103700	99200	83600	61700	45600	24000	6600	0	0
10	90200	102400	104400	104100	94200	80900	68400	48200	24500	5100	0	0
11	81200	81800	92900	83400	75400	67500	51900	30000	19800	5800	0	0
12	67200	83000	105700	94000	82200	58800	51200	31200	11300	3600	0	0
13	80800	93300	96000	100300	86300	68900	59200	47600	19900	4500	0	0
14	83000	90200	93400	94500	87000	74600	57000	34700	20700	5700	0	0
15	87100	95600	102600	99400	91600	81900	63900	35400	23800	4800	0	0
16	86300	87700	93100	89100	88800	78700	61800	47200	21500	6100	0	0
17	46400	33800	41300	33300	7400	8900	19400	14500	4100	1800	0	0
18	93400	98200	96700	94700	92600	75300	62300	44000	19800	4600	0	0
19	84800	93700	98400	99600	85600	72500	56000	46100	23900	4900	0	0
20	86000	96700	99800	100100	91300	81200	64100	41600	21200	4000	0	0
21	40300	46100	67800	58600	86200	69000	63500	33600	24100	5700	0	0
22	53400	76600	93000	70200	71800	70600	52000	22500	17600	3200	0	0
23	59000	81700	69800	66300	36100	37200	44100	16400	15000	2200	0	0
24	55400	50700	41600	74600	52300	34400	13100	24600	7200	1400	0	0
25	90400	102800	108000	105700	95600	83600	67400	45600	22400	3200	0	0
26	90200	95700	95600	93500	91000	79200	67100	41700	20600	3700	0	0
27	21300	23700	65400	66200	68600	53600	48600	32300	12100	3200	0	0
28	65600	63000	82000	92000	73400	54700	45600	27900	10900	3000	0	0
29	76300	91000	95300	92200	89300	72700	57400	41700	18700	2900	0	0
30	29500	34000	40600	28900	42200	38800	37800	27500	18100	2900	0	0
31	56200	66500	74800	71300	61100	35900	18300	20400	20900	800	0	0

Table A.16: Illuminance values in Porto for July using Meteonorm data for 2019: Highlighted first values $E_v < 40,000$ [lux] per day after 12:00. Columns are the day of the month and lines are the hour of the day.

	12	13	14	15	16	17	18	19	20	21	22	23
1	98300	107300	108300	106500	100300	86400	66500	46100	22800	1300	0	0
2	76600	91700	95100	93400	78000	67400	52700	35500	19000	4500	0	0
3	57500	58200	85100	79900	88300	61200	52500	43400	21900	5100	0	0
4	74200	80500	93000	82800	76200	55000	37200	30900	23100	4400	0	0
5	69000	73700	76200	73600	77800	68500	59900	48600	23900	7100	0	0
6	49400	56800	70600	78700	60000	40600	47900	29400	11200	2500	0	0
7	92700	103500	110900	108100	99400	87100	67400	45600	24300	2600	0	0
8	96300	103400	106900	106400	98700	84500	68700	47300	19100	6600	0	0
9	88400	98500	106500	103700	99200	83600	61700	45600	24000	6600	0	0
10	90200	102400	104400	104100	94200	80900	68400	48200	24500	5100	0	0
11	81200	81800	92900	83400	75400	67500	51900	30000	19800	5800	0	0
12	67200	83000	105700	94000	82200	58800	51200	31200	11300	3600	0	0
13	80800	93300	96000	100300	86300	68900	59200	47600	19900	4500	0	0
14	83000	90200	93400	94500	87000	74600	57000	34700	20700	5700	0	0
15	87100	95600	102600	99400	91600	81900	63900	35400	23800	4800	0	0
16	86300	87700	93100	89100	88800	78700	61800	47200	21500	6100	0	0
17	46400	33800	41300	33300	7400	8900	19400	14500	4100	1800	0	0
18	93400	98200	96700	94700	92600	75300	62300	44000	19800	4600	0	0
19	84800	93700	98400	99600	85600	72500	56000	46100	23900	4900	0	0
20	86000	96700	99800	100100	91300	81200	64100	41600	21200	4000	0	0
21	40300	46100	67800	58600	86200	69000	63500	33600	24100	5700	0	0
22	53400	76600	93000	70200	71800	70600	52000	22500	17600	3200	0	0
23	59000	81700	69800	66300	36100	37200	44100	16400	15000	2200	0	0
24	55400	50700	41600	74600	52300	34400	13100	24600	7200	1400	0	0
25	90400	102800	108000	105700	95600	83600	67400	45600	22400	3200	0	0
26	90200	95700	95600	93500	91000	79200	67100	41700	20600	3700	0	0
27	21300	23700	65400	66200	68600	53600	48600	32300	12100	3200	0	0
28	65600	63000	82000	92000	73400	54700	45600	27900	10900	3000	0	0
29	76300	91000	95300	92200	89300	72700	57400	41700	18700	2900	0	0
30	29500	34000	40600	28900	42200	38800	37800	27500	18100	2900	0	0
31	56200	66500	74800	71300	61100	35900	18300	20400	20900	800	0	0

Table A.17: Illuminance values in Porto for July using Meteonorm data for 2019: Highlighted first values $E_v < 30,000$ [lux] per day after 12:00. Columns are the day of the month and lines are the hour of the day.

	12	13	14	15	16	17	18	19	20	21	22	23
1	98300	107300	108300	106500	100300	86400	66500	46100	22800	1300	0	0
2	76600	91700	95100	93400	78000	67400	52700	35500	19000	4500	0	0
3	57500	58200	85100	79900	88300	61200	52500	43400	21900	5100	0	0
4	74200	80500	93000	82800	76200	55000	37200	30900	23100	4400	0	0
5	69000	73700	76200	73600	77800	68500	59900	48600	23900	7100	0	0
6	49400	56800	70600	78700	60000	40600	47900	29400	11200	2500	0	0
7	92700	103500	110900	108100	99400	87100	67400	45600	24300	2600	0	0
8	96300	103400	106900	106400	98700	84500	68700	47300	19100	6600	0	0
9	88400	98500	106500	103700	99200	83600	61700	45600	24000	6600	0	0
10	90200	102400	104400	104100	94200	80900	68400	48200	24500	5100	0	0
11	81200	81800	92900	83400	75400	67500	51900	30000	19800	5800	0	0
12	67200	83000	105700	94000	82200	58800	51200	31200	11300	3600	0	0
13	80800	93300	96000	100300	86300	68900	59200	47600	19900	4500	0	0
14	83000	90200	93400	94500	87000	74600	57000	34700	20700	5700	0	0
15	87100	95600	102600	99400	91600	81900	63900	35400	23800	4800	0	0
16	86300	87700	93100	89100	88800	78700	61800	47200	21500	6100	0	0
17	46400	33800	41300	33300	7400	8900	19400	14500	4100	1800	0	0
18	93400	98200	96700	94700	92600	75300	62300	44000	19800	4600	0	0
19	84800	93700	98400	99600	85600	72500	56000	46100	23900	4900	0	0
20	86000	96700	99800	100100	91300	81200	64100	41600	21200	4000	0	0
21	40300	46100	67800	58600	86200	69000	63500	33600	24100	5700	0	0
22	53400	76600	93000	70200	71800	70600	52000	22500	17600	3200	0	0
23	59000	81700	69800	66300	36100	37200	44100	16400	15000	2200	0	0
24	55400	50700	41600	74600	52300	34400	13100	24600	7200	1400	0	0
25	90400	102800	108000	105700	95600	83600	67400	45600	22400	3200	0	0
26	90200	95700	95600	93500	91000	79200	67100	41700	20600	3700	0	0
27	21300	23700	65400	66200	68600	53600	48600	32300	12100	3200	0	0
28	65600	63000	82000	92000	73400	54700	45600	27900	10900	3000	0	0
29	76300	91000	95300	92200	89300	72700	57400	41700	18700	2900	0	0
30	29500	34000	40600	28900	42200	38800	37800	27500	18100	2900	0	0
31	56200	66500	74800	71300	61100	35900	18300	20400	20900	800	0	0

Table A.18: Illuminance values in Porto for August using Meteonorm data for 2019: Highlighted first values $E_v < 60,000$ [lux] per day after 12:00. Columns are the day of the month and lines are the hour of the day.

	12	13	14	15	16	17	18	19	20	21	22	23
1	85900	84300	89200	91800	73900	53600	46400	21300	13700	3000	0	0
2	84100	94000	97700	97600	90400	80500	64200	42400	20300	3300	0	0
3	80100	88500	92100	96100	88700	75200	54000	40500	16300	1600	0	0
4	90500	97000	99400	100100	90800	78600	55800	37000	11200	1300	0	0
5	85400	87600	96300	94300	82900	74000	58600	29000	11400	200	0	0
6	87300	98900	102500	101500	95500	80500	61200	40100	16600	1300	0	0
7	82300	94800	103000	98700	91600	76700	53200	35500	17200	1500	0	0
8	72800	85400	90900	86300	79200	68700	52900	35300	15400	2000	0	0
9	87500	96900	99000	93000	90200	77200	59400	39700	16500	2100	0	0
10	81500	93900	100200	96400	87900	75200	59900	39400	16000	1800	0	0
11	92600	102900	106100	104500	96600	80000	62700	37600	6700	0	0	0
12	58900	78100	80700	84200	87500	59700	44300	17500	9800	0	0	0
13	73800	78200	84100	77700	65100	60500	48200	33000	15700	0	0	0
14	85800	95100	100500	101200	85600	73600	56600	31800	11500	0	0	0
15	91800	102100	106300	103900	94600	79600	59300	37100	10000	0	0	0
16	90900	99700	104100	101800	89200	74400	57400	37300	10700	0	0	0
17	90600	95900	99100	96600	87000	73500	52000	36800	14700	0	0	0
18	51300	62300	54100	42500	38900	17000	29100	28600	7900	0	0	0
19	67300	86500	89600	81100	61600	54200	46200	31900	14100	0	0	0
20	22300	39600	60800	78200	54300	50700	37400	26900	9500	0	0	0
21	40600	38800	46600	43500	55600	51700	49300	25200	8600	0	0	0
22	32000	34500	39000	12900	14100	21300	25800	21900	11800	0	0	0
23	55500	84100	59400	70700	51100	39500	27000	25000	9400	0	0	0
24	37600	25700	44900	49500	44900	32900	16400	19100	10200	0	0	0
25	63800	64200	59000	59800	65100	51600	37900	23000	4600	0	0	0
26	33900	56800	66900	57800	49900	38500	42800	14400	4700	0	0	0
27	76800	88900	94600	85100	79300	71900	53300	29700	10300	0	0	0
28	72300	81700	83200	80400	72800	61700	47500	28800	7600	0	0	0
29	79000	86000	91500	90100	85600	71500	49600	30100	8400	0	0	0
30	80700	89500	94300	91900	84900	71900	50700	25700	6400	0	0	0
31	67700	84000	82000	88500	79200	61300	35500	17200	3700	0	0	0

Table A.19: Illuminance values in Porto for August using Meteonorm data for 2019: Highlighted first values $E_v < 50,000$ [lux] per day after 12:00. Columns are the day of the month and lines are the hour of the day.

	12	13	14	15	16	17	18	19	20	21	22	23
1	85900	84300	89200	91800	73900	53600	46400	21300	13700	3000	0	0
2	84100	94000	97700	97600	90400	80500	64200	42400	20300	3300	0	0
3	80100	88500	92100	96100	88700	75200	54000	40500	16300	1600	0	0
4	90500	97000	99400	100100	90800	78600	55800	37000	11200	1300	0	0
5	85400	87600	96300	94300	82900	74000	58600	29000	11400	200	0	0
6	87300	98900	102500	101500	95500	80500	61200	40100	16600	1300	0	0
7	82300	94800	103000	98700	91600	76700	53200	35500	17200	1500	0	0
8	72800	85400	90900	86300	79200	68700	52900	35300	15400	2000	0	0
9	87500	96900	99000	93000	90200	77200	59400	39700	16500	2100	0	0
10	81500	93900	100200	96400	87900	75200	59900	39400	16000	1800	0	0
11	92600	102900	106100	104500	96600	80000	62700	37600	6700	0	0	0
12	58900	78100	80700	84200	87500	59700	44300	17500	9800	0	0	0
13	73800	78200	84100	77700	65100	60500	48200	33000	15700	0	0	0
14	85800	95100	100500	101200	85600	73600	56600	31800	11500	0	0	0
15	91800	102100	106300	103900	94600	79600	59300	37100	10000	0	0	0
16	90900	99700	104100	101800	89200	74400	57400	37300	10700	0	0	0
17	90600	95900	99100	96600	87000	73500	52000	36800	14700	0	0	0
18	51300	62300	54100	42500	38900	17000	29100	28600	7900	0	0	0
19	67300	86500	89600	81100	61600	54200	46200	31900	14100	0	0	0
20	22300	39600	60800	78200	54300	50700	37400	26900	9500	0	0	0
21	40600	38800	46600	43500	55600	51700	49300	25200	8600	0	0	0
22	32000	34500	39000	12900	14100	21300	25800	21900	11800	0	0	0
23	55500	84100	59400	70700	51100	39500	27000	25000	9400	0	0	0
24	37600	25700	44900	49500	44900	32900	16400	19100	10200	0	0	0
25	63800	64200	59000	59800	65100	51600	37900	23000	4600	0	0	0
26	33900	56800	66900	57800	49900	38500	42800	14400	4700	0	0	0
27	76800	88900	94600	85100	79300	71900	53300	29700	10300	0	0	0
28	72300	81700	83200	80400	72800	61700	47500	28800	7600	0	0	0
29	79000	86000	91500	90100	85600	71500	49600	30100	8400	0	0	0
30	80700	89500	94300	91900	84900	71900	50700	25700	6400	0	0	0
31	67700	84000	82000	88500	79200	61300	35500	17200	3700	0	0	0

Table A.20: Illuminance values in Porto for August using Meteonorm data for 2019: Highlighted first values $E_v < 40,000$ [lux] per day after 12:00. Columns are the day of the month and lines are the hour of the day.

	12	13	14	15	16	17	18	19	20	21	22	23
1	85900	84300	89200	91800	73900	53600	46400	21300	13700	3000	0	0
2	84100	94000	97700	97600	90400	80500	64200	42400	20300	3300	0	0
3	80100	88500	92100	96100	88700	75200	54000	40500	16300	1600	0	0
4	90500	97000	99400	100100	90800	78600	55800	37000	11200	1300	0	0
5	85400	87600	96300	94300	82900	74000	58600	29000	11400	200	0	0
6	87300	98900	102500	101500	95500	80500	61200	40100	16600	1300	0	0
7	82300	94800	103000	98700	91600	76700	53200	35500	17200	1500	0	0
8	72800	85400	90900	86300	79200	68700	52900	35300	15400	2000	0	0
9	87500	96900	99000	93000	90200	77200	59400	39700	16500	2100	0	0
10	81500	93900	100200	96400	87900	75200	59900	39400	16000	1800	0	0
11	92600	102900	106100	104500	96600	80000	62700	37600	6700	0	0	0
12	58900	78100	80700	84200	87500	59700	44300	17500	9800	0	0	0
13	73800	78200	84100	77700	65100	60500	48200	33000	15700	0	0	0
14	85800	95100	100500	101200	85600	73600	56600	31800	11500	0	0	0
15	91800	102100	106300	103900	94600	79600	59300	37100	10000	0	0	0
16	90900	99700	104100	101800	89200	74400	57400	37300	10700	0	0	0
17	90600	95900	99100	96600	87000	73500	52000	36800	14700	0	0	0
18	51300	62300	54100	42500	38900	17000	29100	28600	7900	0	0	0
19	67300	86500	89600	81100	61600	54200	46200	31900	14100	0	0	0
20	22300	39600	60800	78200	54300	50700	37400	26900	9500	0	0	0
21	40600	38800	46600	43500	55600	51700	49300	25200	8600	0	0	0
22	32000	34500	39000	12900	14100	21300	25800	21900	11800	0	0	0
23	55500	84100	59400	70700	51100	39500	27000	25000	9400	0	0	0
24	37600	25700	44900	49500	44900	32900	16400	19100	10200	0	0	0
25	63800	64200	59000	59800	65100	51600	37900	23000	4600	0	0	0
26	33900	56800	66900	57800	49900	38500	42800	14400	4700	0	0	0
27	76800	88900	94600	85100	79300	71900	53300	29700	10300	0	0	0
28	72300	81700	83200	80400	72800	61700	47500	28800	7600	0	0	0
29	79000	86000	91500	90100	85600	71500	49600	30100	8400	0	0	0
30	80700	89500	94300	91900	84900	71900	50700	25700	6400	0	0	0
31	67700	84000	82000	88500	79200	61300	35500	17200	3700	0	0	0

Table A.21: Illuminance values in Porto for August using Meteonorm data for 2019: Highlighted first values $E_v < 30,000$ [lux] per day after 12:00. Columns are the day of the month and lines are the hour of the day.

	12	13	14	15	16	17	18	19	20	21	22	23
1	85900	84300	89200	91800	73900	53600	46400	21300	13700	3000	0	0
2	84100	94000	97700	97600	90400	80500	64200	42400	20300	3300	0	0
3	80100	88500	92100	96100	88700	75200	54000	40500	16300	1600	0	0
4	90500	97000	99400	100100	90800	78600	55800	37000	11200	1300	0	0
5	85400	87600	96300	94300	82900	74000	58600	29000	11400	200	0	0
6	87300	98900	102500	101500	95500	80500	61200	40100	16600	1300	0	0
7	82300	94800	103000	98700	91600	76700	53200	35500	17200	1500	0	0
8	72800	85400	90900	86300	79200	68700	52900	35300	15400	2000	0	0
9	87500	96900	99000	93000	90200	77200	59400	39700	16500	2100	0	0
10	81500	93900	100200	96400	87900	75200	59900	39400	16000	1800	0	0
11	92600	102900	106100	104500	96600	80000	62700	37600	6700	0	0	0
12	58900	78100	80700	84200	87500	59700	44300	17500	9800	0	0	0
13	73800	78200	84100	77700	65100	60500	48200	33000	15700	0	0	0
14	85800	95100	100500	101200	85600	73600	56600	31800	11500	0	0	0
15	91800	102100	106300	103900	94600	79600	59300	37100	10000	0	0	0
16	90900	99700	104100	101800	89200	74400	57400	37300	10700	0	0	0
17	90600	95900	99100	96600	87000	73500	52000	36800	14700	0	0	0
18	51300	62300	54100	42500	38900	17000	29100	28600	7900	0	0	0
19	67300	86500	89600	81100	61600	54200	46200	31900	14100	0	0	0
20	22300	39600	60800	78200	54300	50700	37400	26900	9500	0	0	0
21	40600	38800	46600	43500	55600	51700	49300	25200	8600	0	0	0
22	32000	34500	39000	12900	14100	21300	25800	21900	11800	0	0	0
23	55500	84100	59400	70700	51100	39500	27000	25000	9400	0	0	0
24	37600	25700	44900	49500	44900	32900	16400	19100	10200	0	0	0
25	63800	64200	59000	59800	65100	51600	37900	23000	4600	0	0	0
26	33900	56800	66900	57800	49900	38500	42800	14400	4700	0	0	0
27	76800	88900	94600	85100	79300	71900	53300	29700	10300	0	0	0
28	72300	81700	83200	80400	72800	61700	47500	28800	7600	0	0	0
29	79000	86000	91500	90100	85600	71500	49600	30100	8400	0	0	0
30	80700	89500	94300	91900	84900	71900	50700	25700	6400	0	0	0
31	67700	84000	82000	88500	79200	61300	35500	17200	3700	0	0	0

Table A.22: Illuminance values in Porto for September using Meteonorm data for 2019: Highlighted first values $E_v < 60,000$ [lux] per day after 12:00. Columns are the day of the month and lines are the hour of the day.

	12	13	14	15	16	17	18	19	20	21	22	23
1	71100	80600	83800	86300	83500	70500	48400	28900	5500	0	0	0
2	61900	69900	67700	65100	52800	29600	9000	10200	3400	0	0	0
3	81000	82500	82600	71100	62500	51400	42500	25300	5000	0	0	0
4	84500	94200	94000	92800	81100	65100	39500	24900	4500	0	0	0
5	83200	91800	96900	91200	80500	66200	45500	23600	4100	0	0	0
6	47100	58600	83600	58700	43900	44200	31100	21600	4700	0	0	0
7	71400	79600	76500	70800	59000	57400	35900	18700	4700	0	0	0
8	76500	88400	91800	89700	83500	68100	47100	22900	3400	0	0	0
9	81600	92500	92600	88600	80300	63900	46100	18900	4100	0	0	0
10	65100	70600	73100	69400	58100	49100	35700	18800	4000	0	0	0
11	73900	87900	88900	88300	78100	63600	44200	19900	2700	0	0	0
12	79100	87700	89500	84400	76700	55500	39300	21300	3500	0	0	0
13	75900	81500	80900	75600	66000	52000	36600	14000	1500	0	0	0
14	68000	79200	84500	79600	69000	59500	42100	20500	2900	0	0	0
15	80400	90100	91900	85300	77900	60300	42000	17400	2000	0	0	0
16	74100	82900	88600	85400	75900	62200	40900	16800	2200	0	0	0
17	70000	79400	79900	82300	75300	52000	38800	13500	1600	0	0	0
18	64700	78900	85600	79600	70400	54800	35800	17800	0	0	0	0
19	70600	73300	66600	69900	55900	40000	27600	14600	0	0	0	0
20	71700	68400	69300	67200	65500	55800	33300	7800	0	0	0	0
21	58300	46000	62000	63000	38700	42200	26700	13200	0	0	0	0
22	12500	11300	13100	9300	10400	8500	5800	2800	0	0	0	0
23	25300	29300	12600	22500	18200	15200	4100	1900	0	0	0	0
24	7200	13100	25900	24600	25600	14700	10900	4200	0	0	0	0
25	20600	32200	32300	50200	51000	15300	4900	5100	0	0	0	0
26	39000	61800	54400	33400	47100	42800	29300	6600	0	0	0	0
27	69600	77700	85400	78200	68500	56000	33900	10900	0	0	0	0
28	61100	63400	80000	66200	64700	44800	28800	8800	0	0	0	0
29	54600	58300	59700	65600	46600	33500	25900	9400	0	0	0	0
30	66100	71100	76700	74200	63600	44000	24600	9200	0	0	0	0

Table A.23: Illuminance values in Porto for September using Meteonorm data for 2019: Highlighted first values $E_v < 50,000$ [lux] per day after 12:00. Columns are the day of the month and lines are the hour of the day.

	12	13	14	15	16	17	18	19	20	21	22	23
1	71100	80600	83800	86300	83500	70500	48400	28900	5500	0	0	0
2	61900	69900	67700	65100	52800	29600	9000	10200	3400	0	0	0
3	81000	82500	82600	71100	62500	51400	42500	25300	5000	0	0	0
4	84500	94200	94000	92800	81100	65100	39500	24900	4500	0	0	0
5	83200	91800	96900	91200	80500	66200	45500	23600	4100	0	0	0
6	47100	58600	83600	58700	43900	44200	31100	21600	4700	0	0	0
7	71400	79600	76500	70800	59000	57400	35900	18700	4700	0	0	0
8	76500	88400	91800	89700	83500	68100	47100	22900	3400	0	0	0
9	81600	92500	92600	88600	80300	63900	46100	18900	4100	0	0	0
10	65100	70600	73100	69400	58100	49100	35700	18800	4000	0	0	0
11	73900	87900	88900	88300	78100	63600	44200	19900	2700	0	0	0
12	79100	87700	89500	84400	76700	55500	39300	21300	3500	0	0	0
13	75900	81500	80900	75600	66000	52000	36600	14000	1500	0	0	0
14	68000	79200	84500	79600	69000	59500	42100	20500	2900	0	0	0
15	80400	90100	91900	85300	77900	60300	42000	17400	2000	0	0	0
16	74100	82900	88600	85400	75900	62200	40900	16800	2200	0	0	0
17	70000	79400	79900	82300	75300	52000	38800	13500	1600	0	0	0
18	64700	78900	85600	79600	70400	54800	35800	17800	0	0	0	0
19	70600	73300	66600	69900	55900	40000	27600	14600	0	0	0	0
20	71700	68400	69300	67200	65500	55800	33300	7800	0	0	0	0
21	58300	46000	62000	63000	38700	42200	26700	13200	0	0	0	0
22	12500	11300	13100	9300	10400	8500	5800	2800	0	0	0	0
23	25300	29300	12600	22500	18200	15200	4100	1900	0	0	0	0
24	7200	13100	25900	24600	25600	14700	10900	4200	0	0	0	0
25	20600	32200	32300	50200	51000	15300	4900	5100	0	0	0	0
26	39000	61800	54400	33400	47100	42800	29300	6600	0	0	0	0
27	69600	77700	85400	78200	68500	56000	33900	10900	0	0	0	0
28	61100	63400	80000	66200	64700	44800	28800	8800	0	0	0	0
29	54600	58300	59700	65600	46600	33500	25900	9400	0	0	0	0
30	66100	71100	76700	74200	63600	44000	24600	9200	0	0	0	0

Table A.24: Illuminance values in Porto for September using Meteonorm data for 2019: Highlighted first values $E_v < 40,000$ [lux] per day after 12:00. Columns are the day of the month and lines are the hour of the day.

	12	13	14	15	16	17	18	19	20	21	22	23
1	71100	80600	83800	86300	83500	70500	48400	28900	5500	0	0	0
2	61900	69900	67700	65100	52800	29600	9000	10200	3400	0	0	0
3	81000	82500	82600	71100	62500	51400	42500	25300	5000	0	0	0
4	84500	94200	94000	92800	81100	65100	39500	24900	4500	0	0	0
5	83200	91800	96900	91200	80500	66200	45500	23600	4100	0	0	0
6	47100	58600	83600	58700	43900	44200	31100	21600	4700	0	0	0
7	71400	79600	76500	70800	59000	57400	35900	18700	4700	0	0	0
8	76500	88400	91800	89700	83500	68100	47100	22900	3400	0	0	0
9	81600	92500	92600	88600	80300	63900	46100	18900	4100	0	0	0
10	65100	70600	73100	69400	58100	49100	35700	18800	4000	0	0	0
11	73900	87900	88900	88300	78100	63600	44200	19900	2700	0	0	0
12	79100	87700	89500	84400	76700	55500	39300	21300	3500	0	0	0
13	75900	81500	80900	75600	66000	52000	36600	14000	1500	0	0	0
14	68000	79200	84500	79600	69000	59500	42100	20500	2900	0	0	0
15	80400	90100	91900	85300	77900	60300	42000	17400	2000	0	0	0
16	74100	82900	88600	85400	75900	62200	40900	16800	2200	0	0	0
17	70000	79400	79900	82300	75300	52000	38800	13500	1600	0	0	0
18	64700	78900	85600	79600	70400	54800	35800	17800	0	0	0	0
19	70600	73300	66600	69900	55900	40000	27600	14600	0	0	0	0
20	71700	68400	69300	67200	65500	55800	33300	7800	0	0	0	0
21	58300	46000	62000	63000	38700	42200	26700	13200	0	0	0	0
22	12500	11300	13100	9300	10400	8500	5800	2800	0	0	0	0
23	25300	29300	12600	22500	18200	15200	4100	1900	0	0	0	0
24	7200	13100	25900	24600	25600	14700	10900	4200	0	0	0	0
25	20600	32200	32300	50200	51000	15300	4900	5100	0	0	0	0
26	39000	61800	54400	33400	47100	42800	29300	6600	0	0	0	0
27	69600	77700	85400	78200	68500	56000	33900	10900	0	0	0	0
28	61100	63400	80000	66200	64700	44800	28800	8800	0	0	0	0
29	54600	58300	59700	65600	46600	33500	25900	9400	0	0	0	0
30	66100	71100	76700	74200	63600	44000	24600	9200	0	0	0	0

Table A.25: Illuminance values in Porto for September using Meteonorm data for 2019: Highlighted first values $E_v < 30,000$ [lux] per day after 12:00. Columns are the day of the month and lines are the hour of the day.

	12	13	14	15	16	17	18	19	20	21	22	23
1	71100	80600	83800	86300	83500	70500	48400	28900	5500	0	0	0
2	61900	69900	67700	65100	52800	29600	9000	10200	3400	0	0	0
3	81000	82500	82600	71100	62500	51400	42500	25300	5000	0	0	0
4	84500	94200	94000	92800	81100	65100	39500	24900	4500	0	0	0
5	83200	91800	96900	91200	80500	66200	45500	23600	4100	0	0	0
6	47100	58600	83600	58700	43900	44200	31100	21600	4700	0	0	0
7	71400	79600	76500	70800	59000	57400	35900	18700	4700	0	0	0
8	76500	88400	91800	89700	83500	68100	47100	22900	3400	0	0	0
9	81600	92500	92600	88600	80300	63900	46100	18900	4100	0	0	0
10	65100	70600	73100	69400	58100	49100	35700	18800	4000	0	0	0
11	73900	87900	88900	88300	78100	63600	44200	19900	2700	0	0	0
12	79100	87700	89500	84400	76700	55500	39300	21300	3500	0	0	0
13	75900	81500	80900	75600	66000	52000	36600	14000	1500	0	0	0
14	68000	79200	84500	79600	69000	59500	42100	20500	2900	0	0	0
15	80400	90100	91900	85300	77900	60300	42000	17400	2000	0	0	0
16	74100	82900	88600	85400	75900	62200	40900	16800	2200	0	0	0
17	70000	79400	79900	82300	75300	52000	38800	13500	1600	0	0	0
18	64700	78900	85600	79600	70400	54800	35800	17800	0	0	0	0
19	70600	73300	66600	69900	55900	40000	27600	14600	0	0	0	0
20	71700	68400	69300	67200	65500	55800	33300	7800	0	0	0	0
21	58300	46000	62000	63000	38700	42200	26700	13200	0	0	0	0
22	12500	11300	13100	9300	10400	8500	5800	2800	0	0	0	0
23	25300	29300	12600	22500	18200	15200	4100	1900	0	0	0	0
24	7200	13100	25900	24600	25600	14700	10900	4200	0	0	0	0
25	20600	32200	32300	50200	51000	15300	4900	5100	0	0	0	0
26	39000	61800	54400	33400	47100	42800	29300	6600	0	0	0	0
27	69600	77700	85400	78200	68500	56000	33900	10900	0	0	0	0
28	61100	63400	80000	66200	64700	44800	28800	8800	0	0	0	0
29	54600	58300	59700	65600	46600	33500	25900	9400	0	0	0	0
30	66100	71100	76700	74200	63600	44000	24600	9200	0	0	0	0

Appendix B

Selection of the main components

B.1 Synthetic meteorological data generated by PVsyst

Meteo and incident energy

	GlobHor	DiffHor	T_Amb	WindVel	GlobInc
	kWh/m ²	kWh/m ²	°C	m/s	kWh/m ²
January	58.0	28.32	8.34	2.5	57.9
February	80.6	32.99	8.96	2.7	80.5
March	127.9	50.06	11.38	2.9	127.8
April	156.3	67.43	12.92	2.8	156.2
May	201.7	73.64	15.79	2.6	201.6
June	215.3	77.44	18.44	2.6	215.3
July	232.9	61.01	20.16	2.5	232.8
August	204.7	61.18	20.57	2.4	204.6
September	149.7	46.49	18.73	2.2	149.6
October	101.1	42.72	15.95	2.4	101.1
November	64.0	28.13	11.10	2.6	63.9
December	51.2	24.26	9.10	2.5	51.1
Year	1643.4	593.67	14.32	2.6	1642.6

Figure B.1: Monthly average values of global horizontal irradiation, diffuse horizontal irradiation, ambient temperature, wind velocity and global incident horizontal irradiation in Portejões, Viseu.

Monthly Hourly averages for T_Amb [°C]

	0H	1H	2H	3H	4H	5H	6H	7H	8H	9H	10H	11H	12H	13H	14H	15H	16H	17H	18H	19H	20H	21H	22H	23H
January	7.1	6.6	6.2	6.0	5.8	5.6	5.5	5.4	6.1	7.6	9.1	10.3	11.1	11.7	11.9	11.7	11.1	10.1	9.6	9.2	8.8	8.4	7.9	7.4
February	7.3	6.8	6.3	6.0	5.8	5.6	5.4	5.4	6.8	8.4	9.9	11.2	12.2	12.8	13.0	13.0	12.4	11.4	10.6	10.1	9.5	8.9	8.4	7.8
March	9.4	8.8	8.2	7.8	7.5	7.3	7.3	8.2	9.8	11.3	12.7	13.8	14.7	15.3	15.7	15.6	15.2	14.4	13.4	12.7	12.1	11.4	10.7	10.0
April	10.7	10.0	9.5	9.1	8.8	8.6	9.1	10.5	11.9	13.3	14.6	15.5	16.3	16.9	17.1	17.1	16.7	16.0	15.0	14.2	13.4	12.7	11.9	11.1
May	12.7	12.0	11.7	11.3	11.0	11.1	12.4	13.7	15.1	16.4	17.7	18.7	19.4	20.0	20.3	20.3	20.0	19.3	18.4	17.4	16.4	15.5	14.5	13.6
June	15.1	14.4	13.9	13.5	13.2	13.5	14.9	16.2	17.7	19.1	20.4	21.4	22.3	22.9	23.2	23.3	23.0	22.4	21.5	20.3	19.2	18.1	17.0	15.9
July	16.7	15.9	15.5	15.0	14.7	14.8	16.1	17.6	19.1	20.7	22.1	23.3	24.2	24.9	25.3	25.4	25.2	24.5	23.5	22.2	21.1	19.9	18.7	17.5
August	17.3	16.4	16.0	15.5	15.2	15.1	16.0	17.4	19.0	20.7	22.3	23.6	24.8	25.5	26.0	26.1	25.8	25.1	23.9	22.6	21.5	20.4	19.2	18.1
September	16.2	15.5	14.8	14.5	14.1	13.8	14.1	15.7	17.3	19.0	20.5	21.8	22.9	23.6	23.9	23.8	23.2	22.2	20.9	20.0	19.2	18.3	17.5	16.6
October	14.2	13.6	13.1	12.8	12.5	12.4	12.3	13.2	14.5	15.9	17.3	18.3	19.2	19.9	20.2	19.9	19.3	18.3	17.5	16.9	16.3	15.7	15.1	14.5
November	9.8	9.3	8.8	8.6	8.4	8.3	8.1	8.3	9.6	11.1	12.5	13.6	14.3	14.6	14.6	14.2	13.4	12.5	12.2	11.7	11.3	10.9	10.5	10.1
December	8.0	7.6	7.1	6.9	6.7	6.6	6.4	6.3	7.1	8.3	9.6	10.6	11.4	12.2	12.5	12.3	11.4	10.9	10.5	10.1	9.7	9.2	8.8	8.4
Year	12.1	11.4	11.0	10.6	10.3	10.3	10.7	11.5	12.9	14.3	15.7	16.9	17.8	18.4	18.7	18.6	18.1	17.3	16.5	15.7	14.9	14.1	13.4	12.6

Figure B.2: Hourly average values of ambient temperature in Portejões, Viseu.

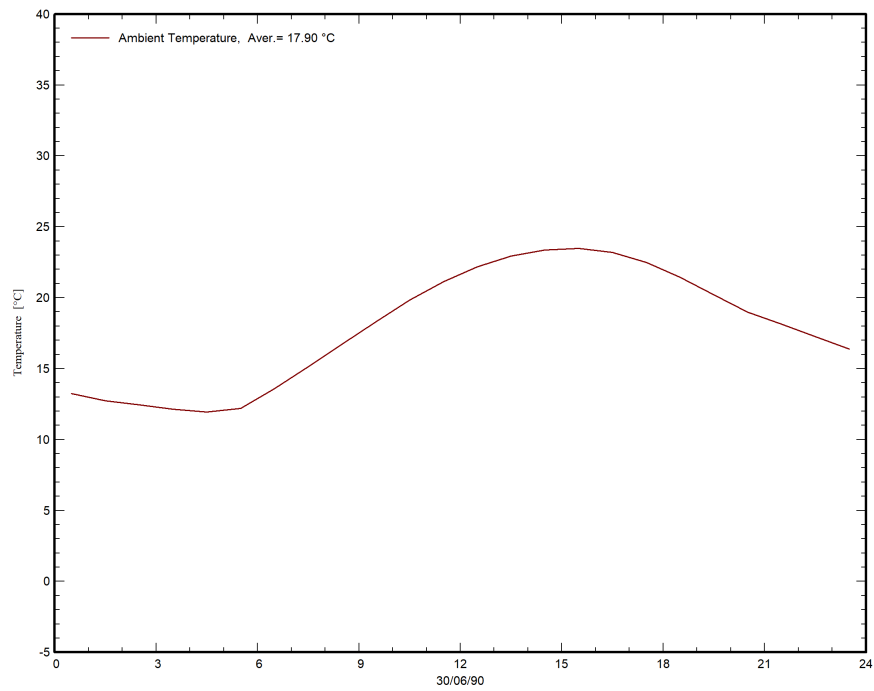


Figure B.3: Ambient temperature during a random day (30/06) in Portejões, Viseu.

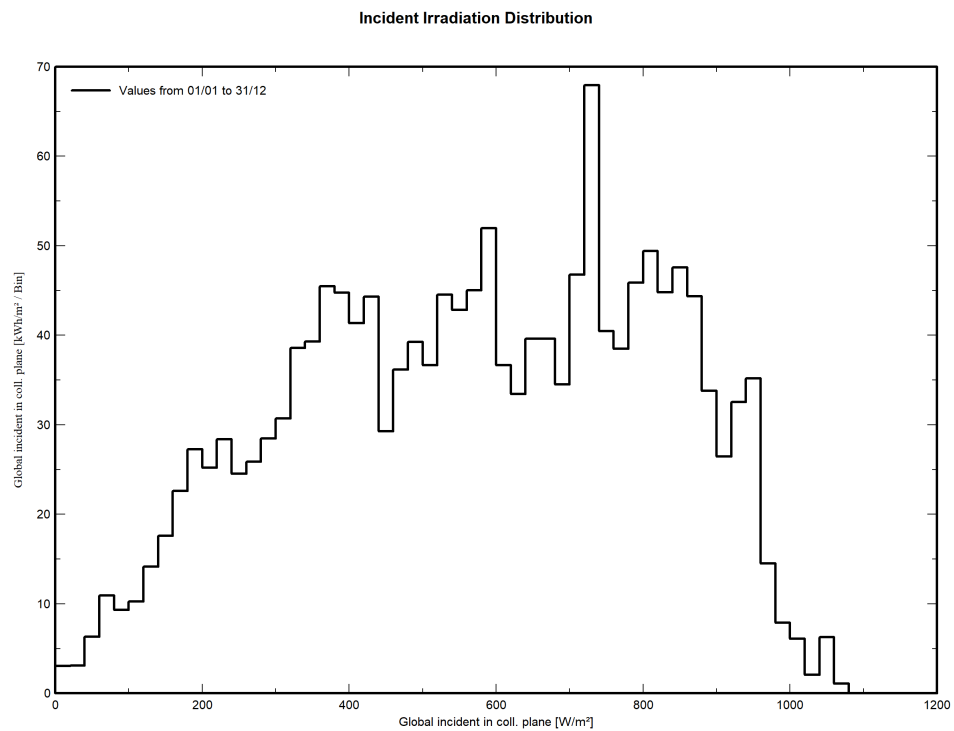


Figure B.4: Incident irradiation distribution in Portejões, Viseu.

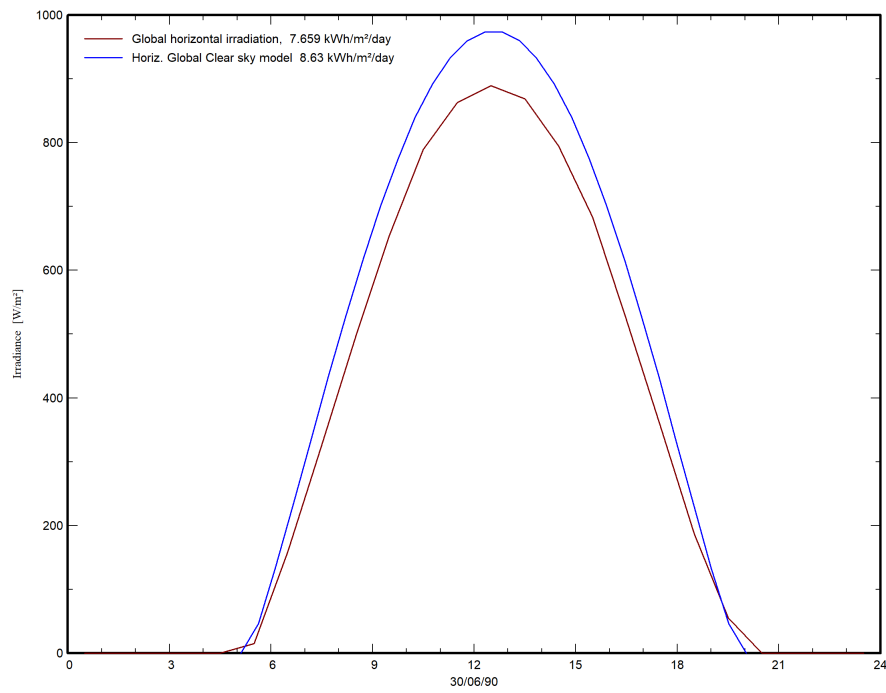


Figure B.5: Global horizontal irradiation during a random day (30/06) in Portejões, Viseu.

Monthly Hourly averages for GlobHor [W/m²]

	0H	1H	2H	3H	4H	5H	6H	7H	8H	9H	10H	11H	12H	13H	14H	15H	16H	17H	18H	19H	20H	21H	22H	23H
January	0	0	0	0	0	0	0	0	35	141	235	295	313	320	265	182	84	2	0	0	0	0	0	0
February	0	0	0	0	0	0	0	3	101	227	353	425	453	436	381	292	168	38	0	0	0	0	0	0
March	0	0	0	0	0	0	1	76	223	364	475	542	573	569	512	391	268	127	5	0	0	0	0	0
April	0	0	0	0	0	0	43	192	343	489	591	625	679	660	567	470	330	179	43	0	0	0	0	0
May	0	0	0	0	0	8	137	295	453	592	704	751	759	757	670	554	429	269	124	5	0	0	0	0
June	0	0	0	0	0	17	167	321	482	628	737	785	820	805	727	631	505	340	175	35	0	0	0	0
July	0	0	0	0	0	8	148	321	500	656	787	842	853	836	780	684	536	355	177	29	0	0	0	0
August	0	0	0	0	0	1	84	246	420	582	708	779	816	788	712	614	454	282	116	3	0	0	0	0
September	0	0	0	0	0	0	11	160	309	448	567	666	695	650	583	457	296	140	9	0	0	0	0	0
October	0	0	0	0	0	0	1	66	187	313	406	463	476	487	409	283	152	22	0	0	0	0	0	0
November	0	0	0	0	0	0	0	5	98	215	310	361	362	325	248	156	54	0	0	0	0	0	0	0
December	0	0	0	0	0	0	0	0	39	119	207	263	279	303	252	153	35	0	0	0	0	0	0	0
Year	0	0	0	0	0	3	50	141	267	399	507	567	590	579	510	406	276	147	55	6	0	0	0	0

Figure B.6: Hourly average values of global horizontal irradiation in Portejões, Viseu.

B.2 15 W/17,000 mAh System

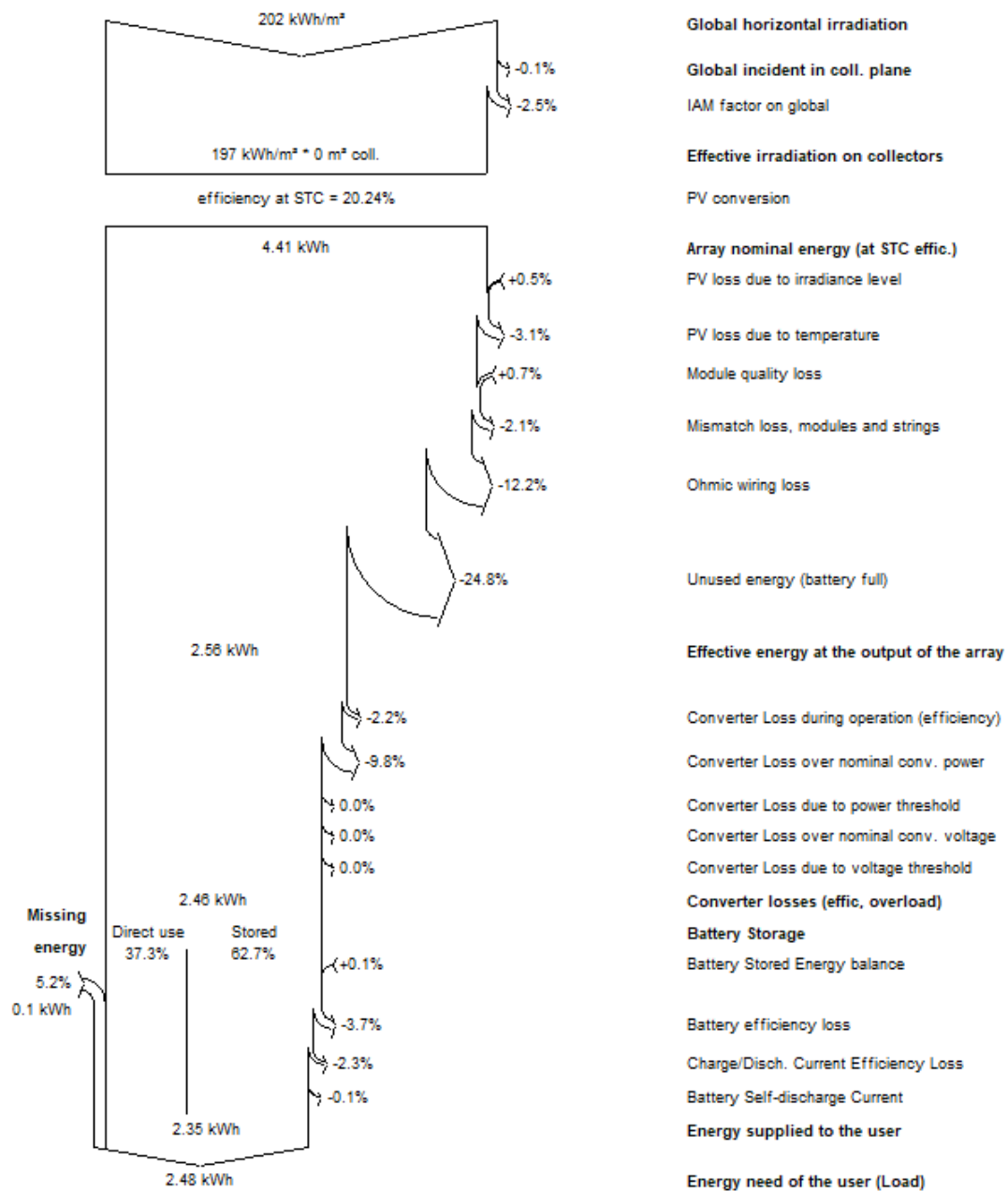


Figure B.7: Loss diagram of the 15 W/17,000 mAh system in May.

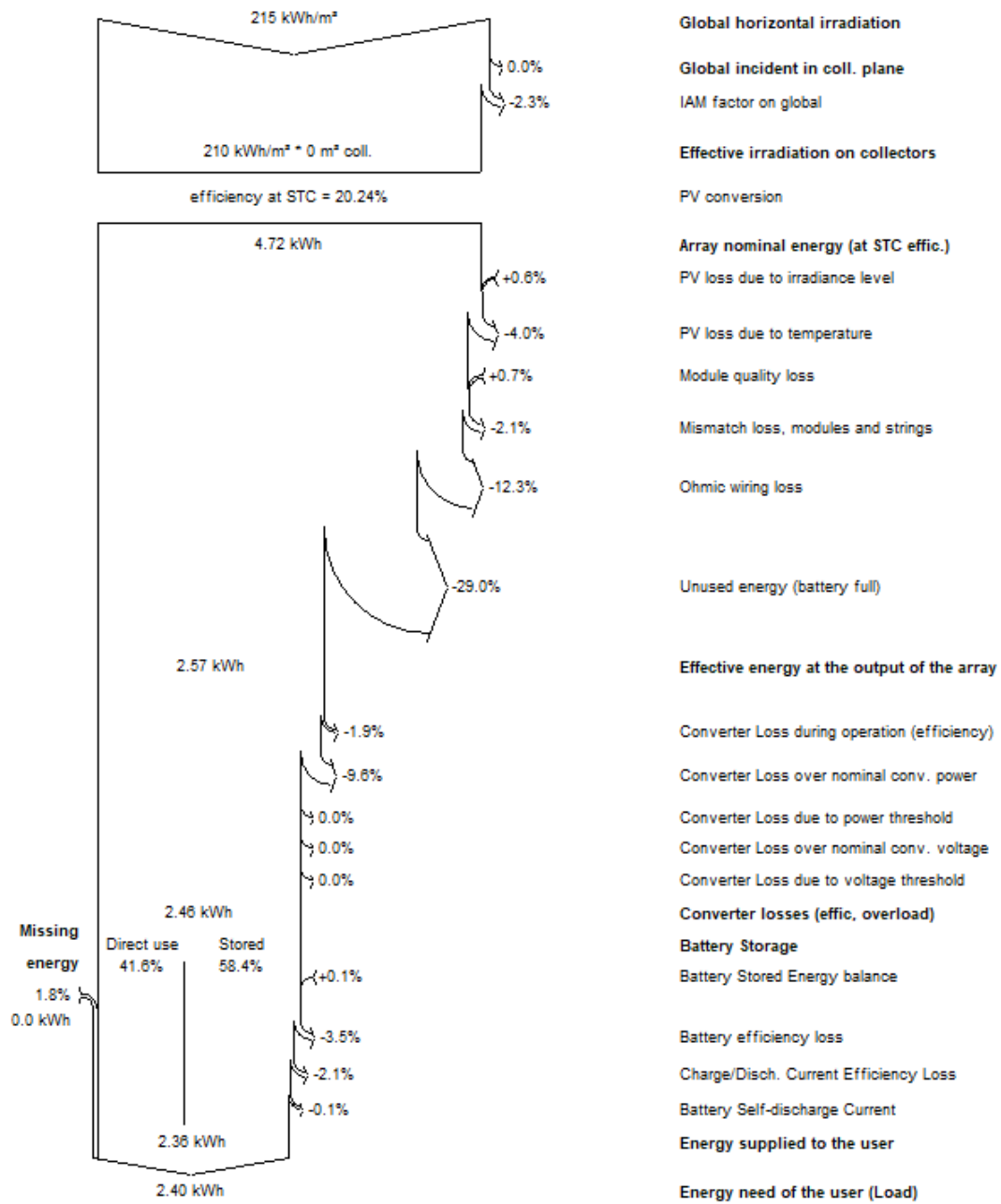


Figure B.8: Loss diagram of the 15 W/17,000 mAh system in June.

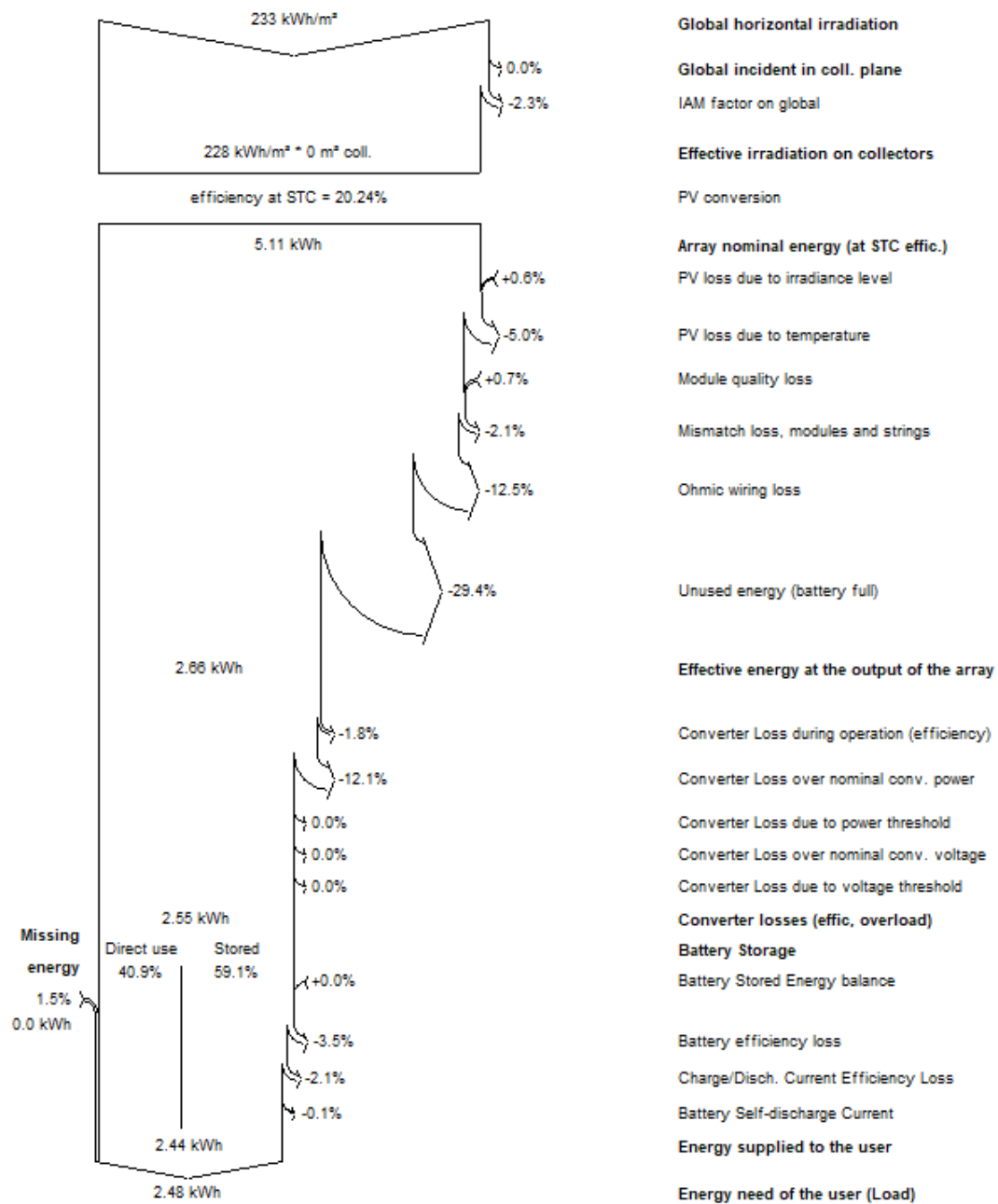


Figure B.9: Loss diagram of the 15 W/17,000 mAh system in July.

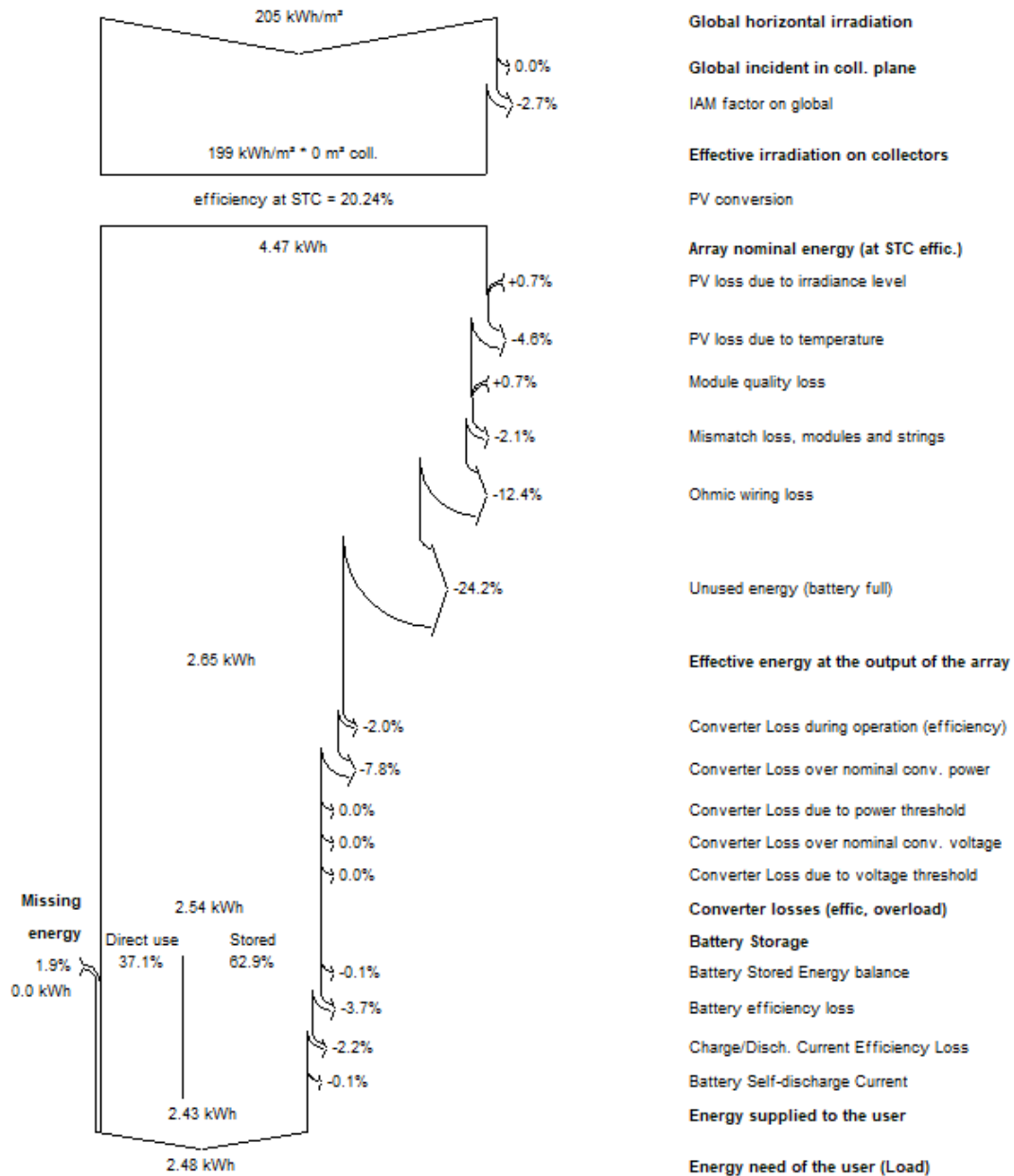


Figure B.10: Loss diagram of the 15 W/17,000 mAh system in August.

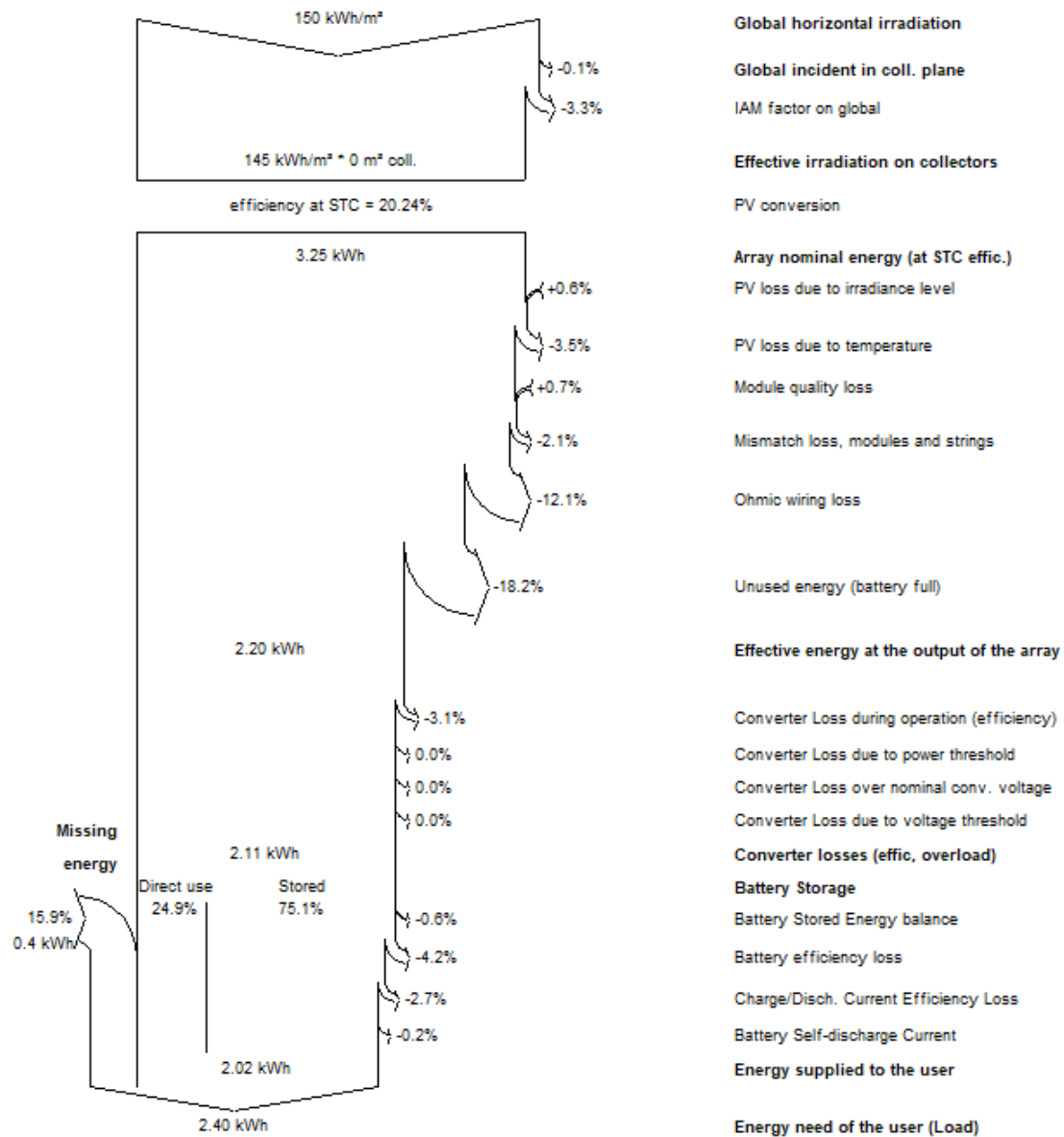


Figure B.11: Loss diagram of the 15 W/17,000 mAh system in September.

Balances and main results

	GlobHor kWh/m ²	GlobEff kWh/m ²	E_Avail kWh	EUnused kWh	E_Miss kWh	E_User kWh	E_Load kWh	SolFrac ratio
January	58.0	53.5	0.987	0.000	1.523	0.957	2.480	0.386
February	80.6	76.1	1.439	0.141	1.045	1.195	2.240	0.534
March	127.9	123.0	2.302	0.535	0.815	1.665	2.480	0.672
April	156.3	151.6	2.742	0.588	0.347	2.053	2.400	0.855
May	201.7	196.5	3.379	0.921	0.128	2.352	2.480	0.948
June	215.3	210.4	3.606	1.146	0.043	2.357	2.400	0.982
July	232.9	227.5	3.788	1.241	0.037	2.443	2.480	0.985
August	204.7	199.1	3.436	0.898	0.048	2.432	2.480	0.981
September	149.7	144.8	2.573	0.480	0.408	1.992	2.400	0.830
October	101.1	96.4	1.770	0.172	0.992	1.488	2.480	0.600
November	64.0	59.6	1.099	0.016	1.386	1.014	2.400	0.423
December	51.2	46.6	0.838	0.000	1.694	0.786	2.480	0.317
Year	1643.4	1585.1	27.958	6.137	8.464	20.736	29.200	0.710

Figure B.12: Energy results of the 15 W/17,000 mAh system throughout the year.

Monthly Hourly averages for ArrayON [Hour]																									
		0H	1H	2H	3H	4H	5H	6H	7H	8H	9H	10H	11H	12H	13H	14H	15H	16H	17H	18H	19H	20H	21H	22H	23H
	January	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.84	0.97	1.00	1.00	1.00	0.97	0.84	0.74	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	February	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.71	0.93	0.96	1.00	1.00	1.00	1.00	0.96	0.89	0.21	0.00	0.00	0.00	0.00	0.00	0.00
	March	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.45	0.97	0.97	0.97	1.00	1.00	1.00	1.00	1.00	1.00	0.90	0.00	0.00	0.00	0.00	0.00	0.00
	April	0.00	0.00	0.00	0.00	0.00	0.00	0.30	0.97	0.97	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.93	0.87	0.27	0.00	0.00	0.00	0.00	0.00
	May	0.00	0.00	0.00	0.00	0.00	0.00	0.97	0.97	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.97	0.00	0.00	0.00	0.00	0.00
	June	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.97	0.00	0.00	0.00	0.00	0.00
	July	0.00	0.00	0.00	0.00	0.00	0.00	0.97	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.94	0.00	0.00	0.00	0.00	0.00
	August	0.00	0.00	0.00	0.00	0.00	0.00	0.61	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.84	0.00	0.00	0.00	0.00	0.00
	September	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.93	0.93	0.97	1.00	1.00	1.00	1.00	0.97	0.97	0.93	0.87	0.00	0.00	0.00	0.00	0.00	0.00
	October	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.45	0.90	0.97	1.00	1.00	0.97	1.00	1.00	1.00	0.90	0.03	0.00	0.00	0.00	0.00	0.00	0.00
	November	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.73	0.93	0.97	0.97	1.00	0.97	0.93	0.80	0.27	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	December	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.65	0.90	0.90	0.90	1.00	0.94	0.90	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Year	0.00	0.00	0.00	0.00	0.00	0.00	0.32	0.57	0.78	0.94	0.98	0.99	0.99	1.00	0.98	0.96	0.81	0.58	0.33	0.00	0.00	0.00	0.00	0.00

Figure B.13: Monthly hourly averages of the duration that the PV is on of the 15 W/17,000 mAh system throughout the year.

Monthly Hourly sums for E_User [kWh]																								
	0H	1H	2H	3H	4H	5H	6H	7H	8H	9H	10H	11H	12H	13H	14H	15H	16H	17H	18H	19H	20H	21H	22H	23H
January	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.01	0.02	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.27	0.27	0.23	0.11	0.00	0.00
February	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.17	0.00	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.27	0.27	0.25	0.21	0.00	0.00
March	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.23	0.08	0.02	0.13	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.31	0.31	0.30	0.29	0.00	0.00
April	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.27	0.21	0.17	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.30	0.30	0.30	0.29	0.00	0.00
May	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.31	0.30	0.26	0.24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.31	0.31	0.31	0.31	0.00	0.00
June	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.29	0.29	0.29	0.29	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.30	0.30	0.30	0.30	0.00	0.00
July	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.31	0.31	0.29	0.29	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.31	0.31	0.31	0.31	0.00	0.00
August	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.31	0.31	0.29	0.28	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.31	0.31	0.31	0.31	0.00	0.00
September	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.27	0.20	0.14	0.18	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.30	0.30	0.30	0.29	0.00	0.00
October	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.21	0.05	0.00	0.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.31	0.31	0.28	0.25	0.00	0.00
November	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.07	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.30	0.29	0.20	0.13	0.00	0.00
December	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.29	0.27	0.15	0.05	0.00	0.00
Year	0.00	0.00	0.00	0.00	0.00	0.00	0.00	2.48	1.76	1.49	1.77	0.00	0.00	0.00	0.00	0.00	0.00	0.00	3.58	3.54	3.25	2.86	0.00	0.00

Figure B.14: Monthly hourly sum of the energy delivered to the user in the 15 W/17,000 mAh system throughout the year.

Monthly Hourly averages for SOC_End [ratio]																								
	0H	1H	2H	3H	4H	5H	6H	7H	8H	9H	10H	11H	12H	13H	14H	15H	16H	17H	18H	19H	20H	21H	22H	23H
January	0.15	0.15	0.15	0.15	0.15	0.15	0.15	0.13	0.12	0.15	0.21	0.30	0.40	0.49	0.57	0.62	0.64	0.64	0.64	0.48	0.33	0.20	0.14	0.14
February	0.22	0.22	0.22	0.22	0.22	0.22	0.22	0.10	0.12	0.19	0.29	0.42	0.56	0.69	0.79	0.84	0.85	0.86	0.69	0.52	0.36	0.22	0.22	
March	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.13	0.15	0.25	0.32	0.48	0.65	0.81	0.87	0.90	0.91	0.92	0.75	0.57	0.41	0.24	0.24	
April	0.27	0.27	0.27	0.27	0.27	0.27	0.27	0.17	0.15	0.21	0.27	0.44	0.63	0.80	0.91	0.94	0.95	0.95	0.78	0.61	0.44	0.27	0.27	
May	0.29	0.29	0.29	0.29	0.29	0.29	0.32	0.24	0.22	0.26	0.32	0.50	0.68	0.86	0.93	0.95	0.96	0.97	0.80	0.64	0.47	0.29	0.29	
June	0.30	0.30	0.30	0.30	0.30	0.30	0.34	0.27	0.26	0.28	0.32	0.52	0.71	0.89	0.94	0.95	0.96	0.96	0.80	0.63	0.47	0.30	0.30	
July	0.31	0.31	0.31	0.31	0.31	0.31	0.34	0.27	0.26	0.29	0.34	0.54	0.73	0.90	0.95	0.97	0.98	0.98	0.81	0.65	0.48	0.31	0.31	
August	0.32	0.32	0.32	0.32	0.32	0.32	0.33	0.23	0.19	0.21	0.26	0.46	0.66	0.85	0.96	0.98	0.98	0.98	0.82	0.66	0.49	0.32	0.32	
September	0.28	0.28	0.28	0.28	0.28	0.28	0.28	0.16	0.14	0.19	0.26	0.44	0.62	0.79	0.90	0.93	0.94	0.95	0.78	0.61	0.44	0.28	0.28	
October	0.23	0.23	0.23	0.23	0.23	0.23	0.23	0.12	0.14	0.23	0.31	0.44	0.58	0.71	0.81	0.85	0.86	0.86	0.69	0.52	0.36	0.23	0.23	
November	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.10	0.12	0.18	0.26	0.37	0.48	0.57	0.64	0.68	0.68	0.68	0.51	0.34	0.22	0.14	0.14	
December	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.11	0.14	0.19	0.27	0.35	0.44	0.51	0.55	0.55	0.55	0.38	0.23	0.14	0.11	0.11	
Year	0.24	0.24	0.24	0.24	0.24	0.24	0.25	0.17	0.17	0.22	0.28	0.43	0.59	0.73	0.82	0.84	0.85	0.86	0.69	0.53	0.37	0.24	0.24	

Figure B.15: Monthly hourly averages of the state of charge of the batteries in the 15 W/17,000 mAh system throughout the year.

B.3 Selection of the main components

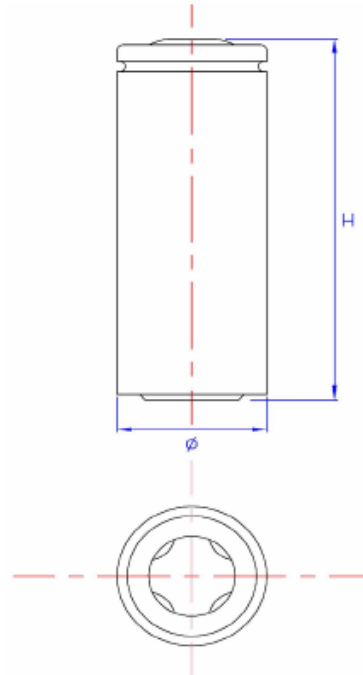
cylindrical Lithium-ion battery Product Specification	Doc. No.	<u>APL-20131007</u>
	Edition No.	1.0
	Sheet	2/10

1.1 Li-ion Battery Pack Data Sheet

Type-----	Li-ion battery Pack	
Model-----	ICR18650 3.7V 2200mAh	
Normal Voltage-----	3.7V	
Weight-----	48 g (ref)	
C5mAh-----	2200mAh	
Charge voltage-----	4.20 $\pm$ 0.05V	
Minimum discharge end voltage-----	2.75V	
Maximum charge voltage-----	4.2V	
Standard continuous charge current-----	0.2C5mA	
Maximum continuous charge current-----	2200mA	
Maximum continuous discharge current-----	2200mA	
Capacity (20} C150C, 0.2Cs to 3.0V)		
Nominal capacity-----	2200mAh	
Minimum capacity-----	2180mAh	
Internal impedance(200C $\pm$ 50C AC Impedance 1 KHz)-----	$\leq$ 260m Ω	
Charge and discharge conditions (20°C)		
Standard charge-----	Constant current and constant voltage (CC/CV)	
Current=0.2C5mA Voltage=4.20V End Current=0.01C5mA		
Fast charge-----	Constant current and constant voltage (CC/CV)	
Current=1500mA Voltage=4.20V End Current=0.01C5mA		
Standard discharge-----	Constant current (CC)	
Current=0.2C5mA End Voltage=3.0V		
Operation conditions (recommended)		
Standard charge-----	0--45°C	
Discharge-----	-20°C--60°C	
Storage humidity		
Relative humidity-----	45-75	
Temperature range for Storage (Percentage of recoverable capacity 80%)		
1 month-----	-20+60°C	
3 months-----	-20+45°C	
1 year-----	-20+20°C	
Standard Test Conditions (Except additional quest)		
Temperature-----	20°C $\pm$ 50C	
Relative humidity-----	65 $\pm$ 20%	

Figure B.16: 2,200 mAh battery data sheet part 1.

Cylindrical Lithium-ion battery Product Specification	Doc. No.	<u>APL-20131007</u>
	Edition No.	1.0
	Sheet	3/10



1.3 Specification

Item	Specifications		Remark
Nominal Capacity	<u>2200mAh</u> ±2%		0.2C ₅ A discharge, 25℃
Nominal Voltage	3.7V		Average Voltage at 0.2C ₅ A discharge
Standard Charge Current	0.2 C ₅ A		Working temperature: 0~40℃
Max Charge Current	1C ₅ A		Working temperature: 0~40℃
Charge cut-off Voltage	4.2V		CC/CV
Standard Discharge Current	0.5C ₅ A		Working temperature: 25℃
Discharge cut-off Voltage	2.75V		
Cell Voltage	3.7-3.9V		When leave factory
Impedance	≤35mΩ		AC 1KHz after 50% charge, 25℃
Weight	Approx:48.0g		
Storage temperature	≤1month	-10~45℃	Best 20±5℃ for long-time storage
	≤3month	0~30℃	
	≤6month	20±5℃	
Storage humidity	65±20% RH		

Figure B.17: 2,200 mAh battery data sheet part 2.

Discharge Characteristics

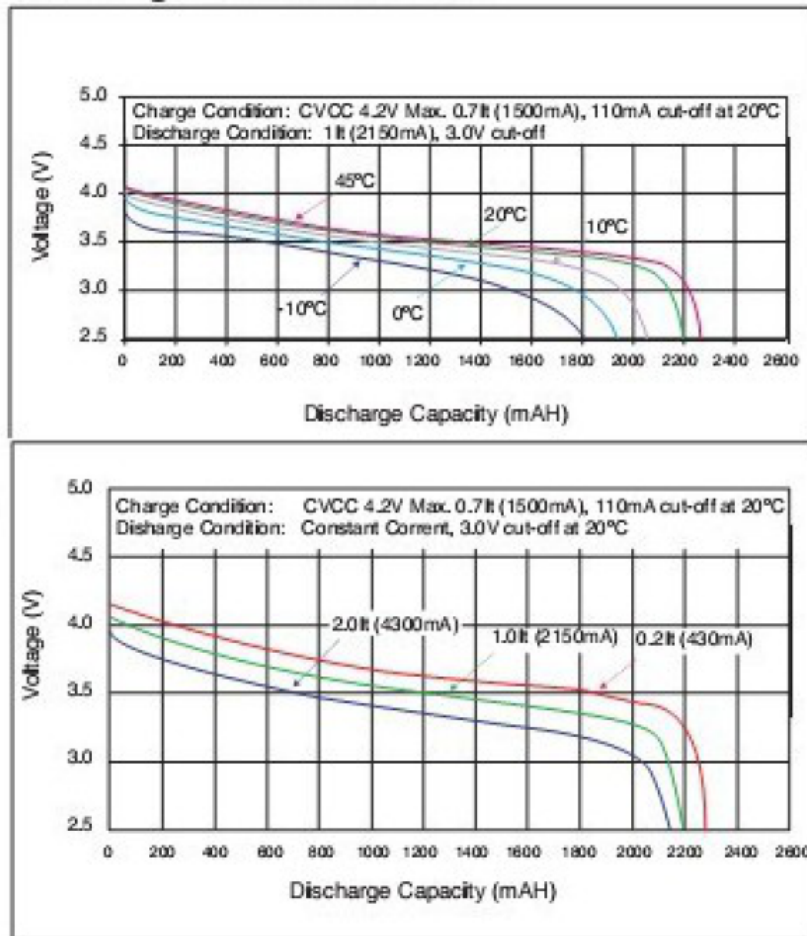


Figure B.18: 2,200 mAh battery data sheet part 3.

Light Output Characteristics

Relative Light Output vs. Junction Temperature at 350mA

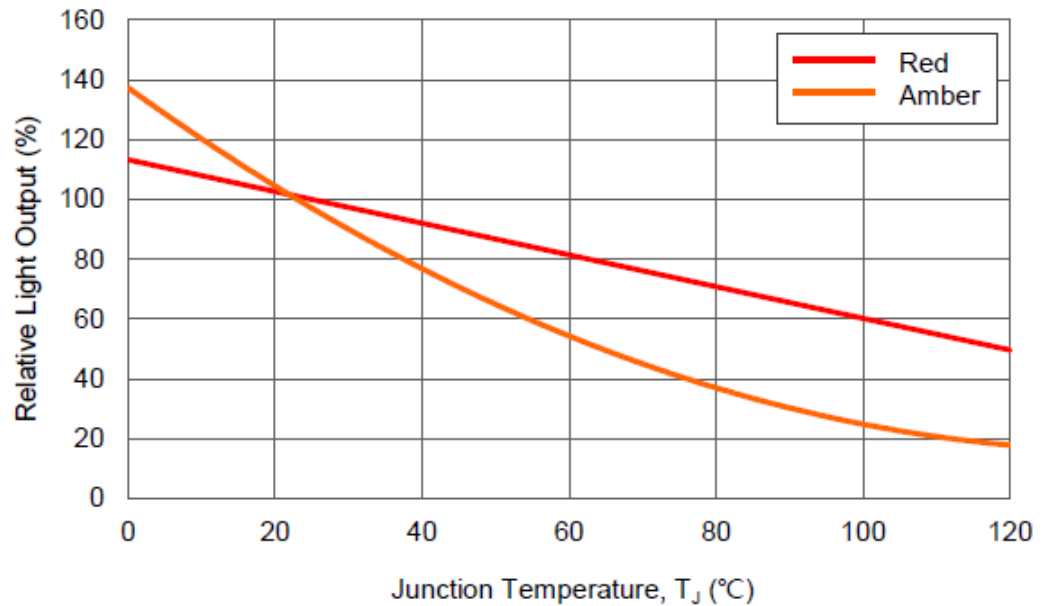
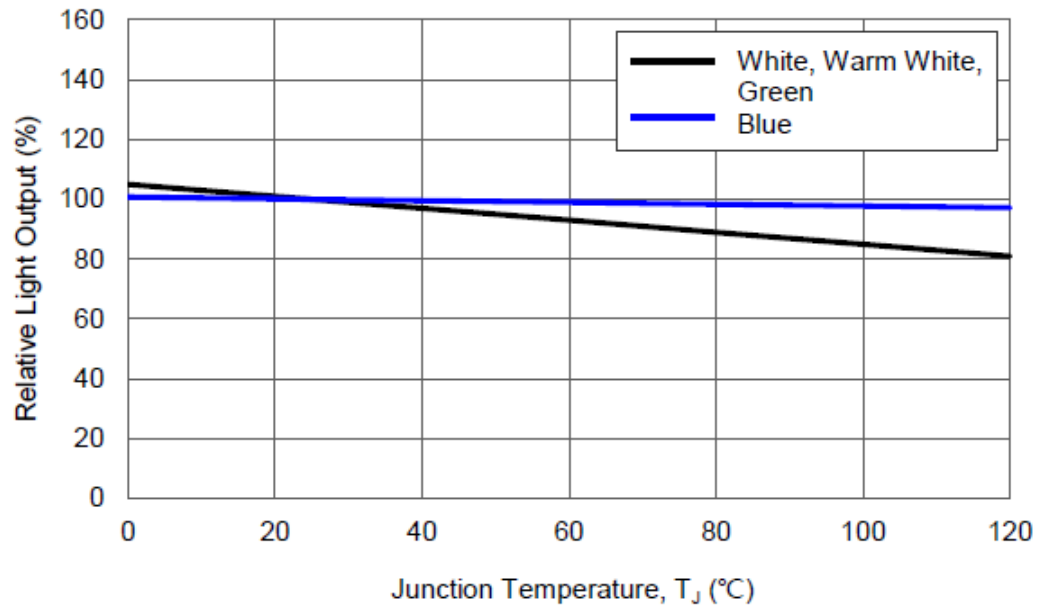
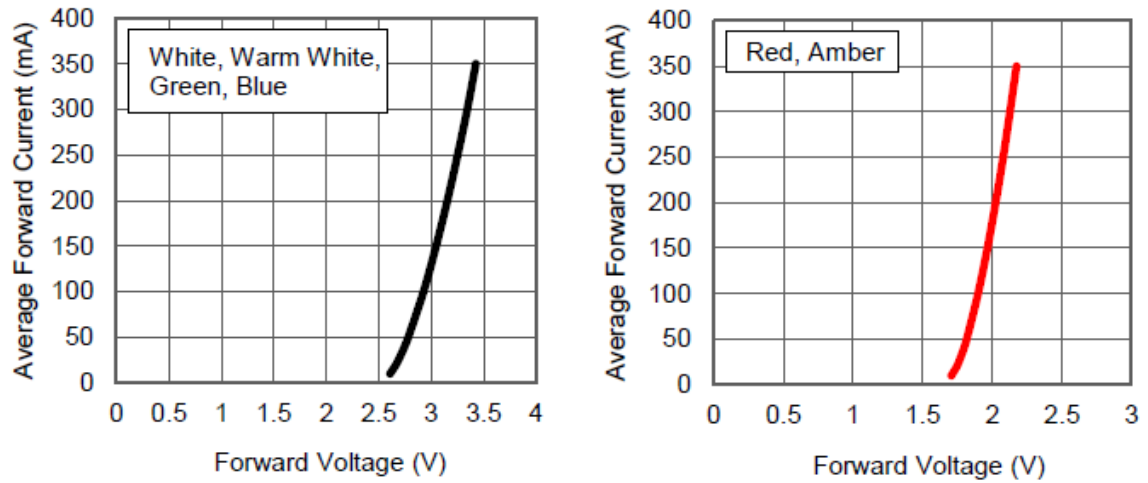


Figure B.19: Relative light output vs junction temperature at 350 mA for different colour LEDs [96].

Forward Current Characteristics, $T_J = 25^\circ\text{C}$

1. Forward Voltage vs. Forward Current



2. Forward Current vs. Normalized Relative Luminous Flux

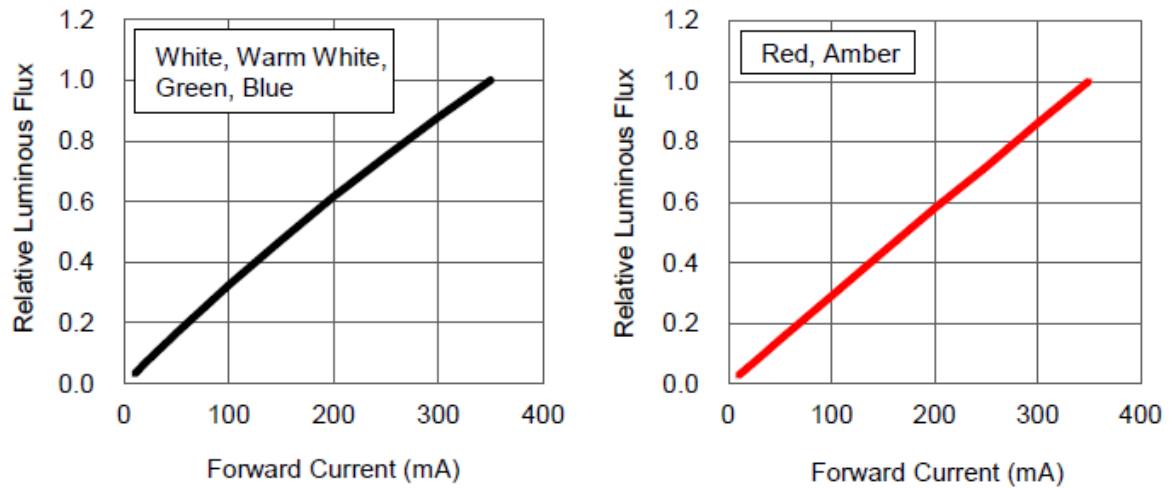
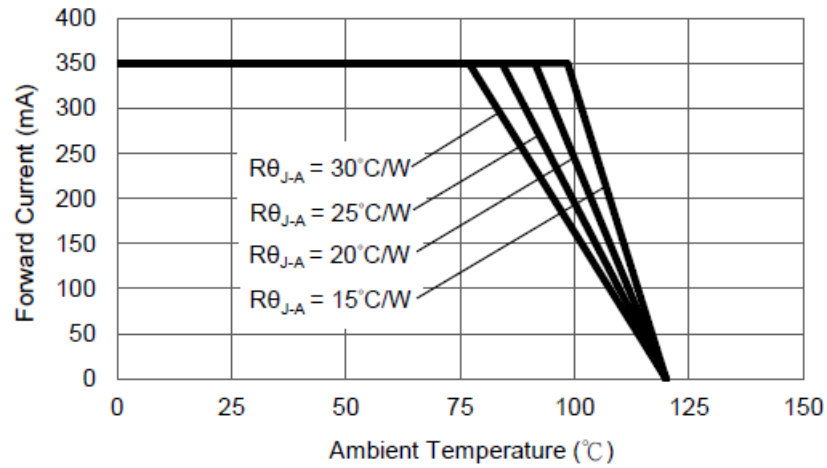


Figure B.20: Forward current characteristics for different colour LEDs at junction temperature of 25°C [96].

Ambient Temperature vs. Maximum Forward Current

1. White, Warm White, Green, Blue ($T_{JMAX} = 120^{\circ}\text{C}$)



2. Red, Amber ($T_{JMAX} = 120^{\circ}\text{C}$)

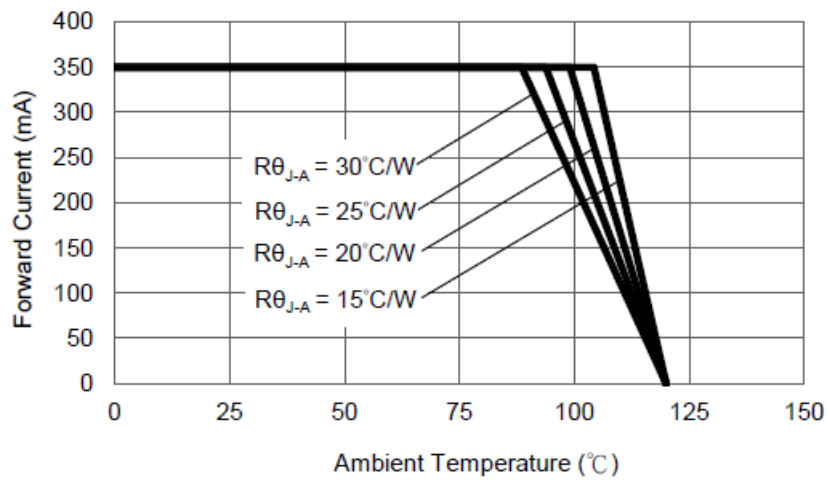


Figure B.21: Ambient temperature vs maximum forward current for different colour LEDs [96].

B.4 15 W/22,000 mAh System

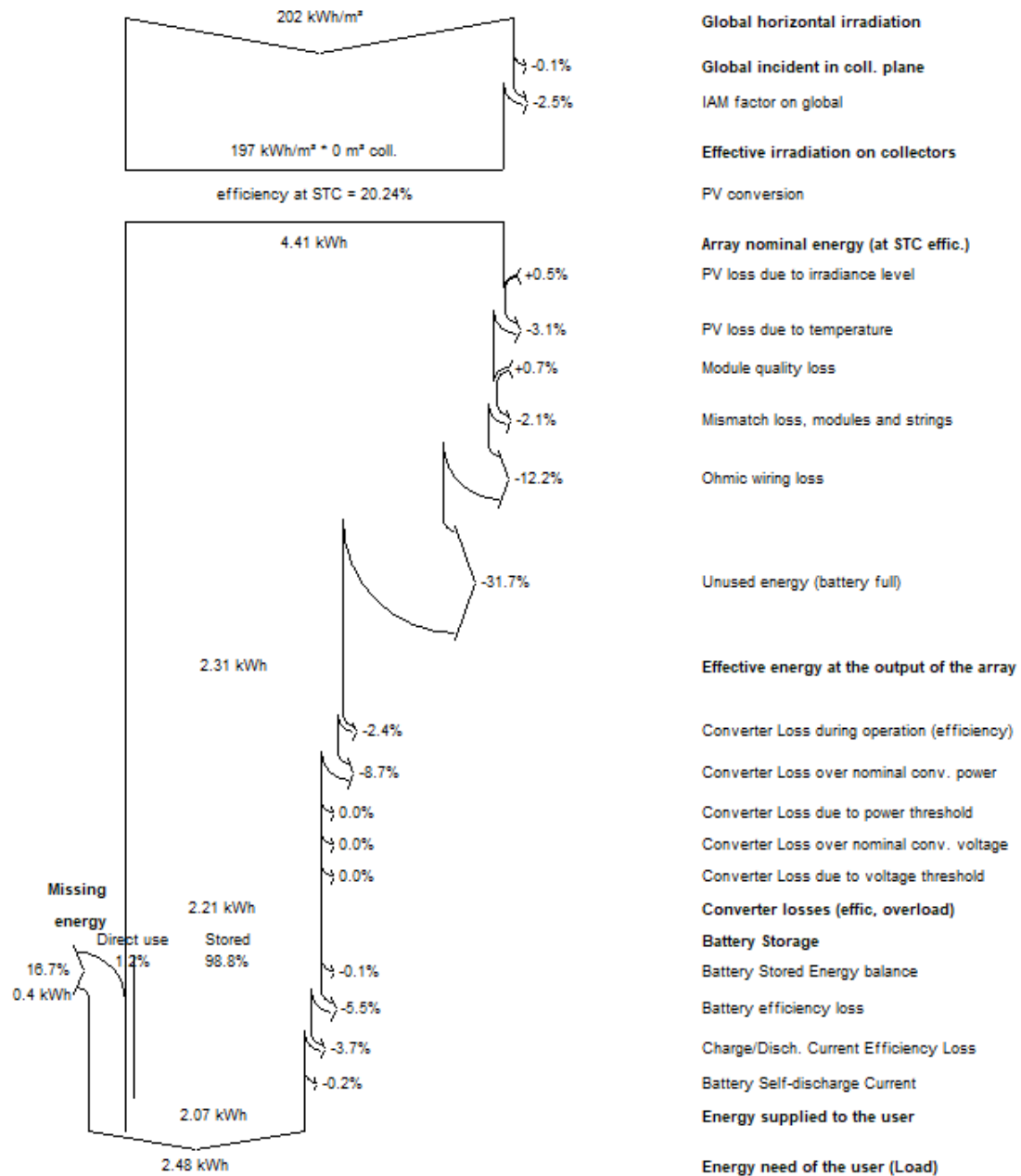


Figure B.22: Loss diagram of the 15 W/22,000 mAh system in May.

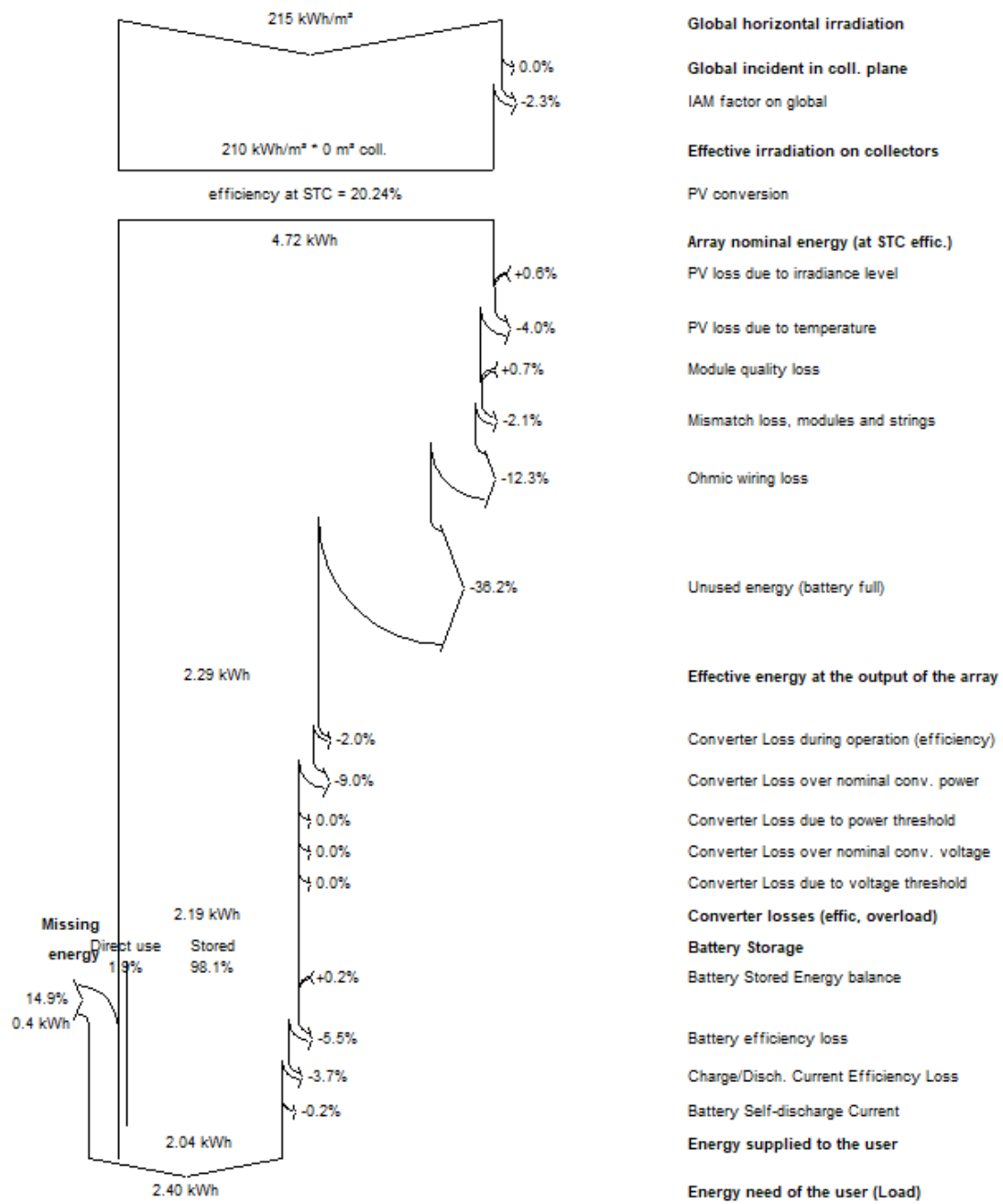


Figure B.23: Loss diagram of the 15 W/22,000 mAh system in June.

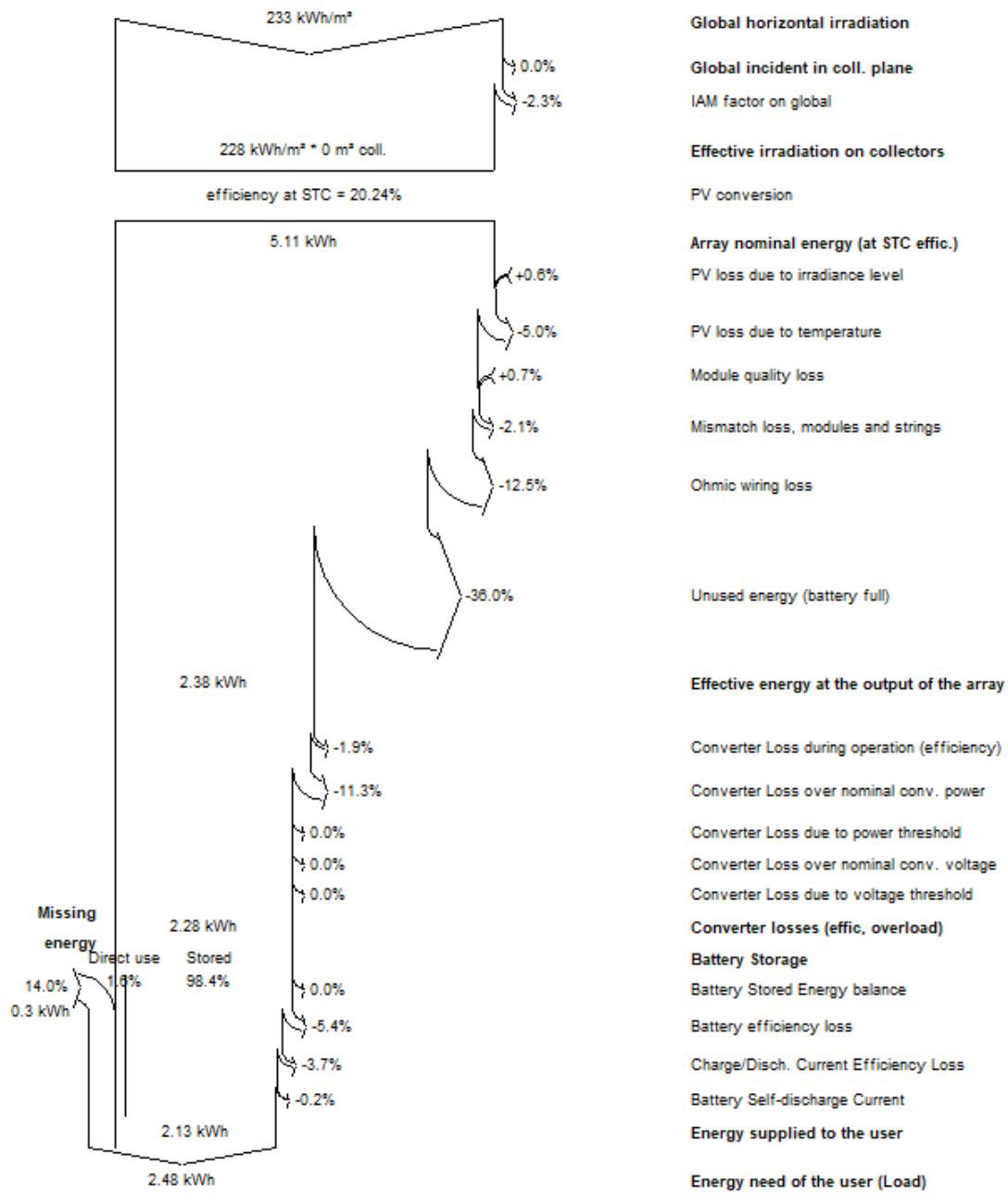


Figure B.24: Loss diagram of the 15 W / 22,000 mAh system in July.

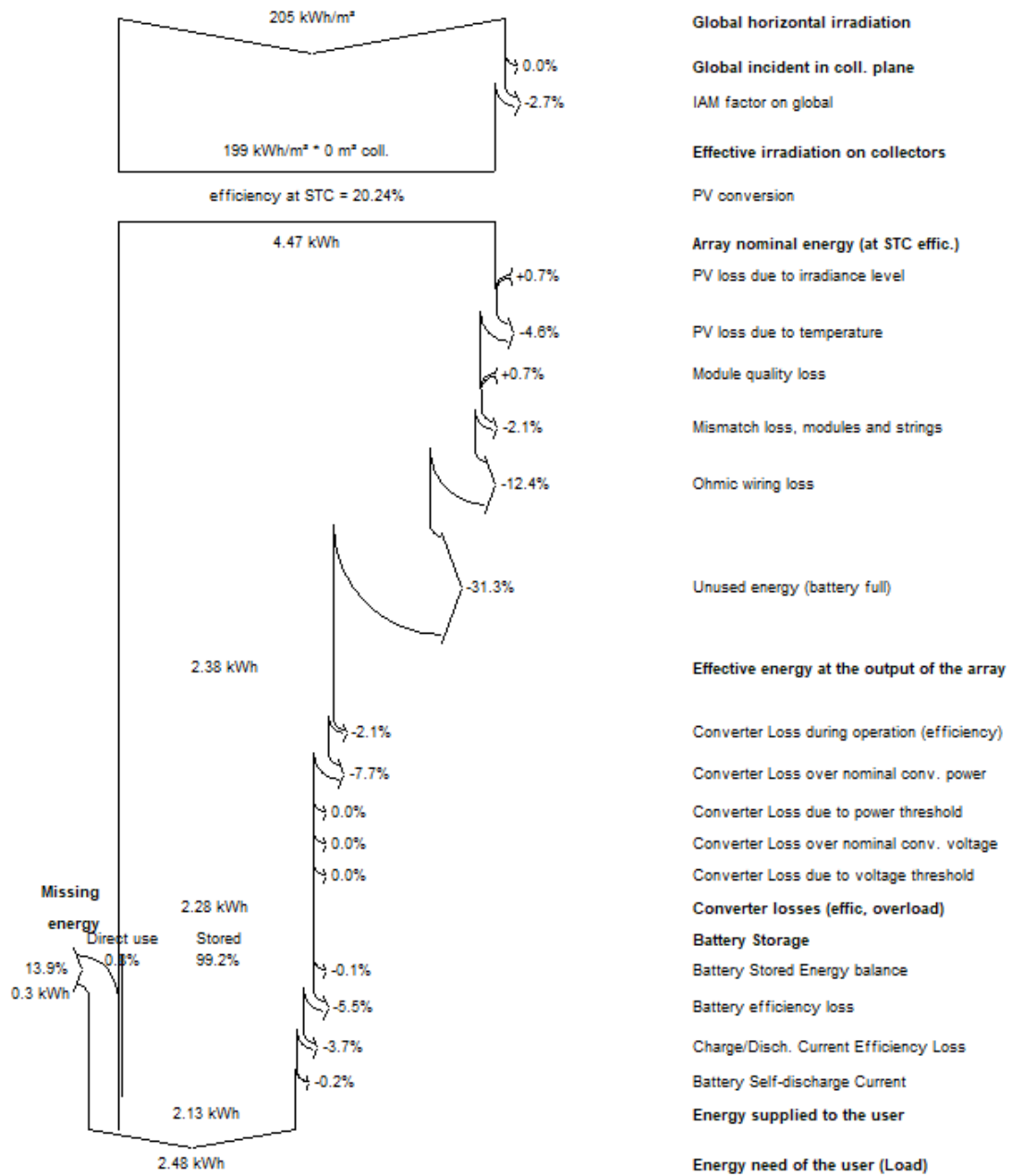


Figure B.25: Loss diagram of the 15 W/22,000 mAh system in August.

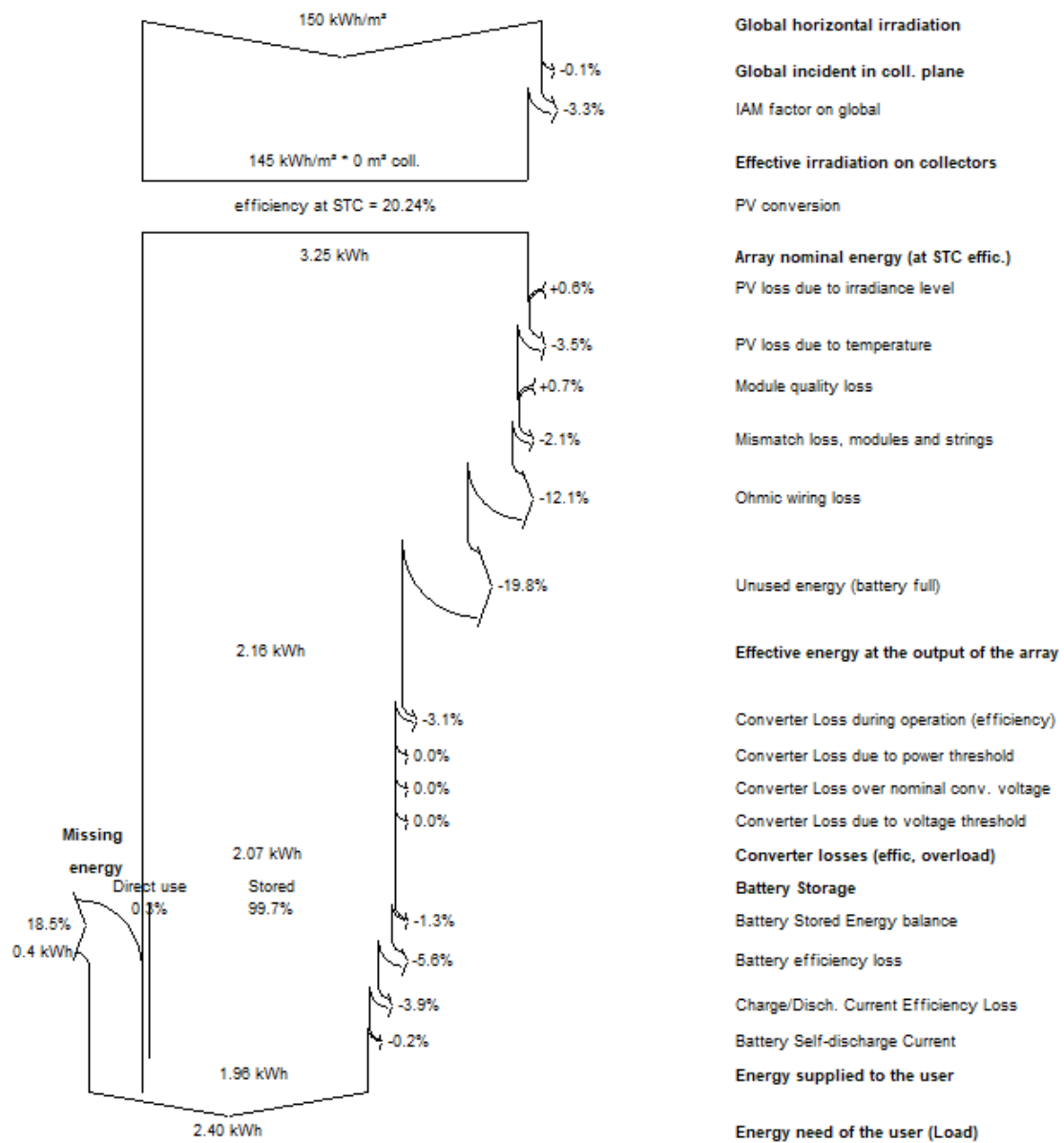


Figure B.26: Loss diagram of the 15 W/22,000 mAh system in September.

Balances and main results

	GlobHor kWh/m ²	GlobEff kWh/m ²	E_Avail kWh	EUnused kWh	E_Miss kWh	E_User kWh	E_Load kWh	SolFrac ratio
January	58.0	53.5	0.987	0.000	1.537	0.943	2.480	0.380
February	80.6	76.1	1.434	0.015	0.925	1.315	2.240	0.587
March	127.9	123.0	2.296	0.377	0.713	1.767	2.480	0.713
April	156.3	151.6	2.748	0.741	0.531	1.869	2.400	0.779
May	201.7	196.5	3.390	1.179	0.414	2.066	2.480	0.833
June	215.3	210.4	3.618	1.428	0.357	2.043	2.400	0.851
July	232.9	227.5	3.800	1.516	0.346	2.134	2.480	0.860
August	204.7	199.1	3.447	1.163	0.346	2.134	2.480	0.861
September	149.7	144.8	2.577	0.561	0.518	1.882	2.400	0.784
October	101.1	96.4	1.766	0.085	0.894	1.586	2.480	0.640
November	64.0	59.6	1.097	0.000	1.386	1.014	2.400	0.423
December	51.2	46.6	0.838	0.000	1.707	0.773	2.480	0.312
Year	1643.4	1585.1	27.997	7.065	9.673	19.527	29.200	0.669

Figure B.27: Energy results of the 15 W/22,000 mAh system throughout the year.

Monthly Hourly averages for ArrayON [Hour]																								
	0H	1H	2H	3H	4H	5H	6H	7H	8H	9H	10H	11H	12H	13H	14H	15H	16H	17H	18H	19H	20H	21H	22H	23H
January	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.03	0.84	0.97	1.00	1.00	1.00	0.97	0.84	0.74	0.00	0.00	0.00	0.00	0.00	0.00	0.00
February	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.71	0.93	0.96	1.00	1.00	1.00	1.00	0.96	0.89	0.21	0.00	0.00	0.00	0.00	0.00	0.00
March	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.45	0.97	0.97	0.97	1.00	1.00	1.00	1.00	1.00	1.00	0.90	0.00	0.00	0.00	0.00	0.00	0.00
April	0.00	0.00	0.00	0.00	0.00	0.00	0.30	0.97	0.97	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.93	0.87	0.27	0.00	0.00	0.00	0.00	0.00
May	0.00	0.00	0.00	0.00	0.00	0.00	0.97	0.97	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.97	0.00	0.00	0.00	0.00	0.00
June	0.00	0.00	0.00	0.00	0.00	0.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.97	0.00	0.00	0.00	0.00	0.00
July	0.00	0.00	0.00	0.00	0.00	0.00	0.97	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.94	0.00	0.00	0.00	0.00	0.00
August	0.00	0.00	0.00	0.00	0.00	0.00	0.61	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	0.84	0.00	0.00	0.00	0.00	0.00
September	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.93	0.93	0.97	1.00	1.00	1.00	1.00	0.97	0.97	0.93	0.87	0.00	0.00	0.00	0.00	0.00	0.00
October	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.45	0.90	0.97	1.00	1.00	0.97	1.00	1.00	1.00	0.90	0.03	0.00	0.00	0.00	0.00	0.00	0.00
November	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.73	0.93	0.97	0.97	1.00	0.97	0.93	0.80	0.27	0.00	0.00	0.00	0.00	0.00	0.00	0.00
December	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.10	0.65	0.90	0.90	0.90	1.00	0.94	0.90	0.03	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Year	0.00	0.00	0.00	0.00	0.00	0.00	0.32	0.57	0.78	0.94	0.98	0.99	0.99	1.00	0.98	0.96	0.81	0.58	0.33	0.00	0.00	0.00	0.00	0.00

Figure B.28: Monthly hourly averages of the duration that the PV is on of the 15 W/22,000 mAh system throughout the year.

Monthly Hourly sums for E_User [kWh]																								
	0H	1H	2H	3H	4H	5H	6H	7H	8H	9H	10H	11H	12H	13H	14H	15H	16H	17H	18H	19H	20H	21H	22H	23H
January	0.00	0.00	0.00	0.00	0.00	0.07	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.52	0.34	0.00	0.00
February	0.00	0.00	0.00	0.00	0.00	0.28	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.54	0.47	0.00	0.00
March	0.00	0.00	0.00	0.00	0.00	0.45	0.12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.62	0.58	0.00	0.00
April	0.00	0.00	0.00	0.00	0.00	0.52	0.16	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.60	0.59	0.00	0.00
May	0.00	0.00	0.00	0.00	0.00	0.61	0.22	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.62	0.62	0.00	0.00
June	0.00	0.00	0.00	0.00	0.00	0.59	0.25	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.60	0.60	0.00	0.00
July	0.00	0.00	0.00	0.00	0.00	0.62	0.28	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.62	0.62	0.00	0.00
August	0.00	0.00	0.00	0.00	0.00	0.62	0.27	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.62	0.62	0.00	0.00
September	0.00	0.00	0.00	0.00	0.00	0.50	0.19	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.60	0.60	0.00	0.00
October	0.00	0.00	0.00	0.00	0.00	0.37	0.08	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.60	0.54	0.00	0.00
November	0.00	0.00	0.00	0.00	0.00	0.12	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.52	0.38	0.00	0.00
December	0.00	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.48	0.28	0.00	0.00
Year	0.00	0.00	0.00	0.00	0.00	4.76	1.59	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	6.93	6.24	0.00	0.00

Figure B.29: Monthly hourly sum of the energy delivered to the user in the 15 W/22,000 mAh system throughout the year.

Monthly Hourly averages for SOC_End [ratio]

	0H	1H	2H	3H	4H	5H	6H	7H	8H	9H	10H	11H	12H	13H	14H	15H	16H	17H	18H	19H	20H	21H	22H	23H
January	0.14	0.14	0.14	0.14	0.14	0.11	0.10	0.10	0.10	0.13	0.18	0.25	0.33	0.40	0.47	0.50	0.51	0.51	0.51	0.51	0.28	0.12	0.12	0.12
February	0.24	0.24	0.24	0.24	0.24	0.09	0.08	0.08	0.09	0.15	0.23	0.34	0.45	0.55	0.64	0.71	0.74	0.74	0.74	0.74	0.48	0.24	0.24	0.24
March	0.33	0.33	0.33	0.33	0.33	0.13	0.08	0.08	0.13	0.22	0.33	0.46	0.59	0.72	0.82	0.85	0.86	0.87	0.87	0.87	0.60	0.34	0.34	0.34
April	0.39	0.39	0.38	0.38	0.38	0.14	0.07	0.11	0.19	0.31	0.44	0.58	0.72	0.84	0.88	0.90	0.91	0.92	0.92	0.92	0.65	0.38	0.38	0.38
May	0.43	0.43	0.43	0.43	0.43	0.16	0.08	0.15	0.26	0.40	0.54	0.69	0.83	0.90	0.93	0.94	0.96	0.96	0.96	0.96	0.70	0.43	0.43	0.43
June	0.45	0.45	0.45	0.45	0.45	0.18	0.09	0.17	0.28	0.42	0.57	0.73	0.88	0.95	0.95	0.96	0.97	0.97	0.97	0.97	0.71	0.45	0.45	0.45
July	0.45	0.45	0.45	0.45	0.45	0.18	0.09	0.16	0.27	0.42	0.58	0.73	0.88	0.95	0.96	0.97	0.97	0.98	0.98	0.98	0.72	0.45	0.45	0.45
August	0.45	0.45	0.45	0.45	0.45	0.18	0.06	0.12	0.21	0.35	0.50	0.65	0.81	0.93	0.95	0.96	0.97	0.97	0.97	0.97	0.71	0.45	0.45	0.45
September	0.38	0.38	0.38	0.38	0.38	0.15	0.06	0.09	0.16	0.26	0.39	0.53	0.68	0.81	0.86	0.89	0.90	0.90	0.90	0.90	0.64	0.38	0.38	0.38
October	0.28	0.28	0.28	0.28	0.28	0.12	0.08	0.09	0.13	0.20	0.29	0.40	0.51	0.62	0.70	0.75	0.77	0.77	0.77	0.77	0.51	0.27	0.27	0.27
November	0.17	0.17	0.17	0.17	0.17	0.12	0.12	0.12	0.13	0.18	0.25	0.34	0.42	0.50	0.55	0.58	0.59	0.59	0.59	0.59	0.35	0.17	0.17	0.17
December	0.13	0.13	0.13	0.13	0.13	0.12	0.12	0.12	0.12	0.14	0.19	0.25	0.32	0.39	0.44	0.47	0.47	0.47	0.47	0.47	0.26	0.13	0.13	0.13
Year	0.32	0.32	0.32	0.32	0.32	0.14	0.09	0.12	0.17	0.26	0.38	0.50	0.62	0.71	0.76	0.79	0.80	0.80	0.80	0.80	0.55	0.32	0.32	0.32

Figure B.30: Monthly hourly averages of the state of charge of the batteries in the 15 W/22,000 mAh system throughout the year.

Appendix C

Control system design

(VCC=15V, T_A=−40°C to 85°C, unless otherwise noted)

Parameters	Symbol	Conditions	Min	Typ	Max	Unit
Input Voltage Range	VCC		4.5		28	V
Under voltage lockout Threshold	VUVLO		3.1	3.8	4.4	V
Operating Current	I _{VCC}	No switching	0.7	1.0	1.3	mA
Regulation Voltage	V _{REG}	Constant voltage mode	4.158	4.2	4.247	V
Current Sense	V _{CS}	V _{BAT} > V _{PRE} , V _{CSP} − V _{BAT}	110	120	130	mV
		V _{BAT} < V _{PRE} , V _{CSP} − V _{BAT}	10	21	36	
Current into BAT Pin	I _{BAT1}	Termination, V _{BAT} = 3.7V		10	15	uA
	I _{BAT2}	Sleep mode, V _{BAT} = 3.7V			15	
Precharge Threshold	V _{PRE}	V _{BAT} rises	64	66.5	69	%V _{REG}
Precharge Threshold Hysteresis	H _{PRE}	V _{BAT} falls		2.5		%V _{REG}
Charge Termination Threshold	I _{term}	Charge current decreases		16		%I _{CC}
Recharge Threshold	V _{RE}	V _{BAT} falls		95.5		%V _{REG}
Overvoltage Trip Level	V _{OV}	V _{BAT} rises	1.04	1.07	1.1	V _{REG}
Overvoltage Clear Level	V _{CLR}	V _{BAT} falls	1.0	1.02	1.04	
MPPT Pin						
MPPT Regulation Voltage	V _{MPPT}	Maximum power point track	1.18	1.205	1.23	V
MPPT Pin Bias Current	I _{MPPT}		−100	0	+100	nA
CHRG Pin						
CHRG Pin Sink Current	I _{CHRG}	V _{CHRG} = 1V, charge mode	7	12	18	mA
CHRG Leakage Current	I _{LK1}	V _{CHRG} = 25V, termination mode			1	uA
DONE Pin						
DONE Sink Current	I _{DONE}	V _{DONE} = 1V, termination mode	7	12	18	mA
DONE Leakage Current	I _{LK2}	V _{DONE} = 25V, charge mode			1	uA
Oscillator						
Switching Frequency	f _{OSC}		240	300	360	kHz
Maximum Duty Cycle	D _{max}			94		%
Sleep Mode						
Sleep Mode Threshold	V _{SLP}	VCC falling, V _{BAT} = 3.7V, measure VCC − V _{BAT}	0.0	0.02	0.1	V
Sleep mode Release Threshold	V _{SLPR}	VCC rising, V _{BAT} = 3.7V, measure VCC − V _{BAT}	0.26	0.32	0.39	V
DRV Pin						
V _{DRV} High (VCC − V _{DRV})	V _H	I _{DRV} = −10mA		60		mV
V _{DRV} Low (VCC − V _{DRV})	V _L	I _{DRV} = 0mA		6.3		V
Rise Time	t _r	C _{load} = 2nF, 10% to 90%	30	40	65	ns
Fall Time	t _f	C _{load} = 2nF, 90% to 10%	30	40	65	ns

Note: V_{REG} is the regulated voltage in constant voltage mode; I_{CC} is the charge current in constant current mode.

Figure C.1: Electrical characteristics of CN3791 chip [70].

(VIN=5V, TA=−40℃ to 85℃, Typical Values are measured at TA=25℃, unless otherwise noted)

Parameters	Symbol	Test Conditions	Min	Typ	Max	Unit
Input Supply Voltage	VIN		4.4		6	V
Operating Current	IVIN	Charge Termination Mode	400	650	950	uA
Undervoltage Lockout	Vuvlo	VIN falling		3.7	3.9	V
Undervoltage Lockout Hysteresis	Huvlo			0.1		V
Regulation Voltage	VREG	Constant Voltage Mode	4.158	4.2	4.242	V
BAT pin Current	IBAT	RISET=2K, VBAT=3.6V	720	900	1080	mA
		RISET=2K, VBAT=2.4V	45	90	135	
		VBAT=VREG, standby mode	1.75	3.5	7	uA
		VIN=0V, sleep mode			3	
Precharge Threshold						
Precharge Threshold	VPRE	Voltage at BAT pin rising	2.9	3.0	3.1	V
Precharge Threshold Hysteresis	HPRE			0.1		V
Charge Termination Threshold						
Charge Termination Threshold	Vterm	Measure voltage at ISET pin	0.18	0.22	0.26	V
Recharge Threshold						
Recharge Threshold	VRECH			VREG−0.1		V
Sleep Mode						
Sleep Mode Threshold	VSLP	VIN from high to low, measures the voltage (VIN−VBAT)		40		mv
Sleep mode Release Threshold	VSLPR	VIN from low to high, measures the voltage (VIN−VBAT)		90		mv
ISET Pin						
ISET Pin Voltage	VISET	Precharge mode		0.2		V
		Constant current mode		2.0		
TEMP PIN						
Input Threshold	VTEMP		43.5	46	48.5	%VIN
TEMP input Current		TEMP to VIN or to GND			0.5	uA
DONE Pin						
DONE Sink Current	IDONE	VDONE=0.3V, termination mode		10		mA
DONE Leakage Current		VDONE=6V, charge mode			1	uA
CHRG Pin						
CHRG Sink Current	ICHRG	VCHRG=0.3V, Charge status		10		mA
CHRG Leakage Current		VCHRG=6V, termination mode			1	uA

Figure C.2: Electrical characteristics of CN3065 chip [72].

Electrical Characteristics (VCC = 3.0V, DVI = 3.0V, Ta = 25°C, unless otherwise noted)

Parameter	Symbol	Limits			Units	Conditions
		Min.	Typ.	Max.		
Supply Current	Icc1	—	120	190	μA	Ev = 100 lx ^{※1}
Powerdown Current	Icc2	—	0.01	1.0	μA	No input Light
Peak Wave Length	λp	—	560	—	nm	
Measurement Accuracy	S/A	0.96	1.2	1.44	times	Sensor out / Actual lx ^{※1, ※2}
Dark (0 lx) Sensor out	S0	0	0	3	count	H-Resolution Mode ^{※3}
H-Resolution Mode Resolution	rHR	—	1	—	lx	
L-Resolution Mode Resolution	rLR	—	4	—	lx	
H-Resolution Mode Measurement Time	tHR	—	120	180	ms	
L-Resolution Mode Measurement Time	tLR	—	16	24	ms	
Incandescent / Fluorescent Sensor out ratio	rIF	—	1	—	times	EV = 1000 lx
ADDR Input 'H' Voltage	VAH	0.7 * VCC	—	—	V	
ADDR Input 'L' Voltage	VAL	—	—	0.3 * VCC	V	
DVI Input 'L' Voltage	VDVL	—	—	0.4	V	
SCL, SDA Input 'H' Voltage 1	VIH1	0.7 * DVI	—	—	V	DVI ≥ 1.8V
SCL, SDA Input 'H' Voltage 2	VIH2	1.26	—	—	V	1.65V ≤ DVI < 1.8V
SCL, SDA Input 'L' Voltage 1	VIL1	—	—	0.3 * DVI	V	DVI ≥ 1.8V
SCL, SDA Input 'L' Voltage 2	VIL2	—	—	DVI – 1.26	V	1.65V ≤ DVI < 1.8V
SCL, SDA, ADDR Input 'H' Current	IiH	—	—	10	μA	
SCL, SDA, ADDR Input 'L' Current	IiL	—	—	10	μA	
I ² C SCL Clock Frequency	fSCL	—	—	400	kHz	
I ² C Bus Free Time	tBUF	1.3	—	—	μs	
I ² C Hold Time (repeated) START Condition	tHDSTA	0.6	—	—	μs	
I ² C Set up time for a Repeated START Condition	tsUSTA	0.6	—	—	μs	
I ² C Set up time for a Repeated STOP Condition	tsUSTD	0.6	—	—	μs	
I ² C Data Hold Time	tHDDAT	0	—	0.9	μs	
I ² C Data Setup Time	tsUDAT	100	—	—	ns	
I ² C 'L' Period of the SCL Clock	tLOW	1.3	—	—	μs	
I ² C 'H' Period of the SCL Clock	tHIGH	0.6	—	—	μs	
I ² C SDA Output 'L' Voltage	VOL	0	—	0.4	V	IOL = 3 mA

Figure C.3: Electrical characteristics of BH1750FVI light sensor [74].

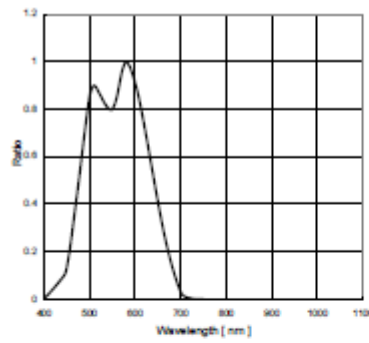


Fig.1 Spectral Response

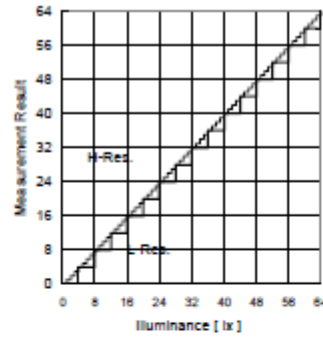
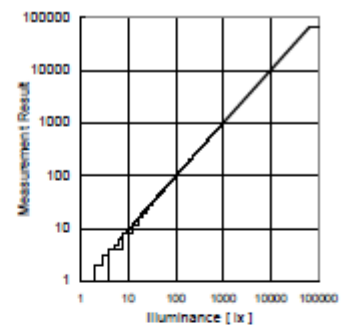
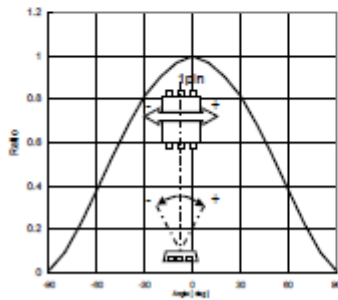
Fig.2 Illuminance -
Measurement Result 1Fig.3 Illuminance -
Measurement Result 2

Fig.4 Directional Characteristics 1

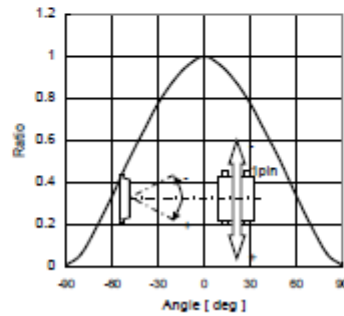


Fig.5 Directional Characteristics 2

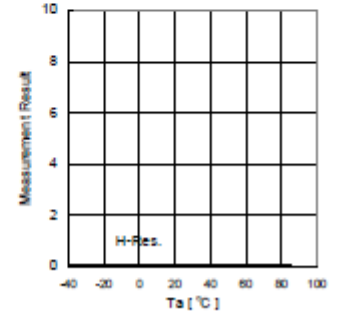


Fig.6 Dark Response

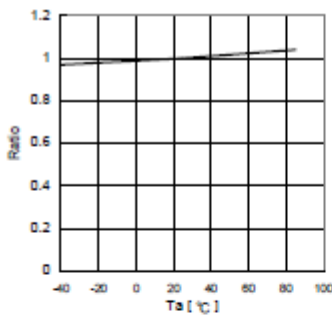
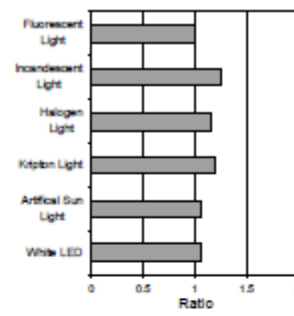
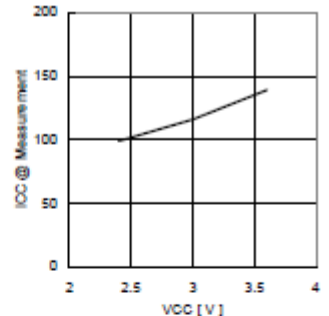
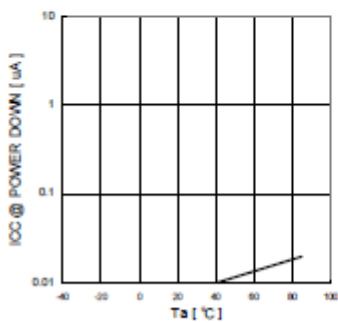
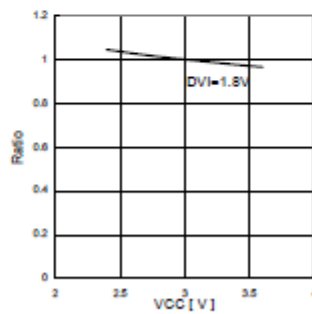
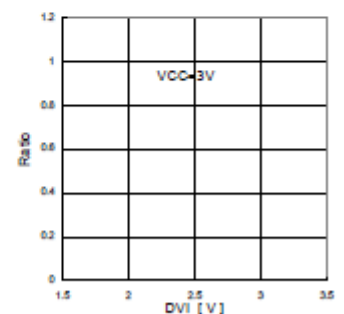
Fig.7 Measurement Accuracy
Temperature DependencyFig.8 Light Source Dependency
(Fluorescent Light is set to '1')Fig.9 VCC - ICC
(During measurement)Fig.10 VCC - ICC@0 Lx
(POWER DOWN)Fig.11 Measurement Result
VCC DependencyFig.12 Measurement Result
DVI Dependency

Figure C.4: Reference data of BH1750FVI light sensor [74].

RECOMMENDED DC OPERATING CONDITIONS(T_A = 0°C to +70°C, T_A = -40°C to +85°C.)

PARAMETER	SYMBOL	CONDITIONS	MIN	TYP	MAX	UNITS
Supply Voltage	V _{CC}		4.5	5.0	5.5	V
Logic 1 Input	V _{IH}		2.2		V _{CC} + 0.3	V
Logic 0 Input	V _{IL}		-0.3		+0.8	V
V _{BAT} Battery Voltage	V _{BAT}		2.0	3	3.5	V

DC ELECTRICAL CHARACTERISTICS(V_{CC} = 4.5V to 5.5V; T_A = 0°C to +70°C, T_A = -40°C to +85°C.)

PARAMETER	SYMBOL	CONDITIONS	MIN	TYP	MAX	UNITS
Input Leakage (SCL)	I _{LI}		-1		1	μA
I/O Leakage (SDA, SQW/OUT)	I _{LO}		-1		1	μA
Logic 0 Output (I _{OL} = 5mA)	V _{OL}				0.4	V
Active Supply Current (f _{SCL} = 100kHz)	I _{CCA}				1.5	mA
Standby Current	I _{CCS}	(Note 3)			200	μA
V _{BAT} Leakage Current	I _{BATLKG}			5	50	nA
Power-Fail Voltage (V _{BAT} = 3.0V)	V _{PF}		1.216 x V _{BAT}	1.25 x V _{BAT}	1.284 x V _{BAT}	V

DC ELECTRICAL CHARACTERISTICS(V_{CC} = 0V, V_{BAT} = 3.0V; T_A = 0°C to +70°C, T_A = -40°C to +85°C.)

PARAMETER	SYMBOL	CONDITIONS	MIN	TYP	MAX	UNITS
V _{BAT} Current (OSC ON); SQW/OUT OFF	I _{BAT1}			300	500	nA
V _{BAT} Current (OSC ON); SQW/OUT ON (32kHz)	I _{BAT2}			480	800	nA
V _{BAT} Data-Retention Current (Oscillator Off)	I _{BATDR}			10	100	nA

AC ELECTRICAL CHARACTERISTICS(V_{CC} = 4.5V to 5.5V; T_A = 0°C to +70°C, T_A = -40°C to +85°C.)

PARAMETER	SYMBOL	CONDITIONS	MIN	TYP	MAX	UNITS
SCL Clock Frequency	f _{SCL}		0		100	kHz
Bus Free Time Between a STOP and START Condition	t _{BUF}		4.7			μs
Hold Time (Repeated) START Condition	t _{HD:STA}	(Note 4)	4.0			μs
LOW Period of SCL Clock	t _{LOW}		4.7			μs
HIGH Period of SCL Clock	t _{HIGH}		4.0			μs
Setup Time for a Repeated START Condition	t _{SU:STA}		4.7			μs
Data Hold Time	t _{HD:DAT}		0			μs
Data Setup Time	t _{SU:DAT}	(Notes 5, 6)	250			ns
Rise Time of Both SDA and SCL Signals	t _R				1000	ns
Fall Time of Both SDA and SCL Signals	t _F				300	ns
Setup Time for STOP Condition	t _{SU:STO}		4.7			μs

Figure C.5: DS1307 electrical characteristics [76].

C.1 Codes

```

1 // Libraries
2 include <Wire.h>
3 include "RTCLib.h"
4 // Set PIN output
5 define LEDPIN 10
6 // Set how long the LEDS are ON (milliseconds)
7 const int TimeOperation =7200000; // 2 hours
8 // Set time between measurements
9 const int WaitTime=180000 // 3 minutes
10 // Identify the type of light meter
11 BH1750 LightMeter;
12 void setup(){
13     delay(10000);
14     Serial.begin(9600);
15 // Information about whether the light sensor is connected or not
16 if (LightMeter.begin()) {
17     Serial.println(("BH1750 initialised"));
18 }
19 else {
20     Serial.println(("Error initialising BH1750"));
21 }
22 // Begin connection of external devices to the Arduino
23 Wire.begin();
24 // Begin the measurement by the light sensor
25 LightMeter.begin();
26 Serial.println(("BH1750 measurements begins"));
27 // Set PIN 10 as output
28 pinMode(LEDPIN,OUTPUT);
29 // Necessary on Arduino boards with direct USB connection. Allows the serial port
30 // data to be opened by the serial software
31 while (!Serial);
32 }
33 void loop(){
34 // Assigns measurements to a variable
35 float LightIntensity = LightMeter.readLightLevel();
36 // Information about light intensity
37 Serial.println("Lux Levels: ");
38 Serial.println(LightIntensity);
39 // Threshold limits to activate LEDs
40 if( (LightIntensity > 400 and LightIntensity < 500) or (LightIntensity > 20000 and
41     LightIntensity < 30000)) {
42     // Turn LED ON
43     digitalWrite(LEDPIN, HIGH);
44     Serial.print("Sensor Triggered");
45     delay(TimeOperation);
46 }
47 else{
48     // Turn LED OFF
49     digitalWrite(LEDPIN, LOW);
50 }
51 Serial.println();
52 delay(WaitTime);
53 }

```

Listing C.1: Light meter code

```

1 // Libraries
2 include <Wire.h>
3 include "DS1307.h"
4 // Identify the type of RTC
5 DS1307 clock;
6 void setup(){
7     Serial.begin(9600);
8 // Sets time indicated

```

```

9      clock.begin();
      clock.fillByYMD(2022,6,30);
11     clock.fillByHMS(13,30,0);
      clock.fillDayOfWeek(THU);
13 // Write time to the RTC chip
      clock.setTime();
15 }
void loop(){
17     printTime();
}
19 // Information about current time
void printTime()
21 {
    clock.getTime();
23     Serial.print(clock.hour, DEC);
    Serial.print(":");
25     Serial.print(clock.minute, DEC);
    Serial.print(":");
27     Serial.print(clock.second, DEC);
    Serial.print(" ");
29     Serial.print(clock.month, DEC);
    Serial.print("/");
31     Serial.print(clock.dayOfMonth, DEC);
    Serial.print("/");
33     Serial.print(clock.year+2000, DEC);
    Serial.print(" ");
35     Serial.print(clock.dayOfMonth);
    Serial.print("*");
37     switch (clock.dayOfWeek)
    {
39         case MON:
            Serial.print("MON");
41         break;
            case TUE:
            Serial.print("TUE");
43         break;
            case WED:
            Serial.print("WED");
45         break;
            case THU:
            Serial.print("THU");
47         break;
            case FRI:
            Serial.print("FRI");
49         break;
            case SAT:
            Serial.print("SAT");
51         break;
            case SUN:
            Serial.print("SUN");
53         break;
55         break;
57         break;
59     }
61     Serial.println(" ");
}

```

Listing C.2: Set time of the RTC

```

// Libraries
2 include "RTClib.h"
// Define PIN output
4 define AlarmPin 10
int CountTime ;
6 // Choose alarm start and end for May
const int Alarm1[]={5,0,0};
8 const int AlarmEnd1[]={7,0,0};
const int Alarm2[]={20,0,0};
10 const int AlarmFim2[]={22,0,0};

```

```

const int CountAlarm1= Alarm1[0]*60*60+Alarm1[1]*60+Alarm1[2];
12 const int CountAlarmEnd1= AlarmEnd1[0]*60*60+AlarmEnd1[1]*60+AlarmEnd1[2];
const int CountAlarm2= Alarm2[0]*60*60+Alarm2[1]*60+Alarm2[2];
14 const int CountAlarmEnd2= AlarmFim2[0]*60*60+AlarmFim2[1]*60+AlarmFim2[2];
// Identify the type of RTC
16 RTC_DS1307 rtc;
void setup () {
18   delay(10000);
   //Set pin 10 as output
20   pinMode(AlarmPin,OUTPUT);
   // Necessary on Arduino boards with direct USB connection. Allows the serial port
   data to be opened by the serial software
22   while (!Serial);
   Serial.begin(9600);
24   // Information about whether the light sensor is connected or not
   if (! rtc.begin()) {
26     Serial.println("Couldn't find RTC");
     while (1);
28   }
   if (! rtc.isrunning()) {
30     Serial.println("RTC is NOT running!");
   }
32 }
void loop () {
34   // Assigns time to a variable
   DateTime Time = rtc.now();
36   // Information about current time
   Serial.println();
   Serial.print("Time: ");
   Serial.print(Time.year(), DEC);
40   Serial.print("-");
   Serial.print(Time.month(), DEC);
42   Serial.print("-");
   Serial.print(Time.day(), DEC);
44   Serial.print("-");
   Serial.print(Time.hour(), DEC);
46   Serial.print("-");
   Serial.print(Time.minute(), DEC);
48   Serial.print("-");
   Serial.print(Time.second(), DEC);
50   Serial.println();
   if(CheckAlarm1(Time) or CheckAlarm2(Time)){
52   // Turn LED ON
     digitalWrite(AlarmPin, HIGH);//
54     Serial.print("Alarm Triggered");
     delay(60000);
56   }
   if(CheckAlarmEnd1(Time) or CheckAlarmEnd2(Time)){
58   // Turn LED OFF
     digitalWrite(AlarmPin, LOW);
60     delay(60000);
   }
62 }
boolean CheckAlarm1(DateTime timeNow){
64   if(
   // Compares month and days of the month
66   timeNow.month()==5
   &&
68   timeNow.day()>=1
   &&
70   timeNow.day()<=25
   // Counts seconds of current time
72   CountTime=timeNow.hour()*60*60+timeNow.minute()*60+timeNow.second();
   // Compares current time with alarms
74   CountTime>=CountAlarm1
   &&
76   CountTime<=CountAlarmEnd1

```

```

    ){
78     return true;
    }else{
80     return false;
    }
82 }
boolean CheckAlarmEnd1(DateTime timeNow){
84     if(
        timeNow.month()==5
86     CountTime=timeNow.hour()*60*60+timeNow.minute()*60+timeNow.second();
        CountTime>CountAlarmEnd1
88     &&
        CountTime<CountAlarm2
90     ){
        return true;
92     }else{
        return false;
94     }
    }
96 boolean CheckAlarm2(DateTime timeNow){
    if(
98     timeNow.month()==5
        CountTime=timeNow.hour()*60*60+timeNow.minute()*60+timeNow.second();
100     CountTime>=CountAlarm2
        &&
102     CountTime<=CountAlarmEnd2
    ){
104         return true;
    }else{
106         return false;
    }
108 }
boolean CheckAlarmEnd2(DateTime timeNow){
110     if(
        timeNow.month()==5
112     CountTime=timeNow.hour()*60*60+timeNow.minute()*60+timeNow.second();
        CountTime>CountAlarmEnd2
114     ){
        return true;
116     }else{
        return false;
118     }
    }
}

```

Listing C.3: Alarm with RTC code

```

1 // Libraries
  include "ArduinoLowPower.h"
3 // Declare variable volatile since it's incremented inside an interrupt
  volatile int Repetitions = 1;
5 // PIN used to trigger a wakeup
  const int PIN = 8;
7 void setup() {
    pinMode(LED_BUILTIN, OUTPUT);
9 // Set pin 8 as INPUT_PULLUP to avoid false wakeups
    pinMode(PIN, INPUT_PULLUP);
11 // Attach a wakeup interrupt on pin 8, calling repetitionsIncrease when the device
    is woken up
    LowPower.attachInterruptWakeup(PIN, RepetitionsIncrease, CHANGE); //Change means
    the PIN voltage needs to change
13 }
void loop() {
15     for (int i = 0; i < Repetitions; i++) {
        //Blinking of built-in LEDs
17         digitalWrite(LED_BUILTIN, HIGH);
        delay(500);
19         digitalWrite(LED_BUILTIN, LOW);
    }
}

```



```
21     delay(500);  
    }  
    // Triggers an infinite sleep (the device will be woken up only by the registered  
    // wakeup sources, like the DS3231 RTC)  
23    LowPower.deepSleep();  
    }  
25    void RepetitionsIncrease() {  
    // This function will be called once on device wakeup  
27    Repetitions ++;  
    }
```

Listing C.4: Sleep mode using external interrupt

Appendix D

Prototype conceptual design and performance results

D.1 Prototype conceptual design

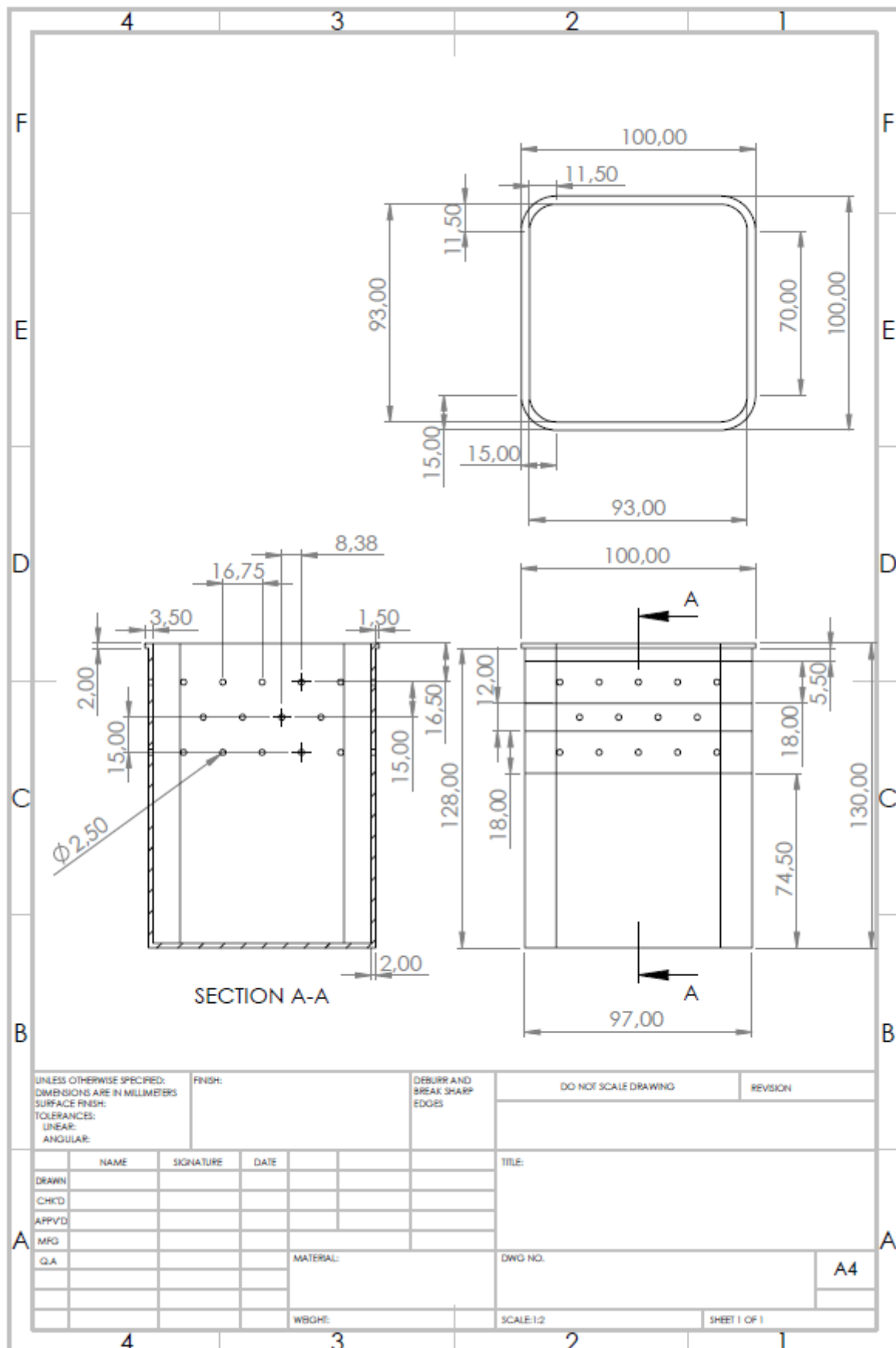


Figure D.1: Bait holder conceptual design technical drawing (scale 1:2).

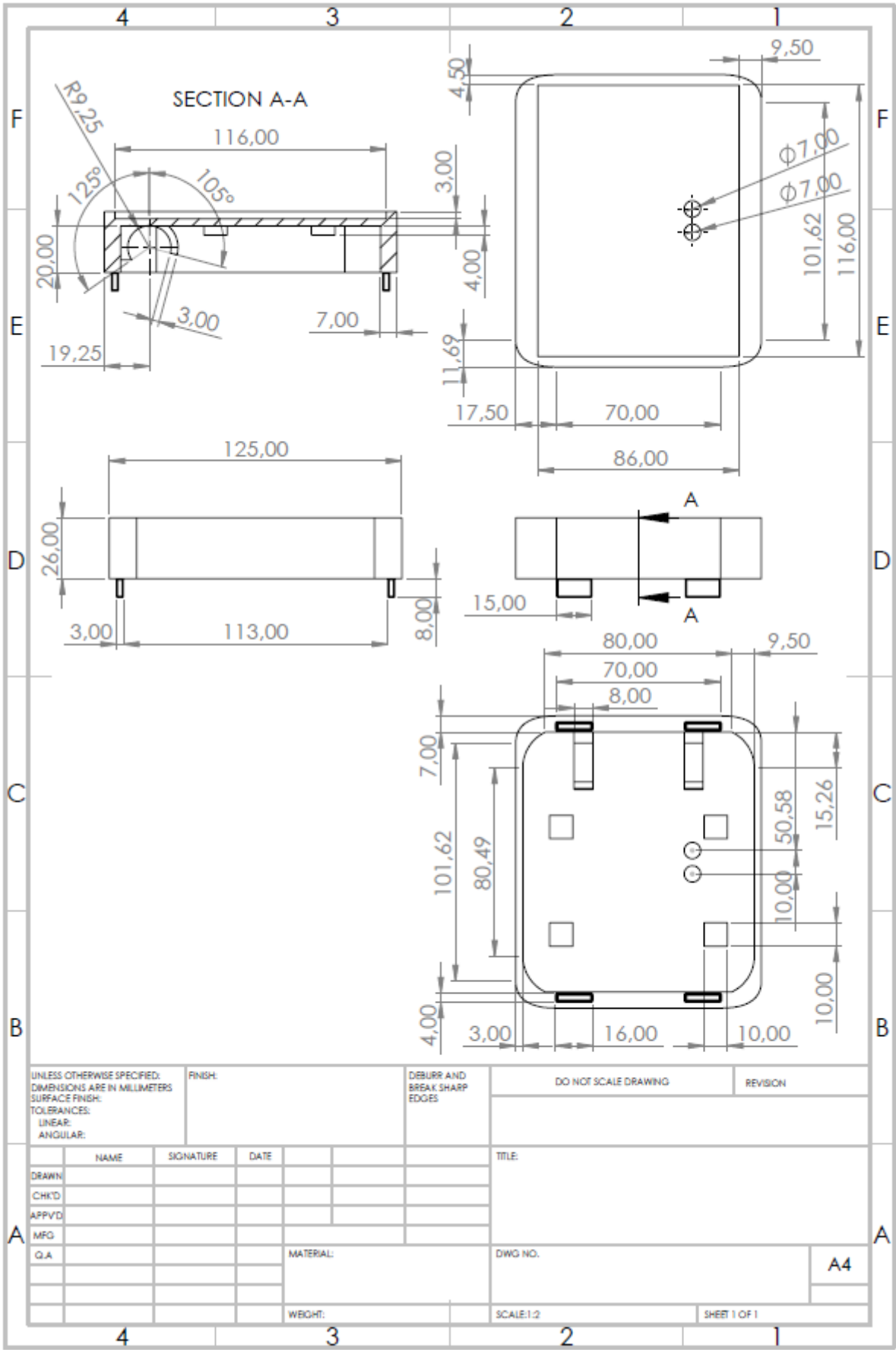
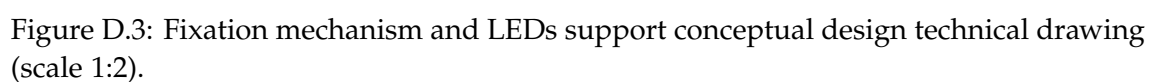


Figure D.2: Lid conceptual design technical drawing (scale 1:2).



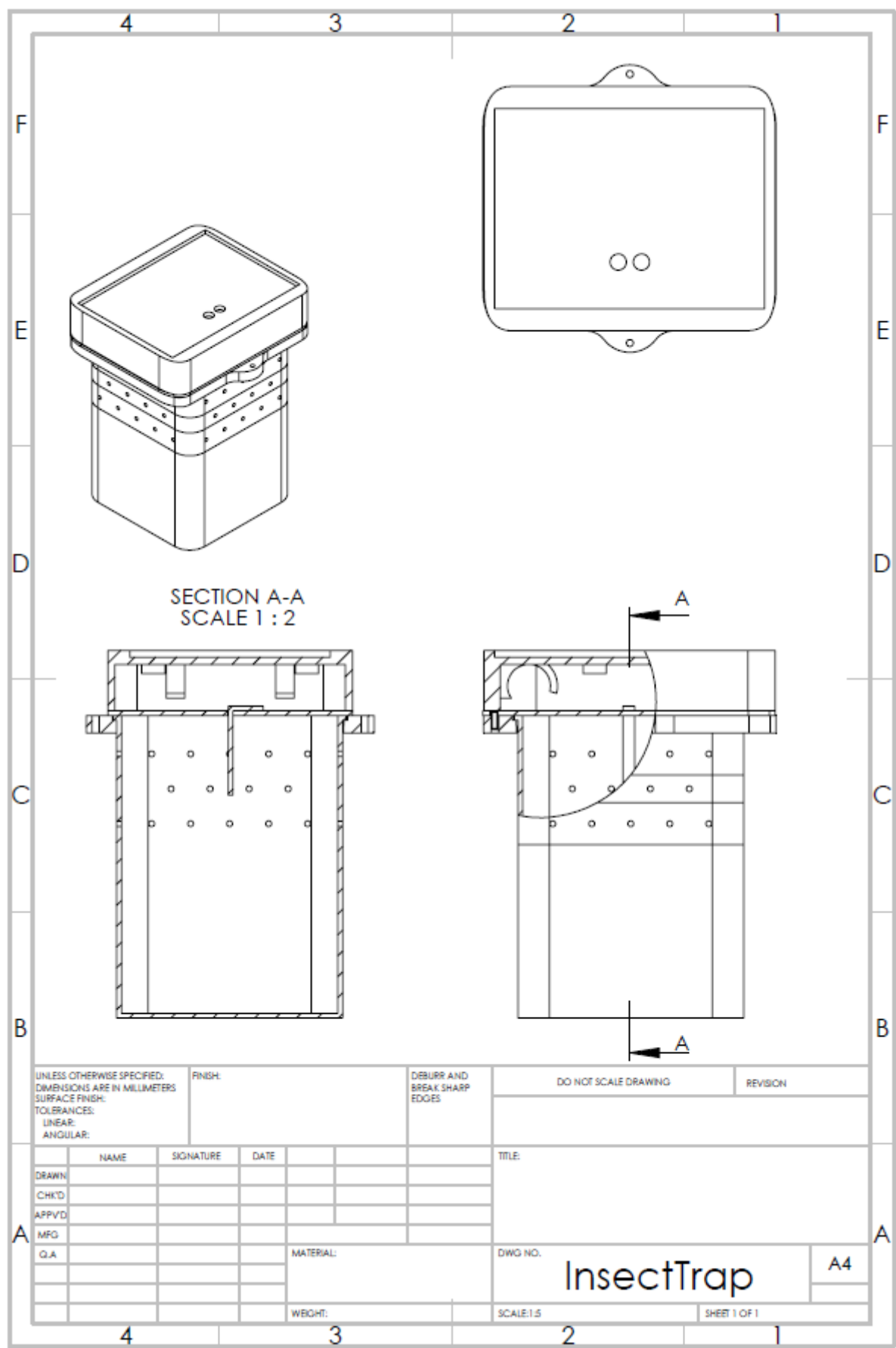


Figure D.4: Mechanical assembly drawing conceptual design (scale 1:2).

D.2 Performance results

Table D.1: Voltage values measured at each instant of time obtained by the discharge experimental test at 380 mA constant current.

Voltage [V]	Time [min]	Capacity [%]
4,20	0	100,00
4,06	7	98,57
4,04	13	97,35
4,03	19	96,13
4,01	30	93,88
3,96	42	91,44
3,90	55	88,79
3,88	66	86,55
3,84	76	84,51
3,81	87	82,26
3,78	98	80,02
3,74	111	77,37
3,71	122	75,13
3,68	127	74,11
3,66	143	70,85
3,63	158	67,79
3,60	175	64,32
3,59	195	60,25
3,57	214	56,37
3,54	240	51,07
3,53	249	49,24
3,52	265	45,98
3,50	281	42,71
3,47	300	38,84
3,43	320	34,76
3,40	340	30,69
3,37	356	27,42
3,35	375	23,55
3,33	391	20,29
3,29	407	17,03
3,10	429	12,54
3,05	434	11,52
2,98	440	10,30
2,91	446	9,08
2,83	452	7,85
2,73	458	6,63
2,63	466	5,00

Table D.2: Voltage values measured at each instant of time obtained by the charge experimental test with a 2 A maximum current charging device.

Voltage [V]	Time [min]
2,54	0
2,8	0
3,03	0
3,09	0
3,13	1
3,16	2
3,19	2
3,23	3
3,26	4
3,3	5
3,33	6
3,37	7
3,4	8
3,43	9
3,44	12
3,45	14
3,46	18
3,5	25
3,52	28
3,57	34
3,61	46
3,65	58
3,69	69
3,73	80
3,78	91
3,9	111
3,96	122
4	133
4,05	144
4,08	155
4,1	167
4,13	179
4,14	191
4,17	205
4,2	210